Zero Emission Drive Unit - overview of the braking concepts

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Abstract. As part of the ZEDU1 (Zero Emission Drive Unit Generation 1) project, both a conventional electric vehicle, as a reference vehicle, and a test vehicle of the Zero Emission Drive Unit, were designed for metrological characterization and tested. A central element of the project was the investigation and characterization of a cast iron and a carbide-coated brake disc in real operation as well as on a component test bench. The influence of recuperation on the braking emissions of airborne particles was also measured.

The measurement results show that the temperature of the brake mainly has an influence on the generation of particles in the size range of 10 nm, whereas the braking process mainly produces particles in the size range 200 nm to 300 nm.

It was also shown by measurement results that recuperation during real driving, RDE cycle, can reduce airborne abrasion emissions by up to almost 90 %. A further reduction in abrasion of up to 83 % was determined for particles of size 300 nm to 10 µm for carbide-coated brake discs.

In the course of the measurements, it was shown that the driving cycles used to determine the brake abrasion have a decisive influence on the measurement results.

In the scope of the project a novel braking system without airborne abrasion emissions was developed and validated. For this purpose, a demonstrator vehicle, as a carrier of the newly developed technology, the ZEDU1 unit, was designed, constructed, built, measured and examined for its suitability for everyday use. Suitable methods and measurement concepts for on-board characterization have also been developed and successfully implemented in use.

Furthermore, the full functionality as well as fatigue strength and thus suitability for everyday use were confirmed for the developed multi-disc brake.

Keywords: ZEDU1, particulate matter, ultrafine dust, brake abrasion, brake emissions, abrasion emissions, non-exhaust emission, emissions from non-combustion processes, PM_{10}, $PM_{2.5}$, multi-disc brake, carbide coating, recuperation.

1 Introduction

In addition to exhaust fumes from combustion engines, particulate matter in particular pollutes the environment. These are small particles that are emitted into the air and are less than 10 microns in diameter. Particulate matter can come from a variety of sources. The largest share comes from traffic. In Stuttgart at the Neckartor, this is about 58 % LUBW [1]. A particularly high proportion of traffic emissions is recorded for ultrafine particulate matter (UFP). The particulate matter pollution can lead to significant health problems. In particular, the exposure to ultrafine particles, as these are not only respirable (see **Fig. 1**), but also penetrate to the alveoli (approx. 50 %) [2], penetrate into the lung tissue there and thus pass into the bloodstream and thus affect all organs [3]. Due to their high surface area in relation to their size, these particles, although their contribution to the mass is rather small, can have a high potential for health hazards, depending on their nature [2, 22]. The WHO sees a reduction in particulate matter pollution as a reduction in the burden of disease in asthma, lung cancer, stroke, cardiovascular diseases as well as acute and chronic respiratory diseases and therefore recommends reducing the limit value for $PM_{2.5}$ to 5 µg/m 3 and for PM_{10} to 15 µg/m3 [4]. From this, the EU derived new binding limit values for the member states, of less than 10 µg/m 3 for $PM_{2.5}$ and 20 µg/m3 for PM_{10}, for 2030, as well as the achievement of zero air pollution by 2050 at the latest [5, 6].

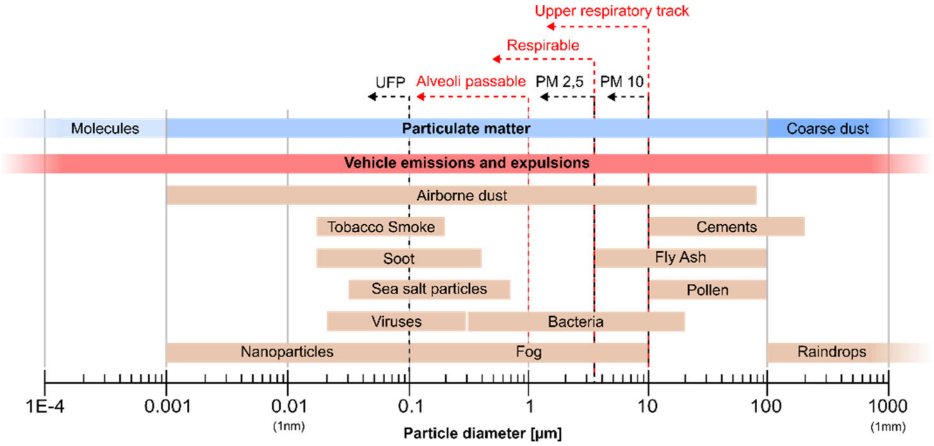

Fig. 1. Fine dusts and particle diameters

In order to counteract particulate matter pollution, the EU is introducing at Euro 7 limits for brake abrasion of 7 mg/km as of 1.7.2025 (plan), which is later to be reduced to 3 mg/km.

The electrification of transport alone is not a solution as far as particulate matter emissions from non-combustion processes, such as brake abrasion, are concerned. The proportion of fine congestion from non-combustion processes is steadily increasing and has been higher than the proportion from combustion processes since 2013 for PM_{10}

and since 2018 for $PM_{2.5}$ [7]. This is due to the increase in mileage and the increase in vehicle weight.

As part of the ZEDU1 (**Z**ero **E**mission **D**rive **U**nit Generation **1**) project, new innovative solutions for brake and tire abrasion were investigated and implemented. Both a conventional electric vehicle, as a reference vehicle for the metrological characterization of the state of the art, and a demonstrator vehicle, which is used as a carrier of the newly developed technology, the Zero Emission Drive Unit, were designed, constructed, built, measured and examined for its suitability for everyday use. Methods and suitable measurement concepts for online on-board characterization were also developed and successfully tested in use.

2 Brake concepts

For a selection of braking concepts for the abrasion-emission-free ZEDU1 unit, five concepts were shortlisted and evaluated [20, 21]. **Table 1** shows the evaluation of the concepts.

Table 1. Evaluation of braking concepts.

Concept	Coating	Partial filters	Encapsulation	Multi-disc	Induction
Emissions	reduced	reduced	none	none	none
Effort	no	small	medium	medium	very high
Risk	None	small	very high	small	very high
Weight	very low	small	medium	small	medium
Cost	very low	very high	high	small	high
Assessment	+	--	0	+++	++
Development	Frenoza			HWA	DLR

Since the claim was to completely avoid brake abrasion, the ZEDU1 project did not look further at the braking concepts with partial emissions of brake abrasions, but developed a wet multi-disc brake and an induction hybrid brake up to TRL level (Technology Readiness Level) 7 or 6 and tested it as a prototype in a test vehicle, or on the test bench in the case of the hybrid brake, characterized and tested.

The braking concept of a metal-coated brake disc was given a special position. With regard to future Euro 7 with limit values for brake emissions, potential was seen in this concept. In this context, also due to the relatively low technical effort and the cost structure, metal-coated brake disc was included in the reference studies for characterization.

At this point, only the individual development concepts will be briefly discussed in the further course and the investigations on reference characterization will be reported.

2.1 Multi-disc brake

As part of the ZEDU1 project, HWA developed and built a multi-disc brake suitable for everyday use as a compact transmission brake unit [8, 20]. This was first tested on a test bench, put into operation and then installed in the ZEDU1 test vehicle [21].

The multi-disc brake consists of a multi-disc package consisting of seven steel ring slats. Every second slat is interlocked with the gear ring which is permanently connected to the housing. The other slats are toothed with the planetary gear, which is coupled to the shaft via sun gear. Thus, achieving a gear ratio of 1.9 for the rotating slats and reduces the rotational speed of the fin and possible oil splash losses.

The multi-disc brake is actuated via a Break by Wire System (BBW) and is flanged directly onto the electric motor as a very compact package. This is controlled by the specially developed Vehicle Control Unit (VCU) software. Most of the braking deceleration is recuperated VCU-controlled via the electric motor as well as the high-performance electronics and battery specially developed for this purpose. If necessary, the remaining torque is generated mechanically by pressing the slats together. At the same time, oil is supplied to the system and thus the thermal management is regulated.

An emergency mode has also been implemented. In the event of a failure of the electrical system, the disc pack is actuated directly via hydraulics as a through-drive and thus braked purely mechanically. This is designed in such a way that the vehicle is brought to a complete standstill from a speed of 100 km/h without further braking assistance in at least 168 m.

2.2 Tungsten carbide coated brake disc

In order to investigate the potential of a carbide coated brake discs, a conventional cast iron brake of the reference vehicle, BMW i3, from Frenoza GmbH was coated. For this purpose, first a connecting layer of stainless steel and then a carbide layer of 20 % tungsten carbide with 30 % titanium carbide in a 50 % ductile matrix of stainless steel was applied over an oxy-fuel coating [9].

Fig. 2. Original cast iron brake disc of the BMW i3

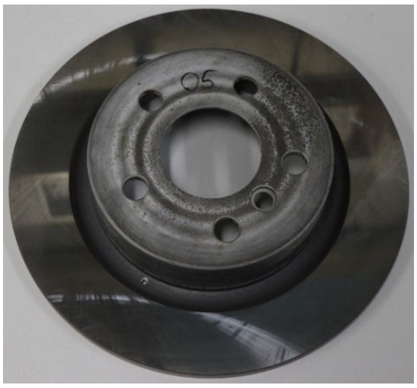

Fig. 3. Tungsten carbide-coated brake disc of the BMW i3

Fig. 2 shows the original brake disc and **Fig. 3** shows the carbide-coated brake disc**.** This was then measured both in the reference measuring vehicle and on a component test bench and compared with the uncoated original brake in terms of abrasion emission behavior with regard to airborne particles.

2.3 Induction hybrid brake

Parallel to the multi-disk brake, an induction hybrid brake was developed, designed, built and validated in the project, starting with the design, modelling and field calculation to design and construction [10, 11].

The fundamental challenges with this braking system are, on the one hand, the low power density resulting from the skin effect and the thermal management, and, on the other hand, the fact that at low speeds the induction and thus the braking torque is also lower. So that there is no braking at zero speed.

The basic challenges of this braking system are on the one hand the low power density resulting from the skin effect and the thermal management, and on the other hand the fact that at low speeds the induction and thus the braking torque is also lower. So that at zero speed there is no braking.

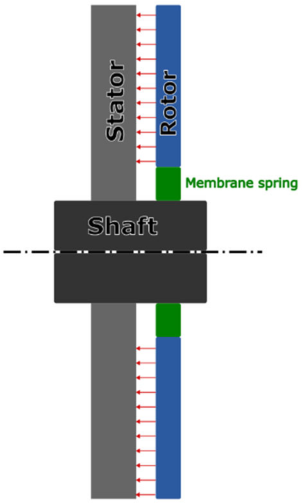

Fig. 4. Induction hybrid brake. Schematic diagram.

To solve this, the pure induction brake was designed as a hybrid brake [12]. **Fig. 4** shows the functional principle. Friction surfaces were designed in the space between the stator and rotor. By utilizing the magnetic attraction force between the rotor and stator, a gap is maintained between the two components with the help of a spring. At low speeds, the electromagnetic braking torque decreases. The axially acting reluctance force increases and enables braking to a standstill by decelerating through friction between the rotor and stator. The achievement of the required power densities was realized by developed structures made of anisotropic materials. The high temperatures caused by the required power densities generated in this way were released via thermal management of the stator and the resulting heat was dissipated via water glycol.

The characterization and investigations of this brake are not part of this article. The results have been published in a separate publication [see also 10, 11,12 & 21].

2.4 Reference brake

The original cast iron brake of the BMW i3 was used as a reference for determining brake abrasion emissions. On the one hand, with the developed method and the measurement concept, brake abrasion size distribution could be determined from 4 nm to 10 µm and a conventional electric vehicle could be characterized. On the other hand, this concept served as a comparison in relation to the other brake concepts that were examined.

3 Measurement concept and experimental set-up

3.1 Metrology

The measurement technique was chosen to determine the size-distributed particle number concentration (PNC) of airborne particles (PSD) of non-exhaust emissions. The devices were combined in such a way that they cover the entire measuring range 4 nm (UFP) to 10 µm (PM10).

In addition, this option also allows it to be used for mobile measurement in real road traffic. An overview of the measuring instruments used and the respective measuring ranges is given **Fig. 5**. For example, the particle concentration was measured with a condensation particle counter (CPC) from TSI GmbH. The particle size distribution was measured with an EEPS and OPS from TSI GmbH. For offline analysis, samples were also collected with the low-pressure cascade impactor ELPI+, and analyzed using scanning electron microscopy with X-ray spectroscopy, or SEM-EDX for short.

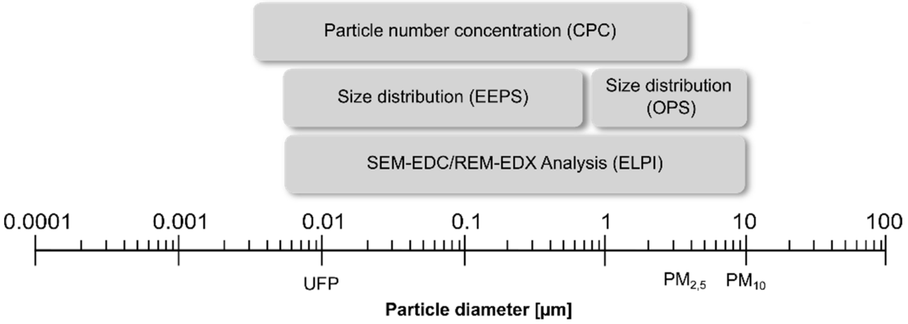

Fig. 5. Measuring ranges and used measurement equipment

3.2 Reference vehicle

Selection of test vehicles

A BMW i3 was chosen as the test setup to characterize the standard cast iron brake for conventional electric vehicles and the carbide-coated brake disc. Due to its rear-wheel drive, this vehicle enables a simplified separate enclosure of the brake on the awkward rear brake and, via special approval, an investigation of brake abrasion not only on DLR's own chassis dynamometer, but also in real road operation such as the DLR-RDE (Real Drive Emission) test track. The BMW i3 used was built in 2015 with a curb weight of 1228 kg and a battery with a capacity of 60 Ah.

Measurement concept

In order to clearly determine the brake emissions, the rear brake was separated by a spacer plate.

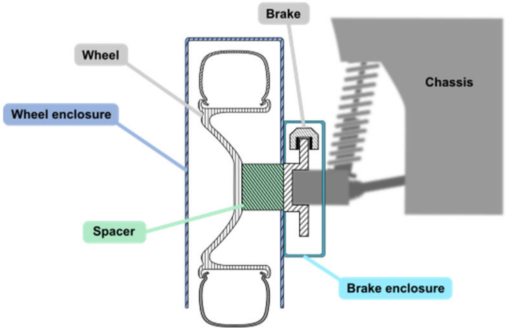

Fig. 6. Test concept for brake emissions measurement

As a result, the brake removed from the wheel could be enclosed (**Fig. 6**) [13] and the airborne abrasion emissions could also be measured in mobile use, regardless of those of the tire. For temperature adjustment, thermal management was implemented via ventilation with two fans [17, 19].

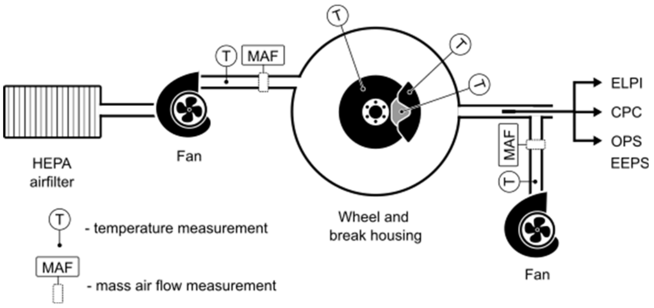

Fig. 7. Measurement concept for sampling brake emissions on the reference vehicle

For this purpose, the temperature of the brake was recorded during a real drive and the volume flow of the ventilation was regulated in such a way that it is within the permissible temperature range of the PMP-Group recommendation. In addition, a volume flow rate of 31 m^3/h for the brake abrasion measurements was evaluated. As a check, the brake temperatures on both brakes were measured during the tests. For the examination, the temperature of the test specimen is measured on the brake disc via telemetry, the brake shoes and the brake pads.

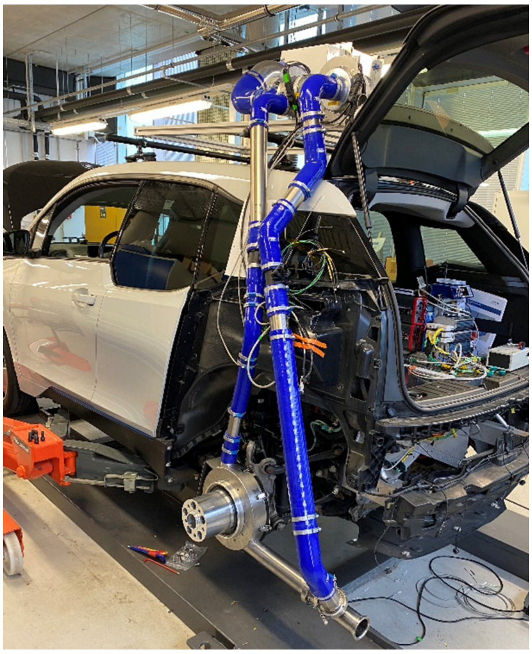

Fig. 8. Enclosure and ventilation system of the brake on the reference test vehicle

To demonstrate a zero-emission vehicle, a test vehicle with the ZEDU1 concept was designed and built. The ZEDU1 unit was used, consisting of two electric motors close to the wheels with integrated lamella brakes and corresponding wheel housings with tire abrasion extraction and filter system. Together with the project partner HWA, a separate powertrain, including the VCU, was developed for the vehicle.

3.3 ZEDU1 - Experimental vehicle

To demonstrate a zero-emission vehicle, a test vehicle with the ZEDU1 concept was designed and built. The ZEDU1 unit was used, consisting of two electric motors close to the wheels with integrated lamella brakes and corresponding wheel housings with tire abrasion extraction and filter system [20]. Together with the project partner HWA, a separate powertrain, including the VCU, was developed for the vehicle.

Fig. 9. ZEDU1 test vehicle on the test

Early on in the project, the decision was made to choose the multi-disc brake to be integrated into the ZEDU1 demonstrator, as this can be implemented more critically in development and at a higher TRL level during the project period (**Table 1**).

Measurement concept

The test vehicle was equipped with the same measurement technology similar to that of the reference vehicle (see above). Since the multi-disc brake, as an encapsulated system, has no braking emissions, these have only been used to determine the airborne tire abrasion emissions. For the characterization of the multi-disc brake, additional measurement technology was installed. This includes temperature measurement, determination of braking torques and pressures in the hydraulic braking system as well as current and voltages of the high-voltage system to detect the amount of energy recuperated during braking.

3.4 Driving cycles

The standard-compliant driving cycles WLTC Class 3b, WLTC Brake Part 10, RDE-Cycle as well as the ZEDU-Accelerate and ZEDU-Brake defined in the project were used as test cycles.

The ZEDU Accelerate cycle is a driving cycle in which the driving speed is increased in 30 km/h increments from 30 km/h to 120 km/h and driven consistently for a while. The speed is reduced to 0 km/h between the gears.

The ZEDU-Brake is a defined driving cycle in which it is strongly certified up to 80 km/h and braked to 0 km/h after a short holding time. At the same time, the braking deceleration becomes more and more pronounced with each subsequent braking process.

Through the use of precisely defined driving cycles, it was possible to carry out reproducible and comparable measurements both on the test benches and in real use.

On the one hand, the RDE cycle was recorded during real driving including speed, acceleration and gradient over time in order to be able to drive it under controlled conditions. *On the other hand*, e.g. the WLTC driving profile was designed also to be shown on a display as a speed sol specification and the speed correlates with it in order to be able to drive e.g. WLTC with the test vehicle on the test site.

3.5 Test environment

The investigations into brake abrasion were carried out on the DLR chassis dynamometer, a test site, a component test bench and on **DLR's own RDE track**.

RDE route

The tests were carried out in the vicinity of Stuttgart, where a standard-compliant route was defined that starts and ends at the DLR site. The DLR-RDE route has a length of 47.4 km and takes about 3619 s with a city share of 50 %, a share of intercity travel of 31 % and a motorway trip of 19 % (**Fig. 10**).

Fig. 10. Real RDE test drive with the reference vehicle

Chassis dynamometer

The air-conditioned four-wheel chassis dynamometer was used for measurement with standard-compliant cycles such as the WLTPC, but also for reproducing the RDE track. This consists of four independent 48" rollers with 100 kW each and one 3600 N per wheel. This means that vehicles weighing up to 4.5 tons and a wheelbase of up to 4 m can be tested in a climate environment of -40 °C to 60 °C and a relative humidity of up to 80%. On the test bench, all driving cycles including gradients can be driven in road simulation. The test bench has been approved by TÜV according to GTR15 and certified according to ISO 9001 [14].

Proving ground

For special driving maneuvers but also, since the test vehicle is not approved to drive on public roads, these tests were *dodged* on test sites. The Bosch test site in Boxberg [20] and a test site in Asperg were used.

Component test bench

In order to correlate the measurements carried out with measurements on a component test bench, the original BMW i3 brakes and the carbide-coated brake discs were carried out with the original brake pads on the test bench of Horiba in Flörsheim.

To ensure comparability, a size-dependent calibration was carried out with the help of a particle generator. The test measurements on the component test bench were carried out with the same DLR equipment, which was also used in the tests on the chassis dynamometer and on the road.

4 Results

4.1 Characterization of particulate emissions

Particulate emissions

Investigations of braking emissions with the ZEDU Accelerate cycle show that braking emissions occur not only during braking, but also during constant driving and acceleration processes. When looking at the size distribution, two main emission modes can be seen. One around ultrafine range with approx. 10 nm and a second range 200 nm to 300 nm. During constant speeds, the number of emissions of particles with a particle size between 200 nm and 300 nm is significantly higher than that of the order of 10 nm and increases many times over during braking [16].

Temperature

The ZEDU-Brake was used to investigate the influence of temperature. The temperature of the brake rose rapidly. When looking at the size distribution of the brake emissions for different temperature windows, two emission modes can also be seen. One around ultrafine range with approx. 10 nm and a second range 200 nm to 300nm. In contrast to the emissions during constant speeds, the number of emissions of particles with particle sizes of 200 nm to 300 nm is essentially constant for the different temperatures and the same speed. In the range of the order of magnitude of 10 nm, these remain constant in the temperature range between 20 °C and 245 °C and increase significantly exponentially with temperature after this critical temperature. The increase in brake emissions here is due to the increase in UFP particles [16].

4.2 Influence of recuperation on abrasion emissions

In order to investigate the influence of recuperation on brake particle emissions, driving tests were carried out with the BMW i3 in standard operating mode and with deactivated recuperation with the driving profiles WLTC 3b, RDE on the chassis dynamometer and on the WLTC-Brake Part 10 component dynamometer. Particle emissions, brake temperature, speed and, to detect the number of braking events., hydraulic pressure at the brake system were measured

A relative reduction in braking emissions could be measured for all driving profiles when recuperation was switched on. However, the reduction in emissions is highly dependent on the driving profile. This was highest during real driving (RDE cycle). In this cycle, a reduction of 89.8 % was measured for the ultrafine and fine particles (4 nm to 3µm). For the WLTC Class 3b driving cycles, 65.4 % and for the WLTC Brake Part 10 only 4.3 % [16].

Table 2. Reduction of braking emissions of ultrafine and fine particles through recuperation in the size range 4 nm to 3 µm for different test cycles [16].

Cycle	PN reduction through recuperation (%)
Real Driving Cycle (RDE)	89,8
WLTC Class 3b	65,4
WLTC Brake Part 10	4,3

4.3 Influence of carbide coating on abrasion emissions

In addition to the influence of recuperation on brake emissions, the effect of the carbide coating on electric vehicles was also investigated and compared with the original cast iron brakes of the BMW i3. The same original brake pads were used for the carbide-coated brake disc as for the cast iron brake. The determination of the coefficient of friction shows that, depending on the driving cycle, an improvement in the coefficient of friction ratio due to the coating is between 1.1 and 2.

Abrasion measurements

The investigations of the effect of the carbide coating of the brake disc were carried out both on the chassis dynamometer and on the component dynamometer. Here, too, the WLTC Class 3b, WLTC-Brake Part 10 and the DLR-RDE cycle for real journeys were used to characterize the emissions. Also, in the case of the carbide-coated brake, the airborne abrasion emission measurements show the greatest savings with 83% in the RDE cycle for the particles with the size distribution in the range 300 nm to 10µm (OPS measurement) and a saving of aprox.79 % in the ultrafine and fine particles in the size range 4 nm to 3 µm (CPC measurement) [16].

Tabele 3. Mass loss of cast iron brake (brake disc and brake pads) and one carbide-coated brake (brake disc and brake pads) per 100 km [16].

Cycle	**PN-Reduction** 4 nm – 3 µm (CPC) (%)	**PN-Reduction** 300 nm – 10 µm (OPS) (%)
Realer Fahrzyklus (RDE)	78,9	83
WLTC-Brake Part 10	71,7	78
WLTC Class 3b	18,5	33,9

Gravimetric determination

Before the start of the measurement campaigns on the component test rig, both the original brake discs and the coated brake discs and the associated brake linings were weighed. These were also weighed again after the end of the measurement campaign. During the measurement campaign, a total of 1,684 km was driven with the original cast iron brake and 1,127 km with the carbide-coated brake. This includes different driving cycles.

Tabele 4. Mass loss of cast iron brakes (brake disc and brake pads) and a carbide-coated brake (brake disc and brake pads) per 100 km.

Brake	**Mass loss** (g/100 km)
Cast iron brake	0,77
Carbide-coated brake	0,20

The measurements show a higher mass loss of the cast iron brake by a factor of 3.85 compared to the coated brake. *Or* a reduction in abrasion emissions through coating by an average of 74 % over all cycles.

4.4 Multi-disc brake

The multi-disc brakes were examined on the roller test stand and in the Boxberg test site [20]. The same cycles were used for characterization as for measurements on the reference vehicle: WLTC Class 3b, WLTC Break Part10 and ZEDU Accelerate. When inserting the slats, the ZEDU1 vehicle showed the same braking behavior as when using the disc brake and was able to apply all braking decelerations specified by the driving cycles up to the adhesion limit of the tire. The resulting maximum temperatures of up to 95 °C as a peak temperature are far below the maximum permitted. The consideration of the recuperation energy for the ZEDU brake cycle, *on the one hand*, with the disc brakes installed in the vehicle and in comparison, to the multi-disk brake, *on the other hand*, also shows identical behavior when placed on top of each other. The characterization of the multi-disc brake shows that this braking system is durable and suitable for everyday use.

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