

Article

Evaluation of Active and Passive Brake Emission Mitigation Strategies in Real Driving Scenarios

Alexander Hentschel ¹, Miles Kunze ¹, Patrick Habedank ¹, Valentin Ivanov ¹ and Sebastian Gramstat ^{2,*}

¹ Smart-Vehicle-Systems Working Group, Department of Control Engineering, Technische Universität Ilmenau, Robert-Bosch-Ring 1, 98693 Ilmenau, Germany; alexander.hentschel@tu-ilmenau.de (A.H.); miles.kunze@tu-ilmenau.de (M.K.); patrick.habedank@tu-ilmenau.de (P.H.); valentin.ivanov@tu-ilmenau.de (V.I.)

² Audi AG, Auto-Union-Straße 1, 85057 Ingolstadt, Germany

* Correspondence: sebastian.gramstat@audi.de; Tel.: +49-3677-69-1338

Abstract

Brake wear particles are an increasingly relevant source of traffic-related particulate emissions and are addressed by the recently introduced Euro 7 emission regulation. Airborne fractions of brake wear emissions, in particular, have been associated with adverse effects on human health and other organisms. Although several brake particle mitigation strategies have demonstrated promising results under controlled laboratory conditions, their effectiveness under variable open-road driving conditions remains insufficiently understood. This study therefore investigates the transfer of two test-bench-validated mitigation strategies to a fully instrumented passenger vehicle capable of measuring brake particle number (PN) and particulate mass (PM) emissions. The first strategy is a passive approach based on a modified brake pad–disc material pairing, while the second is an active filtration system that extracts particle-laden air directly from the brake friction zone. Both approaches were evaluated during two open-road driving cycles: a real driving emissions (RDE)-compliant cycle and a more dynamic cycle characterized by higher brake stress. Airborne particle emissions were measured over a size range from 300 nm to 10 µm. During the RDE-compliant cycle, the passive approach reduced PN and PM emissions by 44% and 94%, respectively, compared with the reference brake system. Under the higher thermal and mechanical loads of the dynamic cycle, the reductions decreased to 10% for PN and 64% for PM. The active filtration system achieved an increase in PN of 4% in RDE conditions and 11% under high-severity driving. Nevertheless, PM emissions were reduced by 23–97%, depending on its operating mode of the filtration system and the associated airflow and energy demand. For high-severity driving, the PM emissions have been reduced by 40% compared to the reference braking system. These results show that both mitigation approaches hold the potential to reduce brake particle emissions under open-road conditions, although their effectiveness depends strongly on brake load and system operation. The study extends previous laboratory-based investigations by directly comparing passive and active mitigation strategies on the same vehicle under real-world driving conditions.

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1. Introduction

As the contribution of exhaust emissions to total road-traffic particulate matter continues to decline, non-exhaust sources are becoming increasingly important. This trend may be further intensified by the increasing mass and performance of modern vehicles. Current emission inventories indicate that exhaust emissions, tire and road wear, and brake wear can contribute comparable shares to total vehicle-related particulate emissions. Especially for smaller vehicles as passenger cars or vans, brake emissions contribute the most to PM₁₀ with almost 35% of the whole emission level, whereas on larger vehicles exhaust emissions still dominate the overall emission balance of the vehicle. For PM_{2.5} emissions, shares of emission sources are equal between tire and road wear, brake particle emissions and exhaust emissions [1]. Environmental concerns have received increasing attention for several decades, which has obliged governments to impose limitations on vehicle emissions since the 1960s in the USA [2] and the 1970s in Europe [3]. The Euro 7 emission standard, which will apply from November 2026 for passenger cars and N1 light commercial vehicles [4] in Europe, also includes emission limits for brake emissions [5]. For standardized brake emission measurements, the UN GTR No. 24 procedure and its prescribed boundary conditions are mandatory. These define both the measurement setup and the dedicated test cycles required to ensure reliable and comparable results. The regulation is designed to reproduce representative real-world driving behaviour on a test bench while providing a stable testing environment with low background particle concentrations, thereby enabling precise emission measurements [6]. Although numerous studies have quantified brake emission factors and evaluated mitigation strategies [7–11], the transfer to measurements on open-road tests is still rarely conducted [12,13]. Most investigations focus on PM (particle mass) measurements, whereas PN (particle number) measurements remain challenging under open-road conditions. One main reason is the enclosed brake measurement system, which must be implemented for on-road tests to separate brake emissions from environmental influences. Due to spatial restrictions on a vehicle, these enclosures cannot follow UN GTR No.24 requirements, therefore introducing deviations in thermal management and sampling efficiency. The altered thermal conditions are likely to increase overall brake temperatures subsequently to the absence of natural cooling and therefore may promote a higher occurrence of volatile particle emissions. Excluding environmental influences also leads to a change in the real emission behaviour, even though they are needed for a standardized measurement procedure of brake particle emissions [14].

The objective of this study is to advance existing research by transferring two test-bench-validated brake particle emission mitigation strategies to a fully instrumented vehicle and evaluating their effectiveness under real-world driving conditions. Previous studies have investigated brake emission mitigation approaches under laboratory conditions. Firstly, Bondorf et al. [15] evaluated brake wear emissions from of an OEM configuration and a modified, hard coated disc on a full vehicle dynamometer, while Woo et al. [16] developed an active particle collection system combining local suction with electrostatic precipitation and demonstrated its collection performance under laboratory conditions in both a brake dynamometer and a full vehicle dynamometer. Nevertheless, comparative studies evaluating technologically distinct mitigation approaches with the same vehicle during open-road operation remain limited. The present work addresses this gap by directly comparing a passive material-based approach and an active filtration approach using simultaneous brake particle number (PN) and particulate mass (PM) measurements.

The first approach is a passive solution in which the standard brake pad and disc materials are replaced by a modified friction pairing. The second approach is an active filtration system that uses modified brake pads with a standard friction-material

composition to extract particle-laden air directly from the friction zone. Both systems were evaluated during two open-road driving cycles: an RDE-compliant cycle representing typical, moderate driving conditions and a more dynamic cycle characterized by higher brake loads. This experimental design enables the assessment of whether the emission-reduction performance demonstrated under controlled test-bench conditions can be maintained under variable real-world operating conditions and across a broad range of passenger-car brake applications, including loads exceeding those encountered during average everyday driving.

2. Experimental Section

2.1. Materials and Methods

To enable brake emission measurements, a specially equipped vehicle had to be provided. The vehicle parameters and necessary implementations, such as a full brake enclosure, are listed in Table 1. The stated mitigation strategies #1 and #2 are described below

Table 1. Vehicle parameters and implementations for brake emission measurements.

Vehicle class		N1		
Vehicle mass		2260 kg		
Axle		Front		Rear
Rim dimension		8JxR18		8JxR18
Tire dimension		255/45R18		255/45R18
Rolling radius		343.5 mm		343.5 mm
Brake type		Disc brake		Disc brake
Calliper type		Floating		Floating
Retraction elements		No		No
Disc dimension		308 mm × 29.5 mm		294 mm × 22 mm
Disc		GCI ventilated		GCI ventilated
Pad type	OEM	Mitigation #1	Mitigation #2	OEM
Enclosed		Yes		Yes
Measured		Yes		No

In order to measure particulate emissions of any kind, a suitable measurement system is required. Therefore, a custom-built measurement vehicle was used to carry out brake particle emission investigations. The measurement system consists of three main parts for brake dust measurements, forming the CVS (Constant Volume Sampling) system: an air filter, a brake enclosure and a fan (see Figure 1).

The fully sealed brake enclosure is located at the front right wheel to prevent the measurement from parasitic emissions. It has an air inlet at the front, which introduces clear air through a H13 filter box from the inside of the vehicle into the enclosure, and an aerosol outlet at the back to guide the particle-loaded flow towards the nozzle position and thus to the measurement devices. The fan is located at the end of the CVS system, inducing a volume flow of approx. 81 m³/h. To analyze the particle flow, an Optical Particle Sizer (OPS 3330, TSI Incorporated, Shoreview, MN, USA) is used. This measurement device enables not only measurements of the particle number concentration, but also provides information about particle size distribution in 16 channels. The used OPS has a measurement range from 0.3 to 10 µm at a sampling frequency of 1 Hz. Furthermore, it provides the possibility for gravimetric sampling of the exhaust air on a 37 mm quartz fibre filter pad [17]. The filter pads have been weighed unloaded before the tests and loaded after testing. The used precision scale provides a resolution of 0.01 mg at a repeatability of 0.02 mg [18].

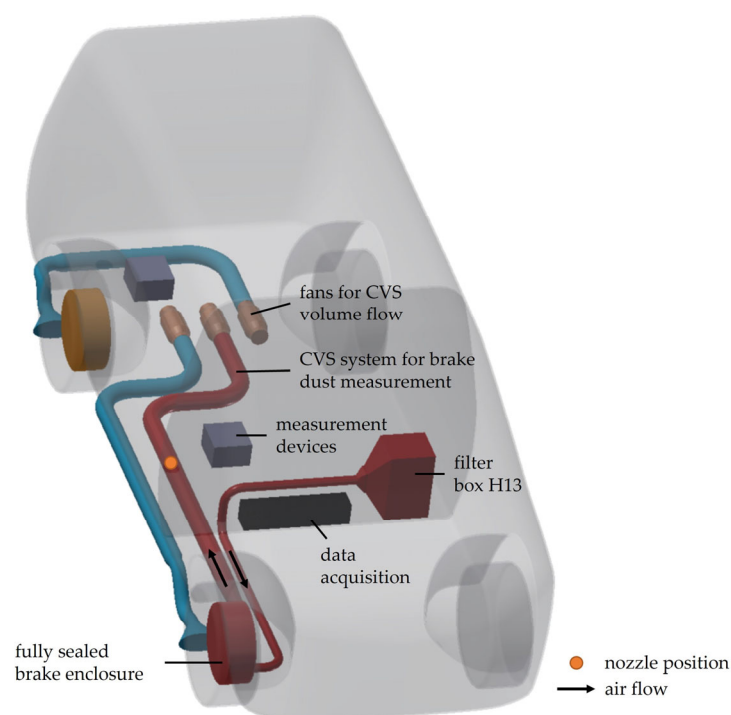


Figure 1. A schematic overview of the measurement vehicle.

At this point it has to be stated that the CVS system cannot comply with UN GTR24 due to spatial restrictions in vehicle packaging [6]. Neither the dimensions of the brake enclosure, nor duct lengths and sampling positions, align with the regulation and are rather designed to provide a fully functional vehicle, which is applicable for open-road testing. Due to the absence of natural cooling in the encapsulated brake system, a differing thermal behaviour can be expected. Hesse et al. [19] stated a minor influence on average temperatures, which rarely exceeds 10 K in temperature difference compared to the unencapsulated brake. Although this increase is not negligible, it has not been shown to cause a measurable change in emissions under the investigated temperature conditions [20].

The stated mitigation strategies listed in Table 1 are: #1 a low emission braking pad and #2 a filtration system. As the original brake pad is a low metallic brake pad, Mitigation #1 uses a modified, NAO-like material composition for the brake pad on a standard GCI (Grey Cast Iron) disc, expecting to keep abrasion as low as possible [21], while Mitigation #2 enables the filtration of brake dust by evacuating emissions directly out of a slot which was machined into each braking pad (see Figure 2c). The part of the slot across the entire width of the brake pad is located at the trailing edge, whilst the orthogonal slot mainly guides the extracted particle-laden air towards the outlet at the centre of the brake pad. The metal tubing mounts as a connector to the pump at this position on the back plate. The air inlet of the machined slot is on the lower-back side of the brake pad. To both brake pads, metal tubing is mounted to extract the air (see Figure 3) and further on, via connected rubber tubing, guide the air towards the filtration system. In completion, the filtration system consists of a filter, a pump for emission evacuation, a controlling unit and pipes from the brake pad to the filter. The controlling unit has two different settings: a sequential and a continuous setting. The sequential setting uses a trigger signal, in this study the brake light signal of the vehicle, to enable the pump and start the evacuation for the braking event with a follow-up time of four seconds after the signal turns off. The continuous setting lets the pump run during the whole test drive, which leads to a constant evacuation of brake emissions while driving.

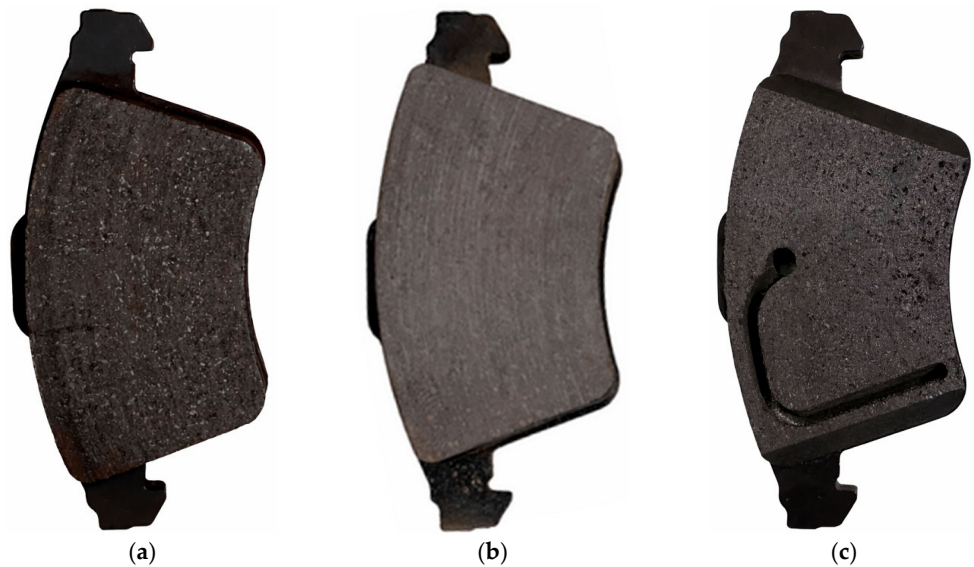


Figure 2. Tested brake pad derivatives: (a) OEM ECE brake pad, (b) Mitigation #1 NAO-like brake pad, (c) Mitigation #2 grooved ECE brake pad.

For baseline testing as an OEM derivative, the factory equipped brake materials have been measured. Since the testing vehicle has been in use for emission measurements for a few years, the OEM brake configuration has been bedded for approximately 25,000 km. Both mitigation strategies used already bedded material from previous tests, ensuring no combination has been tested green. Every combination of brake pad, Mitigation #1 as well as #2, were in use with the respective brake disc. The machined-out brake pad for Mitigation #2 shared the same part number with the OEM counterpart but they were manufactured in different years. Hence, minor differences in material composition cannot be excluded.

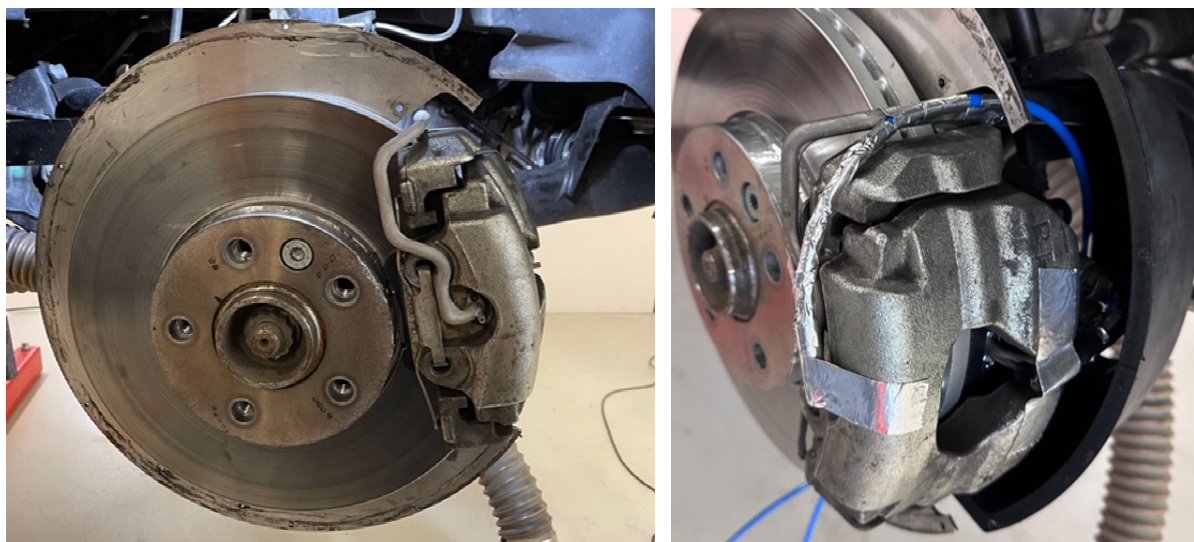


Figure 3. Implementation of Mitigation #2, active brake dust evacuation system.

2.2. Characterization of the Driving Cycles

Two test cycles were conducted to evaluate brake dust emissions in real-world driving situations. The first cycle was designed in accordance with the RDE guidelines and comprised 38% urban traffic, 37% rural traffic and 25% motorway traffic. According to RDE guidelines, the target range for urban driving is 29–44% and 23–43% for both rural road and motorway [22]. This test cycle imposes a moderate stress collective on the

braking system through its emphasis on moderate driving, a mix of operating scenarios between city, country roads and motorway driving, and a moderate elevation profile along the route. As stated in Table 2, the number of curves per driven kilometre is considerably lower than on the second implemented cycle. The latter, named the high-severity cycle, is located in the vicinity of Ilmenau, but southbound, as opposed to the RDE-compliant cycle, which is located north of Ilmenau. With the low mountain range of the Thuringian Forest, which extends particularly south of Ilmenau, the high-severity cycle is distinguished by a more pronounced altitude profile as well as a much higher curviness, resulting in six times the normalized elevation gain compared to the RDE-compliant cycle.

Table 2. Route information on implemented driving cycles.

	RDE-Compliant Cycle (RDE)	High-Severity Cycle (HS)
Total Length	91 km	20.44 km
Elevation Gain Uphill	1148 m	1497 m
Elevation Gain Downhill	1146.8 m	1497 m
# Of Curves	171	132
Curviness	1.9 curves/km	6.5 curves/km
Normalized Elevation Gain	12.6 m/km	73.2 m/km
Repetitions	3	3 each direction, total 6

Figure 4 shows GPS-Plots of both driving cycles, with the RDE-compliant cycle on the left and the high-severity cycle on the right. Both cycles are designed as closed loops. The RDE-compliant cycle however differs a few metres in the starting and end points, resulting in different elevation gains up- and downhill.

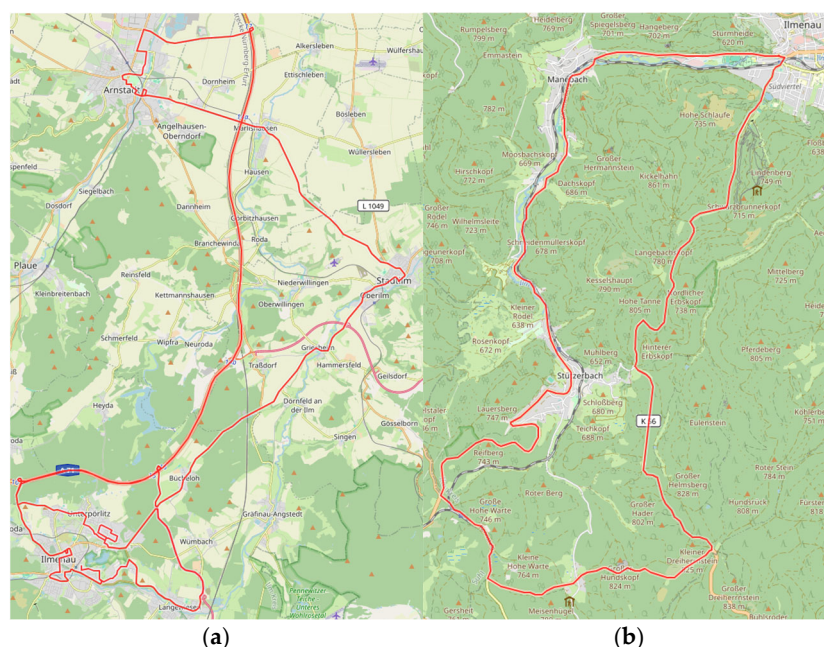


Figure 4. RDE-compliant cycle (a) and high-severity cycle (b).

The tests took place within 2 months in late summer and early autumn, while aiming to maintain similar boundary conditions of a max. outside temperature variation of 10 K between tests and dry road conditions. Each test on the RDE-compliant cycle was repeated 3 times to even out sporadic anomalies. Due to weather constraints in the late summer, it was determined that increasing the number of repetitions would not be feasible. This

decision was made to enable all tests to take place in the same season and hence similar weather conditions. Tests on the high-severity cycle were repeated 3 times in each direction. Since this cycle is almost halved in its elevation profile, driving both directions enabled us to assess the different routes both uphill and downhill.

The differentiation in route direction of the high-severity cycle can be observed in Figure 5a. The shown RMS values indicate a clear opposing position of the forward and backward driven cycle forming two areas almost point-mirrored at (0,0). Meanwhile the values of the RDE-compliant cycle range in the middle of the two areas of the high-severity cycle. The variability in these data derives from always-changing boundary conditions in open-road testing due to traffic, although all testing was carried out at the same time of day. Since the entire value range is quite narrow, some markers in the diagram are positioned on top of each other. This effect is emphasized in Figure 5b, which shows the values of Interquartile Range (IQR) of both longitudinal and lateral acceleration. The IQR values are particularly suited to evaluate the range in acceleration profile, since the mean 50% of data get evaluated and outliers as well as anomalies can be excluded from evaluation. With regard to the IQR in particular, it is clear that, despite changing traffic conditions, acceleration profiles range in a similar variability, indicating that reproducible driving cycles were carried out.

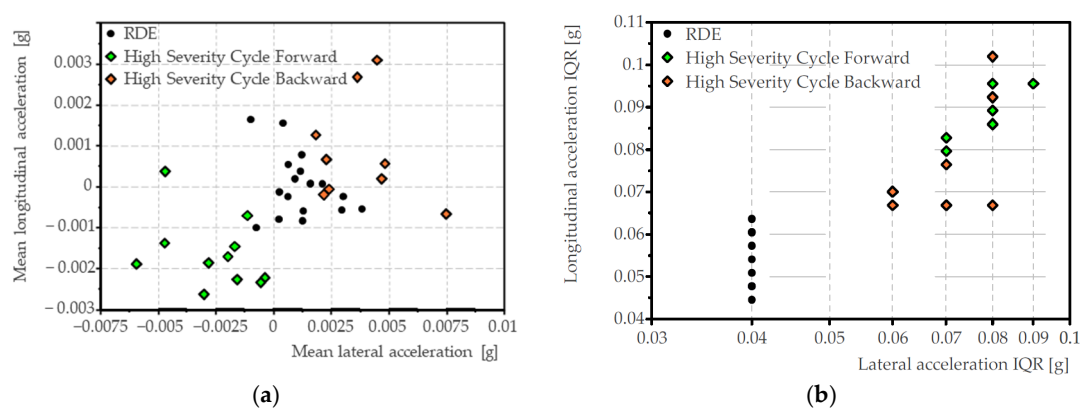


Figure 5. (a) RMS values of lateral and longitudinal acceleration on all driven cycles, (b) Interquartile Range of accelerations of every driven cycle.

3. Results

3.1. Comparative Assessment of Emission Behaviour Across Driving Cycles

The cycles described in the previous section are shown below in Figures 6 and 7 alongside the related particle size distributions. For each combination, one representative cycle is displayed. The associated particle size distribution is then shown in (b) of each figure. The data shown are standardized to test length, making all of the curves directly comparable. The velocity curves in (a) are shown over the driven distance. The shift in the curve of OEM velocity in respect to the others can be explained by a short detour right at the start of the cycle caused by a construction site. The overall length however remains the same, because the additional city driving share subsequent to the detour was cut off the last city section to maintain RDE compliance.

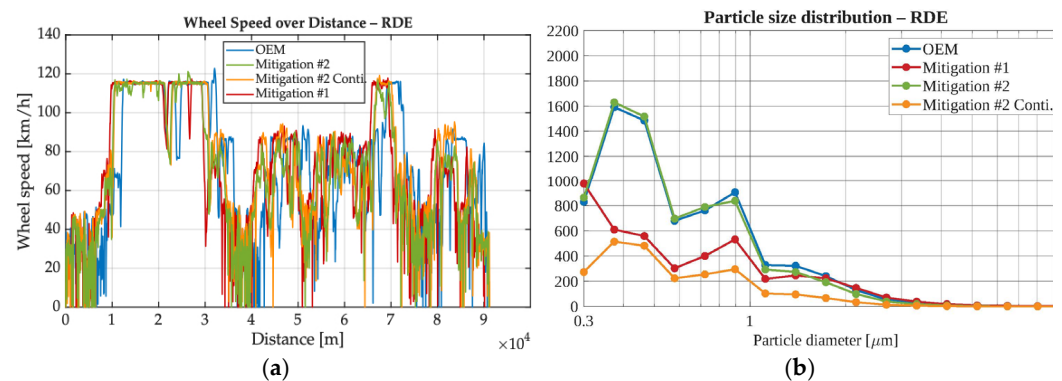


Figure 6. Velocity profiles of different mitigation approach tests on RDE-compliant cycle (a) and related particle size distributions (b).

Despite the test conditions being similar, the particle emission behaviour in Figure 6b differs noticeably. Under the shown conditions, the OEM brake configuration exhibits the highest particle number concentration overall with two concise modes showing local maxima at 0.4 μm and 1 μm particle diameter. Mitigation #1 shows large reduction potential in particle number distribution. The peak of emissions is at 1000 $\#/cm^3$ roughly one third of OEM emissions. Furthermore, a shift in emission behaviour is noticeable through altering modes in respect to the OEM material combination. While the local maximum at $\sim 1 \mu m$ remains in a similar size range as OEM, the lower maximum shifts largely toward the measurement device's lower cut-off at 300 nm. Emission levels in PN above 4 μm are similar across all the tested approaches. Mass-relevant emissions in larger particle diameters are discussed below.

The active mitigation solution #2 was tested as described in two different operation modes. The sequential mode, which triggers the filtration system on brake operation, is represented by the green graph in Figure 6. It utilizes the same material as the OEM configuration but the pads are modified through milling a groove in the last quarter of the pad with respect to the rotation of the disc. This adds two more tapered edges on each brake pad, which are prone to cause a higher emission level due to double entering and leaving edges into the friction zone per pad. This most likely explains the higher emission level in fine sections below 0.8 μm in comparison to the OEM pad. Since both pads contain the same material mixture, the modes of the emission behaviour are the same. In the second mode, above 0.9 μm , Mitigation #2 can reduce brake emissions compared to OEM. Under usage of the continuous operation mode of Mitigation #2, the reduction potential is amplified across the whole size range. Again, modal distribution remains the same as OEM but the overall emission level is 1/3rd of OEM emissions.

Figure 7 shows the results of the high-severity cycle in a similar manner, with the diagrams for vehicle speed in (a) and particle size distribution in (b). Again, the shown results are standardized to test length, making them directly comparable. While velocity remains comparable over the three selected repetitions, the particle size distributions show noticeable differences in comparison to the results of the RDE-compliant cycle.

The emissions of the OEM configuration show a lower overall level than in RDE while maintaining the general distribution modes and altering the range between maxima and minima. A lesser emission level in the fine particle range can be observed below 1 μm , while emissions in particle sizes above remain comparable.

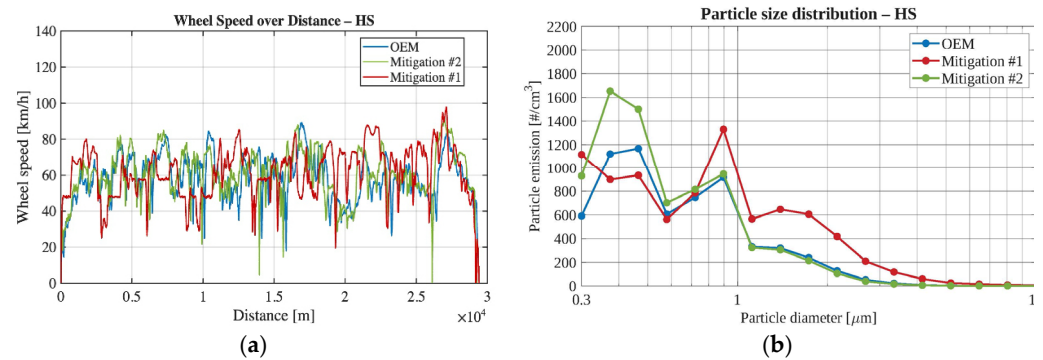


Figure 7. Velocity profiles of different mitigation approach tests on high-severity cycle (a) and related particle size distributions (b).

Both applied mitigation approaches, however, show distinguishable differences in their emission behaviour. The passive approach in Mitigation #1 utilizes a modified, NAO-like material combination. The lower emission level on RDE-compliant driving can be supported by the literature [21,23]. These materials have been reported to emit larger amounts of particles below $0.4 \mu\text{m}$ in respect to ECE material combinations like the used OEM. This can be seen in Figure 7b, where the emission level of Mitigation #1 exceeds OEM towards the lower cut-off of the measurement device. While maintaining its distribution modes generally, the emission level of Mitigation #1 is amplified to an extent, so that it exceeds the emissions of both OEM and Mitigation #2 in sizes above $1 \mu\text{m}$. In the sections below, this characteristic will be discussed further, since it might be derived from different thermal management and effects of brake temperature.

Mitigation #2 has been tested only in its energy efficient sequential mode alongside the high-severity cycle. The sequential mode, however, promotes similar emission behaviour as in the RDE-compliant cycle, exceeding the OEM emissions in the fine section below $1 \mu\text{m}$ and showing minor reduction potential above this threshold. It has to be noted that the minor shift in modal distribution, as it occurs in the OEM configuration between particle sizes of $0.35 \mu\text{m}$ to $0.5 \mu\text{m}$, does not apply to Mitigation #1, which remains unchanged.

3.2. Emission Behaviour Alongside RDE-Compliant Cycle and Thermal Particularities

The RDE-compliant cycle is designed to incorporate city, rural, road and motorway driving. To assess the progression of influence in each cycle on thermal management of the braking system and the resulting differences in emission behaviour, the following figures contain excerpts. Figure 8 shows an excerpt of two urban braking events, which are marked in their respective positioning in the top left graph by two sets of markers. As shown in the top right graphs, both events share a similar gradient in brake pressure and decelerate from almost the same speed, with a difference of 3 km/h. The main difference in both events remains the disc temperature. Due to the brake encapsulation and lack of deliberate cool-down phases along the route, the brake disc temperature tends to increase over the whole cycle. The temperature of both excerpts remains steady with minor variation and is around 36°C in the first section and 41°C in the second. The emission behaviour however differs largely especially in the smaller sections below $1 \mu\text{m}$, indicating that in on-road testing the known shifts in emission behaviour towards smaller particles from the literature occur as well [24].

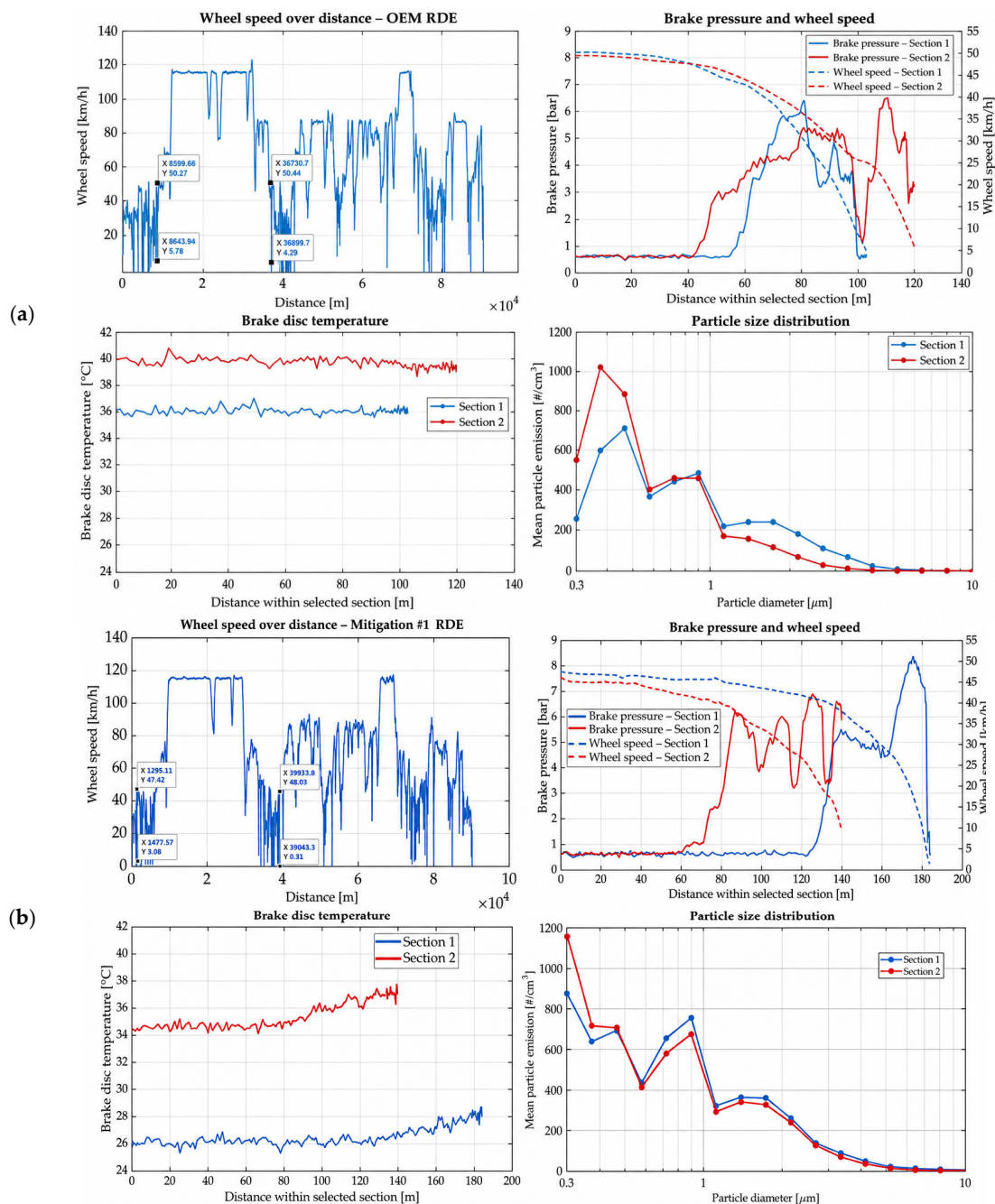


Figure 8. Excerpts of RDE-compliant cycle with (a) OEM brake configuration and (b) Mitigation #1 material configuration of urban braking events.

This comparison of two urban braking events shows a clear tendency of the OEM friction pair to increase fine particle emissions up to 1 μm while maintaining a similar modal distribution with higher amplitude.

The bottom half of Figure 8b displays similar urban braking events as (a). While Mitigation #1 shows lower temperatures in both selected excerpts, the emission level is more than doubled below 1 μm in comparison to the OEM configuration. Since it is expected for a NAO-like configuration like Mitigation #1 [10], this behaviour is counterintuitive to this observation. However, even if the decrease in speed is comparable, the application of brake pressure differs largely between the OEM and Mitigation #1 sections. While the applied brake pressure in Figure 8a is gradually increasing over a relatively short distance, the graphs in (b) show a modelling of brake pressure over a longer duration, possibly due to traffic restraints.

The emission characteristics in Figure 8b however do not show a significant change in value or mode as a consequence of the increased temperature as in (a). An increase of 8–10 K is similar to the 7.5 K increase in Figure 8a but does not result in an increased emission behaviour in (b) between sections 1 and 2. It has to be stated that these sections are not representative of the complete cycle and only serve to investigate the influence of brake disc temperature in open-road measurements on the emission characteristics.

Similar behaviour in different pronouncements can be observed in Figure 9, showing two excerpts of each OEM configuration and Mitigation #1 on rural road braking events. The composition of the diagrams is shortened to show only vehicle speed, brake pressure and particle size distribution, but with different axle spacings in comparison to Figure 8. The complete excerpt of two rural road braking events is shown in Appendix A. Again, the displayed sections of the whole cycle are mainly comparable in speed decrease and applied brake pressure. The higher gradients in brake pressure of both first sections on the OEM configuration appear within the deceleration and in both cases in the second half of the respective braking events. So, while the initial brake pressure in the first half is roughly the same, and the majority of the energy conversion takes place at higher speeds, it is most likely that this section is responsible for a higher proportion of event-specific emissions [23]. The second rural road section in Appendix A shows a slightly higher brake disc temperature in comparison to the first, especially once the braking event starts. The emission behaviour however is characterized by an overlap of the two graphs at 0.8 μm particle size. While the first section remains below the second in particle sizes below 0.7 μm , it exceeds the second in the range between 0.8 μm to 5 μm . This indicates that higher brake disc temperatures are again prone to cause higher emissions in the fine emission range, while higher brake pressure and therefore higher brake torque causes a shift in emission behaviour towards larger particles, especially above 1 μm [25].

The figures under (b) in Figure 9 show similar excerpts of the RDE-compliant cycle testing Mitigation #1. As for the urban sections, applied brake pressure and velocity decrease are not directly comparable. The braking events of Mitigation #1 start at the same initial velocity but decrease to roughly 30 km/h other than in the OEM sections, in which the braking events ended at 40 km/h. The significantly higher temperature levels of Mitigation #1 in Appendix A may not completely be a result of higher transformed braking energy. Presumably, the difference in temperature derives from the differing heat management of each material combination. Since NAO-like materials tend to have worse heat conduction and general thermal management, Mitigation #1 is more likely to form longer lasting hot sections in the friction zone. [21]. Both shown sections in (b) differ largely in start and end temperature. While maintaining similar trends throughout the braking event, the magnitude of the second section is 35 K hotter than the first section, underlining the thermal behaviour of NAO-like materials. With regard to the measured emissions, this difference in temperature just shows minor effects on the overall characteristics. This might be due to not reaching the turning point in emission behaviour of NAO-like materials, which show a significant increase once surpassing said threshold, according to the literature [26]. In comparison to the OEM emissions, a noticeable reduction of roughly 50% can be observed in Mitigation #1. The reduction in these shown segments is most of all to be observed around the 1 μm particle size fraction, but continues over other size fractions as well. This is concomitant with a slight change in modes as well, leading to a relative increase in fine particles around 1.1 μm as well.

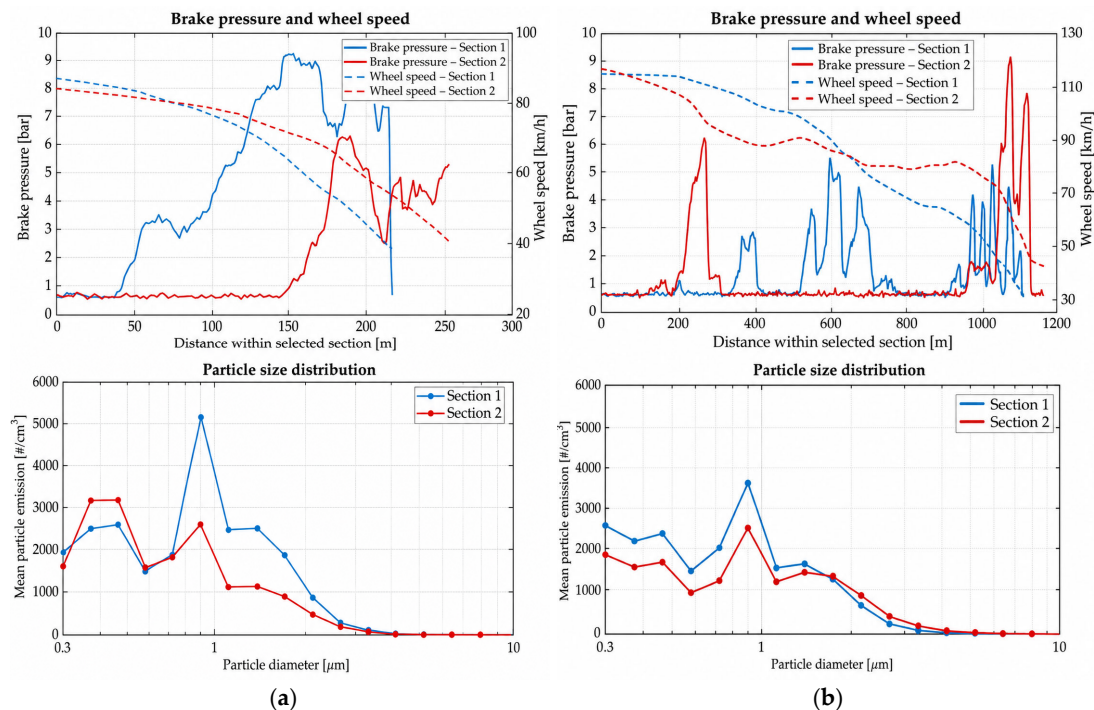


Figure 9. Excerpts of RDE-compliant cycle with (a) OEM brake configuration and (b) Mitigation #1 material configuration of rural road braking events.

An analogy to the correlation of brake torque and respective shifts in emission behaviour above can be observed in the motorway braking events of the OEM material combination in Figure 10a. The complete excerpt together with transient data for vehicle velocity and brake disc temperature is shown in Appendix B. While disc temperatures range within 1.5 K in both, the applied brake torque and brake duration differ. Whereas both sections observe a speed decrease of roughly 70 km/h, the emissions of the first section scale almost linear with respect to the second section. This indicates that similar temperatures cause similar modal distributions in emissions and the applied braking power as a consequence of higher brake pressure increases emissions in all particle sizes below 5 μm simultaneously.

An opposing observation is made in (b) of Figure 10, showing two sections of Mitigation #1 in motorway braking conditions. While the second section is characterized by higher disc temperatures and two major brake pressure applications, the first section is colder and undergoes an increased quantity of brake applications to a lesser brake pressure. These conditions promote a higher emission level below 1 μm even under lower temperatures. In direct comparison to the temperatures in Figures 9 and 10, motorway temperatures are lower by different amounts. The emission behaviour however remains comparable in magnitude. The biggest difference between the colder, higher energy converting braking events in motorway sections and the warmer, less energy converting events in rural road sections is the different modal distribution in particle size. While motorway brake emissions peak at 1 μm in PN and decline steadily, rural road brake emissions increase between 1 and 1.1 μm. Furthermore, fine particle size sections show a higher level in motorway sections than on rural road.

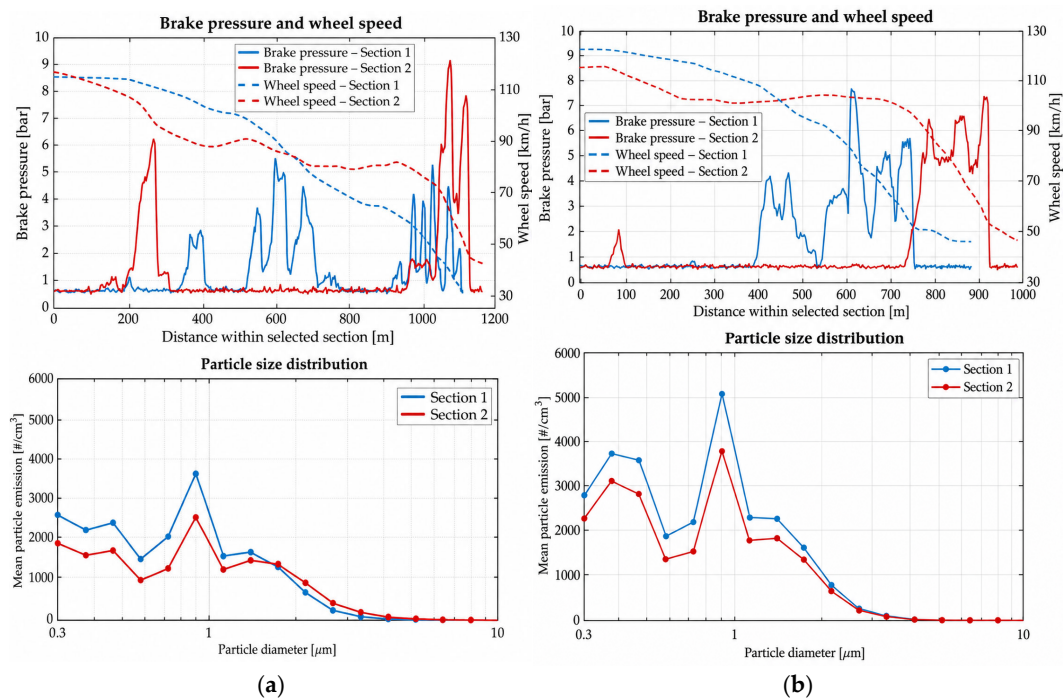


Figure 10. Excerpts of RDE-compliant cycle with (a) OEM brake configuration and (b) Mitigation #1 material configuration of motorway braking events.

3.3. PM Emission Behaviour

Figure 11 shows the emission factors of both different cycles and the OEM configuration as well as both mitigation strategies. These emission factors differ in their creation from widely known ones in the literature due to the different testing setup. As stated above, the brake encapsulation does not follow GTR24 Guidelines. The particles were sampled at the exhaust of the used OPS, which uses an upstream impactor or particle separator, but the measurement setup with its approximate transport efficiency is highly unlikely to transport particles $>10\ \mu\text{m}$ in larger quantities. Since this sampling setup and methodology in emission factor determination differs largely from standardized methods, the absolute emission factors should primarily be compared within the present measurement setup.

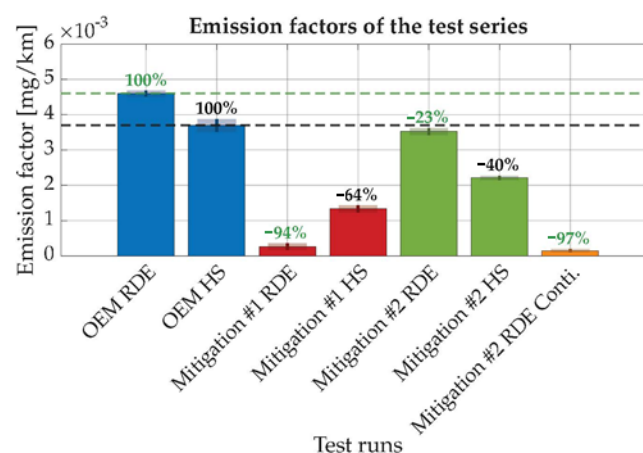


Figure 11. Emission factors of test runs.

The diagram in Figure 11 shows the same brake material combination in the same color. Both cycles of the OEM brake configuration were used as the baseline, each

represented by the 100% dotted line, starting at the blue bars. Reduction potential in PM of the following tests is referring to these numbers.

The blue and red bar represent the RDE (blue) and HS (red) tests of Mitigation #1. The use of Mitigation #1 in RDE-compliant driving holds a great reduction potential overall. However, the same material configuration shows less potential in the HS cycle, emitting more mg/km than in RDE but also gaining a smaller reduction in comparison to the OEM solution. This might be due to the NAO-like material characteristics of Mitigation #1, which tend to show a switching point in emission behaviour once surpassing a critical temperature. Mitigation #1 tends to run higher temperatures than the OEM configuration in general, making it likely to exceed said critical temperature locally and therefore emit more particles in general.

The green bars of RDE and HS of Mitigation #2 in Figure 11 under usage of the filtration system utilizing the same material as OEM shows mitigation potential in both cycles while in sequential filtration mode. The reduction however does not reach the levels of Mitigation #1. The tendency to emit less mg/km in PM of the OEM configuration in the HS cycle remains and is partly amplified, showing larger reduction potential (40%) in the HS cycle as opposed to the RDE cycle (23%). This might be due to a better overlap of brake event and thus emission event and operation time of the filtration system. The RDE-compliant cycle encourages gentle braking over longer time periods, whilst the HS cycle is characterized by shorter and more intense brake events. Thus, not only does the emission behaviour of the material differ, but also the relationship of the overrun time of the filtration system in sequential mode to the brake event duration is longer. While the sequential mode of Mitigation #2 has the advantage of a more efficient energy consumption, being only active if the brake is activated + four seconds overrun time after each operation, the continuous mode holds greater reduction potential, exceeding Mitigation #1. When Mitigation #2 is operating in continuous mode, the pump is constantly evacuating air out of the friction zone, which results in 97% PM reduction on the RDE-compliant cycle. This mode of operation has not been tested on the HS cycle.

3.4. Particle Emission Characteristics

While PM measurements show a clear picture, the particle size distributions of each mitigation strategy differ. Figure 12 shows the particle size distribution of (a) the RDE-compliant cycle and (b) the high-severity cycle.

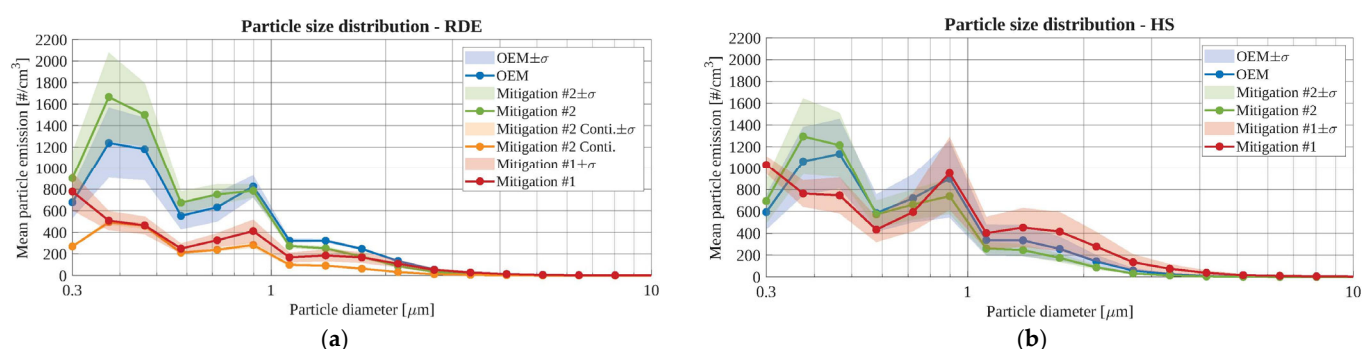


Figure 12. Particle size distributions of all mitigation strategies on (a) RDE-compliant cycle ($n = 3$) and (b) high-severity cycle ($n = 6$).

Considering the graph in Figure 12a, the overall trends in emission behaviour match the PM measurements above. Following the sequential operating mode of Mitigation #2, it shows advantages against the OEM solution upwards of $1 \mu\text{m}$ but fails to reduce fine emissions. This may be attributable to the different states of wear on the OEM pad versus the pads used in Mitigation #2. Even if both were bedded sufficiently, the OEM derivatives

are approximately 7 years older, resulting in an uncertainty on the ageing of the pads. Furthermore, the milled slot adds further tapered edges, which might increase initial emissions, unsettling the results of extraction efficiency of Mitigation #2. This effect can be excluded in the continuous operation mode of the filtration system, reducing overall emissions while keeping the same modal distribution, making it unlikely to emit unexpectedly high emissions outside of the measurement boundaries. This cannot be stated with certainty about Mitigation #1, showing great reduction potential overall but also shifting the modal distribution towards the fine section. This emission behaviour confirms observations on PM. According to the literature, NAO-like materials like Mitigation #1 are prone to emit larger amounts of particles below 1 μm , reducing mass-relevant emissions but neglecting health-relevant, readily inhalable fine particles [21].

This behaviour changes in Figure 12b. While relations between OEM and Mitigation #2, only tested in sequential operation mode, remain similar and decrease in overall amount, the emissions of Mitigation #1 increase and shift their modes simultaneously. This aligns with data from the literature, that NAO-like materials emit higher PN once surpassing a threshold in brake temperature [26]. The following Figure 13 puts this relation in perspective.

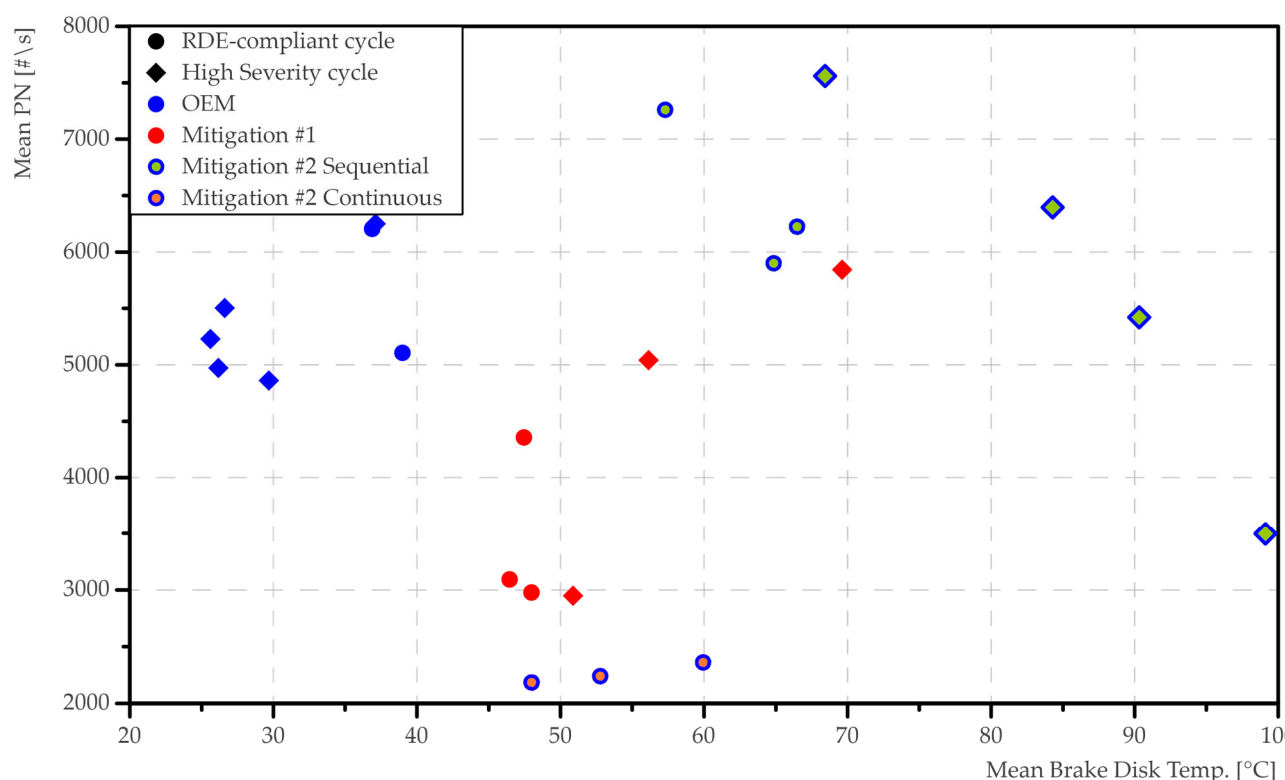


Figure 13. Standardized PN per cycle over mean brake disc temperature.

3.5. Relationship Between Mean Disc Temperature and PN Emissions

Considering the observations of the previous points, the correlation between PN and brake disc temperature is crucial to the results in mitigation potential within this study. Therefore, each test is plotted in Figure 13 with its standardized cumulative PN emissions over the values of arithmetic mean brake disc temperatures. Spherical-shaped markers represent tests on the RDE-compliant cycle, while rectangular ones are used for the high-severity tests. Since Mitigation #2 uses OEM pad material for its filtration system, both Mitigation #2 and OEM are coloured blue, while Mitigation #1 is represented in red. Different infills of markers typify the operation mode of Mitigation #2. It is evident that each test group of each material combination and mitigation strategy forms areas in which

the respective markers lay within. Some tests show these markers in a closer area, relating to a smaller range of results, whereas especially tests on the high-severity cycle show a larger range and therefore higher standard deviation. Additionally, it has to be noted that some markers lay on top of each other. Still, the tendency toward a larger range of results in high-severity cycle testing can be observed. This might be due to its high dynamic and differing starting temperatures of the braking system of each cycle, because the cool-down phases were, depending on the direction of the high-severity cycle, not long enough to let the brake cool down to ambient temperature. Although data from the high-severity cycle testing of Mitigation #2 are included in Figure 13, they cannot be a fundament of interpretation due to the high variation in data. Boundary conditions like ambient temperature itself, however, can be neglected, since all brake combinations were subsequently tested on the same day.

Concerning the OEM material combinations, once in standard form, once modified for Mitigation #2, a trend to higher temperatures after the modifications can be seen. This trend is linked to higher emissions in the sequential operation mode of Mitigation #2, showing similar to slightly higher emissions compared to OEM on the RDE-compliant cycle as well as on the high-severity cycle. On the latter, the mean disc temperature reaches its maximum and for at least one repetition exceeds even OEM emission levels. Again, the continuous mode of Mitigation #2 shows significant reduction potential while being hotter than OEM as well. This indicates that the higher temperature derives from the modification of the pad but can be influenced by the additional heat dissipating effect of a continuous aspiration of the filtration system.

While Mitigation #1 shows varied behaviour under increasing temperature, in overall consideration, the mitigation potential is clear. Especially the three tests on the high-severity cycle visualize an increase in PN emission over rising mean temperature. Since the RDE-compliant cycle is noticeably longer than the high-severity cycle and mixed in stress profile, it allows cool-down phases of the braking system. Hence the results of Mitigation #1 on RDE do not show such clear dependency on PN and temperature.

The mean PN concentrations in Figure 14 reveal distinct emission characteristics compared with the previously discussed PM emission factors. Mitigation strategy #1 reduced PN by approximately 44% during the RDE cycle and by 10% during the more dynamic HS cycle relative to the corresponding OEM configuration. The differences between the PN- and PM-based reductions indicate that the modified friction pairing affects the particle size distribution and not only the total emitted mass. In contrast, mitigation strategy #2 showed a pronounced dependence on the operating mode. Under non-continuous operation, the mean PN concentrations exceeded the corresponding OEM values by approximately 4% in the RDE cycle and 11% in the HS cycle, despite the reductions observed in the PM emission factors. This divergence suggests that larger, mass-dominating particles were removed more effectively than the smaller particles contributing more strongly to PN. Under continuous operation, mitigation strategy #2 achieved the largest PN reduction of approximately 64%, consistent with the improved PM reduction observed for this operating mode. Overall, the comparison demonstrates that mitigation performance cannot be assessed solely on the basis of particulate mass, as both strategies exhibit different effects on particle number and mass emissions.

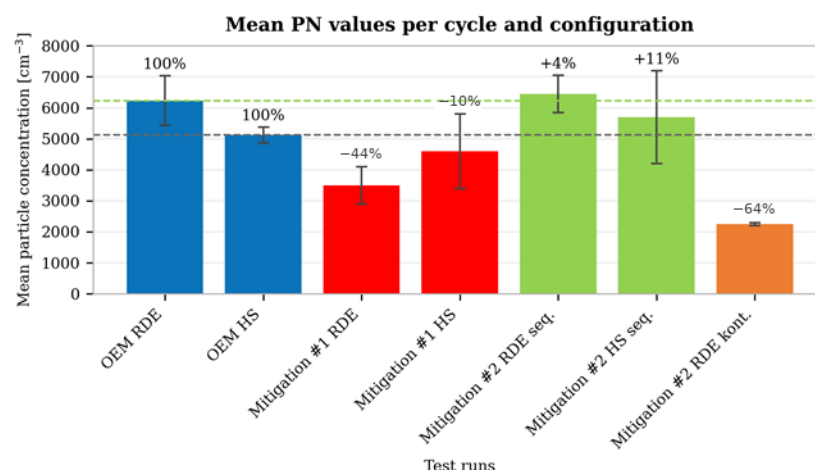


Figure 14. Mean PN values of test runs.

4. Discussion and Limitations

The brake particle mitigation approaches assessed in this study following an active and a passive solution both prove promising. The results of this study, however, are limited and only transferable to results gained in other tests or especially laboratory tests. As stated above, the brake enclosure does not follow GTR24 regulations and the sampling setup has a higher duct length to transfer samples from the emission source to the measurement devices compared to GTR24-conforming setups. This sampling setup is characterized by a transport efficiency that is the subject of debate. Furthermore, this transport efficiency varies for different particle sizes. While larger particles are susceptible to gravitational and inertial losses in long ducts, smaller particles may be affected by diffusion and aspiration losses at probe inlets [25]. This discontinuity will affect particle size distribution measurements, especially in long sampling setups.

In the measurements of brake disc temperature, an optical sensor was utilized at three-quarter turns of the brake respectively to the calliper position. As established in the investigations conducted on the impact of temperature, the positioning of the sensor has the potential to induce a delay in the measurement of peak temperature. However, the cooling of the disc within the three-quarter turn has to be considered a systematic error. Furthermore, the utilized discs for the different approaches might differ in degree of reflectivity, altering optical measurements via pyrometer [27].

Other limitations of this study include sporadic events like the reproduction quality of driving cycles due to traffic, weather conditions and driver error. By ensuring enough repetitions, the impact of most of the sporadic errors can be reduced.

As shown in Figure 3, most components of Mitigation #2 have been covered in aluminum tape as a heat shield during testing. However, in final disassembly, it became evident that the blue pressure line, which measures differential pressure to observe the working condition of the filtration system, was impacted by the heat of the brake disc. This leads to lost results in the pump efficiency of the filtration system. The particle emission results before and after this incident however remain comparable. Investigations show that the damaged pressure line did not affect the operational conditions for the braking system, since the aluminum tape in combination with the plastic pressure pipe sealed it sufficiently enough to eliminate air leakage according to the differential-pressure signal.

The present study was conducted using a single vehicle configuration and vehicle mass. Since vehicle mass directly affects braking energy, thermal loading and brake wear, the results cannot be generalized to other vehicle classes without further validation.

Further investigations will be necessary, as well as PN measurements below the lower cut-off of 300 nm that the used measurement device of this study was limited by. The courses of the graphs of particle size distribution suggest a steady incline towards smaller size fractions, which may be interrupted by the measurement devices' lower cut-off. Within this study, however, Mitigation #1 still tends to be a promising approach.

Because only a limited number of independent test runs were available (at least three repetitions) and real-world driving conditions varied between measurements, the dataset was not considered sufficient for a reliable statistical analysis. Hence, measurements collected within the same driving cycle are temporally related. The findings are therefore discussed on a descriptive basis. Further measurement campaigns with a larger number of repeated test runs and inclusion of environmental data would be needed to assess the variability of the results and determine whether the observed differences are statistically significant.

Both mitigation strategies investigated in this study demonstrated the potential to reduce brake particle emissions under open-road driving conditions. However, their effectiveness differed between PM and PN and depended on the driving cycle and, in the case of Mitigation #2, on the operating mode of the extraction system. These findings highlight that the performance of brake emission mitigation measures cannot be assessed using a single emission metric or operating condition.

The PM10 emission factors measured for the OEM configuration ranged from 3.7×10^{-3} to 4.55×10^{-3} mg km⁻¹, whereas values of 0.3 to 1.3×10^{-3} mg km⁻¹ and $0.14\text{--}3.5 \times 10^{-3}$ mg km⁻¹ were obtained for Mitigation #1 and Mitigation #2, respectively. For example, Liu et al. [28] summarized PM10 brake wear emission factors for passenger cars ranging from approximately 5.2 to 9.3 mg km⁻¹ vehicle⁻¹ and PM2.5 emission factors between approximately 2.2 and 3.0 mg km⁻¹ vehicle⁻¹. Their reported dynamometer measurements for a C-segment vehicle resulted in mean PM10 and PM2.5 emission factors of 7.02 and 2.26 mg km⁻¹ vehicle⁻¹, respectively. Emission factors are highly dependent on the respective experimental setup, including the brake system and friction-material combination, test cycle, braking severity, thermal boundary conditions, conditioning procedure, enclosure and sampling configuration, particle measurement instrumentation, and the applied data-normalization method. Consequently, absolute emission levels obtained using different setups cannot be interpreted as directly comparable quantities.

Mitigation #1, being a passive solution due to modified material having the simplest implementation effort, showed a reduction in PM emissions relative to the OEM configuration under RDE driving conditions, indicating that the modified friction pairing can reduce the release of mass-dominating wear particles. The corresponding PN reduction was approximately 44% during the RDE cycle but decreased to approximately 10% under the more dynamic HS conditions. Together with the previously presented PM emission factors, these findings indicate that the effectiveness of the passive approach depends on brake load and thermal conditions. Differences between the PN- and PM-based reduction rates further suggest that the modified friction pairing affects the emitted particle size distribution rather than reducing all particle fractions uniformly. A comparatively strong PM reduction with a smaller PN reduction would indicate preferential suppression of larger particles, which contribute substantially to particle mass but less strongly to particle number. The reduced performance under dynamic conditions may result from changes in wear mechanisms, friction-layer stability and thermal loading at higher brake temperatures.

Mitigation #2 exhibited a pronounced dependence on the operating mode of the extraction system. Under non-continuous operation, PM emissions were reduced by 23% during the RDE cycle and 40% during the HS cycle, whereas PN increased by approximately 4% and 11%, respectively, relative to the corresponding OEM

configurations. This divergence indicates that the active extraction system collected larger, mass-dominating particles more effectively than the smaller particles contributing strongly to PN. Modified airflow around the brake may additionally influence particle transport, deposition and resuspension. Under continuous operation, Mitigation #2 achieved the largest PN reduction of approximately 64%, together with a PM reduction of 97%. The improvement under continuous operation demonstrates that sufficient and uninterrupted extraction flow is required to capture particles across a broader size range. However, this benefit must be weighed against the additional electrical energy demand of the filtration system. The net environmental benefit of the active approach therefore depends not only on its particle collection efficiency but also on the energy required to operate the pump and filtration components. Therefore, future investigations should examine different operating strategies of the filtration system to combine energy efficiency advantages of sequential operation mode with collection efficiency advantages in continuous operation mode.

In the broader context of brake emission control, the passive and active strategies offer different advantages and limitations. Passive material-based measures do not require additional energy or auxiliary components and can therefore provide emission reductions without increasing vehicle energy consumption. Their performance, however, may deteriorate under higher thermal and mechanical loads and remains dependent on the interaction between the pad, disc and friction layer. Active extraction systems can remove particles after their formation and may provide high collection efficiencies when operated continuously, but they introduce additional complexity, packaging requirements, maintenance demand and energy consumption.

Despite the promising results, direct transfer of the measured emission factors to other studies or standardized laboratory measurements is limited. The vehicle-mounted brake enclosure does not conform to all the geometrical and flow requirements of UN GTR No. 24. In addition, the sampling ducts were longer than those typically used in GTR-compliant test-bench systems. Particle transport efficiency through such a system is size-dependent. Larger particles are particularly susceptible to gravitational and inertial losses along the ducts, whereas smaller particles may be affected by diffusion, aspiration efficiency and inlet losses. These effects can alter both the measured particle concentration and the apparent particle size distribution. Consequently, the reported emission factors should primarily be interpreted as comparative results obtained within the same experimental setup rather than as directly transferable absolute values.

Brake disc temperature was measured optically at a position approximately three-quarters of a disc revolution downstream of the calliper. This arrangement may delay the detection of peak temperatures because the observed disc section cools between leaving the friction contact and reaching the measurement position. This effect represents a systematic limitation of the temperature measurement. Furthermore, differences in surface reflectivity between the brake discs used for the individual configurations may influence the pyrometer response. The temperature results should therefore be interpreted mainly in terms of relative trends rather than exact local peak temperatures.

Additional variability arose from the open-road test conditions. Traffic, ambient conditions and deviations in driver behaviour affected the reproducibility of the driving cycles. Although at least three repetitions were performed for each configuration, the number of independent test runs remained limited. Measurements obtained within an individual driving cycle are temporally correlated and cannot be treated as independent replicates. The results were therefore evaluated descriptively. A larger number of repeated runs, combined with the systematic recording of environmental and traffic-related parameters, would be required to quantify uncertainty and determine the statistical significance of the observed differences.

During the testing of Mitigation #2, most components were covered with aluminum tape to protect them from thermal radiation. Inspection after testing showed that the pressure line used to monitor the differential pressure of the filtration system had nevertheless been thermally damaged. This deteriorated the evaluation of pump efficiency for part of the measurement campaign. However, comparison of the differential-pressure signal before and after the damage indicated that the aluminum tape and the remaining pressure-line material maintained a sufficient seal, and no corresponding change in the operating conditions of the braking or extraction system was observed. The particle emission measurements recorded before and after the incident were therefore considered comparable. The study was conducted using a single vehicle configuration and vehicle mass. Since vehicle mass directly affects braking energy, thermal loading and wear, the measured emission factors and reduction efficiencies cannot be generalized to other vehicle classes without further validation. This limitation is particularly relevant because previous studies have reported increasing brake and total non-exhaust emission factors with increasing vehicle mass.

Finally, the PN measurements were restricted to particles larger than 300 nm. The particle size distributions increased towards the lower measurement limit in several tests, suggesting that a relevant fraction of the emitted particles may have remained outside the detectable range. Future studies should therefore include measurements below 300 nm, particularly under high-temperature braking conditions, to determine whether the mitigation strategies exhibit different efficiencies for ultrafine particles. Further investigations should also cover additional vehicle masses, repeated driving campaigns and a wider range of environmental conditions. Such measurements are required to assess the robustness of the observed reductions and to determine the contribution of each strategy to total vehicle particulate emissions under representative fleet conditions.

5. Conclusions

The scope of this study was to assess one passive and one active brake particle emission mitigation strategy in open-road vehicle testing. By comparing both approaches on a vehicle equipped for measuring PN and PM brake emissions, the study demonstrates that mitigation performance established under controlled laboratory conditions can be transferred to open-world driving applications.

Both approaches hold the potential to reduce PM emissions by more than 90% compared to the OEM solution, as stated in Table 3. Mitigation #1 achieved PM reductions of 94% during the RDE-compliant cycle and 64% during the high-severity cycle in comparison to the OEM solution. The corresponding PN emissions were reduced by 44% in RDE driving and 10% in high-severity driving. Under high-severity driving conditions, Mitigation #1 achieved a smaller reduction in particle emissions than under lower-severity conditions. This result suggests that the emission-reduction effectiveness of the modified material combination decreases as the thermal and mechanical load on the brake increases. The different reduction rates observed for PN and PM further show that the modified friction pairing does not affect all particle size fractions equally and appears to reduce mass-dominating particles more effectively than PN-relevant small size fractions. Mitigation #2 showed a pronounced dependence on the operating mode of the filtration system. In sequential operation, activating the collection system on brake applications, PM emissions were reduced by 23% during the RDE-compliant cycle and by 40% during the high-severity cycle, whereas PN increased by 4% and 11%, respectively. This divergence indicates that the system preferentially removed larger particles contributing strongly to PM, while smaller particles relevant to PN were captured less effectively. Under continuous operation during the RDE-compliant cycle, Mitigation #2 achieved the highest overall reduction, with decreases of 97% in PM and 64% in PN. However, this

operating mode also requires continuous power supply and therefore increases total vehicle energy consumption. The practical application of the filtration system additionally causes higher integration effort, packaging requirements and filter maintenance.

Table 3. Comparison of mitigation strategies in emission reduction and economical aspects.

Criteria	Mitigation #1	Mitigation #2	
		Sequential	Continuous
PN reduction on RDE-compliant cycle	44%	−4%	64%
PN reduction on high-severity cycle	10%	−11%	No data available
PM reduction on RDE-compliant cycle	94%	23%	97%
PM reduction on high-severity cycle	64%	40%	No data available
Integration effort	Low	High	High
Economic impact	Depending on mileage/lifetime no influence despite cost	Additional implementation effort, constant power supply, filter maintenance	

The conclusions are limited to the investigated vehicle configuration and mass and cannot be directly generalized to other vehicle classes. Further limitations arise from the use of a non-GTR 24-compliant brake enclosure, size-dependent particle transport losses in the extended sampling system, the lower PN detection limit of 300 nm, and the limited number of independent test repetitions under variable real-world conditions. The results should therefore be interpreted as a comparative and exploratory assessment.

Author Contributions: Conceptualization, A.H., M.K. and P.H.; methodology, A.H., M.K. and P.H.; validation, A.H., M.K. and P.H.; investigation, A.H., M.K. and P.H.; resources, S.G.; data curation, P.H.; writing—original draft preparation, A.H. and M.K.; writing—review and editing, A.H., M.K. and P.H.; visualization, A.H., M.K. and P.H.; supervision, V.I.; project administration, V.I. All authors have read and agreed to the published version of the manuscript.

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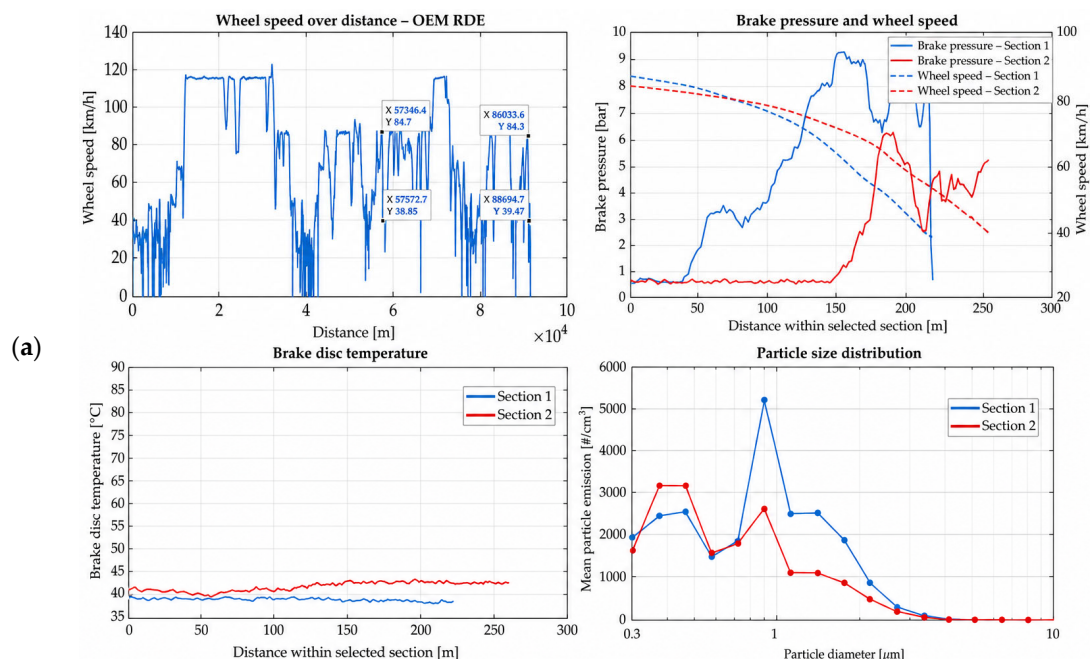
Conflicts of Interest: The authors declare no conflicts of interest. Dr. Sebastian Gramstat is an employee of Entwicklung Bremssystem / Development Brake System, Audi (Germany), Ingolstadt, Germany. The paper reflects the views of the scientists and not the company.

Abbreviations

The following abbreviations are used in this manuscript:

PM10	Particulate matter with an aerodynamic diameter $\leq 10 \mu\text{m}$
PM2.5	Particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$
PM	Particle Mass
PN	Particle Number
RDE	Real Driving Emissions
HS	High Severity
UN	United Nations
GTR24	UN Global Technical Regulations Nr. 24
OEM	Original Equipment Manufacturer
GCI	Grey Cast Iron
ECE	Economic Commission for Europe
NAO	Non-Asbestos Organic
CVS	Constant Volume Sampling
OPS	Optical Particle Sizer
IQR	Interquartile Range
Conti.	Continuously
$\#/\text{cm}^3$	Particles Per Cubic Centimetre
$\#/\text{km}$	Particles Per Kilometre
mg/km	Milligram Per Kilometre
km/h	Kilometre Per Hour

Appendix A



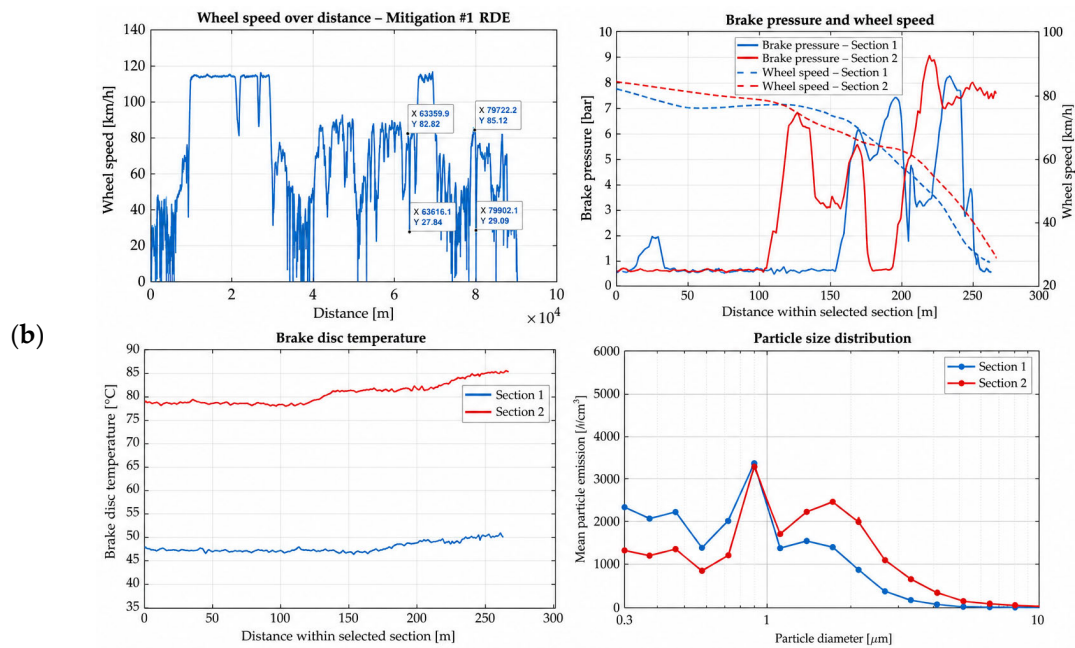


Figure A1. Excerpts of RDE-compliant cycle with (a) OEM brake configuration and (b) Mitigation #1 material configuration of rural road braking events.

Appendix B

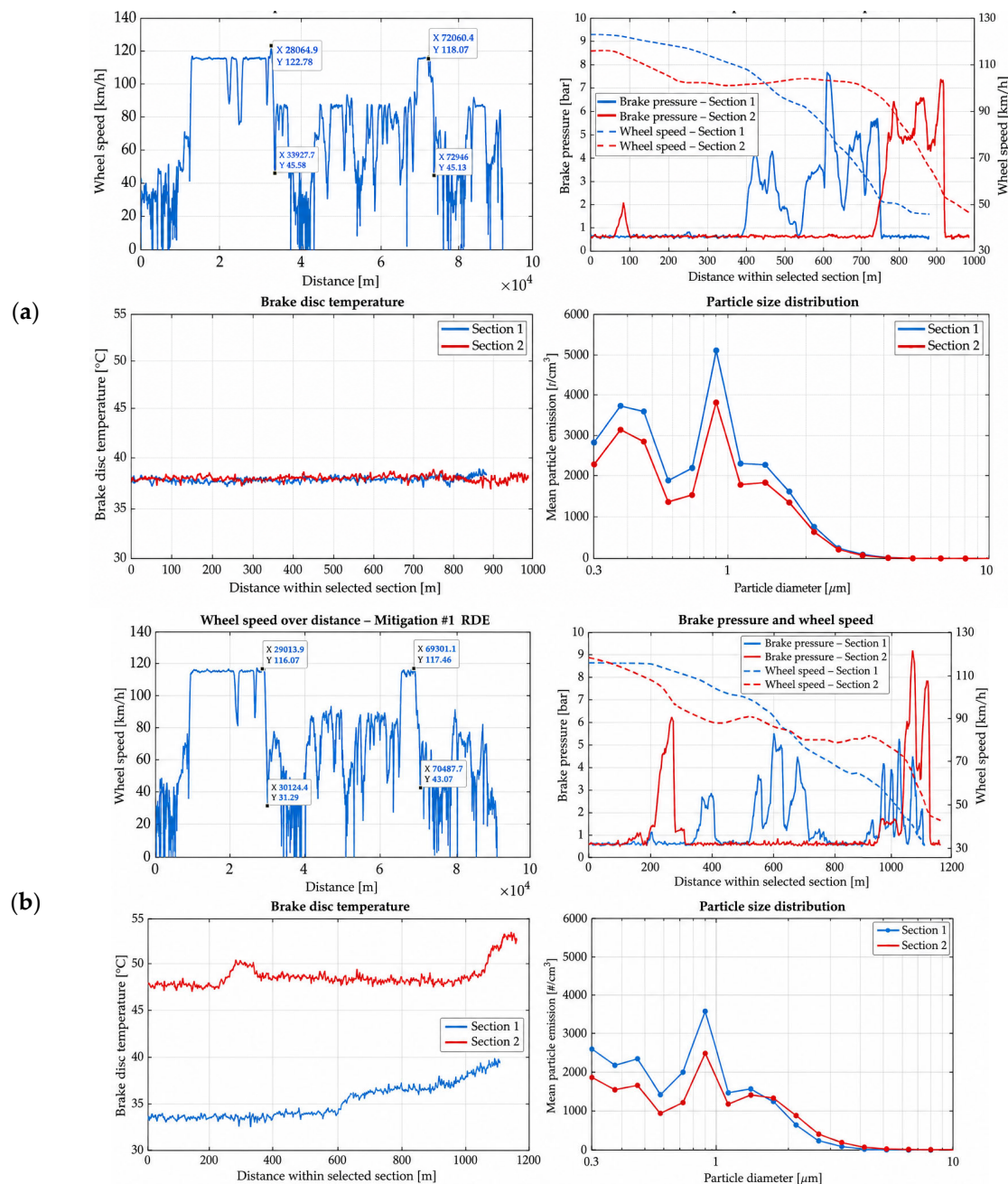


Figure A2. Excerpts of RDE-compliant cycle with (a) OEM brake configuration and (b) Mitigation #1 material configuration of motorway braking events.

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