Article citation info:
Stępień Z. Vehicle related non exhaust particle emissions – Euro 7 requirements. Combustion Engines. 2024;199(4):15-29. https://doi.org/10.19206/CE-190606

Zbigniew STĘPIEŃ

Combustion Engines
Polish Scientific Society of Combustion Engines

Vehicle related non exhaust particle emissions – Euro 7 requirements

ARTICLE INFO

Received: 6 April 2024
Revised: 28 June 2024
Accepted: 28 June 2024
Available online: 10 July 2024

The article is a multi-directional review of the current knowledge in the field of particulate matter emissions from motor vehicles, but not related to the combustion process in piston combustion engines. A summary of the research results available in the literature was provided regarding the size and composition of particulate emissions from abrasive wear of working elements of brake systems and tires. The mechanisms of particulate matter formation related to the wear processes of brake pads, discs, and tires were described. Reference was made to currently available research results regarding the harmful, toxicological impact on the health of chemical components contained in particulate matter, in particular on diseases of the respiratory and cardio-vascular systems. A critical analysis of various, previously unstandardized measurement and assessment methods for the emissions of this particulate matter category was carried out, pointing to future needs. Relating, in particular, to the requirements of the new Euro 7 standard.

Key words: *particulate matter, brake system emissions, tire wear emissions, methods of particulate matter measurement, Euro 7*

1. Introduction

Current epidemiological and experimental research on environmental pollution related to road traffic more commonly focuses on particulate matter (PM). These particles range in diameter from a few nanometers to hundreds of microns. The evidence obtained in the studies clearly indicated a harmful, toxicological health impact of chemical components contained in particulate matter, in particular on diseases of the respiratory and cardiovascular systems [2, 22, 47, 51]. Among all critical risk factors for mortality, exposure to ambient fine particulate matter ranks seventh (OECD 2017). According to OECD studies, the contribution of NEE (non-exhaust emissions) to traffic-induced particulate matter concentrations in local hotspots may exceed 50% [50, 122], which highlights the importance of NEE in urban environments.

PM emitted from motor vehicles are classified based on two main sources of origin, i.e. exhaust emissions, which represent PM resulting from incomplete combustion of fuel and lubricating oil in the combustion chamber, and PM emissions not related to the combustion process in the engine resulting from braking processes, tire wear as well as the resuspension of particles generated by road traffic [59, 138, 139, 142]. Non-combustion emissions (NEE) from road traffic refer to particles released into the air as a result of the wear of the friction elements of the braking system, tires, road surface, and road dust re-suspension during vehicle use on the road [10, 39, 42, 46, 110]. The size, chemical composition, and emission rate of particles from such sources affect the concentration of particles in the atmosphere and how harmful they are to human health. Such particles have a chemical composition and size different from particulate matter in exhaust gases.

NEE arises regardless of the type of vehicle and the type of its drive unit (power source). With the implementation of the vehicle exhaust emission control policy and the successive reduction of permissible emission limits for regulated exhaust gas components, the emission of particulate matter arising from the combustion process in engines has gradually decreased, and the relative share of particulate matter emissions from brake and tire wear has therefore grown unchecked. The concentration of airborne particulate matter is often referred to as PM_{10}. These are particles with a diameter of less than 10 µm expressed per unit volume. In certain conditions, car brake materials also emit ultrafine particles (with diameters below 0.1 µm), and their numerical concentration is several orders of magnitude greater than the concentration of fine particles (PM_{10}) [8, 84, 129, 155].

It was noted in other studies that particulate emissions from brake wear in Europe are made up of 30% ($PM_{2.5}$) and 40% (PM_{10}) for emissions from sources unrelated to combustion in engines [18, 32, 45, 53]. PM emissions not related to the combustion process accounted for a share ranging from 30% ($PM_{2.5}$) and 45% (PM_{10}) in 2010 to 54% ($PM_{2.5}$) and 69% (PM_{10}) in 2020 (after the introduction of DPF filters), and will probably exceed 90% in 2040 (Fig. 1) [18]. Research results indicate that particles originating from the wear of brake friction elements may constitute up to 21% of the total amount of PM10 emitted by motor vehicles in large urban areas, of which approximately 35-55% is suspended in the air, the remaining portion is usually deposited on the brake system elements. or on the road surface [52, 71, 79, 87, 142, 162]. The tire wear process generates and releases particles that consist of degraded tire tread compound (elastomer) mixed with minerals from the road surface. These particles are often called tire and road wear particles (TRWP) [56, 83, 134, 152]. Studies conducted over the last 10 years show that tire particulate matter emissions range from 0.2 kg/year/capita in countries with low vehicle numbers to 5.5 kg/year/capita in countries with high vehicle numbers. Therefore, the average is approximately 0.8 to 1 kg/year/inhabitant [14, 15, 81, 148]. Tire wear causes the formation and emission of microplastics, which constitute a huge environmental pollution problem.

Electric vehicles have been gaining increasing popularity for over a dozen years now [13, 78, 126]. The research results from various sources regarding the particulate matter emission produced from the wear of brakes and tires vary. Some studies indicate that these emissions may be greater than the total PM emissions from an internal combustion engine vehicle (ICEV) [16, 143]. Many researchers indicate that electric vehicles are about 20% heavier than ICEVs due to the mass of their batteries, which would be expected to cause particulate emissions from increased brake wear, tire wear, road wear, and road dust resuspension [1, 131].

a)

b)

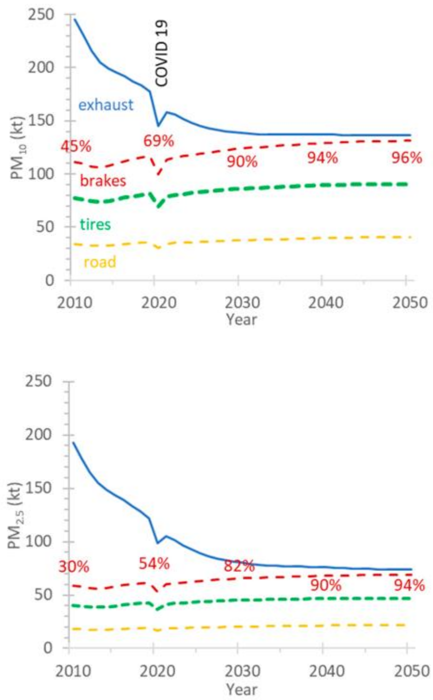

Fig. 1 Changes and forecasts of emissions from exhaust gases and other sources (brake, tire, and road wear) and total PM emissions from road transport in the EU27: (a) PM10; (b) PM2.5 [32]

On the other hand, it should be noted that the amount of braking done in battery electric vehicles is typically several times lower due to the use of a regenerative braking system. Despite this, recent studies based on updated emission analyzes have shown that the high mass of electric vehicles can offset the positive effect of regenerative braking on reducing particulate emissions [16, 63, 143]. The results of other studies state that electric vehicles' particulate emissions are comparable to conventional ICEVs' emissions [150]. Consequently, further research is needed to better understand the overall impact of vehicle electrification on emissions primarily related to braking and tire wear.

Emissions of regulated substances, including PM, from combustion engines have been restricted based on emission limit values for more than 30 years. There are no legal restrictions on non-exhaust emissions relating to particulate matter emissions and their resuspension. Already, NEEs have supplanted exhaust emissions as the largest source of PM emissions from road traffic. The growing trend in NEE emissions is also indicated by data from EU vehicle emissions analyzes done up to the year 2021 [28, 106] and after [6]. Most importantly, this major source of PM emissions from road traffic is currently not subject to any legislative process. It is therefore essential that future regulations introduce restrictions on NEEs and their contribution to total PM emissions. Taking this into account, the European Union has proposed that the standard currently being developed for limiting emissions of harmful components from motor vehicles – Euro 7 – should include reductions in particulate emissions not only from ICE exhaust gases [51, 142, 149]. However, the biggest problem that remains to be solved before the introduction of the new Euro 7 standard is the development of a standardized method for measuring NEE PM that will ensure obtaining reliable, repeatable measurement results.

The measurement of particulate emissions from NEE is a complicated challenge due to the open configuration of the vehicle brake system and the tires operating in the area of significant air flow influence. As a result, the particles are immediately diluted and dispersed by the surrounding air. This means that making repeatable measurements becomes a complex and difficult task. Moreover, measurement conditions on the road are greatly influenced by a set of highly variable parameters. In this regard, performing emission measurements in real operating conditions (RDE) becomes essential for a better understanding of the actual emission behavior and its reliable assessment. This led to the establishment of a dedicated Working Group on Particle Measurement Program (PMP) for the United Nations Economic Commission for Europe (UNECE) to develop a dedicated PM measurement methodology for NEE sources. Overall, further detailed investigation of PM from NEEs is necessary to reduce road traffic-related PM emissions and assess future health risks [1, 51, 142, 149].

The aim of this article was to perform a broad literature review, systematize the existing knowledge and to critically analyze it in the field of NEE.

2. Particulate emissions from brakes and tires

Non-combustion emissions (NEE) refer to particulate emissions released as a result of wear of brake friction elements, corrosion processes [52, 53, 162], tire-road surface interactions [69], and particle resorption [106, 127]. The vast majority of the brake and tire mass that becomes particles is released as the result of abrasion processes. Moreover, it has been shown that both sources can emit ultra-fine particles through thermochemical processes [157]. When assessing the emission of particulate matter, it is necessary to take into account not only their mass distribution but also their size distribution, as well as their quality (e.g., chemical composition and biological effect). The amount of emissions and the composition of PM from the wear of brake components can vary depending on many factors, the most important of which are:

– composition of the brake pad friction material, which may be organic or metallic. When specifying the materials from which brake pads can be made, the following should be mentioned: organic pads without asbestos (NAO – non-asbestos organics), low-alloy steel, carbon and aluminum [41, 155]. Metallic pads are divided into low-metallic (LM) or low-alloy, semi-metallic (SM) and fully metallic (rare). The Economic Commission for Europe (ECE) typically refers to the most representative brake pads for Europe, which are either LM or SM [20, 26, 105, 132]. The results of previous research have shown that replacing ECE pads with NAO pads can reduce PM emissions from brakes [84, 129, 140, 159, 160]. The reduction was approximately 62% for PM10, 55% for PM2.5, and 64% for PN. It was also shown that brake disc wear can be easily reduced by replacing LM brake pads with NAO pads [155]. Brake pads described as NAO are popular in the USA, Japan, and Korea, while brake pads described as ECE are the most popular in Europe. Brake discs made of grey cast iron (GCI) are often used because of their high melting point, high heat storage capacity, as well as damping. Their other advantages are good castability and machinability [12, 105]. It is estimated that for brake discs made of grey cast iron, cooperating with high emission brake pads of the ECE type, the disc contributes to the emission of approximately 60% of the total PM mass [60, 64, 130, 136], while when using ceramic discs, this share can be reduced to < 5% [130]. When drum brakes were used, the brake drum with GCI contributed approximately 37% of the total mass of PM emissions [64]

- type of brake assembly, including discs, drums, their sizes, surface structure, and groove depths [41]
- vehicle operating conditions, including initial speed, deceleration rate, fluid pressure acting on the brake pistons, torque, and brake temperatures [41, 75, 128].

Generally speaking, the processes of brake wear and changes in kinetic energy or energy dissipated from the brakes are all related [35, 61, 103, 159]. Therefore, in the case of specific, identical braking cycles, the wear of brake friction elements should be correlated with the load (vehicle mass) [33, 143]. Reliably estimated emission factors are necessary to calculate with the required precision the contribution of PM emissions to the total PM emissions of a vehicle, as well as to estimate the emission reduction potential of different brake technologies and materials. To determine the emission factors, the required measurements shall be carried out both under laboratory conditions (e.g. PoD on dynamometer) and in the vehicle (chassis dynamometer, road measurements). In practice, measurements can be made using different equipment and test methods (most often gravimetric filtration method, optical and electrical meters, etc.) using different driving cycles [99, 146]. Therefore, in the past, various tests were used in which different test conditions were expected (ambient temperature, simulated vehicle mass), and the tests used different methods of determining the emission factors. Therefore, due to differences in methodology, test formulae and measurement instrumentation used, a direct, reliable comparison of the emission factors thus obtained may be subject to significant error [38, 52, 57, 93, 95, 116, 119, 122, 125, 132, 153, 158]. It will not be until the introduction of the EU – Global Technical Regulation (GTR 24) on PM emissions from the brakes of light motor vehicles that it will become possible to standardize measurement procedures. This regulation specifies the test procedure, the necessary system requirements, the test conditions, and the method and scope of equipment preparation for the WLTP-B test cycle using brake dynamometers. Table 1 summarizes the mass-dependent emission factors (mg/km/B) or particulate emissions (#/km/B) from different sources measured according to the requirements of GTR 24 for light vehicles, i.e. according to the WLTP-B test cycle. [45].

Not the entire mass of the worn brake pad and disc ends up suspended in the air as the so-called total suspended fraction. It usually constitutes 30–42%, with the majority of the airborne fraction being PM10 (usually ≫ 80%) [4, 48, 60, 62, 68, 95, 116]. The results of the tests showed that from a theoretical point of view, about 43% of the fraction corresponded to a median mass with a particle diameter of approximately 6.3 μm [81]. PM size distributions measured in the same study showed that the mass peak was expected in the PM range of 3–6 μm [15, 82]. From the analysis of the results of many tests carried out in accordance with the GTR 24 standard, WLTP-B test cycle [38, 52, 57, 93, 95, 116, 119, 122, 125, 132, 153, 158], of which some are shown in Table 1, the PM2. 5 to PM10 ratio was found to be 40% for ECE brake pads, 45% for NAO brake pads, 59% for CC and HMC brake discs and 60–100% for drum brakes [54, 160].

The constantly growing share of electrified (hybrid) and fully electric vehicles means that more attention ends up being paid to measuring their NEEs. On the one hand, it is assumed that the NEE value for such vehicles will increase due to their higher mass (between 15 and 25%) but on the other hand, it should also be assumed that it will decrease due to the high rate of regenerative braking and thus the lower actual use of friction brakes [16, 67, 133, 143]. So far, the number of available research results, based on which PM emission factors from brakes in electrified vehicles were determined, is limited [33, 61, 103, 143, 159]. Selected results are included in Table 2. In this case, the emission factors, which are absolute values, were lower than those given in Table 1, where the results were based solely on total frictional braking. As a result, compared to ICE equivalents, the reductions obtained are usually > 60% (Table 2) [45].

The emission factors described apply only to particulates (i.e. those that do not evaporate at 350°C) and to total particles, without a separate nucleation mode. The volatile nucleation mode occurs when the brake friction elements exceed the permissible (critical) temperature, usually within the range of 165 to 240°C [16, 48, 49, 94, 119, 126]. In such cases, the increase in emissions may be several orders of magnitude higher and is dependent on local supersaturation rates. Therefore, further tests in accordance with the GTR 24 protocol are necessary to confirm the repeatability of the results in such cases of brake operation.

Moreover, in accordance with the current version of GTR24, the PM10 emission factors for electrified vehicles shall be calculated using the PM emission factor of the internal combustion engine vehicle (ICV) using the so-called friction braking contribution coefficients [55]. For plug-in hybrid vehicles (PHEV), the friction braking contribution factor is set at 0.3 and for fully electric vehicles at 0.15. In practice, both electrification variants have slightly higher measured PM emission factors than those used in the above calculation method. Properly selected factors are a good first approximation for a typical mid-size electrified

Table 1. Particle matter emission factors of friction brakes related to vehicle mass (mg/km/B) or number of particulates emitted (#/km/B) measured according to the light vehicle brakes procedure GTR 24, i.e. with the WLTP-B braking cycle, unless otherwise specified

Year	Reference	Type	Pad	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN × 10^9 #/km/B	Comments
2021	[97, 98]	Disc	ECE	1700	8.5	4.5	3.5	Medium sedan
2021	[77]	Disc	LM	2250	4.7	2.4	1.0	Class J
2021	[77]	HMC	LM	2250	2.1	1.2	1.3	Class J
2021	[77]	CC	LM	2250	1.4	0.9	0.8	Class J
2022	[99]	Disc	ECE	1800	4.5	1.45	3.4	Luxury sedan
2023	[88, 100]	Disc	ECE	1600	6.0	2.0	2.2	Class C
2023	[88, 100]	Disc	NAO	1600	2.3	0.7	1.0	Class C
2023	[88, 100]	Disc	ECE	1668	10.7	3.8	8.6	Class J
2023	[88, 100]	Disc	ECE	2623	9.1	3.1	3.3	SUV
2023	[88, 100]	Drum	n/a	1253	0.5	0.3	1.7	Super mini
2023	[101]	Disc	LM	1660	5.3	2.8	4.3	Class C
2023	[101]	Disc	NAO	1660	3.9	2.2	1.8	Class C
2023	[101]	Disc	ECE	1660	1.5	0.9	5.1	Class C
2023	[101]	Drum	LM	2041	1.1	0.8	2.8	Class C
2023	[101]	Drum	NAO	2041	0.3	0.3	0.5	Class C
2023	[101]	Disc	ECE	2113	7.6	3.5	3.9	Class J
2023	[101]	Disc	ECE	2027	4.1	1.2	2.1	Luxury sedan
2023	[94]	Disc	ECE	1840	6.5	1.8	0.5	Japanese market

B – brake; CC – carbon ceramic; D – disc (GCI); ECE – Economic Commission for Europe; GCI – grey cast iron; HMC – hard metal coated discs; LACT – Los Angeles City Traffic; LCV – light-commercial vehicle; LM – low metallic; NAO – non-asbestos organic; SUV – sports utility vehicle.

Table 2. Particulate emission factors from electric vehicle brakes related to vehicle mass (mg/km/V) or number of particulates emitted (#/km/V), percentages in brackets include emission reductions compared to electric vehicles with their ICE counterparts with friction brake only (i.e. regenerative braking disabled)

Year	Reference	Type	Pad	Vehicle or Mass	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN × 10^9 #/km/V	Comments
2020	[89]	Disc	NAO	1600	2.0–2.3	1.0–1.4	1.3–8.9	PHEV
2021	[102]	Disc	n/a	1800	0.9	–	–	BEV
2023	[101]	Disc	ECE	1660	5.7 (–62%)	3.4 (–57%)	7.3 (–40%)	PHEV
2023	[101]	Disc	ECE	1660	3.1 (–79%)	2.3 (–71%)	2.1 (–82%)	BEV
2023	[103]	Disc	ECE	1350	10.5	4.5	141	HEV, Chassis, WLTP-E
2023	[104]	Disc	ECE	1228	–	–	0.5* (–4%)	Chassis, WLTP-B
2023	[104]	Disc	ECE	1228	–	–	0.5* (–65%)	Chassis, WLTP-E
2023	[104]	Disc	ECE	1228	–	–	4* (< 90%)	Chassis, RDE
2023	[80]	Disc	NAO	1553	0.3 (–86%)	0.14 (–78%)	0.05 (–84%)	PHEV, WLTP-B**

* back-calculated for emissions without regenerative braking and multiplied by 2,83/0,83 to be converted into total emissions related to the brakes of the rear axle; ** multiplied by 2.83 to convert to vehicle emissions. n/a = not available.

.

vehicles. However, given the multitude of different topologies and performance capabilities of electrified powertrains, a single factor per vehicle group will never reliably compare emissions from conventionally powered vehicles to electrified vehicles. Therefore, a suitable, dedicated method for determining vehicle-specific coefficients is already in development and will be added to GTR at a later stage.

The tire structure includes the following elements: tread, tire shoulder, tire side, belt ply, cord ply, inner lining, etc.

The tire wear process is quite complex, but it can be reduced to three main factor groups that influence it:

– related to the tire (structure, material, wear resistance, etc.)
– related to the vehicle (suspension parameters, load, speed, driving force, etc.)
– related to the environment (road conditions, temperature, method of operation, etc.).

The wear mechanism for rubber is very important for the tire wear particle generation process, which needs to be investigated. In the field of tribology, research on the rubber wear mechanism is relatively mature, including fatigue wear, friction wear, adhesive wear, and chemical erosion wear [92, 162]. While driving (accelerating, braking, turning), the tires have direct contact with the ground and support the vertical, lateral, and tangential load and reversing, capsizing, and rolling resistance moments. When tires contact the ground, direct friction and slippage occur, which causes micro-cutting and tearing of tires and the road surface. The wear process then progresses between the tires and the ground. When the cumulative friction energy in the relevant contact area reaches the critical energy, the tire surface is damaged; some of this surface is removed in the form of abrasive chips [1], and wear occurs. Tire wear usually manifests itself in the form of mixed tire and road surface wear, each accounting for approximately 50% [34].

The share of tire and road wear particles (TRWP) in PM emissions was estimated at 5–30%, up to 10% of the tire wear weight emits particulate matter in the air with a size of < 10 μm [36]. The literature [152] has collected and analysed data on PM size distribution, including tire wear particles (TWP) and TRWP. The test results included particle sizes from 1 μm up to hundreds of μm for road simulators, from about 0. 4 to 20 μm for road tests and above 1 μm up to 200 μm from road run-off. The results discussed in [34] placed the diameter of TRWP in the range of 4 to 350 μm, with an average diameter of 100 μm and a particle density of 1.8 g/cm^3. Similar results were presented in [24, 52, 88, 89, 98]. As in the case of particle size testing from brake friction wear, differences in TWP and TRWP measurement results occur due to different testing procedures, sampling systems, and particle size measurement systems. The research described in [162] showed that the number of particles consists mainly of ultrafine particles with a maximum concentration of 100 nm. The particle mass was mainly represented by fine and coarse particles with a maximum concentration of 0.5 μm and 1.3–2.5 μm.

Table 3 compares the degree of tire tread wear and the PM emission factor (EF) for cars equipped with different drive systems operating in different road conditions. "Total," in this case, indicates the ratio of total tire tread loss and the total vehicle traveled distance. The obtained research results have shown that the degree of tire tread wear of electric vehicles was 1.2 times greater than that of vehicles powered by combustion engines due to their 20% greater weight [94, 161]. At the same time, the degree of wear of the tire tread of a vehicle powered by a compression-ignition engine was 5% higher than in the case of a vehicle powered by a spark-ignition engine due to the slightly (~2%) greater mass and greater (~20%) engine torque. Analyzing the effect of road type, tire tread wear rates were 10% and 50% higher on rural roads and highways, respectively, than in urban areas due to the increased wear occurring when travelling at high speed. Generally, tire tread wear rates have been found to be highest in urban areas, followed by highways and rural roads [43, 94]. The research did not take into account the impact of braking events on tire wear because each tested vehicle moved on an asphalt surface at a constant speed, without changing the direction of movement and without braking. Based on the PM_{10} and $PM_{2.5}$ tire wear EFs, it was estimated that tire tread wear was responsible for 5% of PM_{10} particle emissions, 16% of which were classified as airborne $PM_{2.5}$ particles [67, 161]. The EF values of PM_{10} for the SI vehicle, the CI vehicle and the electric vehicle were 7.9, 8.4 and 10.1 mg/V·km, respectively, and the EF for $PM_{2.5}$ was 1.3, 1.3 and 1.6 mg/V·km respectively. Typically, the degree of tire tread wear was strongly related to the weight of the vehicle and the maximum torque of the drivetrain. In the case of the tested vehicles, the maximum torque values of the vehicle powered by a spark ignition engine, a compression ignition engine and an electric vehicle were 265 Nm, 320 Nm and 395 Nm, respectively [43, 94, 161]. However, since the vehicles travelled on the test track at a constant speed, the effect of the torque difference on tire wear was negligible. Differences in PM EF tire wear depending on vehicle type resulted primarily from the difference in vehicle weight [161].

3. Formation mechanisms of particulate matter not related to the combustion process

Non-combustion particles arise from a variety of vehicle-related sources. The main sources are:

– Wear of brake friction elements. Emissions resulting from brake wear arise both as a result of mechanical processes, due to the impact of friction on brake linings and discs during braking, as well as volatilization processes of brake pad materials as a result of very high local temperatures [156]. PM emissions from brakes depend on the type and geometry of the brakes, the wheels and the rim. The flow of air through the rims to cool the brakes and discs also plays a key role in the wear characteristics. Emissions are also sensitive to the driving style of the driver. Studies have shown that PM emissions caused by mechanical processes are usually larger and contain particles with larger diameters, and are therefore decisive for the volume of PM mass emissions. Emissions resulting from thermal processes include much smaller particles, they are strongly correlated with brake temperature and constitute the vast majority of PN concentrations [99, 114, 122, 142, 156, 164]. The contribution of $PM_{2,5}$ typically accounts for about one third of the total PM_{10} emissions from wear of friction brake components [53].

– Tire wear. The surface of the tire in contact with the road surface is gradually abraded. This leads to the formation of large amounts of small rubber particles that cover a wide range of sizes below 10 micrometers, thus contributing to the formation of PM_{10} and $PM_{2.5}$. Generally, emissions from tire wear arise mechanically as a result of friction between the tire tread and the road surface or as a result of the volatilization of substances [53, 99]. Studies show that ultrafine PM concentrations are generally low [52, 99] and usually correlate with "abnormal" or "extreme" driving conditions [98].

– Road surface wear. Friction between the tire surface and the road surface not only leads to tire abrasion, but also to the abrasion of the road surface.

– Suspended road dust. Dust from various sources, including abrasion products of various vehicle elements, settles on road surfaces. Road dust studies have shown that much of it falls within the particle size range $PM_{2,5}$ and PM_{10}.

The mechanical interactions between the brake pad and the disc generates brake wear particles (BWP) of various sizes during the braking process [154]. Most studies indicate a unimodal mass distribution of BWP sizes with diameters in the range of 1–10 μm [59, 75, 76, 84, 88, 112]. The quantitative distribution of BWP depends on factors such as

Table 3. EFs of non-exhaust tire wear PM emitted from the ICEVs and EV according to road type [161]

Model	Tire tread wear rate (g/V·km)				Tire wear PM EF (mg/V·km)							
	Urban areas	Rural roads	Motorways	Total	Urban areas		Rural roads		Motorways		Total	
					PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5
Gasoline ICE	123.3	135.6	200.0	158.9	6.2	1.0	6.8	1.1	10.0	1.6	7.9	1.3
Diesel ICE	132.7	141.9	209.5	167.4	6.6	1.1	7.1	1.1	10.5	1.7	8.4	1.3
EV	160.7	178.1	246.8	201.7	8.0	1.3	8.9	1.4	12.3	2.0	10.1	1.6

brake pad material [115, 128] and operation history [35]. Moreover, the brake temperature may influence the BWP size distribution above the critical brake temperature in the range (140°C < T_{crit} < 240°C) when the smallest BWPs are generated [8, 9, 35, 107]. The research has shown that at temperatures T > 185°C, particles with a size of 0.011–0.029 μm were numerically predominant [110]. Other studies [8] found that the emission of particles with a size of 0.011–0.034 μm increased for temperatures in the range of 165–190°C. It was also found that the average density of the particle material slightly depended on the aerodynamic diameter of the particle in the range of 0.06–10 μm, which means that the mass fraction of ultrafine particles in PM_{10} can be assumed to be equal to the volume fraction [8]. To sum up, the following statements could be made:

– The temperature of the brake friction elements has a significant influence on the number and mass fractions of ultrafine particles [110].
– At temperatures below 200°C, ultrafine particles have no measurable mass contribution to PM_{10} [110].
– At temperatures above 200°C, the mass share of ultrafine particles in PM_{10} reached several dozen percent. This fraction generally increased with temperature and decreased with slip duration [110].

During the production process, after the pressing machine, the brake pads are heat treated by scorching. In this process, the surface of the blocks is exposed to high temperature (usually above 700°C) for a short time (from several dozen seconds to several minutes) [25, 97]. This results in the removal of the less thermally stable phenolic resin as a result of the carbonization reaction, and its absence increases the brittleness of the surface, which becomes more abrasive than the surface of brake pads that were not scorched. Higher abrasiveness of the friction surface results in faster smoothing of both new pads and new friction surfaces of discs, but on the other hand it is responsible for greater wear of pads and discs, and therefore increased PM emissions when they start to be used. Due to carbonization reactions, the friction surface of new brake pads may consist of more condensed organic substances, including volatile and semi-volatile organic compounds. These compounds can evaporate from the friction surface when braking and be released in the form of ultrafine particles smaller than 0.1 μm. A more adhesive nature of the friction phenomenon begins to take place as the contact surfaces become smoother as a result of abrasive polishing accompanied by the formation of a stable friction layer. The presence of stable primary and secondary contact surfaces is believed to be crucial to maintaining the desired friction parameters without excessive wear due to abrasion caused by the movement of loose abrasive particles [25, 96, 120].

Tire wear particulates are produced mechanically as a result of shear forces occurring between the tire tread and the road surface. The physical properties of such particles vary depending on driving style, tire material, road condition, the weather, etc. [69]. Tribological mechanisms of rubber wear are known and understood, including fatigue wear, friction wear, adhesive wear, and chemical erosion wear [1, 34, 36, 89, 118, 123, 152, 162]. As a result of friction and slip, micro-cracks and cracks in the tire and the road surface are formed, causing continuous, increasing wear. Particulate formation occurs when the accumulated local friction energy in the area of contact reaches enough energy to damage (critical energy) the tire surface in the area of contact with the road surface. Tire wear typically occurs simultaneously in different forms, as a mixture of tire wear and road surface wear, accounting for about 50% of each type of wear. Variable factors influencing tire wear include tire characteristics (e.g., its composition, construction), road surface characteristics and operating method, and vehicle characteristics (e.g., speed, cornering method, vehicle weight, and power) [11]. The tire operating temperature and the interaction of the tire surface with the road surface material are also important [3, 56, 83]. BWP sampling and TRWP (tire and road wear particles) measurements in road conditions may be carried out according to various methodologies [30, 66, 121]. Research carried out in accordance with the TRAKER method showed that particles collected behind the front wheels of a car have a PM size distribution reaching 2–3 μm, with a high content of earth's crust elements, which indicates a high share of PM from road wear and dust [17, 88, 90].

4. Composition of solid particles not related to the combustion process

Friction elements materials of the braking systems must meet several basic requirements, the most important of which are high wear resistance, high coefficient of friction, and limited noise and vibration [20, 26, 45]. These materials can be broadly divided into organic and metallic. Other categories that are usually rarely used are ceramics, carbon (only for high brake heating temperatures), and aluminum (only for light vehicles and rear brakes) [26]. Brake pads consist of various components, the most important of which are binders, fillers, friction enhancers, reinforcing fibers and lubricants, while the brake disc is usually made of grey cast iron with additional coatings to improve performance. Fibrous ingredients play a key role in strengthening the friction material. Since the ban on asbestos, many different new fibers have been developed for use in brake friction materials. Among them, organic fibers are based on cellulose, aramid, or natural plants, while inorganic fibers are made of metals or minerals. Fibers improve the strength and tribological properties of friction materials [45, 132, 159]. The synergistic effect of different fibers is often sought to improve the performance of friction materials [45, 159].

Grey cast iron (GCI) is the most commonly used material for brake discs used in cars [12, 105, 135]. However, GCI has poor corrosion resistance and excessive wear, which results in high particulate emissions from the brakes. The results of the tests have shown that corrosion of brake discs reduces the braking performance by reducing the coefficient of friction and, at the same time, significantly increases both the number and the mass of particulates emitted (between 2 and 30 times compared to a non-corroded disc under the same test conditions) [44]. Various technological processes and conditioning forms (e.g. cryogenic, thermal) are used to improve tribological parameters and reduce brake disc wear [117, 135]. Another preferred solution that may be employed is to apply a special abra-

sion resistant coating to the disc surface, e.g. a hard metal coating (HMC), using tungsten carbide, cobalt or chromium carbide [12, 151]. Another option would be to use carbon-ceramic (CC) brake discs. Despite the high costs, CC and HMC discs are becoming an increasingly popular method of reducing the amount of particles produced [44, 58, 130].
Tires typically consist of rubber/elastomers, fillers, additives, reinforcing agents and vulcanizing agents, which vary depending on the tire type and application [152]. For example, truck tires contain about 80% natural rubber, while passenger car tires contain only about 15% [21]. Some of these can be used as markers for tire wear in the environment. Such examples include components used in the vulcanization process, such as 2-(4-morpholinyl)-benzothiazole [86] and Zn, [67] or those originating from thermal decomposition of tire tread polymers [147] such as styrene, isoprene, dipentene, butadiene, vinylcyclohexene, and benzothiazole. Benzothiazoles are used in the ISO standard to determine TRWP (tire and road wear particles) [77]. Compared to particles from tires themselves, TRWPs also include metals from brake linings and road surface materials and contain lower concentrations of polymers [3, 83].

The large variety in the compositions of currently used brake pads causes large differences in the chemistry and morphology of the emitted particulates [84, 95, 104, 155]. The composition of particulate matter from brakes and the degree of their emission are also influenced by the conditions in which braking occurs (pad pressure on the disc during braking, disc/pad temperature, and environmental conditions, etc.) [41, 75, 84, 88, 104, 111, 127]. Brake operations are primarily related to the emission of particulate matter Fe, Cu, Zn, Ba, and Sb, which are used as indicators of brake wear [23, 27, 70]. Moreover, gasification of the resins contained in brake pads often occurs, and hydrocarbon particles are formed [27, 41, 128]. In turn, metal oxides may be formed as a result of metal oxidation [75]. The particle size distribution from brake wear is usually homogeneous, with peak particle size ranging from 1 μm to 6 μm [16, 32, 39, 85, 87]. At the same time, many researchers, e.g. [23, 27, 41, 52, 70, 102, 124, 128] note the possibility of bi- or even multimodal PM size distribution with at least one peak in the fine and/or ultrafine fraction and increased particulate mass in the $PM_{2.5}$ range. It is believed that these particles are formed by the evaporation, condensation, and aggregation of primary particles and are the result of high braking forces and high brake disc temperature [27, 59].

The most important factors affecting the intensity, degree of wear, and the formation of particles emitted by tire abrasion are the design and structure of the tire, the chemical composition of the tire material, wear resistance, tire pressure, the size of the contact area with the road surface and the tire temperature. Vehicle-related factors include driving speed, longitudinal/lateral acceleration, vehicle weight and load distribution, suspension type, braking frequency and force, and cornering frequency and sharpness. Factors related to the road surface are also important, including surface structure, micro and macro texture, porosity, road dust load, and surface binder (bitumen, cement). [36, 52, 69, 91, 98].

The chemical composition of PM emitted from tires depends on the composition of rubber/elastomers and fillers (black carbon, silica, silanes), the additives used (preservatives, antioxidants), the type of textile and metal reinforcements, and vulcanizing agents (ZnO, S, Se, Te, thiazoles, organic peroxides, nitro compounds) and process oils. The morphology of particles emitted from tires would classify them as circular/dendritic particles [36, 52, 69, 91, 98].

5. Methods of particle emission measurement

Measuring non-exhaust particulate emissions from ICE posed a new technological and logistical challenge. The reason for this was the complexity of the vehicle and its operation as a whole and the difficulty of dynamically measuring PM resulting from wear and tear of mechanical components of the vehicle's braking system and running gear. [74, 99, 100]. It is necessary to develop a unified method for sampling particulate matter emitted from the wear of brake and tire friction elements in order to obtain representative, reliable, accurate, and repeatable results. So far, various researchers have used different, non-standardized methods to sample and measure PM emissions unrelated to the engine combustion process [35, 61, 99, 103, 143, 146, 159, 164]. However, each of the methodologies used so far has its own set of drawbacks. Laboratory simulations of the brake friction elements wear are most often based on standard test cycle conditions, but the main disadvantage of such measurements is the inability to simulate the course of brake activation encountered during real driving conditions on the road. In turn, laboratory tests on tire wear do not yet use a unified standard test cycle, which makes it difficult to analyze the emission characteristics resulting from tire wear. Chassis dynamometer tests provide good control of the measurement process, but are limited by the possibility of obtaining an appropriate sample size and are not representative of real braking processes. [37, 74, 100]. Standardized emission factors for each particulate source are used to calculate emissions (Table 1). In the case of tires, specific emission factors for each vehicle type (car, truck, motorcycle, etc.) are combined with distance travelled statistics to generate an emitted mass estimate. Emission factors are expressed in mg/vehicle/km with different values for PM_{10} and $PM_{2.5}$. Most countries use the methodology provided in the 2016 version of the EMEP/EEA Air Pollutant Emissions Inventory Guidebook (EMEP/EEA, 2016) for estimating PM emissions from tire and brake wear and road surface wear. This provides a fairly simple approach that combines PM emission factors in milligrams emitted per kilometer (mg/km) for passenger cars, light trucks, heavy goods vehicles and two-wheelers with the number of vehicle-kilometers travelled per year. For Europe, all emission factors are collected in the Guidebook [109]. Current emission factors are based on studies published between 1990 and 2000 [109], with conclusions based on indirect measurements. Hence, many publications admit that emission factors are imprecise, even in the DEFRA report [7]. The values given in the guides are indirect measurements, resulting from the total loss of the tire mass (tire weight lost is the data being measured, not the mass of airborne particles specifically). As a result, in 2021, the Working Party on Energy and Pollution (GRPE) entrusted the Particle

Measurement Programme Informal Working Group (PMP-IWG) to develop a global technical regulation (GTR) covering the sampling PM and measurement of PM emissions from brake wear of light vehicle (LDV) friction brake components for vehicles up to 3.5 t [20, 45, 129]. Similarly, in 2022, a joint task force was established within the Working Party on Noise and Tires (GRBP) and the GRPE to develop a procedure for measuring tire wear and assessing the PM wear performance of a wide range of tires available on the market [19, 129]. These two activities were carried out on the basis of the United Nations Economic Commission for Europe World Forum for Harmonization of Vehicle Regulations (UNECE WP.29). As part of the work on the GTR, PMP-IWG developed the first version of a test methodology comprising a set of technical procedures for measuring brake PM emissions on dynamometers [129]. These specifications include provisions for the conduct of the test [45, 129], the methodology for regulating the cooling process, the procedure for preparing the brake pads, the measurement of PM and PN emissions and the presentation of the results [45, 97, 99]. Throughout this process, it was found that the losses of emitted particles between the brake and the sampling point must be kept as low as possible. To ensure this, isokinetic sampling is necessary, where the volume flow used to cool the brake must be precisely matched to the extraction or sampling rate of the measuring device. This ensures that the measured particle mass values are reliable. To ensure that the measurement results can be related to actual conditions encountered during vehicle operation on the road, the standardized WLTP-B braking test cycle has been successfully developed [45, 74, 129]. The cycle was established using actual vehicle data, and it maps different brake application points over the required period of time. This guarantees the repeatability of the recorded PM emission resulting from the abrasion of brake friction elements. It was assumed that the measurements of PM emissions from brakes carried out on the test stand will be standardized in the future in the developed WLTP braking cycle. Due to the fact that a given vehicle model must be accurately reproduced on a test bench, the combination of the working assembly of brake pads and brake disc with the vehicle mass and its distribution has a significant impact on the observed wear patterns. These parameters must be programmed on a test bench, except for brakes used in electric vehicles. In this case, under real operating conditions, regenerative braking ensures that the friction brake is used less frequently and therefore PM emissions are lower. In September 2021, PMP-IWG organized the first Inter-Laboratory Study (ILS) to evaluate the newly developed methodology. The main ILS results were presented to the IWG in March 2022 in the form of six different presentations [155]. In June 2022, GRPE adopted GTR 24 on a broad methodology for measuring PM emissions from brakes [53, 69, 74, 95, 145]. The Global Technical Regulation (GTR 24) on PM emissions from brakes of light commercial vehicles includes harmonized measurement procedures. GTR 24 is the world's first regulation that systematizes and establishes procedures for measuring particulate emissions from sources other than ICE exhaust gases. GTR 24 will be implemented as part of the Euro 7 exhaust emissions regulation, which aims to reduce PM and PN emissions from road transport, both for particulate matter from the combustion process in ICE and for particulate matter from NEE, and to improve air quality in Europe.

6. Euro 7 – particles not related to the combustion process

The scope of the proposed Euro 7 standard goes beyond the current vehicle type approval requirements contained in Euro 6 [45, 74, 129]. The Euro 7 standard extends regulatory requirements to the type approval of braking systems and tires, in particular with regard to particulate emissions and the occurring abrasion process. The regulation applies to tires of classes C1 (passenger cars and commercial vehicles), C2 (light commercial vehicles) and C3 (heavy commercial vehicles), in accordance with UN Regulation 117. As a result, the Euro 7 standard will include a requirement to limit the maximum emissions of PM_{10} particulate matter from brake pads and tires. Generally speaking, for electric cars it will be 3 mg/km, for combustion passenger cars, hybrids and hydrogen cars 7 mg/km, and for large vans and delivery vehicles 11 mg/km [7, 27]. The Euro 7 emission standard will apply for the first time to the type approval of new models of light vehicles and their braking systems 2.5 years after the regulation enters into force – Fig. 2. A year later, all newly registered vehicles will have to meet the new Euro 7 requirements. Euro 7 heavy goods vehicles will apply to new vehicle models 4 years after entry into force, and after 5 years to all new vehicles.

Fig. 2 Schedule for the rollout of the Euro 7 standard for vehicles of various categories [27]

Regardless of the final date of introduction of the Euro 7 standard (currently set for July 1, 2030), brake particle limits for heavy goods vehicles will only begin to apply from 2030. In the case of tires, abrasion limits will be introduced in July 2028 for class C1 tires, in April 2030 for class C2 tires, and in April 2032 for class C3 tires [27].

Compared to ICE-powered vehicles, electric and electrified vehicles can reduce PM emissions from brakes by using regenerative braking. In practice, this means that instead of brakes, an electric motor operating in generator mode is used to slow the vehicle down. This technological difference was reflected in the requirements of the Euro 7 standard by establishing lower particulate limits for electric vehicles compared to other types of drive systems – Table 4 [27].

In the first step, Euro 7 lists particulate matter emission limits for passenger cars and light commercial vehicles N_1 until the end of 2029. Starting in 2030, the regulation also provides particulate emission limits extended to buses and trucks of categories M_2, M_3, and N_2, N_3. Particulate emissions from braking systems for M_1 and N_1 vehicles will be tested in accordance with UN Global Technical Regulation No. 24.8.

A test procedure for PM measurements from truck braking systems has not been developed yet (Table 4) [27].

Table 4 Particulate matter emission limits during braking for Euro 7 [27]

Date	Powertrain type	Vehicle categories		
		M_1/N_1 class I & II	N_1 class III	M_2/N_2 and M_3/N_3
Until December 2029	Battery electric vehicles	3 mg/km	5 mg/km	none
	Other powertrain types	7 mg/km	11 mg/km	none
January 2030 – December 2034	Battery electric vehicles	tbd	tbd	tbd
	Other powertrain types	tbd	tbd	tbd
From January 2035	All powertrain types	3 mg/km	tbd	tbd

Fig. 3. Dates of introducing tire wear limits through the Euro 7 standard [27]

The Euro 7 standard will also introduce limits on PM emissions from tire abrasion. As a consequence, only tires with abrasion rates below the Euro 7 limits will receive type approval. The required testing procedure and emission limits are currently being developed by the United Nations Economic Commission for Europe (UNECE) and will be introduced as an amendment to the Euro 7 regulations. If the UNECE regulation is not adopted in time, the Commission will be given the authority to develop a procedure for assessing PM emissions from tires and setting limits on this emission. As shown in Fig. 3, the Euro 7 requirements will cover different tire classes at different times – first, C1 tires from July 2028, then C2 tires from April 2030, and finally, C3 tires from April 2032. The order of introduction will be same for all categories. In the first stage, the Euro 7 standard will apply to new tire models that receive type approval for the first time. A year later, new vehicles placed on the market will have to be equipped with Euro 7 approved tires, and a year later all tires placed on the market must meet Euro 7 requirements.

7. Conclusions

- Emissions of particulate matter not related to the engine combustion process (resulting from wear of brake friction elements and tire friction processes with the road surface) are currently unregulated both in terms of measurement methodology as well as emission limits.
- Non exhaust PM vehicle emissions have already exceeded PM emissions from exhaust gases as the main source of particulate matter emissions from road traffic. Despite this, this major source of PM emissions from road traffic is currently not covered by any legal regulation to control and limit these emissions.
- The health risks posed by particulate matter emitted from braking systems and tire abrasion are not yet clearly understood in their entirety. This requires multidisciplinary research efforts to adopt effective and appropriate evidence-based emissions reduction legislation and strategies to protect human health.
- When taking action to reduce particulate emissions resulting from the wear of brake friction elements and tire abrasion, the chemical profile of the emissions, as well as the total mass and number of particles, should be taken into account.
- With the growing popularity of alternative vehicle powertrains, NEEs are increasingly contributing to air pollution. This is reflected in mitigation strategies through new requirements that will be introduced by the Euro7 emissions standard, which plans to take into account non-combustion emissions for the first time.
- Measuring particulate emissions not related to the combustion process in the engine presents a new technological challenge. This is due to the complexity of the vehicle and its operation as a whole and to the difficulty of dynamically measuring particulate emissions caused by the wear of both friction brake components and tires.
- One of the main reasons for the observed inconsistencies in the particulate matter measurements (PM and PN) is the lack of a unified, standardized methodology for sampling and measuring both particulate matter caused by brake elements abrasion and tire wear.
- Realistic PM coefficients with NEE are necessary to reliably calculate the contribution of PM emissions from brake and tire wear to air pollution, but also to estimate the reduction potential of these emissions through the use of new or existing technologies and improved formulae for brake and tire friction components.

Nomenclature

BWP	brake wear particles
CC	carbon ceramic
ECE	Economic Commission for Europe
EF	emission factor
EU	European Union
GCI	grey cast iron
GTR	global technical regulation
HMC	hard metal coated discs
ICE	Internal Combustion Engine
ILS	inter-laboratory study
LACT	Los Angeles City Traffic
LDV	light duty vehicles
LM	low-metallic
NAO	non-asbestos organics
NEE	non exhaust emissions
OECD	Organisation for Economic Co-operation and Development
PHEV	plug-in hybrid electric vehicles
PM	particle matter
PMP	particle measurement programme

PMP-IWG Particle Measurement Programme Informal Working Group
PoD pin-on- disc
RDE real driving emission
SM semi-metallic
SUV sports utility vehicle
TRWP tire and road wear particles
TWP tire wear particles
UNECE United Nations Economic Commission for Europe
WLTP Worldwide Light duty Test Procedure

Bibliography

[1] Aatmeeyata DSK, Sharma M. Traffic generated non-exhaust particulate emissions from concrete pavement: a mass and particle size study for two-wheelers and small cars. Atmos Environ. 2007;43(35):5691-5697. https://doi.org/10.1016/j.atmosenv.2009.07.032

[2] Adamiak B, Szczotka A, Woodburn J, Merkisz J. Comparison of exhaust emission results obtained from Portable Emissions Measurement System (PEMS) and a laboratory system. Combustion Engines. 2023;195(4):128-135. https://doi.org/10.19206/CE-172818

[3] Adachi K, Tainosho Y. Characterization of heavy metal particles embedded in tire dust. Environ Int. 2004;30(8): 1009-1017. https://doi.org/10.1016/j.envint.2004.04.004

[4] Adamczak L. At source brake dust active filtering system EB2023-EFA-008. Proceedings of the EuroBrake 2023. Barcelona 12-14 September 2023.

[5] Agudelo C, Vedula RT, Collier S, Stanard A. Brake particulate matter emissions measurements for six light-duty vehicles using inertia dynamometer testing. SAE Int J Adv&Curr Prac in Mobility. 2021;3(2):994-1019. https://doi.org/10.4271/2020-01-1637

[6] Air Quality Expert Group (AQEG) non-exhaust emissions from road traffic. UK 2019 (accessed on 7 January 2024).

[7] Air Pollution in the UK 2019. September 2020. https://uk-air.defra.gov.uk/library/annualreport/ (accessed on 1 March 2024).

[8] Alemani M, Nosko O, Metinoz I, Olofsson U. A study on emission of airborne wear particles from car brake friction pairs. SAE Int J Mater Manuf. 2016;9(1):147-157. https://doi.org/10.4271/2015-01-2665

[9] Alemani M, Wahlström J, Olofsson U. On the influence of car brake system parameters on particulate matter emissions. Wear. 2018;396-397:67-74. https://doi.org/10.1016/j.wear.2017.11.011

[10] Amato F, Cassee FR, van der Gon HAC, Gehrig R, Gustafsson M et al. Urban air quality: the challenge of traffic non-exhaust emissions. J Hazard Mater. 2014;275:31-36. https://doi.org/10.1016/j.jhazmat.2014.04.053

[11] Amato F. An urban air quality problem for public health; impact and mitigation measures. Elsevier 2018. https://doi.org/10.1016/B978-0-12-811770-5.01001-3

[12] Aranke O, Algenaid W, Awe S, Joshi S. Coatings for automotive gray cast iron brake discs: a review. Coatings. 2019; 9:552. https://doi.org/10.3390/coatings9090552

[13] Axsen J, Wolinetz M. Reaching 30% plug-in vehicle sales by 2030: modeling incentive and sales mandate strategies in Canada. Transport Res D-Tr E. 2019;65:596-617. https://doi.org/10.1016/j.trd.2018.09.012

[14] Baensch-Baltruschat B, Kocher B, Stock F, Reifferscheid G. Tyre and road wear particles (TRWP) – a review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Sci Total Environ. 2020;733: 137823. https://doi.org/10.1016/j.scitotenv.2020.137823

[15] Baensch-Baltruschat B, Kocher B. Kochleus C, Stock F, Reifferscheid G. Tyre and road wear particles – a calculation of generation, transport and release to water and soil with special regard to German roads. Sci Total Environ. 2021; 752: 141939. https://doi.org/10.1016/j.scitotenv.2020.141939

[16] Beddows DCS, Harrison RM. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles. Atmos Environ. 2021;244:117886. https://doi.org/10.1016/j.atmosenv.2020.117886

[17] Beji A, Deboudt K, Khardi S, Muresan B, Lumière L. Determinants of rear-of-wheel and tire-road wear particle emissions by light-duty vehicles using on-road and test track experiments. Atmos Pollut Res. 2021;12(3):278-291. https://doi.org/10.1016/j.apr.2020.12.014

[18] Belis CA, Karagulian F, Larsen BR, Hopke PK. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. Atmos Environ. 2013;63:94-108. https://doi.org/10.1016/j.atmosenv.2012.11.009

[19] Bondorf L, Kohler L, Grein T, Epple F, Philipps F, Aigner M et al. Airborne brake wear emissions from a battery electric vehicle. Atmosphere. 2023;14:488. https://doi.org/10.3390/atmos14030488

[20] Borawski A. Conventional and unconventional materials used in the production of brake pads – review. Sci Eng Compos Mater. 2020;27:374-396. https://doi.org/10.1515/secm-2020-0041

[21] Camatini M, Crosta G, Dolukhanyan T, Sung C, Giuliani G, Corbetta G et al. Microcharacterization and identification of tire debris in heterogeneous laboratory and environmental specimens. Mater Charact. 2001;46:271-283. https://doi.org/10.1016/S1044-5803(00)00098-X

[22] Czerwinski J, Mayer A, Stepien Z, Oleksiak S, Andersen O. Reduction of emissions and unregulated components with DPF + SCR. Conference DEXFIL 2009;11.

[23] Dall'Osto M, Querol X, Amato F, Karanasiou A, Lucarelli F, Nava S et al. Hourly elemental concentrations in PM2.5 aerosols sampled simultaneously at urban background and road site during SAPUSS – diurnal variations and PMF receptor modelling. Atmos Chem Phys. 2013;13:4375-4392. https://doi.org/10.5194/acp-13-4375-2013

[24] Dall'Osto M, Beddows DC, Gietl JK, Olatunbosun O, Yang X, Harrison RM. Characteristics of tyre dust in polluted air: studies by single particle mass spectrometry (ATOFMS). Atmos Environ. 2014;94:224-230. https://doi.org/10.1016/j.atmosenv.2014.05.026

[25] Dante RC. Handbook of friction materials and their application. Elsevier 2016. https://doi.org/10.1016/C2015-0-00634-7

[26] Day A, Bryant D. Braking of road vehicles. 2nd ed. Butterworth-Heinemann, Kidlington, Cambridge 2022. https://doi.org/10.1016/B978-0-12-822005-4.00064-0

[27] Dornoff J, Rodríguez F. Euro 7: the new emission standard for light- and heavy-duty vehicles in the European Union. ICCT policy update | Euro 7: emission standard for light- and heavy-duty vehicles in the EU. https://theicct.org/wp-content/uploads/2024/03/ID-116-%E2%80%93-Euro-7-standard_final.pdf (accessed on 21 March 2024).

[28] EEA EIONET Central Data Repository, 2023. https://cdr.eionet.europa.eu (accessed on 7 January 2024).

[29] EPA. Brake and tire wear emissions from onroad vehicles in MOVES3. Report EPA-420-R-20-014, 2020. https://www.epa.gov/sites/default/files/2020-11/documents/420r20014.pdf (accessed on 7 January 2024).

[30] Etyemezian V. Vehicle-based road dust emission measurement: I methods and calibration. Atmos Environ. 2003; 37(32):4559-4571. https://doi.org/10.1016/S1352-2310(03)00528-4

[31] Euro 7 vehicle emission standards: a European Green Deal proposal. Technical studies for the development of Euro 7: testing, pollutants and emission limits. 2022. https://doi.org/10.2873/97170 (accessed on 1 March 2024).

[32] European Commission. Directorate general for internal market, industry, entrepreneurship and SMEs. In Euro 7 impact assessment study. Publications Office: Luxembourg 2022.

[33] European Commission; EEA Climate and Energy in the EU. Country Comparison. 2023. https://climate-energy.eea.europa.eu/topics/transport/emissions-cars/data (accessed on 7 January 2024).

[34] Faino. 48th PMP IWG meeting tyre and road wear particles: the tyre industry perspective UN WP29 GRPE PMP-48-13. ISPRA – November 8, 2018 (accessed on 1 March 2024).

[35] Farwick zum Hagen FH, Mathissen M, Grabiec T, Hennicke T, Rettig M, Grochowicz J et al. Study of brake wear particle emissions: impact of braking and cruising conditions. Environ Sci Technol. 2019;53(9):5143-5150. https://doi.org/10.1021/acs.est.8b07142

[36] Feißel T, Kunze M, Hesse D, Ivanov V, Augsburg K, Gramstat S. On-road vehicle measurement of tire wear particle emissions and approach for emission prediction. Proceedings of the 40th Annual Meeting of the Tire Society. Akron 2 September 2021 (accessed on 1 March 2024).

[37] Feißel T, Hesse D, Ricciardi V, Schiele M, Augsburg M. Novel approaches for measuring and predicting particulate emissions from automotive brakes and tires. 12th International Munich Chassis Symposium 2021:708-728 (accessed on 1 March 2024).

[38] Feo ML, Torre M, Tratzi P, Battistelli F, Tomassetti L, Petracchini F et al. Laboratory and on-road testing for brake wear particle emissions: a review. Environ Sci Pollut Res. 2023;30:100282-100300. https://doi.org/10.1007/s11356-023-29229-7

[39] Furusjö E, Sternbeck J, Cousins AP. PM10 source characterization at urban and highway roadside locations. Sci Total Environ. 2007;387(1-3):206-219. https://doi.org/10.1016/j.scitotenv.2007.07.021

[40] Fussell JC, Franklin M, Green DC, Gustafsson M, Harrison RM, Hicks W et al. A review of road traffic-derived non-exhaust particles: emissions, physicochemical characteristics, health risks, and mitigation measures. Environ Sci Technol. 2022;56:6813-6835. https://doi.org/10.1021/acs.est.2c01072

[41] Garg BD, Cadle SH, Mulawa PA, Groblicki PJ. Brake wear particulate matter emissions. Environ Sci Technol. 2000;34: 4463-4469. https://doi.org/10.1021/es001108h

[42] Gasser M, Riediker M, Mueller L, Perrenoud A, Blank F, Gehr P et al. Toxic effects of brake wear particles on epithelial lung cells in vitro. Part Fibre Toxicol. 2009;6:30. https://doi.org/10.1186/1743-8977-6-30

[43] Geilenkirchen G, Hulskotte J, Dellaert S, Ligterink N, Sijstermans M, Roth K et al. Methods for calculating the emissions of transport in the Netherlands. 2021 PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/ methods-for-calculating-the-emissions-of-transport-in-the-netherlands-2021 (accessed on 1 March 2024).

[44] Ghouri I, Barker R, Brooks P, Kosarieh S, Barton D. The effects of corrosion on particle emissions from a grey cast iron brake disc. SAE Technical Paper 2022-01-1178. 2022. https://doi.org/10.4271/2022-01-1178

[45] Giechaskiel B, Grigoratos T, Dilara P, Karageorgiou T, Ntziachristos L, Samaras Z. Light-duty vehicle brake emission factors. Atmosphere. 2024;15:1-20. https://doi.org/10.3390/atmos15010097

[46] Gietl JK, Lawrence R, Thorpe AJ, Harrison RM. Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road. Atmos Environ. 2010; 44(2):141-146. https://doi.org/10.1016/j.atmosenv.2009.10.016

[47] Goel A, Kumar P. A review of fundamental drivers governing the emissions, dispersion and exposure to vehicle-emitted nanoparticles at signalised traffic intersections. Atmos Environ. 2014;97:316-331. https://doi.org/10.1016/j.atmosenv.2014.08.037

[48] Gramstat S, Mertens T, Waninger R, Lugovyy D. Impacts on brake particle emission testing. Atmosphere. 2020;11: 1132. https://doi.org/10.3390/atmos11101132

[49] Gramstat S, Mertens T, Waninger R, Augsburg K, Hamatschek C, Hesse D. Functional coatings of gray-cast iron brake discs – impact on the tribology. Mayer R. (ed). Berichte aus dem µ-Club 2020. Springer Berlin/Heidelberg 2021:162-170. https://doi.org/10.1007/978-3-662-63028-0_10

[50] Grange SK, Fischer A, Zellweger C, Alastuey A, Querol X, Jaffrezo J-L et al. Switzerland's PM10 and PM2.5 environmental increments show the importance of non-exhaust emissions. Atmos Environ. 2021;12:100145. https://doi.org/10.1016/j.aeaoa.2021.100145

[51] Grigoratos T, Martini G. Non-exhaust traffic related emissions. Brake and tyre wear PM. Literature review. Report EUR 26648 EN. European Union, Luxembourg 2014.

[52] Grigoratos T, Martini G. Brake wear particle emissions: a review. Environ Sci Pollu. Res. 2015;22:2491-2504. https://doi.org/10.1007/s11356-014-3696-8

[53] Grigoratos T, Mathissen M, Vedula R, Mamakos A, Agudelo, C, Gramstat S et al. Interlaboratory study on brake particle emissions – part I: particulate matter mass emissions. Atmosphere. 2023;14:498. https://doi.org/10.3390/atmos14030498

[54] Grigoratos T, Mamakos A, Vedula R, Arndt M, Lugovyy D, Hafenmayer C et al. Characterization of laboratory particulate matter (PM) mass setups for brake emission measurements. Atmosphere. 2023;14:516. https://doi.org/10.3390/atmos14030516

[55] GRPE-2023-4e. Clean-(PMP) proposal to amend ECE/TRANS/WP.29/GRPE/2023/4. Proposal for a New UN GTR on laboratory measurement of brake emissions for light-duty vehicles. https://unece.org/transport/documents/2023/01/informal documents/clean-pmp-proposal-amend-ecetranswp29grpe20234 (accessed on 1 March 2024).

[56] Gunawardana C, Goonetilleke A, Egodawatta P, Dawes L, Kokot S. Source characterisation of road dust based on chemical and mineralogical composition. Chemosphere. 2012;87(2):163-170. https://doi.org/10.1016/j.chemosphere.2011.12.012

[57] Guo D, Wei H, Guo Y, Wang C, Yin Z. Non-exhaust particulate matter emission from vehicles: a review. E3S Web Conf. 2021;268:01015. https://doi.org/10.1051/e3sconf/202126801015

[58] Güney B, Mutlu I. Tribological properties of brake discs coated with Cr2O3 – 40% TiO2 by plasma spraying. Surf Rev Lett. 2019;26:1950075. https://doi.org/10.1142/S0218625X19500756

[59] Hagino H, Oyama M, Sasaki S. Laboratory testing of airborne brake wear particle emissions using a dynamometer system under urban city driving cycles. Atmos Environ. 2016;131:269-278. https://doi.org/10.1016/j.atmosenv.2016.02.014
[60] Hagino H, Iwata A, Okuda T. Iron oxide and hydroxide speciation in emissions of brake-wear particles from different friction materials using X-ray absorption fine structure. Atmosphere. 2023;15:49. https://doi.org/10.3390/atmos15010049
[61] Hagino H. Brake wear particle emission measurements based on real driving cycles in several urban areas in a laboratory testing. EB2023-TST-009. Proceedings of the Euro Brakes 2023. Barcelona 12-14 September 2023.
[62] Hagino H. Investigation of brake-wear particle emissions from regenerative-friction brake coordination systems via dynamometer testing. Atmosphere. 2024;15:75. https://doi.org/10.3390/atmos15010075
[63] Hall TJ. A comparison of braking behavior between an IC engine and pure electric vehicle in Los Angeles city driving conditions. SAE Technical Paper 2017-01-2518. 2017. https://doi.org/10.4271/2017-01-2518
[64] Hamatschek C, Hesse D, Augsburg K, Gramstat S, Stich A. Comparison of the particle emission behaviour of automotive drum and disc brakes. 12th International Munich Chassis Symposium 2021. Springer Berlin/Heidelberg, Germany 2022:541-563.
[65] Hamatschek C, Augsburg K, Schobel D, Gramstat S, Stich A, Gulden F et al. Comparative study on the friction behaviour and the particle formation process between a laser cladded brake disc and a conventional grey cast iron disc. Metals. 2023;13:300. https://doi.org/10.3390/met13020300
[66] Han S, Jung YW. A study on the characteristics of silt loading on paved roads in the Seoul metropolitan area using a mobile monitoring system. J Air Waste Manag Assoc. 2012; 62(7):846-862. https://doi.org/10.1080/10962247.2012.686892
[67] Harrison RM, Jones AM, Gietl J, Yin J, Green DC. Estimation of the contributions of brake dust, tire wear, an resuspension to nonexhaust traffic particles derived from atmospheric measurements. Environ Sci Technol. 2012;46;6523-6529. https://doi.org/10.1021/es300894r
[68] Hesse D, Hamatschek C, Augsburg K, Weigelt T, Prahst A, Gramstat S. Testing of alternative disc brakes and friction materials regarding brake wear particle emissions and temperature behavior. Atmosphere. 2021;12:436. https://doi.org/10.3390/atmos12040436
[69] Hesse D, Feißel T, Kunze M, Bachmann E, Bachmann T, Gramstat S. Comparison of methods for sampling particulate emissions from tires under different test environments. Atmosphere. 2022;13:1262. https://doi.org/10.3390/atmos13081262
[70] Hinrichs R, Soares MRF, Lamb RG, Soares MRF, Vasconcellos MAZ. Phase characterization of debris generated in brake pad coefficient of friction tests. Wear. 2011;270:515-519. https://doi.org/10.1016/j.wear.2011.01.004
[71] Hoffmann B, Moebus S, Möhlenkamp S, Stang A, Lehmann N, Dragano N et al. Residential exposure to traffic is associated with coronary atherosclerosis. Circulation. 2007;116: 489-496. https://doi.org/10.1161/CIRCULATIONAHA.107.693622
[72] Hooftman N, Oliveira L, Messagie M, Coosemans T, Van Mierlo J. Environmental analysis of petrol, diesel and electric passenger cars in a Belgian urban setting. Energies. 2016;9: 84. https://doi.org/10.3390/en9020084
[73] Huber MP, Fischer P, Mamakos A, Steiner G, Klug A. Measuring brake wear particles with a real-driving emissions sampling system on a brake dynamometer. SAE Technical Paper 2022-01-1180. 2022. https://doi.org/10.4271/2022-01-1180
[74] Huber MP, Murg J, Steiner G, Wanek-Rüdiger C, Weidinger C, Huemer-Kals S et al. Assessing a vehicle's real-world brake wear particle emissions on public roads. Eurobrake Conference 2023. https://doi.org/10.46720/eb2023-tst-002
[75] Iijima A, Sato K, Yano K, Tago H, Kato M, Kimura H et al. Particle size and composition distribution analysis of automotive brake abrasion dusts for the evaluation of antimony sources of airborne particulate matter. Atmos Environ. 2007; 41:4908-4919. https://doi.org/10.1016/j.atmosenv.2007.02.005
[76] Iijima A, Sato K, Yano K, Kato M, Kozawa K, Furuta N. Emission factor for antimony in brake abrasion dusts as one of the major atmospheric antimony sources. Environ Sci Technol. 2008;42:2937-2942. https://doi.org/10.1021/es702137g
[77] ISO, ISO/TS 21396:2017 Rubber determination of mass concentration of tire and road wear particles (TRWP) in soil and sediments Pyrolysis-GC/MS method, 2017.
[78] Jeong CH, Wang JM, Hilker N, Debosz J, Sofowote U, Su Y et al. Temporal and spatial variability of traffic-related PM2.5 sources: comparison of exhaust and non-exhaust emissions. Atmos Environ. 2019;198:55-69. https://doi.org/10.1016/j.atmosenv.2018.10.038
[79] Kim HS, Na HW, Jang Y, Kim SJ, Kee NG, Shin DY et al. Integrative analysis to explore the biological association between environmental skin diseases and ambient particulate matter. Sci Rep. 2022;12:9750. https://doi.org/10.1038/s41598-022-13001-x
[80] Kolbeck K, Schroder T, Schlichting M, Bacher H. Evaluation of different influencing parameters on the result of brake particle emission measurements. EB2022-FBR-011. Proceedings of the EuroBrake 2022. 17-19 May 2022.
[81] Kole PJ, Löhr AJ, Van Belleghem FGAJ, Ragas AMJ. Wear and tear of tyres: a stealthy source of microplastics in the environment. Int J Environ Res Public Health. 2017;14(10): 1265. https://doi.org/10.3390/ijerph14101265
[82] Koupal J, Den Bleyker A, Kishan S, Vedula R, Agudelo C. Brake wear particulate matter emissions modelling. Eastern Research Group, Boston 2021. https://rosap.ntl.bts.gov/view/dot/60273/dot_60273_DS1.pdf (accessed on 9 February 2024).
[83] Kreider ML, Panko JM, McAtee BL, Sweet LI, Finley BL. Physical and chemical characterization of tire-related particles: comparison of particles generated using different methodologies. Sci Total Environ. 2010;408(3):652-659. https://doi.org/10.1016/j.scitotenv.2009.10.016
[84] Kukutschová J, Moravec P, Tomášek, Matějka V, Smolik J, Schwarz V et al. On air-borne nano/micro-sized wear particles released fromlow-metallic automotive brakes. Environ Pollut. 2011;159(4):998-1006. https://doi.org/10.1016/j.envpol.2010.11.036
[85] Kumar P, Pirjola L, Ketzel M, Harrison R.M. Nanoparticle emissions from 11 non-vehicle exhaust sources – a review. Atmos Environ. 2013;67:252-277. https://doi.org/10.1016/j.atmosenv.2012.11.011
[86] Kumata H, Sanada Y, Takada H, Ueno T. Historical trends of n-cyclohexyl-2-benzothiazolamine, 2-(4-morpholinyl)-benzothiazole, and other anthropogenic contaminants in the urban reservoir sediment core. Environ Sci Technol. 2000; 34(2):246-253. https://doi.org/10.1021/ES990738K
[87] Kunze M, Feißel T, Ivanov V, Bachmann T, David Hesse D, Gramstat S. Analysis of TRWP particle distribution in urban and suburban landscapes, connecting real road measure-

ments with particle distribution simulation. Atmosphere. 2022;13;1204. https://doi.org/10.3390/atmos13081204
[88] Kwak J-H, Kim H, Lee J, Lee S. Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements. Sci Total Environ. 2013;458-460: 273-282. https://doi.org/10.1016/j.scitotenv.2013.04.040
[89] Kwak J, Lee S, Lee S. On-road and laboratory investigations on non-exhaust ultrafine particles from the interaction between the tire and road pavement under braking conditions. Atmos Environ. 2014;97:195-205. https://doi.org/10.1016/j.atmosenv.2014.08.014
[90] Lee S, Kwak J, Kim H, Lee J. Properties of roadway particles from interaction between the tire and road pavement. Int J Auto Tech. 2013;14(1):163-173. https://doi.org/10.1007/S12239-013-0018-Y
[91] Liati A, Schreiber D, Lugovyy D, Gramstat S, Eggenschwiler PD. Airborne particulate matter emissions from vehicle brakes in micro-and nano-scales: morphology and chemistry by electron microscopy. Atmos Environ. 2019; 212:281-289. https://doi.org/10.1016/j.atmosenv.2019.05.037
[92] Liu J. Experimental investigation on the morphology of the tire wear particles and its generation mechanism. Tribology. 2017;37(5):587-593. https://doi.org/10.16078/j.tribology.2017.05.004
[93] Liu Y, Wu S., Chen H, Federici M, Perricone G, Li Y et al. Brake wear induced PM10 emissions during the World Harmonised Light-Duty Vehicle Test Procedure-brake cycle. J Clean Prod. 2022;361;132278. https://doi.org/10.1016/j.jclepro.2022.132278
[94] Liu Y, Chen H, Li Y, Gao J, Dave K, Chen J et al. Exhaust and non-exhaust emissions from conventional and electric vehicles: a comparison of monetary impact values. J Clean Prod. 2022;331:129965. https://doi.org/10.1016/j.jclepro.2021.129965
[95] Mamakos A, Arndt M, Hesse D, Augsburg K. Physical characterization of brake-wear particles in a PM10 dilution tunnel. Atmosphere. 2019;10:639. https://doi.org/10.3390/atmos10110639
[96] Matejka V, Metineoz I, Alemani M, Wahlstr€om J, Bonfanti A, Oloffson U et al., Dependency of PM10 particles emission on stability of friction coefficient and character of friction surface. Proceeding EuroBrake 2016, EB2016-MDS-009, Milano 2016.
[97] Matejka V, Metinoz I, Wahlstromb J, Alemani M, Perricone G. On the running-in of brake pads and discs for dyno bench tests. Tribol Int. 2017;115:424-431. https://doi.org/10.1016/j.triboint.2017.06.008
[98] Mathissen M, Scheer V, Vogt R, Benter T. Investigation on the potential generation of ultrafine particles from the tire–road interface. Atmos Environ. 2011;45:6172-6179. https://doi.org/10.1016/j.atmosenv.2011.08.032
[99] Mathissen M, Grochowicz J, Schmidt C, Vogt R, Farwick zum Hagen FH, Grabiec T et al. A novel real-world braking cycle for studying brake wear particle emissions. Wear. 2018;414-415:219-226. https://doi.org/10.1016/j.wear.2018.07.020
[100] Mathissen M, Grigoratos T, Lahde T, Vogt R. Brake wear particle emissions of a passenger car measured on a chassis dynamometer. Atmosphere. 2019;10:556. https://doi.org/10.3390/atmos10090556
[101] Mathissen M, Grigoratos T, Gramstat S, Mamakos A, Vedula R, Agudelo C et al. Interlaboratory study on brake particle emissions. Part II: particle number emissions. Atmosphere. 2023;14:424. https://doi.org/10.3390/atmos14030424
[102] Maynard D, Coull BA, Gryparis A, Schwartz J. Mortality risk associated with short-term exposure to traffic particles and sulfates. Environ Health Perspect. 2007;115:751-755. https://doi.org/10.1289/ehp.9537
[103] Men Z, Zhang X, Peng J, Zhang J, Fang T, Guo Q et al. Determining factors and parameterization of brake wear particle emission. J Hazard Mater. 2022;434:128856. https://doi.org/10.1016/j.jhazmat.2022.128856
[104] Mosleh M, Blau PJ, Dumitrescu D. Characteristics and morphology of wear particles from laboratory testing of disk brake materials. Wear. 2004;256;1128-1134. https://doi.org/10.1016/j.wear.2003.07.007
[105] Mulani SM, Kumar A, Shaikh HNEA, Saurabh A, Singh PK, Verma PC. A review on recent development and challenges in automotive brake pad-disc system. Mater Today: Proc. 2022; 56:447-454. https://doi.org/10.1016/j.matpr.2022.01.410
[106] National Emissions Reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention). https://www.eea.europa.eu/ds_resolveuid/f54753b5901e4a8591060bb4ba23c497 (accessed on 1 March 2024).
[107] Niemann H, Winner H, Asbach C, Kaminski H, Frentz G, Milczarek R. Influence of disc temperature on ultrafine, fine, and coarse particle emissions of passenger car disc brakes with organic and inorganic pad binder materials. Atmosphere. 2020;11:1060. https://doi.org/10.3390/atmos11101060
[108] Nosko O, Vanhanen J, Olofsson U. Emission of 1.3–10 nm airborne particles from brake materials. Aerosol Sci Technol. 2017;51(1):91-96. https://doi.org/10.1080/02786826.2016.1255713
[109] Ntziachristos L, Boulter P. EMEP/EEA air pollutant emission inventory guidebook 2019 – road transport: automobile tyre and brake wear. EEA Report No 13/2019.
[110] Oberdörster G, Maynard A, Donaldson K, Castranova V, Fitzpatrick J, Ausman K et al. Principles for characterizing the potential human health effects from exposure to nanomaterials: elements of a screening strategy. Part Fibre Toxicol. 2005; 2:8. https://doi.org/10.1186/1743-8977-2-8
[111] Olofsson U, Olander L. On the identification of wear modes and transitions using airborne wear particles. Tribol Int. 2013;59:104-113. https://doi.org/10.1016/j.triboint.2012.01.013
[112] Oroumiyeh F, Zhu Y. Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity. Atmos Environ. 2021;12:100121. https://doi.org/10.1016/j.aeaoa.2021.100121
[113] Panko J, Hitchcock K, Fuller G, Green, D. Evaluation of tire wear contribution to PM2.5 in urban environments. Atmosphere. 2019;10:99. https://doi.org/10.3390/atmos10020099
[114] Pant P, Harrison RM. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. Atmos Environ. 2013;77:78-97. https://doi.org/10.1016/j.atmosenv.2013.04.028
[115] Park J, Joo B, Seo H, Song W, Lee JJ, Lee WK et al. Analysis of wear induced particle emissions from brake pads during the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Wear. 2021;466-467:203539. https://doi.org/10.1016/j.wear.2020.203539
[116] Perricone G, Alemani M, Metinöz I, Matějka V, Wahlström J, Olofsson U. Towards the ranking of airborne particle emissions from car brakes – a system approach. P I Mech Eng D-J Aut. 2017;231:781-797. https://doi.org/10.1177/0954407016662800

[117] Perricone G, Matejka V, Alemani M, Valota G, Bonfanti A, Ciotti A et al. A Concept for Reducing PM 10 emissions for car brakes by 50%. Wear. 2018;396-397:135-145. https://doi.org/10.1016/j.wear.2017.06.018

[118] Perricone G, Matejka V, Alemani M, Wahlström J, Olofsson U. A test stand study on the volatile emissions of a passenger car brake assembly. Atmosphere. 2019;10:263. https://doi.org/10.3390/atmos10050263

[119] Perricone G, Alemani M, Wahlstrom J, Olofsson U. A proposed driving cycle for brake emissions investigation for test stand. P I Mech Eng D-J Aut. 2020;234:122-135. https://doi.org/10.1177/0954407019841222

[120] Piras J, Pini F, Di Girolamo P. PM10 emissions from tires: a disruptive estimate questioning present pollution mitigation strategies. Atmos Pollut Res. 2024;15:101939. https://doi.org/10.1016/j.apr.2023.101939

[121] Pirjola L, Kupiainen KJ, Perhoniemi P, Tervahattu H, Vesala H. Non-exhaust emission measurement system of the mobile laboratory SNIFFER. Atmos Environ. 2009;43(31): 4703-4713. https://doi.org/10.1016/j.atmosenv.2008.08.024

[122] Piscitello A, Bianco C, Casasso A, Sethi, R. Non-exhaust traffic emissions: sources, characterization, and mitigation measures. Sci Total Environ. 2021;766:144440. https://doi.org/10.1016/j.scitotenv.2020.144440

[123] Plachá D, Vaculík M, Mikeska M, Dutko O, Peikertová P, Kukutschová J et al. Release of volatile organic compounds by oxidative wear of automotive friction materials. Wear. 2017;376-377:705-716. https://doi.org/10.1016/j.wear.2016.12.016

[124] Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J Am Med Assoc. 2002;287:1132-1141. https://doi.org/10.1001/jama.287.9.1132

[125] Rahimi M, Bortoluzzi, D, Wahlstrom J. Input parameters for airborne brakewear emission simulations: a comprehensiv review. Atmosphere. 2021;12:871. https://doi.org/10.3390/atmos12070871

[126] Rexeis M, Hausberger S. Trend of vehicle emission levels until 2020 – prognosis based on current vehicle measurements and future emission legislation. Atmos Environ. 2009; 43:4689-4698. https://doi.org/10.1016/j.atmosenv.2008.09.034

[127] Rienda IC, Alves CA. Road dust resuspension: a review. Atmos Res. 2021;261:105740. https://doi.org/10.1016/j.atmosres.2021.105740

[128] Sanders PG, Xu N, Dalka TM, Maricq MM. Airborne brakewear debris: size distributions, composition, and a comparison of dynamometer and vehicle tests. Environ Sci Technol. 2003; 37(18):4060-4069. https://doi.org/10.1021/es034145s

[129] Semadeni-Davies A, Coulson G, Gadd J, Somervell E, Longely I, Olivares G. Determining the ecological and air quality impacts of particulate matter from brake and tyre wear and road surface dust: Stage 1: Literature review and recommendations for developing new emission factors for New Zealand. Kotahi W. (ed.). Transport Agency: Wellington 2021. https://www.nzta.govt.nz/resources/research/reports/683/

[130] Seo H, Park J, Kim YC, Lee JJ, Jang H. Effect of disc materials on brake emission during moderate-temperature braking. Tribol Int. 2021;163:107185. https://doi.org/10.1016/j.triboint.2021.107185

[131] Simons A. Road transport: new life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in ecoinvent v3. Int J Life Cycle Assess. 2016;21:1299-1313. https://doi.org/10.1007/s11367-013-0642-9

[132] Sinha A, Ischia G, Menapace C, Gialanella S. Experimental characterization protocols for wear products from disc brake materials. Atmosphere. 2020;11:1102. https://doi.org/10.3390/atmos11101102

[133] Smit R. Non-exhaust PM emissions from battery electric vehicles (BEVs) – does the argument against electric vehicles stack up? TER (Transport Energy/Emission Research Pty Ltd.). Australia 2020. https://www.transport-e-research.com/_fles/ugd/d0bd25_029571fc6c8a4d80a46adc23dd74ebfd.pdf (accessed on 7 January 2024).

[134] Sommer F, Dietze V, Baum A, Sauer J, Gilge S, Maschowski C et al. Tire abrasion as a major source of microplastics in the environment. Aerosol Air Qual Res. 2018; 18(8):2014-2028. https://doi.org/10.4209/aaqr.2018.03.0099

[135] Song W, Park J, Choi J, Lee JJ, Jang H. Effects of reinforcing fibers on airborne particle emissions from brake pads. Wear. 2021;484-485. https://doi.org/10.1016/j.wear.2021.203996

[136] Steege R, Welp D, Lange J. The contribution of brake emissions to the total vehicle emissions. 6th International Munich Chassis Symposium 2015. Pfeffer P. (ed.). Proceedings; Springer: Wiesbaden 2015:585-603.

[137] Stępień Z, Czerwinski J, Comte P, Oleksiak S. Nanoparticle and non-legislated gaseous emissions from a gasoline direct-injection car with ethanol blend fuels and detergent additives. Energy&Fuels. 2016;30(9):7268-7276. https://doi.org/10.1021/ACS.ENERGYFUELS.6B00583

[138] Stępień Z, Czerwinski J. Cold start with ethanol-blend fuels and influences on non-legislated emissions of a GDI flex fuel vehicle. Pol J Environ Stud. 2017;26/5:2223-2229. https://doi.org/10.15244/pjoes/69282

[139] Stępień Z. Significance of petrol composition in the formation of fuel injector deposits in direct injection engines. Nafta-Gaz. 2023;3:213-222. https://doi.org/10.18668/NG.2023.03.07

[140] Stojanovic N, Abdullah OI, Grujic I, Boskovic B. Particles formation due to the wear of tires and measures for the wear reduction: a review. P I Mech Eng D-J Aut. 2022;236:3075-3089. https://doi.org/10.1177/09544070211067879

[141] Storch L, Hamatschek C, Hesse D, Feist F, Bachmann T, Eichler P et al. Comprehensive analysis of current primary measures to mitigate brake wear particle emissions from light-duty vehicles. Atmosphere. 2023;14:712. https://doi.org/10.3390/atmos14040712

[142] Thorpe A, Harrison RM. Sources and properties of non-exhaust particulate matter from road traffic: a review. Sci Total Environ. 2008;400:270-282. https://doi.org/10.1016/j.scitotenv.2008.06.007

[143] Timmers VRJH, Achten PAJ. Non-exhaust PM emissions from electric vehicles. Atmos Environ. 2016;134:10-17. https://doi.org/10.1016/j.atmosenv.2016.03.017

[144] Tonegawa Y, Sasaki S. Investigation of analytical methods for tire wear particles. JARI Res J. 2012. 12. J-GLOBAL ID: 201302290885047702. Ref. number: 13A0555596.

[145] Tonegawa Y, Sasaki S. Development of tire-wear particle emission measurements for passenger vehicles. Emission Control Science and Technology. 2021;7:56-62. https://doi.org/10.1007/s40825-020-00181-z

[146] Tutuianu M, Bonnel P, Ciuffo B, Haniu T, Ichikawa N, Marotta A et al. Development of the World-Wide Harmonized Light Duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation. Transport Res D-Tr E. 2015;40:61-75. https://doi.org/10.1016/j.trd.2015.07.011

[147] Unice KM, Kreider ML, Panko JM. Use of a deuterated internal standard with pyrolysis-GC/MS dimeric marker

analysis to quantify tire tread particles in the environment. Int J Environ Res Public Health. 2012;9(11):4033. https://doi.org/10.3390/ijerph9114033
[148] Unice KM, Weeber MP, Abramson MM, Reid RCD, van Gils JAG, Markus AA et al. Characterizing export of land-based microplastics to the estuary – part I: application of integrated geospatial microplastic transport models to assess tire and road wear particles in the seine watershed. Sci Total Environ. 2019;646:1639-1649. https://doi.org/10.1016/j.scitotenv.2018.07.368
[149] Van Der Gon HD, Hulskotte J, Jozwicka M, Kranenburg R, Kuenen J, Visschedijk A. Chapter 5 – European emission inventories and projections for road transport non-exhaust emissions: analysis of consistency and gaps in emission inventories from EU member states. Non-Exhaust Emissions. Amato F. (ed.). Academic Press: Cambridge 2018:101-121. https://doi.org/10.1016/B978-0-12-811770-5.00005-4
[150] Van Zeebroek B, De Ceuster G, Elektrische wagens verminderen fijn stof nauwelijks. Transp Mobil Leuven. https://www.tmleuven.be/uploads/navigationtree/files/belang_ niet-uitlaat_fijn_stof_emissies_lang.pdf
[151] Vasiljević S, Glišović J, Stojanović B, Vencl A. Review of the coatings used for brake discs regarding their wear resistance and environmental effect. P I Mech Eng J-J Eng. 2022;236:1932-1949. https://doi.org/10.1177/13506501211070654
[152] Wagner S, Hüffer T, Klöckner P, Wehrhahn M, Hofmann T, Reemtsma T. Tire wear particles in the aquatic environment – a review on generation, analysis, occurrence, fate and effects. Water Res. 2018;139:83-100. https://doi.org/10.1016/j.watres.2018.03.051
[153] Wahid SMS. Automotive brake wear: a review. Environ Sci Pollut Res. 2018;25:174-180. https://doi.org/10.1007/s11356-017-0463-7
[154] Wahlström J, Söderberg A, Olofsson U. Simulation of airborne wear particles from disc brakes. SAE Technical Paper 2009-01-3040. 2009. https://doi.org/10.4271/2009-01-3040
[155] Wahlström J, Olander, l, Olofsson U. A pin-on-disc study focusing on how different load levels affect the concentration and size distribution of airborne wear particles from the disc brake materials. Tribol Lett. 2010;46(2):195-204. https://doi.org/10.1007/s11249-012-9944-5
[156] Wakeling D., Murrells T, Carslaw D, Norris J, Jones L. The contribution of brake wear emissions to particulate matter in ambient air. VDA 2017. http://worldcat.org/issn/21927863 (accessed on 5 March 2024).
[157] Wik A, Dave G. Occurrence and effects of tire wear particles in the environment – a critical review and an initial risk assessment. Environ Pollut. 2009;157(1):1-11. https://doi.org/10.1016/j.envpol.2008.09.028
[158] Wang Y, Yin H, Yang Z, Su S, Hao L, Tan J et al. Assessing the brake particle emissions for sustainable transport: a review. Renew Sustain Energy Rev. 2022;167:112737. https://doi.org/10.1016/j.rser.2022.112737
[159] Woo S-H, Kim Y, Lee S, Choi Y, Lee S. Characteristics of brake wear particle (BWP) emissions under various test driving cycles. Wear. 2021;480-481:203936. https://doi.org/10.1016/j.wear.2021.203936
[160] Woo S-H, Jang H, Na MY, Chang HJ, Lee S. Characterization of brake particles emitted from non-asbestos organic and low-metallic brake pads under normal and harsh braking conditions. Atmos Environ. 2022;278:119089. https://doi.org/10.1016/j.atmosenv.2022.119089
[161] Woo S-H, Jang H, Lee S-B, Lee S. Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: an experimental analysis. Sci Total Environ. 2022;842:156961. https://doi.org/10.1016/j.scitotenv.2022.156961
[162] Zemlik M, Dziubek M, Pyka D, Konat Ł, Grygier D. Case study of accelerated wear of brake discs made of grey cast iron characterized by increased thermal stability. Combustion Engines 2022;190(3):45-49. https://doi.org/10.19206/CE-146698
[163] Zhang X, Chen P, Liu F. Review of tires wear particles emission research status. IOP Conf Ser: Earth Environ Sci. 2020;555:012062. https://doi.org/10.1088/1755-1315/555/1/012062
[164] Ziółkowski A, Fuć P, Jagielski A, Bednarek M. Analysis of emissions and fuel consumption from forklifts by location of operation. Combustion Engines. 2022;189(2):30-35. https://doi.org/10.19206/CE-141741

Prof. Zbigniew Stępień, DSc., DEng. – Performance Testing Department, Oil and Gas Institute – National Research Institute, Poland.
e-mail: *stepien@inig.pl*