

Comparison of dust emissions from brake systems and tires of electric and conventional cars

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Environmental protection is currently receiving significant attention, particularly in the context of transport's impact on the environment. Limited fossil resources, climate change, and global warming are driving the automotive industry toward more efficient and sustainable solutions. These challenges are driving car manufacturers to adopt new technologies and alternative drive systems. Examples of such vehicles include electric vehicles (EVs) and hybrid vehicles (HEVs or PHEVs). The impact of operating these modes of transport on pollutant emissions other than exhaust gases is crucial. Examples of such emissions include particulate matter generated by brake and tire wear. All vehicles, whether conventionally or alternatively powered, generate such emissions during operation, regardless of their drive type. These particulate matter enter the air and can pose a threat to the environment and human health. While electric cars may emit less particulate matter from their braking systems due to frequent recuperation, tires remain a significant source of emissions. The article included measurements of dust emissions during the operation of an electric vehicle and a conventionally driven vehicle, as well as studies of the elemental composition of particles using scanning electron microscopy, analyzing dust collected from the vehicle's surroundings, braking system and tires.

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1. Introduction

One of the most significant air pollution hazards posed by road transport operations is dust emissions. The main sources of dust during vehicle operation are braking systems, tires, and clutch discs. Dust generated during vehicle operation is typically divided into two types: fine-grained and coarse-grained dust. Fine-grained dust is defined as small solid particles with a diameter below 50 μm . Coarse-grained dust is defined as solid particles with a diameter above 50 μm . Furthermore, the limiting size does not clearly indicate whether dust is released. Sometimes, larger-diameter dust is released into the air, while smaller-diameter dust falls to the ground. This is influenced by various factors, such as precipitation, the chemical composition, and the physical properties of the dust. Both coarse and fine-grained dust are generated during vehicle operation. Most of these are fine-grained particulate matter, namely PM_{2.5} and PM₁₀ [4, 16, 17, 24, 25].

The term PM_{2.5} refers to particulate matter with a particle diameter below 2.5 μm . Soot, among other things, has this diameter. PM₁₀ particulate matter is particulate matter with a particle diameter below 10 μm . By definition, it includes PM_{2.5} particulate matter, as well as larger particles with diameters ranging from 2.5 to 10 μm . These larger particles are largely composed of mineral dust. PM₁₀ and PM_{2.5} particulate matter are not a homogeneous group of harmful substances. They can include dust particles, sand, and even pollen. Particulate matter generated by motor vehicles primarily consists of soot, ash, and heavy metals emitted from the engine. Furthermore, tire wear, brake discs and pads, and road surfaces also contribute significantly to particulate matter formation. Dust generated by these pollutants accumulates on the road surface and is then thrown into the air by passing vehicles and wind. This is called secondary dust. The dust produced depends on many fac-

tors, including the vehicle's braking force (defined by the brake pad's contact force with the disc), the vehicle's speed, and the materials from which the disc and brake pad are made. These factors correspond to different road conditions, i.e., urban or highway [1, 14, 15, 22, 23].

2. Non-exhaust particulate emissions in road transport

Currently, many companies on the market produce brake components and tires. This explains the differences in the materials used, and systematic research and experimentation is leading to the introduction of new materials, including various composite materials. However, this makes it difficult to identify brake dust from the overall road dust and thus determine the impact of operational factors on pollution levels. Identification difficulties are further compounded by differences in the materials used in individual vehicle types, such as passenger cars and trucks. However, to accurately determine this, a chemical analysis of the dust must be performed to assess the content of elements characteristic of the friction materials in vehicle brakes. Studies suggest that particulate matter emissions from braking systems can range from several to several dozen mg/km. It has been reported that average particulate matter emissions from brakes are around 4-6 mg/km, but in intensive use or in heavy vehicles, this value can be significantly higher. Studies show that the wear of a single 250/40 R18 summer tire over 15,000 km is 130 grams per 1000 km, and a winter tire 139 g/1000 km (averaged ADAC test results). From installation to replacement, average tire wear reaches 2 kilograms. Eighty percent of tire wear products are between 100 and 500 μm in size [2, 7, 9, 13, 24, 27].

The Euro 7 regulation establishes regulations for exhaust emissions from road vehicles, as well as other types of emissions, for example, those produced by tire abrasion

and braking. For passenger cars and vans, the regulation maintains the existing Euro 6 emission limits but introduces stricter requirements for PM10 particulate matter. The limits are 3 mg/km for pure electric vehicles and 7 mg/km for other-drive vehicles (internal combustion and hybrid). The new standard was initially expected to be introduced between 2025 and 2026, but the plan was postponed to 2029 [6, 18, 20, 22].

3. Dust from the use of vehicles

Particulate matter emissions largely depend on driving style, speed, vehicle weight, and the type and composition of tires and friction components in the braking system. Tire wear occurs during tire-road interaction, meaning it's constant while driving. However, greater wear occurs during starting, accelerating, and braking than during constant-speed driving. During braking with a traditional friction braking system, kinetic energy is converted into heat resulting from friction. This process causes wear of the interacting components, leading to the formation of friction products [11, 12, 20, 28].

When rolling freely on a road, a tire experiences elastic deformation. The coefficient of friction associated with rolling a tire on the road is approximately $\mu=0.5$. If a tire rolls freely on a smooth surface, wear is not significant. When a vehicle accelerates, decelerates, or changes direction, slight slippage occurs between the tire and the road. Braking is one of the processes in which high friction is beneficial. The coefficient of friction between brake pads and discs is $\mu = 0.4$ for the front axle (engine) and $\mu = 0.3$ for the rear axle. Brake pads consist of abrasive materials, binders, fillers, and reinforcing components. A large number of chemical compounds are used to produce each of these materials, making their characterization difficult. Based on the components used, brake pads are classified as [2, 12, 20, 23]:

- non-asbestos organic (NAO), consisting of organic compounds, mineral fibers, and graphite
- low-metallic (LM), consisting of metallic and organic compounds
- semi-metallic (SM), containing steel and iron.

The main elements in brake pad composition, according to the literature, are iron (Fe), barium (Ba), antimony (Sb), tin (Sn), and copper (Cu). In recent years, a decrease in the content of antimony and copper has been observed. European law prohibits the use of asbestos in the production of brake pads. Furthermore, the use of copper in the production of brake pads is prohibited in the US due to the risk of kidney and liver damage, anemia, allergic alveolitis, and even cancer [2, 12, 18, 23].

4. Dust from the use of electric vehicles

The torque of an electric motor is available from zero rpm, which can increase tire wear and, in turn, the amount of dust generated by operating this type of vehicle. Vehicle weight is also a significant factor in increasing dust emissions. Due to the weight of the batteries, electric vehicles can emit more tire dust than their combustion-powered counterparts, which meet current emission standards. This, in turn, can translate into higher total dust emissions from electric vehicles in some cases. However, it is claimed that

electric and hybrid vehicles, compared to combustion vehicles, emit less dust from worn brake linings thanks to the RBS (Regenerative Braking System). In this system, regenerative braking recovers energy during braking and converts kinetic energy into electrical energy without friction. The electric motors then act as generators. The generated electricity is stored in batteries. This system extends the life of the disc brake system by allowing its components to wear out more slowly. According to The Platform for Electro-Mobility, RBS reduces brake wear by 25–50% [11, 13, 20, 23].

According to a 2020 OECD (Organization for Economic Cooperation and Development) report, a survey was conducted regarding non-exhaust emissions. Respondents assumed that the increased weight of electric vehicles leads to increased tire wear. A comparison of mid-range electric vehicles showed that their weight is 22% greater than that of combustion vehicles in the same class. The same applies to the opinion that the torque in electric vehicles, which is greater and available from zero engine speed, leads to frequent traction loss during take-off and acceleration, and therefore to higher tire particulate emissions [11, 14, 20, 23].

4. Research object

The research object is three passenger cars. A conventional drive car of the Dacia Sandero III brand with a 1.0 TCe petrol engine with a turbocharger with an output of 67 kW. An electric car of the Dacia Spring brand with a synchronous motor with a permanent magnet with an output of 33 kW. A hybrid drive car of the Toyota C-HR brand with a 1.8 internal combustion engine with an output of 72 kW and an electric motor with an output of 53 kW. The total power of the hybrid system is 90 kW. All vehicles were manufactured in 2021 and had Crossover bodies. The cheapest Dacia vehicles were selected for the research. However, this brand does not offer a hybrid car, which is why it was decided to compare it with a Toyota hybrid.

a) Conventional drive car



Fig. 1. Conventional drive car Dacia Sandero

Table 1. Technical data of the Dacia Sandero [6]

Model	Dacia Sandero III Hatchback
Drive	Conventional
Engine	1.0 TCe petrol turbocharged
Displacement	999 cm ³
Engine power	67 kW, 90 HP for 4600 rpm
Torque	160 Nm for 2100–3750 rpm
Drive	Front axle
Range	962 km
Current weight	1152 kg
Year of production	2021

b) Electric car



Fig. 2. Electric drive car Dacia Spring

Table 2. Technical data of the Dacia Spring [5]

Model	Dacia Spring Crossover Electric
Drive	Electric
Engine	Permanent magnet synchronous
Engine power	33 kW, 45 HP for 3000–8200 rpm
Torque	125 Nm for 500–2500 rpm
Drive	Front axle
Battery	lithium-ion
Gross battery capacity	27 kWh
Charging time socket/fast	13 h/1 h
Range	230 km
Own weight	920 kg
Year of production	2021

c) Hybrid car



Fig. 3. Toyota C-HR hybrid car – view under the engine cover

Table 3. Technical data of the Toyota C-HR [26]

Model	Toyota C-HR Crossover SUV – 5d
Drive	Hybrid (HEV)
Engine	1.8 Hybrid
Engine system power	90 kW, 122 HP @ 5200 rpm
Petrol engine power	72 kW, 98 HP @ 3600 rpm
Petrol engine torque	142 Nm @ 3600 rpm
Electric engine power	53 kW, 72 HP
Electric engine torque	163 Nm
Battery	lithium-ion
Gross battery capacity	1 kWh
Gearbox type	Automatic e-CVT
Fuel consumption	4.8 dm ³ / 100 km
Fuel tank capacity	43 dm ³
Range	895 km
Current weight	1380 kg
Year of production	2021

5. Research

5.1. Wear of brake pads and discs

In this study, information on brake pad and disc thickness, as well as tread depth, was used to compare the amount of particulate matter generated by electric and conventionally powered vehicles. Data were obtained from authorized service stations for the selected vehicle brands

tested. The comparison included both electric, conventional, and hybrid vehicles. Front axle brake wear was accounted for, as the rear axle brakes were of different designs (disc or drum). The vehicles analyzed were manufactured in 2021, and the tests were conducted during a scheduled maintenance service at the end of their second year of use. To accurately analyze the results, calculations were performed to account for the different vehicle mileages used in testing. A mileage of 15,000 km was selected as a representative example.

The test results regarding the wear of braking system components are shown in Fig. 4 and 5.

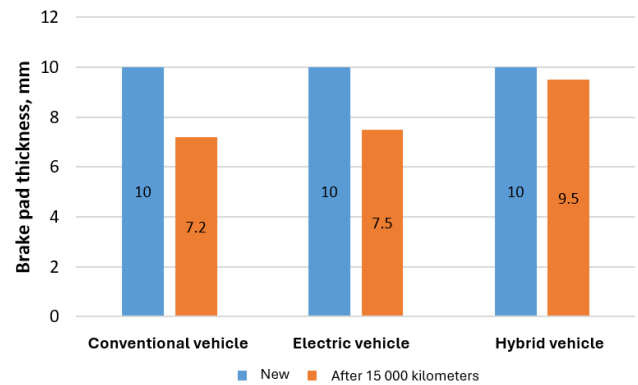


Fig. 4. Brake pad wear after 15,000 kilometers

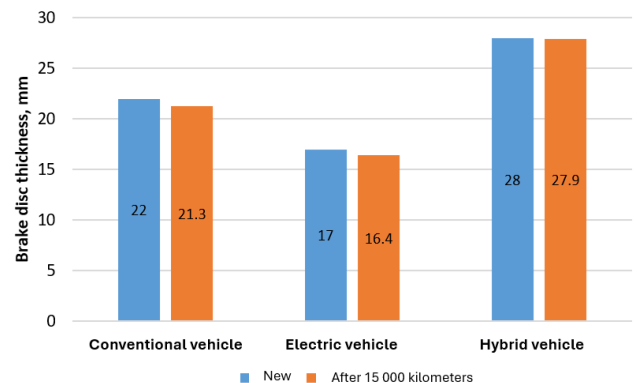


Fig. 5. Brake disc wear after 15,000 kilometers

In a conventionally powered car, after 15,000 kilometers, the front brake pads had worn 2.8 mm, and the front brake discs had worn 0.7 mm. In an electric car, these wear rates were 2.5 mm and 0.6 mm, respectively. In a hybrid vehicle, the front brake pads had worn 0.5 mm, and the front brake discs had worn 0.1 mm.

Based on this data, the volume of dust generated by wear was calculated. The density of the friction material used in brake pads is typically around 2.3–3.2 g/cm³, depending on the mix (resins, mineral fibers, metals). Many manufacturers' materials have a density of around 2.7 g/cm³ [8]. The density of the material used for the brake discs (cast iron) was determined to be 7.3 g/cm³ (gray cast iron) [18, 28]. The mass of dust generated by vehicle operation over 15,000 kilometers was calculated [18].

For 1 kilometer of distance traveled, the dust emissions generated by the operation of various means of transport in

mixed conditions (city and highway traffic), expressed in milligrams, are presented in Fig. 6.

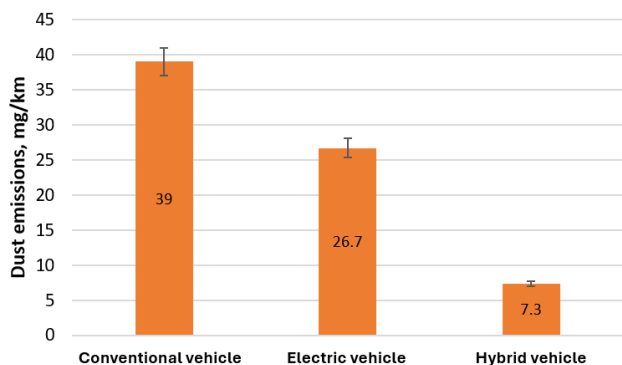


Fig. 6. Dust emission from brake pads and discs per 1 km

Total particulate matter emissions from the braking system (including brake pads and discs) were as follows: 39 mg/km for the conventional vehicle, 26.7 mg/km for the electric vehicle, and 7.3 mg/km for the hybrid vehicle. In the context of particulate matter emissions, it is worth noting that the Euro 7 standard is planned, which will set maximum particulate matter emissions from vehicle braking systems at 0.7 mg/km for conventional and hybrid vehicles and 0.3 mg/km for electric vehicles. Taking the above calculations into account, particulate matter emissions from the vehicles selected for testing exceed those specified by the Euro 7 standard, even when the front axle braking system is included [6, 18, 23].

5.2. Tire wear

Next, tire tread depth was measured on the test vehicles. Tire tread wear after 15,000 kilometers is shown in Fig. 7.

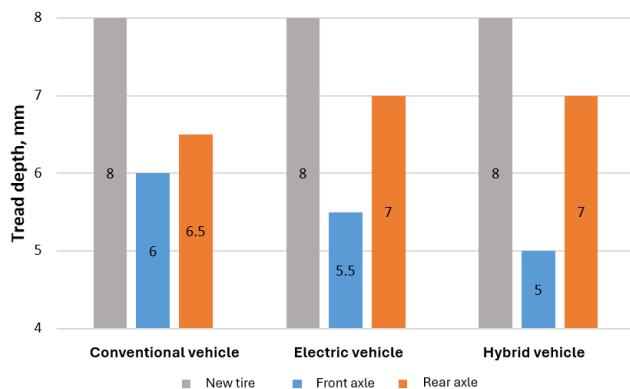


Fig. 7. Tire wear after 15,000 kilometers

The new tires have a tread depth of approximately 8 mm. Tire wear was measured after 15,000 km. The vehicles showed increased brake wear on the front (drive) axle. In the conventionally powered vehicle, the tire tread on both axles wore down by 3.5 mm. In the electric vehicle, wear was also 3.5 mm, but more intense on the front axle. In the hybrid vehicle, total tread wear reached 4 mm.

Due to the tread structure, 80% of the calculated values were used. To calculate the mass of dust generated from tire abrasion, an average tire material density of 1.3 g/cm³ was assumed. Figure 8 shows tire dust emissions over 1 km [18].

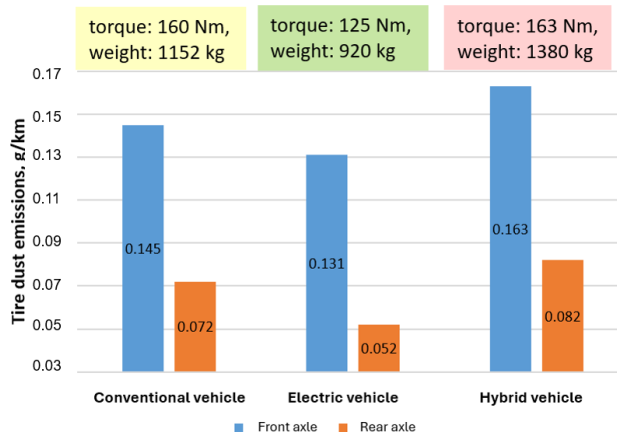


Fig. 8. Dust emission from tires per 1 km

Particulate matter emissions from tire wear on the front axle for the tested vehicles were: 0.163 g/km for the hybrid vehicle, 0.145 g/km for the conventional vehicle, and 0.131 g/km for the electric vehicle. For the rear axle, they were: 0.082 g/km for the hybrid vehicle, 0.072 g/km for the conventional vehicle, and 0.052 g/km for the electric vehicle.

It is worth noting that tire wear is a normal phenomenon and occurs during vehicle use. However, the intensity of this wear varies and depends on factors such as: the torque generated by the drive unit (e.g., engine type – electric, combustion), vehicle weight (tire-road interaction; braking), and traffic conditions (urban and rural). Tire wear is proportional to the torque and weight of the vehicle. The greater the torque and weight of the vehicle, the greater the tire wear [23].

5.3. Chemical composition of dust from vehicle

The next stage of the study involved collecting dust samples from air filters and comparing their chemical composition with wear products from the braking system and tires. The aim of this study was to determine the proportion of dust from worn brakes and tires among the total dust in the environment. Dust samples were analyzed with a Hitachi S-4200 scanning electron microscope equipped with a secondary electron (SE) detector. Chemical composition was determined using a Thermo Scientific Nova 600 energy-dispersive X-ray spectrometer (EDS) at an electron beam acceleration voltage of 15 kV. This spectrometer is coupled to a Hitachi S-4200 microscope.

Dust samples for testing were collected from the air filters of various vehicles operating in both urban and highway traffic. This method of obtaining the test material was chosen because air filters made of cellulose (paper), plastic nonwoven fabric, or a combination of these materials retain almost all particulate matter present in the air. They prevent up to 99.98% of harmful dust and soot particles, as well as tire and brake wear particles. The most precise filters retain almost all particles of environmental pollutants larger than 3 μm. Currently, an air filter permeability of up to two micrometers is considered optimal for passenger cars. It should also be noted that very fine dust is the most harmful. Particles of such a small diameter can be transported considerable distances and are also harmful to the human respiratory system. Therefore, it is important to collect test

material with the smallest possible diameter. To compare the chemical composition of the elements found in the collected dust, it was also decided to collect samples from the braking system and tires. The braking system samples were taken from holes drilled into the brake disc. Collecting dust from this location primarily contains wear products from the brake pad and disc. Tire fragments were also collected for comparison. Figure 9 shows the test samples.



Fig. 9. Dust samples: a), b) passenger car tire sample, c) dust sample collected from the air filter, d) dust sample from the braking system

The study's material was collected from four samples. The dust samples were placed on adhesive-backed supports. The results of the microanalysis of the chemical composition of the samples, along with a quantitative table of elemental composition, are presented below (Fig. 10–12).

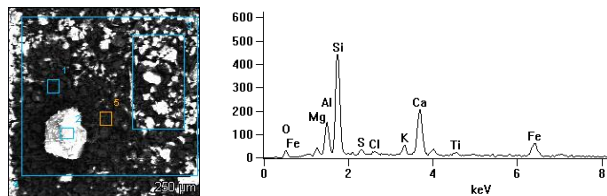


Fig. 10. X-ray microanalysis of the chemical composition of the EDS sample of dust collected from air filters a) with marked areas, b) radiation spectrum

The chemical composition results obtained from dust collected with the air filter indicate the highest concentrations of elements, including 30.5% silicon (Si), 19.5% calcium (Ca), 16.2% iron (Fe), and 9.8% aluminum (Al). Magnesium (Mg) was also detected at 2.3%, and sulfur (S) at 2%.

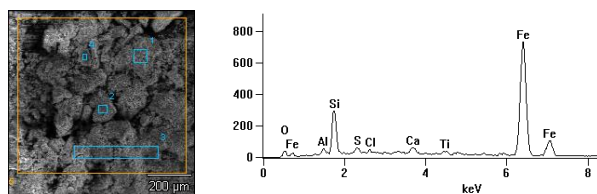


Fig. 11. X-ray microanalysis of the chemical composition of the EDS dust sample collected from the braking system, a) with marked areas, b) radiation spectrum

EDS X-ray microanalysis of the chemical composition of a dust sample collected from the braking system revealed that the dominant element throughout the sample area was iron (Fe) at a level of 84.4%. Silicon (Si) was also present at 5.7%, along with trace amounts of other elements, such as calcium (Ca) at 2.4%, titanium (Ti) at 1.8%, and aluminum (Al) at 1.1%. Brake discs are typically composed of pearlitic gray cast iron, and in some cases, steel, as confirmed by chemical composition analysis.

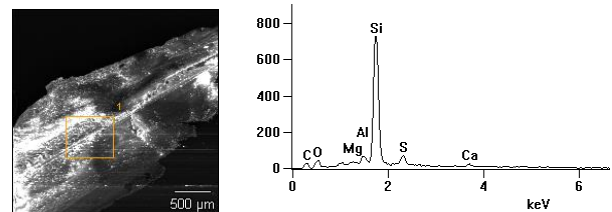


Fig. 12. EDS X-ray microanalysis of the chemical composition of a tire sample, a) with marked areas, b) radiation spectrum

A study of tire wear products revealed that the main elements constituting the tire are silicon (Si) – 39.3%, carbon (C) – 29.3% as carbon black, and sulfur (S) – 4.2%. Aluminum (Al), calcium (Ca), and magnesium (Mg) were also detected. Tire wear particles consist of plasticizers, oils, polymers, carbon black, and minerals.

6. Conclusions

Brake and tire wear is a complex process influenced by both vehicle design features, such as the drive type and materials used, and operational factors, including driving style and road conditions. In the context of the planned Euro 7 standard, particulate matter emissions from brake and tire wear are particularly important, exceeding the expected limits in many of the vehicles tested [18, 23].

The analyses confirmed that regenerative braking significantly reduces wear on the braking system's friction components, particularly in hybrid and electric vehicles. Despite this, particulate matter emissions from the braking system exceeded the limits stipulated by the future Euro 7 standard in all the vehicles tested [27]. The quality of the components used plays a significant role here – a Toyota hybrid vehicle equipped with premium braking components and operated under uniform conditions by a single driver came closest to meeting the standard. In contrast, Dacia vehicles using lower-quality components and used by different drivers in varying conditions exhibited higher wear and higher particulate matter emissions.

Tire wear analysis revealed that particulate matter emissions from this source are strongly dependent on vehicle weight and torque, tire size and class, road surface type, weather conditions, and topography. Electric and hybrid vehicles, due to their high torque available from zero speed and the typically greater mass resulting from battery packs, may exhibit more severe tire wear than conventional vehicles. However, it should be emphasized that in the case of the analyzed electric vehicle, its mass was lower than that of the conventional vehicle, which was a deviation from the general trend.

X-ray EDS microanalysis of the particulate matter chemical composition confirmed its source. In the brake dust samples, the dominant element was iron (Fe), indicating wear of the brake discs and pads. Tire wear products were characterized by the presence of silicon (Si), carbon (C) in the form of soot, and sulfur (S). Dust samples collected from air filters showed a high silicon content, which may indicate the presence of natural silica (e.g., mineral dust) and particles derived from tire wear. A significant finding is the lack of detection of heavy metals, including copper, lead, cadmium, and nickel, which are considered particularly harmful to health.

Summarizing the results of the literature analysis and our own research, it can be concluded that total particulate matter emissions from electric and hybrid vehicles may be higher than from conventionally powered vehicles, primarily due to more intense tire wear. At the same time, the level of these emissions depends largely on vehicle weight, torque, the quality of the materials used, and operating conditions, which indicates the need for a comprehensive

approach to assessing the environmental impact of different drivetrain types.

Research results also indicate that a significant factor influencing the intensity of friction element wear is the vehicle's class and the quality of its components. High-end vehicles, equipped with more advanced braking systems and materials with better tribological properties, may exhibit lower wear rates and lower particulate emissions compared to budget vehicles. These differences result not only from the quality of the components themselves but also from different brake system designs, longer-lasting friction materials, and more advanced braking support systems.

In the analyzed cases, the high-end vehicle achieved results closer to meeting future emission limits, while the budget vehicles exhibited significantly higher wear of wear components. This indicates that comparisons of particulate emissions across different drive types should also account for the vehicle segment, as design and quality differences can significantly affect final test results.

Nomenclature

EDS energy dispersive spectroscopy
SE secondary electrons

PM particulate matter
TRWP tire and road wear particles

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