

Characteristics of pollutants emitted by motor vehicles and their impact on the environment and engine operation

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Gaseous and solid pollutants (dusts) of the atmospheric air are presented. The properties of dusts are given and dusts are subdivided according to various criteria. The sources and characteristics of artificial (anthropogenic) and natural pollutants of ambient air are given. It was shown that the main source of artificial pollution, apart from industry, is motorization. The internal combustion engines of cars are a source of gaseous and particulate pollutants, whose emissions have been significantly reduced. The originality of the article consists in carrying out an extensive literature analysis and demonstrating that the emission of 'non-motor' pollutants in the form of dust from the wear of brake friction linings and discs, clutches and from the wear of tire and road treads, as well as mineral dust lifted from the ground, is currently a greater threat to human health and the environment than engine emissions. The effects of road transport particulate emissions and mineral dust, the primary component of road dust, on human health, vegetation and the performance of engine and vehicle systems are presented.

Key words: *natural and anthropogenic air pollution, internal combustion engines, exhaust emissions, non-engine emissions, road dust*

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1. Introduction

In addition to solid components (N₂, O₂, Ar, Ne, He, CH₄, Kr, N₂O, H₂, Xe) and variable components (H₂O, CO₂, O₃), atmospheric air contains other variable components that are emitted into the atmosphere as a result of nature itself or as a result of human activity. These include dust, plant spores, bacteria, salts, and the gases CO, SO₂, SO₃, He, HF, H₂S, O₃, NH₃, and others (Table 1). The proportions of these components are highly variable over time, varying at different points in the atmosphere, and are considered atmospheric air pollutants. At the same time, however, exceeding the average contents of the solid components of atmospheric air is also considered air pollution.

Table 1. Composition of atmospheric air [42]

The main components of dry air without admixtures, along with the percentage content	Main air pollutants
– nitrogen – 78.08%	– particulate matter
– oxygen – 20.90%	– ozone
– argon – 0.93%	– oxides of nitrogen
– carbon dioxide – 0.03%	– sulfur oxides
	– carbon oxides
	– hydrocarbons
Total 99.99%	Total > 90%

Air pollution is a widespread phenomenon, and the amount, type and extent of the impact of pollution is enormous. Air pollution is understood as the introduction into the atmosphere of solid, liquid, and gaseous substances that are not in their natural composition or natural substances that are present but in exaggerated quantities that can adversely affect human health, nature, soil, and water or cause other adverse changes in the environment. Air pollutants come from both artificial (anthropogenic) and natural sources. Substances emitted into the atmosphere can be in the form of aerosols (solid or liquid particles suspended in the air) or gases (SO₂, NO_x, CO, etc.). Secondary pollutants

have no direct sources but are generated in the atmosphere as a result of various chemical reactions of primary pollutants. The main secondary pollutants are primarily tropospheric ozone (O₃), which is formed by the reaction of nitrogen oxides (NO_x) and hydrocarbons (HC) when sunlight is available. Another secondary pollutant is particulate matter, which is formed when sulfur oxides (SO_x) and nitrogen oxides (NO_x) and nitrogen dioxide (NO₂) react.

All pollutants that are in the atmosphere can undergo processes such as displacement (transport), turbulent diffusion, physical and chemical processes between them, dry deposition (dry deposition), deposition due to leaching by precipitation (wet deposition) and movement into the stratosphere. In addition, an important problem associated with air emissions is the transboundary transfer of pollutants over very long distances.

Airborne pollutants can be divided into those that are gaseous (organic and inorganic) and those that are particulate. As a result, particulate matter is the pollutant whose concentration in the air of many areas of the world is greater or much greater than the permissible limit, and which is most often the cause of poor or very poor quality of atmospheric air, which has a harmful effect on the environment. In addition to the negative effects of dust on human and animal health, harmful effects of dust on plants and on soil and water bodies are also found. Together with sulfur dioxide, carbon monoxide and other compounds, dust contributes to the phenomenon of London smog. Dust also has a debilitating effect on the greenhouse phenomenon in the atmosphere. It should also be noted that dusts reduce visibility and adversely affect the operation of engine systems.

The harmful effects of dust on health and living organisms are multifactorial and depend on the chemical and mineralogical properties of dust particles, their physical structure and dimensions. Ambient air pollution is a very serious problem of modern civilization. Air pollution can lead to local, regional, continental, and, consequently, glob-

al hazards. Locally, there can be such phenomena as smog, degradation of ecosystems, deterioration of air quality in cities, and acidification of the environment, while globally, air pollution contributes to the greenhouse phenomenon and depletion of the stratospheric ozone layer.

Pollution sources that emit dust and gases into the atmosphere can be divided into natural and man-made (anthropogenic) sources (Fig. 1). Emissions of pollutants of natural origin account for 85% of all pollutant emissions into the Earth's atmosphere. Sources of anthropogenic pollution are industry (energy, chemical, mining, construction materials) and motorization, including road transport due to the mass use of cars. These include dust and harmful gases.

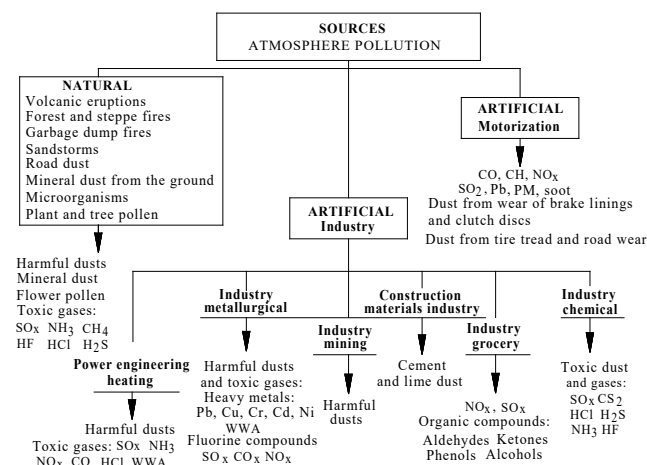


Fig. 1. Sources of atmospheric pollution

Land transportation is still the most popular form of transporting goods, as well as passenger traffic, and includes surface, underground, aboveground, rail and road transportation. Road or otherwise vehicular transportation is the most popular means of transport and is most often used in most logistics operations. Thanks to the extensive road network, it is possible to reach almost any place with the help of a car, and the large number of companies offering this type of transportation makes it possible to choose the most favorable solution.

The threat to the environment posed by motorization is among the most contemporary nuisances of the development of civilization. This is determined by the massiveness of vehicles and the intensity and universality of their use. Means of road transport are primarily responsible for the production of environmentally harmful volatile substances. Most vehicles on the road are powered by internal combustion engines fueled by hydrocarbon fuels. It is estimated that there are 1.47 billion cars on the road worldwide, which means that there are more than 5.5 people on the planet per car. As of 31 December 2023, more than 27 million passenger cars were registered in Poland, almost one million more than the year before. Our country has 703 cars per 1000 people, the highest in the European Union.

The contribution of internal combustion engine emissions to environmental pollution has decreased significantly due to increasingly stringent requirements and new regulations in this area. This has forced engine manufacturers to use modern solutions for electronic control of fuel injection

systems and technologies for cleaning and neutralizing toxic components of exhaust gases. In particular, the use of Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) technologies has significantly reduced NO_x emissions from heavy-duty diesel engines, enabling them to meet increasingly stringent regulations in this area [60, 102]. Exhaust systems of CI engines are being equipped with particulate filters [10, 18] and SI engines with catalysts to reduce CO, HC and NO_x emissions [59, 78].

Current research and regulations on motor vehicle emissions mainly focus on exhaust and particulate emissions from engine exhaust systems. Recently, a very important automotive issue is emissions other than exhaust – “non-engine emissions”. This term is understood as the emission of dust into the environment from the wear of clutch friction linings [41] and brake pads and brake discs of cars [33, 81, 89], as well as tires and road surfaces [97]. This phenomenon affects environmental pollution and human health deterioration due to harmful elements such as antimony and copper found in brake lining materials.

2. Sources and characteristics of anthropogenic atmospheric air pollution

Automotive, along with industry, is a major source of anthropogenic air pollution. Pollution from automotive sources comes from [12, 13]:

- exhaust emissions from motor vehicle engines (carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter, volatile organic compounds)
- motor vehicle emissions of dust from tribological junctions, where the friction materials of brake pads, clutch discs and brake discs are subjected to intensive wear
- dust emissions from the wear and tear of road wheel tires and road surface resulting from the interaction of wheels and road surface
- airborne, by the movement of motor vehicles or by the wind, pollutants from paved road surfaces and ground substrates (mainly mineral dust).

Examples of sources of anthropogenic air pollution are shown in Fig. 2.

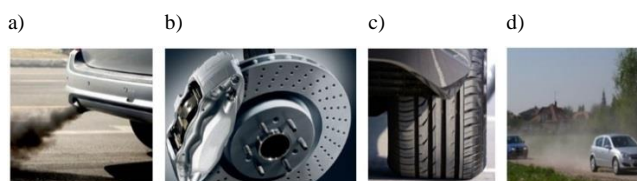


Fig. 2. Sources of anthropogenic air pollution: a) car exhaust, b) wear of the brake pad-disc association, c) wear of the tire tread and roadway, d) airborne dust from the ground [22]

The classification of dust depends on the average aerodynamic diameter of the grains. Particulate matter can be divided as follows [14]:

- TSP – Total Suspended Particles – particles less than 300 μm in diameter
- Particulate matter – particles less than 75 μm in size that remain suspended in the air for some time but settle under their own weight due to gravity
- PM₁₀ (PM – Particulate Matter) – dust with a diameter of less than 10 μm

- $PM_{2.5}$ – particulate matter – particles less than 2.5 μm in diameter
- PM_1 – particulate matter – particles less than 1 μm in diameter (virtually invisible dust)
- Nanoparticles with an equivalent particle size of less than 100 nm (dust invisible to the naked eye).

2.1. Exhaust emissions from motor vehicle engines

When burning hydrocarbon fuel, vehicle propulsion engines are a source of emissions of a significant amount of combustion products. Non-toxic components (N, O, H_2O , CO_2 , H) and toxic exhaust components (CO, NO_x , CH, SO_2 , RCHO, 3,4-benzopyrene) are emitted from engine exhaust systems – Fig. 3 [66, 79].

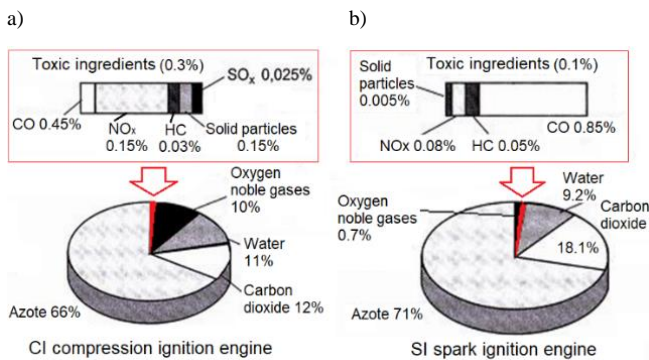


Fig. 3. Components of engine exhaust: a) spark-ignition, b) compression-ignition [79]

Combustion engines are also emitters of PM particles, which are formed during fuel-air mixture combustion in the engine cylinders, where complex chemical and physical processes occur at high temperatures, with local air deficiency and as a result of poor fuel atomization. This results in incomplete fuel combustion. PM particles are soot, which absorbs unburned hydrocarbons from fuel and engine oil, sulfur compounds and ash. On the surface of the soot particle, there may be products of wear of metal engine elements cooperating by friction [5, 55, 84].

Particulate matter is formed in the cylinders of a diesel engine (much less in a gasoline engine) when there is a local or temporary shortage of air during combustion and in the exhaust system and then it propagates in the atmosphere. Particulate matter, which is a polydisperse system, is formed by complex physical and chemical processes that often occur simultaneously at different locations and times. Particulate matter emitted by an engine exhaust system varies considerably in shape and diameter. The most common diameter of particulate matter in diesel exhaust is about 100 nanometers in size. Particulate Matter (PM), a component of engine exhaust, has no clear definition. PM is understood as all solid or liquid matter, organic or inorganic, that accumulates on an absolute filter (with 99% efficiency) after a stream of air-diluted exhaust gas passes through it at 52°C. The symbolic composition of the solid particle is shown in Fig. 4 [14].

The soot itself in the flue gas, due to the fact that it is chemically pure carbon, is not a threat to human health. What is dangerous, however, are the compounds that have been absorbed on its surface.

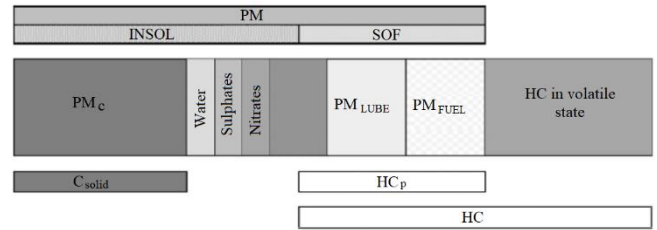


Fig. 4. Composition of PM solid: C_{solid} – carbon fraction, INSOL – insoluble fraction in dichloromethane, SOF – soluble fraction in dichloromethane, PM_{LUBE} – hydrocarbon fraction from oil, PM_{FUEL} – hydrocarbon fraction from fuel, HC_p – hydrocarbon fraction [13]

The highly harmful effects of particulate matter on the human body, air, water and soil, as well as on living organisms, are due to its specific properties, namely [66]:

- the small size of the particles (0.01–30 μm), makes them persist for a long time in the air, so they are absorbed during respiration and penetrate the lower respiratory tract
- the largest part of the emissions are particles with a size of 100 nm comparable to the size of DNA particles (2.5 nm) and red blood cells (800 nm). such particles are not stopped by the respiratory tract and enter the bloodstream, causing cardiovascular diseases
- particulate matter is formed as a result of complex chemical and physical processes that often occur simultaneously at different places and times.

A comparative analysis of $PM_{2.5}$ and PM_{10} particles against human hair with a diameter of $\sim 70 \mu\text{m}$ and silica grains with a diameter of $\sim 90 \mu\text{m}$ is shown in Fig. 5.

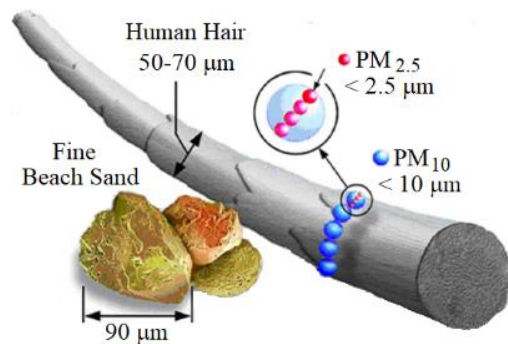


Fig. 5. $PM_{2.5}$ and PM_{10} particle sizes against a background of human hair with a diameter of $\sim 70 \mu\text{m}$ and silica grains with a diameter of $\sim 90 \mu\text{m}$ [48]

Emissions of toxic exhaust components of compression-ignition engines can increase many times over as a result of improper atomization of injected fuel due to injector malfunctions (injection pressure too low, atomizer leaks, wear of atomizer outlet holes), improper adjustment of injection advance angle, improper adjustment of fuel dosage, deterioration of engine condition (improper valve clearances, excessively worn cylinders and piston rings, dirty air filter). Particles derived from brake component wear, tire and road tread wear, and other particles that do not originate from exhaust gases account for 21–50% of total vehicle emissions in cities and urban areas, indicating that non-exhaust emissions in the urban environment are of major importance [29, 70].

Airborne particles were divided by size into conventional classes using maximum particle diameter as a criterion. Particles with a conventional diameter of less than 10 μm were defined as coarse particles and designated PM₁₀. Particles with diameters below 2.5 μm and 1 μm were defined as fine particles and named PM_{2.5} and PM₁, respectively. Particles with the smallest sizes (diameters less than 0.1 μm) were defined as ultrafine particles [93].

2.2. Particulate emissions from tribological nodes of vehicle systems

According to the authors of the paper [26], particles from brake wear are mainly friction products between the brake pads (shoe) and the metal disc, in older solutions, between the bristle lining and the cast iron brake drum. Approximately 40% of wear products are PM₁₀ particles, which become airborne. Research reported in [35] shows that disc brakes emitted PM_{2.5} and PM₁₀ in a wide range of 0.8–4.0 mg/km and 2.2–9.5 mg/km per brake, respectively. The emission values depended on the type of brake and the test load applied, with drum brakes emitting significantly less PM due to their closed design. It was found that 37–45% of the PM emitted from brakes was small particle size, with higher values for the drum brake. At the same time, it was found that almost 50–65% of the total brake mass lost through wear was attributable to particles larger than 10 μm.

Modern passenger cars are fitted with braking systems of two configurations. These are disc brakes, where brake pads with a flat working surface are pressed bilaterally against a rotating metal disc connected to the car wheel, and drum brakes, where two semi-circular brake shoes with friction material are pressed against the inner surface of a rotating drum (Fig. 6). It is assumed that the front wheel brakes should provide about 70% of the car's total braking power and therefore wear on these friction pairs is greater, hence their replacement is performed more frequently than the friction pairs of the rear wheel brakes.

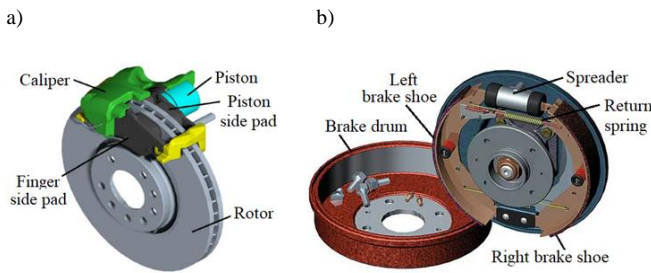


Fig. 6. Configurations of brake systems [33]: a) disc, b) drum [22]

Disc brake discs that are used in passenger cars are usually made of grey cast iron. There are cases where brake discs are made of composites such as carbon, ceramic, and aluminum composites. Brake friction linings are usually made from several main components. These are binders, fibers, fillers, friction additives, and lubricants. The function of the binder is to hold the brake pad components together and to ensure the structural integrity of the lining under thermal and mechanical stress [31].

Non-exhaust emissions accounted for 30% (PM_{2.5}) to 45% (PM₁₀) in 2010 and 54% (PM_{2.5}) to 69% (PM₁₀) in 2020 (after the introduction of particulate filters) and will

exceed 90% in 2040 (Fig. 7). This is the reason why the European Commission has proposed limits to limit emissions from brake and tire wear under the Euro 7 standard [31].

Grey cast iron is a popular material for brake discs in automobiles due to its properties such as high melting point, good heat storage and vibration damping. In addition, cast iron has good castability and machinability. However, the poor wear resistance is the reason for the high particle emissions from brake systems [30].

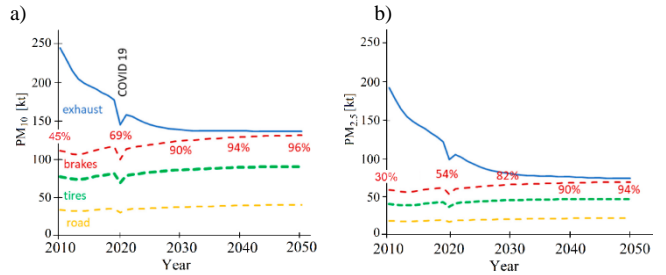


Fig. 7. Changes in the contribution of non-motor emissions (brake, tire and road surface wear) to total PM emissions from road transport in the EU: (a) PM₁₀, (b) PM_{2.5} [31]

The chemical composition of emitted particles from brake lining wear reflects the composition of the friction material. However, the chemical composition of brake lining friction materials is proprietary by the manufacturer and rarely disclosed, so information in this area is not fully complete. The chemical composition of brake linings, according to the work of [26], is shown in Table 2.

Table 2. Composition of standard brake pad material for Volvo 850 [26]

Component	Ingredient	Share (wt%)
fibers	– fibers: steel, aramid and glass	30
	– binder	8
matrix	– other	11
	– brass and bronze	15
	– graphite	15
friction modifiers	– metal sulphides	8
	– quartz	5
fillers	– alumina and iron oxide	8

- Fiber – provides mechanical strength. Metallic, mineral, ceramic, or organic fibers produced mainly from copper, steel, brass, potassium titanate, glass, organic material (aramid) and Kevlar are used.
- Abrasives – are used to increase frictional forces. Many substances are used as abrasives, including aluminum oxide, iron oxides, quartz (silicon oxide) and zirconium (zirconium silicate).
- Lubricants – help stabilize frictional properties, especially with high lining temperatures during braking. Typical examples include graphite and various metal sulfides, such as antimony trisulfide (Sb₂S₃), and other common materials: ground rubber, metallic particles, carbon black, cashew nut dust.
- Fillers – substances used to reduce production costs and improve the properties of brake pads (reducing noise intensity, improving thermal properties). These are usually inexpensive materials such as inorganic compounds

(barium and antimony sulfate, magnesium oxides and chromium oxides), silicates (kaolinitic clays), ground slag, stone and metal powders.

- Binders – important for maintaining the structural integrity of brake linings under mechanical and thermal loads. Phenol-formaldehyde resins are widely used as binders.

Brake discs are usually made from perlitic grey cast iron with a carbon content of 3–4%, which contains free graphite in the form of small flakes. Grey cast iron has many advantages, including high heat capacity and mechanical strength, wear resistance, good damping and casting properties, and relatively good susceptibility to machining [26].

Based on the chemical composition of dust emitted from brake wear, it is claimed that iron, copper, bar zinc and lead are the most abundant metals present in brake lining material. Based on the brake dust samples collected, the mass proportion of elements such as potassium, titanium, copper, antimony and barium were found to be several percent. Copper and barium were the most prevalent, with a mass share of 13.0–17.6% for copper and 7.3–13.2% for barium, respectively [93]. Potassium, with a mass share of 1.4–4.1%, and titanium, with a mass share of 4.6–9.5%, came from the potassium titanate used in brake pads, a compound often added to improve wear resistance and thermal resistance. Other metals, such as barium, magnesium, manganese, nickel, tin, cadmium, chromium, titanium, potassium and antimony, are also present in smaller amounts (mass share of less than 0.1%) [11, 37]. The mass proportion of metals in brake linings and in emitted brake dust, according to [93], is given in Table 3.

Emissions from the braking systems of land vehicles in urban areas are much higher than in areas outside of metropolitan areas due to the frequency of braking.

Table 3. Mass fraction of metals in brake linings and in emitted brake dust [93]

Metal	Brake linings for vehicles [mg/kg]	Vehicle brake dust [mg/kg]	Metal	Brake linings for vehicles [mg/kg]	Vehicle brake dust [mg/kg]
Al	3765	330–2500	K	857	190–5100
As	< (2.0–18)	< (2.0–11)	Mg	6140	83,000
Ba	2638	5900–74,400	Mn	181–3220	620–5640
Ca	14,300	920–8600	Mo	0.4–215	5.0–740
Cd	< 1.0–41.4	< 0.06–2.6	Na	15,400	80
Co	6.4–45.8	12–42.4	Ni	3.6–660	80–730
Cr	< (10–411)	135–1320	Pb	1.3–119,000	4.0–1290
Cu	11–234,000	70–39,400	Sb	0.07–201	4.0–16,900
Fe [%]	1.2–63.7	1.1–53.7	Zn	25–188,000	120–27,300

SEM images of particles from brake component wear produced during the simulation study are shown in Fig. 8 and 9.

According to the authors of the paper [33], aluminum oxide, iron oxides, quartz and zirconium are the components that are most often appropriate in brake lining materials. Three different types of brake linings are used in passenger car brakes: asbestos-free organic, semi-metallic, and low-metallic. Literature data shows that the chemical composition of asbestos-free brake linings used today is significantly different from older linings, but the metal content is at a similar level. Table 4 shows that there are significant

amounts of copper and iron in the brake lining material. The content of other metals is lower, but the proportion of calcium, sodium and zinc is significant.

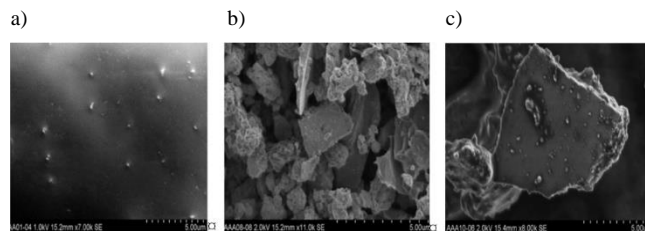


Fig. 8. SEM images of particles from brake component wear created during a simulation test: a) $d_p < 56 \text{ nm}$, b) $d_p < 2.5 \mu\text{m}$, c) $d_p < 10 \mu\text{m}$ [54]

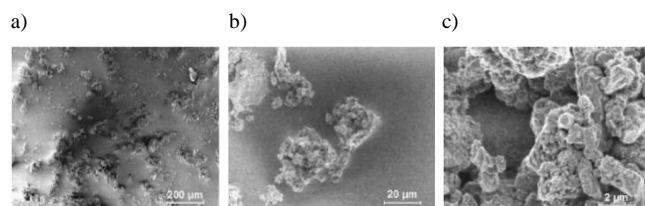


Fig. 9. Scanning electron microscope images of brake dust: a) 100x microscopic magnification of typical hemispherical agglomerates, b) 1000x magnification of the same sample, c) 10,000x magnification of the same sample [95]

The metal content of the brakes is presented in Table 4. The results show that significant amounts of copper and iron can be present, with mass fractions of up to 4% and 1.4%, respectively. Other metals, especially calcium, sodium, and zinc, also have a significant share.

Table 4. The metal content of brakes [33]

Metal	Concentration of metals [mg/kg]	Metal	Concentration of metals [mg/kg]
Al	3770	Na	15,400
Ca	14,300	Pb	1960–3900
Cu	15,100–142,000	Sb	10,000
Fe	115,000–399,000	Sn	7000
Mg	6140	Ti	3600
Mo	10,000	Zn	270–21,800

Non-engine pollutants contribute almost equally to the total PM_{10} emissions from road traffic. Brake dust emissions have been identified as one of the main sources of non-exhaust-related dust pollution. The relative contribution of brake dust emissions to non-exhaust pollution is in the range of 16–55%, while for total traffic-related PM_{10} emissions, this contribution is 11–21%. It is estimated that about 50% of the total brake dust is emitted as airborne PM_{10} . The remainder is deposited by gravity on the road or roadside and in the surrounding area. Brake dust particles are present in all fractions of air pollutants inhaled by living organisms. Consequently, airborne brake dust particles have been identified as being particularly hazardous to human health.

2.3. Dust emission from wear of road wheel tires and road surface

According to the latest statistics, around 1.4 billion land vehicles are currently in use worldwide, including passenger cars, trucks, buses and motorcycles. Most of these vehi-

cles are equipped with pneumatic tires, which wear out over time as they travel on different surfaces and in different operating conditions. In 2020, worldwide emissions from tire wear were estimated at almost 6 million tons, with 2.6 kg per person per year in Europe alone [7, 62].

The number of car tires produced is significant and growing all the time. In 2019, a total of 3 billion tires were produced worldwide. In the EU, tire production was at around 335 million in 2015. In contrast, tire production in the USA was around 300 million in 2022. Around 800 million tires were produced in China in 2021 [65].

The tire is an important component of a mechanical wheeled vehicle. It is a structurally complex, flexible rubber product that is the only part of the vehicle in contact with the ground while driving. Tires are in direct contact with the road surface and, at the same time, work with the vehicle's suspension to provide shock absorbers, smooth handling, and ride comfort. The primary function of tires is to support the weight of the vehicle. In addition, tires are designed to provide a good grip on the road surface, enabling adequate braking and safe overtaking. The tire structure consists mainly of the tread, shoulder, sidewall, belt, cord, inner liner, etc., as shown in Fig. 10 [103]. Tire manufacturers usually specify a tire life of three years. This period may vary depending on the mileage of the tire in a given year but will not exceed five years. During their lifecycle, tires release up to 12% of their weight into the environment, making them one of the main sources of "microplastics" in the environment. It is estimated that the annual emissions from tire consumption in different countries are in the range of 0.2–5.5 kg per capita [75].

Each tire is equipped with a current tread wear indicator (TWI), which allows self-monitoring and determining when the tire should be replaced due to tread wear. The indicator, in the form of a bead (hump), is usually located at the bottom of the water drainage grooves in six places on the tread (Fig. 10b). The height of the hump's hg indicates the limit of the maximum tread wear level (Fig. 10c).

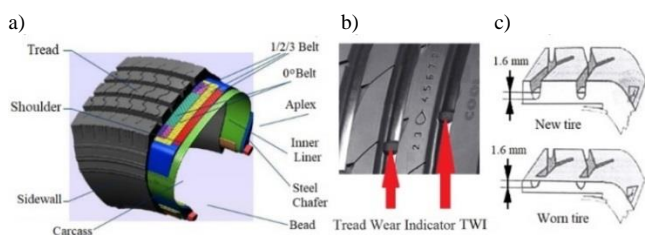


Fig. 10. Characteristic features of the tire: a) tire structure, b) location of the TWI tire indicator, c) height of the h_g hump informing about the limit of the maximum tread wear level [103]

If the groove is level with the bead, the tire should be replaced immediately. The bead value for all summer tires applicable in most European countries is $h_g = 1.6$ mm and for winter tires, $h_g = 4$ mm. In the case of summer tires, the tread groove depth of a new tire is between 8.5 and 10 mm. Once $h_g = 1.6$ mm is reached, the tread thickness of the tire is reduced by more than 8 mm around the entire circumference.

Tires are constructed from various highly engineered components, including tread, belts, inner liners, and side-

walls, each designed to meet performance parameters that create durable, strong, reliable, and safe tires. Tires contain many materials and chemicals, many of which are proprietary. Tires are usually constructed using metal mesh or textiles and rubber. The rubber structure used to manufacture tires has proprietary formulas that vary depending on the vehicle make, tire type and shape, and tire components [43]. Most often, synthetic or natural rubber is used in the production of tires in the amount of 40–60% or a mixture of both in a ratio of 50:50. Important ingredients are fillers and reinforcing agents: carbon black and silica in the amount of 20–25% and process oils and diluents in the amount of 12–15%. In addition, tire production uses vulcanizing agents such as thiazoles (1–2%) and other additives, namely preservatives and adjuvants, in a total amount of 5–10% [98]. More synthetic rubber is used in the production of passenger car tires, while more natural rubber is used in the production of truck tires. Tires contain a significant amount of chemicals, including those intentionally added, such as N-(1,3-dimethylbutyl)-N'-phenyl-p-phenyl-enediamine, polycyclic aromatic hydrocarbons (PAHs) and tire aging products [51]. For this reason, it is difficult to establish a standard chemical composition of tire wear particles. The authors of [87] provide the most common tire tread components that determine its durability and driving properties:

- base rock (40–50% by weight): natural rubber and synthetic rubber
- filler (30–35% by weight): carbon black (C), silica (SiO_2) and chalk (CaCO_3)
- softener (15% by weight): oil and resin
- vulcanizing agents (2–5% by weight): sulfur (S) and zinc oxide (ZnO)
- additives (5–10% by weight): preservatives, antioxidants, desiccants, plasticizers, excipients.

The tire wear process is relatively complex, with four main factors influencing wear and particle formation [40, 46]:

- tire-related factors: structure and construction, tire type, size
- road surface-related factors: surface structure, micro- and macro-texture, binder (asphalt, cement)
- vehicle-related factors: driving speed, longitudinal (lateral) acceleration, vehicle weight and load distribution, suspension type and parameters, braking frequency and range, acceleration frequency, cornering technique
- environmental factors.

Particulate matter emissions from tire-road interaction result from the tire's interaction with the road surface on a small surface, which results in tread wear. Tire wear itself is a complex physicochemical process that results from the friction force generated at the contact between the tread and the road surface. During the interaction of the tire tread with the road surface, there are shearing forces that mechanically cause both components to wear and generate a coarse fraction of particles. Generating much smaller particles from tread and road surface wear by volatilization. Fine particle generation is described as a thermomechanical process in which local hot spots on the tire tread reach high temperatures, resulting in the evaporation of the volatile content of the tires. It is believed that the interaction of the tire tread with the cured road surface changes through heat,

friction, or the incorporation of material from the road surface, as well as the chemical composition and characteristics of the generated particles compared to the original tread chemical composition.

In the field of tribology, the following are distinguished during the study of tire wear: fatigue, frictional, adhesive and erosive wear mechanisms, as well as chemical wear. Tires, which are in direct contact with the ground while the car is moving and during turning and braking maneuvers, are tasked with transferring vertical load, lateral load, tangential load, reversing moments and rolling resistance.

In the process of contact between the tire tread and the road surface, there is both friction and sliding, which causes micro cuts and tears in the surface of the tire tread and the road surface. When frictional energy accumulates in the contact area between the tread and the road surface, which reaches the damage energy (critical value), the local volume is removed from the surface in the form of abrasive chips, which is equivalent to wear [103]. Practically, tire wear due to friction does not occur in a single form but in a complex process of wear due to the interaction of the tire with the road surface. However, tire wear due to friction usually does not occur in a single form but in the process of complex wear during the interaction of the tire with the road surface. The interaction of the tire with the road surface causes that, as a result of friction and intensive heat generation, as well as the introduction of material from the road surface, both the chemical composition and the characteristics of the generated particles change in comparison with the original chemical composition of the tire tread [103]. Particles from just the tire tread wearing out are practically present in the environment in very small amounts. Most of the particles from tire wear are usually associated with material from the road surface. According to the authors of [1, 104], tire and road wear particles never occur in their pure form but from a combination of road surface wear material (about 50%) and tire about 50%. Figure 11a shows the shape of the particles emitted into the environment by tire tread wear. Figure 11b shows the concentration of particles as a function of their size for different driving patterns during left and right turns for different lateral accelerations of the car. As the lateral acceleration increases, there is an increase in particle concentration, especially in the range of 2–3 μm and around 0.5 μm , which can be attributed to high shear forces [40].

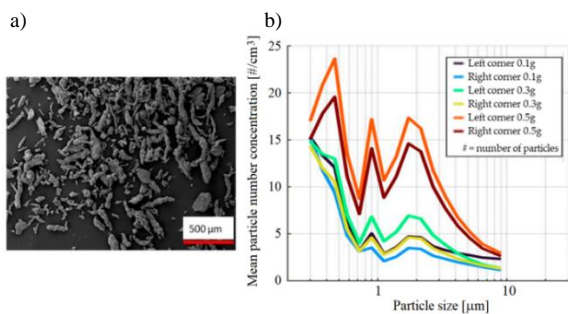


Fig. 11. Test results: microscopic images of collected tire particles, b) comparison of TRWP particle size distribution during cornering (left or right) for different lateral accelerations of the car [40]

The factors affecting the size distribution characteristics of vehicle tires and road wear particles have been studied in laboratory tests [9, 27, 38, 53, 58, 69, 76, 83, 85, 94, 104, 106].

Figure 12 shows the physical characteristics of tire and road wear particles. According to the research presented in [27], the tire and road wear particle diameter (TRWP) is mainly distributed in the range of 4–350 μm with an average diameter of 100 μm , which is larger than the volume of $\text{PM}_{2.5}$ ($\leq 2.5 \mu\text{m}$) and PM_{10} ($\leq 10 \mu\text{m}$). The density of particulate matter is about 1800 kg/m^3 , which is higher than the density of water.

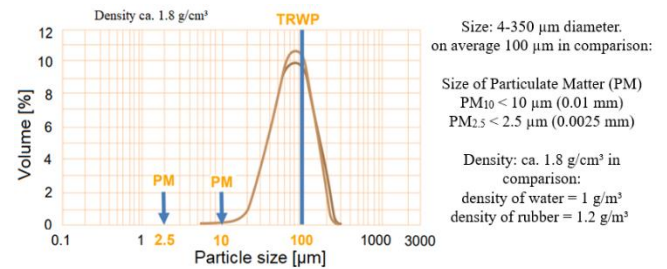


Fig. 12. Physical characteristics of tire and road abrasive particles (TRWP) [27]

Figure 13 shows photos of road and tire wear particles [53]. Road wear particles (Fig. 13a and 13b) are elongated and contain mineral inclusions from the road surface. Tire wear particles retain a similar shape and mineral inclusions (Fig. 13c and 13d).

The elongation of the particles indicates that the shape of road particles and TWP tire wear particles is almost identical.

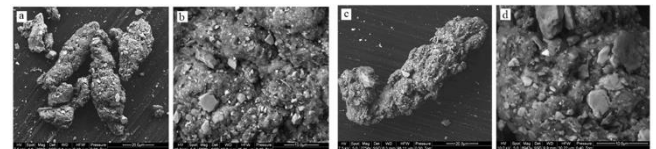


Fig. 13. Photos of particles: a, b) from road wear, c, d) from tire wear (b, d – appropriate magnification of photos a and c, where mineral inclusions are visible) [53]

In [106], the particle size distribution characteristics from vehicle tire wear and road surface wear were shown under different laboratory test conditions. The influence of four tire wear factors (slip angle, speed, load and roll angle) on PM_{10} emissions from tire wear was investigated. It was found that tire wear emitted mainly ultrafine particles, which accounted for 94.8% of the particles in the 6–10 μm range. During the study, it was shown that there are two ranges of maximum particle concentrations for each of the studied agents. The first maximum was registered in the 10–13 nm range, and the second for larger particles at 23–41 nm. In addition, the experiments showed that particle emissions from tire tread wear are least affected by wheel roll angles while slip angles have the greatest effect.

The authors of the paper [94] studied and analyzed non-motor vehicle emissions and showed that PM_{10} particles contain various components in their composition. The main component is mineral and cement dust, whose content is

51–64%. Tailpipe exhaust contains 26–40%. Particles from tire tread wear are at 7–9%, and particles from brake lining wear are at 1–3%. $PM_{2.5}$ emissions are quite different, where the main component is tailpipe exhaust at 59–80%. The content of road and cement dust is much lower and is in the range of 11–31%. Particles from tire wear and brake linings contribute 4–10% and 1–5%, respectively. A study conducted in Delhi [104], found that non-motor emissions contributed 86% to total particulate emissions. Non-combustion emissions were found to contribute variously to total PM_{10} emissions. The largest contribution came from particulate matter emissions again, followed by wear products from brake components, particles from tire tread wear and products from road surface wear.

A study [85] on sources of particulate matter other than exhaust gases showed that various sources contribute to the total emissions, with particulate matter again accounting for 38.1%, particulate matter from brake wear 55.3% and particulate matter from tire wear 10.7%. [38] shows that brakes can contribute to the total "non-engine" PM_{10} particulate matter emissions and up to 55%, or 21% of the total PM_{10} mass generated by road traffic. The study presented in the paper [69] shows that the braking system in urban areas contributes 16–55% of the total non-engine PM_{10} emissions.

According to the analysis and research presented in the paper [69], it appears that the tread wear of a tire used for a period of five to eight years had a value of 0.79–1.33 mm in one year. During this time, the vehicle covered a distance of 12,000 kilometers per year. The tire's tread depth at the beginning of use was about 8–9 mm. The applicable tread depth for summer tires is assumed to be a minimum of 1.6 mm.

The authors of the paper [58] found that a new 10-kg passenger car tire can wear out and lose mass between 1 and 1.5 kg over its lifetime, or about 0.03 g/km. It was also calculated that if a tire wears 218 g per year, this corresponds to tread wear of about 1mm over the life of a car for six years. It was found that tire wear depends on tire dimensions. The larger diameter of the tire (SUV) and the greater width of the tire result in a greater emission of particle mass from wear. Tire wear also depends on the road profile, the type of road surface, the time of year, the weather conditions (air temperature, rain), the weight of the vehicle and the distribution of the load, the number of corners and the technique used to negotiate them, the technical condition of the suspension and shock absorbers, the power of the engine, the speed and driving style, the frequency of braking and starting. This means that operating a vehicle on mountain roads causes more tire tread wear than operating the same car on urban terrain. Paved concrete roads may cause more tire tread wear than asphalt-paved roads. More tire tread wear will be caused by roads with soggy pavement than clean and dry surfaces. An increase in air temperature increases the intensity of tire tread wear.

On the other hand, higher engine torque and horsepower give the possibility of rapid acceleration and the need to brake, as well as the possibility of driving at higher speeds, which has an impact on greater tread wear [58].

In [9], a laboratory study of the effects of five variable factors (tire load, speed, air humidity, slip rate and braking time) on tire wear particle (TWP) emissions was presented. The tires were made of soft styrene-butadiene rubber, and the tests were conducted on concrete pavement. The soft rubber was shown to have good grip and good vibration absorption but low wear resistance, resulting in intense particle emissions.

Under braking conditions, higher humidity and braking time cause lower emission of wear particles, while load, speed and slip coefficient have a positive correlation with emission. The emission of 3 μm particles is much higher than that of 5 and 10 μm particles. The load effect coefficient is about twice as high as the speed and slip coefficient and three times as high as the humidity and braking deceleration coefficient. With the increase of load, the increase in emission increases. The 3 μm emission quantity increment shows a rapid nonlinear exponential growth, while the 5 μm and 10 μm quantity increments grow more slowly, especially for the 10 μm particles. With increasing speed, the emission quantity increments for all particle sizes increase (Fig. 14).

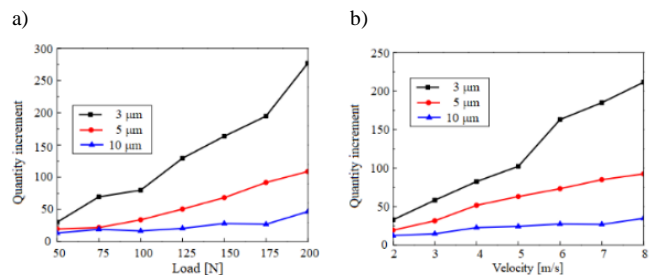


Fig. 14. Increase in the amount of particle emission from tire tread wear caused by a) change of load, b) change of sliding speed [9]

3. Sources and characteristics of natural air pollutants

Natural sources of pollution are primarily those resulting from the actions of nature, including:

- volcanic activity as a source of volcanic ash (dust) and harmful gases: sulphur (IV) oxide, carbon dioxide, hydrogen sulphide
- forest, savannah and steppe fires (carbon monoxide and dust)
- landfill fires (noxious gases)
- marine aerosols and material of plant and animal origin
- swamps emitting methane, carbon dioxide, ammonia, hydrogen sulphide, etc.
- road dust, mainly mineral dust stirred up from the ground by moving vehicles, the operation of machinery and agricultural equipment
- rock and soil erosion, resulting in mineral dust being carried long distances by the wind
- sandstorms in the desert are a source of mineral dust
- biological pollution: micro-organisms (mites, fungi, bacteria), pollen
- forests, meadows, trees and shrubs are sources of pollen.

Among natural air pollutants, organic and inorganic pollutants are distinguished. Sources of inorganic pollutants

include volcanic eruptions, forest, savannah and steppe fires, peat bogs and landfill fires, as well as sandstorms (Fig. 15). The main components of these pollutants are dust and sulfur dioxide. Due to the decomposition processes of organic matter, marshes are a source of methane, hydrogen sulfide, carbon dioxide and ammonia.



Fig. 15. Natural (inorganic) sources of air pollution: a) volcanic eruption, b) forest fire, c) landfill fire, d) sandstorm [20]

Natural (organic) pollutants are primarily suspended biological particles in the air (viruses, bacteria, mold particles, mites, microscopic fungi or fragments of living and dead organisms) forming a "bioaerosol" which is a collection of biological particles dispersed in the air or another gas phase (Fig. 16). These can include plant pollen, viruses, mites and mold. Bioaerosol is biological material carried by itself or carried by larger non-biological particles, e.g., dust particles. Biological air pollutants are primarily pollen, fungi (mainly spores), bacteria and viruses. They occur in the air in the form of so-called biological aerosols (aeroplankton) and may play an important role in the transmission of allergic and infectious diseases and even contribute to epidemics. The qualitative and quantitative composition of the above-mentioned organisms undergoes significant changes in time and space. Due to the type and size of bioaerosol particles that form the dispersed phase, the most common are viruses (0.01–1 μm), bacteria (0.1–2 μm), algae (1–9 μm), spores of fungi, mosses and lichens (1–100 μm), pollen (9–90 μm) and small seeds and fruits (9–900 μm) [16, 34].

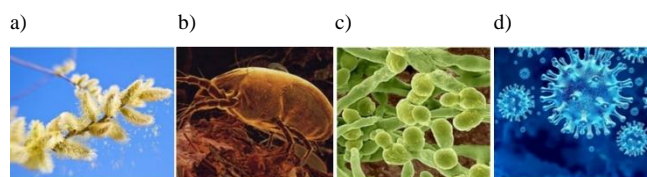


Fig. 16. Natural (organic) sources of air pollution: a) pollen, b) mites, c) mould fungi, d) viruses [21]

The authors of the paper [77] conducted an analysis of particles retained on the filter cartridge of the intake air of a passenger car engine used on public roads. It was shown that the composition of the particles varied in size, shape and material. It was found visually that the particles with the largest sizes were biological contaminants, such as small insects and their parts. Plant fragments, flower remains and dry leaves were found on the surface of the filter in smaller amounts. Inorganic compounds and synthetic elements were also found, as well as numerous elements in large agglomerates, such as Si, Al, Ca, Fe, Mg, and Na.

Road surfaces are primarily a place of deposition of mineral dust, which was carried by the wind from the soils surrounding the road, formed as a result of field and road

works and construction works. The sources of mineral dust are sandy areas, off-road areas and dirt roads used by wheeled and tracked vehicles, work and agricultural machines, and military vehicles (Fig. 17).

Mineral dust is formed by particles formed by the weathering of rocks and soil. Different temperatures during the day and night and precipitation cause the crumbling of the earth's surface. Its most important natural source areas of dust are deserts and semi-deserts, located mainly in northern Africa, the Middle East and central and eastern Asia. More than 58% of the total mineral dust emission comes from the Sahara, while the deserts of the Arabian Peninsula, eastern China, and central Asia account for 12%, 8%, and 7% of their emissions, respectively [91].

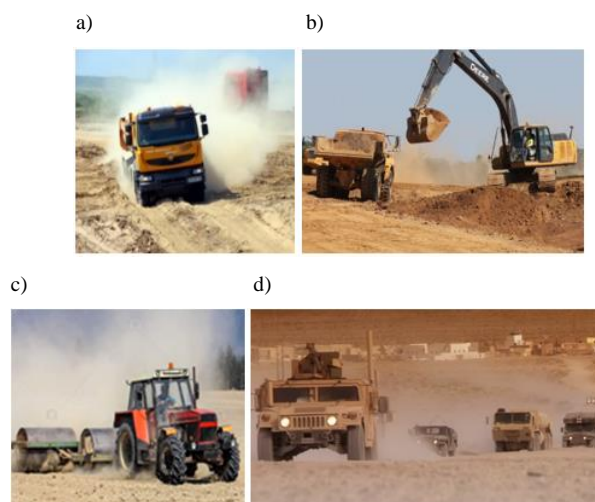


Fig. 17. Air dustiness during operation of technical devices: a) trucks, b) work machines, c) agricultural machines, d) a column of military vehicles [21]

The main constituent of mineral dust is quartz (silica), the compactness of which is variable in the dust. In addition, feldspar (plagioclase and alkali feldspar), mica (mainly muscovite and biotite) and various clay minerals (illite, montmorillonite, palygorskite, kaolinite) are present in the dust. In the dust, there are carbonates (calcite and dolomite) and metal oxides, for example, hematite, magnetite, and rutile. Minerals such as halite, gypsum, and potassium sulfate can be found in dust. Minerals in dust occur as single grains or agglomerates with grain sizes ranging from less than 1 μm to ~30 μm . Airborne dust also contains microfauna in its composition, such as fungi, bacteria and viruses.

4. Characteristics of resuspended dust

Solid pollutants emitted into the ambient air fall under the influence of gravity. As the particles of the pollutants have different densities and, therefore, different masses, as well as shapes and sizes, they fall to the ground at different speeds. The residence time of the particles in the air then depends on the falling velocity, the value of which is determined by the reciprocal relationship between the drag force of the medium and the gravitational force. The falling velocity of dust particles increases significantly with increasing grain diameter and particle material density. Dust particles less than 0.1 μm in size are subject to random

Brownian motion resulting from mutual collisions with gas particles. Collisions with other dust particles, whose motion is mainly caused by moving gas particles, are negligible. Dust particles in the 0.1–1 μm range show low falling velocities in still air. Dust particles larger than 1 μm have low falling velocities, but these are noticeable. Dust particles larger than 20 μm have high enough falling velocities to be removed from the air by gravity or other inertial mechanisms.

The approximate settling velocities of particles with a density of 1000 kg/m³ are 4 × 10⁻⁷ m/s for particles of size 0.1 μm, 4 × 10⁻⁵ m/s for particles of size 1 μm, 3 × 10⁻³ m/s for 10 μm and 3 × 10⁻¹ m/s 100 μm [99]. On the other hand, grains of silica SiO₂ (density: 2650 kg/m³) of size 10, 50 and 100 μm settle at velocities of 0.035, 0.11 and 0.72 m/s, respectively (Fig. 18) [19].

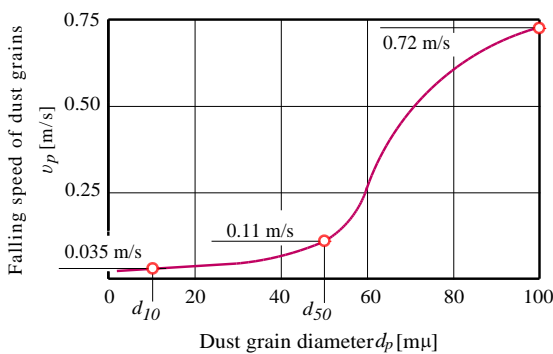


Fig. 18. Dependence of the settling velocity of silica grains on their diameter [19]

Road surfaces are places where mineral dust is deposited, which is carried by the wind from the soil surrounding the road, created as a result of fieldwork or as a result of road construction work. The road surface contains pollutants emitted from the engine together with exhaust fumes, such as solid particles and products of wear of engine elements cooperating by friction. These are also particles that have been emitted into the atmosphere as a result of abrasion processes occurring in brake and clutch friction pairs, and as a result of tire tread wear from interaction with the road surface, and which fall to the ground by gravity after some time. Significant quantities of particles that fall by gravity to the road surface are industrial dust, volcanic dust or dust from desert regions, which have been carried by air movements. On the road surface, especially in winter, there may be salt to reduce icing on the surface, fragments of plants, flowers and dry leaves, pollen, animal dander and moulds, insects and their remains and other biological materials carried from nearby locations by air movements.

In the road environment, particles of many solid pollutants (from natural and anthropogenic sources) settled by gravity on the ground surface (roads) tend to mix and form heterogeneous dust, which can be resuspended in the atmosphere by motor vehicle traffic or by wind and is therefore popularly called "road dust" [39, 44]. Three main material groups can be distinguished in road dust, which has a diverse chemical composition: metals, organic compounds (OCs) and inorganic compounds [17]. Metal particles are mainly derived from brake pad materials, while

organic compounds are products of wear and tear on asphalt pavement and tire materials. Inorganic compounds are materials on the road surface and come from construction or industrial emissions [96].

Since falling atmospheric dust comes from various sources and processes, it has a complex mineral and chemical composition. Figures 19 and 20 show SEM images of falling dust samples, which illustrate the diversity of matter found in the atmosphere [2, 105].

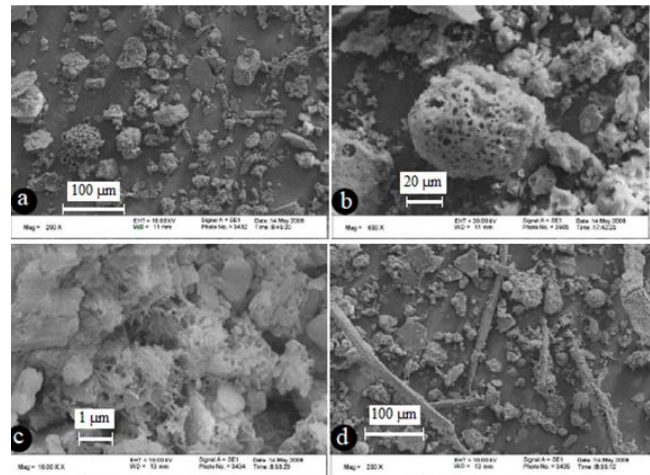


Fig. 19. Scanning electron microscope images of dry settling dust: a) particles with various minerals, b) large particles with smooth, spherical surface and macroporous structures, c) fly ash with mineral particles placed in holes, d) various minerals with elongated/layered structures and flat surface [105]

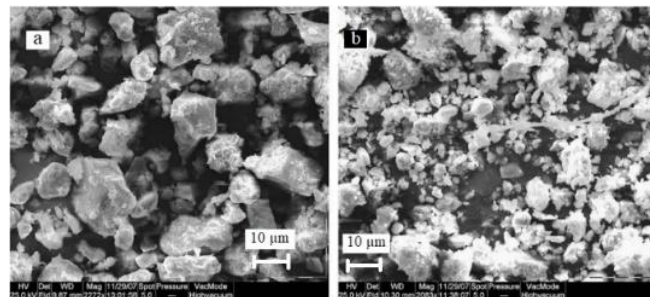


Fig. 20. SEM images showing grain size and shape of dust from different regions of Saudi Arabia: a) Wadi Araba, b) Azraq City [2]

Images of particles of falling anthropogenic and natural dust, taken by scanning microscopy, are shown in Fig. 21. Observations of individual particles prove that grains are usually characterized by an irregular shape (Fig. 20c), often with sharp edges (Fig. 21b, 21d), and also assume cube shapes (Fig. 21f).

Particles with a regular spherical structure can combine to form agglomerates (Fig. 21h, 21i) or fractal-like clusters, which are characterized by a much larger surface area, a longer residence time in the atmosphere, and a higher unit light absorption capacity than spherical particles of the same size. A typical example of a fractal structure is soot particles (Fig. 21a) [32].

The authors [49] report that road dust present on street surfaces in Southern California consists of a complex mixture of soil dust, embedded motor vehicle exhaust particles, tire dust, brake lining wear dust, plant fragments and other

biological materials. Road dust contains allergens from at least 20 different source materials. These include pollen and flower fragments, animal dander and mold. When road dust is re-suspended in the atmosphere by passing vehicles, the concentration of allergens in the air rises above levels that would occur without traffic.

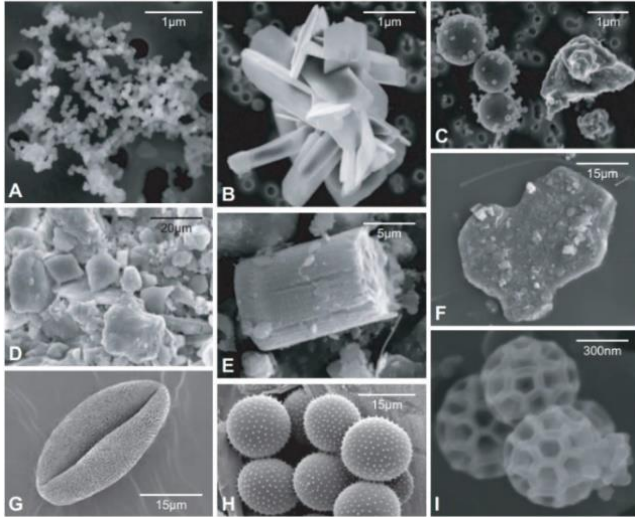


Fig. 21. Scanning microscope photographs of anthropogenic (A–C) and natural (D–I) dust particles: A) cluster of soot particles; B) calcium sulfate crystals from combustion; C) plagioclase particles and spherical magnetite particles from combustion; particles contained in mineral dust from the Sahara (D–F): D) calcite and clay particles; E) diatom, F) halite crystals (small light cubes) attached to illite particles; G) fire bush pollen (*Hamelapatens*); H) wheat brown rust spores (*Pucciniatriticina*); I) agglomerate of bronchoscopes (organic particles produced by cicada insects) [32]

5. Road dust parameters

The majority of dusts found in nature, are polydisperse dusts with varying physicochemical properties, in which there is a macroscopic fraction with particle sizes of 1–1000 μm and a microscopic (colloidal) fraction – of submicron particles with sizes of 0.001–1 μm [56, 82].

According to [47], dusts are heterogeneous atmospheric air pollutants that are formed by a variety of natural (e.g., dust storms) and anthropogenic (e.g., fossil fuel combustion) processes, are subject to physical and chemical processes in the atmosphere, and ultimately affect human health, climate and the environment in a variety of ways are the cause of accelerated tribological wear of machinery. Dust, fine particles (grains) of solid or liquid matter, once emitted into the atmosphere, remain suspended in it, forming atmospheric aerosol, with different – depending on the morphology, fraction, surface, shape and chemical composition of the particles – properties. The term dust is most often used to refer to the dispersed phase of a two-phase solid system.

The main component of road dust is mineral dust, which is characterized by the following parameters: chemical composition, hardness, fractional (granulometric) composition, density, grain shape, air concentration, propensity to coagulate [6].

Chemical composition determines the proportion of individual components in the dust. The main component of road dust is silica, the proportion of which in the dust reaches 60–95%. The remaining 4–19% is made up of ox-

ides of various metals: aluminum oxide, iron oxide, calcium oxide, magnesium oxide and organic components. Silica occurs in nature in three forms: crystalline, amorphous and cryptocrystalline. It can occur in its pure form as quartz (share of about 12%) and in the form of mineral compounds, such as aluminosilicates, whose share in the mass of the earth's crust totals about 50%. Transparent and colored varieties of quartz are used, as ornamental stones (amethysts, citrines, aventurines, opal). Colorless varieties of quartz (rock crystal) are used in optics.

The chemical composition of dust depends mainly on the composition and type of substrate. The chemical composition of road dust is also influenced by climatic factors (high winds, rains, droughts, etc.) and human-induced precipitation of industrial dust, as well as the type and amount of vegetation. The proportion of components in dust varies depending on the substrate. The main components of dust are silica SiO_2 , alumina Al_2O_3 and Fe_2O_3 , the proportion of which in dust reaches respectively: 90%, 12,5% and 19%. In addition, oxides MgO , CaO , K_2O , Na_2O , TiO_2 , NiO and SO_2 are found in dust in smaller quantities not exceeding 3% [8, 25, 86, 88, 92]. Figure 22 shows the average chemical composition of road dust found on roads in Poland [6].

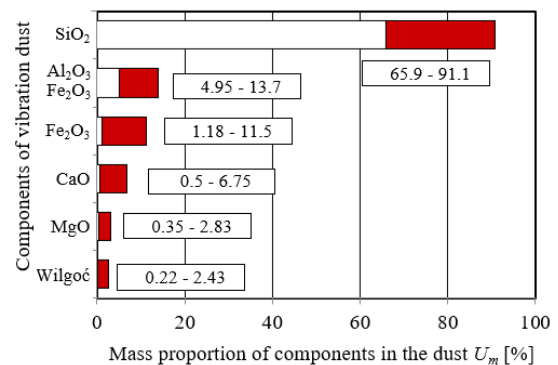


Fig. 22. Mass fraction of individual components in road dust in Poland [6]

The hardness of the dust grains depends on their chemical composition. According to the hardness evaluated on the basis of the 10-grade Mohs scale (Fig. 23), in which talc corresponds to a hardness of 1 and diamond to 10, silica has a hardness of 7 and alumina has a hardness of 9. Silica and alumina are minerals whose proportion in dust reaches 95%, and their hardness is much higher than that of structural materials used in engine construction.

The density of dust as a function of its chemical composition and the main components of road dust varies widely and is for quartz – 2650 kg/m^3 , alumina – 3990 kg/m^3 , iron (III) oxide – 5240 kg/m^3 , calcium oxide – 3400 kg/m^3 . According to data in [6], the average density of dust in Poland is in the range of 2360–2660 kg/m^3 .



Fig. 23. The form of selected minerals and their corresponding hardness on the Mohs scale [67]

The shape of dust grains also depends on their chemical composition. In real conditions, dust grains usually have a very irregular shape: igneous, angular (with sharp edges, shaped like polyhedrons), dendritic (a collection of crystals), fibrous, granular, crystalline (with regular geometric shapes), modular (with round, irregular shape) [6]. Figure 24 shows an example view of quartz grains of different sizes and shapes.

The lack of geometric regularity of the grains makes it difficult to determine their dimensions. To evaluate the dimensions of grains, the conventional concept of equivalent grain diameter d_p is used, which is defined according to the method of its determination.

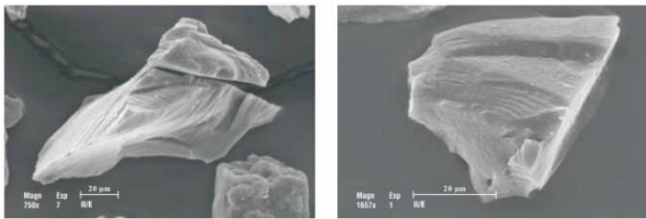


Fig. 24. View of quartz grains of different sizes and shapes [100]

Most commonly, the equivalent grain diameter d_p means the diameter of a sphere made of material with the density of the mineral under consideration and exhibiting (in still air with a pressure of 1010.8 hPa, a temperature of 293 K and a relative humidity of less than 50%) under the influence of gravity a falling velocity equal to the laminar falling velocity of the grain of the dust under consideration [6]. In measurement practice, the concept of the diameter of the projection area d_A is used to denote the diameter of a circle with the same area as the projection area of the particle.

The granulometric (fractional) composition is an indicator of the heterogeneity of dust grain size, which can be presented in the form of a graph (Fig. 25) characterizing the relative contribution to the total mass of dust of grains smaller or larger than a given dimension d_p . The granulometric composition of dust depends on the location and height above the ground. The relationship is closely related to the speed of grain fall in calm air.

The presented characteristics show that the granulometric compositions of dust from substrates from different regions of the world vary considerably. For example, in the dust from the Tashkent area, about 60% of the total mass of dust are grains with dimensions of less than 10 μm , and 92.8% of its mass are dust grains with dimensions of less than 30 μm . This means very fine dust, whose maximum grain size takes the value of about $d_{p\text{max}} = 60 \mu\text{m}$. In comparison, in the dust from the Libyan desert region, only 20% of the total dust by weight are dust grains with dimensions of less than 10 μm , and 33% of its weight are dust grains with dimensions of less than 30 μm . On the other hand, 75.9% of the dust by weight are grains of less than 100 μm .

Dust concentration in the air (air dustiness) is a characteristic of polluted air, and its measure is the mass of dust (in grams or mg) contained in 1 m^3 of atmospheric air. Air dust concentration is a variable quantity and depends on

many factors. The value of dust concentration in the air around a moving vehicle is influenced by:

- movement of other vehicles: number of vehicles in a column, bypassing or overtaking, distance between vehicles
- vehicle movement conditions: speed, type of movement (single vehicle or column)
- meteorological conditions: air temperature, humidity, wind speed and direction, type and timing of precipitation, time since last rainfall, season, cloud cover
- aerodynamic characteristics of the vehicle (body shape)
- type of running gear (wheeled, tracked)
- type of industrial plants located near roads
- type of surrounding soils
- height above the ground surface.

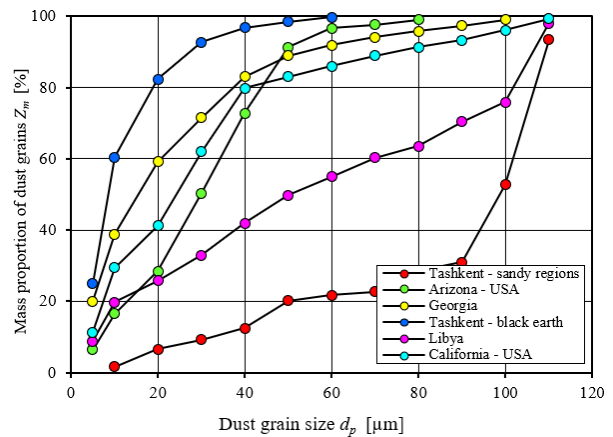


Fig. 25. Granulometric composition of road dust from various regions of the world [45]

Depending on the soil type, the dust concentration in the air takes on varying values (Fig. 26).

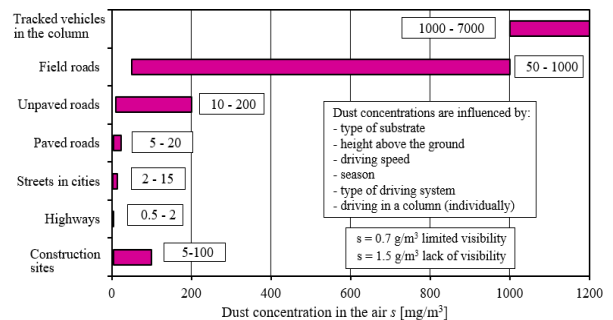


Fig. 26. Dust concentration in the air depending on the type of substrate [21]

6. The impact on human health of particulate emissions from road transport

The impact of particulate emissions from road transportation on human health and the environment has been the subject of much research and analysis [4, 15, 28, 52, 63, 71, 72, 74, 80]. Particles from tire wear, brake friction components and the road cause serious impacts on the environment, including human health by causing cardiovascular disorders, pneumonia, asthma, chronic lung disease, cancer and pulmonary fibrosis. The largest particle sizes (above 10 μm) are retained inertially at the nose-throat section and do

not enter the respiratory system. The smallest particles (less than $2\ \mu\text{m}$) can be retained by Brownian diffusion. Particles smaller than $0.5\ \mu\text{m}$ enter the bronchi and lungs [49, 72].

An adult human takes about 20–22,000 breaths per day, inhaling more than $10\ \text{m}^3$ of air during this time, and sometimes up to $20\ \text{m}^3$ [16]. The human respiratory system consists of tubes whose diameter becomes thinner as they approach the lungs. Consequently, only smaller particles are able to reach the alveoli, thus causing toxic effects in the lungs. According to the authors of the paper [16], particles between 4.7 and $7\ \mu\text{m}$ in diameter are deposited in the pharynx, 3.3 – $4.7\ \mu\text{m}$ particles reach the trachea and primary bronchi, 1.1 – $3.3\ \mu\text{m}$ particles penetrate the secondary and terminal bronchi, and particles smaller than $1.1\ \mu\text{m}$ can reach the bronchi of the lungs. Particles smaller than $2.5\ \mu\text{m}$ pose the greatest threat. Such particles can pass through the lung epithelium and be transported in the blood to other organs [15]. Thus, particles in the 0.1 – $1\ \mu\text{m}$ size range can penetrate the farthest elements of the respiratory system.

The main effect of PM pollution entering the cells of a living organism is the formation of reactive oxygen species and “oxidative stress.” Metals associated with PM particles contribute to the toxic effects [52]. Damage resulting from toxic particles can cause chronic inflammation and carcinogenic changes, making PM largely responsible for adverse health changes [63]. Figure 27 shows the proportion of particulate deposition retained by various organs of the respiratory system as a function of dust grain size [48].

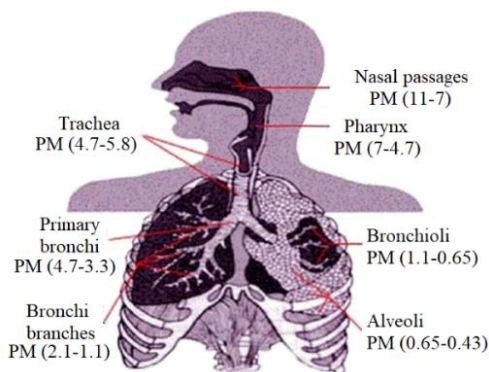


Fig. 27. Deposition of particles of different sizes (in μm) in the human respiratory system [48]

The most dangerous for human health are particles with small diameters, i.e., $\text{PM}_{2.5}$ and PM_1 . At the beginning of the human respiratory system, i.e., in the nasopharynx, dusts with a diameter larger than $10\ \mu\text{m}$ are retained. There they are either accumulated or excreted with secretions. Dusts with smaller diameters enter the deeper parts of the respiratory system. Dust grains with an aerodynamic diameter of $(0.05$ – $2.0)\ \mu\text{m}$ enter the alveoli, while dust with finer diameters can enter the human body by gas exchange.

The depth of penetration of the human body's respiratory system by the different fractions of particulate matter is shown in Fig. 28.

The analysis shows that the most dangerous to human health are particles with small diameters, i.e., $\text{PM}_{2.5}$ and PM_1 . At the beginning of the human respiratory system, in the nasopharynx, dusts with diameters larger than $10\ \mu\text{m}$

are trapped. There, they are either accumulated or excreted with secretions. Dusts with smaller diameters enter the deeper parts of the respiratory system. Dust grains with aerodynamic diameters in the range of 0.05 – $2.0\ \mu\text{m}$ enter the alveoli, while dust with smaller diameters can enter the human body by gas exchange, that is, like oxygen [15].

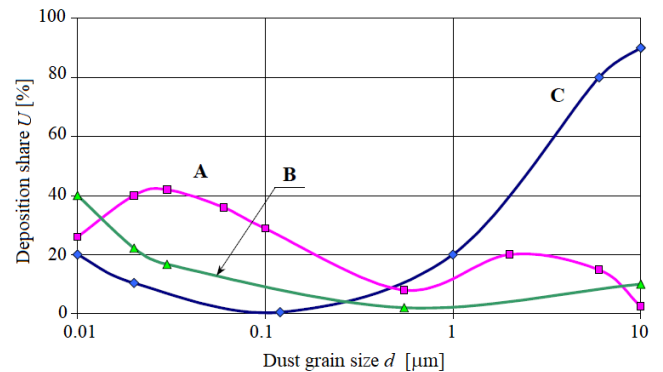


Fig. 28. Size distribution of particulate matter retained in different sections of the human respiratory system: A – lungs, B – trachea and bronchi, C – nasopharynx [15]

7. The impact of road dust on the environment and the operation of engine systems

Mineral dust, which is the main component of road dust, is one of the main factors that have a harmful effect on the human body and are the cause of many diseases, mainly pneumoconiosis and cancer. Dust particles with large sizes and sharp edges can mechanically irritate and damage the mucous membrane during nasal air intake, leading to bleeding and even hemorrhaging. Dust particles can cause skin and eye irritation and allergic reactions. Fine dust particles, especially those less than $2.5\ \mu\text{m}$ in size, can enter the alveoli by gas exchange, then enter the bloodstream and cause adverse changes in the human body [61]. Sandstorms and desert dust are recurrent environmental phenomena that cause serious health risks worldwide.

According to the generally accepted definition, pneumoconiosis is characterized by the accumulation of dust clusters in the lung tissue and the reaction of the lung tissue to the presence of dust. Dust, in turn, is defined as an aerosol composed of inanimate particulate matter.

Under normal conditions, when exposure to dust is not large and does not last long, most inhaled dust particles are trapped in the secretions of the mucous membranes of the respiratory tract and are quickly removed by the movement of cilia (small structures whose movement clears the respiratory tract). However, if the particles are larger in diameter and one inhales a lot of them every day, then they are deposited in the foramen of the alveolar ducts and absorbed by macrophages, which in response release a few products that mediate the inflammatory response and initiate fibroblast proliferation. The consequence for the lungs is the deposition of collagen – the main culprit in lung fibrosis.

Silicosis, otherwise known as silicosis, is caused by long-term inhalation of organic silica dust. It affects everyone, including drivers, working in quarries and mines, in the construction of tunnels, mine shafts and galleries, in septic masons, in the porcelain, refractory and abrasives industry and in the metallurgy industry [68]. It is caused by

inhalation of crystalline silica dust. As a result of such lung exposure, focal fibrosis of collagenous lung tissue develops.

The pathogenic effect of silica is determined by the reaching of dust particles into the lumen of the alveoli. Part of the dust penetrates through the alveolar membrane into the interstitial tissue, where macrophages are recruited, and the dust is phagocytosed. The cytotoxic properties of silica lead to damage to the cells of the immune system and the release of substances responsible for the development of lung tissue fibrosis. Pulmonary tissue fibrosis in silicosis is focal and is visible microscopically in the form of nodules of varying diameters. These nodules may cluster into larger foci, resulting in extensive nodular lesions. This, in turn, is called progressive extensive fibrosis [68].

Air pollutants, gaseous as well as particulate, can become an ecological threat to vegetation. Toxic gases, especially from engine exhaust systems, as well as dust from brake and tire wear, have a detrimental effect on their morphological development and growth characteristics as biological and physiological parameters. Particulate matter that accumulates on the leaves of shrubs, trees, and plants adversely affects both their growth and their morphology, biological and physiological parameters. The effects of such activities depend on the chemical and granulometric composition of PM and the mass retained on the leaf surface. Negative effects of PM on plants include mechanisms of blocking the stomatal apparatus and blocking light. Toxic contaminants in PM cause mechanical damage to the leaf surface [101]. A common type of particle (about 74.2%) found on the leaves of crop plants located at a considerable distance from roads was wind-blown road dust containing silica, silt, and clay. Bacteria, seeds, plant spores, pollen and leaf parts were found on plant leaves. Metallic particles were found in small amounts. About 2.2% of the particles analyzed on leaf samples were microplastics. Most of these were dark particles of nearly spherical shape from wear on the tread of car tires and the asphalt surface of the road [101].

The ability to collect dust on the leaf surface depends on the leaf structure, the presence of wax on the leaf surface, the structure of the canopy and the size of the petioles [73]. Leaves with a waxy canopy and rough surfaces and short petioles have a higher dust accumulation capacity. Dust particles have a definite effect on the biochemical parameters of the leaves, causing morphological symptoms in the leaves, which depend on the plant's tolerance for dust particles and on the chemical composition of the dust. All these factors have an impact on plant physiology. Vegetation growing along the road is particularly at risk. According to the authors of the paper [57], the dust content of the surface peat was highest closest to the road and then decreased exponentially with increasing distance from the road over a distance of up to 200 m.

Figure 29 shows two plants of the Periwinkle Thorn (Latin: *Cenchrus ciliaris*), growing near a cement plant in Saudi Arabia and a long distance from the cement plant [3]. Some differences in appearance could be seen depending on the plant's distance from the pollution source. There was an impairment of leaf development. The appearance of leaves was reduced. A drastic reduction in leaf area and leaf number was observed.

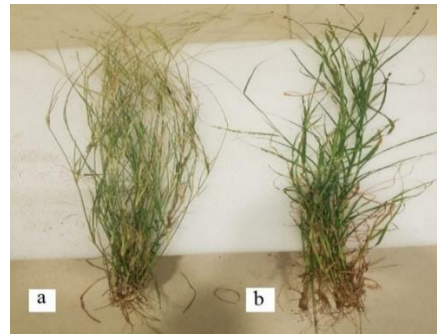


Fig. 29. Appearance of the *Cenchrus ciliaris* plant growing at different distances from the dust source: a) close to the source, b) far from the dust source (control sample) [3]

Due to the low speed of descent (0.035 m/s), silica dust grains with dimensions of $d_p = 2\text{--}10 \mu\text{m}$ persist for a long time in the air and thus are found in the air sucked into the engine cylinders. Dust particles with dimensions below $d_p = 10\text{--}50 \mu\text{m}$ is sucked up by engine intake systems when vehicles are operated in conditions where air dustiness is particularly high, such as on military training grounds, during machine operation in quarries, and in areas where construction and road work is being carried out [19].

Mineral dust sucked into the engine cylinders along with the air negatively affects the operation of the engine and its systems. First and foremost, it is the cause of accelerated wear of frictionally cooperating engine components, particularly the piston-piston-cylinder (P-PR-C) and journal-crankshaft and camshaft associations. Excessive wear of the P-PR-C association is responsible for a decrease in compression pressure, resulting in a decrease in engine power [50]. Excessive wear of the crankshaft pivot-crankshaft association is the cause of a drop in lubrication system pressure below the permissible value, which can cause a lower oil film thickness or disappearance and result in engine seizure [36]. Dust deposited on the radiator, the main component of which is SiO_2 (65–95%), forms an insulating layer that impedes the exchange of heat with the environment, which is the cause of overheating of the vehicle's engine and a decrease in power or even its failure.

An insulating layer of dust also forms on the components of the car's chassis: gearbox housing, oil pan, and hungry gear housing. This reduces the efficiency of heat dissipation from these assemblies to the environment, which raises the temperature of the lubricating oil and reduces its viscosity, worsening the conditions for oil film formation. This has a direct impact on the accelerated wear of gears. In the case of wheeled vehicles, dust can get into the suspension and steering components whose surfaces mesh. Accelerated wear then occurs in wheel rolling bearings, joints, leaf springs, steering gear components, and shock absorbers. Dust particles accelerate the wear of rubber seals, causing grease to leak from the bearings and hydraulic oil from the shock absorber cylinder. Pistons and cylinders of hydraulic or air brake spreaders are subject to similar wear.

Mineral dust grains suspended in the air settle on or hit windshields, damaging the surface, thus reducing the driver's clarity and field of vision. An airborne dust concentra-

tion of 0.7 g/m^3 limits visibility, and at 1.5 g/m^3 there is no visibility [90].

Along with the flow of inlet air into the engine cylinders, dust grains move at an average speed $v_z = 15\text{--}25 \text{ m/s}$, depending on the cross-sectional area of the inlet duct. In the inlet air to the engine, due to the air filter, there may be dust grains of less than $5 \mu\text{m}$ in size, which may strike the surface of the airflow meter measuring element, a platinum wire with a diameter of 0.07 mm . Due to the sharp edges of the grains, and most of them are silica with high hardness, the surface of the wire may be scratched, its strength weakened, and in special cases, it may break. Some of the dust grains are deposited on the measuring element, forming a layer that, due to the properties of the dust, becomes a thermal shield. Silica SiO_2 , whose dust content reaches 95%, is a good insulator. The insulating layer that is formed hinders the exchange of thermal energy between the heated element and the flowing air stream; thus, cooling the element is less intensive, resulting in a lower value of current drawn and the generation of a lower voltage value. This results in a misreading by the onboard computer of the value of the airflow required for proper engine operation, which translates into a decrease in engine power [23].

In the air supply system of a modern internal combustion engine with an ICS, the standard equipment is a supercharging device – a turbocharger. This is an assembly, the basic element of which is two rotors located in two separate channels but connected to each other by a common shaft and embedded in a single housing. The rotor (turbine) located in the engine's exhaust outflow duct obtains a speed of about 240,000 rpm, which it transmits to the compressor rotor. The speed of air arriving at the compressor blades varies in the range of $50\text{--}80 \text{ m/s}$ [24]. The high values of the peripheral speed of the compressor blades and the flowing dust grains result in a high impact force of the dust particles. Erosive wear then occurs, which is evident in the deterioration of the smoothness of the change in the geometry of the blades, which can affect the filling of the engine.

Conclusions

An extensive literature analysis has been carried out, which shows that “non-engine” dust emissions from wear of brake friction linings and brake discs, clutches, and from tire and roadway tread wear, as well as mineral dust lifted from the ground, are currently a greater threat to human health and the environment than engine emissions. The effects of road transport particulate emissions and mineral dust, the primary component of road dust, on human health, vegetation and the performance of engine and vehicle systems are presented. Road surfaces are the site of gravitational deposition of any solid pollutants in the ambient air. The accumulated pollutants are carried away again by vehicle traffic or by the wind, contributing to an increase in the total amount of particulate matter in the air, which can have serious consequences for the health of the driver and passengers.

1. The atmospheric air sucked up by internal combustion engines contains a variety of gaseous pollutants and dust (organic and inorganic) that are of natural and anthropo-

logical origin, resulting from nature, industry and motorization, with motorization being the main source of anthropogenic pollution.

2. Automotive is a source of atmospheric emissions of gaseous pollutants from the combustion of propulsion engine fuels (carbon monoxide, nitrogen oxides, hydrocarbons, sulfur oxides) and $\text{PM}_{2.5}$ and PM_{10} particulate matter, as well as emissions to the environment of “non-motor” pollutants (dust) from the wear of clutch friction linings and brake pads and car brake discs, as well as tires and road surfaces. Therefore, it is assumed that automotive pollution is the biggest threat to the environment.
3. The contribution of exhaust emissions to environmental pollution has decreased worldwide due to increasingly stringent regulations in this area and the use of modern technologies for exhaust gas cleaning (particulate filters) and the neutralization of toxic components of exhaust gases (CO , HC and NO_x) by catalytic reactors. Exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) have become important technologies for reducing NO_x emissions in heavy-duty diesel engines to meet increasingly stringent emission regulations.
4. Pollutants from “non-engine” emissions are primarily very small dust (mostly below $2.5 \mu\text{m}$), the chemical composition of which results from the materials that are components of friction discs and linings, as well as the tire tread and road surface. For this reason, non-engine particles contain harmful chemical compounds and numerous metals. Iron, copper, zinc, barium and lead are the most abundant metals present in the brake lining material. The mass fractions of elements such as potassium, titanium, copper, antimony and barium reach the level of several percent. The mass fraction of copper and barium is 13.0–17.6% and 7.3–13.2%, respectively. Other metals also occur in smaller quantities (below 0.1%), such as barium, magnesium, manganese, nickel, tin, cadmium, chromium, titanium, potassium and antimony. Metals added to friction lining materials are used to improve wear resistance, thermal resistance and strength.
5. Due to their very small particle size, “non-engine” pollutants can reach the lung alveoli after entering the respiratory system and then, through the gas exchange, enter the human bloodstream, causing deterioration of health due to harmful elements such as antimony and copper found in the materials from which brake linings and tire treads are made. Until now, non-engine emissions have received limited attention, but due to the electrification of vehicles, non-exhaust particle emissions from brake wear and tire wear are of increasing interest.
6. Dust has the widest spectrum of impacts of all air pollutants, as it negatively affects human health, vegetation, soil and water, and also contributes to global climate change and reduced visibility.

Nomenclature

CI	compression ignition	SI	spark ignition
EGR	exhaust gas recirculation	TRWP	tire-road wear particles
PM	particulate matter	TWI	tread wear indicator
P-PR-C	piston-piston ring-cylinder	TWP	tire wear particles
SCR	selective catalytic reduction		

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