Assessment of the composition of solid particle emissions from tire and roadway wear that pollute the atmosphere of large cities

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Abstract. The development of road transport has led to significant pollution of the environment, including solid particles of non-exhaust origin. These particles are among the most dangerous pollutants generated during the operation of wheeled vehicles and contribute to the development of cardiovascular and respiratory diseases in the world's population. At the same time, scientific research and legal regulation in this area are insufficient for making informed decisions to actually reduce the impact of these emissions on the environment and public health. The article presents an overview of the composition and main components of solid particles from the wear of brake mechanisms, tires and roadway, and analyzes the results of research in this field. The main tasks of scientific research of non-exhaust particulate matters emissions during the operation of wheeled vehicles are formed. The solution of these tasks should become the basis for the formation of the main directions for reducing urban environmental pollution.

1. Introduction

One of the most dangerous types of air pollution is the emissions of particulate matters (PM), which is formed during the operation of wheeled vehicles from the wear of brake mechanisms, tires and the roadway. These particles consist of a mixture of organic and inorganic substances suspended in the surrounding air. Tire dust contains 140 chemical compounds of varying degrees of toxicity, but polycyclic aromatic hydrocarbons and N-nitrosamines are particularly dangerous [1]. Air pollution by solid particles is especially dangerous for the population of large cities with significant traffic flows. At the same time, scientific research and legal regulation in this area are insufficient for making informed decisions to actually reduce the impact of these emissions on the environment and public health.

Particles with a diameter of 10 microns or less (≤PM\text{10}) can penetrate deep into the lungs, particles with a diameter of 2.5 microns or less (≤PM\text{2.5}) can directly enter the circulatory system. Long-term exposure to particulate matter contributes to the development of cardiovascular and respiratory diseases, including the formation of lung cancer [2].

Currently, a significant portion of the world's urban population is exposed to high concentrations of particulate matter, in many cases generated by the operation of wheeled vehicles. For example, Table 1 shows the percentage of the urban population in Europe that was exposed to the limit of exposure to particulate matter concentrations in the air above the existing standards of the European Union (EU) and the World Health Organization (WHO) in 2015-2017 [3].
Table 1. Percentage of the EU urban population exposed to increased particulate matter concentrations

| Particulate matter | EU regulations N 2008/50/EC | Urban population, % | WHO recommendations | Urban population, % |
|--------------------|----------------------------|---------------------|---------------------|---------------------|
| PM$_{10}$, mg/m$^3$ | 50 per day                 | 13-19               | 20 per day          | 42-52               |
| PM$_{2.5}$, mg/m$^3$ | 25 per year                | 6-8                 | 10 per year         | 74-81               |

2. Materials and methods

To assess specific emissions of solid particles of non-exhaust origin, as a rule, three approaches are used – direct measurement in the conditions of bench or road tests, computational and mixed (experimental and calculated) studies [4, 5].

Direct measurement on stands with running drums allows you to determine emissions from tire wear, but at the same time there is uncertainty associated with the difference in the coating material of the drum treadmill from the real road surface.

Direct measurement in road testing conditions allows you to determine emissions from tire and roadway wear in specific operating conditions, while the wear of the brake mechanisms and clutch can be ignored, excluding braking and gear shifting during measurements.

Calculated estimates can be carried out on the basis of averaged specific mileage emissions per unit of track, based on regulatory data on the resource or timing of replacement of car tires and the timing of repair of the roadway from the formed track.

The most objective are the measurement results obtained during road tests by sampling directly from the tire-road contact spot. The main problem in this case is the separation of emissions from tire wear and from the wear of the roadway, as well as from the resuspension of existing road dust. Partially resuspension can be eliminated by pre-cleaning the measured road section.

The following methods are used to study solid particle emissions (composition and volume concentration): gravimetric, thermogravimetric, photometric, nephelometric, turbidimetric radioisotope and microscopy methods. The main advantages and disadvantages of some of these methods are given in [6].

3. Results from monitoring studies concerning tire and road wear particles

In general, air pollution by particulate matter during the operation of wheeled vehicles can be divided into pollution from emissions of solid particles with exhaust gases from internal combustion engines (hereinafter referred to as internal combustion engines) and pollution from emissions of non-exhaust particulate matter (wear of tires, brakes and roadway). At the same time, it should be noted that the emissions of non-exhaust particulate matter have recently significantly exceeded the emissions of solid particles with exhaust gases of internal combustion engines. This is due to the fact that the parameters of exhaust gas emissions of internal combustion engines are regulated by international and national regulatory legal acts, which are periodically amended to tighten the requirements for emissions of pollutants.

At the same time, emissions of non-exhaust particulate matter, the share of which is constantly growing due to the global growth of the global fleet, are currently not regulated in any way. This is largely due to the fact that systematic research on the study of emissions of non-exhaust particulate matter from wheeled vehicles during their operation began relatively recently and there are currently no generally accepted methods for studying such emissions.

The analysis of the works concerning the non-exhaust particulate matter emissions (their sources, quantity and physico-chemical composition) showed that depending on the place and time of sampling, modes of movement of wheeled vehicles, research methods and equipment used, the results may differ significantly. The situation is complicated by the existing uncertainty associated with the variability of the composition of the materials of brake pads, tires and road surface.
Some researchers believe that non-exhaust particulate matter emissions from wheeled vehicles in the total mass of emissions are: PM$_{2.5}$ – up to 60%, and PM$_{10}$ emissions – up to 73%. At the same time, the share of PM10 particulate matter emissions in the total emissions from braking mechanisms is estimated from 3% to 16-55%. For tire wear, this figure is 5-30%. In mass equivalent (Emission Factor), PM$_{10}$ particulate emissions, depending on the driving conditions for light trucks, are: from brake wear – 2.0-8.8 mg/km, from tire wear – 3.5-9.0 mg/km, from road surface wear – 7.5 mg/km. In some researchers for brakes and tires, this figure reaches 18.2 mg/km and 13.8%, respectively. Emissions of PM$_{2.5}$, depending on the driving conditions, are: from brake wear – 2.1-5.5 mg/km, from tire wear – 3.0-7.0 mg/km [7, 8].

Another source of uncertainty is the proportion of PM$_{2.5}$ relative to PM$_{10}$. Many countries, including the United Kingdom, France, and Germany, use PM$_{2.5}$/PM$_{10}$ coefficients to determine the wear of brakes, tires, and roadway, taken from the EMEP/EEA Guidebook (Table 2) [7].

### Table 2. The coefficient PM$_{2.5}$/PM$_{10}$

|                  | PM$_{2.5}$/ PM$_{10}$ |
|------------------|-----------------------|
| Tire wear        | 0.7                   |
| Brake wear       | 0.4                   |
| Roadway wear     | 0.54                  |

At the same time, in the Netherlands, the tire wear coefficient is 0.2, and the brake and roadway wear is 0.15. This means that a much larger share of particulate emissions is accounted for by large fractions. Sweden uses a coefficient of 0.2 for all sources, while Finland uses a coefficient of 0.09 for road wear, which is mainly due to the increased use of studded tires, resulting in a higher proportion of large fraction emissions.

The composition of automobile tires includes a wide range of chemicals, which depends on the standards and production technologies of the manufacturers. An ordinary all-season passenger car tire can contain about 30 types of synthetic rubber, 8 types of natural rubber, 8 types of soot, steel cord, polyester and nylon fiber, and 40 different chemicals, waxes, oils, pigments, silica and clays. For commercial reasons, tire manufacturers rarely publish accurate tire composition data.

The chemical composition of solid particles from the wear of brake mechanisms and tires is shown in Table 3 [7].

### Table 3. The chemical composition of particulate matter

|                  | PM$_{2.5}$ | PM$_{2.5}$/PM$_{10}$ |
|------------------|------------|----------------------|
| Brake wear       | Cu, Fe, Sb (III), Sb (V), Sn, Ba, Zr, Al, S, OC>>EC | FeO, Fe$_2$O$_3$, oxides Cu, Sb (III), Sn (V), Sn, Ba, Zr, Al |
| Tire wear        | Zn, Cu, Si, Si, EC, organic carbon | Zn, Cu, Si, Mn |

Within the framework of the Working Group on Energy and Environmental Pollution (Working Group) of the UNECE World Forum for Harmonization of Vehicle Regulations (the World Forum), an international methodology for studying particulate emissions from brake wear is currently being finalized. In the 4th quarter of 2021, the draft methodology is planned to be presented for discussion at the World Forum [9].

Measuring particle emissions generated by the interaction between tires and road was considered much more challenging due to the difficulty of distinguishing the contributions from tires, material deposited on the road and the road itself. In the meantime the EC has proposed in its European on the Move III initiative (Third Mobility Package) to develop a standard methodology to measure the abrasion rate of tires in view of a possible future labelling scheme. This methodology will be
developed through a process still under discussion, but in any case – without the direct involvement of the Working Group. The Working Group proposes to continue monitoring all information relevant to tire and road wear particles and once the abrasion rate methodology is developed, to investigate the possibility of establishing a relationship between different abrasion rates and particle emissions [10].

4. Conclusion
The main source of ambient air pollution by particulate matter in the operation of wheeled vehicles is non-exhaust particulate matter emissions, with PM$_{2.5}$ emissions accounting for 60%, PM$_{10}$ emissions for 73% of the total volume of these emissions from all sources associated with road transport.

The chemical and particle size distribution, as well as the volume concentration of particulate emissions from the wear of brakes, tires, and roadway, vary widely depending on the material and construction of brakes, tires, road surface, and the type and mode of movement of vehicles. At the same time, the separation of particulate emissions by source of origin is quite a difficult task.

In 2021 the development of an international methodology for studying the emissions of solid particles from the wear of brake mechanisms formed during the operation of wheeled vehicles is being completed.

Methods for determining the mass concentration (mcg/g) and mass fraction (%) of tire and road wear particles in the air are described by ISO/TS 20593: 2017.

EC has proposed in its European on the Move III initiative (Third Mobility Package) to develop a standard methodology to measure the abrasion rate of tires in view of a possible future labelling scheme.

It seems necessary to develop a methodology that allows one to determine the emissions of solid particles from tire wear and roadbed separately by the source of origin.

This methodology should become the basis for the formation of the main directions for reducing urban environmental pollution.

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