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Krystian Szczepański*, Zdzisław Chłopek**, Hubert Sar**, Magdalena Zimakowska-Laskowska*

Analysis of Pollutant Emission in Poland From Road Vehicles of the Generalised Category in Accordance With the Vehicle Application Criterion

* Institute of Environmental Protection – National Research Institute, 5/11D Krucza Str., 00-548 Warsaw, Poland
** Institute of Vehicles and Construction Machinery Engineering, Warsaw University of Technology, 84 Narbutta Str., 02-524 Warsaw, Poland
e-mail: krystian.szczepanski@ios.edu.pl

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Abstract
This paper presents the results of analyses that were focused on pollutant emissions from road vehicles classified into the generalised categories with respect to vehicle use. The analyses were performed using the authorised results of Poland's pollutant emission inventory, carried out in 1990–2020 by the National Centre for Emissions Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute (IOŚ-PIB) in order to meet requirements for the national emissions reporting under EU legislation and the UNECE Convention on Long-range Transboundary Air Pollution. The following road vehicle categories were analysed: passenger cars, light duty vehicles, heavy-duty trucks, buses (urban buses and coaches) and L category (motorcycles, mopeds, quads, microcars). The emissions of selected pollutants that are harmful to the health of living beings were studied, i.e. nitrogen oxides, non-methane volatile organic compounds, sulfur compounds, particulate matter size fractions, carbon monoxide and lead compounds. The shares of national annual pollutant emissions from each studied vehicle category of the total pollutant emissions from road transport were determined. With the aim to assess trends in improving environmental properties of road vehicles, there were determined changes of the energy emission factors for individual pollutants in all the vehicle categories under the study. The results obtained showed dynamic decreases in the energy emission factors for nitrogen oxides, non-methane volatile organic compounds and carbon monoxide. In the case of particulate matter emission, the improvement was not as pronounced. The evident reduction in the emissions of sulfur and lead compounds in the 21st century was confirmed to be a consequence of practical elimination of these compounds from road vehicle fuels.

1. INTRODUCTION

The aim of this study was to assess the contribution of pollutant emissions from road vehicles as they are classified into the generalised categories with respect to the total pollutant emissions from road transport.
The authorised results of the national pollutant emission inventory carried out by the National Centre for Emissions Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute (IOŚ-PIB) were used in the analyses carried out. The reports from KOBiZE [Poland's Informative Inventory Report 2021] comprise the data on air pollutant emissions required for reporting under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) [LRTAP Convention] and European Union legislation. These data are compliant with the Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC (the EU National Emission Ceilings Directive). Besides, data included in the reports prepared by KOBiZE are used in the reports prepared by Statistics Poland (GUS).

2. SCOPE OF ANALYSIS OF POLLUTANT EMISSIONS FROM ROAD VEHICLES

The analyses of pollutant emissions from road vehicles in Poland were carried out with respect to:
– categories of road vehicles,
– sources of pollutant emissions,

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– substances (emissions of which were examined under this study),
– period of emission testing,
– characteristics of road vehicles and their working conditions.

Categorisation is the concept of philosophy: introducing a structure. A category is a class of objects which have certain characteristics and are connected through mutual relationships. The road vehicle categories were created according to certain criteria, and primarily with regard to [Bebkiewicz et al. 2020; Chłopek et al. 2018; EEA/EMEP Emission Inventory Guidebook 2019; Poland's Informative Inventory Report 2021]:
– use,
– conventional size,
– characteristics,
– fuel,
– technical level.

The elementary category of road vehicles is the set of vehicles with all the same criterion characteristics. The cumulative category of road vehicles is the set of vehicles with not all the same criterion characteristics. The supreme cumulative category of road vehicles comprises all road vehicles.
According to their uses, road vehicles are most commonly classified into the following categories [Bebkiewicz et al. 2021b; Bebkiewicz et al. 2021a; Bebkiewicz et al. 2020; Chłopek et al. 2018; EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021; Poland's Informative Inventory Report 2021]:
– passenger cars,
– light duty vehicles,
– heavy-duty trucks,
– buses: urban buses and coaches,
– L category: motorcycles, mopeds, quads and microcars.

The criteria applied in the categorisation of road vehicles with respect to the conventional size are typically [Bebkiewicz et al. 2021b; Bebkiewicz et al. 2021a; Bebkiewicz et al. 2020; EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021; Poland's Informative Inventory Report 2021]:
– the displacement of the internal combustion engine for the so-called light vehicles, i.e. passenger cars, light duty trucks and the volume of the internal combustion engine for L-category vehicles,
– the maximum vehicle mass (for heavy vehicles, i.e. heavy-duty trucks and buses),
– the comparison of the maximum mass of an electrically propelled vehicle and the maximum mass of a vehicle powered by an internal combustion engine (for electric vehicles).

Regarding vehicle characteristics, several detailed classification criteria can be used, such as [Bebkiewicz et al. 2021b; Bebkiewicz et al. 2021a; Bebkiewicz et al. 2020; Chłopek et al. 2018; Directive (EU) 2016/2284; Emissions of air pollutants from transport. EEA. 2021; Poland's Informative Inventory Report 2021]:
– drive: internal combustion engine, electric motor or hybrid,
– mode of internal combustion engine cooling: direct and indirect,
– thermal cycle: two-stroke and four-stroke,
– ignition: compression ignition and positive ignition.

With respect to fuel, road vehicles are usually classified in line with the fuel types used to generate engine power [Bebkiewicz et al. 2021b; Bebkiewicz et al. 2021a; Bebkiewicz et al. 2020; Chłopek et al. 2018; EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021; Poland's Informative Inventory Report 2021]:
– motor gasoline, with its additional detailed characteristics,
– diesel oil, with additional specific features,
– liquefied petroleum gas[1],
– methane fuels: natural gas and biomethane,
– biogas fuel,
– hydrogen as a fuel and as an energy carrier[2],
– fuels of biological origin.

The technical level of road vehicles is determined by the requirements related to pollutant emissions; in European countries these are popularly called 'euro levels' [DieselNet: Engine & Emission Technology 2022; INFRAS AG. Handbook emission factors for road transport 2014; Worldwide emission standards 2020/2021].
During this study, the generalised categories of road vehicles were analysed in terms of their use [Poland's Informative Inventory Report 2021]:
– passenger cars,
– light duty trucks,
– heavy-duty trucks and buses,
– L category: motorcycles, mopeds, quads and microcars,
– all road vehicles.

In the categories 'passenger cars' and 'light duty trucks', there are classified vehicles powered by spark ignition engines, compression ignition engines, electric motors and combustion-electric hybrids with the vast majority of spark ignition engines. The light duty truck category has a much higher proportion of vehicles with compression ignition engines than that in the passenger car category. In the two

1 To denominate gaseous fuels, it is customary to apply the names of raw materials used for the production of these fuels. Thus, the term liquefied petroleum gas (LPG) is used for a fuel produced from liquefied petroleum gas. The same applies to natural gas and biogas. Biomethane is accepted as a fuel from biogas that was purified to achieve the standard of the fuel derived from natural gas.
2 Hydrogen used to power fuel cells is not formally a fuel as there occurs no combustion in the fuel cell. Hydrogen used to power the fuel cell is an energy carrier. Fuels are a subset of the set of energy carriers.

categories 'heavy-duty trucks' and 'buses', compression ignition engines solely are used. In the category 'buses', especially in the case of urban buses, electric drives and diesel-electric hybrid drives are also used. The vehicles from L category use mainly spark ignition engines, and a considerable quantity of mopeds are equipped with two-stroke engines. In mopeds and microcars, electric motors are also used, though rarely in motorcycles and quads.
The emission sources taken into account in this study were [EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021; Poland's Informative Inventory Report 2021]:

- exhaust system of internal combustion engine,
- additionally, the vehicle fuel system, from which fuel vapours are emitted (in the case of emission of non-methane volatile organic compounds),
- additionally, wear of brakes and tires as well as abrasion of the road surface (in the case of particulate matter emission).

The substances analysed under this study are listed in Table 1. The choice of substances was driven by the factors specified in the following. The selected substances are harmful to health of living beings. Some of them are substances the emissions of which are subject to testing in approval procedures associated with pollutant emissions [DieselNet: Engine & Emission Technology 2022, Worldwide emission standards 2020/2021; Worldwide emission standards 2016/2017]. The group of substances selected for the analyses were nitrogen oxides, non-methane volatile organic compounds and particulate matter (under the national emission inventory examined in detail in terms of particle conventional size – as PM2.5, PM10 and as total suspended particulate matter (TSP)). Additionally, the emissions dependent on pollutant contents in fuel were analysed. The latter included sulfur compounds and lead compounds.
The period of the study on pollutant emissions from road vehicles in Poland covered the years 1990–2020, which overlapped with the period of authorised reporting on the national pollutant emissions.
The following characteristics of road vehicles and their operating conditions are included in the COPERT model (Computer Programme to Calculate Emissions From Road Transport), used for modelling pollutant emissions:

- number of vehicles in specific elementary categories,
- annual mileage in specific elementary categories,
- share of road travelled by vehicles from specific categories under the following conditions: congested streets, non-congested streets in cities, rural roads and highways,
- average speed of vehicles from specific categories under the following conditions: congested streets, non-congested streets in cities, rural roads and highways,
- minimum and maximum air temperature in the months of the year,
- distance travelled by the vehicle after cold start.

Table 1. Substances: The study subject with respect to their emission

Substance
Nitrogen oxides (NOx) as nitrogen dioxide - NO_2
Non-methane volatile organic compounds - NMVOC
Sulfur oxides (SOx) as sulfur dioxide - SO_2
Particulate matter - PM2.5
Particulate matter - PM10
Total suspended particulate matter - TSP
Carbon monoxide - CO
Lead compounds as lead - Pb

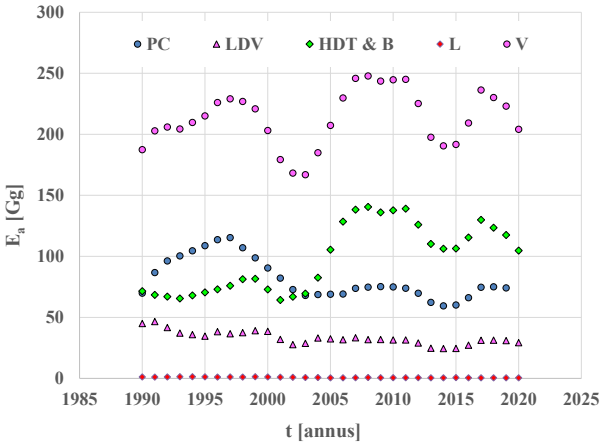


Figure1. National annual emission - E_a of nitrogen oxides - NO_x for road vehicle categories: PC - passenger cars, LDV – light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

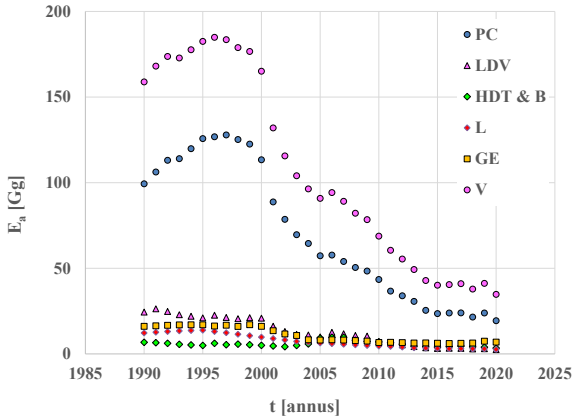


Figure 2. National annual emission - E_a of non-methane volatile organic compounds – NMVOC, for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, GE - fuel vapours

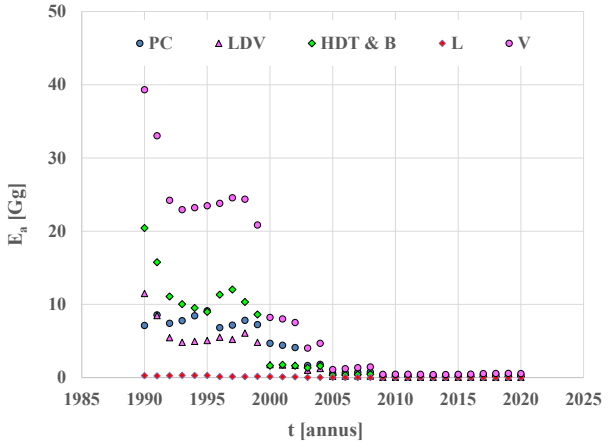


Figure 3. National annual emission - E_a of sulfur oxides - SO_x for road vehicle categories: PC - passenger cars, LDV – light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

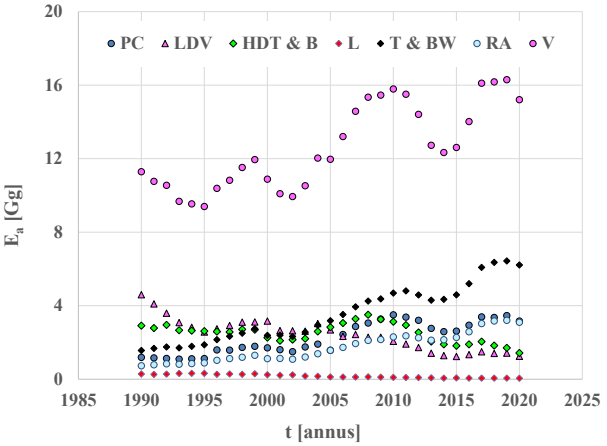


Figure 5. National annual emission - E_a of PM10 for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

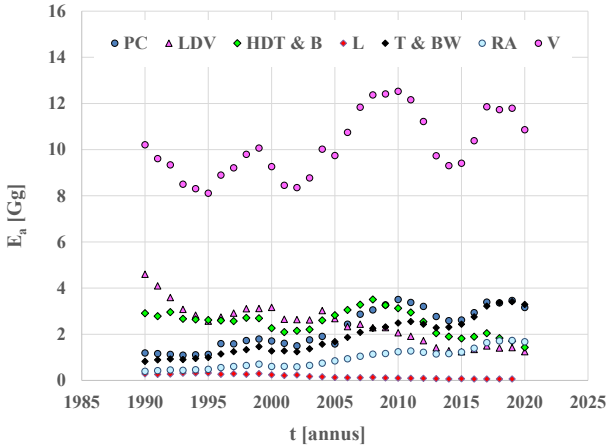


Figure 4. National annual emission - E_a of PM2.5 for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

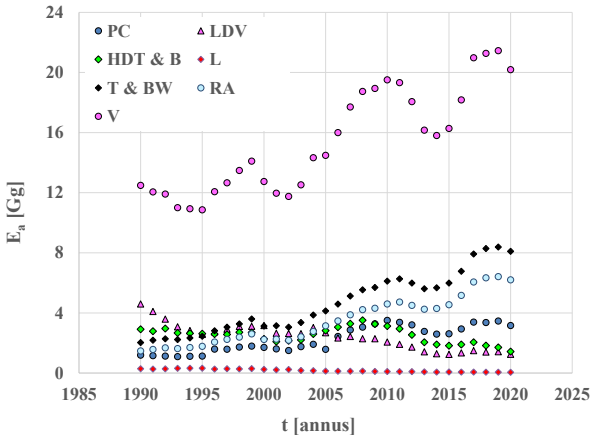


Figure 6. National annual emission - E_a of total particulate matter - TSP for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

The values for the above characteristics are adopted as officially binding in the reports prepared by KOBiZE.

3. CHANGES IN ANNUAL EMISSIONS FROM ROAD VEHICLES IN POLAND IN THE YEARS 1988-2020

Figures 1–8 show changes in annual emissions (E_a) from specific categories of road vehicles for each pollutant analysed.

Figures 9–16 show changes in the shares of national annual emissions of the analysed pollutants from different road transport categories and emission sources, in the period 1990–2020.

The annual emission of pollutants is an extensive quantity a linear function of the increasing number of vehicles of the considered category and the intensity of their use, the measure of which is the annual mileage [Bebkiewicz et al. 2020; Chłopek et al. 2018]. The annual emission of pollutants is also a function of the specific distance emission of pollutants, which is a zero-dimensional characteristic—a derivative of the emission of pollutants from a vehicle with respect to the distance travelled by this vehicle. The specific distance emission depends on vehicle characteristics, and in particular, on the engine type, fuel

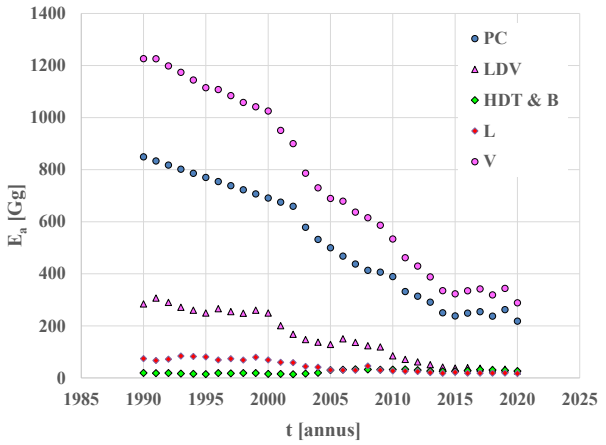


Figure 7. National annual emission - E_a of carbon monoxide - CO for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

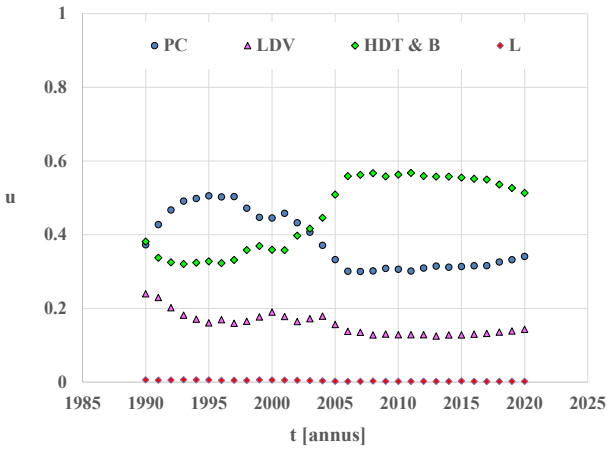


Figure 9. Shares of national annual emission – u of nitrogen oxides - NO_x for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

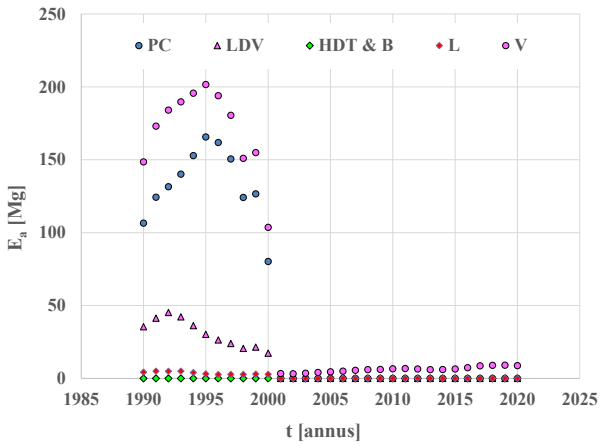


Figure 8. National annual emission - E_a of lead compounds - Pb for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

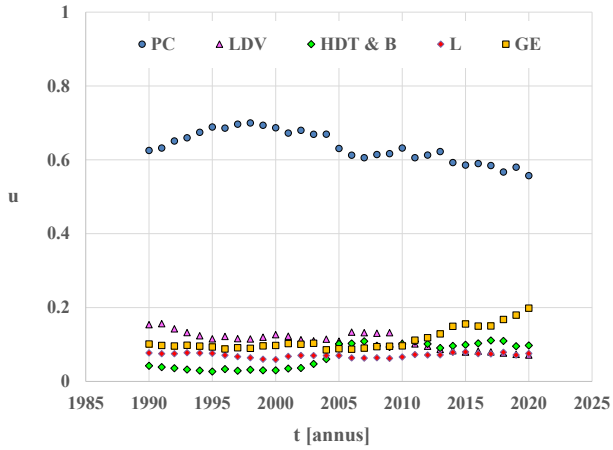


Figure 10. Shares of national annual emission - u of non-methane volatile organic compounds - NMVOC for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, GE - fuel vapours

properties and vehicle operating conditions, primarily in relation to weather conditions and terrain as well as traffic organisation. Vehicle and fuel properties are included in the classification of vehicles into the elementary categories [EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021]. The average values of minimum and maximum air temperature are parameters included in the COPERT model. The topography and traffic organisation determine vehicle movement patterns, qualified as: congested driving, non-congested driving under urban conditions, rural driving, and highway and expressway driving [Bebkiewicz et al. 2021b; COPERT; EEA/EMEP Emission Inventory Guidebook 2019; Emissions of air pollutants from transport. EEA. 2021]. The quantity that characterizes the driving model is the average value of velocity [Bebkiewicz et al. 2021b; COPERT]. Additionally, the model parameters are the shares of the length of roads travelled by a vehicle in each traffic model, in the total lengths of roads in all models [COPERT].

The observed changes in national annual emissions vary depending on the pollutant (substance) analysed. The changes in the annual national emissions of non-methane volatile organic compounds and carbon monoxide are the most explicit. There are two regularities in these cases. The first regularity results from the fact that passenger cars are the dominant source of emissions, mainly due

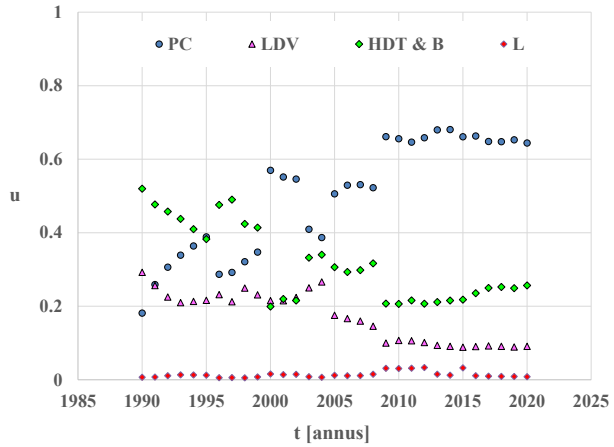


Figure 11. Shares of national annual emission - u of sulfur oxides - SO_x for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

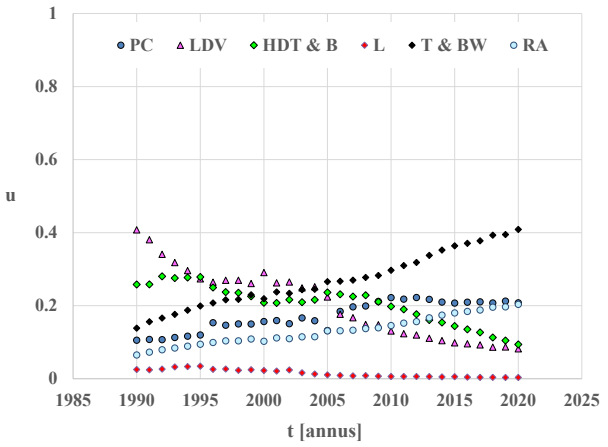


Figure 13. Shares of national annual emission – u of PM10 particulate matter for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW – tire and brake wear, RA - road surface abrasion

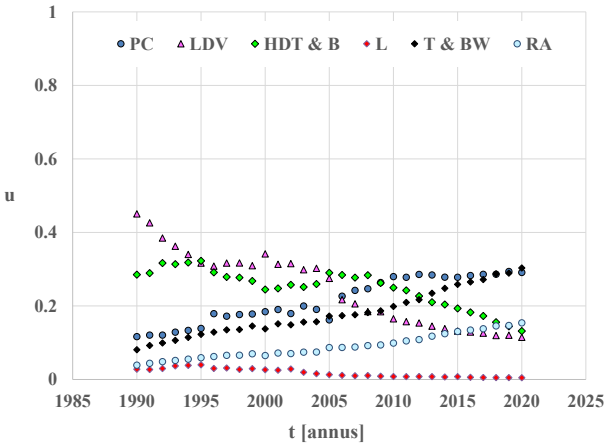


Figure 12. Shares of national annual emission - u of PM2.5 for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T&BW - tire and brake wear, RA - road surface abrasion

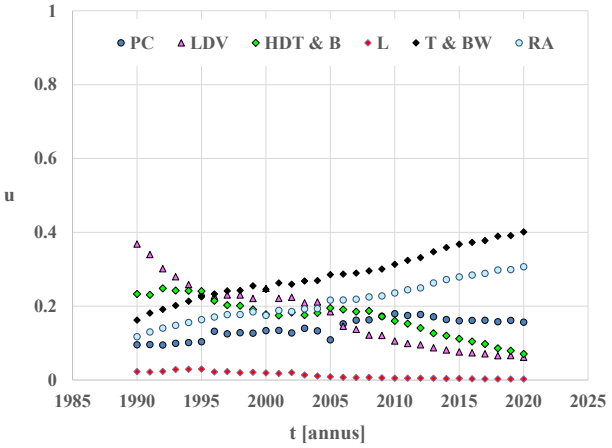


Figure 14. Shares of national annual emission - u of total suspended particulate matter - TSP for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

to the prevalent use of spark ignition engines. Light duty vehicles are the next dominant emission source. The second regularity is associated with a downward tendency in the annual national emission of carbon monoxide observed since 1990, and that of non-methane volatile organic compounds observed since the last years of the 20th century, even though the number of vehicles and intensity of their use have continued to grow dynamically. Decreasing emissions result from substantial technical progress achieved, particularly in the case of spark ignition engines - first of all, precise control of the fuel mixture ratio as a result of replacement of the carburettor systems by the injection systems as well as considerable improvement of the effectiveness of catalytic exhaust after-treatment systems [Parthiban, Pazhanivel 2016; Subramanian et al. 2020; Worldwide emission standards 2020/2021].

The trend in nitrogen oxide emissions is not as pronounced. In this case the downward tendency has been observed for passenger cars since the last years of the 20th century, which is also a result of significant improvement in the effectiveness of catalytic reduction of nitrogen oxides in spark ignition engines owing to widespread application of multifunctional catalytic reactors [Parthiban, Pazhanivel 2016; Subramanian et al. 2020; Worldwide emission standards 2020/2021]. In the case of compression ignition engines, the reduction of nitrogen oxides is a much more

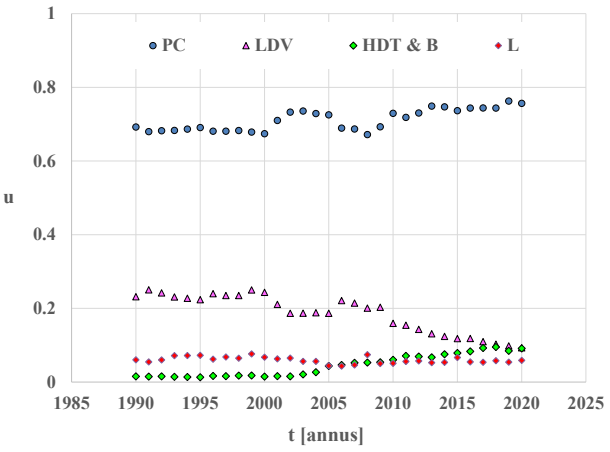


Figure 15. Shares of national annual emission - u of carbon monoxide - CO for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

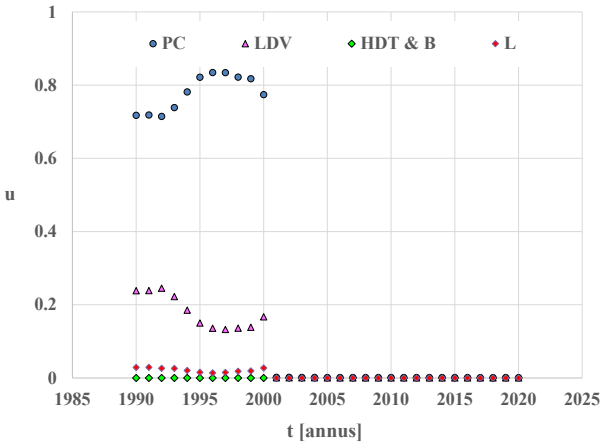


Figure 16. Shares of national annual emission - u of lead compounds - Pb for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

difficult task, due to the fact that such engines burn lean mixtures. For this reason, since the beginning of 21st century, the dominant source of nitrogen oxide emissions has been heavy-duty trucks and buses equipped with compression ignition engines.

In the case of particulate matter, a clear tendency is observed for an increase in the share of its emissions from sources other than combustion engines: from friction pairs and abrasion of road surfaces. This tendency results from very important technical advancements in the reduction of particulate matter emissions from internal combustion engines, first and foremost - compression ignition engines, due to widespread application of particulate matter catalytic filters [Brahma 2012; Liu et al. 2008]. Then again, particulate matter emissions associated with tire wear and the road surface abrasion are difficult to reduce as these are related to tyre/road adhesion, and in this context, safety considerations undeniably come first.

In the case of sulfur and lead compounds, a rapid decrease in their national annual emissions, observed since the beginning of the 21st century, is related to the radical reduction of lead and sulfur contents in fuels for road vehicle engines. The significant reduction in the contents of sulfur and lead compounds in fuels was driven by the need to ensure the effectiveness and durability of catalytic exhaust after-treatment systems. As a result, there is also an obvious benefit in the form of reduced emissions of these pollutants which are dangerous to the environment, and, especially, to the health of living beings.

4. ANALYSIS OF ENVIRONMENTAL QUALITY OF ROAD VEHICLES WITH RESPECT TO POLLUTANT EMISSIONS IN 1988–2020

From among the zero-dimensional characteristics of pollutant emissions as they apply to the environmental impacts of vehicles from the designated categories, energy emission factors were taken into account [Chłopek et al. 2018]. The energy emission factor is a derivative of the pollutant emission against the energy consumed by the vehicle. The reason behind choosing such a characteristic is as follows: it is problematic to associate pollutant emissions with the mass of fuel consumed in the case of the analysed cumulative categories of road vehicles, and different fuel types are used. For instance, there is gasoline—for spark ignition engines and diesel oil—for compression ignition engines. Nonetheless, energy equivalents can be generally used for fuels consumed and other drive systems (chiefly electric drives). In fact, in the case of electric drives, in the emission inventory, the issue of taking into account pollutant emissions in connection with electricity generation and distribution remains unsolved. For the time being, this problem has not been appropriately addressed. On the other hand, admittedly, the share of pollutant emissions due to electric energy generation and distribution for road vehicle drives has not so far been substantial due to a relatively small proportion of electric road vehicles in the whole category of road vehicles. However, as the electrification of road transport develops, it will be necessary to modify the global emission models.

Figures 17–24 show changes in the energy emission factors for the analysed pollutants from each road transport category and emission sources under this study, in the period of 1990–2020.

In the case of nitrogen oxides, non-methane volatile organic compounds and carbon monoxide, the energy emission factors show clear downward tendencies. This is a result of the dynamic technical progress of road vehicles, mainly the application of effective methods to reduce pollutant

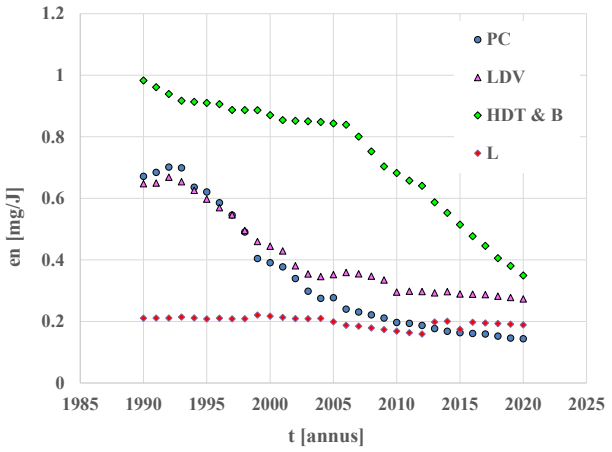


Figure 17. Energy emission factor for nitrogen oxides - NO_x for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

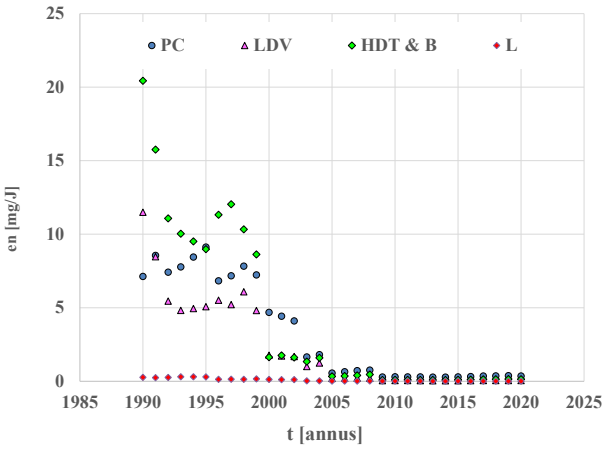


Figure 19. Energy emission factor for sulfur compounds - SO_x, for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

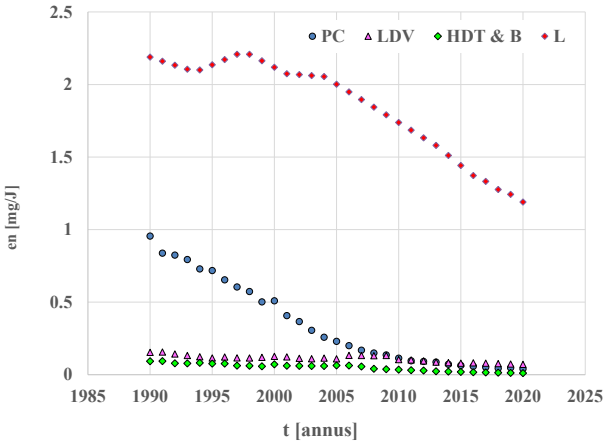


Figure 18. Energy emission factor for non-methane volatile organic compounds – NMVOC, for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, GE - fuel vapours

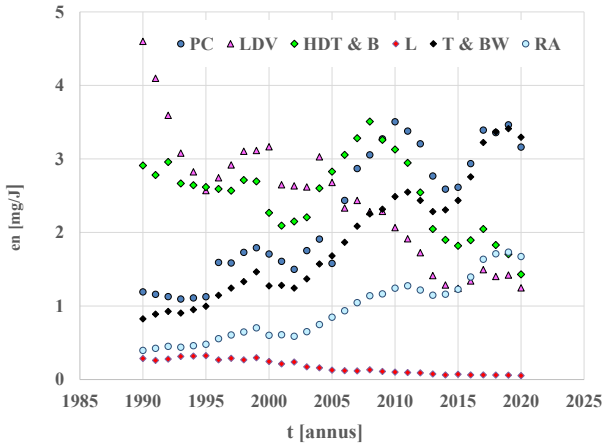


Figure 20. Energy emission factor for PM2.5, for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

emissions from internal combustion engines [Latha et al. 2019; Liu, Gao 2011; Parthiban, et al. 2016; Subramanian, et al. 2020 Subramanian; Worldwide emission standards 2020/2021; Worldwide emission standards 2016/2017].

There is a clear tendency that the value of the energy emission factor for nitrogen oxides is much higher for heavy-duty trucks and buses than that for other categories studied. This is a result of greater difficulties in reducing the emission of nitrogen oxides from compression ignition engines as compared to spark ignition engines [Latha et al. 2019; Liu, Gao 2011; Worldwide emission standards 2020/2021; Worldwide emission standards 2016/2017].

In the case of non-methane volatile organic compounds, the highest energy emission factor is observed for vehicles in the category L, which is related to a considerable share of vehicles with two-stroke engines in this category.

As far as the categories containing heavy-duty trucks and buses are concerned, it is noteworthy that the energy emission factors for carbon monoxide and non-methane volatile organic compounds are the lowest. This is due to the fact that compression ignition engines powering the vehicles in this category run on lean mixtures.

Regarding emissions of particulate matter, energy emissions factors are increasing in the case of emission sources other than combustion engines—from the friction pairs and from road surface abrasion.

Evidently, in the case of lead and sulfur compounds, the energy emission factors have been decreasing since the

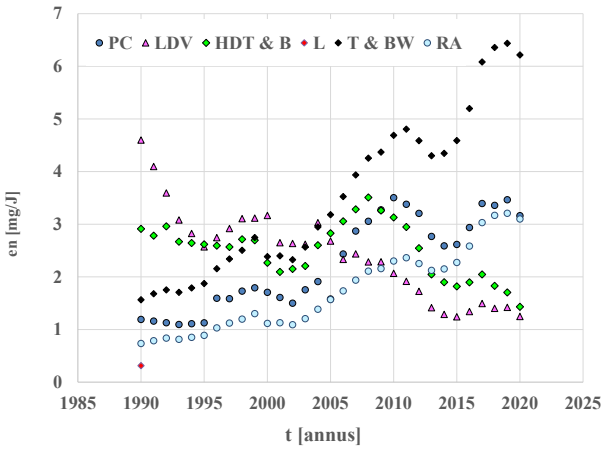


Figure 21. Energy emission factor for PM10, for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

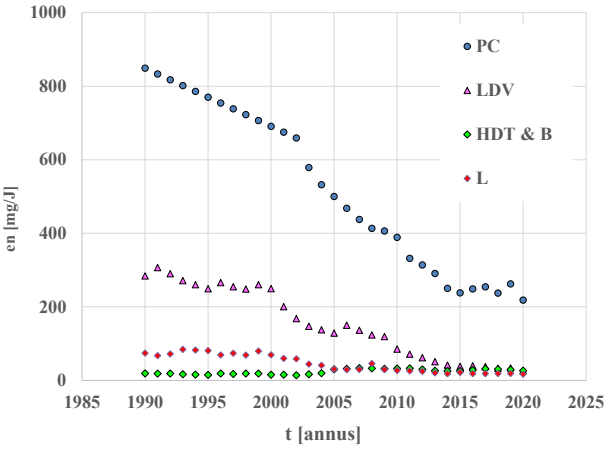


Figure 23. Energy emission factor for carbon monoxide – CO, for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

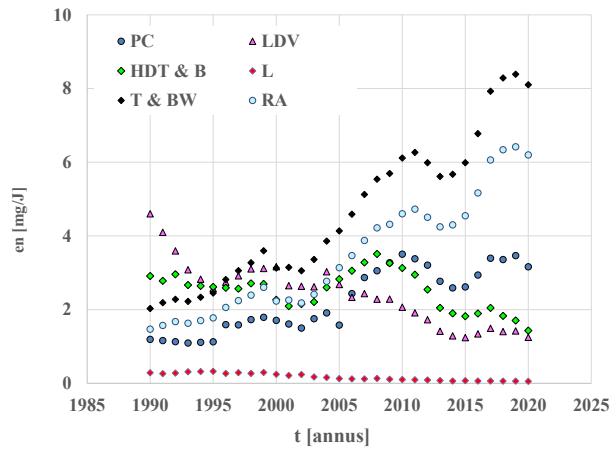


Figure 22. Energy emission factor for total suspended particulate matter – TSP, for emission sources: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles, T & BW - tire and brake wear, RA - road surface abrasion

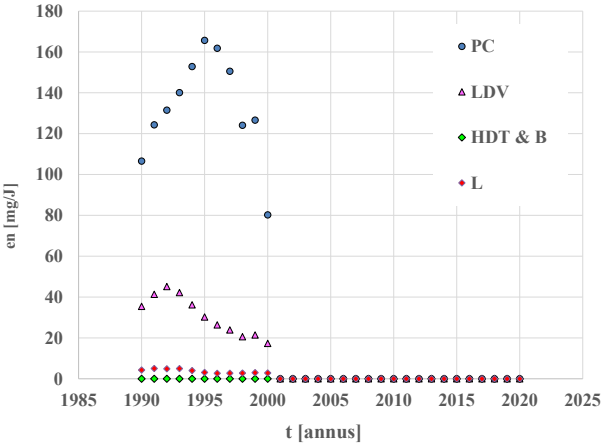


Figure 24. Energy emission factor for lead compounds – Pb, for road vehicle categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, V - road vehicles

beginning of the 21st century, due to a radical reduction of the content of these substances in fuels.

5. CONCLUSIONS

The most important concise conclusion of the present study refers to the overall trend of gradual decrease in the national annual pollutant emissions, observed in the majority of cases analysed in the successive study years, irrespective of very dynamic development of road transport in Poland in 1990–2020 and regardless the fact that the annual pollutant emission is a linear function of the growing number of road vehicles and their annual mileage. Figure 25 shows the national annual energy consumption by road vehicles.

Notwithstanding such dynamic development of road transport, the emission of pollutants from road vehicles has been decreasing. This is mainly a result of very large technical progress in the construction of motor vehicles. A particular advancement is the application of new methods to reduce pollutant emissions using catalytic exhaust after-treatment systems.

Figures 26–29 present specific distance emission limits for selected pollutant emissions from passenger cars and light duty vehicles, as well as the specific brake emission of pollutants from heavy-duty trucks and buses [DieselNet:

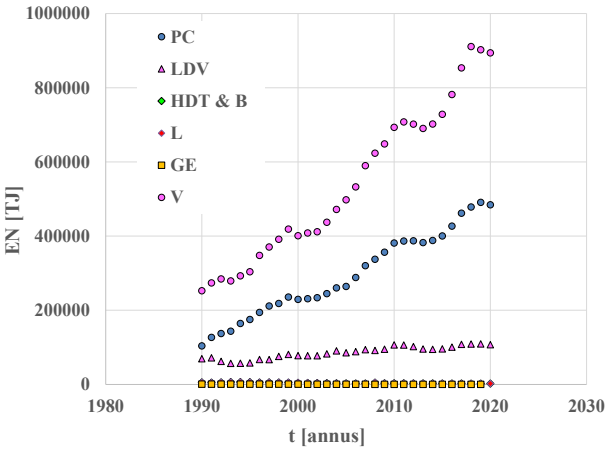


Figure 25. National annual energy consumption by road vehicles in the cumulative categories: PC - passenger cars, LDV - light duty vehicles, HDT & B – heavy-duty trucks and buses, L - category L, GE - fuel vapours, V - road vehicles

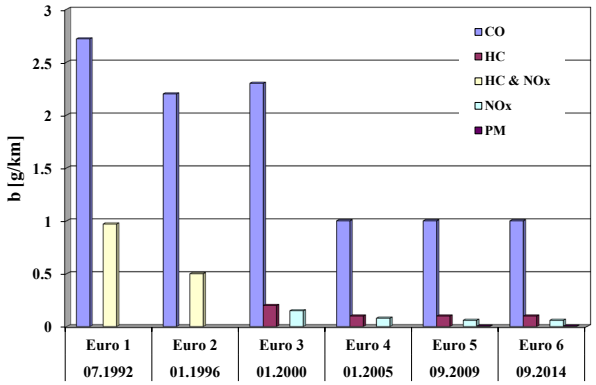


Figure 26. Specific distance emissions limits for pollutants from passenger cars and light duty vehicles with spark ignition engines

Engine & Emission Technology 2022; Worldwide emission standards 2020/2021; Worldwide emission standards 2016/2017].

In the approval procedures, the test objects are [DieselNet: Engine & Emission Technology 2022; Worldwide emission standards 2020/2021; Worldwide emission standards 2016/2017]:

- vehicles (in the case of passenger cars and light duty vehicles),
- internal combustion engines (in the case of heavy-duty truck and bus engines).

It is noteworthy that partially different terminology is used to denote the substances included in the emission inventories and in the approval tests for internal combustion engines. In the engine tests, organic compounds are referred to as hydrocarbons and named HC for the reason that exhaust gas analysers are characterised in terms of organic compounds with hydrocarbons. Particulate matter in engine tests is labelled PM and corresponds with the term. Total suspended particulate matter was used in the emissions inventory.

The axes of the independent variable show the numbers of successive versions of the approval regulations and the dates of their introduction.

For passenger cars and light trucks, the following tests are used [DieselNet: Engine & Emission Technology 2022; Worldwide emission standards 2020/2021]:

- ECE R83 (Emission Test Cycles - Regulation 83) with exhaust sampling for analysis after 40 s - for Euro I and Euro II,
- ECE R83 with collection of the exhaust gas for analysis immediately after starting the engine - for Euro III–Euro VI,
- WLTC (Worldwide Harmonized Light Vehicles Test Cycle) - since 01.09.2017.

For heavy-duty truck and bus engines, the following tests are used [DieselNet: Engine & Emission Technology 2022; Worldwide emission standards 2016/2017]:

- ECE R49 (Emission Test Cycles - Regulation 49) - for Euro I and Euro II,
- ESC (European Steady Cycle) - for Euro III–Euro V,
- ETC (European Transient Cycle) - for Euro III–Euro V,
- WHSC (World Harmonized Stationary Cycle) - for Euro VI,
- WHTC (World Harmonized Transient Cycle) - for Euro VI.

In the graphs below, there can be observed a specific differentiation of substances, whose zero-dimensional emission characteristics are limited:

- for passenger cars and light duty vehicles with spark ignition engines from the Euro I and Euro II stages, the sum of the specific distance emissions of hydrocarbons (HC) and nitrogen oxides (NO_x) and for Euro 3 onwards, there are separate limits for the specific distance emissions of hydrocarbons and the specific distance emissions of nitrogen oxides;
- for passenger cars and light duty vehicles with compression ignition engines, the sum of the specific distance emissions of hydrocarbons and nitrogen oxides;
- in addition, for engines of heavy-duty trucks and buses from the Euro V stage, there the particle number (PN) emissions are also limited, yet, the limits are the same for Euro V and Euro VI.

At the Euro II level, there are different specific distance emissions limits for indirect injection (IDI) and direct injection (DI) compression ignition engines.

At the Euro I level, two sets of limits are introduced, depending on the rated engine power: Euro Ia - for engines with rated power of 85 kW or less and Euro Ib for engines with rated power of more than 85 kW.

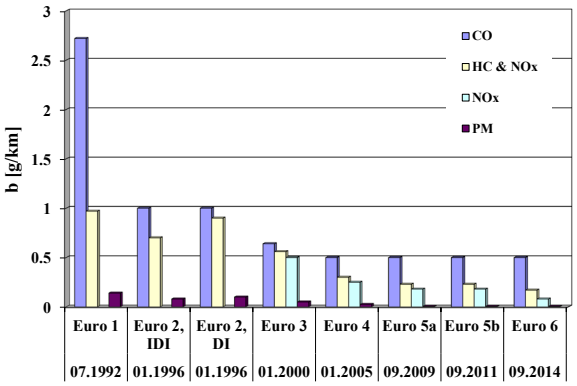


Figure 27. Specific distance emissions limits for pollutants from passenger cars and light duty vehicles with compression-ignition engines

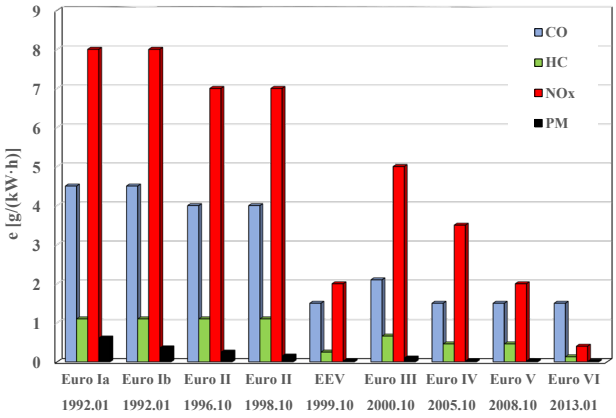


Figure 28. Specific brake emission limits in static tests on heavy-duty trucks and buses

In engine testing for heavy-duty trucks and buses, a special category, EEV (Enhanced Environmentally Friendly Vehicle) was introduced in 1999 [DieselNet: Engine & Emission Technology 2022; Worldwide emission standards 2016/2017]. These are vehicles with particularly good characteristics in terms of emissions, used mainly in places with very high risk for people, i.e. in urban centres. EEV vehicles are predominantly urban buses, usually with spark ignition engines powered by natural gas. EEC vehicle engines, therefore, have the specific brake emission limits in static tests lesser than those for Euro V limits.

Likewise, in the dynamic tests, the engines of EEC vehicles have specific brake emission limits lesser than those for Euro V.

As can be seen in the graphs, as successive stages of the regulations are introduced, there occurs a significant reduction in the limits of the quantities characterising pollutant emissions. This is particularly true for the emissions of nitrogen oxides and particulate matter from compression ignition engines of heavy-duty trucks and buses.

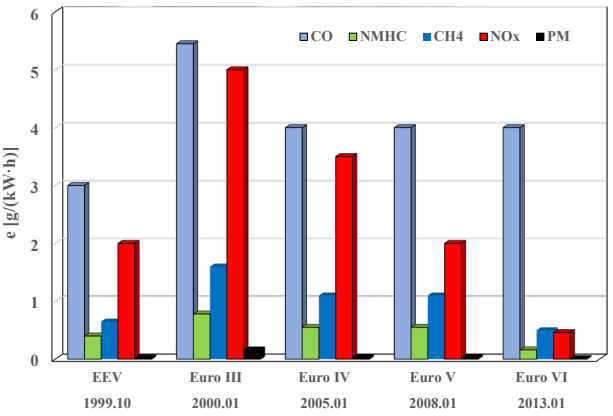


Figure 29. Heavy-duty truck and bus specific brake emission limits in dynamic tests

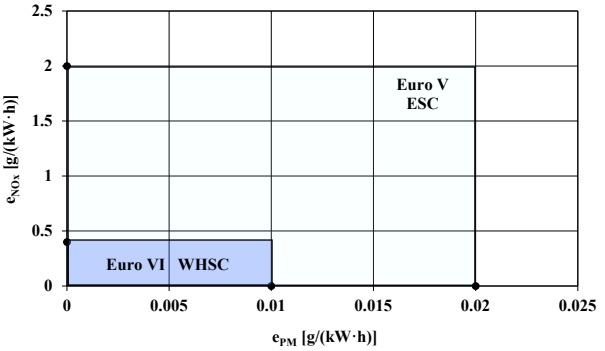


Figure 30. Specific brake emission values for nitrogen oxides and particulate matter from compression ignition engines of heavy-duty trucks and buses in static tests: ESC for Euro V regulation level and WHSC for Euro VI regulation level

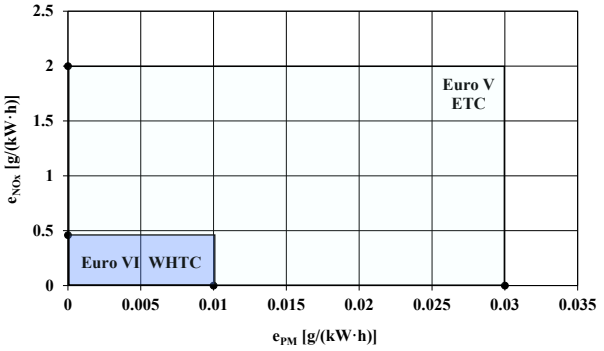


Figure 31. Specific brake emission values for nitrogen oxides and particulate matter from compression ignition engines of heavy-duty trucks and buses in dynamic tests: ETC for Euro V regulation level and WHTC for Euro VI regulation level

Figures 30 and 31 present, in a schematic form, the values of specific brake emissions of nitrogen oxides and particulate matter from compression ignition engines of heavy-duty trucks and buses under in static tests: ESC for Euro V regulation level and WHSC for Euro VI regulation level, and in dynamic tests, ETC for Euro V and WHTC VI regulation level.

The difference in characteristics for the levels of regulations is clearly visible. The consequence of such a big difference between the binding limits of values characterising the emission of pollutants is the necessity to introduce to the market new vehicles with good environmental properties, which will result in a decrease in the annual emission of pollutants from road vehicles, notwithstanding the dynamic increase in their number and intensity of use.

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