


Article

The Inventory of Pollutants Hazardous to the Health of Living Organisms, Emitted by Road Transport in Poland between 1990 and 2017

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Abstract: The paper provides the results of the inventory of pollutants hazardous to the health of living organisms, emitted by road transport in Poland between 1990 and 2017. For estimating pollutant emissions from road transport, a standardized methodology was applied, consistent with the guidance of EEA/EMEP Emission Inventory Guidebook 2019 and the COPERT 5 software. The following substances were analyzed: carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x) and particulate matter size fractions (total suspended particles—TSP, PM₁₀, PM_{2.5}). For the pollutants, emission values averaged over the distance travelled by the road fleet (average specific distance emission) were determined. The results obtained indicated that between 1990 and 2017 the annual pollutant emissions from road vehicles in Poland had an increasing trend concerning TSP (74%), PM₁₀ (64%), PM_{2.5} (52%) and NO_x (25%), while the corresponding emissions had a decreasing trend for CO (−117%) and NMVOC (−85%). However, a clear downward trend was found for the average specific distance emissions of all substances throughout the subsequent inventory years: TSP (−28%), PM₁₀ (−100%), PM_{2.5} (−91%), NO_x (−84%), CO (−208%) and NMVOC (−173%), which is due to the dynamic progress in the technological advancement of road vehicles.

Keywords: pollutant emission; emission inventory; road transport; road vehicles

1. Introduction

Air pollution from anthropogenic sources contributes to climate change and is recognized as a major environmental health risk to human health. It is clear that pollutant emissions need to be reduced or at least stabilized in a possibly effective way in order to counter these negative effects and to achieve sustainable development. The successful implementation of air quality plans, new policies and commitments depend on detailed estimation of emissions of hazardous substances [1]. Therefore national inventories of pollutant emission arising from human activities have been established in the majority of developed countries and reported to the international organizations. The reported inventories of air pollutants are commonly accessible, as, e.g., the report for the EU [2,3], the United States of America [4] and Canada [5].

The primary sources of air pollutants due to anthropogenic activity include the combustion of fossil fuels to produce energy (heat and electricity), major industrial processes (e.g., metallurgy, cement and construction industry), agriculture and transport [6]. However, inventorying the emission of pollutants from road transport is more challenging than the emission from other human made sources. There are two reasons for that: the first one is the mobility of emission sources, and the second is the strong dependence of the emission on the mode of operation of combustion engines, which drive road vehicles [7]. Estimation of the pollutant emission from all road transport in a given region over a given period of time is only possible through the use of emission modelling [8–10]. It is likewise in the case of energy consumption by road vehicles [9]. On the other hand, it is possible to approximate the fuel consumption of all vehicles in a given region over a given period of time, based on the statistical data on fuel sales [9].

In terms of air pollution, Poland continues to be a hotspot in the European Union (EU). Polish cities are regularly ranked high among the most polluted cities in the EU [11]. The main sources of air pollutants in Poland are the municipal and household sector, as well as road transport [12]. Road transport in Poland dominates other modes of transport; Polish railways are largely electrified, the use of civil aviation for domestic transport is inefficient due to the relatively small area of the country, the range of domestic shipping is limited due to the configuration of the coastline and low utility of rivers as transport routes [13]. Therefore, the above modes of transport hardly influence the national emission compared to road transport, especially in terms of the scope of pollutants typically associated with motor vehicles, i.e., nitrogen oxides (NO_x) and carbon monoxide (CO) [12]. The emission of pollutants from motor vehicles results mainly from the burning of fossil fuels, the consumption of which will increase in the near future [14].

Already the subject of numerous scientific studies, the inventory of pollutants emitted by road transport is the focus of continuous research, because of its complexity and difficulty to gather the necessary data. In Poland, pollutant emission is inventoried by the National Centre for Emissions Management (KOBiZE) at the Institute of Environmental Protection—National Research Institute, subject to the Minister of Climate. On the basis of high quality data from KOBiZE [15], numerous scientific papers have been published, which concern various aspects of inventory and modeling of emission, both from vehicles and other anthropogenic sources [8,9,16–18]. Some papers deal with the impact of automotive pollution on human health [19] and its cost [12]. Finally, there are many publications devoted exclusively to the inventory of greenhouse gases, e.g., [20,21].

This paper provides original results of the inventory of selected pollutants hazardous to the health of living organisms, emitted by road transport in Poland between the years 1990 and 2017. The inventory was carried out according to the guidelines of the European Environmental Agency contained in EEA/EMEP Emission Inventory Guidebook 2019 at a more detailed level—Tier 3 [22], using the COPERT 5 software [23] and the most recent data available at the time of the study (up to 2017). Previous studies listed above [8–10,15–18], concerning pollutant emission from road transport in Poland, have demonstrated the effectiveness of the adopted research methodology. The report [15] can be considered as the most comprehensive source of high quality quantitative data on the pollutant emission in Poland in years 1988–2017. On the other hand, the report provides only a brief description of the data, and is not intended for their analysis. In contrast, the paper [20] refers to a similar period (1990–2017) and considers the emission of pollutants related to the distance traveled by vehicles, however, the analysis is limited solely to greenhouse gases. The novelty of the current study consist of revealing trends in carbon monoxide, non-methane volatile organic compounds, nitrogen oxides and particulate matter size fractions emission from road transport in Poland, by taking into account the number and annual mileage of vehicles. As such, it shows this emission from a different perspective than that of the previous studies.

2. Methods

The adopted modeling approach is based on the assumption that the total pollutant emission from road transport is a superposition of pollutant emission released from individual vehicles. This is justified, since the intensity of the emission of particular pollutants is an additive quantity [7,9]. Another assumption is that the substances are in the state in which they were emitted from vehicles, i.e., they do not undergo physical and chemical changes in the environment [7,9].

National emission of pollutants from motor vehicles is the sum of annual emission from all vehicles driven during the calendar year in the country:

$$E_{ax} = \sum_{i=1}^N \int_t^{t+1} b_{ix}(\tau) d\tau \quad (1)$$

where: E_{ax} —national emission of pollutant “x”, $b_{ix}(t)$ —specific distance emission of pollutant ‘x’ from vehicle ‘i’ at time ‘t’, τ —integral variable with time dimension: $\tau \in <t; t + 1>$, t —time—year number (in calendar years): $t \in <1990; 2016>$, N —total number of vehicles.

Specific distance emission of pollutant is a derivative of pollutant emission to the distance traveled by the vehicle [7]:

$$b(s) = \frac{dm(s)}{ds} \quad (2)$$

where: b —specific distance emission of pollutant as a function of the distance traveled by the vehicle, m —emission of pollutant ‘x’ from the vehicle, s —distance traveled by the vehicle.

All vehicles are classified into categories. The basic criteria for classifying road vehicles may vary, but the following have most often been adopted [9,10,22,23]:

- intended use of vehicle;
- conventional size of a vehicle and its propulsion engine;
- properties of vehicles and their propulsion engines regarding e.g., pollutant emission;
- type of fuel;
- technological level of vehicles and their propulsion engines (i.e., the advancement of the applied technical solutions that affect vehicle and engine properties, which are considered relevant for the classification of vehicles into categories).

The elementary category of road vehicles embraces vehicles having all the same criterion characteristics, e.g., passenger vehicles with spark-ignition engines of displacement volume less than 1.4 dm³, compliant with Euro 3 emission standard and supplied with gasoline. Cumulated category of road vehicles embraces vehicles having not all the same criterion characteristics, as e.g., passenger vehicles with spark-ignition engines of displacement volume less than 1.4 dm³. All road vehicles (road fleet) represent the most cumulated category.

The elementary categories of vehicles included in this study correspond to the relevant categories in the COPERT 5 software. The software applies a disaggregation of the road fleet into the categories, according to the vehicle intended use, the ignition system of combustion engine and fuel used, including vehicles with hybrid electric-combustion drive [22,23]. Accordingly, this study concerns: passenger cars, light commercial vehicles (delivery vehicles), heavy duty trucks, urban buses, coaches, motorcycles, mopeds and micro-cars. The complete specification of vehicle categories is provided in the Supplementary Materials.

Therefore, the national annual emission of pollutants is modeled as the superposition of annual emission from vehicles of the cumulative categories:

$$E_{ax} = \sum_{j=1}^K n_j \cdot b_{AVxj} \cdot L_j \quad (3)$$

where: j —cumulative category, K —total number of cumulative categories, n_j —number of vehicles of cumulative category ' j ', b_{AVxj} —average value of specific distance emission of pollutant ' x ' from vehicles of cumulative category ' j ', L_j —distance traveled by an imaginary vehicle of cumulative category ' j '.

In models of pollutant emission from road vehicles, it is assumed that the intensity of pollutant emission associated with the use of motor vehicles with internal combustion engines is the sum of pollutant emission for the states of [7,9,22,23]:

- internal combustion engine heated to a stable temperature;
- internal combustion engine heating up;
- fuel evaporation from the car fuel system.

In addition, the emission of particulates from sources other than combustion engines is taken into account, i.e., from the braking system, clutch and tires in contact with the road surface, and wear of other vehicle components.

The list of substances included in the EU pollutant emission inventories are shown in Table 1. For the purposes of the analysis carried out in this study, the number of substances was narrowed to those harmful to the health of living organisms, which are covered in vehicle type-approval regulations in the EU, i.e., carbon monoxide, non-methane volatile organic compounds, nitrogen oxides and particulate matter, with two particle size fractions distinguished, namely PM_{10} and $PM_{2.5}$ (the latter were intentionally included, since virtually all particulate matter from the exhaust system of combustion engines belongs to the $PM_{2.5}$ fraction).

Table 1. Substances (or group of substances) included in pollutant emission inventories of the European Union [22,23].

Name	Chemical Formula or Abbreviation
Carbon monoxide	CO
Non-methane volatile organic compounds	NMVOC
Nitrogen oxides reduced to nitrogen dioxide	NO _x
Sulphur oxides, in sulphur dioxide equivalent terms	SO ₂
Ammonia	NH ₃
Total suspended particles	TSP
Particulate matter fractions	PM ₁₀ , PM _{2.5}
Black carbon	BC
Persistent organic pollutants	POPs (PAHs, HCB, PCBs, dioxins/furans)
Main heavy metals	Pb, Cd, Hg
Additional heavy metals	As, Cr, Cu, Ni, Se, Zn
Carbon dioxide	CO ₂
Methane	CH ₄
Dinitrogen monoxide	N ₂ O

The general rules for preparing data regarding road vehicles and their motion are outlined in the literature [8–10,15–17]. Data on the numbers of vehicles classified within cumulative categories in respect of the COPERT 5 software were elaborated, based on official data published by the Central Vehicle and Drivers Register. Annual distances travelled by road vehicles, by respective elementary category due to the technological level in terms of reducing pollutant emission, were adopted, after the model described in [18]. This model is based on the observation that newer vehicles with a higher technology level (defined by European emission standards) are used more intensively than older vehicles. Hence, to determine the annual mileage of vehicles belonging to the elementary categories, an increasing function is used, the argument of which is the quantity describing the subsequent stages of emission standards used in vehicle type-approval regulations. The values of this quantity are increasing, as newer stages of the regulations are implemented. Details, including the mathematical form of the model, are given in [18]. Data on consumption of different types of fuel in road transport come from Eurostat Database, which is fed by the Statistics Poland (GUS) [24]. Total fuel consumption

was disaggregated into individual vehicle categories based on the COPERT 5 calculations, so that the mass of calculated fuel consumption is equal to that provided in the statistics. All detailed data used in the inventory of pollutant emission is published in official KOBiZE reports, including [15].

To evaluate changes in the quantities under consideration, the relative change in their values between the years 1990 and 2017 was assumed, according to the formula:

$$\delta_X = 2 \cdot \frac{X_{\text{apr}}(2017) - X_{\text{apr}}(1990)}{X_{\text{apr}}(2017) + X_{\text{apr}}(1990)} \quad (4)$$

where: $X_{\text{apr}}(1990)$ —value of the quantity 'X' in 1990, approximated by the linear function, $X_{\text{apr}}(2017)$ —value of the quantity 'X' in 2017, approximated by the linear function.

The authors decided to use the absolute difference related to the mean value, because it allows for a more objective assessment than the absolute difference related to one of the extreme values. More specifically, if the absolute difference was related to a smaller extreme value, a large result (relative change) would be obtained, while relating the absolute difference to a larger extreme value would give a small result, although the extreme values do not change. The formula proposed in the paper is unambiguous and independent of the choice of extreme value.

The national annual emission of pollutants, as the extensive-type characteristic, depends not only on the properties of road vehicles due to pollutant emission but, above all, on the number of vehicles and the intensity of their use. Therefore, while analyzing the results of the study on pollutant emission from road vehicles, the intensive characteristics of pollutant emission were assessed in order to estimate changes in the vehicle technical quality in terms of pollutant emission.

The average specific distance emission was adopted as the characteristic of pollutant emission [10] for the cumulative category of road vehicles in Poland between 1990–2017. This is the annual national pollutant emission related to the measure of the road vehicle activity, expressed as the distance travelled by road fleet over a year:

$$b_{\text{AVx}} = \frac{E_x}{L} \quad (5)$$

where: b_{AVx} —average specific distance emission of pollutant 'x' for cumulative category of road vehicles, E_x —national annual emission of pollutant 'x' from the road fleet, L —distance travelled by the road fleet over a year.

The distance travelled annually by road fleet is the sum of the products of numbers and annual distances travelled by road vehicles, by respective elementary categories 'i'.

$$L = \sum_{i=1}^K N_i \cdot P_i \quad (6)$$

where: N_i —number of road vehicles of elementary category 'i', P_i —annual distance travelled by road vehicles of elementary category 'i', K —number of elementary categories of road vehicles.

The effects of the vehicle quality in terms of pollutant emission were also taken into account in the analyses. The quality of road vehicles concerning pollutant emission was estimated using data on the vehicles' structure at the level of elementary categories over the subsequent years. The estimation was made by comparing the measure of the activity of road vehicles by respective categories, due to pollutant emission, e.g., Euro 1 versus Euro 6 for passenger cars [25] and light commercial vehicles, and Euro I versus Euro VI for heavy duty trucks and urban buses [26]. The activity of road vehicles from individual categories in terms of pollutant emission is expressed by the distance travelled annually by aggregated vehicles from the respective category.

3. The Results of Pollutant Emission Inventory

Figures 1 and 2 illustrate the national annual emission of carbon monoxide, non-methane volatile organic compounds, nitrogen oxides, total suspended particles, particulate matter PM_{10} , and particulate

matter $PM_{2.5}$. It should be noted that these results have already been published in the report [15], however, they are also included in this paper, due to the fact that they constitute the most important input for the analysis, the results of which are presented in the following sections. This certainly should facilitate assessment of trends in the quantities under consideration.

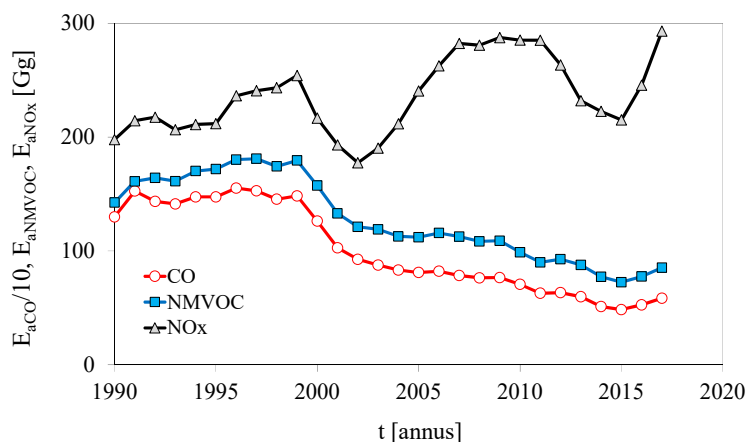


Figure 1. National annual emission of carbon monoxide— E_{aCO} , non-methane volatile organic compounds— E_{aNMVOC} and nitrogen oxides— E_{aNOx} , arising from road transport in Poland between 1990 and 2017.

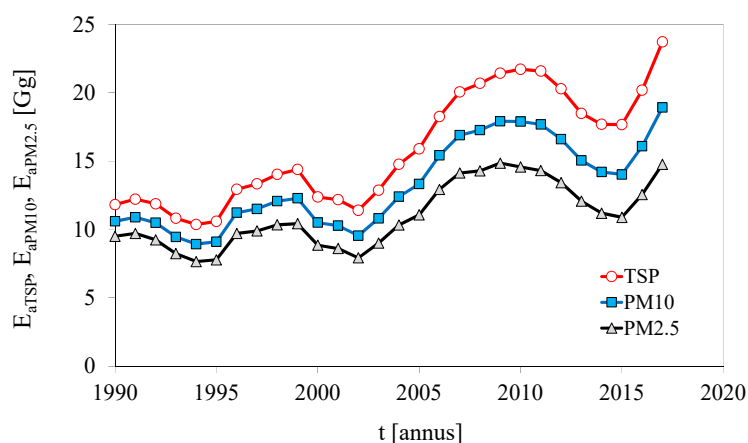


Figure 2. National annual emission of total suspended particles (TSP)— E_{aTSP} , particulate matter PM_{10} — E_{aPM10} and particulate matter $PM_{2.5}$ — $E_{aPM2.5}$, arising from road transport in Poland between 1990 and 2017.

For all the pollutants examined, the annual emission varied over the subsequent years, however, there were differences between individual substances. Carbon monoxide and non-methane volatile organic compounds showed a downward trend. This is associated with a significant improvement in the properties of internal combustion engines in terms of emission of these substances—it is known that reducing emission of gaseous substances with oxygen-reducing properties is much easier and more effective than in the case of particulates and substances with oxidizing properties in an environment with high oxygen concentration [7]. Therefore, for nitrogen oxides and particle matter size fractions, there is a tendency for the national annual emissions to increase in subsequent years of inventory.

Figure 3 shows the relative change in the national annual emission of pollutants.

The largest drop was noted for the national annual emission of carbon monoxide, while the emission of nitrogen oxides showed a small increase, and the emission of particulate matter size fractions showed the largest increase. In the latter case, much of the growth in the national annual emission of particulate matter is a consequence of the increase in the contribution of larger sized

particulates from tires and brakes wear and, primarily, from road abrasion, while the emission of fraction $PM_{2.5}$, which contains particles emitted by combustion engines, showed a minor increase.

Overall, the increase in the national annual emission of pollutants is a result of the dynamic development of motorization in Poland during the period from 1990, as is shown in Figures 4 and 5, but the numbers of road vehicles, distances travelled and fuel consumption have all grown most.

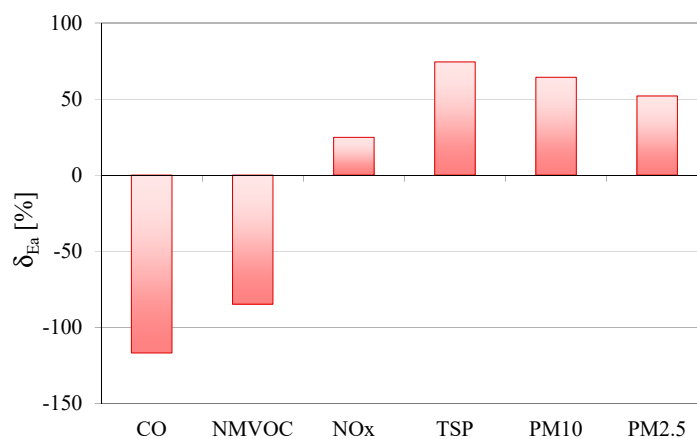


Figure 3. Relative change in the national annual emissions of pollutants— δ_{Ea} arising from road transport in Poland in 2017 as compared to 1990.

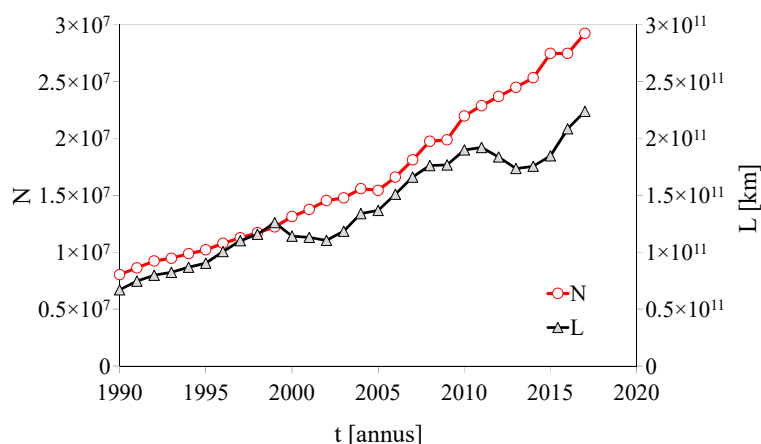


Figure 4. Number of road vehicles— N and distance travelled annually by the road fleet— L in Poland between 1990 and 2017.

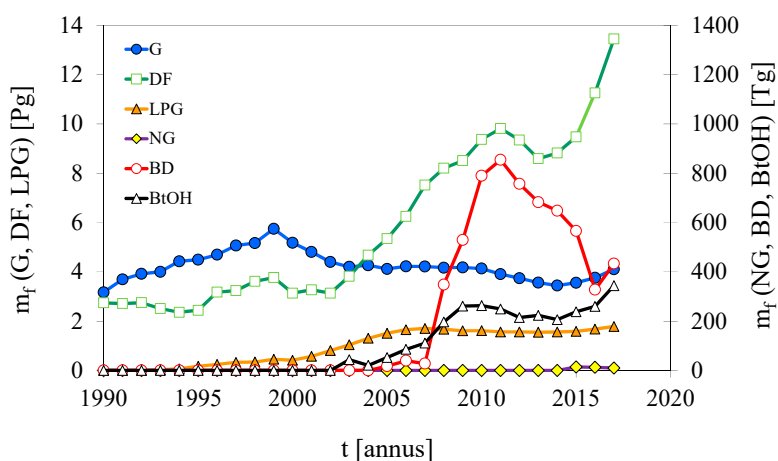


Figure 5. Fuel mass consumption in road transport in Poland between 1990 and 2017: G—gasoline, DF—diesel fuel, NG—natural gas, LPG—liquefied petroleum gas, BD—biodiesel, BtOH—bio-ethanol.

Fuel consumption, shown in Figure 5, corresponds to the total energy consumption in road transport, from 285.73 PJ in 1990 to 864.75 PJ in 2017. The relative difference in fuel consumption for 1990 and 2017 is over 100%, and the relative increase in 2017 compared to 1990 is over 200%.

The drop in the national annual emission resulted mostly from the technological advancement in both the construction and operation of road vehicles, which helped to curb pollutant emission, in particular from combustion engines. Over almost two decades, mass-produced vehicles have introduced many systems that significantly reduce pollutant emissions and fuel consumption, such as advanced exhaust after treatment systems, start-stop, brake energy recuperation, variable valve actuation, gasoline direct injection, improved engine thermal management (e.g., for faster warm-up after cold start), advanced gearbox variations (increased number of gears, different gear ratios) and others [27,28]. The technologies facilitating the operation of vehicles have also been introduced, e.g., navigation systems with fuel-optimal route advise [29] or automated driving assistance systems supporting truck platooning [30]. Short-term changes in the national annual pollutant emissions (Figures 1 and 2), which are also reflected in the total fuel consumption (Figure 5), are largely due to fluctuations in the countrywide economic situation. Some qualitative similarities can be observed with the changes of gross domestic product (GDP) growth rate in Poland, especially around 2000–2003 and 2012–2015 [31].

4. Analysis of the Results of Pollutant Emission Inventory

Given the knowledge of the distance travelled by the vehicle fleet, it was possible to determine the average specific distance emission of pollutants and the average energy emission factor for the cumulative category of road vehicles.

Figures 6 and 7 give the average specific distance emissions for the cumulative category of road vehicles in Poland between 1990 and 2017.

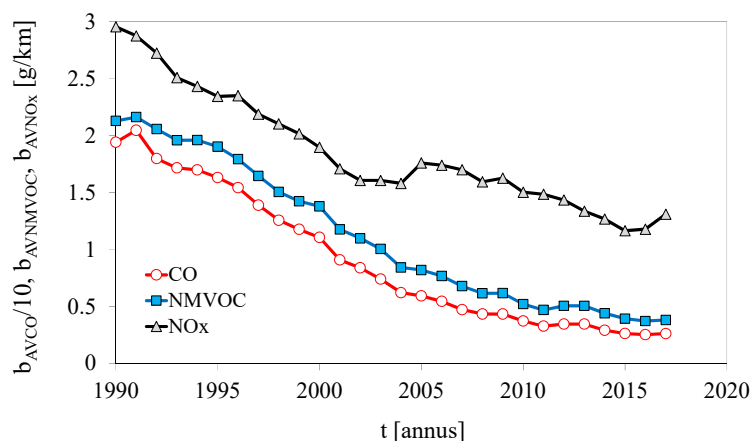


Figure 6. Average specific distance emission of carbon monoxide— b_{AVCO} , non-methane volatile organic compounds— $b_{AVNMVOC}$ and nitrogen oxides— b_{AVNOx} for cumulative category of road vehicles in Poland between 1990 and 2017.

By far the strongest is the decrease in average road emissions of carbon monoxide and non-methane volatile organic compounds due to technical progress. Achieving a reduction in average road emission of nitrogen oxides is more difficult. For particulate matter, it is important to consider the different sources of origin, apart from the exhaust system of internal combustion engines. A particularly difficult problem is the reduction of particulate emissions from abrasion of the braking system components, as well as tires in contact with the road surface. In the first case, they are very fine particles, mostly with characteristic dimensions smaller than 1 μm , while in the second—with relatively large characteristic dimensions [22].

The relative change in the average specific distance emission of pollutants from road vehicles in 2017, as compared to 1990, is shown in Figure 8.

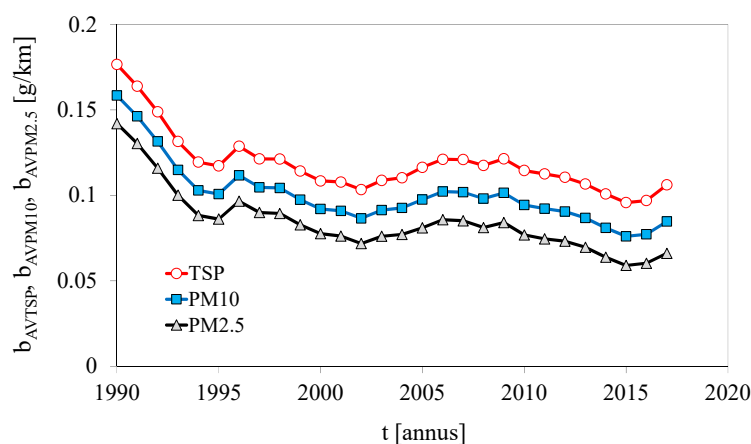


Figure 7. Average specific distance emission of total suspended particulates— b_{AVTSP} , particulate matter PM_{10} — b_{AVPM10} and particulate matter $PM_{2.5}$ — $b_{AVPM2.5}$ for cumulative category of road vehicles in Poland between 1990 and 2017.

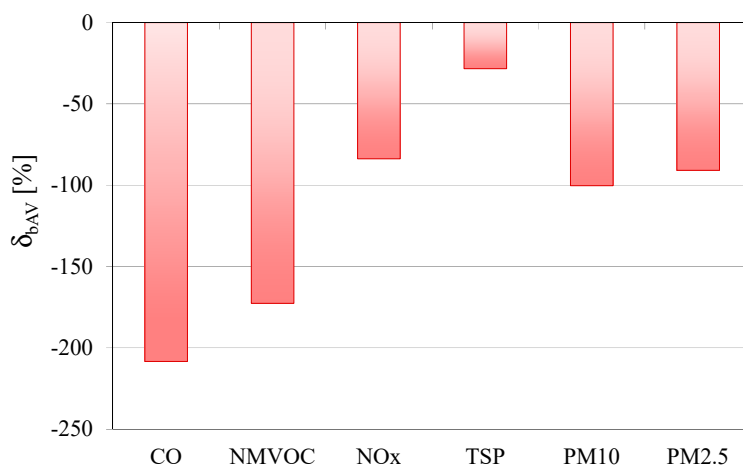


Figure 8. Relative change in the average specific distance emissions of pollutants— δ_{bAV} from road transport in Poland in 2017 as compared to 1990.

The tendency for the increase in the national annual emission of pollutants, i.e., characteristic with extensive properties, is possible as a result of the dynamic development of the automotive industry. On the other hand, average specific distance emissions of pollutants, i.e., characteristic with intensive properties, has a clear tendency to decrease over the period considered. Of course, according to the results presented previously, the strongest tendency to decrease is for the emission of carbon monoxide and non-methane volatile organic compounds. The main reason behind this tendency is the technological advancement of vehicles in terms of pollutant emission. Figure 9 provides a comparison of the road vehicle structure, expressed by distance travelled annually, according to vehicle environmental categories in the years 1990, 1995, 2000, 2005, 2015 and 2017.

In Figure 9, a distinct improvement can be seen in the road vehicles in use, regarding pollutant emission from the cumulative category of road vehicles. Similar results can be observed for other cumulative categories of road vehicles, e.g., passenger cars, light commercial vehicles, heavy duty trucks and urban buses [15].

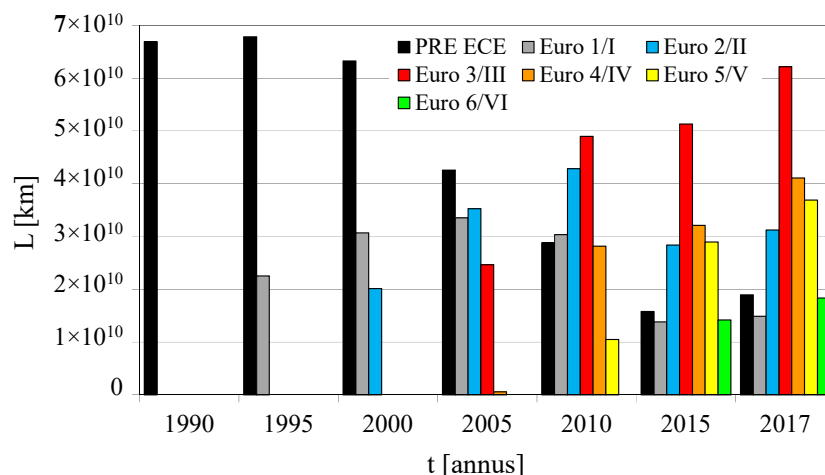


Figure 9. Comparison of the road vehicles structure— L , expressed by distance travelled annually, according to environmental categories, in the years 1990, 1995, 2000, 2005, 2015 and 2017.

5. Conclusions

Based on the results of the above analyses, the following conclusions can be formulated:

1. Between 1990 and 2017, the national annual emission from road vehicles in Poland has increased for some substances, first of all, for particulate matter size fraction and, to a lesser extent, for nitrogen oxides. This is mostly the consequence of the dynamic development of motorization in Poland after 1989. The national annual emissions of carbon monoxide and non-methane volatile organic compounds, in spite of the dynamic development of motorization, have decreased. The measure of the dynamic development of the automotive industry in Poland is an increase in the number of vehicles from about 8 million in 1990 to over 29 million in 2017. Additionally, the total annual mileage of vehicles increased from about 67 billion km in 1990 to about 223 billion km in 2017. This resulted in an increase in the total energy consumption of vehicles from 285.73 PJ in 1990 to 864.75 PJ in 2017. In the face of such dynamic development of the automotive industry in Poland after 1990, the results of the inventory of pollutant emission in the years 1990–2017 should be considered favorable, due to the actions taken in road transport for environmental protection.
2. The relative reduction in national annual emission is the greatest for carbon monoxide—almost 120%—and for non-methane volatile organic compounds it is almost 85%. The relative increase in the national annual emission of nitrogen oxides is equal to about 25%, and the total particulate matter—almost 75%—including the PM_{10} fraction—over 60%—and $PM_{2.5}$ —about 50%. The results of the relative reduction in the emission of the particle size fraction confirm the fact that reducing the emission of particles from sources other than the exhaust system of internal combustion engines is one of the most difficult technical tasks.
3. Between 1990 and 2017, the average specific distance emission arising from road vehicles has decreased considerably. This clear improvement in the intensive characteristic of pollutant emission results from significant upgrading of the vehicle technology level in terms of reducing emission. In addition, it is known that the intensity of use of vehicles of higher ecological categories is much greater than of vehicles of lower ecological categories [18], which is confirmed by the data for inventory of pollutant emission from road transport in Poland, documented in the report [15].

Since the annual mileages of the newer generation cars overbalance those of older generation cars, the rise in the pollutant emission due to the dynamic development of motorization in Poland was considerably lower than could be expected, judging from the growth in numbers and intensity of use of road vehicles. However, according to authors, this is not yet the preferred situation. There is a need

to establish and implement a system for eliminating old vehicles from road traffic and to implement an effective, in-depth control of the vehicle technological grade.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/13/5387/s1>, Vehicle categories included in the COPERT 5 software, Table S1: National annual emission of pollutants arising from road transport in Poland between 1990 and 2017, Table S2: Relative change in the national annual emission of pollutants arising from road transport in Poland in 2017 as compared to 1990, Table S3: Number of road vehicles in Poland between 1990 and 2017, Table S4: Distance travelled annually by the road fleet in Poland between 1990 and 2017, Table S5: Fuel mass consumption in road transport in Poland between 1990 and 2017: G—gasoline, DF—diesel fuel, NG—natural gas, LPG—liquefied petroleum gas, BD—biodiesel, BtOH—bio-ethanol, Table S6: Average specific distance emission of pollutants for cumulative category of road vehicles in Poland between 1990 and 2017, Table S7: Relative change in the average specific distance emission of pollutants from road transport in Poland in 2017 as compared to 1990, Table S8: Comparison of the road vehicles structure according to environmental categories, in the years 1990, 1995, 2000, 2005, 2015 and 2017.

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