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ASSESSMENT OF RESULTS OF POLLUTANT EMISSION INVENTORY OF THE ROAD TRANSPORT SECTOR IN POLAND IN 2000–2015

OCENA WYNIKÓW INWENTARYZACJI EMISJI ZANIECZYSZCZEŃ W SEKTORZE TRANSPORTU DROGOWEGO W POLSCE W LATACH 2000–2015

KATARZYNA BEBKIEWICZ[1], ZDZISŁAW CHŁOPEK[2], KRYSTIAN SZCZEPAŃSKI[3], MAGDALENA ZIMAKOWSKA-LASKOWSKA[4]
Institute of Environmental Protection – National Research Institute

Summary

The article presents results of inventorying pollutant emission from road transport in Poland in the years 2000–2015, prepared at the National Centre for Emissions Management (KOBiZE) of the Institute of Environmental Protection – National Research Institute. The pollutant emission was determined by modelling, which was carried out with using the EU-recommended COPERT 4 program. The fleet sizes and annual mileage (in kilometres) of vehicles classified in each cumulated category have been

[1] Institute of Environmental Protection – National Research Institute – National Centre for Emissions Management (KOBiZE); ul. Chmielna 132/134; 00-805 Warszawa, Poland; e-mail: katarzyna.bebkiewicz@kobize.pl

[2] Institute of Environmental Protection – National Research Institute – National Centre for Emissions Management (KOBiZE); ul. Chmielna 132/134; 00-805 Warszawa, Poland; e-mail: zdzislaw.chlopek@kobize.pl

[3] Institute of Environmental Protection – National Research Institute; ul. Krucza 132/134; 00-548 Warszawa, Poland; e-mail:krystian.szczepanski@ios.edu.pl

[4] Institute of Environmental Protection – National Research Institute – National Centre for Emissions Management (KOBiZE); ul. Chmielna 132/134; 00-805 Warszawa, Poland; e-mail: magdalena.zimakowska-laskowska@kobize.pl

given. The motor vehicle traffic was characterized by the shares of vehicle mileages covered in the urban, extra-urban (rural), and high-speed (highway) driving modes in the total vehicle mileage and by the average vehicle velocity values determined for the said different driving modes. Data on annual national emission of carbon monoxide – CO, volatile organic compounds – VOC, nitrogen oxides – NO_x, particulate matter – PM, and carbon dioxide – CO_2 have been specified for the years 2000–2015, for which the emission balance was inventoried. A marked downward trend was revealed in the annual national emission, especially for carbon monoxide and volatile organic compounds. This is an effect of technological progress in the field of automotive engineering. The average specific distance emission and average emission factor values were also experimentally determined.

Based on results of these tests, conclusions have been formulated as regards clearly visible improvement in the environmental properties of motor vehicles in the years 2000–2015; an effect of this improvement is a considerable reduction in the environmental loading caused by road transport.

Keywords: inventory of pollutant emission, motor vehicles, road transport

Streszczenie

W artykule przedstawiono wyniki inwentaryzacji emisji zanieczyszczeń w sektorze transportu drogowego w Polsce w latach 2000–2015, opracowane w Krajowym Ośrodku Bilansowania i Zarządzania Emisjami Instytutu Ochrony Środowiska – Państwowego Instytutu Badawczego. Emisję zanieczyszczeń wyznaczono na podstawie modelowania z zastosowaniem oprogramowania COPERT 4, rekomendowanego przez Unię Europejską. Przedstawiono liczność i przebiegi roczne pojazdów kategorii skumulowanych. Parametry charakteryzujące ruch samochodów przyjęto jako udział długości drogi przebywanej przez pojazd w warunkach jazdy: w miastach, poza miastami oraz na autostradach i drogach ekspresowych, a także prędkość średnią pojazdów w tych warunkach. Przedstawiono krajową emisję roczną: tlenku węgla, lotnych związków organicznych, tlenków azotu, cząstek stałych i dwutlenku węgla dla lat bilansowania 2000–2015. Stwierdzono tendencję do znaczącego zmniejszania się krajowej emisji zanieczyszczeń, szczególnie tlenku węgla i lotnych związków organicznych. Jest to wynik postępu technicznego pojazdów samochodowych. Zbadano również średnią emisję drogową i średni wskaźnik emisji zanieczyszczeń dla wszystkich pojazdów samochodowych.

Sformułowano na podstawie tych badań wnioski na temat wyraźnej poprawy właściwości ekologicznej pojazdów samochodowych w latach 2000–2015, czego skutkiem jest znaczące zmniejszenie obciążenia środowiska przez transport drogowy.

Słowa kluczowe: inwentaryzacja emisji zanieczyszczeń, pojazdy samochodowe, transport drogowy

1. Introduction

The civilization-related pollutant emission has been regularly inventoried for several decades, on local, national, and worldwide scale. Among the first European initiatives in this field, there was the one taken within CORINAIR (Core Inventory of Air Emissions) [19]. Poland has been participating in the CORINAIR works from the beginning of 1990s. Many projects related to pollutant emission from road transport were undertaken within European scientific programs, e.g. COST[5] 319 "Estimation of pollutant emissions from transport" [14] and MEET (*Methodology for Calculating Transport Emissions and Energy Consumption*) [31]. Moreover, some computer tools have also been developed to support the inventorying

[5] COST – *European Cooperation in the Field of Scientific and Technical Research*

of pollutant emission and fuel consumption in the road transport sector, with the program named COPERT (*Calculation of Emissions from Road Transport*) being one of those most important [20].

Apart from that, computer programs have been prepared to determine the quantities that characterize the emission and fuel consumption of motor vehicles. The program developed by INFRAS [26] (described in HBEFA – *Handbook Emission Factors for Road Transport* [30]) makes it possible to determine the specific distance emission and specific distance fuel consumption for motor vehicles of various types, operated in various traffic conditions.

Other programs devised for estimating pollutant emission and fuel consumption include e.g. special versions of the MOBILE program [24] developed in the USA for road and non-road transport facilities as well as numerous programs to assist the estimation of emission from various civilization-related sources, including motorization, e.g. GAINS (*Greenhouse Gas and Air Pollution Interactions and Synergies*) [20], TREMOVE (*Transport & Mobility Leuven*) [27], ForFITS (*Future Inland Transport Systems*) [28], TRANSTOOLS (*Tools for Transport Forecasting and Scenario Testing*) [19], or SULTAN (*Sustainable Transport*) [25]. There are also a number of very simplified pollutant emission models, used to assist the modelling of road vehicle traffic, e.g. PTV Visum [21].

The results of inventorying the national pollutant emission, presented herein, were obtained with using the COPERT 4[6] program [13, 15]. The obligation to report pollutant emission arises from the United Nations Framework Convention on Climate Change (UNFCCC or FCCC). For the sake of uniformity of emission inventory results, a standard method, identical for all the EU member states, has been developed under the auspices of the European Environment Agency (EEA) and described in the IPCC 2006 [1] and EMEP/EEA [14] guidelines. The COPERT model is a program based on this EU preferred method.

The COPERT program is based on results of tests and projects supported by, *inter alia*, the Joint Research Centre in Ispra (Italy) and ERMES (*The European Research Group on Mobile Emission Sources*).

2. Principles of modelling pollutant emission and fuel consumption in the road transport sector

The inventorying of pollutant emission from road transport is one of the most difficult tasks in the field of determining the balance of pollutant emission from various civilization-related sources. This is because of the fact that in the case of mobile emission sources, only modelling results may be utilized, as the measurements of total emission from motor vehicles, as opposed to other stationary emission sources, are technically infeasible [3, 11, 12].

In the model of total pollutant emission from road transport, the following assumptions have been adopted [3, 12]:

- the intensity of emission of individual pollutants is an additive quantity;

[6] The COPERT 5 version of this program has already been available since October 2016.

- the inventory of pollutant emission exclusively applies to the pollutants in the state as emitted from vehicles rather than the substances produced in result of the processes that occur in the environment.

The total pollutant emission from motor vehicles is modelled as a sum of the total emission from [3, 6, 10, 12–15, 17, 18, 22, 23, 30]:

- internal combustion (IC) engines heated to a stabilized temperature;
- IC engines during the heating process;
- fuel evaporation from vehicles' fuel systems.

In the inventory of pollutant emission from road transport, the notion of vehicle category has been introduced. Motor vehicles are classified in individual categories according to the following basic criteria [3, 6, 10, 12–15, 17, 18, 22, 23, 30]:

- operational purpose of the vehicle (vehicle type);
- conventional size of the vehicle or its IC engine (gross vehicle mass or engine capacity);
- vehicle properties in consideration of the engineering solutions adopted;
- fuel used;
- technological level, primarily the emission control level.

The elementary category of motor vehicles, defined by the features considered as classification criteria, exclusively covers the vehicles whose features meet all the classification criteria of the same vehicle category. The vehicles with not all features meeting the same classification criteria are classified in cumulated motor vehicle categories.

The cumulated categories of motor vehicles, defined by the intended vehicle use and vehicle's combustion system type, include (the English category names and their acronyms used in this publication are identical with those used in the COPERT 4 program) [13, 15]:

- Passenger Cars – PC:
  - passenger cars with spark-ignition engines, fuelled with gasoline – PC-SI-G,
  - passenger cars with spark ignition engines, fuelled with liquefied petroleum gas – PC-SI-LPG,
  - passenger cars with compression-ignition engines;
- Light Commercial Vehicles – LCV:
  - light commercial vehicles with spark-ignition engines – LCV-SI,
  - light commercial vehicles with compression-ignition engines – LCV-CI;
- Heavy Duty Trucks – HDT:
  - heavy duty rigid trucks (platform trucks) – HDT-R,
  - heavy duty articulated trucks (truck tractors, ballast tractors) – HDT-A;
- Urban Buses – UB;
- Coaches – C;
- Motorcycles – Mc;

- Mopeds[7] – Mp.

In the categories of passenger cars, motorcycles and mopeds, the subcategories of vehicles with 4-stroke and 2-stroke engines are also distinguished.

The conventional vehicle size is defined by the following criteria [3, 6, 10, 12–15, 17, 18, 22, 23, 30]:

- for passenger cars and light commercial vehicles and for motorcycles and mopeds, cubic capacity of their IC engines;
- for heavy duty trucks and buses, their maximum authorized mass (MAM).

The criterion of classifying motor vehicles in specific technological level categories is referred to the successive stages of development of the regulations that govern the protection of natural environment from the impact of motor vehicle operation [2, 37, 38]; thus:

- for vehicles with MAM not exceeding 3.5 Mg for regulation stages EURO 1–4 and for vehicles with reference mass not exceeding 2.61 Mg for regulation stages EURO 5 and EURO 6, the categories are named Pre-EURO (or, alternatively, Conventional), Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, and Euro 6;
- for vehicles with MAM exceeding 3.5 Mg for regulation stages EURO I–IV and for vehicles with reference mass exceeding 2.61 Mg for regulation stages EURO V and EURO VI, the categories are named Pre-EURO (or, alternatively, Conventional), Euro I, Euro II, Euro III, Euro IV, Euro V, and Euro VI.

The pollutant emission from road transport is modelled depending on the vehicle motion conditions typical for the following driving modes [3, 6, 10, 12–15, 17, 18, 22, 23, 30]:

- urban;
- extra-urban (rural);
- high-speed (highway).

The vehicle velocity process is primarily characterized by the average velocity value [3, 6, 10, 12–15, 17, 18, 22, 23, 30].

In the inventorying of pollutant emission from road transport, one calendar year is usually adopted as the averaging period and the emission intensity thus averaged is referred to as annual pollutant emission [10]. The annual pollutant emission determined for the territory of a specific state is referred to as annual national pollutant emission [4].

The annual pollutant emission is modelled for each of the elementary vehicle categories and for each of the driving modes as a quantity proportional to [4, 6, 10, 12–15, 17, 18, 22, 23]:

- number of vehicles of an individual category (population of the fleet);
- distance travelled during one year by a representative vehicle of an individual category, (annual mileage) and being a measure of the intensity of vehicle operation;

[7] Pursuant to the "Road Traffic Law" Act of 20 June 1997 (Dz. U. of 202, item 1137), motor vehicle is a self-propelled vehicle other than a moped or a rail-vehicle. Regardless of this definition, the set of motor vehicles taken into account in the modelling of pollutant emission from road transport facilities includes mopeds, too.

- characteristic specific distance emission for a representative vehicle of an individual category, referred to as specific distance emission of a pollutant.

The specific distance emission b_x of pollutant "x" is defined as derivative of the emission (by mass) mx of pollutant "x" with respect to the distance s travelled by the vehicle [10]:

$$b_x = \frac{dm_x}{ds} \tag{1}$$

The annual pollutant emission from the vehicles of a cumulated category is a sum of pollutant emission from vehicles of the elementary categories the cumulated category is composed of.

The annual national pollutant emission is a sum of the annual pollutant emission from the vehicles of all the cumulated categories.

The basic substances the emission of which may be determined by the COPERT 4 program include [13–15, 23]:

- carbon monoxide – CO;
- Volatile Organic Compounds – VOC;
- Non-Methane Volatile Organic Compounds – NMVOC;
- methane – CH_4;
- groups of organic compounds, such as alkanes, alkenes, alkynes, furans, aldehydes, ketones, cycloalkanes, aromatic compounds, or Polycyclic Aromatic Hydrocarbons – PAH;
- nitrogen oxides – NO_x;
- nitrogen monoxide – NO;
- nitrogen dioxide – NO_2;
- dinitrogen monoxide – N_2O;
- ammonia – NH_3;
- particulate matter – PM emitted from the IC engine exhaust system;
- particulate matter PM10;
- particulate matter PM2.5;
- Black Carbon – BC;
- carbon dioxide – CO_2;
- lead and its compounds, in lead equivalent terms – Pb;
- sulphur oxides, in sulphur dioxide equivalent terms – SO_2;
- heavy metals: Cd, Cr, Cu, Ni, Se, Zn.

The following quantities are applied as inputs to the COPERT program [1, 13, 14]:

- number of vehicles of an individual category of specific elementary categories – N;
- intensity of operation of the fleets of specific elementary categories (annual mileage) – p;
- shares of the mileage covered in individual driving modes in the total mileage of the fleets of specific elementary categories, i.e. urban – u_U, rural – u_R, and highway – u_H;

- average velocity of the fleet of a specific elementary category in individual driving modes, i.e. urban, rural, and highway – v;
- minimum and maximum ambient temperature values in individual months;
- sulphur content of fuels;
- lead content of fuels;
- elementary composition of fuels;
- heavy metal contents of fuels;
- saturated vapour pressure of fuels;
- average length of the vehicle trip under cold start conditions.

3. Data for the inventory of pollutant emission from road transport in Poland for 2000–2015

Figure 1 shows sizes of the fleets of individual cumulated vehicle categories. The numbers of the motor vehicles classified in the cumulated categories adopted were determined for the years 2000–2014 from the data kept in the Computer System of the Central Register of Vehicles and Drivers (CEPiK); the figures for 2015 were based on the data published by the Central Statistical Office [16].

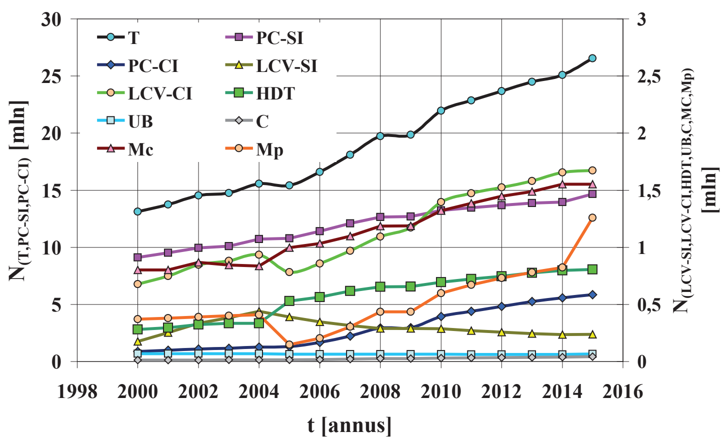

Fig. 1. Sizes of the fleets of cumulated vehicle categories

Figure 2 shows the assumed annual mileage of the vehicles classified in individual cumulated categories. The average annual mileage of such vehicles was estimated on the grounds of information about [9]:

- transport work;
- number of vehicles registered;

- average values of the technical and operational indicators that characterize the motor transport operation, e.g. number of people transported by a vehicle, average rate of utilization of the rolling stock, etc.

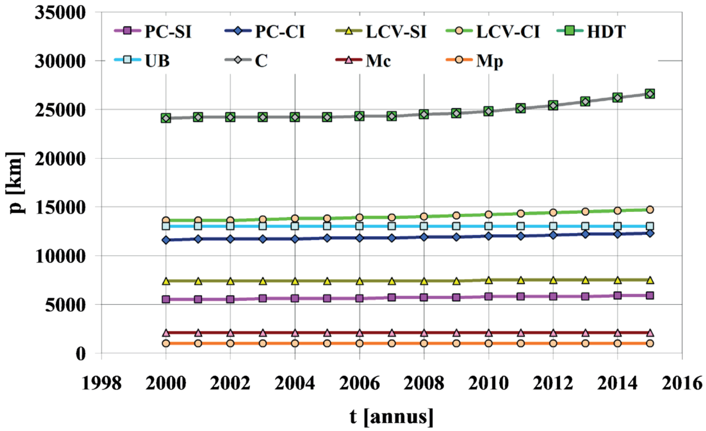

Fig. 2. Annual mileage of the vehicles classified in individual cumulated categories

The annual mileage of motor vehicles classified in elementary pollutant emission (ecological) categories was estimated with using an authors' model of intensity of motor vehicle operation. The said model is based on the functional similarity principle [8, 33]. Its structure has the form of an increasing function of a quantity that describes successive stages of development of the vehicle type-approval regulations concerning pollutant emission control, with the values of this quantity rising with the regulation stages. The model is consistent with a characteristic trend in the annual mileage of vehicles of elementary categories corresponding to various pollutant emission classes, observed e.g. in reports of national pollutant emission [29, 34–36] and in the databases incorporated in the INFRAS program for determining characteristics of pollutant emission from motor vehicles: newer vehicles, which are classified in a higher pollutant emission category, are more intensively used than the older ones. The model of intensity of operation of motor vehicles classified in elementary pollutant emission categories was adjusted with using the INFRAS data about the structure of the fleet of motor vehicles at the level of elementary categories.

Figures 3 and 4 show the average annual mileage of motor vehicles classified in elementary pollutant emission categories for two cumulated categories taken as an example, i.e. passenger cars with spark-ignition engines of (1.4÷2) dm^3 cubic capacity and heavy duty articulated trucks of (40÷50) Mg MAM, respectively.

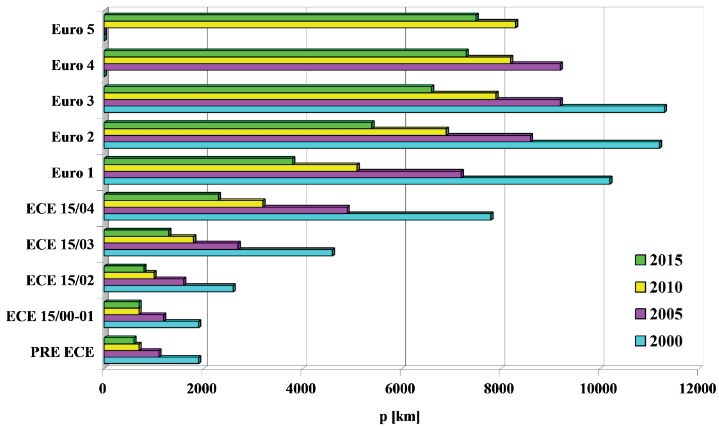

Fig. 3. Average annual mileage of passenger cars with spark-ignition engines of (1.4÷2) dm^3 cubic capacity, classified in ecological categories

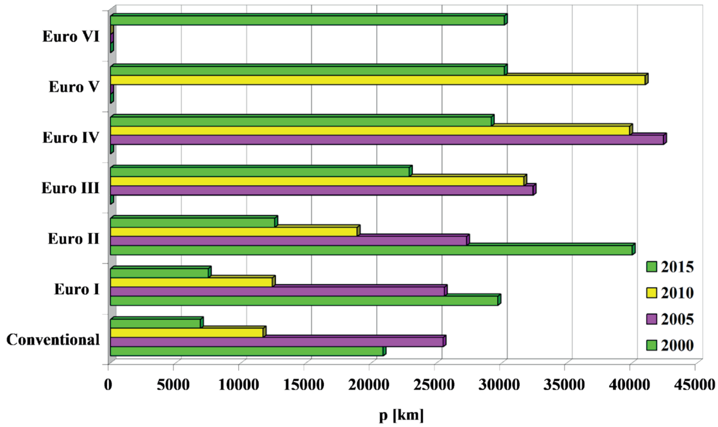

Fig. 4. Average annual mileage of heavy duty articulated trucks of (40÷50) Mg MAM, classified in ecological categories

Figures 5–7 show the adopted shares of the mileage covered in individual driving modes modelled, i.e. urban – u_U, rural – u_R, and highway – u_H driving modes, in the total mileage of the fleets of specific cumulated categories [9].

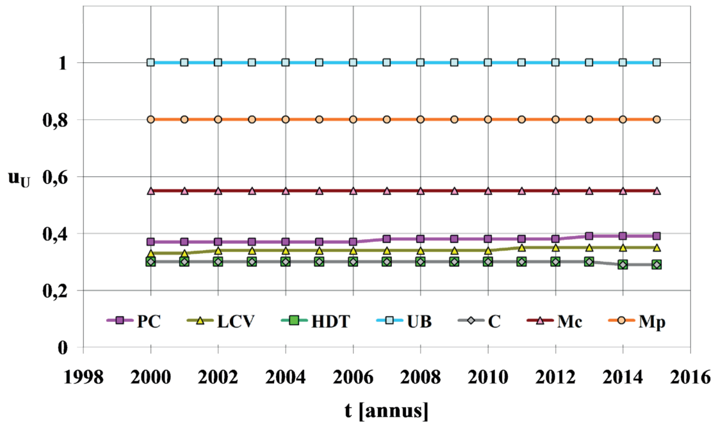

Fig. 5. Shares of the mileage covered in the urban driving mode modelled – u_U in the total mileage of the fleets of specific cumulated categories

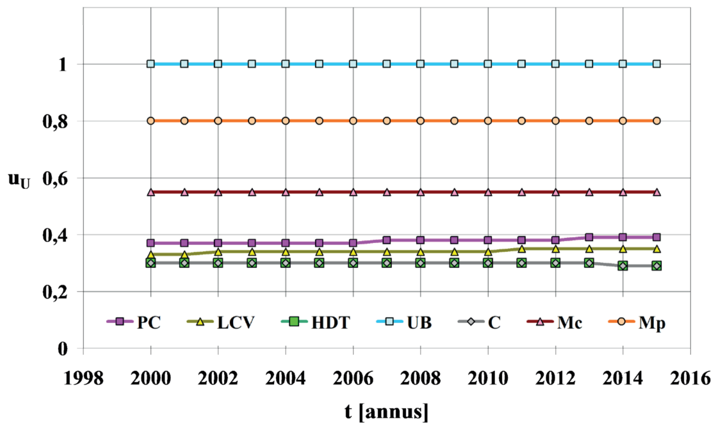

Fig. 6. Shares of the mileage covered in the rural driving mode modelled – u_R in the total mileage of the fleets of specific cumulated categories

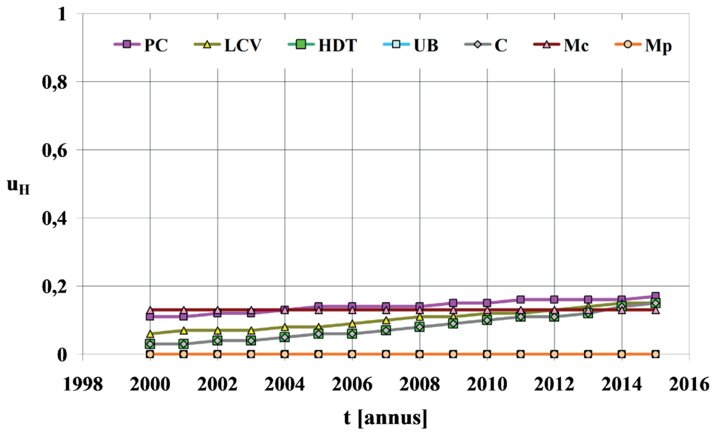

Fig. 7. Shares of the mileage covered in the highway driving mode modelled – u_H in the total mileage of the fleets of specific cumulated categories

Figures 8–10 show the average velocity of the fleets of specific cumulated categories, adopted for individual, i.e. urban – v_U, rural – v_R, and highway – v_H, driving modes modelled [9].

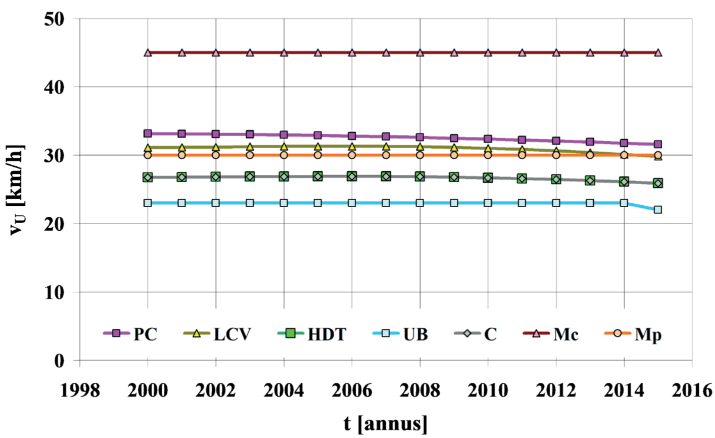

Fig. 8. Average velocity of the fleets of specific cumulated categories in the urban driving mode modelled – v_U

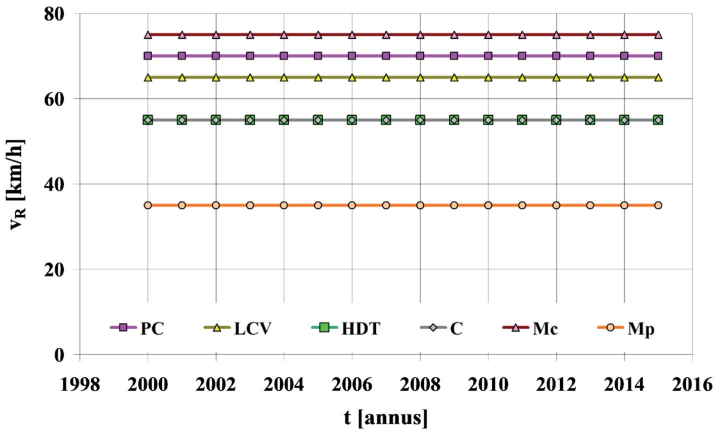

Fig. 9. Average velocity of the fleets of specific cumulated categories in the rural driving mode modelled – v_R

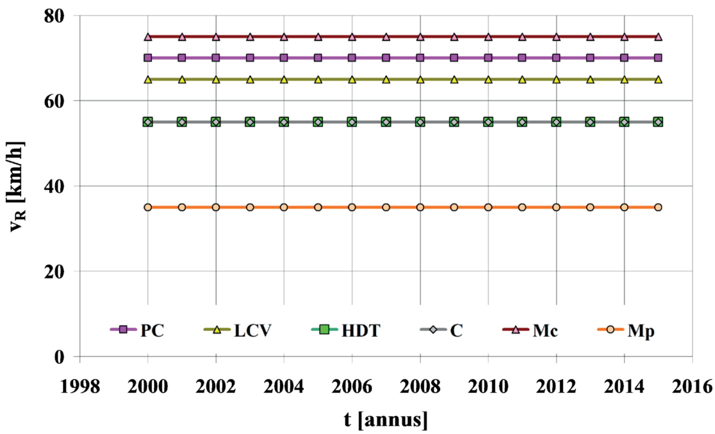

Fig. 10. Average velocity of the fleets of specific cumulated categories in the highway driving mode modelled – v_H

The average length of the vehicle trip under cold start conditions was assumed as 12 km, according to [14].

The other coefficients of the model adopted in the COPERT 4 program, concerning the motor vehicle's technical level related to emission control, were adopted in accordance with program suggestions.

Results of the inventory of pollutant emission from road transport in Poland for 2000–2015

Complete results of the official inventory of pollutant emission in Poland can be found in a report prepared at the National Centre for Emissions Management (KOBiZE) of the Institute of Environmental Protection – National Research Institute [31].

Selected results of the inventory of pollutant emission from road transport in Poland for 2000–2015, i.e. annual national emission of selected pollutants, have been presented in figures 11–17.

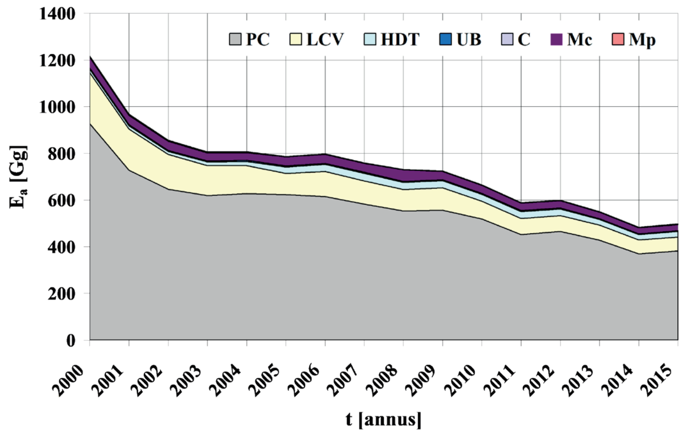

Fig. 11. Annual national emission of carbon monoxide – CO from vehicles of specific cumulated categories

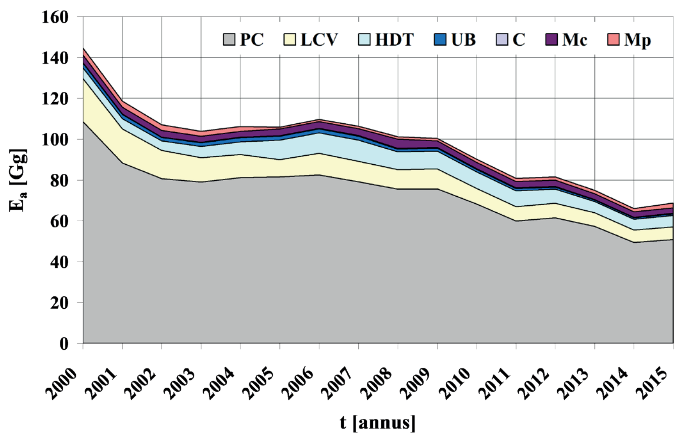

Fig. 12. Annual national emission of volatile organic compounds – VOC from vehicles of specific cumulated categories

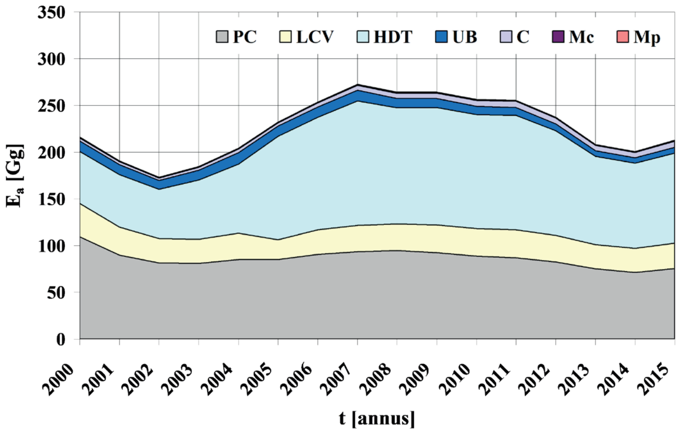

Fig. 13. Annual national emission of nitrogen oxides – NO_x from vehicles of specific cumulated categories

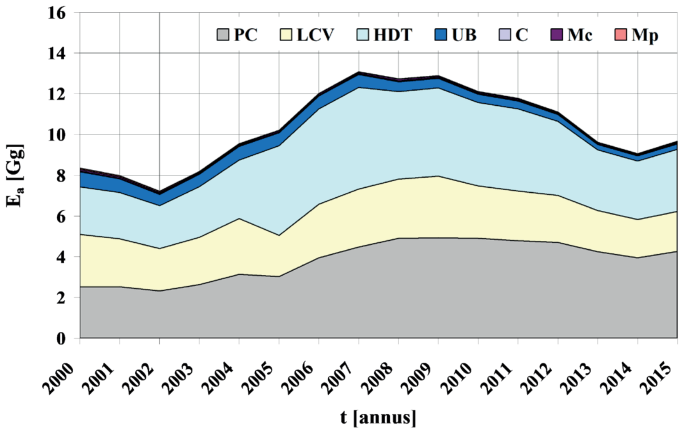

Fig. 14. Annual national emission of particulate matter PM2.5 from tribological pairs of vehicles of specific cumulated categories

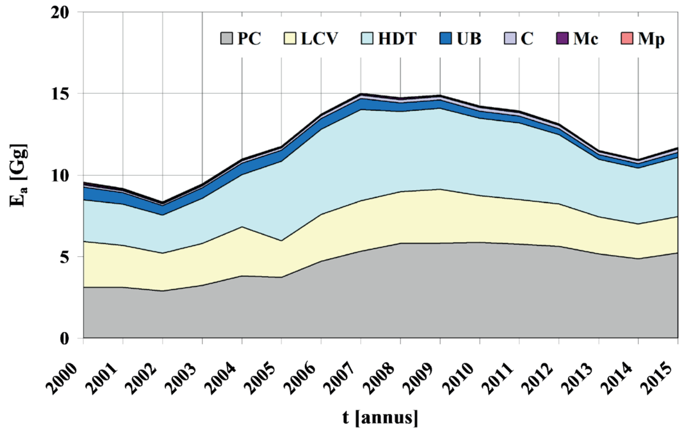

Fig. 15. Annual national emission of particulate matter PM10 from tribological pairs of vehicles of specific cumulated categories

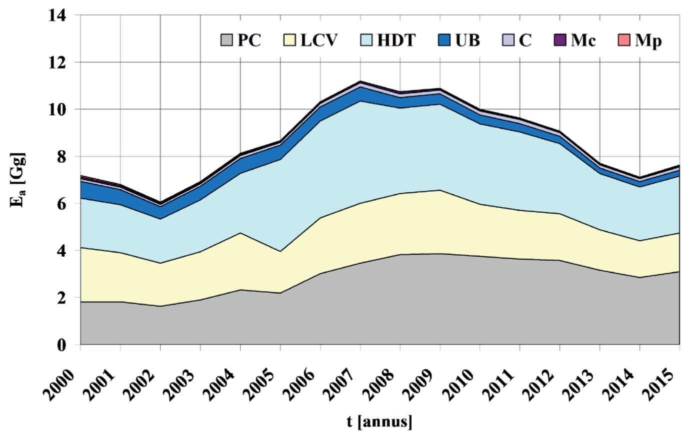

Fig. 16. Annual national emission of particulate matter – PM from IC engines of vehicles of specific cumulated categories

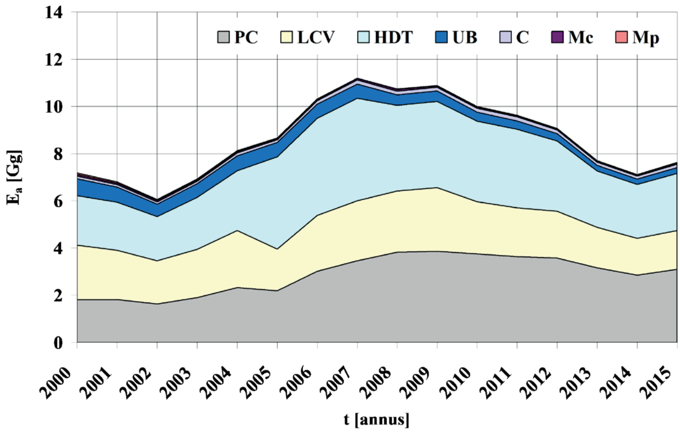

Fig. 17. Annual national emission of carbon dioxide – CO_2 from vehicles of specific cumulated categories

The annual national emission of carbon monoxide and volatile organic compounds shows a downward trend while for the particulate matter and nitrogen oxides, a downward trend can only be noticed since 2007. The annual national emission of carbon dioxide, corresponding to fuel consumption, has been approximately stable from 2011 on.

Noteworthy is a predominating share of passenger cars in the emission of carbon monoxide, volatile organic compounds, and carbon dioxide. As regards nitrogen oxides and particulate matter, a significant share of motor trucks in this emission can be observed.

To assess the progress in the reduction of pollutant emission from road transport, the average pollutant emission factor and the average specific distance emission were determined for an equivalent motor vehicle (figures 18 and 19).

The emission factor W_x for pollutant "x" is defined as derivative of the emission (by mass) m_x of this pollutant with respect to the mass m_f of the fuel consumed [10].

$$W_x = \frac{dm_x}{dm_f} \tag{2}$$

Example time histories of the specific distance emission and emission factor for carbon monoxide have been presented in figures 18 and 19, respectively.

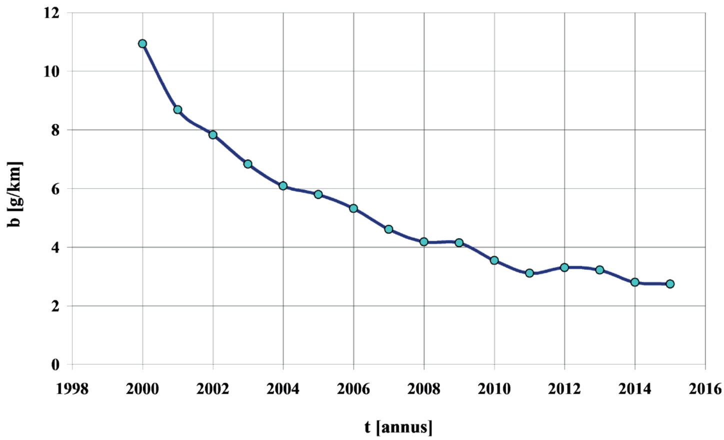

Fig. 18. Average specific distance emission of carbon monoxide – CO for an equivalent motor vehicle

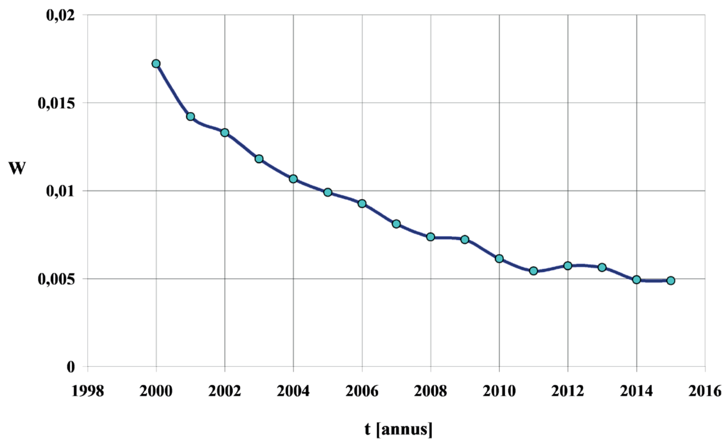

Fig. 19. Average carbon monoxide – CO emission factor for an equivalent motor vehicle

A marked downward trend in both the average specific distance emission and the average emission factor can be seen for carbon monoxide – CO. This is an effect of technological progress in the field of pollutant emission control, which is consistent with the evolution in the pollutant emission limits stipulated in the regulations that govern vehicle type-approval procedures [2, 37, 38].

To evaluate the effects of reduction in emission of the pollutants under consideration, resulting from technological progress, relative specific distance emission and relative emission factors were determined, compared with the corresponding figures of 2000 (figures 20 and 21).

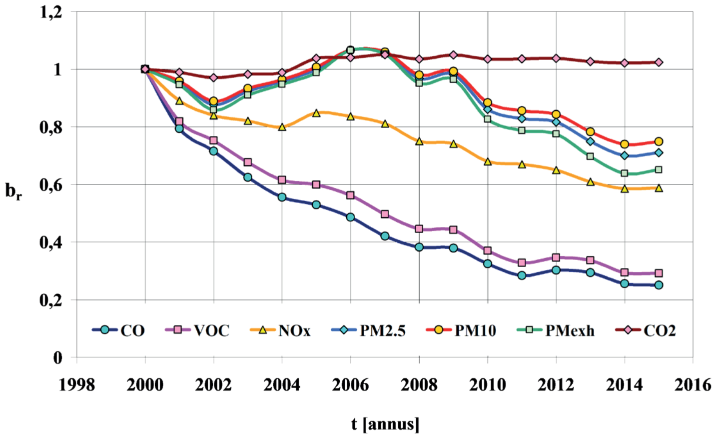

Fig. 20. Relative average specific distance emission of individual pollutants from an equivalent vehicle

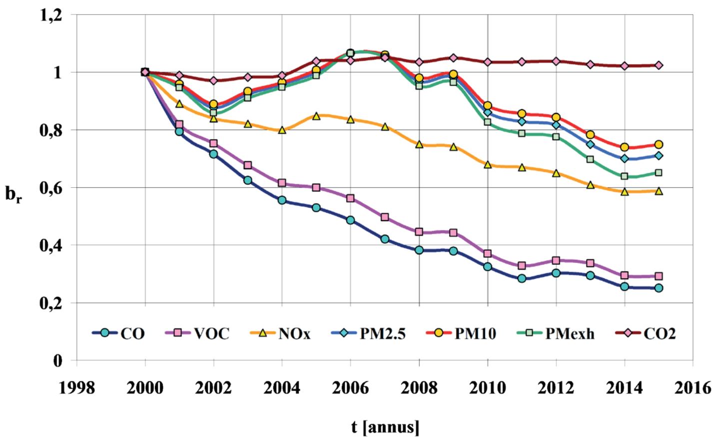

Fig. 21. Relative average factors of emission of individual pollutants from an equivalent motor vehicle

The most significant progress in the controlling of pollutant emission occurred for carbon monoxide (by 75%) and, next, for volatile organic compounds (by 70%). From 2005 on, a drop in the quantities under analysis has been recorded for nitrogen oxides: the difference in relation to the figures of 2000 has reached 41%. As regards particulate matter, the relative average specific distance emission has been declining since 2007. In comparison with the 2000 figures, the emission of particulate matter fractions PM2.5 and PM10 decreased by 30% and 25%, respectively, and the particulate matter – PM emission from the IC engine exhaust systems dropped by 35%.

Recapitulation

The results of the inventory of pollutant emission from road transport in Poland for 2000–2015 as presented herein, officially reported within cooperation in the European Union [32], were obtained for the first time with using the COPERT program preferred in the EU. The problems found to be most difficult in the modelling of pollutant emission were encountered at determining model parameters. The data about the sizes of the fleets of specific elementary categories were determined from databases of the Central Register of Vehicles and Drivers (CEPiK) and the Central Statistical Office. The annual mileages of the vehicles classified in individual cumulated categories were estimated on the grounds of works dedicated to determining the balance of fuel consumption [9]. The annual mileages of motor vehicles classified in elementary pollutant emission categories were estimated with using an authors' model of intensity of motor vehicle operation. To estimate the data on the vehicle driving modes, fuel consumption modelling results [9] were used.

A complete set of results of the inventory of pollutant emission in Poland, including the emission from road transport, can be found in a report prepared at the National Centre for Emissions Management (KOBiZE) of the Institute of Environmental Protection – National Research Institute [32]. This paper shows the results obtained for selected pollutants, chiefly those considered damaging to health and taken into account in the European type-approval procedures applicable to motor vehicles. A marked downward trend was revealed in the annual national emission of substances damaging to health, in spite of dynamic increase in the number of motor vehicles and in the intensity of operation of such vehicles. This is a conclusion of great practical importance, especially in the situation where it has become customary to disseminate opinions about disastrous environmental impact of motorization. The favourable changes in the environmental impact of road transport are chiefly an effect of technological progress in the construction of motor vehicles, which is also reflected in evolution in the limits imposed on the parameters adopted as acceptance criteria in vehicle type-approval procedures. The relative average specific distance emission of pollutants from an equivalent vehicle was significantly reduced in comparison with the 2000 figures, e.g. by 75% for carbon monoxide, by 70% for volatile organic compounds, by 41% for nitrogen oxides, or by (25÷30)% for particulate matter, with a special stress being put on a reduction by 35% in the relative specific distance emission of particulate matter from the IC engine exhaust systems (such particles are extremely dangerous to health because of their very small dimensions, below 1 μm in most cases, and their chemical composition, especially the content of polycyclic aromatic hydrocarbons).

Of course, in spite of the intensification of road transport, which unquestionably may be expected, further decrease may be anticipated in the annual national pollutant emission, chiefly thanks to favourable changes in the ecological composition of the fleet of motor vehicles, e.g. a growth in the number of vehicles with hybrid drive systems. If a change in the fleet composition is considered, with electrically driven vehicles being also taken into account, the analysis of annual national emission will become more complicated, because its scope must cover not only the road transport sector but also the power industry in its part related to the generation and distribution of electric energy [11]. Another problem related to the ecological assessment of the road transport sector is the Life Cycle Assessment[8] of motor vehicles [7].

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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