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THEORY AND PRACTICE OF INVENTORY POLLUTANT EMISSION FROM CIVILIZATION-RELATED SOURCES: SHARE OF THE EMISSION HARMFUL TO HEALTH FROM ROAD TRANSPORT

TEORIA I PRAKTYKA INWENTARYZACJI EMISJI ZANIECZYSZCZEŃ ZE ŹRÓDEŁ CYWILIZACYJNYCH: UDZIAŁ EMISJI ZANIECZYSZCZEŃ SZKODLIWYCH DLA ZDROWIA Z TRANSPORTU DROGOWEGO

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Summary

The article presents authors' generalization of the methods used for the inventory of pollutant emission from civilization-related sources. The study has been illustrated with results of an evaluation of the share of road transport in pollutant emission from civilization-related sources in Poland

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in 2015 with respect to the contribution of road transport to total pollutant emission. Official results of an inventory of the emission of substances harmful to health of living organisms, carried out by the National Centre for Emissions Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute, have been presented. The said results are reported in the European Union. They pertain to the civilization-related sources classified as in SNAP (Selected Nomenclature for sources of Air Pollution). It has been found that among the most important environmental hazards related to the emission of substances harmful to health from civilization-related sources, road transport is chiefly accountable for nitrogen oxides emission; however, the national annual emission of nitrogen oxides in Poland has been decreasing from as long ago as 2007, in spite of a significant growth in the number and intensity of use of motor vehicles. The contribution of motorization to the air pollution with particulate matter is relatively small. Definitely, dusts are predominantly emitted by the power industry, especially the dispersed emission sources. Road transport has been found to emit particularly small quantities of one of the most harmful air pollutants, i.e. sulphur oxides. This has been achieved thanks to widespread introduction of low-sulphur fuels. Thanks to the introduction of unleaded fuels to general use, only trace influence of road transport on lead emission has been recorded.

Keywords: inventory of pollutant emission, road transport

Streszczenie

W artykule przedstawiono autorskie uogólnienie metodyki stosowanej w inwentaryzacji emisji zanieczyszczeń ze źródeł cywilizacyjnych. Rozważania zilustrowano wynikami oceny transportu drogowego w emisji zanieczyszczeń ze źródeł cywilizacyjnych w Polsce w 2015 r. ze względu na udział transportu drogowego w całkowitej emisji zanieczyszczeń. Przedstawiono oficjalne wyniki inwentaryzacji emisji substancji szkodliwych dla zdrowia organizmów żywych, wykonanej w Krajowym Ośrodku Bilansowania i Zarządzania Emisjami Instytutu Ochrony Środowiska – Państwowego Instytutu Badawczego. Wyniki te są raportowane w Unii Europejskiej. Wyniki emisji zanieczyszczeń dotyczą źródeł działalności cywilizacyjnej zgodnie z klasyfikacją SNAP (Selected Nomenclature for sources of Air Pollution). Stwierdzono, że spośród najważniejszych zagrożeń środowiska w związku z emisją ze źródeł cywilizacyjnych substancji szkodliwych dla zdrowia transport drogowy jest przede wszystkim odpowiedzialny za emisję tlenków azotu, jednak krajowa emisja roczna tlenków azotu w Polsce już od 2007 r. zmniejsza się, mimo znacznego przyrostu liczby samochodów oraz intensyfikacji ich użytkowania Stosunkowo mały jest wkład motoryzacji w zanieczyszczenie powietrza cząstkami stałymi. Decydującym źródłem emisji pyłów jest energetyka, szczególnie rozproszone źródła emisji. Szczególnie mała jest emisja z transportu drogowego jednego z najpoważniejszych zanieczyszczeń powietrza – tlenków siarki.

Osiągnięto to dzięki powszechnemu wprowadzeniu niskosiarkowych paliw. Śladowy jest również wpływ transportu drogowego na emisję ołowiu – dzięki wprowadzeniu do eksploatacji paliw bezołowiowych.

Słowa kluczowe: inwentaryzacja emisji zanieczyszczeń, transport drogowy

1. Introduction

The propaganda of populistic circles, not verified by facts because of having arised in a part from lack of knowledge, blames road transport for all evil for the environment. Some scientific circles, either, do not remain faithful to a saying attributed to Aristotle "Amicus Plato, sed magis amica veritas" ("Plato is my friend, but truth is a better friend") and are easily influenced by populistic vogues. Therefore, an attempt was made to analyse the actual share of emission of pollutants harmful to health from road transport in all the emission from civilization-related sources. To do this, the researchers made use of the official inventory results reported by Poland to the European Union in 2015 about pollutant emission from civilization-related sources, according to a Report of the National Centre for Emission Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute in Warsaw) [16]).

In spite of many methodological limitations, the inventory of pollutant emission from both natural and, especially, civilization-related sources has considerable importance for the rationalization of actions aimed at environmental improvement. The limitations chiefly include the impossibility, in many cases, of taking as a basis the results of empirical research and the necessity of using modelling to explore the problem. Of course, a problem arises in such cases as regards the standard of the models adopted and the identification of the models. An air pollutant emitter that is particularly sensitive to the modelling method is road transport, which is characterized by the fact that individual pollution sources are mobile and, in consequence, the empirical verification of the total pollutant emission is impracticable [7]. Therefore, the modelling of pollutant emission is the only way to acquire knowledge of the total emission. The information thus obtained has been used here for evaluating the share of pollutant emission harmful to health from road transport in all the civilization-related emission.

The pollutant emission from civilization-related sources is inventoried in all the developed countries. In the European Union, it is obligatory for all the member states to report results of inventories of national annual emission of pollutants harmful to health of living organisms [11] as well as greenhouse gases [2]. The reports are commonly available, e.g. [4, 12, 14, 18–20]. The inventories of pollutant emission are also carried out in developed states outside of the European Union, e.g. in the USA [3, 17] and Canada [1]. In most cases, the methods of inventory the pollutant emission are similar to each other, thanks to which comparable inventory results are obtained. Although so extensive knowledge about the pollutant emission from individual civilization-related sources is available, popular views relatively often predominate in the formulation of opinions about environmental pollution. This arises in a part from lack of sufficiently thorough analyses of results of the examination of total pollutant emission. An attempt to carry out such an analysis has been made herein.

Results of an analysis of the inventory of national pollutant emission in Poland have been presented.

2. Subject and method of the research

The article presents authors' generalization of the methods used for the inventory of pollutant emission from civilization-related sources.

The subject of this research is the emission of pollutants harmful to health of living organisms from civilization-related sources. The sources of this kind have been classified according to SNAP (Selected Nomenclature for sources of Air Pollution) – Table 1 [11, 12, 14, 15, 18–20].

Table 1. Classification of the civilization-related sources of the emission of pollutants harmful to health of living organisms

SNAP	Selected Nomenclature for sources of Air Pollution
01	Combustion in energy production and transformation industries
02	Non-industrial combustion plants
03	Combustion in manufacturing industry
04	Production processes
05	Extraction and distribution of fossil fuels and geothermal energy
06	Solvent and other product use
07	Road transport
08	Other mobile sources and machinery
09	Waste treatment and disposal
10	Agriculture
11	Other sources and sinks

The following substances are covered by the subject of this research [7, 11–16, 18–20]:

- carbon monoxide – CO;
- non-methane volatile organic compounds – NMVOC;
- polycyclic aromatic hydrocarbons – PAH;
- nitrogen oxides – NO_x;
- total suspended particles – TSP;
- particulate matter PM10 emitted from tribological pairs in motor vehicles – PM10;
- particulate matter PM2.5 emitted from tribological pairs in motor vehicles – PM2.5;
- black carbon – BC;
- ammonia – NH_3;
- sulphur dioxide – SO_2;
- polychlorinated dibenzodioxins and furans – PCDD/F;
- hexachlorobenzene – HCB;
- polychlorobiphenyls – PCB;
- cadmium – Cd;
- mercury – Hg;
- lead – Pb;
- arsenic – As;
- chromium – Cr;
- copper – Cu;
- nickel – Ni;
- zinc – Zn.

This study has been based on results of the inventory of pollutant emission from civilization-related sources carried out in Poland in 2015.

In the inventory of pollutant emission, the following assumptions are usually adopted [7]:

1. The intensity of emission of individual pollutants is an additive quantity.
2. The inventory of pollutant emission exclusively applies to the pollutants in the state as emitted from the emission sources rather than to the substances produced in result of the processes that occur in the environment.

In the inventory of pollutant emission, the basic notion is emission – m, defined as the mass of a pollutant introduced into the environment.

The pollutant emission intensity (rate) – E is a derivative of the pollutant emission treated as a function of time – t with respect to time

$$E = \frac{dm}{dt} \tag{1}$$

The annual emission of pollutants from the whole territory of a specific state is referred to as the national annual pollutant emission – E_a.

The annual pollutant emission is the pollutant emission intensity averaged for the year of the inventory.

In the inventory of pollutant emission in its most general form, the national annual pollutant emission is determined as a product of a pair of mutually conjugated coefficients of inventory of pollutant emission:

- coefficient of pollutant emission – w_e;
- coefficient of activity of pollutant emission from the territory of a state – w_a.

The coefficient of pollutant emission is a zero-dimensional characteristic of a pollutant emission and it is an intensive quantity. The coefficient of activity of pollutant emission represents the total effective work done during the year of the inventory by the pollutant-emitting objects on the territory of the state subject to the inventory of pollutant emission. Thus, the coefficient of activity is an extensive quantity. Hence, the determining of an annual emission from an area other than the territory of a state, e.g. from the area of a region, differs from the one mentioned above only in the referring of the extensive quantity, i.e. the coefficient of activity, to the area under the inventory of pollutant emission.

The annual energy consumption as well as the annual consumption of e.g. fuels and raw materials may be inventoried in a similar way.

In general, the national annual pollutant emission is defined by a formula:

$$E_a = \sum_{i=c}^{C} w_{ec} \cdot w_{ac} \tag{2}$$

where: w_{ei} – mean coefficient of pollutant emission from the c^{th} object, averaged in relation to the total activity of the object during one year of the inventory;

w_{ai} – activity of the c^{th} object during one year of the inventory;

C – number of the pollutant-emitting objects used in the state subject to the inventory of pollutant emission.

The following basic pairs of mutually conjugated coefficients of the inventory of pollutant emission may be discerned in the inventory of pollutant emission:

1. Specific distance emission of a pollutant and distance travelled by the means of transport

   The specific distance emission of a pollutant – b is a derivative of the pollutant emission from a means of transport, treated as a function of distance – s, with respect to the distance travelled by the means of transport:

$$b = \frac{dm}{ds} \tag{3}$$

   Thus, the national annual pollutant emission is:

$$E_a = \sum_{i=1}^{N} b_i \cdot S_i \tag{4}$$

   where: b_i – mean specific distance emission of the pollutant from the i^{th} means of transport, averaged in relation to the total distance travelled by the means of transport during one year of the inventory;

   Si – distance travelled by the i^{th} means of transport during one year of the inventory;

   N – number of the means of transport used in the state subject to the inventory of pollutant emission.

2. Pollutant emission indicator and fuel consumption by mass

   The pollutant emission indicator – W is a derivative of the pollutant emission, treated as a function of fuel consumption by mass – m_f, with respect to the fuel consumption by mass:

$$W = \frac{dm}{dm_f} \tag{5}$$

   Thus, the national annual pollutant emission is:

$$E_a = \sum_{j=1}^{M} W_j \cdot m_{fj} \tag{6}$$

   where: W_j – mean indicator of the pollutant emission from the j_{th} object, averaged in relation to the total fuel consumption by mass of the object during one year of the inventory;

   m_{fj} – fuel consumption by mass by the j_{th} object during one year of the inventory;

M – number of the objects under consideration that were used in the state subject to the inventory of pollutant emission.

3. Energy-related pollutant emission indicator and energy consumption

The energy-related pollutant emission indicator – WE is a derivative of the pollutant emission, treated as a function of energy consumption – Ω, with respect to the energy consumption:

$$WE = \frac{dm}{d\Omega} \tag{7}$$

Thus, the national annual pollutant emission is:

$$E_a = \sum_{k=1}^{K} WE_k \cdot \Omega_k \tag{8}$$

where: WE_k – mean energy-related indicator of the pollutant emission from the k^{th} object, averaged in relation to the total energy consumption of the object during one year of the inventory;

Ω_k – energy consumption by the k^{th} object during one year of the inventory;

K – number of the objects under consideration that were used in the state subject to the inventory of pollutant emission.

4. Specific brake emission of a pollutant and work done by the object

The specific brake emission of a pollutant – e is a derivative of the pollutant emission, treated as a function of the work done by the object – L, with respect to the work done by the object:

$$e = \frac{dm}{dL} \tag{9}$$

Thus, the national annual pollutant emission is:

$$E_a = \sum_{g=1}^{G} e_g \cdot L_g \tag{10}$$

where: e_g – mean specific brake emission of the pollutant from the g^{th} object, averaged in relation to the total work done by the object during one year of the inventory;

Lg – work done by the g^{th} object during one year of the inventory;

G – number of the objects under consideration that were used in the state subject to the inventory of pollutant emission.

5. Production-related pollutant emission indicator and production output indicator

The production-related pollutant emission indicator – $W\Psi$ is a derivative of the pollutant emission, treated as a function of the production output indicator – Ψ, with respect to the production output indicator:

$$W\Psi = \frac{dm}{d\Psi} \tag{11}$$

Thus, the national annual pollutant emission is:

$$E_a = \sum_{r=1}^{R} W\Psi_r \cdot \Psi_r \tag{12}$$

where: $W\Psi_r$ – mean production-related indicator of the pollutant emission from the r^{th} object, averaged in relation to the indicator characterizing the total production output of the object during one year of the inventory;

Ψ_r – indicator characterizing the production output of the r^{th} object during one year of the inventory;

R – number of the objects that were involved in the production under consideration in the state subject to the inventory of pollutant emission.

6. Size-related pollutant emission indicator and object size indicator

The size-related pollutant emission indicator – $W\Theta$ is a derivative of the pollutant emission, treated as a function of the object size indicator – Θ, with respect to the object size indicator:

$$W\Theta = \frac{dm}{d\Theta} \tag{13}$$

Thus, the national annual pollutant emission is:

$$E_a = \sum_{u=1}^{U} W\Theta_u \cdot \Theta_u \tag{14}$$

where: $W\Theta_u$ – mean size-related indicator of the pollutant emission from the u^{th} object, averaged in relation to the indicator characterizing the total size of the object during one year of the inventory;

Θ_u – indicator characterizing the size of the u^{th} object during one year of the inventory;

U – number of the objects under consideration that were present in the state subject to the inventory of pollutant emission.

The pair of the coefficients of inventory of pollutant emission composed of specific distance emission of a pollutant and distance travelled by the means of transport is applicable to the inventory of pollutant emission from transport means.

The pairs of the coefficients of inventory of pollutant emission that consist of:

- pollutant emission indicator and fuel consumption by mass; or
- energy-related pollutant emission indicator and energy consumption

are used for inventory pollutant emission from stationary objects.

The pair where the specific brake emission of a pollutant is taken together with the work done by the object may be used for an inventory of pollutant emission from devices other than transport means, e.g. from building machinery.

A production-related pollutant emission indicator paired with a production output indicator is used for the inventory of pollutant emission from production processes, e.g. in industry, agriculture, or forestry.

The pair of the coefficients of inventory of pollutant emission composed of size-related pollutant emission indicator and object size indicator finds application in the inventory of pollutant emission from dispersed sources, e.g. from fields under cultivation or from households.

In the inventory of pollutant emission from civilization-related sources in Poland, carried out in 2015 [16], the methods as recommended in the EEA guidebook [11] were used. The national annual pollutant emission from road transport was determined with using the COPERT 4 program [13]. The input data for the COPERT program were prepared on the grounds of, *inter alia*, statistical information about motor vehicles in Poland. The said input data have been described in detail in publications [6, 8].

3. Results of the research

The national annual emission of selected pollutants harmful to health of living organisms, from all the sources covered by the inventory – T and from road transport – RT as recorded in Poland in 2015, has been presented in Table 2.

Table 2. National annual pollutant emission in Poland in 2015

	CO	NMVOC	PAH	NO_x	TSP	PM10	PM2.5
				[Mg]			
T	2 401 347.1	530 618.9	139.4	713 803.8	317 739.3	221 115.6	124 562.5
RT	497 931.8	72 051	0.9	213 408.2	14 384.5	11 680.6	9 798.7

	BC	NH_3	SO_2	PCDD/F	HCB	PCB
		[Mg]		[g]	[kg]	
T	24 432.8	267 100.7	690 260.2	290.2	13.3	678
RT	9 798.7	4 390.3	241.2	6.6	2.2	49.4

	Cd	Hg	Pb	As	Cr	Cu	Ni	Zn
					[kg]			
T	13 472.8	10 575.9	507 849	43 547.7	47 292.7	415 557	138 532	1 407 130
RT	184	0	11 711.3	0	4 455.3	90 426.5	791.8	61 018.5

Figs 1–9 visualize the national annual emission of selected pollutants in absolute values and as shares of pollutant emission from sources classified in individual categories; the emission from the sources classified in the road transport category has been marked out in the graphs.

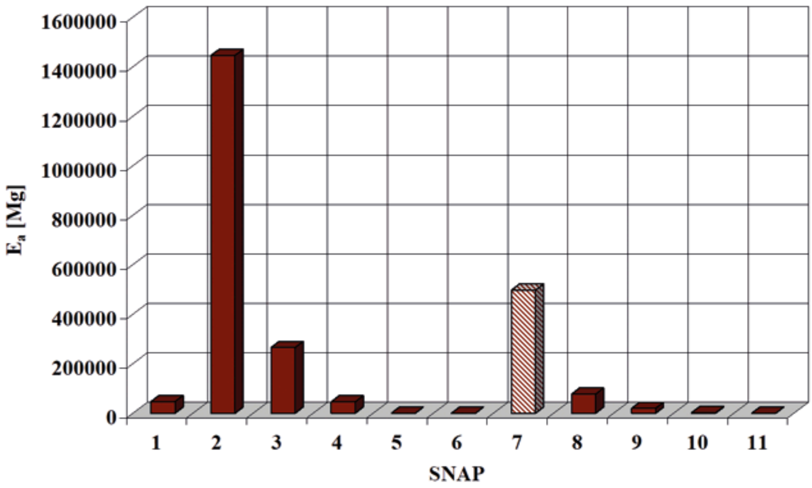

Fig. 1. National annual emission of carbon monoxide – CO

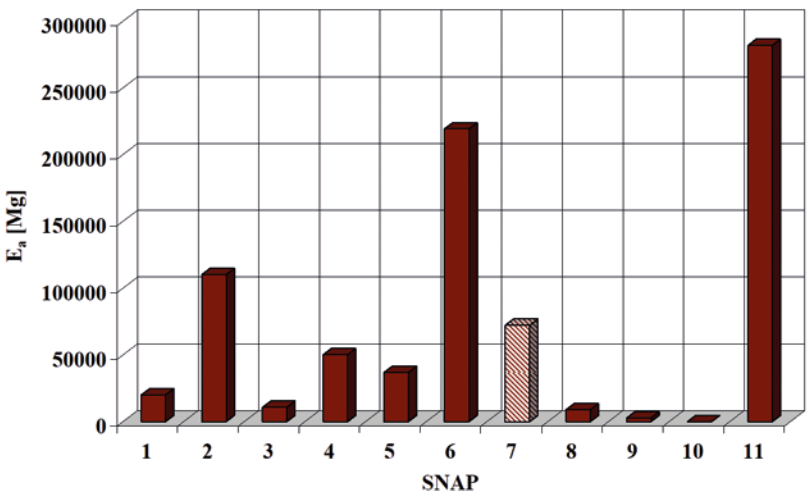

Fig. 2. National annual emission of non-methane volatile organic compounds – NMVOC

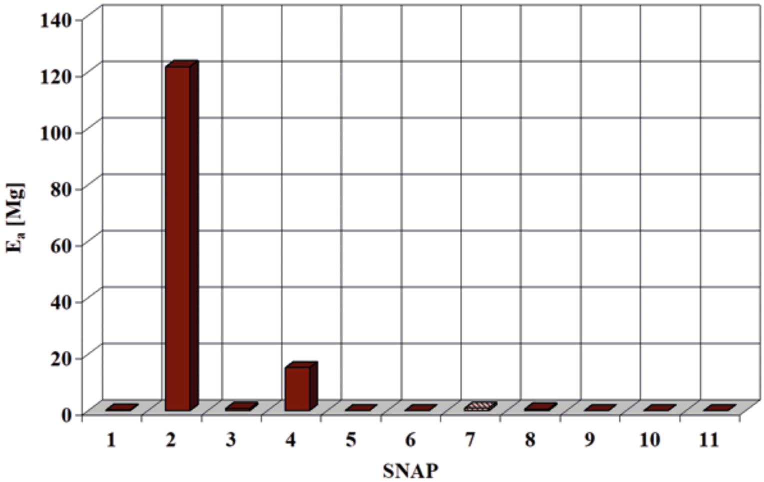

Fig. 3. National annual emission of polycyclic aromatic hydrocarbons – PAH

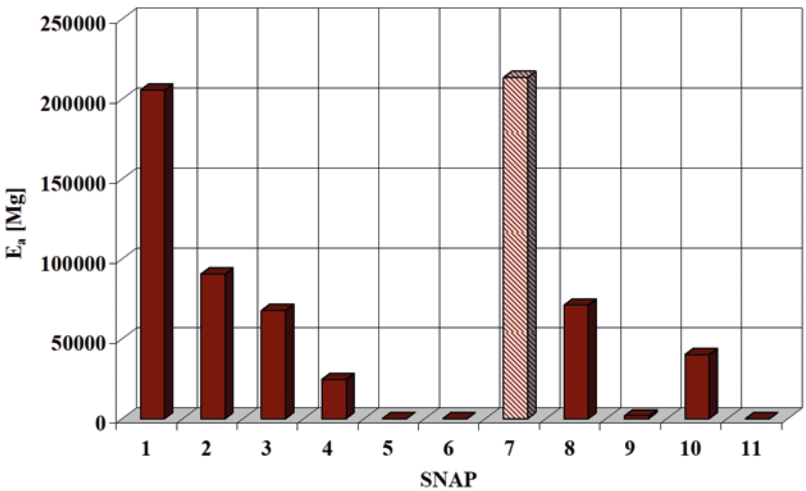

Fig. 4. National annual emission of nitrogen oxides – NO_x

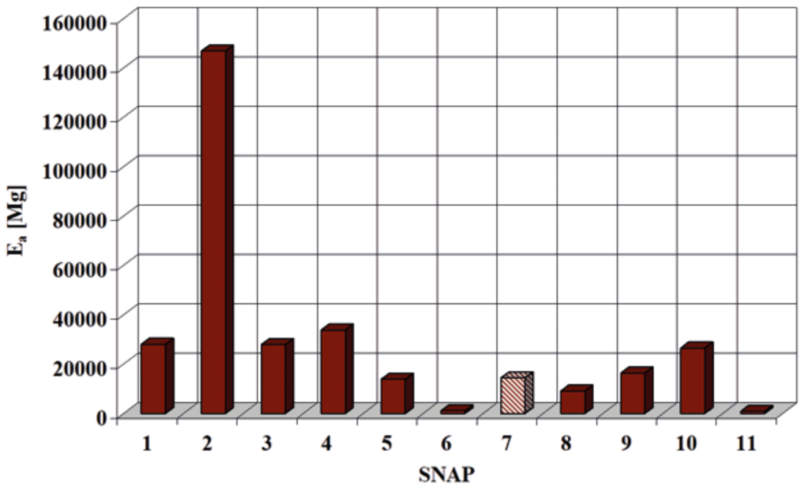

Fig. 5. National annual emission of total suspended particles – TSP

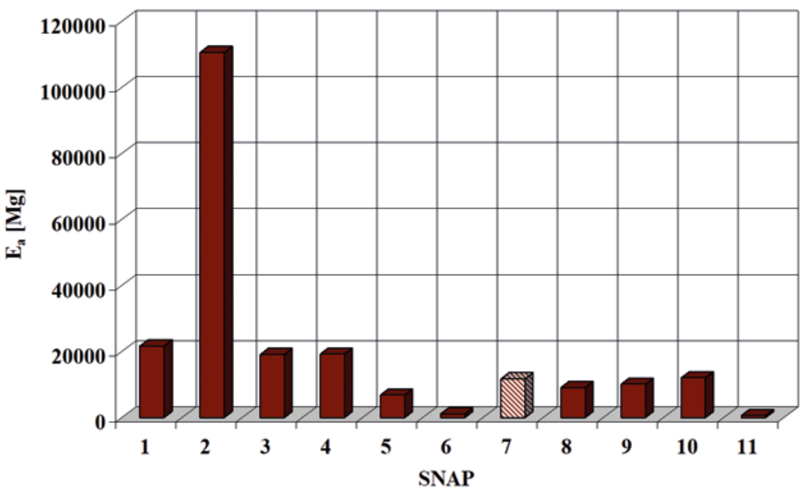

Fig. 6. National annual emission of particulate matter PM10

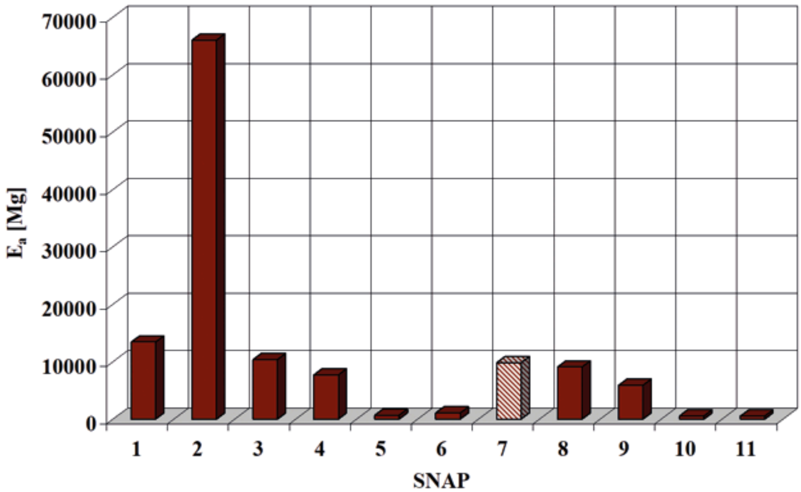

Fig. 7. National annual emission of particulate matter PM2.5

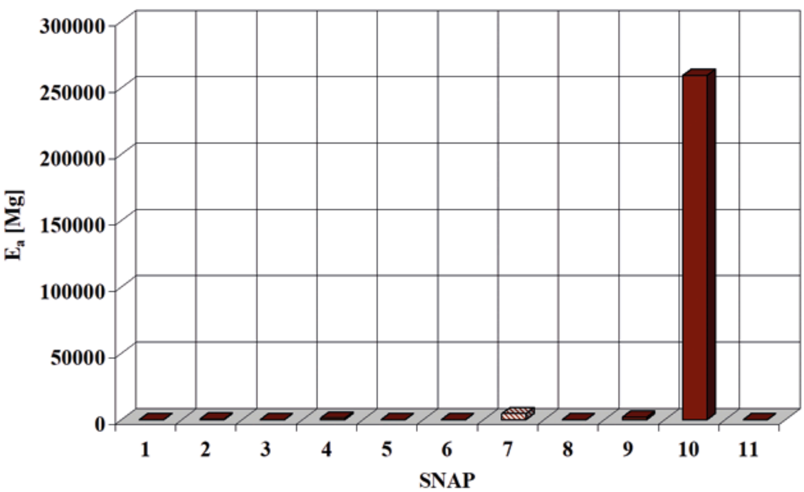

Fig. 8. National annual emission of ammonia – NH3

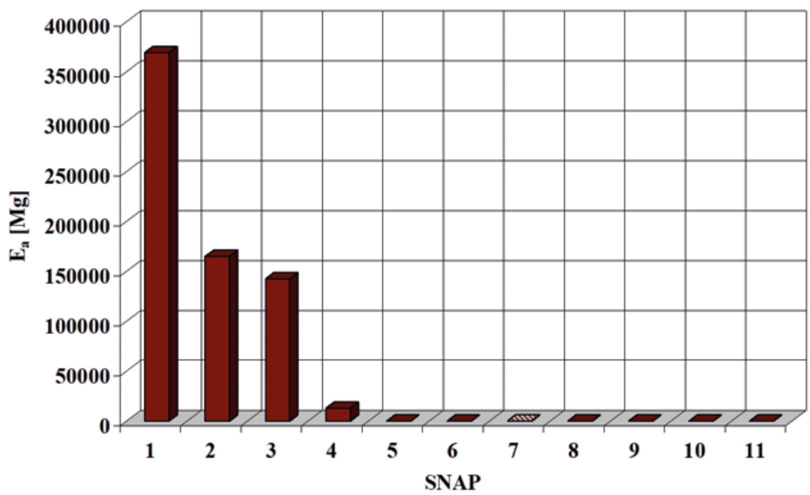

Fig. 9. National annual emission of sulphur dioxide – SO_2

It can be clearly seen how wide diversity exists between the shares of the national annual emission of individual pollutants from all the sources covered by the inventory. Among all the substances the annual emission values of which have been presented, only nitrogen oxides are the pollutant whose emission is in its biggest part attributed to road transport compared with all the other sources under consideration. Road transport has also a considerable share in the emission of non-methane volatile organic compounds. This is confirmed by the fact that the occurrence of photochemical smog in large urban agglomerations is chiefly caused by road transport. However, the emission of polycyclic aromatic hydrocarbons, extremely dangerous for health, from motor vehicles is rather insignificant. So is the share of dusts emitted from road transport in all the dust emission. In additional consideration of the inappreciable emission of sulphur oxides from motor vehicles, a statement may be made that the blaming of chiefly the road transport for the London smog in in most cases unjustified.

Figs 10 and 11 show the share of national annual pollutant emission from road transport in the national annual pollutant emission from all the emission sources under inventory.

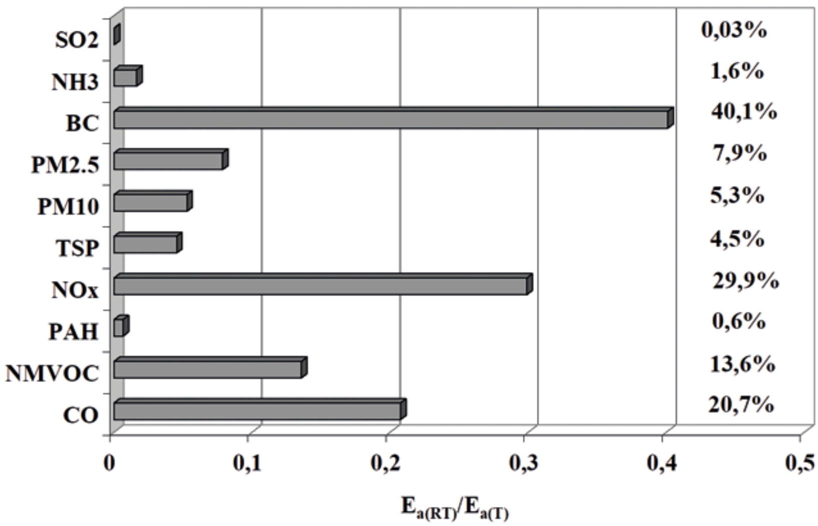

Fig. 10. Share of national annual pollutant emission from road transport in the national annual pollutant emission from all the emission sources under inventory

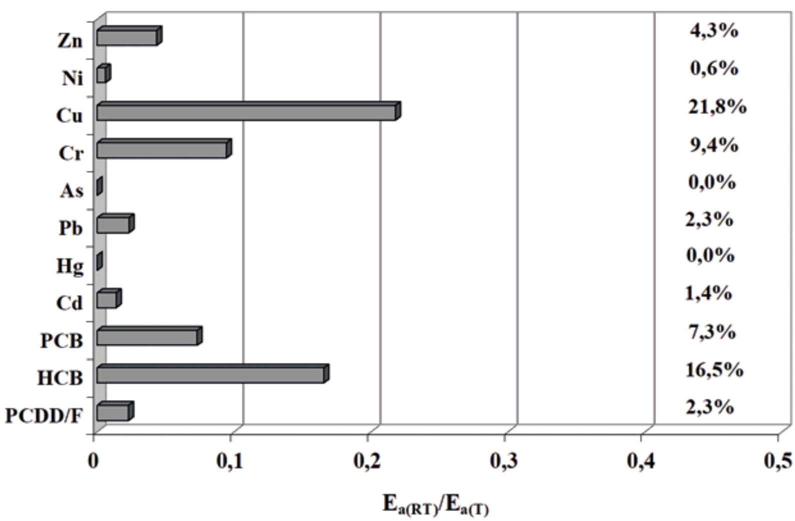

Fig. 11. Share of national annual pollutant emission from road transport in the national annual pollutant emission from all the emission sources under inventory

The share of road transport in the national annual pollutant emission from all the emission sources is the highest (40%) in the case of black carbon. This is caused by the fact that the carbon fraction is the main component of the particulate matter that is discharged from exhaust systems of internal combustion engines. For nitrogen oxides, this share is about 30%. In the case of carbon monoxide and non-methane volatile organic compounds, this share is about 20% and almost 14%, respectively. As regards heavy metals, this share is small, except for copper, for which it is about 22%. An extremely small share is observed for sulphur oxides, thanks to the fact that practically sulphurless fuels have been introduced since 1990, chiefly because of the requirements arising from the use of catalytic systems of exhaust gas treatment [5]. A similar cause-and-effect connection could be seen in result of the introduction of unleaded petrol grades; in consequence, the share of road transport in the lead emission has become very small (2.3%).

4. Recapitulation

The article presents authors' generalization of the methods used for the inventory of pollutant emission from civilization-related sources.

In recapitulation of the evaluation of the share of road transport in pollutant emission, the following conclusions may be formulated:

1. Among the most important environmental hazards related to the emission of substances harmful to health from civilization-related sources, road transport is chiefly accountable for nitrogen oxides emission. The emission of this pollutant is conducive to the risk of occurrence of photochemical smog in large urban agglomerations in the summer season. It is worth noticing, however, that the nitrogen oxides emission from internal combustion engines could be successfully reduced to a significant extent thanks to new technological solutions [5, 21, 22]; in this connection, the national annual emission of nitrogen oxides has already been declining in Poland since 2007, in spite of a significant growth in the number of motor vehicles and in the intensity of their operation [6].

2. The contribution of motorization to the air pollution with particulate matter is relatively small. Definitely, dusts are predominantly emitted by the power industry, especially dispersed emission sources; this has been confirmed by measurements of dust concentration in the atmosphere depending on the time of the year and the related heating seasons [9, 10]. It should be remembered, however, that the local dust concentrations in areas close to arterial roads is strongly correlated with the intensity of particulate matter emission from motor vehicles [9, 10].

3. Particularly advantageous is the very small emission of sulphur oxides, which are counted among the most harmful air pollutants, from the road transport sector. This has been achieved thanks to widespread introduction of low-sulphur fuels.

4. The impact of road transport on lead emission is also small, thanks to the introduction of unleaded fuels to general use.

An analysis of results of pollutant emission inventories carried out in other countries [1, 3, 4, 12, 13, 17–20] provides grounds for the formulation of similar conclusions: the substantial technological progress in the automotive industry has considerably contributed to a reduction in the environmental hazard caused by road transport.

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
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Basic notation

CO	carbon monoxide
NMVOC	**N**on-**M**ethane **V**olatile **O**rganic **C**ompounds
PAH	**P**olycyclic **A**romatic **H**ydrocarbons
NOx	nitrogen oxides
TSP	**T**otal **S**uspended **P**articles
PM10	**P**articulate **M**atter 10
PM2.5	**P**articulate **M**atter 2.5
BC	**B**lack **C**arbon
NH_3	ammonia
SO_2	sulphur dioxide
PCDD/F	**P**oly**C**hlorinated **D**ibenzo-p-**D**ioxins and polychlorinated dibenzo**F**urans
HCB	**H**exa**C**hloro**B**enzene
PCB	**P**oly**C**hloro**B**iphenyls
Cd	cadmium
Hg	mercury
Pb	lead
As	arsenic
Cr	chromium
Cu	copper
Ni	nickel
Zn	zinc
SNAP	**S**elected **N**omenclature for sources of **A**ir **P**ollution
E_a	national annual emission
(RT)	**R**oad **T**ransport
(T)	**T**otal emission sources