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Simulation studies of pollutant emissions from road vehicles using models for inventories of pollutant emissions

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Countries are obliged by international regulations to conduct annual pollutant emissions inventories. Road transport is one of the sectors for which an inventory of pollutant emissions is carried out. Determining pollutant emissions from road transport is possible only by modeling these emissions – that is why unified emission models are used. In this work, the COPERT and HBEFA INFRAS software are used to determine pollutant emissions characteristics for various vehicle traffic models. The article presents the principles of modeling pollutant emissions from road vehicles. The rules for qualifying road vehicles into elementary and cumulative categories have been systematized. Models of road vehicle traffic and ways of taking them into account in modeling pollutant emissions are presented. The following emissions of pollutants harmful to the health and life of living organisms are considered: carbon monoxide, non-methane volatile organic compounds, nitrogen oxides and total suspended particles. The trends of the national annual emissions of the tested pollutants for the years 2000–2020 and the results of simulation tests of pollutant emissions models are presented.

Key words: *road transport, air pollutant emissions inventory, emission modeling*

1. Introduction

The aim of the work is to use the procedures applied in the official pollutant emissions inventory from sector of road transport to study the model of this emission. The operating states of combustion engines, that determine emissions of pollutants from combustion engines are [6]:
– engine speed process
– torque process
– thermal state of the combustion engine.

The quantities determining pollutant emissions from road vehicles are [6]:
– vehicle velocity process
– vehicle movement resistance
– thermal state of the combustion engine.

Therefore, in the pollutant emissions inventory from road vehicles, vehicle traffic models are adopted.

Road transport emission inventories are currently performed in every developed country. The inventory of pollutant emissions from mobile sources is compiled using dedicated models of emissions. This is due to the fact that it is not possible to estimate the total emissions from mobile sources using empirical methods, unlike stationary sources. For this reason, it is necessary to use standardized procedures for comparative purposes. In the pollutant emissions inventory, procedures are used in accordance with the guidebook for the national inventories prepared by the Convention's Task Force on Emission Inventories and Projection (TFEIP) and the European Environmental Agency (EEA) [1–3, 10, 18]. To estimate emissions of air pollutants from vehicles, COPERT software is used [13, 14, 19]. This model was developed at Aristotle University of Thessaloniki in cooperation, among others, with the creators of the HBEFA INFRAS AG software [8, 20].

Activities connected to modeling pollutant emissions from road vehicles were also part of the CORINAIR program [15]. Moreover, the European programs COST 319 „Estimation of pollutant emission from transport" [16, 21] and MEET [23] played an important role.

The article aims to use the procedures applied in the official inventory of pollutant emissions from road vehicles to study the model of this emission due to the input data and model parameters:
– the input data characterizes the configuration of road vehicles in relation to the number and intensity of their use in the elementary category
– the model parameters concern the nature of road vehicle movement.

2. Objectives of modeling emissions from road vehicles

The most important objectives of modeling emissions connected with road transport are [3, 26, 27]:
– preparing inventory of pollutant emissions associated with the use of road vehicles in time as well as space, depending on their types and the conditions of use
– examining the influence of road vehicles configuration and operating conditions on road transport pollutant emissions
– assessing the environmental effects of pollutants emitted from road vehicles.

The Polish Air Pollutant Emission Inventory is performed by the National Centre for Emission Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute (IOŚ-PIB). Following Poland's international obligations, reports with the results [24, 25] are provided to the European Union as a result of Directive (EU) 2016/2284 of the European Parliament and the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants [12, 17] and to the United Nations Economic Commission for Europe under the Convention on Long-Range Transboundary Air Pollution [12].

As a result of KOBiZE's activities in the field of pollution emission inventory, many articles were published, including [3–7, 26, 27].

The paper [3] presents the results of an inventory of pollutants hazardous to the health of living organisms emitted by road transport in Poland between 1990 and 2017. The following substances were analysed: carbon monoxide, non-methane volatile organic compounds, nitrogen oxides and size fractions of particulate matter. The results showed that between 1990 and 2017, annual emissions from road vehicles in Poland had an increasing trend for TSP (74%), PM10 (64%), PM2.5 (52%) and NO_x (25%), while emissions of CO (–117%) and NMLZO (–85%) had a decreasing trend.

The paper [26] presents the results of an inventory of pollutant emissions from road transport in Poland for the period 1990–2020. The energy intensity of road vehicles of the cumulative categories was also studied. Analysis of the energy emission factor of pollutants clearly shows that it is decreasing, except ammonia, which is linked to the use of catalytic reduction systems for nitrogen oxides.

The article [27] analysed the changes in annual national emissions of selected pollutants due to the contribution of these emissions from the cumulative category of road vehicles to total national annual emissions from transport. Road transport has the dominant share in national emissions, and significant progress in reducing emissions can be attributed to significant technical improvements in the internal combustion engines of road vehicles.

The paper [4] investigated the environmental risks posed by particulates generated by road transport. Areas with characteristic traffic conditions were used for the study: within and outside cities, as well as highways and expressways. The obtained results showed that technical progress in the automotive sector contributed largely to reducing the emission of particulate matter contained in exhaust gases, but had a small impact on the emission of particulate matter from tribological processes.

Article [5] presents the results of research on pollutant emissions from road vehicles in cumulative categories depending on traffic conditions: in cities, outside cities, as well as on highways and expressways. Large differences were found in the shares of individual pollutants from vehicles in the tested traffic conditions. This is particularly visible in the case of nitrogen oxides, which have the largest share of emissions outside cities, unlike other substances with the largest share of emissions in cities with heavy traffic.

Paper [6] presents the results of research on the impact of the thermal state of vehicle combustion engines on pollutant emissions in the years 1990–2017. The results show that during engine warm-up, carbon monoxide emissions constitute the largest share (up to 50%) in the national annual total emissions. Next in order are volatile organic compounds, and the lowest is share of nitrogen oxides (less than 5%).

Paper [7] presents the results of the inventory of pollutant emissions from motor vehicles in Poland using COPERT 5 software. The relative increase in emissions of carbon monoxide and non-methane volatile organic compounds is less than 10%, that of nitrogen oxides and particulate matter is less than 15%, and that of carbon dioxide is approximately 14%.

The article [27] included an inventory of pollutant emissions in Poland from various transport categories in the years 1990–2020. The shares of the national annual emission of the tested pollutants from each examined transport category in the total national annual emission from transport were assessed.

Research on the inventory of pollutant emissions from anthropogenic sources is also carried out in other countries

For example, [9] presents the results of an inventory of pollutant emissions from road transport in China. The results of testing the intensity of pollutant emissions in a grid with a high resolution of 0.5° × 0.5° made it possible to determine the distribution of their concentrations using models of the spread of pollutants.

Paper [22] presents the results of an inventory of pollution from various sectors, including road transport, in Jakarta in 2005–2015. To determine the intensity of pollutant emissions, pollutant emission averaged factors for the cumulated categories of road vehicles were used. In the road transport sector, heavy duty vehicles had the largest share in pollutant emissions.

3. Methodology

The following physical quantities are used in modeling emissions associated with road transport activities for the inventory purposes [11]:

- Specific distance emission of pollutants – b_m – that is, the derived emission of pollutants – m, relative to the length of road travelled by the road vehicle – s.

$$b_m = \frac{dm}{ds} \quad (1)$$

- Pollutant emissions intensity – E_m – derivative of pollutant emissions concerning time – t.

$$E_m = \frac{dm}{dt} \quad (2)$$

National annual emission of pollutants, defined as the intensity of national emissions averaged over one calendar year – E_a.

The methodology for simulation studies of road vehicles emissions using emission inventory models includes the following tasks:

1. Systematizing the problems of:
   - modeling pollutant emissions from road transport
   - identification of the model of emissions related with road vehicles.
2. Modeling the nature of road vehicle traffic under given conditions:
   - in urban congestion – Cg
   - in urban with no congestion – U
   - rural – R
   - motorways and highways – H.
3. Simulation studies on the model of pollutant emissions arising from road traffic considering a variety of model inputs in Poland between 2000 and 2020:
   - number of vehicles in individual cumulative categories

- use intensity of road vehicles of cumulative categories
- model parameters.

4. Sensitivity studies of the road vehicles emission model on different vehicle traffic conditions.

The substance pollutants considered in this work, and whose emissions are inventoried are as follows:
- carbon monoxide – CO
- non-methane volatile organic compounds – NMVOC
- nitrogen oxides – NO_x
- total suspended particulate matter – TSP.

Specific distance emissions in the case of road transport are modeled as a function of the average value of the vehicle speed process.

Data for modeling pollutant emissions from road transport in Poland were adopted following official data used in the pollutant emission inventory [24, 25].

4. Modeling the structure of road vehicles

The classification of road vehicles is defined in so-called categories [8, 9]. In general, a category is a set of entities that share certain attributes and are interrelated. The elementary category comprises those vehicles that have the same criterion characteristics. The cumulative category comprises those vehicles, which do not have the same criterion characteristics.

The criterion characteristics for elementary categories [13, 14] are as follows:
- purpose of a road vehicle
- conventional size of the road vehicle
- ecological category due to pollutant emissions
- engine circulation
- fuel type
- type of engine and drive system.

The cumulative categories due to the use of a road vehicle [13, 14] are as follows:
- passenger cars
- light commercial vehicles
- heavy duty trucks
- city buses
- coaches
- L-category road vehicles.

5. Simulation studies on the model of pollutant emissions from road vehicles

5.1. Types of simulation studies

The simulation studies on the pollutant emission model from road vehicles was carried out in accordance with the following program:
- simulation studies of emissions from passenger cars in 2020 based on the HBEFA INFRAS model [20]
- simulation studies of emissions from individual cumulative categories of vehicles between 2000 and 2020 based on the COPERT model [13, 14]
- simulation studies of emissions from passenger cars due to model vehicle traffic conditions based on the HBEFA INFRAS model [20].

5.2. Example results of the emission model simulation studies for passenger cars in 2020

Figures 1–4 show the characteristics of the specific distance emissions from the cumulative category of passenger cars as a function of the average speed.

Specific distance emission are determined for traffic in model conditions (available in the HBEFA INFRA software): urban traffic congestion, urban traffic with no congestion, rural, motorways and highways.

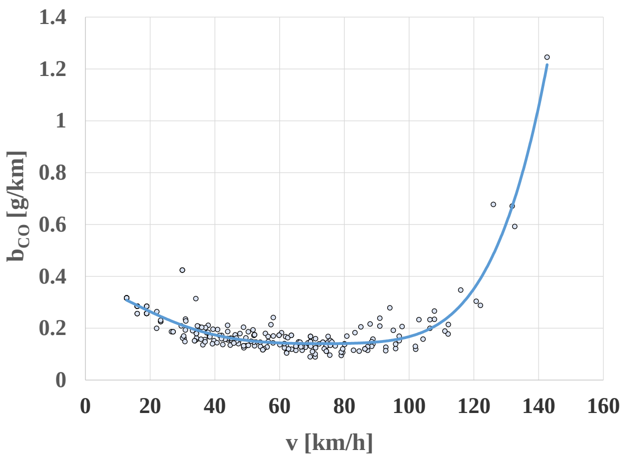

Fig. 1. Characteristics of the specific distance CO emission – b_{CO} depending on the average speed – v of passenger cars

There is a clear increase in specific distance emission of CO as the average speed of the vehicle increases, which results in an increase in engine load.

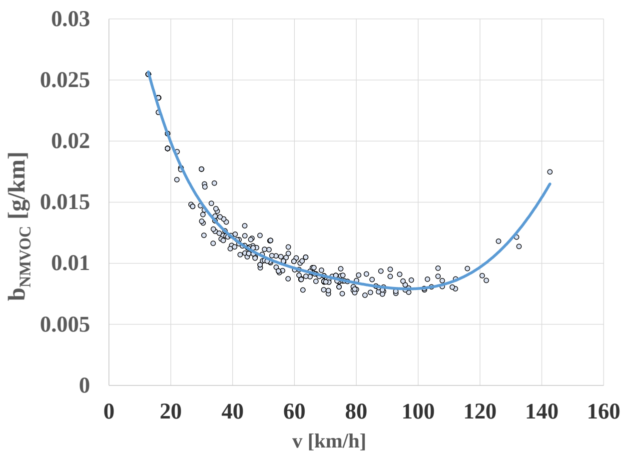

Fig. 2. Characteristics of the specific distance NMVOC emission – b_{NMVOC} depending on the average speed – v of passenger cars

The high value of specific distance NMVOC emissions for low average vehicle speed results from the large share of engine operating time at idle speed and at low loads in these traffic models. The increase in specific distance emission of NMVOC at a high average speed of the vehicle corresponds to a high engine load.

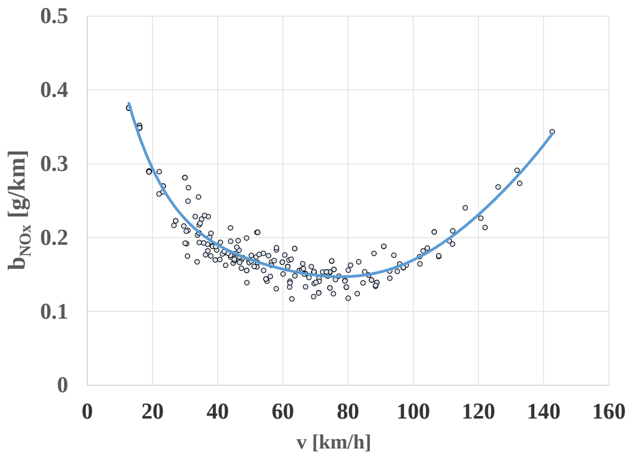

Fig. 3. Characteristics of the specific distance NO_x emission – b_{NOx} depending on the average speed – v of passenger cars

The high value of specific distance emissions of NO_x for a low average vehicle speed results from high traffic instability – frequent braking and acceleration. The increase at high vehicle speed results from the increasing engine load.

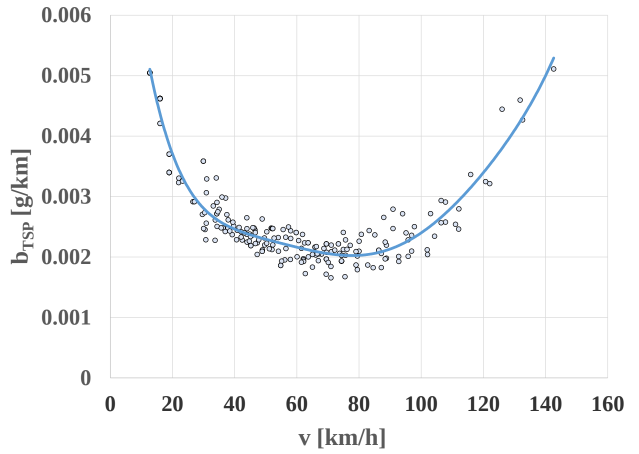

Fig. 4. Characteristics of the specific distance TSP r – b_{TSP} depending on the average speed – v of passenger cars

The correlation of the specific distance TSP emission with the average speed of the vehicle is similar to the pattern of specific distance NO_x emission.

Despite some differences in specific distance pollutant emissions for traffic models with a similar value of average vehicle velocity, the dependence of these emissions on average velocity shows a clear regularity.

The characteristics of the specific distance emissions for all traffic conditions enable the approximation of the dependence on the average velocity in a regular form.

5.3. Example results of the emissions model simulation studies for road transport between 2000 and 2020

In the Figures 5–8 are shown examples of national annual emissions of selected pollutants in the years 2000–2020 from selected cumulative categories of road vehicles in model traffic conditions: urban congestion, urban outside traffic congestion, rural, highways and motorways, and the total emission of pollutants.

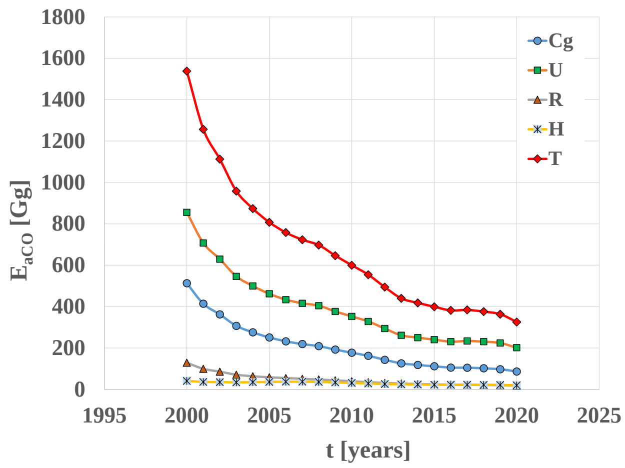

Fig. 5. National annual CO emission – E_{aCO} from passenger cars in years 2000–2020 in model traffic conditions: Cg – urban congestion, U – urban outside traffic congestion, R – rural, H – highways and motorways and T – the total CO emission

There is a general dependence on the decrease in the CO emission from passenger cars in subsequent balancing years in all model traffic conditions, despite the significant intensification of vehicle use. This environmentally beneficial trend results from the technological progress of introduced vehicles.

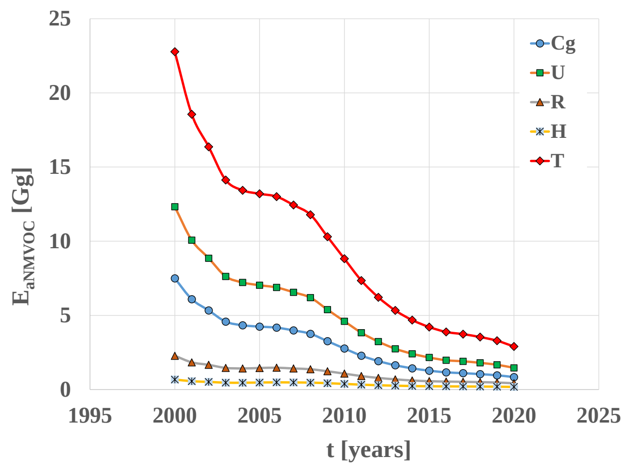

Fig. 6. National annual NMVOC emission – E_{aVMVOC} from light commercial vehicles in years 2000–2020 in model traffic conditions: Cg – urban congestion, U – urban outside traffic congestion, R – rural, H – highways and motorways and T – the total NMVOC emission

The trend in the NMVOC emission from light commercial vehicles is similar to the trend of CO emission.

The trend of the NO_x emission is different than for the emission of CO and NMVOC. Initially – until 2009 – NO_x emission increased as a result of the significant intensification of the use of heavy duty trucks, which is linked to the economic progress in that period. Only in recent years, the value of NO_x emissions has been determined by increasing the effectiveness of catalytic nitrogen oxide reduction systems.

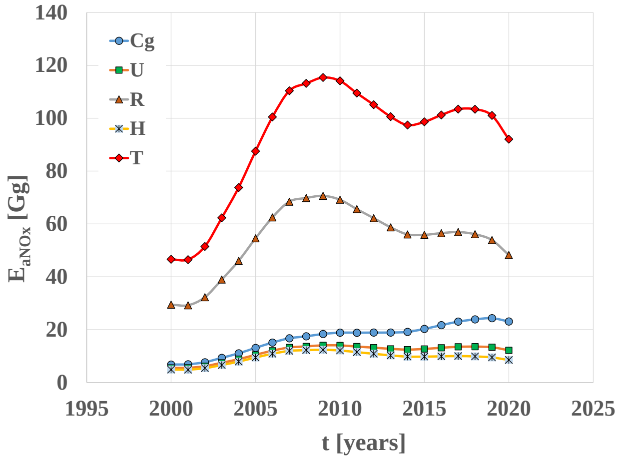

Fig. 7. National annual NO_x emission – E_{aNOx} from heavy duty trucks in years 2000–2020 in model traffic conditions: Cg – urban congestion, U – urban outside traffic congestion, R – rural, H – highways and motorways and T – the total NO_x emission

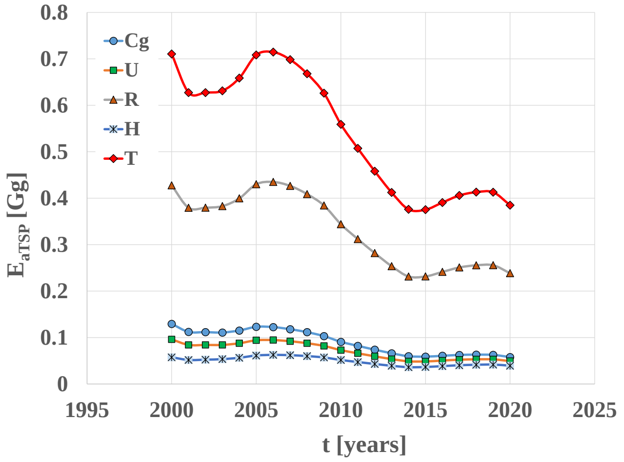

Fig. 8. National annual TSP emission – E_{aTSP} from coaches in years 2000–2020 in model traffic conditions: Cg – urban congestion, U – urban outside traffic congestion, R – rural, H – highways and motorways and T – the total TSP emission

TSP emission from coaches has a general tendency to decrease (the exception is the period from 2002 to 2006 and from 2015 to 2019). This is due to significant progress in the technical vehicles properties.

The dependency between annual national emissions in the years 2000–2020 for various categories of road vehicles and various pollutants varies. In general, despite the significant intensification of the use of vehicles (their number and annual mileage), CO and NMVOC emissions have a clear downward trend. Progress in technology, particularly in the area of emissions reduction, has contributed to this. For NO_x and TSP emissions, there is no such clear dependency. In this case, there is a more difficult way to reduce pollutant emissions – this trend occurs after 2006–2009.

5.4. Emissions model simulation studies for passenger cars due to model vehicle traffic conditions

Simulation studies on the emission model for passenger cars due to model vehicle traffic conditions was carried out in order to test the sensitivity of road emissions in model traffic conditions differing in average driving velocity.

Table 1 presents the simulation program for the model of emissions from passenger cars in terms of their average speed in model traffic conditions.

Table 1. Simulation program for the model of pollutant emissions from passenger cars in terms of their average speed in model traffic conditions

Simulation number		1	2	3	4	5
Model traffic conditions	Average speed [km/h]					
Urban congestion	v_{Cg}	4	5	6	7	8
Urban outside traffic congestion	v_U	30	35	40	45	50
Rural	v_R	60	65	70	75	80
Highways and motorways	v_H	100	105	110	115	120

In the Figures 9–12 are shown the dependencies of specific distance emission from passenger cars in model traffic conditions on average velocity.

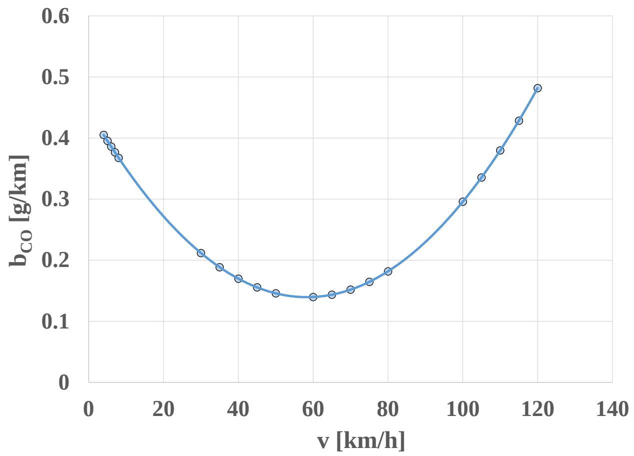

Fig. 9. Dependency of specific distance CO emission from passenger cars in model traffic conditions – b_{CO} on average speed – v

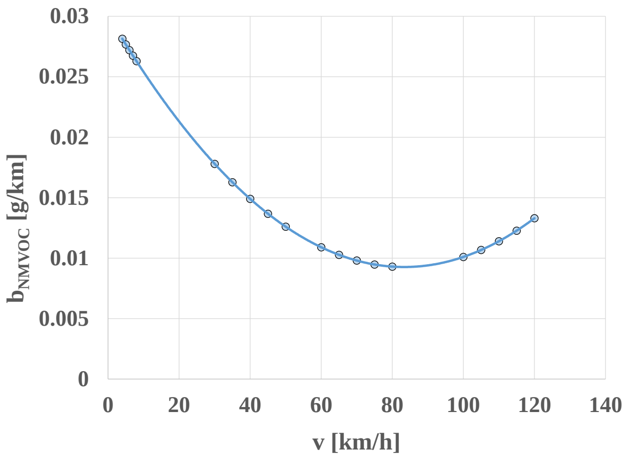

Fig. 10. Dependency of specific distance NMVOC emission from passenger cars in model traffic conditions – b_{NMVOC} on average speed – v

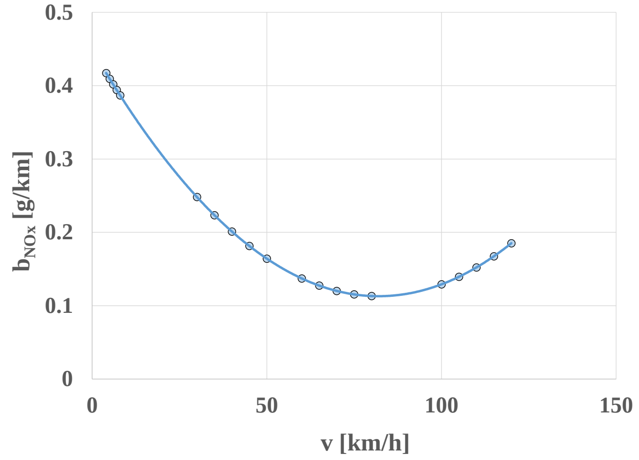

Fig. 11. Dependency of specific distance NO_x emission from passenger cars in model traffic conditions – b_{NOx} on average speed – v

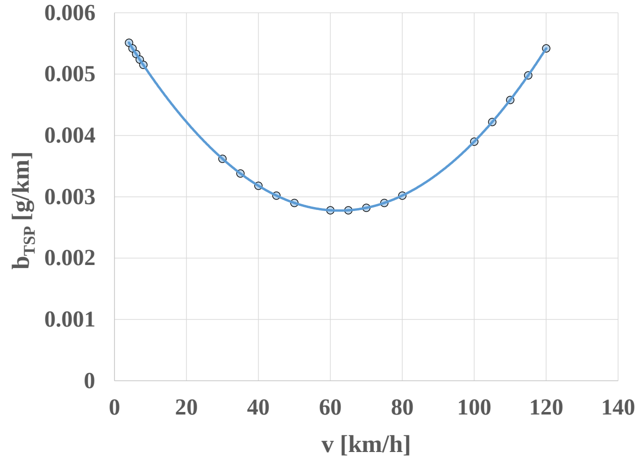

Fig. 12. Dependency of specific distance TSP emission from passenger cars in model traffic conditions – b_{TSP} on average speed – v

The regularity of specific distance pollutant emissions from passenger cars in model traffic conditions for various average velocity values is clearly visible. The figures show that it is possible to approximate specific distance emission depending on the average vehicle speed.

It is characteristic that for the vehicle movement in model of traffic congestion, specific distance emissions decrease as the average velocity increases. The situation is similar for the urban vehicle traffic model outside congestion. For the traffic model in rural areas, specific distance emissions increase as the average velocity increases. This dependence is even stronger for traffic on highways and motorways.

6. Conclusions

Based on the presented analyses and simulation studies results, the following conclusions can be formulated:

1. Modeling is the only possible way to determine the total pollutant emissions from mobile sources.
2. It is possible to use the procedures used for the official air pollutant emission inventories from road vehicles to study the model of this emission due to the input data and model parameters characterizing the structure, intensity and method of use of road vehicles.
3. The average vehicle speed is an effective zero-dimensional characteristic for assessing the nature of vehicle movement in the task of inventorying pollutant emissions from road vehicles.
4. The dependence between specific distance emissions and the average speed of vehicles of elementary categories is used for modeling pollutant emissions from road transport. This dependency is determined based on the empirical research results.
5. Despite the significant intensification of the use of road vehicles between 2000 and 2020, the total national annual emissions have a clear downward trend. This is the effect of a change in the structure of road vehicles due to their ecological properties – pollutant emissions.
6. The most visible tendency is to reduce the annual national CO and NMVOC emissions. The tendency to decrease the national annual NO_x and TSP emissions is less visible.

Nomenclature

b	specific distance emission
Cg	urban congestion
CO	carbon monoxide
Ea	national annual emission
H	highways and motorways
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxides
R	rural
TSP	total suspended particulate matter
U	urban outside traffic congestion
V	average vehicle velocity

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