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Spatial inventory of greenhouse gas emissions from the road transport in Poland

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Abstract. A novel approach is presented to spatial inventory of greenhouse gas emissions from the sector of road transport, based on official fuel statistics and digital maps. The territorial distribution of these emissions in Poland with the resolution of 2x2 km is obtained, using the developed geo-information technology.

Key words: greenhouse gases, spatial inventory, geo-information technology, road transport.

INTRODUCTION

Greenhouse gas (GHG) emissions are the object of international agreements aimed at stopping warming of the Earth atmosphere. These agreements mostly deal with estimates of GHG emissions and absorptions on a country scale. However, for various climatic models and uncertainty analysis techniques a spatial distribution of GHG emissions within a country is needed [7, 13, 14, 17]. Knowledge of the emission structure and location of main sources as well as absorbers greatly facilitates the decision making process, concerning emission reductions within an individual country or region. The major asset of spatially distributed inventory is the fact of associating emissions with the very place where they actually occur. This provides an opportunity to largely improve the inventory process and to reduce its overall uncertainty [8].

This article discusses bottom-up inventory from the road transport sector in Poland. Various methods for spatial analysis of GHG emissions in transport sector have been published thus far [2, 9, 15, 16, 18, 19, 21-23, 27]. The main differences among these methods lie in: (i) the level of specification of emission sources, (ii) vehicle operation stages selected for analysis — for example in [9, 20, 21] emissions are calculated for each stage of automobile operation, and (iii) the selection of raw data for emission localization. In general, there exist three, the most frequently used methods for emission estimates in road transport. They differ according to the way how emissions are calculated from available information on transport activity. The first approach requires only the data on vehicle miles traveled for a certain territory, and this method is usually used in top-down inventories. The second approach takes into account also the dependence of emissions on the vehicle speed; the average speed of a trip is calculated. The third approach foresees the vehicle speed fluctuations during a trip.

Both top-down or bottom-up techniques can be used in GHG inventory of transport sector. In the bottom-up approach, the model of vehicle operation is built for individual road segments, and the modeling results for all the segments become input data for basic inventory model. The top-down approach bases on total emission estimates for the investigated territory, which can be calculated from statistical data, such as vehicle quantity, average mileage per vehicle, etc. These total emissions are further disaggregated to individual emission sources using raw data, such as road densities. This approach is widely used since it is much less resource- and time-consuming, although the obtained results have higher uncertainty as compared to the bottom-up method [23].

Another problem related to the spatial inventory of GHG in the road transport sector is the selection of the raw data localizations. Most of the relevant models rely on the assumption that the territorial distribution of GHG emissions from the road transport depends either on population density or location of road network and capacity of each road. Brandmeyer and Karimi [5] compared these two approaches on the example of the transport sector in Atlanta (USA). The obtained results revealed significant differences. Therefore, both these parameters should be exploited for adequate results.

The generalized models for spatial GHG inventory in road transport, such as MOBILE6 [20] and MEASURE [3], are appropriate for inventory in various countries, and, formally, the models do not reflect any country specificity. On the other hand, to use these models, a highly developed monitoring system of road transport activity is required. The system should include: detailed digital maps of roads, systems of trip fixing, setting trip type methodology, actual update of road capacity and load, territorially distributed data on vehicle types and operation modes, etc. The results obtained with MOBILE6 mostly depend on average speed of vehicles, while the emissions calculated with MEASURE depend on vehicle speed and acceleration change. Therefore, the direct use of these models is not possible for the territory of Poland, as it demands highly detailed input data, which are not available at the moment.

MATHEMATICAL MODELS FOR THE ROAD TRANSPORT GHG INVENTORY

Based on the IPCC classification, the road transport subcategory includes GHG emissions from fuel combustion and evaporation from the motor transport, which consists of passenger cars, light and heavy duty vehicles, buses, tractors, motorcycles and mopeds. According to Poland's National Inventory Report to the United Nations Framework on Climate Change, the transport sector is responsible for 14,5% of all GHG emissions in Poland in 2010 [24].

On a scale of the whole country, the distribution of GHG emission sources in road transport is very irregular — automobile transport is highly dense in large cities as compared to low emissions in villages and inhabited territories. In order to adequately grasp this diversity, the territory of Poland is split into cells using the 2 x 2 km grid and administrative borders of municipalities. The spatial inventory of GHG emissions consists in carrying out bottom-up inventory for each grid cell, and then summing up the inventory results for all the fuel and vehicle types.

GHG emission from the road transport in a grid cell is in turn a sum of emissions from all the emission sources, which are fully or partially located within its borders [6, 12]. In order to build the spatial cadastre of certain gas emissions, it is necessary to calculate the territorially distributed specific emissions of this gas. Such specific emission values are calculated using parameters and data which describe emission process for selected activity, and which also take into account geographical location of emission sources. That is, the specific GHG emission is a function of: (i) the activity intensity parameters in a certain territory and a period of time, (ii) the proper emission coefficients, as well as (iii) the geographical coordinates of the territory under investigation and time.

In the road transport sector, motor vehicles operating on roads are the sources of GHG emissions. For practical implementation of spatially distributed inventory, motorways and highways are interpreted as GHG emission sources in this sector. These sources are classified as the line emission sources. Urban road network is treated as an area source due to a very high density, and only main urban roads are separately treated as line sources.

In general, the level of GHG emissions in a grid cell depends on the amount of fuel consumed by transport within cell borders. That is, the amount of fossil fuel used by transport is disaggregated to specific emission sources before the spatial GHG emission inventory from road transport is attempted. The obtained fuel quantity is multiplied by the corresponding emission factors to calculate emissions for a certain GHG. For the road transport, the emission sources are as follows:

– the automobile roads of all types, including main roads that cross settlements;
– the territories of settlements, which are the area sources of emissions from fuel combustion in transport on internal road network of a settlement (on roads and streets of settlements that do not cross their administrative borders).

The following steps are taken to disaggregate regional fuel combustion data to individual roads and settlements.

1) The fuel used for road transport in an administrative unit is disaggregated by settlements and suburban areas for large cities within the unit. If exact information on fuel consumption on road transport sector is available for some cities, it is directly located to the territory of the city and suburban areas around it. For small cities, disaggregation of transport fuel is proportional to the population density.

2) The fuel used in road transport sector in a certain administrative unit (district – in Polish 'powiat' or voivodship) is disaggregated to the automobile roads of the unit according to the developed algorithms (including main roads within settlements). This step takes into account the length and width of each road segment, its capacity and current state. The amount of fuel used in suburban territories, which were found in p.1, is disaggregated to road segments located within their borders.

3) For each emission source which is fully or partially located within a grid cell, the total amount of fuel used by a certain road transport category is calculated taking into account either the area of emission source – for area emission sources, or the length of an object – for line sources. In this approach to fuel disaggregation the following assumptions are taken: (a) a part of the fuel that was bought in a settlement for the road transport purposes is used (burnt) within its borders (for the needs of internal urban transport), (b) a large part of the fuel is used on automobile roads in suburban territories that are located within a certain distance from the administrative borders of settlement, and (c) the rest of the fuel is used outside the settlements and located to the road segments according to the road maps.

The territory of a smaller settlement is treated as one zone (n=1 below), while two level buffer zones are built around administrative borders of each city with population over 20,000 people. The first one (n=2 below) has the width of half radius of city area, and the second one (n=3 below) the width of one radius:

$$\tilde{Z} = \begin{cases} Z_{1,i}, \text{ the territory of settlement } i, \\ Z_{2,i}, \text{ the zone radius} = \frac{1}{2}\sqrt{S(i)/\pi}, \\ Z_{3,i}, \text{ the zone radius} = \sqrt{S(i)/\pi}, \end{cases} \tag{1}$$

where:
$Z_{n,i}$ is the n-th buffer zone around the i-th settlement,
$S(i)$ is the settlement's area.

The reason for building the zones is to identify suburban roads and road segments with a very dense traffic (Figure 1).

Emissions for each source type (area and line sources) are calculated using the bottom-up approach [1]. The quantity of the different type fuel used (diesel, gasoline etc.) is multiplied by the corresponding emission factor. Emission factors differ for various automobile operation modes, as well as for different automobile types and control systems. Total emissions are calculated by summing up emissions from the different phases, namely, the thermally stabilized engine operation (hot) and the warming-up phase (cold start) [10]. Additionally, the age distribution of vehicles is taken into account, as well as the average speed of vehicles on different road segments (using digital maps of road network and their capacity) and within cities.

Following the above specification of variables, the corresponding GHG emissions in a settlement S (or one of its buffer zones $S_{n_s} \in \tilde{S}^{Z}$) and a road segment $L_{rd,i} \in \tilde{L}_{rd}$, are calculated using (2) and (3), respectively.

$$E_{Tr}^{g}\left[Z_i(S)\right] = \frac{Q^{R_2(S)}(f,t,b)}{\sum_w a_b^{R_1(S)}(t,w)} \cdot \frac{P(S)\cdot C_n}{\sum_{s\in\tilde{S}^{R_2}} P(s)} \times$$
$$\times \sum_{b=1}^{B}\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{w} EF_{hot}^{g}\left[f,t,V(H_S),w\right] \cdot$$
$$\cdot a_b^{R_1}(t,w)\left\{1 + K_S(\beta)\left[\left.\frac{EF_{cold}^{g}}{EF_{hot}^{g}}(t_a,w)\right|_j - 1\right]\right\},$$

$$R_2(S) = \left\{R_2 \in \tilde{R}_2 \wedge S \Subset R_2\right\};\ R_1(S) = \left\{R_1 \in \tilde{R}_1 \wedge S \Subset R_1\right\};$$
$$\tilde{S}^{R_2} = \tilde{S} \cap \tilde{R}_2, \tag{2}$$

where:
$E_{Tr}^{g}\left[Z_i(S)\right]$ – the emissions of the g-th GHG in the settlement S (i = 1) or one of the buffer zones around it (i=2,3);
$Q^{R_2(S)}(f,t,b)$ – the vehicle mileage in the administrative unit $R_2(S)$ (f – fuel type, t – type of vehicle, b – ownership);
$R_2(S)$ – the district where the settlement S is located,
$R_1(S)$ – the voivodship where the settlement S is located,
$P(S)$ – the population density in the settlement S,
$a_b^{R_1(S)}(t,w)$ – the number of the automobiles of the type t and the ownership b in the administrative unit $R_1(S)$, within the age group w;
– the emissions of the g-th GHG during operation of the vehicle of a certain type, construction, and age, in the condition of thermally stabilized engine operation,
V – the average annual speed of vehicles within the borders of a settlement of the type H_S (city, village, small town etc.),

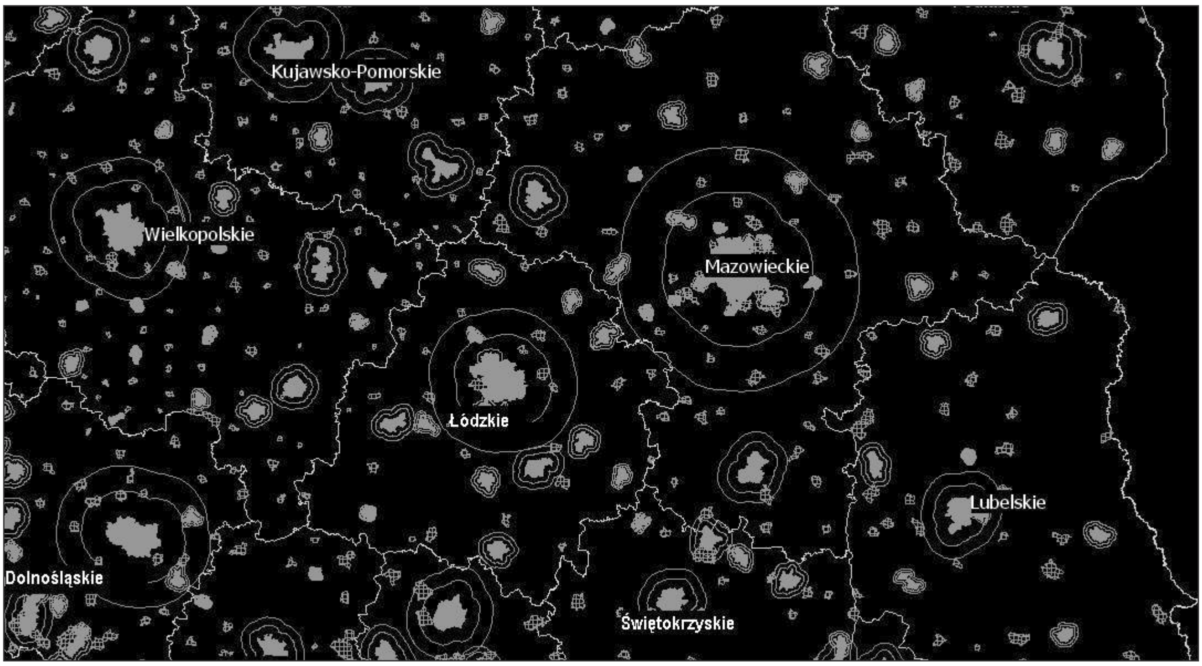

Fig. 1. Fragment of a digital map of settlements with 2-level buffer zones built for cities with population higher than 20 thousand people

$K_S(\beta)$ – the ratio of the mileage during the warming-up phase for the settlement S (depending on the settlement type and the ratio of overall mileage during the warming-up phase β),

$\frac{EF^g_{cold}}{EF^g_{hot}}$ – the ratio of the emissions of g GHG during the warming-up phase (cold start) and thermally stabilized engine operation for 1 km,

t_a – average annual temperature,

C_n – coefficient of buffer zone around settlement.

For some transport categories and fuel types, the vehicle mileage parameter $Q^{R_2(S)}(f,t,b)$ in (2) is not available from statistical yearbooks. Then, it is recalculated based on the information about fuel consumption by corresponding vehicle types:

$$E^g_{Tr}\left[L_{rd,n_l}\right] = \frac{Q^{R_2\left(L_{rd,n_l}\right)}(f,t,b)}{\sum_w a_b^{R_1\left(L_{rd,n_l}\right)}(t,w)} \cdot \frac{C_{total}\left(L_{rd,n_l}\right)}{\sum_{l\in\tilde{L}_{rd}^{R_2}} C_{total}(l)} \times$$
$$\times \sum_{b=1}^{B}\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{w} EF^g_{hot}\left(f,t,V\left[k\left(L_{rd,n_l}\right)\right],w\right)\cdot a_b^{R_1(S)}(t,w)\cdot$$
$$\cdot\left\{1+K_{L_{rd,n_l}}(\beta)\left[\left.\frac{EF^g_{cold}}{EF^g_{hot}}(t_a,w)\right|_j -1\right]\right\}+$$
$$+\sum_{z\in\tilde{Z}_{L_{rd,n_l}}} \frac{E^g(z)\cdot C_{total}\left(L_{rd,n_l}\right)}{\sum_{i\mathbin{\hat{\in}} z} C_{total}(i)},$$

$$R_1\left(L_{rd,n_l}\right)=\left\{R_1\in\tilde{R}_1 \wedge L_{rd,n_l} \mathbin{\hat{\in}} R_1\right\};$$
$$R_2\left(L_{rd,n_l}\right)=\left\{R_2\in\tilde{R}_2 \wedge L_{rd,n_l} \mathbin{\hat{\in}} R_2\right\};\ \tilde{L}_{rd}^{R_2}=\tilde{L}_{rd}\mathbin{\hat{\cap}}\tilde{R}_2, \quad (3)$$

where:

$E^g_{Tr}\left[L_{rd,n_l}\right]$ – the emissions of the g-th GHG in the road segment $L_{rd,nl}$,

$C_{total}(L_{rd,n_l})$ – the road segment's $L_{rd,nl}$ parameter defining its capacity,

$k\left(L_{rd,n_l}\right)$ – the road segment's $L_{rd,nl}$ category or its location (a highway, a rural road, etc.) that helps to define the average speed,

V – the vehicle's average annual speed, which depends on the road category or location,

$K_{L_{rd,n_l}}(\beta)$ – the ratio of the mileage during the warming-up phase for road segment $L_{rd,nl}$,

R_1 and R_2 – the administrative units: voivodship and district, respectively.

For an elementary cell δ, the sources of emissions in the transport sector are parts of the settlements and the road segments located within the cell borders. The sets of the area and the line objects are denoted as $L_{rd}{}^{\delta}=\left\{L_{rd}\mathbin{\hat{\cap}}\delta, L_{rd}\in\tilde{L}_{rd}\right\}$ and $S^{\delta}=\left\{S\mathbin{\hat{\cap}}\delta, S\in\tilde{S}\right\}$, respectively. When a source is only partially located in a cell, the overall emissions are calculated proportionally to the size of the object's part located within the cell. That is, emissions in the cell δ are calculated as follows:

$$E^g(\delta)=\sum_{s\in\tilde{S}}\frac{E^g(s)\cdot area(s\mathbin{\hat{\cap}}\delta)}{area(s)}+$$
$$+\sum_{l\in\tilde{L}_{rd}}\frac{E^g(l)\cdot len(l\mathbin{\hat{\cap}}\delta)}{len(l)}. \quad (4)$$

INPUT DATA

Statistical information concerning the use of the fossil fuels in the road transport in Poland and the general activity parameters are available for administrative units (voivodships, districts or municipalities – in Polish "gmina") in the yearbooks of transport statistics [26] and online statistical database [4]. Other parameters used in the considered model are available from statistical reports containing transport statistics and summarizing yearbooks [11, 25, 28].

For practical implementation of spatially distributed GHG inventory, the following road transport activity data are used:

- the fuel consumption in the road transport sector by fuel and vehicle types,
- the road motor vehicles by age groups,
- the road motor vehicles in total,
- the vehicle mileage,
- the roads' capacity and their current state,
- the operation mode for each road segment,
- the population density.

The digital maps of the road network, the population density map and the administrative map of Poland are used. The average speed of vehicles for a certain road segment is established according to the road type (urban street, rural, highway) by overlapping map of road network with settlements' map in the following way:

- an urban road network – streets and roads located within the borders of cities $\tilde{L}_{rd}{}^{Urb}=\tilde{L}_{rd}\mathbin{\hat{\cap}}\tilde{S}^{Urb}=\left\{\tilde{L}_{rd,1}{}^{Urb},\tilde{L}_{rd,2}{}^{Urb},\ldots\right\}$,
- roads for high, constant-speed vehicle operation – highways, motorways $\tilde{L}_{rd}{}^{Hway}=\left\{\tilde{L}_{rd,1}{}^{Hway},\tilde{L}_{rd,2}{}^{Hway},\ldots\right\}$,
- rural roads – roads located within territories of villages and small towns as well as dirt roads outside the settlements $\tilde{L}_{rd}{}^{Rur}=\tilde{L}_{rd}-\left(\tilde{L}_{rd}{}^{Urb}\cup\tilde{L}_{rd}{}^{Hway}\right)=\left\{\tilde{L}_{rd,1}{}^{Rur},\tilde{L}_{rd,2}{}^{Rur},\ldots\right\}$.

Both the default IPCC emission factors and the emission factors proposed in Poland's National Inventory Report [24] were assumed in the emission calculations.

GEO-INFORMATION SYSTEM AND INVENTORY RESULTS

A geo-information system has been developed for practical implementation of the algorithms for the geospatial inventory of GHG emissions, automatic building of corresponding digital maps, and visual analysis of the obtained results.

All the statistical data and any additional parameters, such as emission factors, are collected in Excel

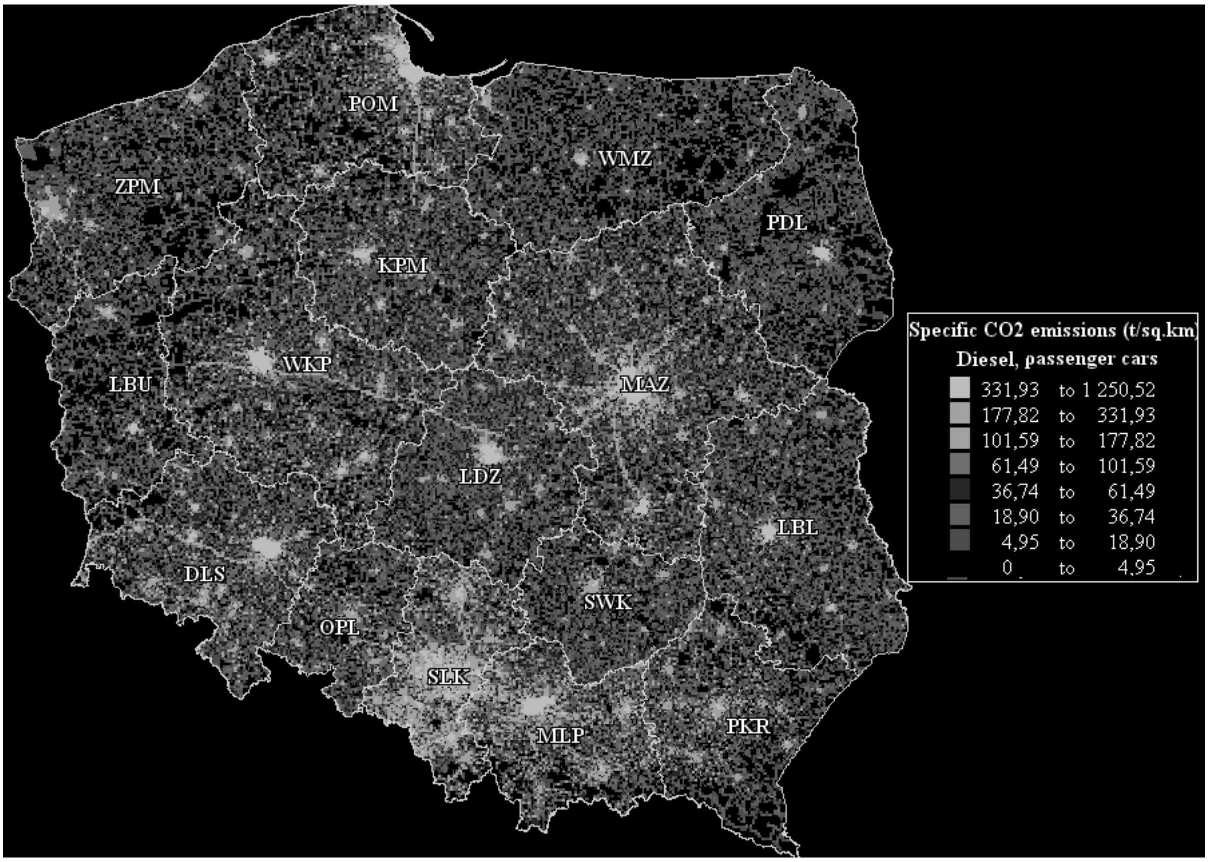

Fig. 2. Specific CO_2 emissions from diesel combustion by passenger cars in Poland (2 km x 2 km; t/km^2; 2009)

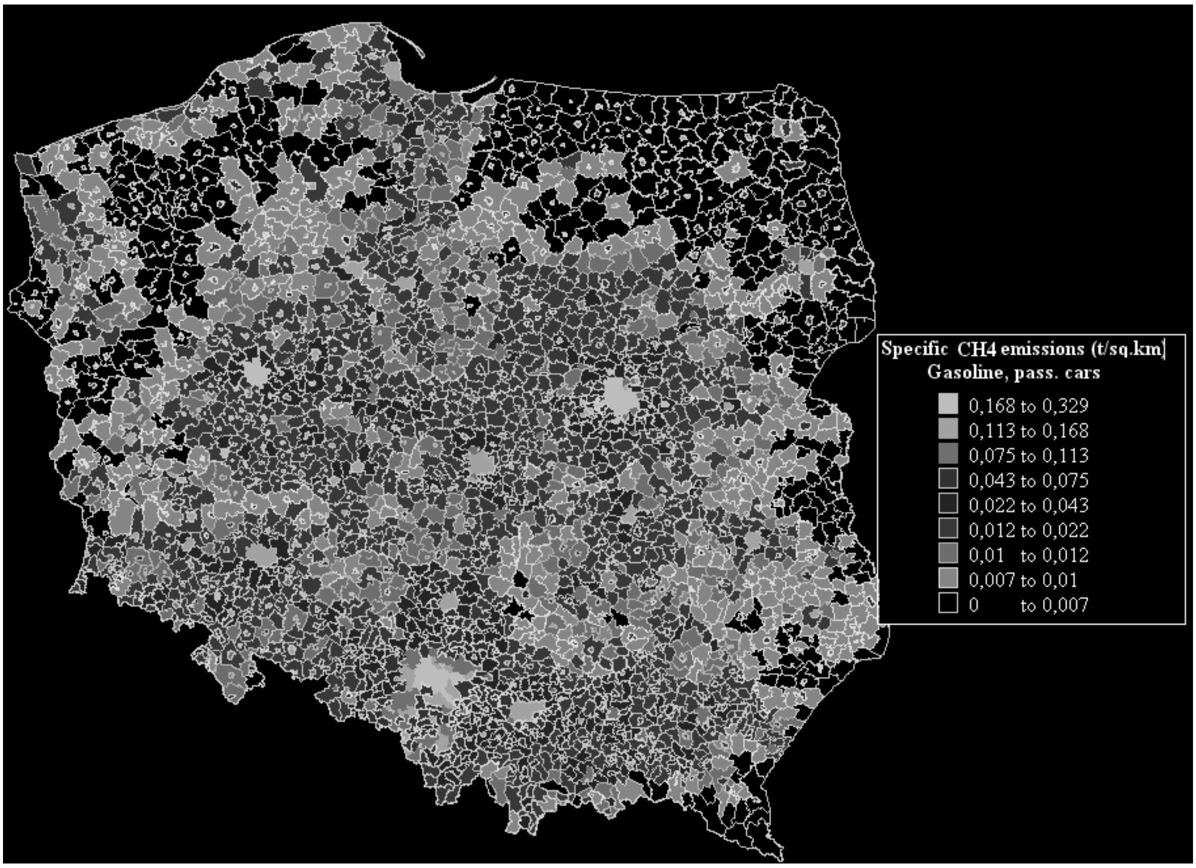

Fig. 3. Specific CH_4 emissions from gasoline combustion by passenger cars in Poland (municipalities; t/km^2; 2009)

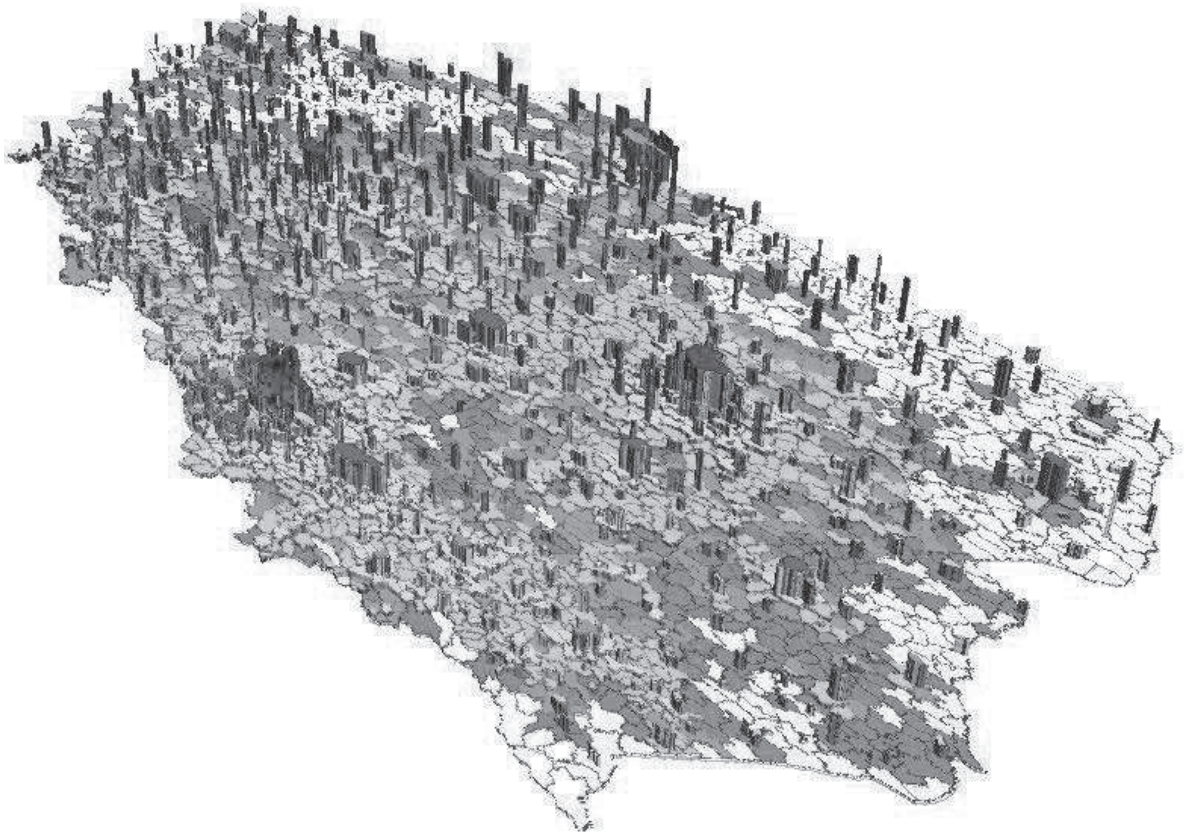

Fig. 4. Prism-map of specific CH_4 emissions from gasoline combustion by passenger cars in Poland (municipalities; t/km^2; 2009)

spreadsheets. Using the input information tables and maps (digital maps of settlements, roadways etc.), and following the developed algorithms, the geo-referenced databases of GHG inventory are finally constructed. Each record in the databases corresponds to a grid cell (of size 2 x 2 km) and contains information about emission source types in the cell, as well as the structure of emissions with regard to the gas, fuel type, and vehicle category.

The results can be visualised as digital maps with various thematic layers. This form helps to roughly and quickly assess emission levels, localise territories with the highest emission rates, investigate emission structure, and make effective decisions on emission reduction. Figures 2 and 3 present some thematic maps with the inventory results for the regular grid or municipalities, respectively.

To improve visualization of differences in emission levels among municipalities, Figure 3 can be also presented in the form of prism-map (Figure 4).

CONCLUSIONS

We constructed mathematical models for spatial inventory of GHG emissions from the road transport sector in Poland. The models are based on the data from the monitoring system of transport activity, currently functioning in Poland and providing valuable information about emission locations at a regional scale. The developed geo-information technology enables analysis of GHG emissions by individual grid cells up to a minimum size of 2x2 km. The analysis can be carried out by emission source types in a cell, as well as by the structure of emissions in the cell with regard to the gas, fuel type, and vehicle category.

The results can be visualized by means of digital maps with various thematic layers. Thematic maps help to analyze emissions' distribution and to make effective decisions on GHG reduction strategies.

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