Raport Badawczy

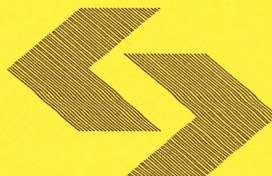# Research Report

Exposure and intake fraction due to multiple air pollutants in an agglomeration

P. Holnicki, M. Tainio,
A. Kałuszko, Z. Nahorski

Instytut Badań Systemowych
Polska Akademia Nauk

Systems Research Institute
Polish Academy of Sciences

POLSKA AKADEMIA NAUK

Instytut Badań Systemowych

ul. Newelska 6

01-447 Warszawa

tel.:   (+48) (22) 3810100

fax: (+48) (22) 3810105

Kierownik Zakładu zgłaszający pracę:
Prof. dr hab. inż. Zbigniew Nahorski

Warszawa 2016

Exposure and intake fraction due to multiple air pollutants in an agglomeration

Piotr Holnicki[1], Marko Tainio[1,2], Andrzej Kałuszko[1], Zbigniew Nahorski[1,3]

[1] *Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland (holnicki@ibspan.waw.pl; kaluszko@ibspan.waw.pl; nahorski@ibspan.waw.pl)*
[2] *UKCRC Centre for Diet and Activity Research (CEDAR), MRC Epidemiology Unit, University of Cambridge, UK (mtk27@medschl.cam.ac.uk)*
[3] *Warsaw School of Information Technology (WIT), Warsaw, Poland (Z.Nahorski@wit.edu.pl)*

Abstract: Adverse health effects of air pollution create a significant public health issue all over the world. Urban areas are especially important because local emissions can potentially influence a large number of inhabitants. In this study, we quantify the health burden due to local air pollution in an urban area for the Warsaw, Poland. From different air pollutants we considered particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO_2), benzo(a)pyrene (B(a)P) and heavy metals. The annual mean concentrations were computed by CALMET/CALPUFF modeling system, by using the emission and meteorological data from the year 2012. The spatial domain resolution of calculations was 500m x 500m. The emission fields comprised high (power generation) and low point sources (industry), mobile sources (transport) and area sources (housing). The exposure (E) for these pollutants and the Intake Fraction index (iF) were estimated for the study population density based on the information on home addresses of the inhabitants. The spatial distributions of the above indexes have been discussed. Changes in mortality and in disability-adjusted life-years (*DALY*s) were estimated with relative risk functions obtained from literature. The local emitted air pollution was predicted to cause approximately 2800 attributable deaths and nearly 50 000 *DALY*s per year. Nearly all the health effects (95%) were due to exposure to fine particulate matter (PM2.5). From different emissions sources, linear sources (transport) and area sources (domestic burning) contributed 45% and 53% of total *DALY*s, respectively. If the inflow from outside was included in the calculations, the burden nearly doubled. These results indicate that local decisions can potentially improve air quality and reduce associated negative health effects. All-national and international co-operation is required for reducing the impact of inflow.

Keywords: urban air pollution; population weighted exposure; intake fraction; adverse health effects.

1. INTRODUCTION

The problem of the steadily increasing level of ambient air pollution implies one of the most adverse health impacts in many of the European cities. According to the latest WHO report [27] , air quality in the majority of urban agglomerations – especially in low- and middle-income countries – do not meet the respective air quality guidelines EEA [4, 5] or CAFÉ [2]. Moreover, ambient air pollution continues to rise at an alarming rate. Air pollutants and particulate matter in particular, are emitted into the atmosphere from the many categories of sources and have a different environmental impact, including hazardous human health effects. Some of them (stroke, heart disease, lung cancer, chronic and acute respiratory diseases, including asthma) are mainly caused by fine fractions of particulate matter EEA [4]. As stated in the WHO report [27], high concentrations of this type of air pollution cause more than 3 million premature deaths worldwide each year.

Health impacts of air pollution in urban agglomerations are the most important ones and necessarily have to be considered in environmental management. Due to high population density, air pollution influences a high number of inhabitants. On the other hand, both pollution emission sources and population are distributed in towns in much diversified space locations. That is why the high space resolution is paramount for good accuracy of health effect estimation.

As in many other European agglomerations [3, 16, 17], Warsaw inhabitants also suffer from high concentrations of some air pollutants which are typical for the urban atmospheric environment. In this case, these are above all particulate matter [3], sulfur- and nitrogen oxides, carbon monoxide, some heavy metals, as well as polycyclic aromatic hydrocarbons in some cases. In practice, the adverse impact of some particular pollutants on urban air quality depends on several individual factors, such as the city location, topography, the structure of

2

the emission field, meteorology, etc. In Warsaw, the composition of the main polluting species, their spatial distribution and their maximum values also reflect the peculiar structure of the local emission field, which is determined by two dominating factors.

As shown in Holnicki *et al.* [12, 13, 14] , the first main factor relates to coal, which is the main fossil fuel used in Poland for power generation and for the residential heating. Majority of Warsaw is covered by the district heating system, but in some peripheral districts and the neighboring rural area the coal fired small scale heating installations are used, which considerably contribute to worsening of air quality. This emission category is responsible for particulate matter pollution (especially $PM_{2.5}$), SO_2, some heavy metals and B(a)P. Particular matter issues, mainly relate to PM_{10} and $PM_{2.5}$ (fine fraction), respectively to the aerodynamic diameter. They are emitted into the atmosphere in similar proportions by sectors of energy generation, industry, transport, communal and household usage. The most harmful fine fraction ($PM_{2.5}$) also contains atmospheric aerosols ($SO_4^=$ and NO_3^- in our case) and heavy metals, such as lead (Pb), nickel (Ni), cadmium (Cd), arsenic (As) and mercury (Hg), which get into the atmosphere as particulate matters and aerosols [4, 7]. Although the concentration levels are low, they contribute to the deposition and build-up of heavy metal contents in soils, sediments and organisms.

The B(a)P pollution, which mainly originates from the municipal sector, exceeds the limit value of the annual mean B(a)P concentration ($EEA^{(11)}$) in the whole area of the Warsaw agglomeration.

Another key pollution category which determines the air quality in Warsaw is traffic-induced emission, due to the steadily increasing number of cars registered in Warsaw. As shown in Holnicki *et al.* [12, 13] their number went up by 80% in the last decade. This trend is different from many other European cities. Traffic originated emission is mainly responsible for NO_X, CO, C_6H_6 and Pb concentrations, but it also contributes to PM_{10} pollutions, mainly via the re-suspended particles [3, 16] . In particular, basing on the reports Holnicki and Nahorski [14], Holnicki *et al.* [12], related to the years 2005 and 2012, respectively -- concentrations

3

of NO_X and PM_{10} have been on the increase during the last decade and both exceed the annual average concentration limits. The transboundary inflow of some pollutants coming from distant sources also contributes significantly to the resulting air pollution in Warsaw, which mainly relates to the fine fractions of particulate matter, as shown in ETC/ACM [7], Wang *et al* [25] and Levy [17].

The paper addresses a quantification of health burden related to an urban scale air pollution, dealing with the Warsaw case study and the main components of air pollution, which are: particulate matter (PM), nitrogen oxides (NO_X), sulfur dioxide (SO_2), carbon monoxide (CO), benzene (C_6H_6), benzo[a]pyrene (BaP) and heavy metals (Pb, As, Cd, Ni). The modeling results of air pollution, which are utilized in analysis of the negative health effects, are presented in more details in Holnicki *et al.* [12, 14] and are not repeated in this study. Here we only recall the main assumptions and findings relevant in an analysis of related health effects.

The annual mean concentrations are computed by CALMET/CALPUFF modeling system, for the emission and meteorological data for the year 2012 and the spatial domain resolution 500m x 500m. The air pollution results are generated as a sequence of 1-h episodes (8785 time steps) which cover the year under question. The final results comprise the annual average concentrations of the main pollutants, recorded at the fictitious receptor points. The air pollution data are next used to assess the population weighted exposure (E) to the main polluting compounds and to compute the respective intake fraction index (iF). The last index is a unified measure of which fraction of the pollution emitted by a source is inhaled by population [1]. It can be attributed to an individual emission source, to one category of emission sources or to the total emission field affecting the domain.

2. METHODS

2.1   The study area and spatial resolution

The base of this study is an air quality analysis for Warsaw agglomeration in the year 2012, presented in Holnicki *et al.* [12]. To simulate pollution dispersion processes the Gaussian puff model CALPUFF v.5, Scire *et al.* [22], was applied. It is a multilayer, non-stationary model designed for calculating concentrations of many substances, emitted by different types of sources. Meteorological fields are re-analyzed by the WRF model [20], and assimilated to the final discretization grid by the CALMET cooperating preprocessor. The aim of this simulation was to obtain the spatial maps of year average concentrations of the main urban pollutants, to show districts/areas where the pollution limits are exceeded and to identify emission sources responsible for these violations. These results, including the earlier uncertainty estimates and model validation in Holnicki and Nahorski 2015[5], give an assessment of the model performance.

Table 1. Primary and secondary pollutants discussed

Primary pollutants	Secondary pollutants
SO_2 – sulfur dioxide	$SO_4^=$ – sulfate aerosol
NO_X – nitrogen oxides	NO_3^- – nitrate aerosol
PPM_{10} – primary PM, $\Phi \le 10$ µm	
PPM_{10_R} – re-suspended PPM10	
$PPM_{2.5}$ – primary PM, $\Phi \le 2.5$ µm	
$PPM_{2.5\_R}$ – re-suspended PPM2.5	
CO – carbon monoxide	
C_6H_6 – benzene	
Pb – lead	
As – arsenic	
Cd – cadmium	
Ni – nickel	
B(a)P – benzo(a)pyrene	
Particulate matter	
$PM_{10} = PPM_{10} + PPM_{10\_R} + SO_4^= + NO_3^-$	
$PM_{2.5} = PPM_{2.5} + PPM_{2.5\_R} + SO_4^= + NO_3^-$	

The air quality analysis presented below deals with the primary and secondary polluting compounds, which characterize an urban atmospheric environment, including transboundary inflow of

5

pollutants from distant sources. The main polluting compounds, which are discussed in this study, are shown in Table 1.

2.2   The structure of the emission field

The Warsaw Metropolitan Area, about 520 km^2 within the administrative borders and total population 1715517 inhabitants [21, 28] shown below in Fig. 1, is discretized for the computational purposes with the homogeneous grid 0.5 km x 0.5 km. To take into account specific technological and the characteristics of the different emission sources, the total emission field was split down into the following categories: point (high/low), area, and line (mobile) sources. A separate class of the high point sources comprises the power and heating plants which feed the Warsaw's district heating system.

As shown in Holnicki *et al.* [12], one of the main factors which determines the local emission field and resulting air pollution in Warsaw relates to coal, which is the main fossil fuel used in Poland for power generation and for residential heating in the residential sector. The district heating system operates in the main part if the city, but in the peripheries and the neighboring rural area coal fired small scale heating installations are used. They considerably contribute to worsening of air quality in the whole city. This category of emission sources is responsible for particulate matter pollution (especially $PM_{2.5}$), SO_2, some heavy metals and B(a)P. The highly toxic B(a)P pollution, originating from the municipal sector, constitutes a serious general problem in Poland (EEA 2012)[4]. In Warsaw the EU limit value of B(a)P is also exceeded Holnicki *et al.* [12].

The second dominating pollution category relates to traffic-induced emission, due to the steadily increasing number of cars registered in Warsaw. Traffic originated emissions are mainly responsible for NO_X, Pb, CO, C_6H_6 concentrations, but it also contributes to PM_{10} pollutions via the re-suspended particles. In particular, concentrations of NO_X and PM_{10} have been on the increase Holnicki and Nahorski [14], Holnicki *et al.* [12].

In case of some polluting compounds, e.g. particulate matter, an important contribution to the resulting air pollution in Warsaw follows from the transboundary inflow, coming from distant sources. In the modelling process this is entered via the boundary conditions for CALPUFF model.

6

The aggregate emission field consists of the following categories, including the quantity of the individual sources in each category:

- High point sources (24) – mainly the energy sector (power or heating plants);
- Low point sources (3880) – other point sources (industry or the local heating installations);
- Area sources (6962) – residential sector;
- Line sources (7285) – urban road transport;
- BC – boundary conditions (the transboundary inflow of some pollutants due to the regional/national level emission based on the EMEP model results).

The total emission field encompasses the Warsaw area in the administrative borders and the surrounding belt of approximately 30 km width (see Fig. 1b). The locations of the point sources are given in the geographical coordinates. The area and line sources are represented as basic grid emission squares, 0.5 km x 0.5 km, inside Warsaw administrative borders (Fig. 1a), and also in more aggregated, 1 km x 1 km, grid in the surroundings (Fig. 1b). The local city areas in the suburban belt are also represented by the nested fine resolution grid.
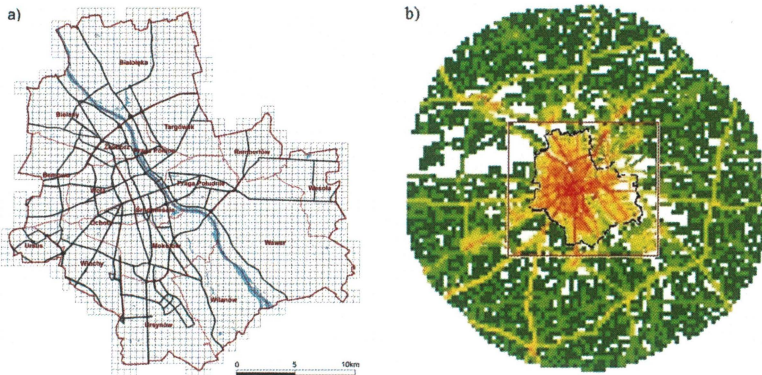

Fig. 1. The study domain: (a) discretization of the receptor area, (b) the total emission area.
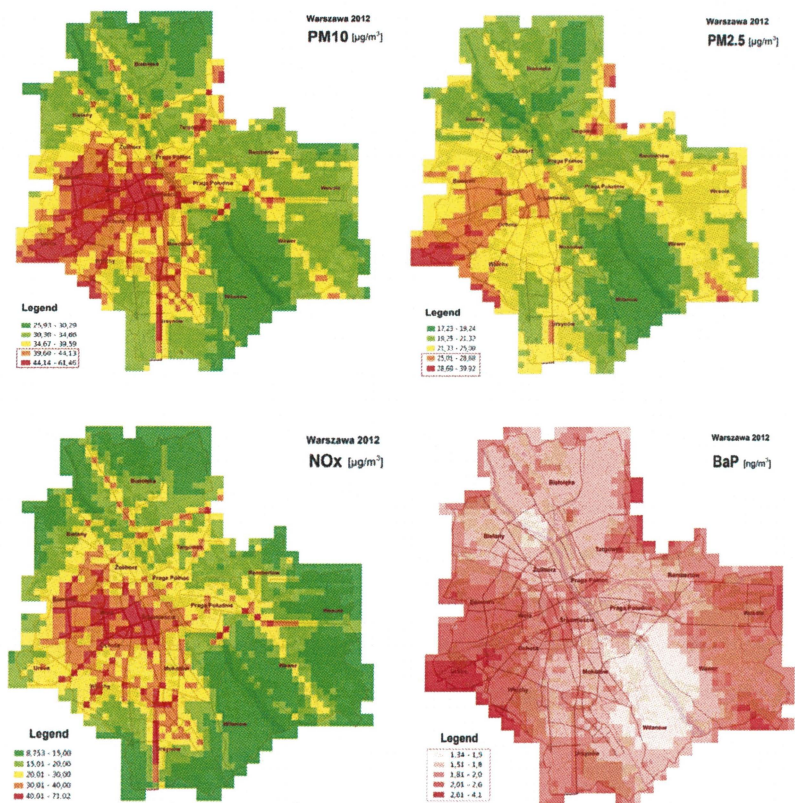
Fig. 2. Selected maps of the annual mean concentrations of PM_{10}, $PM_{2.5}$, B(a)P, where the limit values are exceeded (according to Holnicki *et al.* [12, 13])

The computed annual mean concentrations of the polluting compounds shown in Table I are recorded in 2248 fictitious receptors, which are located as the central points of the spatial resolution elements shown in Fig. 1a. Figure 3 presents four the selected maps of PM_{10}, PM2.5, NO_X and B(a)P pollution, where the admissible levels are exceeded. The concentrations and the respective emission volumes are used in the next section to calculate the exposure and the intake fraction indexes.

3. POPULATION WEIGHTED EXPOSURE AND THE INTAKE FRACTION

The papers Holnicki *et al.* [12, 13] present the modeling results of air pollution in Warsaw agglomeration. They include maps of the annual mean concentrations of the main polluting compounds, indicate some pollutants which exceed the EU limit values[9,10] [2, 4, 19] – e.g. NO_X, PM_{10}, $PM_{2.5}$ and B(a)P) – in some districts of Warsaw. The above results have been used in Holnicki *et al.* [10] to quantify of the adverse health effects of air pollution, which is based on the population average concentration (exposure) to a specified polluting compound. Figure 2 presents the population density map for Warsaw (based on [5, 9, 21, 26], which was used to quantify this index. Exposure is a receptor-oriented descriptor, traditionally used by scientists and policy makers in air quality management. The spatial resolution applied in the population density map is consistent with that one used in the forecasting model computations (0.5 km x 0.5 km). Legend shows the population density, as a number of inhabitants in one elementary resolution square.
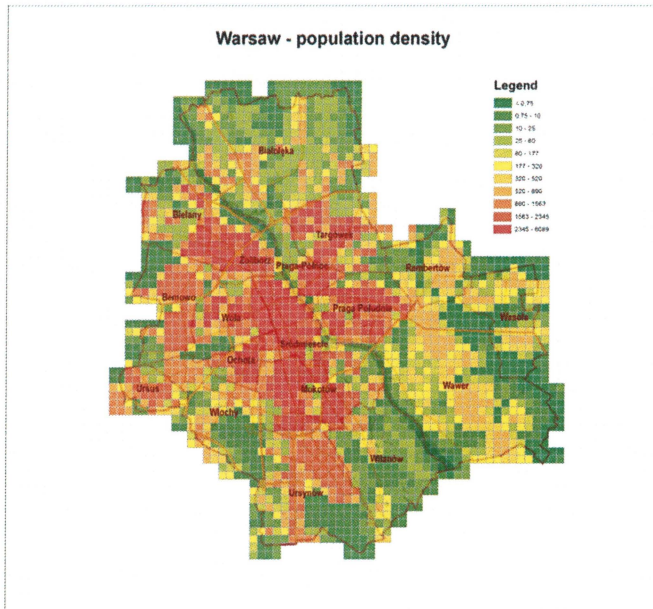

Fig. 2. Population density map for Warsaw

9

3.1 Exposure and the intake fraction indexes attributed to an individual emission source

Population weighted exposure to a selected pollutant, $E_{i,k}$ [μg/m³], can be attributed to a specified emission source. In such a case, this index quantifies an adverse environmental impact of the source and can be useful when emission reduction policy is considered. Its value can be calculated as follows:

$$E_{i,k} = \frac{1}{Pop} \sum_j C_{i,j,k} \cdot Pop_j \tag{1}$$

where $C_{i,j,k}$ – concentration of this pollutant [μg/m³] originating from the i-th source and measured at the j-th receptor element, Pop_j – population of the j-th receptor element [person], Pop – total population (1715517 assumed, [21, 28]), i – emission source's index within emission category, j – receptor's index, k – index of the pollutant.

Intake fraction index (iF) represents the fraction of the emissions that is inhaled by the population of the study region. It is usually defined as the incremental intake of pollutant, summed in a given time over the exposed individuals, and released from a specified source or source class, per unit emission [1, 10, 17, 18]. By definition, it is a dimensionless index and is usually expressed in "per million" units which means that each molecule emitted has one per million chance of being inhaled [24]. It depends on many factors (source location and parameters, receptor location, meteorological conditions, contaminant's properties, population characteristics).

The individual iF (attributed to specific emission source and pollutant) can be computed according to the known formula [1, 24]:

$$(iF)_{i,k} = \frac{BR}{Q_{i,k}} \sum_j C_{i,k,j} \bullet Pop_j \tag{2}$$

where $Q_{k,j}$ – emission, BR – breathing rate (20 m³/day/person or ~0.00021 m³/s/person) [24], i – emission source's index within emission category, j – receptor's index, k – index of the pollutant.

Intake fraction, as it is a standardized measure (calculated per unit emission), does not characterize the environmental impact of the source, but some other factors, such as emission category, source location, population density and pollution dispersion conditions in the vicinity of the source, etc. It quantifies the sensitivity of environmental impact to variation of the source's emission.
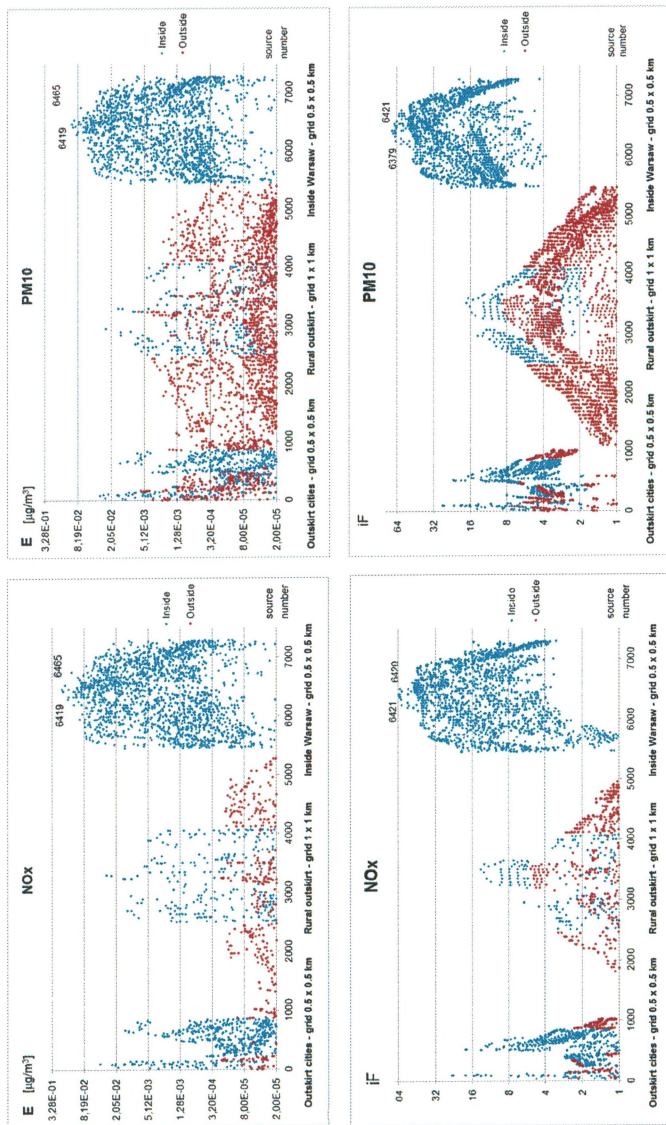
10

Fig. 3. Distributions of the exposure (E) and (iF) for NOx and PM_{10} in the line source category

Fig. 4. Distributions of the exposure (E) and (iF) for NOx and PM$_{2.5}$ in the area source category

The spatial distributions of the E and iF indexes are similar, however there are significant differences in the range of variability of each of them. This fact is illustrated by Figs 3–4, where exemplary distributions of the exposure and intake fraction values are plotted, for the selected pollutants, NOx, PM_{10} for line sources and NOx, PM_{10} for the area sources, respectively. About 2000 dominating emission sources are considered (logarithmic scale applied). All the sources in Figs 3–4 are split down into three subgroups, according to the source location. The blue color indicates sources located inside the administrative border of Warsaw or located in a direct vicinity, in the rectangle domain indicated in Fig. 1, while red color denotes the sources outside this region. The main difference refers to the variability range of the E and iF plots. It is above three rows of magnitude for E and only about $1 - 60$ in the case of iF. The small variability range of iF follows from the unified character of this index (2).

Table 2. The variability ranges of exposure (E) and intake fraction (iF), and the dominating sources, depending on the pollutant and emission category

	Parameters	High Point		Low Point		Area		Line	
		E	iF	E	iF	E	iF	E	iF
SO_2	Variability range	5437	17,7	39084	36,5	422	22,4	988	17,1
	The dominating source	#495	#507	#2892	#566	#6084	#6433	#6465	#6421
	Second dominating source	#494	#519	#567	#805	#6121	#6495	#6419	#6379
NOx	Variability range	20288	19,1	1341	35,3	321	18,8	1163	21,1
	The dominating source	#500	#507	#2892	#566	#6084	#6433	#6465	#6421
	Second dominating source	#495	#519	#3013	#805	#6121	#6495	#6419	#6420
PM_{10}	Variability range	1298	17,5	41975	20,9	317	15,2	197	10,0
	The dominating source	#494	#507	#567	#566	#6084	#6433	#6465	#6421
	Second dominating source	#495	#519	#3085	#805	#3203	#6495	#6419	#6379

The sources attributed to the dominating exposures shown in Fig. 3(top), coincide in each case with the maximum emissions. On the other hand, the highest iF values pointed out in Fig. 3(bottom) never refer to the maximum emission sources, due to the standardized character of this index (2). They rather reflect the other source characteristics, as source location, population density, etc.

The above remarks concerning the variability to the E and iF indexes are also illustrated in Table 2 for selected polluting compounds in the four emission categories, where about 2000 dominated sources are considered. The variability ranges of the E and iF indexes are calculated as the ratios: E_{max}/E_{min} and iF_{max}/iF_{min}, respectively. The table shows the differences in the variability of E and iF, and also confirms that the different emission sources refer to the maximum values of each of these indexes. As stated above, iF does not reflect the emission intensity, but some other characteristics of the source (its location, technological parameters, population, meteorology), which are common and not depend on the pollutant neither emission. This fact is revealed by a very high correlation between different pollutants emitted by a specified source, which is illustrated in Fig. 5. Thus, the iF value calculated for any specified pollutant, also characterizes all the compounds emitted.
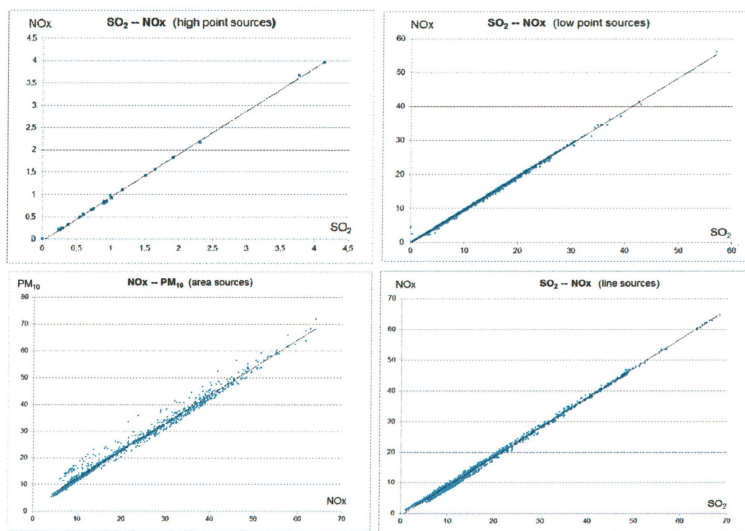

Fig. 5. Correlation of the iFs assigned to different pollutants of the same emission source, area sources (top), line sources (bottom)

The emission category is also reflected in the *iF* value. As seen from Fig. 5 (Y-axis), the maximum values of this index are low for the high point sources, medium for the other point sources and the highest in the area and line categories. Due to the high elevation of the emission points in the first category, the impact on the local receptors is very low. On the other hand, it is significant, especially in the case of the line sources, where the emission point is at the street level.
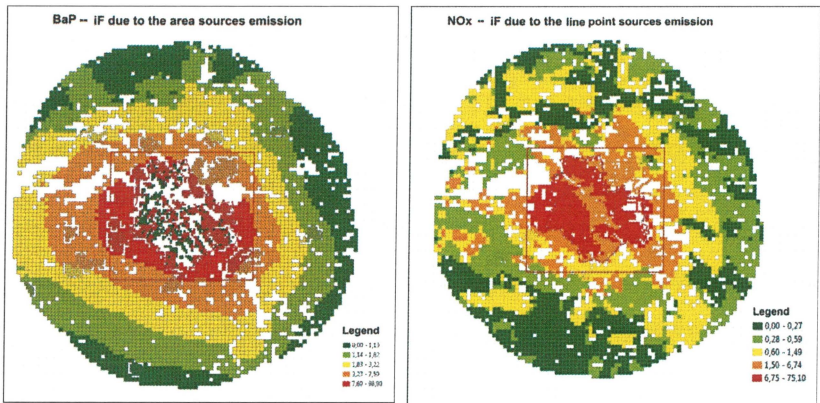

Fig. 6. Spatial distributions of the *iF* index for the area sources (left) and the line sources (right)
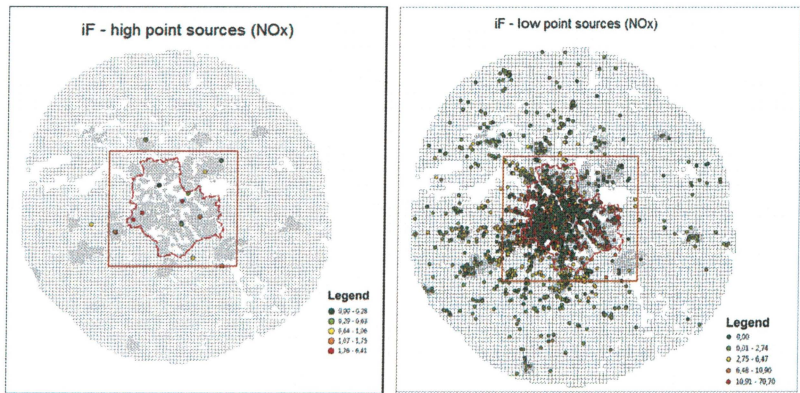

Fig. 7. Spatial distributions of the *iF* index for the point sources: high (left) and low (right)

Figure 6 presents example maps of the spatial distribution of the *iF* index, for the area (B(a)P) and line (NOx) emission categories. In the case of the area sources (Fig. 6 left), the highest values occur inside the peripheral districts of Warsaw or in the direct vicinity of the town, where the location of emission sources (dominating the individual heating/cooking installations) coincides with relatively high population density. On the other hand, the contribution of the area emission in the central part of the agglomeration is low due to the district heating system operating in the main part of Warsaw.

For the NOx pollution of the line sources (Fig. 6 right) the highest *iF* related values occur inside administrative border of Warsaw, where the high density of the street network coincides with the high population density, as shown in Fig. 2. In this case, the area of dominating iFs is limited and more compact compared to that for the area sources, due to the very low elevation the emission point of the mobile sources. This restrains dispersion of a pollutant and the resulting impact on the environment.

Similar, exemplary *iF* distribution maps for NOx pollution in the point source categories (high point sources – left and low point sources – right) are presented in Figure 7.

3.2 Aggregated estimates of the Exposure and the Intake Fraction indexes

The population average exposure, when used to quantify the aggregated impact of an emission category and attributed to a specified pollutant, has been calculated according to the formula:

$$E_k = \frac{1}{Pop} \sum_j Pop_j \sum_i C_{i,j,k} \tag{3}$$

where E_k is the total exposure to the selected polluting compound [$\mu g/m^3$], $C_{i,j,k}$ – concentration of this pollutant [$\mu g/m^3$] originating from the *i*-th source and measured at the *j*-th receptor element, Pop_j – population of the *j*-th receptor element [person], Pop – total population, i – emission source's index within emission category, j – receptor's index, k – index of the pollutant.

In the case of the aggregated index, $(iF)_k$ attributed to a specified pollutant within an emission category, can be calculated as follows:

$$(iF)_k = \frac{BR}{Q_k} \sum_j Pop_j \sum_i C_{i,j,k} \quad \text{and} \quad Q_k = \sum_i Q_{i,k} \tag{4}$$

where BR – breathing rate as in (2), $(iF)_k$ – aggregated index of the k-th pollutant attributed to emission category, Q_k – total pollutant's emission within this category, i – index of the emission source, j – receptor's index, k –index of the polluting compound.

Model calculates concentrations of the secondary pollutants, $SO_4^=$ and NO_3^-, which are the components of the secondary PM concentrations. The related exposures can be calculated according to (3). To include these two compounds in the iF computation process, it is necessary to assess the related emission values. In the case of aerosols the secondary emission was approximated as fraction $Q_{II} = \alpha \cdot Q_I$ of the primary emission Q_I of SO_2 or NO_X, respectively, where $\alpha = E_{II}/(E_I + E_{II})$. Here E_I and E_{II} denote the primary and secondary pollutant exposure, respectively. In this case the emission rates were multiplied by the factors of 0.67 and 0.48 (for $SO_4^=$ and NO_3^-, respectively), to take into account the differences in atomic mass between emission and concentration [24].

The transboundary inflow, considered in this study, contributes significantly to the final exposition and iFs of some pollutants. Aerosols $SO_4^=$ and NO_3^- are the secondary pollutants, where the share of the local sources is minor, mainly due to the time which is required to aerosol formation. The contribution of the aerosol's inflow from distant sources is greater, due to a long time when they are transported and transformed in the atmosphere. Also contribution of the inflow particulate matter, which contain aerosols as components, is considerable.

The values of the aggregated indexes (3) and (4), computed for all the pollutants discussed in this study, together with the related emission Q_k, are shown in Table 3. Exposure of the high point sources – and the related iF index – are low, above all due to the stack height of the main power plants (100 – 300 m). Most of the emitted volume of pollutants is transported outside the domain under question. The impact of the low point sources is more significant, since the real emission point is closer to the earth surface and much more of the receptor points are affected. The ranges of the iF variability in both categories are rather narrow, 0.7 – 1.5 for high and 2 – 7 for low point sources.

Table 3. Exposure [$\mu g/m^3$] ([ng/m^3] for As, Cd, Ni, BaP), emission [g/s] ([mg/s] for As, Cd, Ni, BaP) and iF (per million) for the main emission categories, trans-boundary inflow and the total exposure/emission.

	High Point			Low Point			Area			Line			Local			Inflow	Total
	E	Q	iF	E	Q	iF	E	Q	iF	E	Q	iF	E	Q	iF	E	E
SO2	0,74	358,49	0,74	0,29	50,94	2,03	3,32	113,71	10,53	1,83	33,85	19,47	6,18	556,98	4,00	1,45	7,63
SO4	0,01	3,06	1,11	0,00	0,28	3,21	0,11	5,11	8,10	0,07	0,84	29,06	0,20	12,69	5,54	0,61	0,80
NOx	0,43	256,81	0,63	0,47	44,78	3,80	2,11	74,47	10,19	22,94	458,22	18,04	25,95	834,28	11,20	1,63	27,57
NO3	0,01	2,34	1,25	0,01	0,45	7,91	0,10	3,27	11,43	0,48	4,61	37,58	0,60	13,75	15,82	2,70	3,30
PPM10	0,06	22,74	0,93	0,24	21,51	3,99	9,15	271,96	12,12	2,58	36,43	25,48	12,02	352,64	12,28	9,49	21,51
PPM10_r	-	-	-	-	-	-	-	-	-	12,71	159,39	28,74	12,71	159,39	28,74	-	12,71
PPM25	0,02	7,35	1,05	0,11	9,65	4,08	7,09	212,42	12,02	1,73	24,48	25,39	8,94	253,91	12,69	7,01	15,96
PPM25_r	-	-	-	-	-	-	-	-	-	1,83	22,34	29,48	1,83	22,34	29,48	-	1,83
PM10	0,08	28,74	0,99	0,25	22,23	4,07	9,37	280,34	12,04	15,84	201,26	28,35	25,54	538,47	17,08	12,79	38,33
PM25	0,04	12,74	1,12	0,12	10,38	4,26	7,31	220,80	11,92	4,10	48,15	30,70	11,57	302,69	13,77	10,32	21,89
CO	0,13	61,02	0,85	0,50	69,35	2,62	6,56	202,79	11,66	201,69	2494,27	29,13	208,89	2827,42	26,62	121,14	330,03
C6H6	0,28	178,52	0,61	0,13	17,35	2,68	0,00	0,00		0,97	12,07	28,98	1,38	207,95	2,39	-	1,38
Pb	0,000	0,00	1,30	0,000	0,01	5,39	0,006	0,17	12,71	0,010	0,13	27,52	0,016	0,32	18,48	0,001	0,017
As	0,003	1,04	1,18	0,004	0,48	2,80	0,660	18,73	12,70	0,000	0,00	0,00	0,668	20,26	11,87	-	0,668
Cd	0,001	0,35	0,77	0,047	1,87	9,08	0,964	27,34	12,71	0,009	0,35	9,65	1,021	29,91	12,30	0,041	1,063
Ni	0,063	26,62	0,86	0,115	7,35	5,62	3,040	86,34	12,68	0,922	14,86	22,36	4,140	135,16	11,03	-	4,140
BaP	0,013	3,27	1,41	0,016	2,45	2,31	0,964	30,55	11,36	0,191	3,79	18,19	1,184	40,07	10,64	0,625	1,809

The values of the indexes are more significant in the area and the line sources. In the last category an emission is a segment of the street which usually coincides with densely populated districts of the city. Here again variability of the exposure is very high, comparing with that for *iF*, where the respective ranges are $12 - 14$ for the area sources and $15 - 20$ for the line sources. This results mainly from the fact, that exposure is directly attributed to the emission volume and *iF* is a standardized index, calculated per unit emission. This fact is discussed below in more details.

4. HEALTH EFFECTS

4.1. Estimation of health effects

The health risks due to air pollution were quantified following the methods described in Tainio [23]. For gaseous air pollutants and metals the health risks were estimated for individual pollutant. For particulate matter the health risks were calculated separately for two size fraction: $PM_{2.5}$ and $PM_{2.5-10}$. Thus, we assumed that toxicity of particles vary between primary ($PM_{2.5}$) and coarse ($PM_{2.5-10}$) fraction of the PM, but not between source or chemical composition.

The calculation of the health risks followed the methods described in the supplementary material of Tainio [23] paper for $PM_{2.5}$, $PM_{2.5-10}$, SO_2, NOx, BaP, Cd, Ni and Pb. For As, C_6H_6 and CO we used following concentration-response functions: For CO we adopted CRF from Hosseinpoor et al. [15] study that estimated angina pectoris admissions in Tehran, Iran, for multiple pollutants. The resulting RR was used in this study to estimate changes in ischemic heart disease related risks. For the As we adopted unit risk from Erraguntla et al. [6]. The unit risk for cancer mortality was estimated based on the three epidemiological studies and the resulting unit risk factor was 1.5E-04 per lg/m3. We used this value to estimate the cancer mortality due to As. For C_6H_6 we adopted unit risk value for leukemia from Hänninen and Knol [11] study that estimate burden of disease due to environmental stressors in Europe.

Two measures of health were used: Number of attributable deaths and disability-adjusted life-years (DALY). The advantage of DALY measure is that it combines mortality and morbidity impact to one measure of health, allowing us to compare e.g. mild mental retardation, caused by Pb, with the increased mortality, caused by $PM_{2.5}$.

For the background DALY and mortality data we used the year 2013 Global Burden of Disease country file for Poland -- GBD (2013) Study, [8]. The data was adjusted from national to Warsaw population by using age and gender specific differences in population as a guide.

The health calculations were done with the Monte Carlo simulation program Analytica (Lumina Decision Systems, Inc.), version 4.6. Uncertainty was propagated through the model with 50,000 iterations.

5. HEALTH RESULTS

5.1. Concentration and exposure

The exposure for the studies air pollutants is presented in Table 3 for four local emission categories and to the transboundary inflow from outside the study area.

The transboundary inflow contributes significantly to the final exposition. Aerosols $SO_4^=$ and NO_3^- are the secondary pollutants (Table 1) where the share of the local sources is minor, mainly due to the time which is required to aerosol formation. The contribution of the aerosol's inflow from distant sources is greater, due to a long time when they are transported and transformed in the atmosphere. Also contribution of the inflow particulate matter, which contains aerosols as components, is considerable.

6.2. Health burden

Air pollution was estimated to cause approximately 5400 attributable death per year in study area (Table 4). Over 91% of the total attributable deaths are due to PM2.5 air pollution and 8.5% due to NOx. Less than 1% of the deaths are due to all other pollutants. Approximately 48% of the deaths are due to air pollution influx outside the study area and 52% due to air pollution emissions inside the study area. From local emission sources the area sources were most important one, followed by the line sources. High point sources caused less than 1% of the attributable deaths.

The DALY effects were similar to attributable deaths (Table 5). Most of the DALYs (92%) were due to PM air pollution, followed by NOx (8%). From diseases highest impact were due to COPD, caused by exposure to PM2.5 and lower respiratory symptoms for children, caused by PM10.

20

Table 4. Attributable death per year for the study population

	High point sources	Low point sources	Linear sources	Area sources	Inflow from the outside	Total	%
PM2.5: Natural mortality	7,9	24,6	822,9	1465,5	2565,9	**4886,9**	90,9%
NOx: Natural mortality	7,1	7,8	379,8	34,9	26,9	**456,5**	8,5%
SO2: Lung cancer	0,7	0,3	1,8	3,3	1,4	**7,6**	0,1%
BaP: Lung cancer	0,0	0,0	0,3	1,6	1,0	**2,9**	0,1%
Cd: Cancer	0,0	0,0	0,0	0,7	0,0	**0,8**	0,0%
Ni: Cancer	0,0	0,0	0,0	0,0	0,0	**0,0**	0,0%
Pb: Cardiovascular diseases (adult)	0,0	0,1	6,8	4,1	0,5	**11,4**	0,2%
As: Lung Cancer	0,0	0,0	0,0	0,0	0,0	**0,0**	0,0%
CO: Ischemic heart disease	0,0	0,0	6,5	0,2	3,9	**10,7**	0,2%
C6H6: Leukemia	0,0	0,0	0,1	0,1	0,0	**0,3**	0,0%
Total	**15,8**	**32,9**	**1218,3**	**1510,4**	**2599,7**	**5377,1**	100,0%
%	0%	1%	23%	28%	48%	100%	

Table 5. The DALY index for the study population

	High point sources	Low point sources	Linear sources	Area sources	Inflow from the outside	Total	%
PM2.5: Natural mortality	124	387	12 925	23 017	40 299	**76 752**	**84,00%**
PM2.5: Chronic bronchitis (COPD)	5	15	509	906	1 586	**3 021**	**3,30%**
PM2.5: Restricted activity days (RAD)	1	4	122	217	379	**722**	**0,80%**
PM2.5: LRS symptoms days (School children)	0	1	31	55	96	**182**	**0,20%**
PM2.5: LRS symptoms days (adult)	1	2	71	126	220	**419**	**0,50%**
PM2.5-10: LRS symptoms days (School children)	0	1	88	15	19	**123**	**0,10%**
PM2.5-10: LRS symptoms days (adult)	1	2	202	36	43	**283**	**0,30%**
PM2.5-10: Chronic bronchitis (COPD)	4	16	1 455	256	307	**2 038**	**2,20%**
NOx: Natural mortality	111	123	5 966	548	423	**7 170**	**7,80%**
SO2: Lung cancer	16	6	39	72	31	**164**	**0,20%**
BaP: Lung cancer	0	1	7	34	22	**63**	**0,10%**
Cd: Cancer	0	1	0	16	1	**18**	**0,00%**
Ni: Cancer	0	0	0	0	0	**1**	**0,00%**
Pb: Mild mental retardation (children)	0	0	8	5	1	**13**	**0,00%**
Pb: Cardiovascular diseases (adult)	0	2	166	100	11	**279**	**0,30%**
As: Lung Cancer	0	0	0	0	0	**0**	**0,00%**
CO: Ischemic heart disease	0	0	98	3	59	**160**	**0,20%**
C6H6: Leukemia	1	0	3	3	0	**7**	**0,00%**
Total	**265**	**561**	**21 687**	**25 406**	**43 495**	**91 415**	**100,00%**
%	**0%**	**1%**	**24%**	**28%**	**48%**	**100%**	

6. CONCLUSIONS

- A large fraction of the atmospheric pollution in Warsaw comes from the sources located outside of the Warsaw borders -- inflow from the background pollution but also located in the surrounding belt area.

- Pollutions coming from the area sources cause around 8800 deaths a year in Warsaw. From this 43% is due to the trans-boundary inflow from the outside the study area and the rest due to local emissions.

- Local emissions area sources caused almost 40% of the health effects, followed by the 20% due to linear sources. Impact of point sources was around 1%.

- Nearly all the deaths (91%) were due to $PM_{2.5}$ concentrations, highlighting importance of this pollutant for population health.

- When morbidity effects were included in the calculations, mortality due to $PM_{2.5}$ accounted for 84% of the DALYs, and 92% of all the DALYs were due to PM.

- The results indicate that local decisions can reduce air pollutants and associated health effects in the study area. However, also Mazovian Voievodship and country authorities should participate, in order to take account of pollutants inflowing to the city.

REFERENCES

[1]   Bennet, D.H., McKone, T.E., Evans, J.S., Nazaroff, W.W., Margni, M.D., Jolliet, O., Smith, K.R. Defining Intake Fraction (2002). *Environmental Science and Technology*, 49, May 1, 206A-211A.

[2]   CAFE (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

[3]   Dimitriou, K. & Kassomenos, P. (2014). A study on the reconstitution of daily PM10 and PM2.5 levels in Paris. Atmospheric Environment, 98, 648–654.

[4]   EEA (2012). European Environment Agency. Air quality in Europe – Report No 4/ 2012.

[5]   EEA (2009) (European Environment Agency); http://www.eea.europa.eu/data-and- maps/data-population-density-disaggregated-with-corine-land-cover-2000-1

[6]   Erraguntla NK, Sielken RL Jr, Valdez-Flores C, Grant RL. (2012). An updated inhalation unit risk factor for arsenic and inorganic arsenic compounds based on a combined analysis of epidemiology studies. Regulatory Toxicology and Pharmacology 64 329–341.

[7]   ETC/ACM (2013). Technical Paper 2013/11 (R. Rouil, B. Bessagnet, eds). How to start with PM modelling for air quality assessment and planning relevant to AQD.

[8]   GBD (2013). Global Burden of Disease Study 2013.   Results by Location, Cause, and Risk Factor. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2016.

[9]   GUS Report 2014. Powierzchnia i ludność w przekroju terytorialnym w 2014 r. In: Główny Urząd Statystyczny [on-line]. 2014.

[10] Habilomatis, G., Chaloulakou A (2015). A CFD modeling study in an urban street canyon for ultrafine particles and population exposure: The intake fraction approach. Science of the Total Environment, 530-531, 227-232.

[11] Hänninen O, Knol AB, Jantunen M, Lim TA, Conrad A, Rappolder M, Carrer P, Fanetti AC, Kim R, Buekers J, Torfs R, Iavarone I, Classen T, Hornberg C, Mekel OC, and EBoDE Working Group (2014). Environmental burden of disease in Europe: assessing nine risk factors in six countries. Environmental Health Perspective 122(5): 439-46.

[12] Holnicki, P., Kałuszko, A., Nahorski, Z., Stankiewicz, K., Trapp, W. Air quality modeling for Warsaw agglomeration. Archives of Environmental Protection, (in press).

[13] Holnicki, P., Kałuszko, A., Trapp, W. (2016), The urban scale application and validation of the CALPUFF model. Atmospheric Pollution Research, 7, 393 - 402.

[14] Holnicki, P., Nahorski, Z (2015). Emission Data Uncertainty in Urban Air Quality Modeling – Case Study. Environmental Modeling & Assessment, 2, 583 – 597.

[15] Hosseinpoor AR, Forouzanfar MH, Yunesian M, Asghari F, Naieni KH, Farhood D. (2005). Environmental Research 99: 126-131.

[16] Kiesewetter, G., Borken-Kleefeld, J., Schöpp, W., Heyes, C., Thunis, P., Bessagnet, B., Terrenoire, E. & Amann M. (2014). Modelling street level PM10 concentrations across Europe: source apportionment and possible futures, Atmospheric Chemistry and Physics. Discussions, 14, 18315–18354.

[17] Levy, J.I. (2016). Fine Particulate Matter Assessment. and Risk Management. Risk Analysis, DOI:10.1111/risa.12673.

[18] Marshalla, J.D., Riley, W.J., McKoneb, T.E., Nazaroff, W.W. (2003). Intake fraction of primary pollutants: motor vehicle emissions in the South Coast Air Basin. Atmospheric Environment, 37, 3455-3468.

[19] ME (2012). Ministry of the Environment. Decree 1031, 24 Aug. 2012, On the admissible levels of some substances in the air (in Polish).

[20] NCAR (2008). A description of the advanced research WRF Version 3. NCAR Technical Note, TN–475+STR. Boulder, Colorado, USA June 2008.

[21] Powierzchnia i ludność w przekroju terytorialnym w 2014 r.. W: Główny Urząd Statystyczny [on-line] (2014).

[22] Scire, J.S., Strimaitis, D.G., Yamartino, R.J. (2000). A User's Guide for the CALPUFF Dispersion Model. Earth Technology Inc.

[23] Tainio M. (2015). Burden of disease caused by local transport in Warsaw, Poland. Journal of

[24] Tainio, M.; Holnicki, P.; Loh, M. M.; Nahorski, Z. (2014). Intake Fraction Variability Between Air Pollution Emission Sources Inside an Urban Area. Risk Analysis, 34, 2021-2034.

[25] Wang, T., Jerrett, M., Sinsheimer, P., Zhu., Y. (2016). Estimating PM2.5-associated mortality increase in California due to the Volkswagen emission control defeat device. Atmospheric Environment, 144, 168–174.

[26] Warszawa (2015). https://pl.wikipedia.org/wiki/Warszawa

[27] WHO Report (2016) "Air pollution levels rising in many of the world's poorest cities". http://www.who.int/mediacentre/news/releases/2016/air-pollution-rising/en/

[28] https://pl.wikipedia.org/wiki/Warszawa