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Intake fraction variability between air pollution emission sources inside an urban area

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Terms used in the text:

- Intra-urban iF = iF associated with urban residents' inhalation of emissions that occurred in the same urban area.
- Population-weighted iF: iF weighted based on population counts.
- Emission-weighted iF: iF weighted based on emission rates
- Intra-urban iF variability: iF variability between individual sources for a single pollutant in a single emission source category (e.g. between different Mobile source areas emitting primary PM2.5)

ABSTRACT

The cost-effective mitigation of adverse health effects caused by air pollution requires information on the contribution of different emission sources to exposure. In urban areas the exposure potential of different sources might vary significantly depending on emission height, population density, and other factors. In this study we quantified this intra-urban variability by predicting intake fraction (iF) for 3066 emission sources in Warsaw, Poland. Intake fraction describes the fraction of the pollutant that is inhaled by the people in the study area. We considered the following seven pollutants: particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), benzo [a] pyrene (BaP), nickel (Ni), cadmium (Cd), and lead (Pb). Emissions for these pollutants were grouped to four emission source categories (Mobile, Area, High Point and Other Point sources). The dispersion of the pollutants was predicted with the CALPUFF dispersion model by using the year 2005 emission rate data and meteorology. The resulting annual average concentrations were combined with the population data to predict the contribution of each individual source to population exposure. The iFs for different pollutant-source category combinations varied between 51 per million (PM from Mobile sources) to 0.013 (sulfate PM from High Point sources). The intra-urban iF variability for Mobile sources primary PM emission was from 4 to 100 per million with the emission-weighted iF of 44 per million. These results indicate that spatially targeted emission reduction policies inside an urban area could potentially improve the health of population more than a general reduction of emissions from all the sources.

KEYWORDS

Intake fraction; air pollution; exposure; health impact assessment; atmospheric dispersion model.

1. INTRODUCTION

Ambient air pollution is one of the main risk factors in the World. Out of the 67 risk factors studied in the Global Burden of Disease study 2010 (1) particulate matter (PM) air pollution was the 9th and ozone the 39th most important. PM air pollution was the second most important environment related risk factor after the household air pollution (4th). Lead (25th) is another risk factor that is emitted and dispersed through the air. The regional variability in risk factors was large so that in Oceania, PM air pollution was only 32nd most important risk factor while in the East Asia it was 4th (1).

The cost-effective mitigation of the adverse health effects of air pollution requires information on how different emission sources contribute to exposure. For air pollution, the factors influencing the emission-to-exposure relationships for different sources and source categories have been examined in various geographical areas and for different emission sources (2–13). Many of these studies have used the intake fraction (iF) concept (14) to summarize and communicate the emission-to-exposure differences between sources and source categories. For air pollutants, iF describes the fraction of the emission that is inhaled by the exposed population. Typical iF for non-reactive air pollutants in urban areas vary between 1 per million to 1000 per million (15); meaning that from every kg of air pollution emitted, 1 to 1000 mg is been inhaled, respectively.

The iF concept has been increasingly used in risk and health impact assessment studies to summarize exposure parameters (5,16) and to predict exposure in the areas with limited data (17). In particular, the life-cycle impact assessment (LCIA) field has adopted and developed the iF concept to predict the environmental and health effects of production systems (18,19).

For example, Humbert et al. (20) recommended a set of iFs for primary and secondary PM emissions in urban, rural and remote locations that could be used in LCIA studies.

The studies cited in the previous paragraphs have two common features: Most of them have predicted iFs for primary PM, or to other non-reactive air pollutants, and most of them have predicted iFs in geographical areas varying from tens to thousands of kilometers around the source. Only five of the studies (3,4,10,11,17) have predicted intra-urban iFs, and most of them predicted iFs for primary $PM_{2.5}$ emitted mostly from the mobile sources. Intra-urban iF is the emission-to-exposure relationship of the urban population to the emissions that occurred in the same urban area. Only one of these studies have predicted iF variability between individual emission sources for single pollutant inside the same urban area (so called intra-urban iF variability) (3). That study concluded that there exists substantial intra-urban iF variability for mobile sources PM emissions, and that this variability might be relevant for cost-benefit assessments.

The iF literature is even more thin for reactive pollutants, such as secondary particles. Only two of the previously mentioned iF studies have predicted intra-urban iFs for secondary particles (4,17). Several previous studies have predicted iFs for secondary particles (2,5,12,13) but all of these studies have focused on long range transport of particles. Secondary particles are formed in the air through the oxidation of SO_2, NO_x and VOC gases, and due to the time needed for the oxidation process, the concentrations of secondary particles are lower near the emission sources than respective concentrations of primary particles (per unit of emission). This will also impact iF's. For example, Greco et al. (2) predicted that half of total exposure due to primary $PM_{2.5}$ emissions from mobile sources occurred less than 150 km from the source while for secondary sulfate and nitrate particles respective distances were

450 and 390 km. Therefore the intra-urban iF for secondary particles can be assumed to be lower than the iF for primary particles.

In this study we predict intra-urban iF and intra-urban iF variability for several air pollutants. The main focus of this study is (i) to quantify intra-urban iFs for different pollutants and pollutant-emission source category combinations, and (ii) to quantify intra-urban iF variability within emission source categories. All the calculations were done for the following air pollutants: primary and secondary PM_{10} and $PM_{2.5}$, nitrogen oxides (NO_x), sulfur dioxide (SO_2), benzo [a] pyrene (BaP), nickel (Ni), cadmium (Cd), and lead (Pb). These pollutants were chosen because of their relevance for risk and health impact assessments (1,21).

2. METHODS

2.1. Description of the study area

The study area consisted of the administrative area of the city of Warsaw, Poland (Figure 1). In 2010 Warsaw had approximately 1.7 million inhabitants with an average population density of 3287 inhabitants/km^2 (22). The climate is a humid continental climate with cold winters and warm summers. The landscape is relatively flat with highest point 122 m above the sea level and average elevation 100 m above sea level (23). The main geographical feature is the Vistula River that divides the city to left and right sides (Figure 1).

2.2. Emission rates (Q)

The emission data consisted of emission rates for 12 pollutants emitted from 1790 sources and source areas inside the study area. The source areas present several individual sources (e.g. vehicles) and the emission rates were predicted to approximately 1 km x 1 km source areas. The pollutants and the acronyms used in this article are described in Table I and emission

rates in Table II. The emission sources were grouped into four emission source categories representing Mobile sources, Area sources, High Point sources and Other Point sources. The emission rates for Mobile and Area sources were represented by 1km x 1km source areas. For Point sources, the exact location of the emission was used. Year 2005 emission rates were used in the calculations. The emission data was obtained from EKOMETRIA, Poland (http://www.ekometria.com.pl/).

2.3. Dispersion modeling (*C*)

The dispersion modeling work undertaken in this study has been described in detail in Holnicki et al. (24). In this section we will offer a general overview of the methods.

The dispersion of pollutants inside the study area was predicted with the Gaussian puff dispersion model CALPUFF, version 5 (http://www.src.com/calpuff/calpuff1.htm). The meteorological data was based on year 2005 meteorology. Year 2005 was selected mainly due to the representative meteorological conditions of that year, and because the most consistent emission data was available for that year. The time interval of the dispersion model was 1hour. Topography of the study area was taken into account by including the small slopes along the Vistula River, and the general building topography. Street canyon effect was not considered due to 1 km x 1 km spatial resolution of the model.

The inflow of air pollutants from outside of the study area was included as a boundary condition for the CALPUFF. Boundary conditions were adopted from the regional scale EMEP model (the European Monitoring and Evaluation Programme) predictions for PM_{10}, $PM_{2.5}$, SO_2, SO_4, NO_X and NO_3. The spatial resolution of the EMEP model was 50 km x 50 km. The inflow of Pb, Ni and Cd was approximated from the measurement data.

The annual average concentrations of pollutants (Table I) were predicted for 563 hypothetical receptor points inside the administrative borders of the city of Warsaw (Figure 1). The receptor points formed a 1 km x 1km grid over the study area. The concentration changes due to emissions from the source or source areas were recorded to a database so that the contribution of each source or source area to annual average concentration of pollutants could be calculated.

The accuracy of the concentration predictions were assessed by comparing the modeled annual average concentrations of PM_{10}, NO_x, SO_2, Pb, Ni and Cd with the measured concentrations of these pollutants in different monitoring stations around the city. For PM_{10}, NO_x and SO_2, the difference between modeled and measured annual average concentrations were -2%, -7% and 12%, respectively, when the difference was averaged over 13, 9 and 9 different measurement stations, respectively. For Pb, Ni and Cd the respective difference between modeled and measured concentrations were -13%, -9% and +26%, respectively. The degree of uncertainty due to dispersion modeling was concluded to be reasonable in comparison to uncertainties in health impact estimation (16,25).

2.4. Population (*Pop*)

The residential population data was obtained from the European Environment Agency (EEA) (26). The spatial resolution of the data was 100 m x 100 m and it covered all 28 countries belonging to the European Union. The population of the study area was calculated from the EEA population data by taking 1 km buffers around each of the 563 receptor points, for which the concentrations were predicted, and then joining the population grids to the nearest receptor points. Each 100 m x 100 m population grid was joined only for one receptor point to avoid double counting of same population. Figure 1 shows the population density for the

study area. The population of Warsaw over all the receptor points was 1 790 872. The calculations were done with the ESRI ArcMap version 9.3.

2.5. Calculation of intake fractions (*iF*)

Intake fraction represents the fraction of the emission that is inhaled by the population in the study area. The iF for air pollutants is calculated with the equation:

$$iF_{j,k} = \sum_i (C_{i,j,k} \times Pop_i \times BR)/Q_{j,k} \qquad (1)$$

where $iF_{j,k}$ is the intake fraction for pollutant j and for the source k; $C_{i,j,k}$ is the predicted concentration increase of air pollutant (g/m^3) in a receptor point i for pollutant j and due to emission source k; Pop_i is the number of people at the receptor point i; BR is the average breathing rate; and $Q_{j,k}$ is the emission strength (g/s) for pollutant j in the source k. Source k represented both point sources and source areas. A constant BR of 20 m^3/(day x person) (~0.0002 m^3/(s x person) was used in all the calculations. The same BR value has been used in a number of previous iF studies (3,5,8). The iF calculations were done with Analytica version 4.4 (http://www.lumina.com/).

The iFs were calculated for each individual source (k), combined for all the sources belonging to same emission source category, and combined for all the sources emitting the same pollutant (j). To calculate iFs for emission source categories, we calculated emission-weighted iFs. Emission-weighted iF for $PPM_{2.5}$ due to Mobile sources was calculated by adding all the concentration increases (c) caused by 539 individual Mobile sources together and then calculating the iF by using the combined emission rates (Q) of these sources. Similar approach was used to calculate emission-weighted iF for 1554 sources emitting $PPM_{2.5}$. The

same emission-weighted iFs could have been calculated also by weighting each iF with the emission rates and then calculating emission-weighted mean over all the iFs.

3. RESULTS

The emission-weighted iFs for different pollutants (j) and source categories are presented in Table III. The emission-weighted iFs for different pollutants formed approximately three groups so that the iFs for most of the pollutants were in between 11 and 38 per million, for secondary particles (PM_{SO4}, PM_{NO3}) iFs were less than 1 per million, and for road dust ($PPM_{2.5R}$, PPM_{10R}) iFs were around 50 per million (Table III). For SO2 the emission-weighted iF was 1.8 per million.

The emission-weighted iFs for different pollutant and emission source category combinations were similarly divided to three groups so that the iFs for secondary particles (PM_{SO4}, PM_{NO3}) were less than 1 per million regardless of the emission source category, and iFs for High Point sources were around 1 per million (for other pollutants than secondary aerosols) (Table III). For all other pollutant and emission source category combinations emission-weighted iFs were in between 4.5 per million and 51 per million. For most pollutants, the emission-weighted iFs were highest for Mobile sources. The exceptions were BaP, Cd and Ni for which the emission-weighted iFs were highest for Area sources. The emission data had only eight Mobile sources emission source areas for these pollutants (Figure 2) and all these areas were located on the borders of the study area (data not shown) causing lower than expected iFs for these pollutants due to Mobile sources.

The intra-urban iF variability for pollution and emissions source category combinations is presented in boxplots in Figures 2. The highest predicted iF was 115 per million (PPM_{10R} due

to Mobile sources) and lowest 0.00054 per million (PM_{SO4} due to High Point sources). These two sources differ by a factor of over 200 000 in their potential for exposing the study population with particulate matter.

When examining intra-urban iF variability for pollutant and source category combinations, the highest variability was predicted for NOx emitted from High Point sources (73 times difference between smallest and highest iFs) (Figure 3). From the non-reactive pollutants, $PPM_{2.5}$ emitted from Mobile sources had 25 times difference between smallest and largest iFs. Thus, these two emission source areas had 25 times difference in their potential for exposure in study area, and consequently 25 times difference in their potential to cause adverse health effects. This kind of variability in exposure potential is relevant information for any cost-benefit study that examines the effect of various mitigation actions.

The correlation between iFs and emission rates for different sources and sources areas is presented in Table IV. High positive correlation between iFs and emission rates indicates that sources or source areas with the high emission rates also have high iF. Of the four emission source categories, Area sources and Other Point sources showed insignificant correlation between emission rate strengths and iFs. High Point source results show some negative trend proposing that the iFs might be lower for those sources with highest emission rates. For the Mobile sources the correlation between emission rates and iFs is positive for most pollutants proposing that the emissions from Mobile sources are highest in areas where they have highest potential for exposure.

4. DISCUSSION

We quantified emission-to-exposure relationships for several air pollutants emitted from different emission sources and illustrated the exposure potency variability between pollutants and sources with intake fraction (iF) concept. The predicted intra-urban iF variability between sources (k), source categories and pollutants (j) was significant for most pollutant and source category combinations. For the emissions from Mobile sources, iFs and emission rates were strongly correlated indicating that the emissions are highest on those areas that have highest potency to expose population. The result indicates that the spatially targeted emission reduction policies inside the urban areas could reduce the population health more cost-effectively than general reduction of emissions from all sources belonging to the same emission category.

In the present study our aim was to quantify iF variability between and within the emission source categories. Underlying reasons causing iF variability were not systematically examined. However, some trends can be observed just by comparing the iFs for different pollutants and sources categories. For example, for all the pollutants, emission-weighted iFs for High Point sources were lower than iFs for other source categories (Table III). For SO2, 86% of all the emissions were from the High Point sources, and consequently resulting emission-weighted iFs for both SO_2 and PM_{SO4} are low (Table III).

The significance of pollutant properties can be examined by comparing iFs between different pollutants for same source. For example, iFs for the source "k1197" (Mobile sources) were in between 24 and 27 per million for nonreactive pollutants (PPM_{10}, $PPM_{2.5}$, PM_{10R}, $PPM_{2.5R}$, BaP, Ni, Cd and Pb). For the reactive gases (SO_2 and NO_x) the iFs for this same source were 13 and 12 per million, respectively, and for secondary particles (PM_{SO4} and PM_{NO3}) 0.1 and 0.2 per million, respectively. Because the iF is independent of the emission rate, the

differences in iFs between pollutants for the same source are due to differences in pollutant properties. Thus, the intra-urban iFs for the reactive gases are about half of the iFs for nonreactive pollutants, and the intra-urban iFs for the secondary particles are about 100 times smaller than the iFs for nonreactive gases.

The intra-urban iF variability within the emissions sources, such as the variability in iFs between different $PPM_{2.5}$ emission source areas for Mobile emission, cannot be fully explained by neither pollutant properties nor emissions height differences. The iF review by Humbert et al. (20) concluded that the main factors causing iF variability between sources are population density and meteorological conditions, especially wind speed and mixing height. Although the meteorological conditions vary spatially and temporally inside the study area, the most likely reason for iF differences seen in the present study is population density variability near the emission sources. Thus, the Mobile sources has high emission-weighted iF because emission rates correlated with the population density.

We also calculated correlations between iFs and emission rates for different sources (Table IV) to analyze if same emission sources have high exposure potential and high emission rate. For the Mobile sources the correlation was high while for other pollutants correlation was insignificant or slightly negative (High Point sources). This result propose that for Mobile sources significant reduction in exposure, and associated health effects could be achieved if the mitigation actions could be targeted for those emission areas that have both high exposure potency and high emission rates.

4.1. Intra-urban iF variability within emission source category (k)

For most pollutant and source category combinations the highest iF for a single source was 15 to 60 times higher than the smallest iF for same pollutant and source category combination (Figure 2). We are aware of only one previous study, Greco et al. (3), that has examined intra-urban iF variability. Greco et al. estimated iFs for $PPM_{2.5}$ emissions due to Mobile sources for 23 398 individual road segments inside Boston, US, and the dispersion of pollutants was predicted within 5 km from the road segments with the CAL3QHCR line model. The resulting iFs for different road segments ranged from 0.8 per million to 53 per million, with mean iF of 12 per million (3).

When comparing our results for Mobile sources with the Greco et al. study we notice that the variability was slightly smaller in our study (25 times difference between smallest and largest in comparison to 66 times difference between smallest and highest in Greco et al.) but the emission-weighted mean iF was higher than the mean iF in Greco et al. (44 per million versus 12 per million). Greco et al. did not had emission rate data for road segments and the mean iF was calculated without emission-weighting. If we calculate mean iF similarly without emission weighting, the mean iF for Mobile sources is 26 per million. This difference in emission-weighted iF and mean iF is due to positive correlation between iFs and emission rates, as shown in Table IV.

Greco et al. concluded that there exists substantial intra-urban iF variability for $PPM_{2.5}$ emitted from Mobile sources. Our results support that conclusion, and in addition we can conclude that the variability is high also for other emission source categories and pollutants.

4.2. Intra-urban iF between pollutants and source categories

Table V summarizes and compares the intra-urban iF estimates from previous studies to the iFs predicted in the present study. All but one of the cited studies has predicted intra-urban iFs for the Mobile sources emissions and all but one study have predicted intra-urban iFs for nonreactive gas or $PPM_{2.5}$. The iFs predicted in this study are in same magnitude as the iFs in previous studies although population density, meteorology and analytical framework differ between studies. The main exception is the intra-urban iF for PM_{SO4} for Mexico City. In Stevens et al. (4), the iF for PM_{SO4} was 27 times higher in Mexico City than the iF predicted in this study (Table V). The study area in Stevens et al. study was 10 times bigger than study area in the present study and this, together with analytical differences, might explain the difference.

Our findings are also of same magnitude with the iFs recommended for the Life Cycle Impact Assessment studies in Humbert et al. (20). In that study the recommended iF for $PPM_{2.5}$ from ground-level source was 44 per million. In the present study the ground-level sources were divided to Mobile and to Area sources and the emission-weighted iFs for these two sources were 44 and 20 per million, respectively. The differences to Humbert et al. recommendations are insignificant. For the high-stack sources Humbert et al. recommended iF value of 11 per million, which is 13 times higher than the emission-weighted iF of 0.83 per million predicted for High Point Sources in the present study. The iFs recommended in Humbert et al. included dispersion outside the urban area and this difference probably explains the difference in iFs. For the secondary particles the recommendations were independent of emission height and the iFs for the SO2 and NOx emissions from urban area were 0.99 and 0.20 per million, respectively (20). Respective emission-weighted iFs in the present study were 0.02 (PM_{SO4}) and 0.18 (PM_{NO3}) per million. The iF for PM_{SO4} is of order of magnitude higher in Humbert et

al. when compared to emission-weighted iF in the present study. Most likely the reason for this difference is the lack of dispersion outside the study area in the present study.

For other pollutants we are not aware of any iF studies that would have focused on intra-urban iFs but some comparable iFs have been predicted for other areas. For example, Spadaro and Rabl (27) estimated iFs for Cd, Ni and Pb with a multimedia pathway model using average central-European parameterizations. The resulting iFs were 3.9, 3.9 and 7.1 per million, respectively, for the inhalation pathway while in the present study the emission-weighted iFs for the same pollutants were 12, 20 and 38 per million, respectively (Table III). According to Spadaro and Rabl, these iFs are for typical power plant emissions (high stack) and should be multiplied by 3 for typical industrial emissions (Area) and by 20 for typical automotive emissions (Mobile) (27).

For BaP, two previous iF studies with different methodologies have been published (19,28). Humbert et al.(28) estimated iF for BaP using the multimedia, multi-pathway model IMPACT North America (version 1.0). The resulting iF was 5.0 per million for urban settings and the maximum estimated iF was 30 per million, very similar to this study's emission-weighted mean, which is 11 per million (Table III) and maximum of 64 per million (Figure 2). Bennett et al. (19) predicted average iF for BaP to be 24 per million which is a factor of 2 higher than yhe emission-weighted iF predicted in the present study for BaP (11 per million). Although Bennett et al. included exposure also through the ingestion, the results are remarkably similar.

4.3. Uncertainties and limitations

There are a number of uncertainties and limitations related to this study. We will discuss in more detailes possible underestimation of population, lack of time-activity data and indoor-

outdoor penetration of pollutants. Atmospheric modeling uncertainties are discussed elsewhere (24).

The population of Warsaw was assumed to be 1.7 million, which approximates the city's official population count. However, Warsaw has a large non-official population that lives in the city but may be registered in other parts of the country. If the true population of Warsaw is significantly higher, it means that the iFs calculated in the present study underestimate the true exposure by underestimating the amount of people in the study area. The spatial distribution of this unofficial population may also change the population density of various areas, thus potentially affecting the iF distributions, which are strongly related to population density (2,3,8). However, current data does not allow for the assessment of this unofficial population.

The other main uncertainty relates to the lack of consideration of time-activity and outdoor-indoor infiltration in the intake estimate. We assumed that the outdoor concentrations of pollutants at people's residential addresses represent their exposure. The infiltration of pollutants from outdoors to indoors reduces the exposure to outdoor originated pollutants because only a fraction of the pollutants penetrate indoors. For example, in the measurement in Helsinki, Finland, the indoor-to-outdoor ration varied between 0.6 and 0.8 for outdoor originated air pollutants (29). This suggests that our iF estimates are biased upward. People also spend time in other locations than their homes, including both more and less polluted microenvironments.

Some previous studies have incorporated time-activity and indoor-outdoor infiltration to their assessments (6,11) and by comparing their findings we could generate plausible direction and

range of this bias. For example, Loh et al.(11) compared three methods of calculating iF for vehicular benzene emissions in Helsinki, Finland: (i) Estimation using data from a personal exposure study, (ii) a spatial traffic exposure model, and (iii) a simple box model. The first method used home indoor, outdoor, and workplace concentrations and time use information from the EXPOLIS study (30) (Air Pollution Exposure Distributions of Adult Urban Populations in Europe) to estimate the exposure and intake fraction for benzene from vehicles. The second method used the EXPAND model (31) (EXPosure to Air pollution, especially to Nitrogen Dioxide and particulate matter), which uses a vehicular emissions and line source model and population location activity patterns to estimate the intake fraction for 100 x 100 m2 grid cells. The third method used a simple box model to estimate intake fraction, which only needs the annual average population breathing rate, number of persons, average wind speed, mixing height, and land area. This study found that the personal exposure methods provided higher intake fractions than either the EXPAND or box model methods, with the box model providing the lowest mean estimate. This indicates that the iF for Mobile sources would be higher also in this study if the time use data would be available.

5. CONCLUSIONS

We have quantified the intra-urban iFs for number of pollutants and pollutant-source category combinations, as well as intra-urban iF variability within the source categories. For most pollutant and source category combinations the highest and smallest iFs had 20 to 60 times difference. In addition to iF variability, we also noticed that for Mobile emissions the emission rates are highest for those areas with highest exposure potency. Together these results indicate that the spatially targeted mitigation actions can potentially be more cost effective inside the urban areas than the similar reduction of emissions from all the sources. The iFs predicted in this study can also be used in future assessment studies to predict

exposure for air pollutants for areas with limited data, and to examine possible consequence of iF variability in other study settings.

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TABLES

Table I. Air pollutants considered in the study. Emissions were inputs to the dispersion model and the concentrations were the outputs of the dispersion model. $PM_{2.5}$ and PM_{10} are a sum of both primary and secondary PM.

Emission	Concentration
$PPM_{2.5}$ (primary particulate matter (PPM) with aerodynamic diameter ≤ 2.5 μm)	$PPM_{2.5}$ ($PM_{2.5}$ concentration caused by the $PPM_{2.5}$ emissions)
$PPM_{2.5R}$ ($PPM_{2.5}$ raised by road traffic – secondary emission)	$PPM_{2.5R}$
SO_2 (sulfur dioxide)	SO_2
SO_2 (sulfur dioxide)	PM_{SO4} (sulfate ($SO^{=}_{4}$) aerosol, secondary PM)
NO_x (nitrogen oxides)	NO_x
NO_x (nitrogen oxides)	PM_{NO3} (nitrate (NO^{-}_{3}) aerosol, secondary PM)
-	$PM_{2.5} = PPM_{2.5}+PPM_{2.5R}+ PM_{SO4}+ PM_{NO3}$
PPM_{10} (primary particulate matter with aerodynamic diameter ≤ 10 μm)	PPM_{10} (PM_{10} concentration caused by the PPM_{10} emissions)
PPM_{10R} (PPM_{10} raised by road traffic – secondary emission)	PPM_{10R}
-	$PM_{10} = PPM_{10}+PPM_{10R}+ PM_{SO4}+ PM_{NO3}$
BaP (benso [a] pyrene)	BaP
Ni (nickel)	Ni
Cd (cadmium)	Cd
Pb (lead)	Pb

Table II. Emission rates for different source categories, and the number of emission sources or sources areas included in the study.

	Unit	Mobile sources	Area sources	High Point sources	Other Point sources
Number of sources or source areas (k)	#	539	432	13	570
$PPM_{2.5}$	g/s	16	84	8	15
$PPM_{2.5R}$	g/s	26	-	-	-
SO_2	g/s	23	69	1328	125
NO_x	g/s	328	46	396	60
PPM_{10}	g/s	24	157	21	54
PPM_{10R}	g/s	153	-	-	-
BaP	mg/s	0.045	16	2.02	12
Cd	mg/s	0.20	17	2.02	12
Ni	mg/s	2.0	56	-	-
Pb	mg/s	107	109	-	-

Table III. Mean emission-weighted intake fractions (iF) (per million) for different pollutants and to pollutant-emission source category combinations.

Pollutant	All sources combined	Mobile sources	Area sources	High Point sources	Other Point sources
$PPM_{2.5}$	22	44	20	0.83	11
$PPM_{2.5R}$	50	50	-	-	-
PM_{SO4}	0.02	0.26	0.12	0.009	0.06
PM_{NO3}	0.18	0.42	0.29	0.014	0.10
PPM_{10}	19	45	21	0.72	10
PPM_{10R}	51	51	-	-	-
SO_2	1.8	32	18	0.7	9.5
NO_x	13	30	18	0.6	8.9
BaP	11	11	20	1.4	4.5
Cd	12	11	21	1.4	4.5
Ni	20	11	20	-	-
Pb	38	45	21	-	-

Table IV: Correlation between iFs and emissions rates for different pollutant-source category combinations. Positive correlation means that the exposure potency, indicated with iFs, is highest for those sources that have highest emission rates.

Pollutant	**Mobile sources**	**Area sources**	**High Point sources**	**Other Point sources**
$PPM_{2.5}$	0.81	0.06	-0.35	-0.11
$PPM_{2.5R}$	0.76	-	-	-
PM_{SO4}	0.76	0.08	-0.42	-0.21
PM_{NO3}	0.38	-0.09	-0.47	-0.24
PPM_{10}	0.80	0.08	-0.45	-0.12
PPM_{10R}	0.78	-	-	-
SO_2	0.79	0.11	-0.38	-0.18
NO_x	0.80	0.11	-0.42	-0.18
BaP	0.20	0.10	-	-0.43
Cd	0.15	0.12	-	-0.43
Ni	0.15	0.08	-	-
Pb	0.77	0.13	-	-

Table V. Intra-urban iF estimates for different pollutants and source categories in previous studies, and comparison to the present study.

Study	Pollutant, source category and location	Intake fraction (per million)	Respective intake fraction in the present study[a]
Greco et al. 2007 (3)	$PPM_{2.5}$ emitted from mobile source, Boston, USA.	12 (0.8-53) [b]	44 (4.0-100) (Mobile sources)
Ries et al. 2009 (6)	$PPM_{2.5}$ emissions from wood smoke, Vancouver, Canada.	13 (6.6-24) [c]	20 (4.0-63) (Area sources)
Marshall et al. 2005 (10)	Nonreactive gaseous vehicle emissions in US urban area.	14 (7-21)[d]	44 (4.0-100) (Mobile sources)
Stevens et al. 2007 (4)	$PPM_{2.5}$ emitted from mobile sources, Mexico City, Mexico.	60[e]	44 (4.0-100) (Mobile sources)
Stevens et al. 2007 (4)	PM_{SO4} emitted from mobile sources, Mexico City, Mexico.	7[e]	0.26 (0.04-0.30) (Mobile sources)
Stevens et al. 2007 (4)	PM_{NO3} emitted from mobile sources, Mexico City, Mexico.	0.7[e]	0.42 (0.14-0.44) (Mobile sources)

a) Emission-weighted mean, minimum and maximum.
b) Mean, minimum and maximum iF.
c) Geometric mean and one geometric standard deviation.
d) Best estimate.
e) Central estimate.

Figure 1: Study area. The map shows the location of Vistula River, main roads, city boundary and population density in 100 m x 100 m spatial resolution.

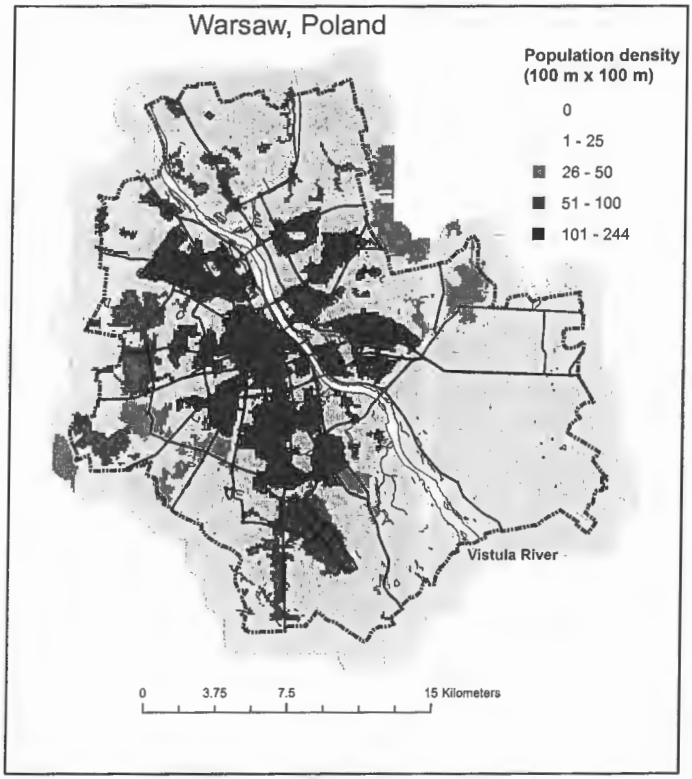

Figure 2: Intra-urban iF variability for different pollutants and source categories combinations. The 'n' defines the number of emissions sources or source areas (k) included in the analysis.

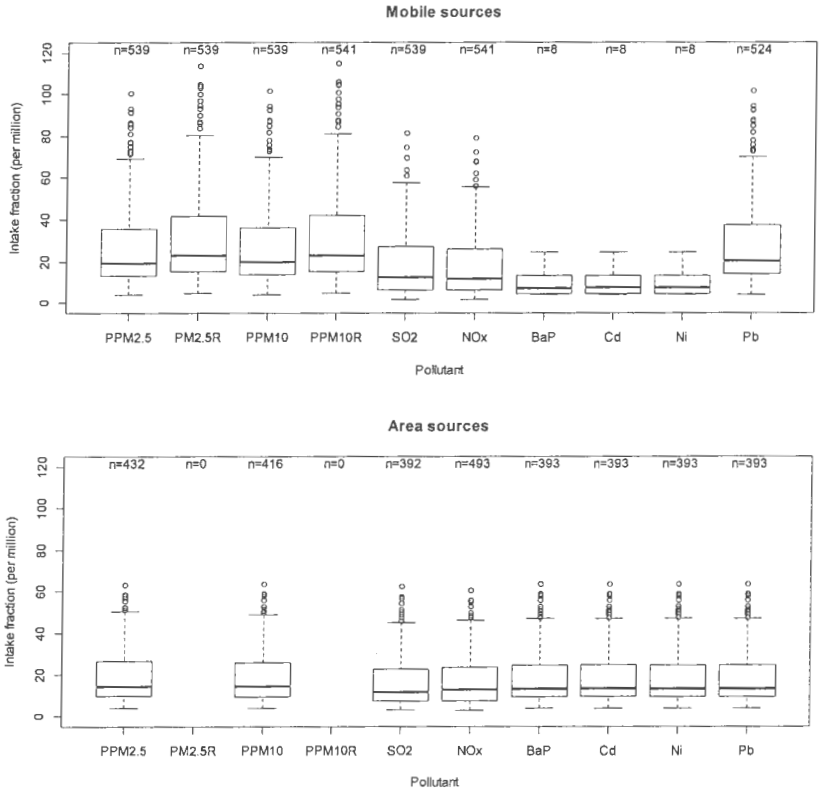

Figure 2 (cont.).

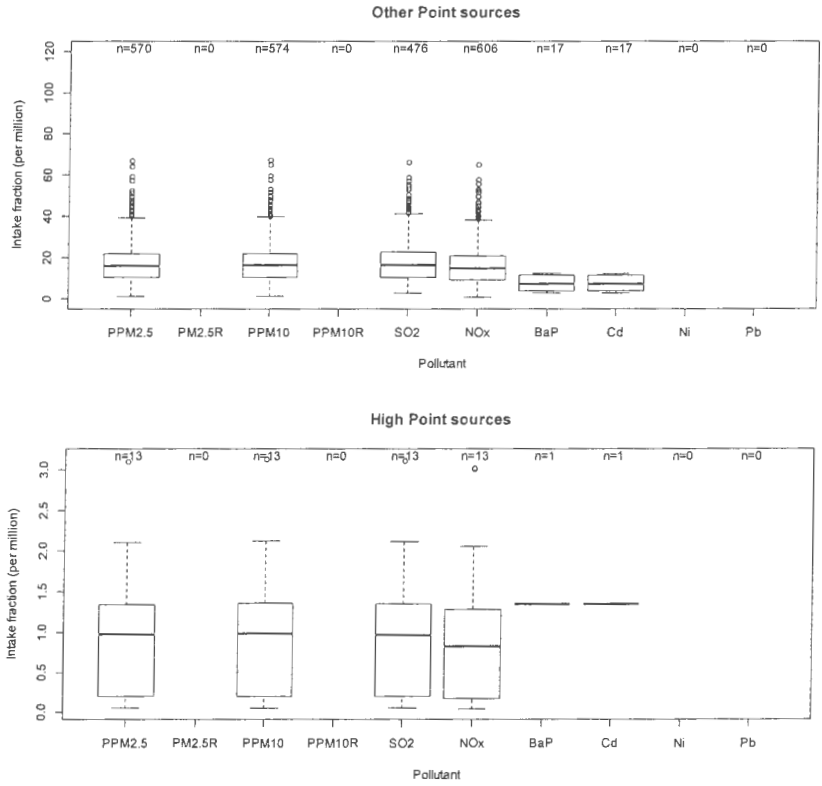

Figure 2 (cont.).