Assessment of the health impacts of exposure to $PM_{2.5}$ at a European level

ETC/ACC Technical Paper 2009/1
June 2009

Frank de Leeuw, Jan Horálek

European Topic Centre on Air and Climate Change

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Cover page: An old delivery van in use as wood storage in Southern France. Road traffic and wood burning, more generally, biomass burning are seen as important sources of primary PM2.5.

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Author affiliation

Frank de Leeuw, Netherlands Environmental Assessment Agency (PBL), Bilthoven, The Netherlands.
Jan Horálek, Czech Hydrometeorological Institute (CHMI), Praha.

ETC/ACC Technical paper 2009/1.
European Topic Centre on Air and Climate Change
PO Box 303
3720 AH Bilthoven
The Netherlands
Phone +31 30 2743550
Fax +31 30 2744433
Email : etcacc@pbl.nl
Website http://air-climate.eionet.europa.eu

Summary

A European $PM_{2.5}$ concentrations map has been prepared on the basis of PM_{10} concentrations maps using $PM_{2.5}/PM_{10}$ ratios inferred from measurements. Different $PM_{2.5}/PM_{10}$ ratios are used depending on location and type of station. The resulting $PM_{2.5}$ map is used to compare the current (2005) concentrations with the limit and target values as laid down in the Air Quality Directive. An annual mean concentration of 25 μg/m^3 (target value for 2010, limit value for 2015) is exceeded in 12 out of the 27 EU Member States. As the map has a spatial resolution of 10x10 km, more exceedances are to be expected at hot-spot locations (city centres, traffic situation, close to local sources). A first estimate of the health related *Averaged Exposure Indicator (AEI)* has been made for each of the Member States. This AEI is the averaged level at urban background locations throughout the territory of a Member State and it reflects the population exposure. By 2020 the AEI has to be reduced with a certain percentage depending on its value in 2010. This exposure reduction target ranges from 10% in the Nordic countries to more than 25% in eastern European countries. Estimates of health impacts attributable to the exposure to PM2.5 has been made for the 2005 situation and for two sensitivity cases assuming that (i) the limit value is met everywhere and (ii) the exposure reduction target has been met by all countries. The exposure reduction approach results in a larger reduction in the burden of disease than meeting the limit values.

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1. Introduction

Epidemiological studies have reported statistical associations between short-term, and to a limited extent also long-term, exposure to increased ambient particulate matter (PM) concentrations and increased morbidity and premature mortality (see e.g. Pope and Dockery, 2006). It is still unclear whether these associations are causal and which PM properties and/or mechanisms (PM_{10}, $PM_{2.5}$, ultrafine-mode particles, physical properties, chemical or biological components) are responsible for these health effects. It is currently assumed that there is no threshold below which health effects of PM are unlikely to occur. The recent update of the World Health Organisation (WHO) Air Quality Guidelines for PM (WHO, 2006) proposed that, despite the apparent lack of a threshold value, guidelines should be set to minimise the risk of adverse effects of both short-term and long-term exposure to PM. These values were set as 20 μg/m^3 for an annual mean and 50 μg/m^3 as a daily mean for PM_{10}, with corresponding values of 10 μg/m^3 and 25 μg/m^3 for $PM_{2.5}$. It is often assumed that $PM_{2.5}$ is more toxic than PM_{10} because it penetrates deeper into the lungs; however, the health effects of the 'coarse' particles ($PM_{2.5\text{-}10}$, that is, the size fraction in the range of 2.5 to 10 μm) should not be neglected (Brunekreef and Forsberg 2005). In the new Air Quality Directive (EC, 2008) the European Commission has included $PM_{2.5}$ as an additional indicator because it reflects better the anthropogenic fine particle primary an d secondary emissions and it is assumed to contribute significantly to the health effects of ambient PM exposure.

Whilst evidence is growing that finer particle size fractions are perhaps more important, ambient air quality measurements and emission data at present are often only available for PM_{10}, i.e. particles of 10 μm diameter and below, including those smaller than 2.5 μm. Sufficient information, both from monitoring stations (Mol *et al.*, 2008), as well as from modelling studies (see e.g. EMEP, 2007) is available to prepare European PM_{10} concentrations maps. These maps may serve as input to studies assessing the health impacts of exposure to air pollution. In the case of $PM_{2.5}$, monitoring information is too limited to prepare a $PM_{2.5}$ concentration map over Europe. In this study we develop a mapping procedure which combines the scarce $PM_{2.5}$ data with the more abundant PM_{10} data. The estimated $PM_{2.5}$ concentrations will be evaluated against the limit and target values set in the Air Quality Directive (EC, 2008) and a health impact assessment will be made.

2. Estimating the $PM_{2.5}/PM_{10}$ ratio

From AirBase (Mol *et al.,* 2008) co-located $PM_{2.5}$ and PM_{10} measurements have been extracted for the period 2004-2006. AirBase collects air quality information submitted by 35 European countries following the *Exchange of Information decision (EoI)* (EC, 1997). As the EoI requires the countries to submit validated data, the PM_{10} and $PM_{2.5}$ data available from AirBase have been used without any further processing except the routine quality checks performed during the EoI data submission cycle (Mol *et al.,* 2008). In line with the EoI it is assumed that, where needed, the PM data has been corrected where non-reference method have been used. Information on PM_{10} methods and correction factors is given in by Buijsman and de Leeuw (2004) and de Leeuw (2005); this information is, however, not up-to-date. Information on the correction factors that might have been applied to $PM_{2.5}$ is not available. Some, but still incomplete information on PM correction factors is available from the reporting questionnaire under the Air Quality Framework Directive (see Vixseboxse and de Leeuw, 2008). This lack of information hampers the comparison of results between countries. Any conclusion regarding $PM_{2.5}/PM_{10}$ relation should be handled with caution in light of this uncertainty.

PM_{10} and $PM_{2.5}$ data fulfilling the following criteria were selected from the available information in AirBase[1]:

- The PM measurements should be co-located.
- A data coverage of 75%: for at least 274 days per year valid daily values for both PM_{10} and $PM_{2.5}$ should be available.
- On an annual basis the correlation between the co-located $PM_{2.5}$ and PM_{10} daily averages should be at least 0.7. As shown by Horálek *et al.* (2008) the correlation shows no interannual variation and is on the average 0.86 – 0.88. At traffic stations[2] a lower correlation (R=0.81) is observed related to the direct PM_{10} emissions from road traffic (e.g. from wearing of tires and brakes, resuspension, winter sanding). When the correlation is below 0.7 it is assumed that the data is not representative and is therefore excluded from the analysis.

After applying these selection criteria, 233 stations with 437 annual time series remain. Additionally, four time series observed at two traffic stations (in Iceland and France) have been excluded as on these stations an unrealistic ratio larger than one ($PM_{2.5}$ concentration exceeds the PM_{10} concentration) was observed. In Figure 1 the annual mean concentrations of PM_{10} and $PM_{2.5}$ are given in relation to the station classification. The figure indicates a wide spread in $PM_{2.5}/PM_{10}$ ratios. For European situations a range of 0.5-0.8 in $PM_{2.5}/PM_{10}$ ratios has been suggested (van Dingenen *et al.,* 2004). The upper end of this range seems to be too high; a ratio of 0.7 would be a more representative high-end value. However, the figure evidently shows that the ratio depends on the type of station and a more detailed analysis is needed.

The simplest approach to estimate the $PM_{2.5}/PM_{10}$ ratio is to calculate it from the annual averaged concentrations. A second approach is to calculate the ratio on a daily base and next

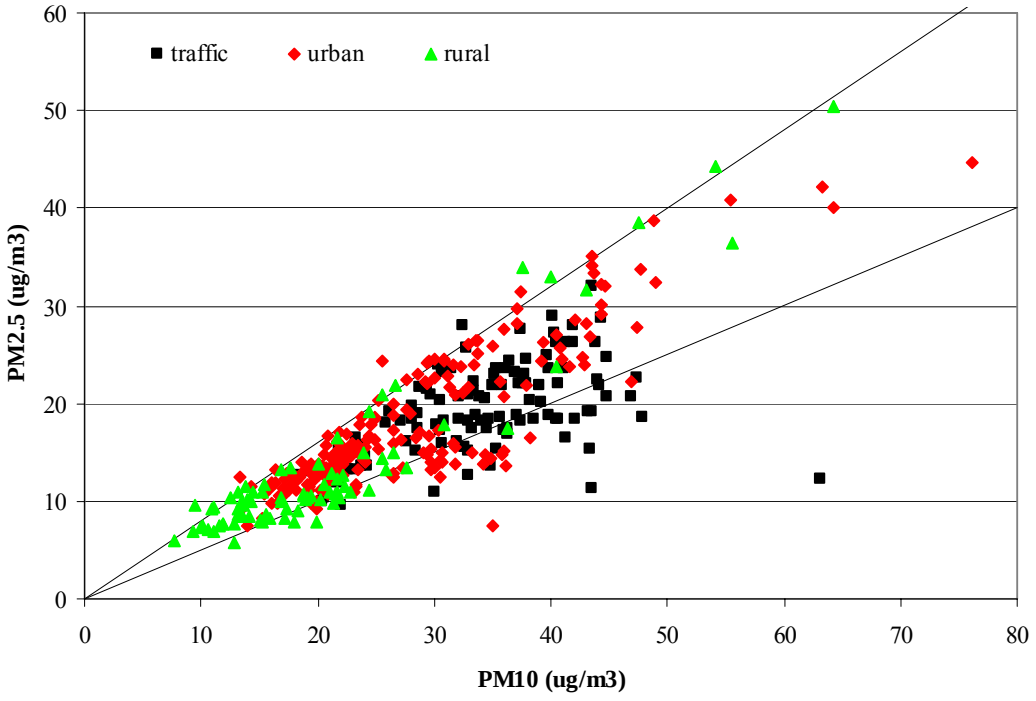

Figure 1. Annual mean concentrations of PM_{10} and $PM_{2.5}$, period 2004-2006. The lines correspond with a $PM_{2.5}/PM_{10}$ ratio of 0.8 and 0.5; source: AirBase.

[1] See http://air-climate.eionet.europa.eu/databases/airbase/index_html

[2] Although information from traffic stations is not used in the production of the interpolated maps nor it is needed in the health impact assessment, the $PM_{2.5}/PM_{10}$ ratio has also estimated for this station type for completeness.

averaged it over the full year. Following Horálek *et al.* (2008) a third method is preferred: the $PM_{2.5}/PM_{10}$ ratio is calculated as the slope of a linear regression of daily concentrations:

$$C_{PM25} = ratio\, C_{PM10} + b$$

where C is the daily mean value and b is the intercept which could – optionally – be forced to zero. In this case, *ratio* is obtained from:

$$ratio = \frac{1}{k}\sum C_{k,PM25} \cdot C_{k,PM10} \Big/ \frac{1}{k}\sum C^2{}_{k,PM10}$$

where the averaging is over the k days with simultaneous measurements of PM_{10} and $PM_{2.5}$.

European wide ratios, averaged per station type over all available time series are given in Table 1 and Figure 2. At rural and urban stations average ratios of 0.62 and 0.65, respectively, are observed while the ratio at traffic locations is slightly lower (0.58) indicating that there is a small contribution of locally emitted PM_{10} to the PM_{10} concentrations observed at traffic stations.
Following the suggestion of Horálek *et al.* (2008) ratios have been calculated for four different European regions (note that co-located PM_{10} and $PM_{2.5}$ data is not available for all countries, these countries are printed in *italic*):

1. Northern Europe: Norway, Sweden, Finland, *Estonia, Lithuania, Latvia,* Denmark and *Iceland*
2. North-western Europe: United Kingdom, Ireland, *the Netherlands*, Belgium, *Luxembourg*, France north of 45 degrees latitude
3. Central and Eastern Europe: Germany, Poland, Czech Republic, Slovakia, Hungary, Austria, *Switzerland, Liechtenstein*
4. Southern Europe: France south of 45 degrees latitude, Portugal, Spain, *Andorra, Monaco,* Italy, *San Marino, Slovenia, Croatia, Greece, Cyprus, Malta, Albania, Bosnia Herzegovina,* Bulgaria, *Romania.*

The observed ratios (Table 1, Figure 2) are in the range of 0.4 to 0.8. In the regions North and Central-East there is a clear tendency for lower ratios from rural to urban to traffic stations. This indicates an increasing contribution of locally emitted coarse particles at urban and traffic sites.
In North-western and Southern Europe there is no such tendency. The rural stations in North-western Europe have a ratio which is surprisingly low compared to the ratio at urban and traffic sites in this region. The reason might be the strongly different geographical distribution of rural and urban stations in these regions. The low number of time series may play a role here: 8 rural time series (6 in the United Kingdom and 2 in Belgium) whereas the urban time series have been measured mostly in France (64 from the 78 time series in total). In the southern region the rural background station are mostly located on the Iberian Peninsula (45 from the 48 time series are measured here). A possible explanation for the low rural ratio here might be an important contribution of mineral (Sahara) dust. To adjust for the different spatial distributions of rural and urban stations, the $PM_{2.5}/PM_{10}$ ratio has been examined in a more detail for station pairs, that is, for rural stations and a close by (less than 75 km) urban background stations. Only 17 rural stations could be linked with one or more urban background station within the required distance. For this subset the $PM_{2.5}/PM_{10}$ ratio

Table 1. $PM_{2.5}$ / PM_{10} ratios and available number of time series as function of region and station type. For the regions North-West and South the second value corresponds to the adjusted rural ratio, see text for explanation (period 2004-2006).

	$PM_{2.5}$ / PM_{10} ratio			number of time series		
region	rural	urban	traffic	rural	urban	traffic
North	0.78	0.55	0.42	5	11	6
North-West	0.53/0.69	0.63	0.59	8	78	32
Central-East	0.75	0.71	0.65	20	73	41
South	0.57/0.64	0.58	0.53	48	39	38
Europe	0.62	0.65	0.58	81	201	117

at a rural background station is on the average 10% larger than at the nearby located urban stations. Based on this the rural ratios in these two regions have been adjusted to 10% above the urban ratio, see Figure 2.
In a third approach country and station type specific ratios have been estimated. Sufficient monitoring data is not available for all 38 countries located within the mapping area to estimate the ratio for each of the station types. For countries without co-located PM2.5 and PM10 monitors, the corresponding region specific ratio has been used.

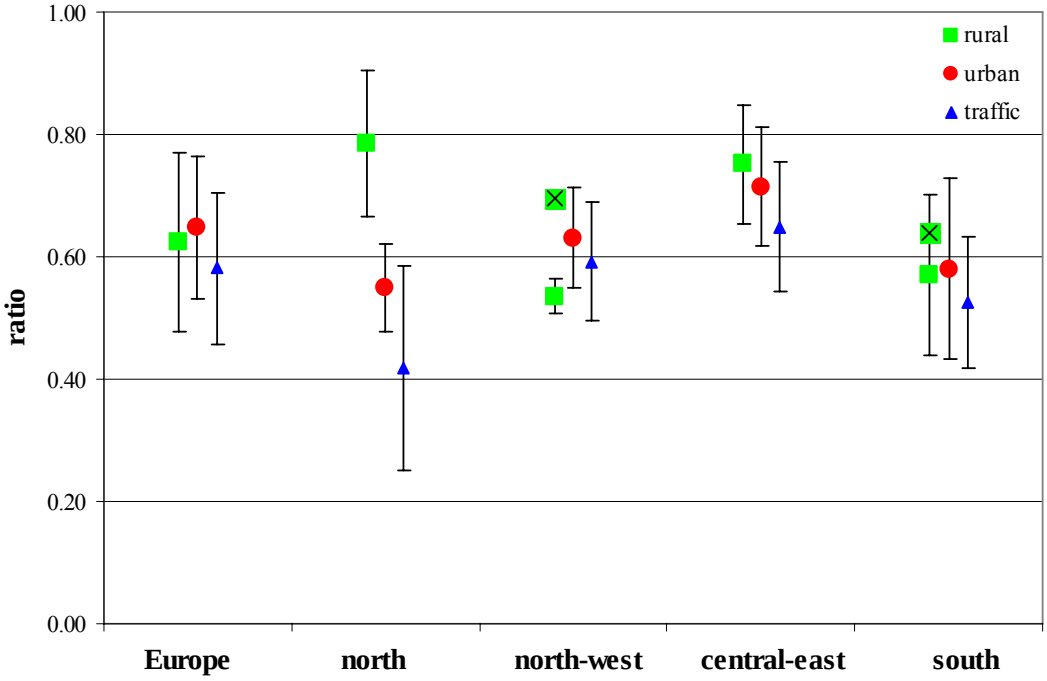

Figure 2. $PM_{2.5}$ / PM_{10} ratios averaged for Europe and averaged per region and station type. The error bars indicate plus/minus one standard deviation. The marked rural dots correspond to the adjusted ratios, see text for explanation.

3. Preparing the PM2.5 concentration maps

The ratio approach could be used to estimate $PM_{2.5}$ levels in regions where none or limited measurements are available. This was tested here for annual mean concentrations. Using the station type specific ratios and the observed PM_{10} concentrations, *pseudo PM2.5* concentrations have been estimated. The $PM_{2.5}$ values, calculated using the three different sets of $PM_{2.5}/PM_{10}$ ratios, are compared with the original observed $PM_{2.5}$ concentrations in Figure 3 and Table 2. As expected the application of European averaged ratios results in the worst agreement. The region approach slightly overestimates the observations (bias, defined as the averaged difference between calculated and observed values is 0.5 µg/m³). The root-mean-square error (RMSE) is 4.4 µg/m³ or about 20% of the overall averaged concentration of 17.3 µg/m³; the mean absolute relative error (MARE) is 16%. The best fit is observed using the country specific ratios, not surprisingly as this method has the lowest degree of freedom. As Figure 3 shows there are a large number of data points which fall outside the range of ± 25%.

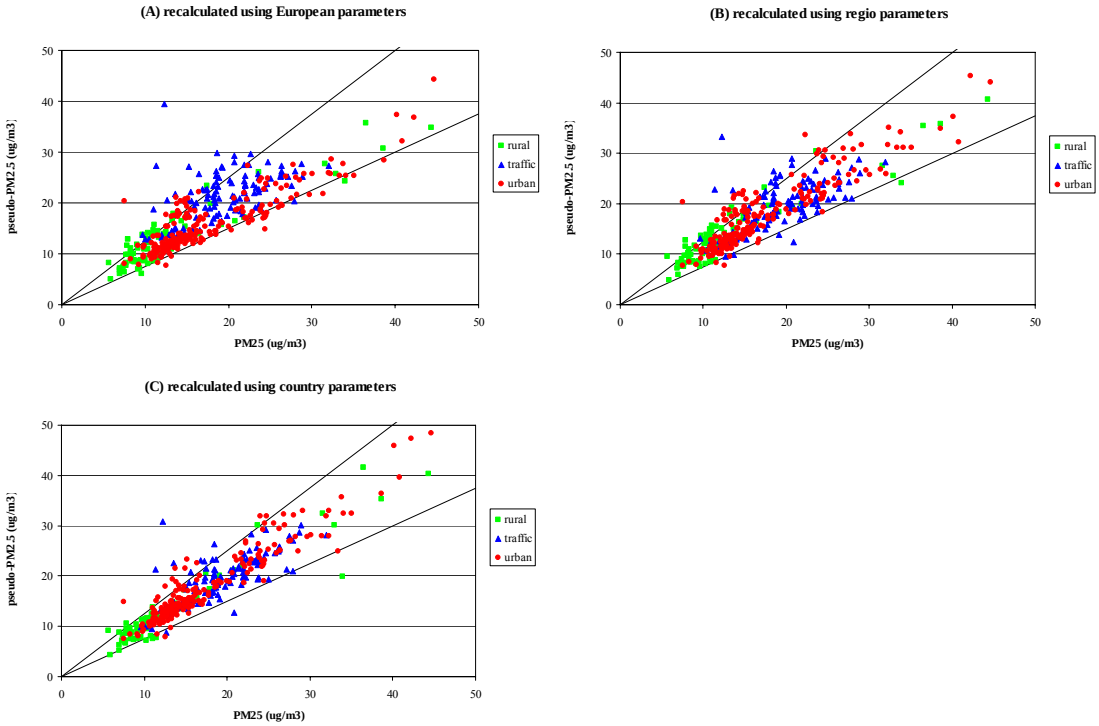

Figure 3. Scatter plot of observed and calculated $PM_{2.5}$ concentrations (all years). Calculations are based on (a) European/station specific ratios; (B) region/station type specific and (C) country/station type specific ratios. The two lines correspond to ± 25 % (y=1.25x and y=0.75x).

Table 2. Comparison between observed and calculated $PM_{2.5}$ concentrations using region and country specific ratios.

Parameter(1)	unit	European specific	Region specific	Country specific	Perfect fit
RMSE	µg/m³	4.17	3.43	2.86	0
bias	µg/m³	0.20	-0.49	-0.24	0
MAE	µg/m³	2.98	2.35	1.84	0
a	-	0.74	0.87	0.94	1
sa	-	0.02	0.02	0.02	0
b	µg/m³	4.23	2.82	1.26	0
sb	µg/m³	0.46	0.40	0.35	0
MARE	%	20	16	12	0
observed averaged	µg/m³	17.27	17.27	17.27	-

(1) The following parameters are given:

RMSE: root mean square error = $\sqrt{\sum \frac{1}{n}\left(C_{obs} - C_{calc}\right)^2}$

Bias = $\frac{1}{n}\sum\left(C_{obs} - C_{calc}\right)$

MAE: Mean absolute error = $\frac{1}{n}\sum \left|C_{obs} - C_{calc}\right|$

Slope (a) and intercept (b) and their standard error (sa, sb) of the regression:

$C_{calc} = a\,C_{obs} + b$

MARE: mean absolute relative error = $100\% \cdot \frac{1}{n}\sum \left|C_{obs} - C_{calc}\right| / C_{obs}$

The estimation of the pseudo $PM_{2.5}$ concentrations can be improved by applying ratios with a higher spatial resolution, that is, averaged at the country level instead of the region level. As mentioned above, co-located PM_{10}-$PM_{2.5}$ data is not available for all countries: of the possible 114 county-station type specific ratios (38 country, rural, urban and traffic station type) only 43 could be estimated from the measurements (10 rural, 17 urban, 16 traffic ratios). Although the fit between observed and calculated concentrations improves - the RMSE drops to 2.9 µg/m³ (12% of the grand average), see Figure 3 and Table 2- this improvement is limited

considering the increase in the number of parameters from 12 region/station type specific ratios to 43 country/station type specific ratios.
Considering that in the above applications the same data set is used both for parameterisation and for validation, it is to be expected that when the approach is used to estimated $PM_{2.5}$ concentrations at the locations of the more than 2000 PM_{10} station locations available in AirBase, the error in these estimates will largely exceed the 15-20% error found here. In combination with the uncertainties in the PM_{10} measurements themselves, the constructed pseudo $PM_{2.5}$ data will most likely not fulfil the data quality objectives as given in the Air Quality Directive (25% for fixed PM measurements).

Notwithstanding the shortcomings sketched above, the $PM_{2.5}/PM_{10}$ ratios have been applied to infer from the PM_{10} data a European $PM_{2.5}$ map. With the limited number of operational $PM_{2.5}$ measuring stations there is no alternative at the moment to construct a monitoring-based $PM_{2.5}$ concentration map.
The $PM_{2.5}$ concentration field is based on the separate urban and rural PM_{10} concentration fields as constructed by Horálek *et al.* (2008). Horálek *et al.* (2008) prepare the annual averages from the measured PM_{10} concentrations at rural background stations with supplementary data from the EMEP model output, altitude field, wind speed and surface solar radiation in a linear regression model, followed by the interpolation of its residuals by ordinary kriging. The urban map is created by combining the measured PM10 annual averages at urban and suburban background stations with the EMEP model output only in a linear regression, followed by the interpolation of its residuals by ordinary kriging. The final map is prepared by a weighted averaging of the rural and urban map based on the population density in a grid cell. Grid cells with a population density of 500 inhabitants per km² or more are seen as urban, a rural cell is defined by a density of less than 100 inhabitants per km². In the mixed cells a weighted average is calculated.
Rural and urban $PM_{2.5}$ maps have been made by applying the three different sets of ratios (European, region or country specific) to the rural and urban PM_{10} maps, respectively. The same weighting procedure as used in Horálek *et al.* (2008) is applied here to prepare the final $PM_{2.5}$ map.
The validation of the maps is hardly possible as almost all of the available $PM_{2.5}$ monitoring data has been used in the estimation of the $PM_{2.5}/PM_{10}$ ratios. Only 15 $PM_{2.5}$ stations which are not co-located with PM_{10} stations, supplemented with two EMEP stations not included in AirBase can be used for validation. Figure 4 gives a scatter plot of the observed concentrations and the values in the 10x10 km cells in which the station is located. The selected stations are all rural or (sub)urban background stations; traffic or industrial

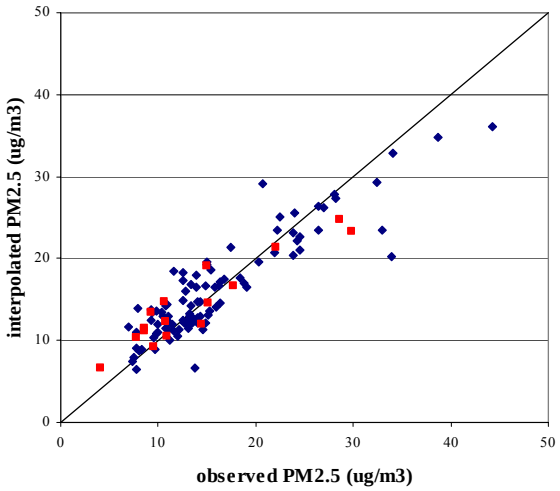

Figure 4. Comparison of observed and interpolated $PM_{2.5}$ concentrations. The blue dots corresponds to stations used in the estimation of the concentration ratios; the red dots correspond to additional monitoring stations.

Table 3. Comparison between observed $PM_{2.5}$ concentrations and the interpolated values of the grid cell in which the measurement station is located using European, region and country specific $PM_{2.5}/PM_{10}$ ratios. Left-hand side gives the results for all stations; right hand side gives the results for station not included in the parameterisation of the concentration ratios (test set).

	all stations			test set		
	Europe	region	country	Europe	region	country
rms (µg/m³)	3.71	3.22	3.11	2.65	3.03	2.50
Bias (µg/m³)	0.30	-0.26	0.19	-0.42	-0.53	-0.59
R^2	0.871	0.903	0.908	0.934	0.936	0.953
N	114	114	114	17	17	17

locations are not included as these hot spot situations are not resolved in the interpolated maps. There is a reasonable agreement; the learning and test sets show a similar behaviour. The interpolation procedure seems to smooth the monitoring data: at low levels (below 20 µg/m³) the interpolation results in an overestimation whereas the higher levels are underestimated.
Statistics on the comparison between the observed and interpolated values is given in Table 3. Differences between the three approaches are not large. The European approach gives the worst and the country approach the best fit. The region approach in preparing a European map is hampered by the fact that a specific ratio is not available for all countries. Therefore the region approach is the selected here as the preferred method. The final $PM_{2.5}$ concentration map is given in Figure 5.

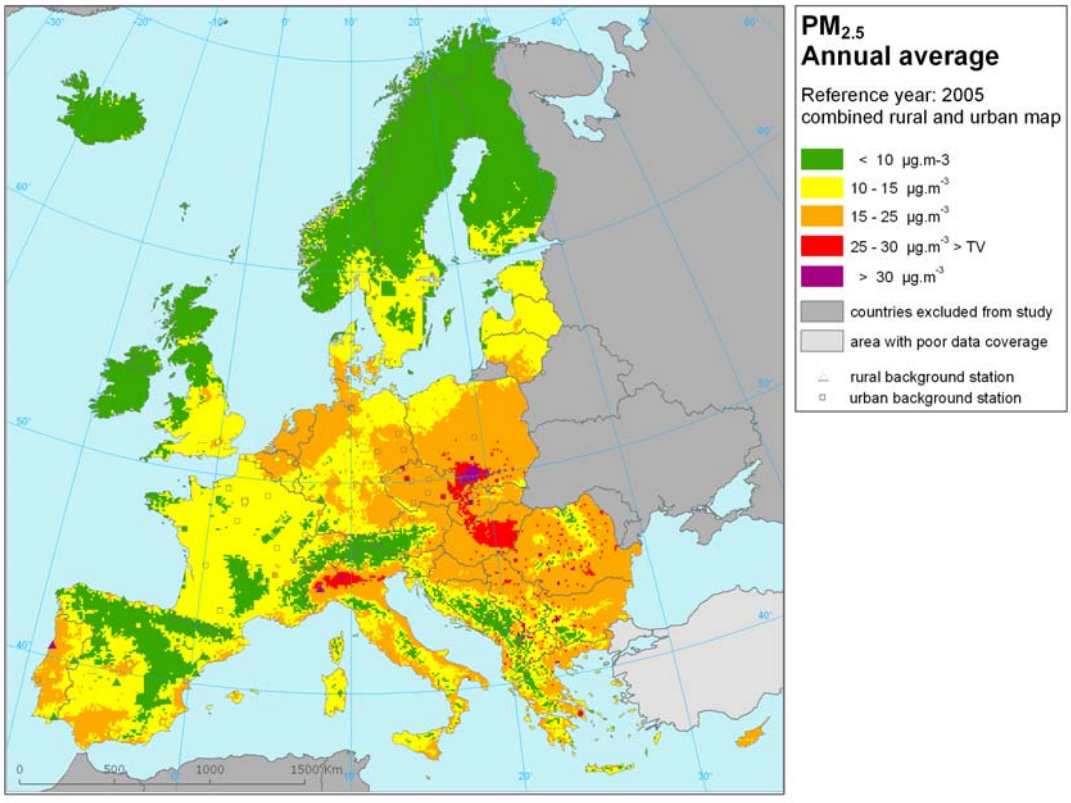

Figure 5. $PM_{2.5}$ concentration map, annual average, year 2005. The map is based on the combination of scaled rural and urban PM_{10} maps using region specific $PM_{2.5}/PM_{10}$ ratios, see text for further details.

Table 4. Population and area weighted concentrations of PM_{10}, and $PM_{2.5}$ (2005) using three different sets of $PM_{2.5}/PM_{10}$ ratios.

	population weighted				area weighted			
country	PM10	PM2.5 (a)	PM2.5 (b)	PM2.5 (c)	PM10	PM2.5 (a)	PM2.5 (b)	PM2.5 (c)
Austria	23.5	15.0	17.2	18.4	16.6	10.4	12.4	13.6
Belgium	28.9	18.6	18.7	14.7	25.6	16.2	17.0	13.3
Bulgaria	37.0	23.6	22.3	23.6	25.2	15.8	16.0	16.1
Cyprus	37.9	24.3	22.6	22.6	28.6	17.9	18.2	18.2
Czech Republic	31.5	20.1	23.1	23.5	27.5	17.3	20.5	20.4
Denmark	19.8	12.6	13.3	12.9	17.2	10.8	13.1	13.0
Estonia	16.4	10.4	10.8	10.8	13.8	8.7	10.8	10.8
Finland	13.3	8.4	9.1	8.5	10.0	6.2	7.8	7.1
France	19.1	12.2	12.3	13.2	16.7	10.5	11.2	12.4
Germany	22.1	14.1	16.0	15.3	20.0	12.6	14.8	14.2
Greece	34.8	22.3	20.8	20.8	22.7	14.2	14.4	14.4
Hungary	33.5	21.2	24.6	24.6	31.5	19.7	23.6	23.6
Ireland	11.5	7.3	7.6	7.6	8.6	5.4	5.9	5.9
Italy	32.8	21.0	19.6	23.8	24.3	15.3	15.2	18.0
Latvia	18.7	11.9	12.4	12.4	15.9	10.0	12.4	12.4
Lithuania	20.3	12.9	13.6	13.6	18.3	11.4	14.2	14.2
Luxembourg	18.4	11.7	12.1	12.1	17.4	10.9	11.9	11.9
Malta	36.5	23.6	21.3	21.3	32.6	21.0	19.2	19.2
Netherlands	29.1	18.7	18.7	18.7	27.4	17.5	18.1	18.1
Poland	30.5	19.5	22.2	20.8	24.0	15.1	17.9	17.7
Portugal	30.6	19.6	18.3	14.1	24.6	15.4	15.5	12.8
Romania	37.3	23.8	22.6	22.6	28.3	17.7	17.9	17.9
Slovakia	31.4	19.9	23.1	21.2	28.1	17.6	20.9	20.4
Slovenia	27.5	17.5	16.8	16.8	22.6	14.2	14.3	14.3
Spain	27.5	17.6	16.4	16.1	17.9	11.2	11.4	10.2
Sweden	15.0	9.5	10.4	11.0	9.9	6.2	7.7	8.2
United Kingdom	20.9	13.4	13.3	10.2	13.4	8.5	9.1	7.0
Albania	33.1	21.1	19.8	19.8	21.2	13.4	13.3	13.3
Andorra	16.9	10.9	10.1	10.1	9.3	5.9	5.7	5.7
Bosnia and Herzegovina	30.0	19.1	18.1	18.1	20.0	12.5	12.6	12.6
Croatia	30.7	19.5	18.7	18.7	24.4	15.3	15.5	15.5
Iceland	11.5	7.3	7.4	7.4	5.5	3.5	4.3	4.3
Lichtenstein	21.5	13.6	15.9	15.9	21.4	13.5	15.9	15.9
Norway	17.3	11.1	10.6	9.6	7.8	4.9	6.0	6.0
San Marino	27.2	17.3	16.5	16.5	27.2	17.3	16.5	16.5
Serbia and Montenegro	38.5	24.6	23.1	23.1	25.0	15.7	15.7	15.7
Switzerland	19.9	12.8	14.4	14.4	13.2	8.4	9.8	9.8
FYR Macedonia	42.2	27.1	25.0	25.0	21.6	13.6	13.6	13.6
EU27	26.0	16.6	17.0	16.8	18.7	11.7	12.9	12.8
Total	26.2	16.8	17.1	16.9	17.9	11.2	12.3	12.3

(a) based on European specific ratios
(b) based on region specific ratios
(c) based on country specific ratios complemented with region specific ratios when country values are missing.

Population and area weighted averages for the three approaches are compared for each country in Table 4. As comparison the average PM_{10} concentrations are listed too; as expected the $PM_{2.5}/PM_{10}$ ratio are within about 0.6-07 but varies from country to country. For the EU27 the population weighted $PM_{2.5}$ concentrations are about 40% higher than the area weighted concentrations. The difference in concentrations between the three approaches are relatively small, for the population weighted concentration less than 5%, for the area weighted concentration differences are slightly larger: up to 10%. At the country level the differences between the three approaches tends to be larger, up to 20-30% (e.g. Portugal).

Horálek et al. (2008) estimate the interpolation uncertainties in the PM10 concentration maps at 20-25%. This includes the uncertainties introduced in the interpolation procedures; other sources of uncertainties, e.g. in the monitoring data or additional information are not considered. Denby *et al* (2009) discuss methods for dealing with these uncertainties; they conclude that air quality mapping is an area with a large range of sources of uncertainty that cannot always be easily determined. Indeed the area becomes more difficult to define as some uncertainties will overlap or are included in other uncertainty estimates. Therefore, an overall uncertainty can not be assessed here. The uncertainty introduced by interpolation and conversion of the PM10 data is estimated as 30-35%.

In the recently published Air Quality Directive (EC, 2008) health based standards and objectives for $PM_{2.5}$ have been set. An annual mean $PM_{2.5}$ concentration of 25 $\mu g/m^3$ has been set as target value to be met in 2010 and as limit value to be met in 2015. The new directive introduced an additional $PM_{2.5}$ objective targeting the exposure of the population to fine particles. These objectives are set at the national level and are based on the average exposure indicator (AEI). The AEI is the averaged level measured at urban background location throughout the territory of a Member State and it reflects the population exposure. For the AEI a legally binding cap of 20 $\mu g/m^3$ has been set in 2015. Additionally a percentage reduction in AEI is required, to be attained in 2020 determined on the basis of the AEI value in 2010.

The $PM_{2.5}$ maps constructed here have been used to evaluate attainment of these standards. The area of exceedance is simply estimated by counting the number of 10x10 km grid cells with concentrations above 25 $\mu g/m^3$. Typical hot spot situations, for example, urban centre hotspots and heavily trafficked situations, might be neglected in this way. The three approaches generally give similar results (Figure 6). In 15 Member States an exceedance is not calculated in any of the approaches although exceedance at local hot spot might not be excluded. In the remaining 12 MS the exceedance area ranges from less than 3% to more than 30%. For four countries, Italy, Czech Republic, Slovakia and Hungary, the estimates of the three approaches varies strongly. Largest difference is observed for Hungary: using European specific ratio the area of exceedance is less than 1% while the other two methods results in a 33% estimate. In large parts of Hungary concentrations are around the target value; a relatively small difference in urban ratios (0.65, 0.71 and 0.72 for the European, region and country specific approach, respectively) is clearly sufficient to bring large areas above the target value. The averaged concentration in the exceedance areas hardly depends on the chosen ratios.

The exposure of the European population is given in Figure 7. The WHO (2006) has set an air quality guideline value (AQG) of 10 $\mu g/m^3$, the lowest level at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to $PM_{2.5}$. Only about 9% of the population is exposed to concentration below this AQG. Besides the AQG the WHO has defined three interim targets. The highest interim target (IT-1) of 35 $\mu g/m^3$ is associated with about 15% higher long-term mortality than at the AQG level. IT-1 is exceeded in some areas: less than 1% of the European population is exposed to concentrations above IT-1. The interim target 2 (IT-2) of 25 $\mu g/m^3$ corresponds to the EU limit value; in addition to other health benefits this IT-2 lowers risk of premature mortality

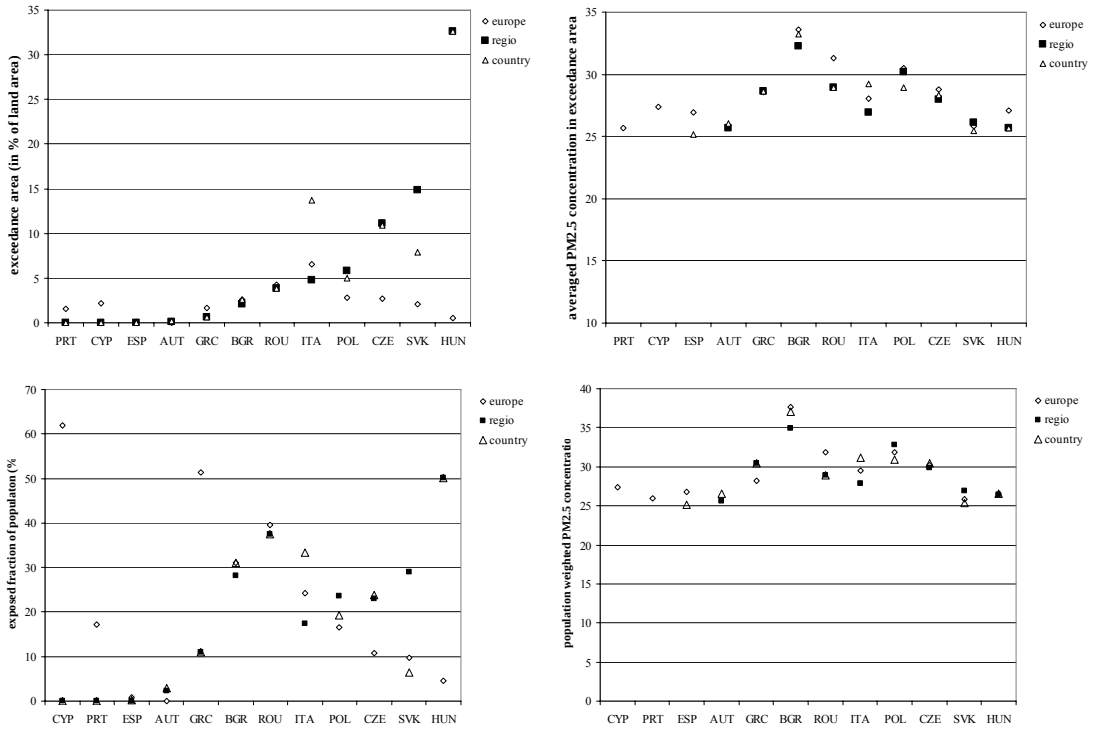

Figure 6. Area of exceedance (as fraction of land area) and PM2.5 concentration in the exceedance area (top) and fraction of population and population exposure in exceedance areas estimated using different PM2.5/PM10 concentration ratios. Only Member States where an exceedance is estimated by either one of the approaches are shown.

by approximately 6% compared to IT-1. 9% of the population is exposed to concentrations above IT-2. At interim target 3 (15 µg/m³; IT-3) health impacts are lowered with another 6% compared to IT-2; 39% of the population is exposed to concentrations below IT-3.

The AEI is calculated here as the average concentration in the urban grid cells weighted according to the population in that cell. An urban cell is defined here as a grid cell with a population density of more than 500 inhabitants per km². The total population in urban cells calculated in this way amounts to be substantially lower than the urban population according to the UN World Urbanisation Prospects (UN, 2006): only 64% of the UN urban population (47% of the total population) in the EU27 is included in the AEI calculation. While covering only about 2/3 of the urban population, it might be argued that the AEI does not reflect the population exposure as required by the directive. Therefore, a second calculation was made in which the urban population in mixed rural/urban cells was included in the AEI averaging procedure. In this way the covered UN urban fraction increased to 87% of the EU27 urban population (64% of the total population). However, it turned out that the differences in AEI caused by the two methods are much smaller than the differences caused by the choice of

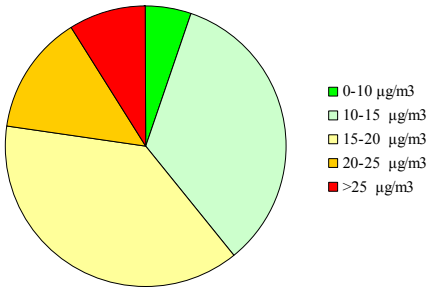

Figure 7. Exposure of the European population to PM2.5 concentrations, annual mean, reference year 2005.

concentration ratios. Irrespective of the calculation method, in 10 MS the AEI is in 2005 well above the obligation of 2015. In 5 MS the AEI is, depending on the calculation method, just below or above the level of 20 µg/m3. In the remaining 12 MS the AEI is estimated to be well below the binding value of 20 µg/m3.
Figure 8 compares the calculated AEI with the averaged urban background concentration as observed in 2007 (data extracted from AirBase, see Mol et al., 2009). There is a fair agreement between the two sets. A strong overestimation is found for Hungary (one urban background station in the city of Esztergom) and in Portugal (two urban background stations on the mainland (Sintra, Lisbao) and two in Funchal on the island of Madeira). In both cases the observed data might not be representative for the whole urban population.

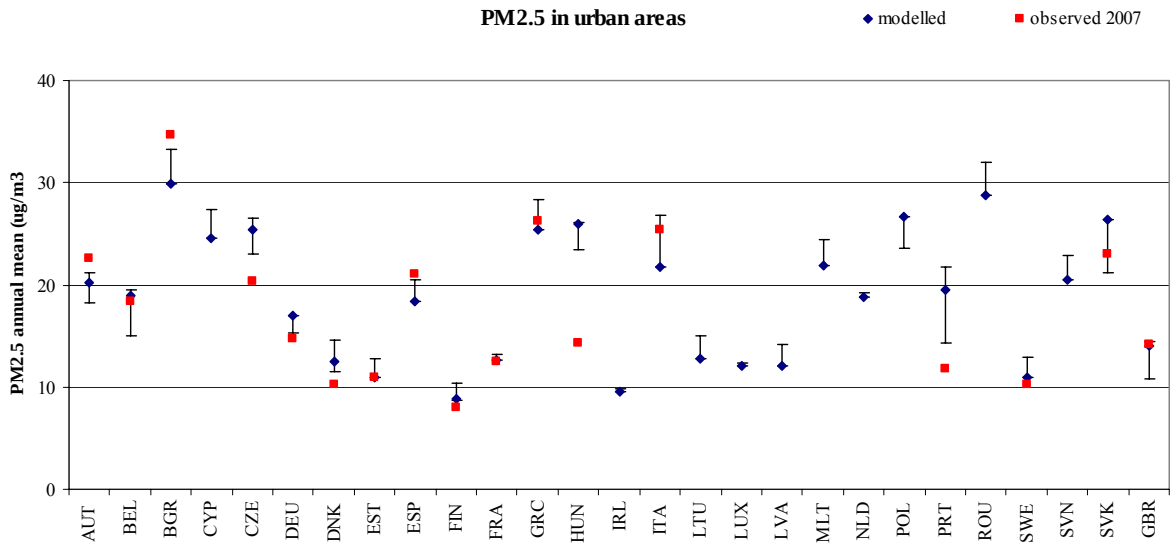

Figure 8. Average exposure indicator (AEI) calculated for 2005 using region specific concentration ratios (diamonds). The error bars indicate the calculated range in AEI when using European, region or country specific concentration ratios. The red squares are the observed concentrations (2007 data) averaged over all (sub)urban background stations (Mol *et al.*, 2009).

4. Health Impact Assessment

The concentration map based on the region specific ratios (Figure 5) is used as input for a health impact assessment. The impact assessment is made using the 10x10 km resolution of the interpolated map. It is assumed that the population within a grid cell is exposed to the same grid cell averaged concentration. Concentration gradients within a cell, differences in exposure for different population classes and indoor pollution have not been included in the assessment.
For quantifying the effect of air pollution, the relative risk (RR) in a population whose exposure is estimated by an average concentration C is given by the concentration-response function:

$$RR = \exp\left[B\left(C - C_0\right)\right]$$

where C_o is a reference concentration (the background concentration that would exist without any man-made pollution determined by natural sources or a concentration below which no health effects are to be expected). B is the estimated effect of the pollutant on the health outcome (e.g. mortality from cardiopulomonary diseases) and is given as an increase

in incidence per unit increase in concentration, see Table 5. In the assessment presented below the reference concentration C_o is set to zero.

Table 5. Mortality relative risk associated with a 10 μg/m³ change in PM2.5 concentration (Pope et al., 2002).

Health outcome	Relative risk per 10 μg/m³ (95% CL)
Mortality from cardiopulmonary disease, adults > 30 year	1.08 (1.02-1.14)
Mortality for lung cancer, adults > 30 year	1.13 (1.04 – 1.22)
Total mortality, adults > 30 year; excluding violent death	1.06 (1.02 – 1.10)

Once the relative risks have been determined, the attributable fraction (AF) of a specific health effect from air pollution for the exposed population is:

$$AF = \sum P_i \left(RR_i - 1\right) / \sum P_i RR_i$$

where P_i = the proportion of the population at exposure category i
RR_i = the relative risk in exposure category i

When the total population is considered with only one exposure level, this simplifies to:

$$AF = \left(RR - 1\right) / RR$$

The expected total number of cases of premature mortality due to air pollution is given by:

$$E = AF \cdot MR \cdot Pop$$

where E is the expected number of deaths due to outdoor air pollution,
MR is the population incidence of the given health effect (i.e. cases per 1000 people per year) and
Pop is the relevant exposed population for the health effect; here only the proportion of the population aged 30 years or older has been considered.

National demographic data (absolute numbers, age/sex distributions) for 2005 have been taken either directly or after downscaling from regionalised level to the national level using data of the World Population Prospects (UN, 2005). Similar age distributions for each grid cell within a country are assumed. Information on baseline incidences is obtained from the WHO Burden of Disease project (WHO, 2004; Mathers and Loncar, 2006). *MR* is estimated using age and sex dependent baseline incidences.

The number of premature deaths attributable to exposure to $PM_{2.5}$ is presented in Figure 9. At one hand the map reflects the spatial differences in $PM_{2.5}$ concentrations, on the other hand, national boundaries are recognized resulting from the use of national specific demographic and health related input data. The result of the assessment is that in Europe $PM_{2.5}$ pollution is associated with more than 492 000 premature deaths, corresponding to a loss of almost 4.9 million years of life (YOLL). These includes 297000 premature deaths (1.84 million YOLL) caused by cardiopulmonary diseases and 54500 premature deaths (457000 YOLL) attributable to lung cancer. These numbers agree well with estimates made for the EU25 during the Clean Air for Europe (CAFE) programme (AEAT, 2005).

Table 6. Number of years of life lost (YOLL) attributable to exposure to PM2.5. Results are given for total mortality (all causes, age over 30), for cardiopulmonary diseases and lung cancer.

country	All cause	CPD	LC
Austria	71700	23200	5600
Belgium	106400	37500	12100
Bulgaria	104200	55300	7600
Cyprus	11000	3200	400
Czech Republic	142600	60800	13700
Germany	738300	254300	68900
Denmark	43800	15900	4300
Estonia	10800	5800	730
Spain	373100	124800	32000
Finland	25500	9700	1600
France	385600	93800	36700
Greece	125200	54800	11900
Hungary	183400	76000	21400
Ireland	17000	6500	1200
Italy	586100	190900	55000
Lithuania	31500	14600	2100
Luxembourg	2800	900	240
Latvia	23000	12400	1500
Malta	4100	1700	280
Netherlands	155600	52600	16500
Poland	403900	150500	53900
Portugal	117800	47800	6400
Romania	284800	150300	22300
Sweden	45000	15500	2900
Slovenia	20100	7200	1900
Slovakia	61100	24000	5100
United Kingdom	452800	191600	37800
Albania	30400	12900	2100
Andorra	370	120	30
Bosnia and Herzegovina	36400	17600	3400
Croatia	58800	26700	5600
Iceland	940	290	90
Lichtenstein	290	100	30
Norway	24400	8600	2000
San Marino	230	70	20
Serbia and Montenegro	138200	66000	12800
Switzerland	51100	14100	4400
TFYR Macedonia	24300	12500	2000
EU27	4527300	1681800	424100
Total	4892700	1840800	456600

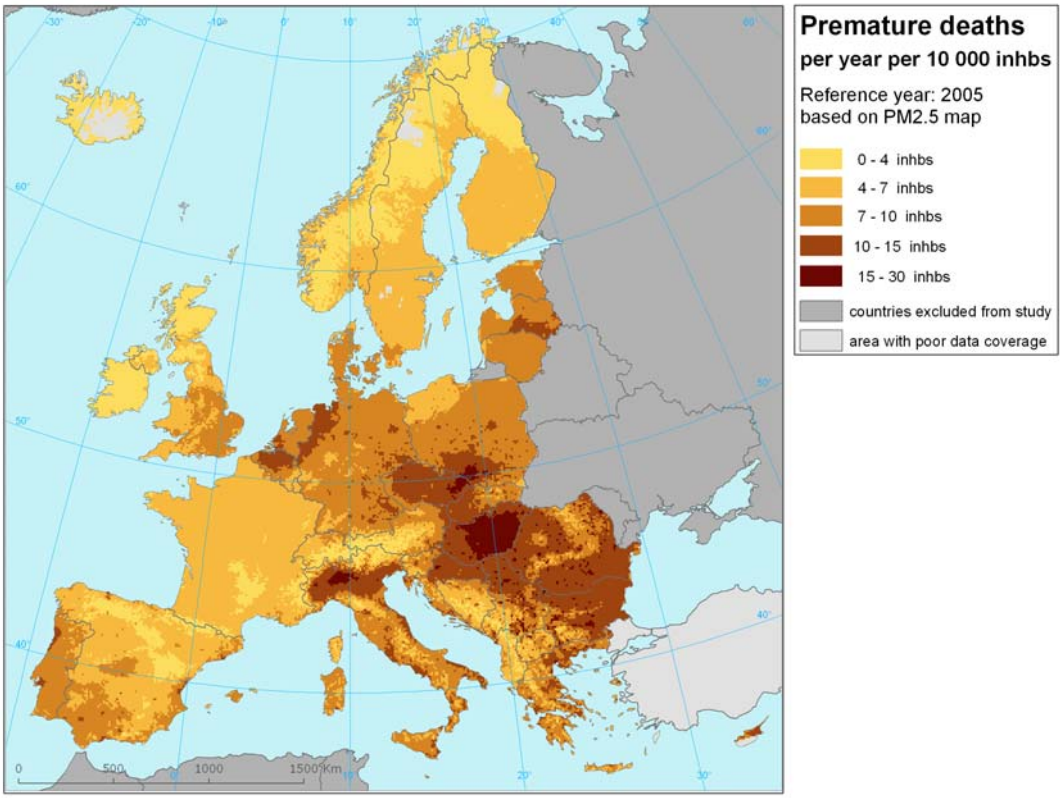

Figure 9. Premature mortality (per 10 000, per year) attributable to $PM_{2.5}$ exposure (reference year 2005).

In two hypothetical scenarios corresponding to the targets set in the EU air quality directive, the health impacts are estimated assuming that in the countries within the European Economic Area (EEA30, that is the 27 EU Member States plus Iceland, Liechtenstein and Norway):

(i) The *LV compliance scenario*. In this scenario it is assumed that the PM2.5 limit value of 25 μg/m³ is nowhere exceeded. Monitoring data shows that at traffic stations concentrations are about 20% higher than in the urban background. By limiting a grid cell concentration to 20.8 μg/m³ any exceedance of the limit value should be avoided. A grid cell concentration is not reduced when in the reference case the concentration is already below 20.8 μg/m³.

(ii) The *AEI-reduction target scenario*. In this scenario it is assume med that in each country the reduction target in AEI has been met. According to the Air Quality Directive the percentage reduction of the exposure indicator depends on the value of AEI in 2010. Here the percentage is based on the AEI value calculated for 2005 for each of the Member States as given in Figure 8. The estimated reduction target for each of the Member States and EEA countries is given in Figure 10. This reduction has been applied to all urban concentrations. Rural concentrations have not been adjusted.

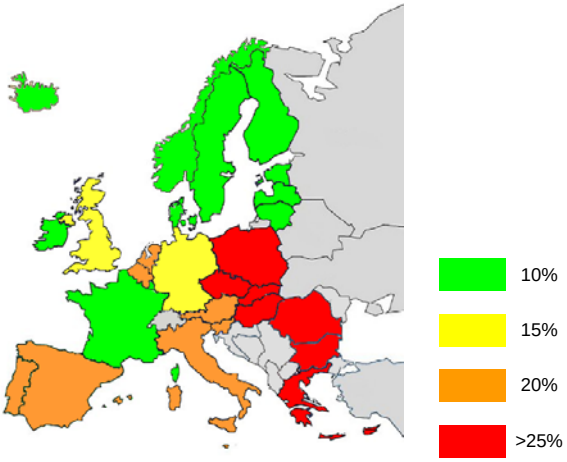

Figure 10. Estimated national exposure reduction targets: reduction to be attained where possible in 2020, determined on the basis of the values of the AEI in Figure 8.

Figure 11 shows the resulting reduction in years of life lost (YOLL) under the scenario assumptions for each of the EU Member States with respect to the reference situation. In the *LV compliance* scenario no effect is seen for a number of countries: the $PM_{2.5}$ concentrations are already below the limit value and no further reduction is assumed. This is a result of the simple approach taken here. As in the scenario approach dispersion of PM is neglected, the benefit from emission reductions in neighbouring countries is not accounted for. When a more sophisticated modelling approach was chosen, some reduction in concentration would be expected here. In the other countries reductions in YOLL up to 18% are estimated. For the EEA30 an overall reduction in burden of mortality of 5% (95% CI : 1.9 to 7.5%) is found. In *LV compliance* scenario the concentration is reduced to the effective gap of 20.8 µg/m³ in a limited number of grid cells. Although this will concern densely populated grid cells, exposure to PM2.5 is reduced for 17% of the population in countries within the European Economic Area.

In the *AEI-reduction target* scenario for the whole urban population the concentrations are reduced with 10% to more than 20% depending on the initial conditions. This results in reductions of 5-30% in YOLL with an EEA30 average of 17% (95% CI : 6.1 to 25.9%). In all countries population exposure and health impacts are reduced.

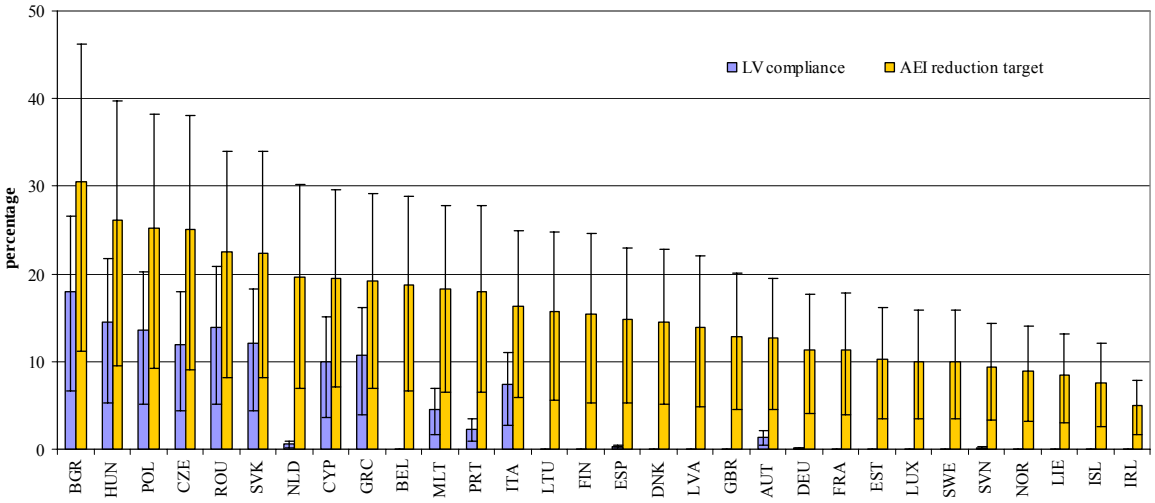

Figure 11. Sensitivity analysis of potential reduction in years of life lost (central estimate and 95% CL) for two scenarios: *LV compliance* assuming that the PM2.5 limit value is met everywhere and *AEI-reduction target* assuming that the exposure reduction target is met.

5. Conclusions

The reporting for 2007 under the Exchange of Information decision (EoI) suggests that the $PM_{2.5}$ monitoring networks at local and national level are not yet fully operational. The air quality directive (EC, 2008) requires the Member States to have a network of urban background location reflecting the exposure of the urban situation to be operational at the latest on 1 January 2009. At the end of 2007 this was not realised in all Member States.
By combination of $PM_{2.5}$ monitoring data and PM_{10} monitoring and modelled data, a European concentration map has been made. The level of 25 μg/m³, set as target value for 2010 and as limit value for 2015, is exceeded widely in Europe. In 2005 9% of the population is exposed to level above this LV. In 2005 more than 25% of the population is exposed to concentrations above the PM_{10} short term limit value (not more than 35 day with a daily mean above 50 μg/m³). This indicates that the $PM_{2.5}$ LV is less stringent than the short-term PM_{10} limit value.
In 10 Member States the Averaged Exposure Indicator is well above the exposure concentration obligation of 20 μg/m³ to be met in 2015. In another 5 Member States the AEI is around the level of 20 μg/m³. By 2020 the AEI has too be reduced with a certain percentage depending on its value in 2010. This exposure reduction target ranges from 10% in the Nordic countries to more than 25% in eastern European countries.
In Europe $PM_{2.5}$ pollution is associated with more than 492 000 premature deaths, corresponding to a loss of almost 4.9 million years of life (YOLL). Meeting the LV in 2020 will, in addition to other health benefits, reduce the number of years of life lost by about 5% . Meeting the exposure reduction targets will result in larger benefits: a reduction of about 17% in years of life lost

References

AEAT (2005) CAFE CBA: Baseline Analysis 2000 to 2020. AEA Technology Environment,Harwell, UK. Reference AEAT/ED51014/ Baseline Issue 5

Brunekreef B. and Forsberg B. (2005) Epidemiological evidence of effects of coarse airborne particles on health. Eur Respir J., **26**, 309-18.

Buijsman E. and de Leeuw F.A.A.M. (2004) Correction factors and PM10 measurements in AirBase, ETC/ACC Technical Paper. Available from: http://air-climate.eionet.europa.eu/docs/meetings/041122_9th_EIONET_AQ_WS/05d_PM10_corr_factors_in_AirBase_Nov2004-TempDraft.pdf.

De Leeuw F.A.A.M. (2005) PM10 measurement methods and correction factors in AirBase 2004 status report. ETC/ACC Technical Paper 2005/6. Available from: http://air-climate.eionet.europa.eu/reports/ETCACC_TechnPaper_2005_6_PM10_CorrFactors2004

Denby B., de Leeuw F., de Smet P., Horálek, J. (2009) Sources of uncertainty and their assessment in spatial mapping. ETC/ACC Technical Paper 2008/20. http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2008_20_spatialAQ_uncertainties

EC (2008) Directive 2008/50/EC of the European Parliament and of the Council on ambient air quality and cleaner air for Europe. Official Journal, L 152 11.6.2008, pp 1-44.

EMEP (2007) Transboundary particulate matter in Europe. Status report 4/2007. Kjeller, Norwegian Institute for Air Research (EMEP Report 4/2007)

EC (1997): Council Decision of 27 January 1997 establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States (Exchange of Information (97/101/EC)). Official Journal L 035, 05/02/1997, pp. 14-22. See http://ec.europa.eu/environment/air/quality/legislation/existing_leg.htm

Horálek, J., Kurfurst, P., Denby, B., de Smet, P., de Leeuw, F., Brabec, M., Fiala, J. (2005) Interpolation and assimilation methods for European scale air quality assessment and mapping - Part II: Development and testing new methodologies. ETC/ACC Technical Paper 2005/8. http://air-climate.eionet.europa.eu/reports/ETCACC_TechnPaper_2005_8_Spatial_AQ_Dev_Test_Part_II

Horálek, J., de Smet, P., de Leeuw, F., Denby, B., Kurfurst, P., Swart R. (2008) European air quality maps for 2005 including uncertainty analysis. ETC/ACC Technical Paper 2007/7. http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2007_7_spatAQmaps_ann_interpol

Mathers C.D. and Loncar D. (2006) Projection of global mortality and burden of disease from 2002 to 2030. PLoS Med 3(11) e442.

Mol W.J.A., van Hooydonk P.R., de Leeuw F.A.A.M. (2008) European exchange of monitoring information and state of the air quality in 2006. ETC/ACC Technical paper 2008/1. http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2008_1_EoI_AQ_meta_info2006

Mol W.J.A., van Hooydonk P.R., de Leeuw F.A.A.M. (2009) European exchange of monitoring information and state of the air quality in 2007. ETC/ACC Technical paper 2009/3. http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2009_3_EoI_AQ_meta_info2007

Pope III C.A., Burnett R.T., Thun M.J., Calle E.E., Krewski D., Ito K., Thurston G.D. (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution J. Amer. Med. Assoc. 287, 1132-1141.

Pope III C.A. and Dockery D.W. (2006) Health effects of fine particulates air pollution: lines that connect. J Air Waste Manag Assoc., **56**, 709-742.

UN (2005) United Nations, Department of Economic and Social Affairs, Population Division *World Population Prospects: The 2004 Revision. CD-ROM Edition - Extended Dataset* (United Nations publications, Sales No. E.05.XIII.12).

UN (2006) United Nations, Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects: The 2005 Revision*. CD-ROM Edition – Data in digital form (POP/DB/WUP/Rev.2005).

Van Dingenen R., Raes F., Putaud J.P. et al., (2004) A European aerosol phenomenology—1:physical characteristics of particulate matter at kerbside,urban, rural and background sites in Europe. Atmospheric Environment, **38**, 2561-2577

Vixseboxse E. and de Leeuw F. (2008) Reporting on the air quality status of zones and agglomerations in 2006 under the Air Quality Framework Directive. ETC/ACC Technical Paper 2008/2. http://air-climate.eionet.europa.eu/reports/ETCACC_TP2008_2_AQQ2006

WHO (2004) Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors. Ezzati M. et al (eds). 2004, WHO.

WHO (2006) Global Update 2005. Air Quality Guidelines. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide.WHO Regional Office for Europe, Copenhagen, Denmark.