emep Co-operative programme for monitoring and evaluation of the long-range transmissions of air pollutants in Europe

Calculation of cause-specific mortality impacts of fine particulate matter in GAINS

Background paper for the Meeting of the UNECE Task Force on Health

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Executive Summary

In the early 2000s, the GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model used emerging epidemiological evidence to estimate premature mortality of the European population that can be attributed to the exposure to fine particulate matter and to identify cost-effective emission control strategies that reduce health impacts at least cost (Amann et al., 2011, p.accepted for publication). Based on the review of available studies on the health effects of PM conducted by the UNECE Task Force on Health (UNECE/WHO, 2003), the GAINS impact assessment employed the associations between population exposure to PM2.5 and all-cause mortality of the American Cancer Society study (Pope et al., 2002).

In the meantime, a wealth of new epidemiological studies have sharpened the evidence about health effects of particulate matter and revealed more specific associations between ambient concentrations of PM2.5 and health impacts (e.g., Pope et al., 2009). In particular, new studies establish robust relationships between exposure to fine particles and specific causes of deaths. These new insights should facilitate a more specific estimate of the role of particular death causes that are associated with bad air quality, and a more precise estimate of the total mortality impacts in different countries as baseline death rates from different diseases vary over countries.

This background paper describes a revised approach of the health impact assessment in GAINS that employs cause-specific concentration-response relationships for lung cancer, cardio-vascular and respiratory diseases for the European countries.

Data on cause-specific deaths in the European countries have been extracted from the 2010 version of the World Health Organization database on mortality indicators by 67 causes of death, age and sex (HFA-MDB) for the latest available year. As a result, the cause-specific approach results in higher impact estimates than the former calculation for all-cause mortality. The difference depends on the relative shares of death causes in the various countries; for the EU-27, cause-specific calculations for the year 2000 result in 16% higher health effects, keeping all other factors constant (i.e., PM exposure, population, etc.). In the non-EU countries, the difference amounts to 54%, essentially due to the higher share of cardio-vascular deaths.

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Acknowledgements

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1 Background

There is ample scientific evidence about harmful impacts of fine particulate matter on human health causing premature mortality and morbidity (Pope et al., 2009; WHO, 2007). Quantifications of such effects can provide important pieces of information for defining emission control strategies that effectively protect human health from exposure to air pollutants. For instance, in 2005 the Thematic Strategy on Air Pollution of the European Union established a specific target of reducing premature mortality from fine particulate matter (PM2.5) by 43% between 2000 and 2020, and developed tailored reduction schedules for the precursor emissions (primary particulate matter, SO_2, NO_x, NH_3) that would achieve this target in a cost-effective way (CEC, 2005).

In the early 2000s, the analyses that underpinned the development of the Thematic Strategies relied on the epidemiological evidence of the health impacts of fine particulate matter that has emerged from studies conducted in the 1990s. At that time studies in the United States have shown that people living in less polluted cities live longer than those living in more polluted cities (Dockery et al., 1993; Pope et al., 1995). After adjustments for other factors, an association remained between ambient concentrations of fine particles and shorter life expectancy. These findings were confirmed by a reanalysis of the original studies published by the Health Effects Institute (Krewski et al., 2000) and by a large-scale assessment of mortality based on data collected by the American Cancer Society (Pope et al., 2002).

This epidemiological evidence was used in the GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model to estimate premature mortality of the European population that can be attributed to the exposure to fine particulate matter and to identify cost-effective emission control strategies that reduce health impacts at least cost (Amann et al., 2011, p.accepted for publication). Based on the review of available studies on the health effects of PM conducted by the UNECE Task Force on Health (UNECE/WHO, 2003), the GAINS impact assessment (Mechler et al., 2002) employed the associations between ambient concentration of PM2.5 in outdoor air and all-cause mortality of the American Cancer Society study (Pope et al., 2002).

In the meantime, a wealth of new epidemiological studies have sharpened the evidence about health effects of particulate matter and revealed more specific associations between PM exposure and health impacts (e.g., Pope et al., 2009). In particular, new studies establish robust relationships between ambient concentrations of PM2.5 and specific causes of deaths. These new insights should facilitate a more specific estimate of the role of particular death causes that are associated with bad air quality, and a more precise estimate of the total mortality impacts in different countries as baseline death rates from different diseases vary over countries.

This paper describes the revised approach of the health impact assessment in GAINS that employs cause-specific concentration-response relationships, as a background document for discussion at the 14th Meeting of the UNECE/WHO Task Force on Health (Bonn, May 12-13, 2011).

The remainder of the paper is organized as follows: Section 2 discusses the methodology and how the new information on cause-specific risk rates is employed in the GAINS calculation. Results of the revised methodology for the year 2000 are presented in Section 3, and compared against the outcomes of the calculations for all-cause mortality. Conclusions are drawn in Section 4.

2 Methodology

2.1 The relative risk for all-cause mortality

For the estimating the concentration-response function that describes the changes in premature mortality, the available epidemiological studies employ the Cox proportional hazards model (Cox, 1972). The proportional hazards model postulates that changing the stress variable (here the change in PM concentrations) is equivalent to multiplying the hazard rate (here the mortality rate) by a proportionality factor, which is here the relative risk function. The fatalities due to PM impacts are usually assumed to be Poisson-distributed, thus the concentration-response function is of log-linear type. The Cox proportional hazard model expresses the number of fatalities in a time period *Y* as a function of the baseline fatalities Y_0 and *PM* concentrations (β is a functional parameter):

$$Y = Y_0 * e^{\beta * PM} \qquad (1)$$

In such a model, the annual baseline death rate is modified as a function of particulate matter concentration in outdoor air, and the associated relative risk *RR* is defined as

$$RR(PM) = e^{\beta * PM} \qquad (2)$$

The epidemiological studies found beta to be low and the RR function to behave quasi-linearly in the concentration range studied (Pope et al., 2002, p. 1136). Thus, RR can be approximated linearly around 0 by a first-order Taylor series:

$$RR(PM) = \beta * PM + 1. \qquad (3)$$

Following advice from the UNECE Task Force on Health (UNECE/WHO, 2003), the GAINS calculation used relative risk factors for all-cause mortality. With a series of calculations using information on cohort-specific mortality rates provided by life tables, the GAINS calculates from this the shortening of life expectancy and associated life years lost. (For reference, these calculations are provided in the Annex).

2.2 Relative risk factors for cause-specific mortality

In the meantime, epidemiological cohort studies developed new and robust information about cause-specific mortality rates. A survey of recent results has been compiled for the 2005 Global Burden of Disease assessment (Burnett, 2010), providing relative risk estimates for five causes of death, i.e., cardiovascular diseases (ischemic heart disease, cerebrovascular diseases), respiratory diseases and lung cancer (see Table 2.1).

Table 2.1: Summary or relative risk estimates from different cohort studies associated with a 10 µg/m^3 change in $PM_{2.5}$ by cause of death. Source: Burnett, 2010, personal communication

Cause of death	*Relative risk factors *)*	**Source**
Cardiovascular	1.17 (1.11, 1.24)	ACS
	1.28 (1.13, 1.44)	SCS
	1.76 (1.25, 2.47)	WHI
	1.11 (0.93, 1.33)	NLDC
Ischemic heart disease (sub-set of cardiovascular)	1.29 (1.18, 1.41)	ACS
	1.26 (1.08, 1.47)	SCS
	2.21 (1.17, 4.16)	WHI
	2.02 (1.07, 3.78)	NHS
	0.99$^+$ (0.87, 1.14)	AHSMOG
	0.96$^+$ (0.75, 1.22)	NLDC
Cerebrovascular (sub-set of cardiovascular)	1.14 (1.02, 1.26)	- ACS
	0.96$^+$ (0.70, 1.31)	- SCS
	1.83 (1.11, 3.00)	- WHI
	1.62 (1.07, 2.44)	– NLDC
Respiratory	1.06 (0.97, 1.16)	- ACS
	1.08 (0.79, 1.49)	- SCS
	1.07 (0.87, 1.52)	– NLDC
Lung cancer	1.14 (1.06, 1.23)	- ACS
	1.27 (0.96, 1.69)	- SCS
	1.06 (0.82, 1.38)	- NLDC

*): Hazard ratio and 95% confidence intervals (in parenthesis) based on 10 µg/m^3 change in $PM_{2.5}$. ACS – American Cancer Society, SCS – Six Cities Study, WHI – Women's Health Inititive , AHSMOG – Adventist Health Study of Smog, NLDC - Netherlands Cohort Study on Diet and Cancer

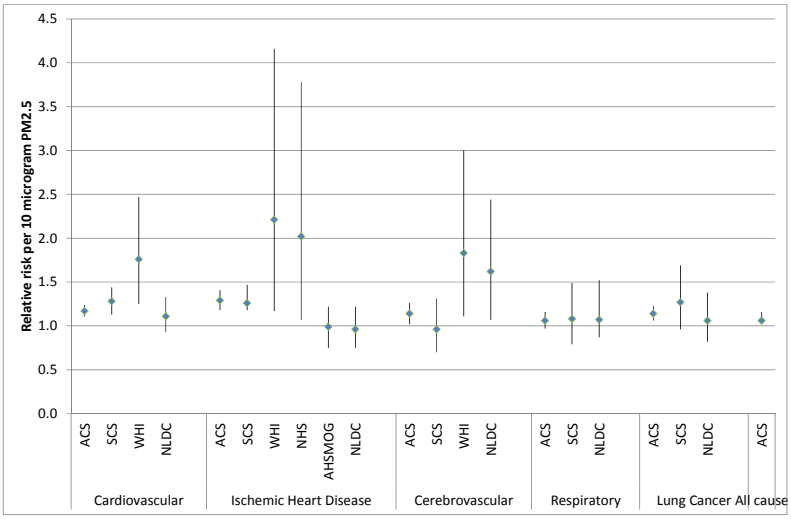

Figure 2.1: Relative risk factors for different causes of death from the literature. Source: Burnett, 2010

As to be expected, the relative risk factors for the individual diseases are significantly higher than the all-cause factor (1.06) of Pope et al., which was used for the GAINS calculations. However, as the higher risk factors apply to lower baseline mortality figures (i.e., only referring to the specific cases), it is not obvious whether a cause-specific health impact assessment would result in lower or higher total estimates.

In order to conduct the GAINS health impact assessment on the basis of these new cause-specific mortality estimates, we develop a 'combined relative risk factor' that can then be used to derive cases of premature mortality, loss in statistical life expectancy and years of life lost with the standard routines in GAINS that have been developed for all-cause mortality. This combined risk factor starts from the definition of the relative risk RR_i for death Y_i due a disease *i* that can be observed from intervention studies:

$$RR_i = \frac{Y_{PM,i}}{Y_{0,i}} \qquad (4)$$

where

- $Y_{0,I}$ is the baseline number of deaths from disease *i* in a given time interval
- $Y_{PM,I}$ is the number deaths from disease *i* in a given time interval at a given (higher) concentration of PM2.5.
- *i* individual diseases; an additional term covers all other causes, associated with a relative risk of 1.

The combined RR can be defined as

$$RR = \frac{\sum_i Y_{PM,i}}{\sum_i Y_{0,i}} \ . \qquad (5)$$

With the linearization we get for a single cause

$$\frac{Y_{PM,i}}{Y_{0,i}} = \beta_i * PM + 1 \qquad (6)$$

and

$$Y_{PM,i} = Y_{0,i} * \beta_i * PM + Y_{0,i} \ . \qquad (7)$$

Assuming that the relation between different death causes remains unchanged over time in the baseline, we can calculate a combined relative risk factor β that incorporates the relative risks of all individual diseases and relates to all-cause total baseline mortality:

$$RR = \frac{\sum_i Y_{PM,i}}{\sum_i Y_{0,i}} = \frac{\sum_i (Y_{0,i} * \beta_i) * PM + \sum_i Y_{0,i}}{\sum_i Y_{0,i}} = \sum_i \frac{Y_{0,i} * \beta_i}{\sum_i Y_{0,i}} * PM + 1 = \beta * PM + 1 \ . \qquad (8)$$

With such a modified combined relative risk factor, this approach allows us to apply the standard GAINS routine that has been developed for all-cause mortality also for cause-specific analyses. As explained in the Annex, this methodology accounts for the 'propagation of the population at risk' during each time interval, in which each age-group cohort decreases due to

a) deaths due to the selected causes (with risk multiplied by the PM-related RR), and

b) deaths to other (non PM related) causes.

We calculate a new β to consider all cause-specific RRs. This β is the weighted sum of (a) all air-pollution related causes and (b) deaths for other (non PM related) causes assuming a RR=1 for these. It enters the integral for calculating life expectancy (LE) by increasing the death rate. This integral considers decreasing cohort because of a) and b).

The observed death rates $Y_{0,i}$ already include air-pollution-related casualties from the actual PM exposure, which should be excluded from the baseline mortality $Y_{0,i}$ of the different death causes in order to avoid double-counting of these deaths. Thus, the observed baseline mortalities reported by WHO have been adjusted for the current (country-specific) PM concentration:

$$Y_{0,i} = \frac{Y_{obs,i}}{(RR_i - 1) * PM_{2000} + 1} \quad . \qquad (9)$$

Finally because of the linear (Taylor) approximation, we can break down the weighted sum of cause specific RRs as shortening of life expectancy caused by a specific disease.

3 Results

An initial calculation estimates total mortality related to outdoor pollution for the cause-specific approach and compares it with the outcome of the all-cause approach that has been used by the GAINS model in the past. This calculation considers mortality due to cardio-vascular diseases, respiratory diseases and lung cancer. In order to avoid double counting, ischemic heart diseases and cerebrovascular diseases are excluded, as they are already covered by cardio-vascular causes. Furthermore, the analysis adopts the central relative risk factors of the American Cancer Society (ACS) study (Pope et al., 2002) as listed in Table 3.1.

Table 3.1: Relative risk factors used for the calculations for a 10 µg/m^3 change of PM2.5

Cause of death	Central value	Confidence interval
Cardiovascular	1.17	1.11 - 1.24
Respiratory	1.06	0.97 - 1.16
Lung cancer	1.14	1.06 - 1.23
For comparison: all-cause reported in Pope et al., 2002	1.06	1.02-1.11

Data on cause-specific deaths in the European countries are extracted from the 2010 version of the WHO database on mortality indicators by 67 causes of death, age and sex (HFA-MDB) (WHO, 2010) for the latest available year (Table 3.2).

As a result, the cause-specific approach results in higher impact estimates than the former calculation for all-cause mortality. The difference depends on the relative shares of death causes in the various countries; for the EU-27, cause-specific calculations for the year 2000 result in 16% higher health effects, keeping all other factors constant (i.e., PM exposure, population, etc.). In the non-EU countries, the difference amounts to 54%, essentially due to the higher share of cardio-vascular deaths.

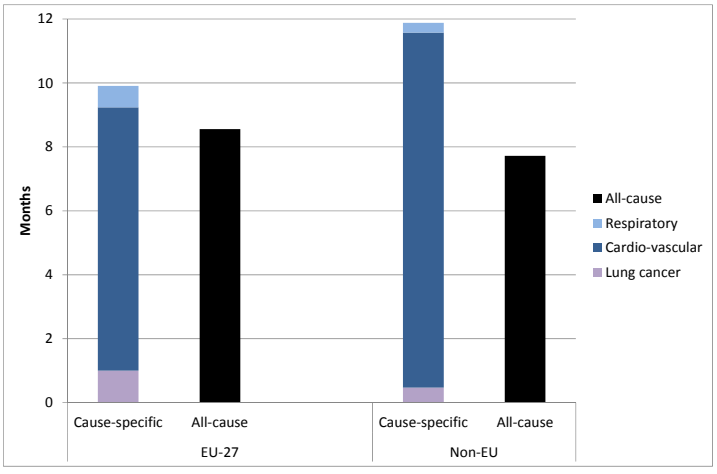

Figure 3.1: Comparison of computed loss in life expectancy for the year 2000, cause-specific approach vs. all-cause approach

Table 3.2: Baseline numbers of mortality by cause, for the latest available year before 2010. Source: WHO, 2010

	All causes	Lung cancer, i.e., malignant neoplasm of larynx, trachea, bronchus and lung	Cardio-vascular, i.e., diseases of the circulatory system	Respiratory, i.e., diseases of the respiratory system
Austria	75083	3741	32294	4130
Belgium	101253	6357	35302	11209
Bulgaria	110523	3908	71492	4466
Cyprus	5194	195	2015	356
Czech Rep.	104948	5647	52280	5736
Denmark	55218	3892	16971	5253
Estonia	16675	739	9074	489
Finland	49090	2037	20281	1980
France	520535	30020	145272	32022
Germany	821627	42348	358953	54888
Greece	107979	6766	49213	10239
Hungary	130027	8875	64749	6231
Ireland	27141	1667	9433	3290
Italy	572881	34610	224311	37812
Latvia	31031	1112	16516	725
Lithuania	43832	1523	23623	1684
Luxembourg	3774	252	1394	283
Malta	3243	154	1273	298
Netherlands	135136	10114	40129	13789
Poland	379399	24128	172943	19297
Portugal	102371	3480	37118	8675
Romania	257213	10618	154541	12891
Slovakia	53475	2287	29049	3109
Slovenia	18308	1155	7225	1142
Spain	386324	21761	122793	44200
Sweden	91542	3611	37466	5848
UK	574687	35345	193766	78388
EU-27	4778509	266342	1929476	368430
Albania	17748	657	8891	933
Belarus	132993	3655	70318	4682
Bosnia-H.	30680	1603	14797	1097
Croatia	52151	2956	26235	2249
Norway	41716	2138	14135	4118
R. Moldova	41948	1033	23470	2460
Russian F.	2166703	56695	1232182	82761
Serbia –M.	102711	5341	57343	3937
Switzerland	61089	3084	22613	3733
TFYROM	18006	720	10184	707
Ukraine	754460	16143	480120	23276
Non-EU	3420205	94025	1960288	129953
Total	8198714	360367	3889764	498383

Table 3.3: Years of life lost estimated for the year 2000 (million years of life lost)

			Years of life lost due to					
	Population >30 (millions)	Mean PM2.5 $\mu g/m^3$	lung cancer	cardio-vascular diseases	respiratory diseases	all air pollution related*)	former all-cause approach	Difference
Austria	5.48	12.6	0.38	3.76	0.20	4.34	3.60	21%
Belgium	6.88	22.2	0.97	6.11	0.88	7.96	7.86	1%
Bulgaria	5.05	12.8	0.27	5.74	0.15	6.16	3.51	75%
Cyprus	0.47	7.4	0.01	0.17	0.01	0.20	0.18	13%
Czech Rep.	6.78	15.0	0.61	6.56	0.31	7.48	5.43	38%
Denmark	3.52	11.1	0.31	1.56	0.20	2.07	2.10	-1%
Estonia	0.83	8.2	0.04	0.54	0.01	0.59	0.39	51%
Finland	3.44	5.1	0.08	0.96	0.04	1.08	0.91	19%
France	38.78	13.2	3.11	17.44	1.62	22.16	26.56	-17%
Germany	57.08	16.3	5.16	50.40	3.33	58.89	48.64	21%
Greece	7.69	13.3	0.69	5.79	0.51	6.99	5.20	34%
Hungary	6.59	17.1	0.90	7.58	0.32	8.80	6.35	39%
Ireland	2.52	6.7	0.12	0.79	0.11	1.01	0.89	14%
Italy	41.26	13.4	3.55	26.65	1.89	32.09	28.31	13%
Latvia	1.44	8.6	0.06	0.97	0.02	1.05	0.72	45%
Lithuania	2.09	8.9	0.08	1.48	0.04	1.61	1.09	48%
Luxembourg	0.30	16.1	0.03	0.22	0.02	0.28	0.26	8%
Malta	0.27	9.5	0.01	0.13	0.01	0.15	0.13	17%
Netherlands	10.66	20.6	1.68	7.63	1.17	10.48	11.52	-9%
Poland	23.50	15.2	2.64	21.81	1.04	25.49	19.92	28%
Portugal	7.10	10.9	0.28	3.52	0.34	4.14	3.99	4%
Romania	13.53	14.5	0.96	16.14	0.57	17.68	10.82	63%
Slovakia	3.32	14.8	0.25	3.66	0.17	4.08	2.75	48%
Slovenia	1.36	13.7	0.13	0.95	0.06	1.14	1.00	14%
Spain	30.32	7.9	1.48	9.80	1.42	12.70	12.36	3%
Sweden	5.91	6.3	0.16	1.95	0.12	2.23	1.87	19%
UK	38.62	12.5	3.23	20.55	3.48	27.26	25.30	8%
EU-27	324.80		27.18	222.88	18.03	268.10	231.62	16%
Albania	1.65	8.5	0.06	0.93	0.04	1.03	0.73	40%
Belarus	6.16	9.7	0.21	4.76	0.13	5.10	3.58	42%
Bosnia-H.	2.74	8.9	0.15	1.65	0.05	1.85	1.36	36%
Croatia	2.97	12.9	0.25	2.61	0.09	2.96	2.11	40%
Norway	1.23	9.5	0.06	0.91	0.03	0.99	0.64	56%
R. Moldova	2.37	11.3	0.08	2.23	0.10	2.41	1.59	51%
Russian F.	2.94	4.0	0.07	0.54	0.06	0.67	0.62	9%
Serbia –M.	87.03	10.2	3.10	78.65	2.17	83.92	54.86	53%
Switzerland	6.42	12.5	0.49	6.03	0.17	6.69	4.34	54%
TFYROM	4.91	10.6	0.28	2.41	0.16	2.85	2.66	7%
Ukraine	29.22	13.1	1.04	35.90	0.73	37.67	22.49	67%
Non-EU	147.63		5.79	136.63	3.74	146.16	94.98	54%
Total	472.43		32.98	359.51	21.77	414.26	326.60	27%

*) sum of the three causes

Table 3.4: Loss of statistical life expectancy (months) estimated for the year 2000

			Loss in statistical life expectancy due to				
	Population >30 (millions)	Mean PM2.5 $\mu g/m^3$	lung cancer	cardio-vascular diseases	respiratory diseases	all air pollution related	former all-cause approach
Austria	5.48	12.6	0.8	8.2	0.4	9.5	7.9
Belgium	6.88	22.2	1.7	10.7	1.5	13.9	13.7
Bulgaria	5.05	12.8	0.6	13.6	0.4	14.6	8.3
Cyprus	0.47	7.4	0.4	4.4	0.3	5.1	4.5
Czech Rep.	6.78	15.0	1.1	11.6	0.5	13.2	9.6
Denmark	3.52	11.1	1.0	5.3	0.7	7.1	7.1
Estonia	0.83	8.2	0.5	7.8	0.2	8.5	5.6
Finland	3.44	5.1	0.3	3.4	0.1	3.8	3.2
France	38.78	13.2	1.0	5.4	0.5	6.9	8.2
Germany	57.08	16.3	1.1	10.6	0.7	12.4	10.2
Greece	7.69	13.3	1.1	9.0	0.8	10.9	8.1
Hungary	6.59	17.1	1.6	13.8	0.6	16.0	11.6
Ireland	2.52	6.7	0.6	3.7	0.5	4.8	4.3
Italy	41.26	13.4	1.0	7.8	0.6	9.3	8.2
Latvia	1.44	8.6	0.5	8.1	0.1	8.8	6.0
Lithuania	2.09	8.9	0.5	8.5	0.2	9.2	6.2
Luxembourg	0.30	16.1	1.4	8.8	0.8	10.9	10.1
Malta	0.27	9.5	0.6	5.7	0.5	6.8	5.8
Netherlands	10.66	20.6	1.9	8.6	1.3	11.8	13.0
Poland	23.50	15.2	1.3	11.1	0.5	13.0	10.2
Portugal	7.10	10.9	0.5	6.0	0.6	7.0	6.7
Romania	13.53	14.5	0.9	14.3	0.5	15.7	9.6
Slovakia	3.32	14.8	0.9	13.2	0.6	14.8	10.0
Slovenia	1.36	13.7	1.2	8.4	0.6	10.1	8.8
Spain	30.32	7.9	0.6	3.9	0.6	5.0	4.9
Sweden	5.91	6.3	0.3	4.0	0.2	4.5	3.8
UK	38.62	12.5	1.0	6.4	1.1	8.5	7.9
EU-27	324.80		1.0	8.2	0.7	9.9	8.6
Albania	1.65	8.5	0.4	6.8	0.3	7.5	5.3
Belarus	6.16	9.7	0.4	9.3	0.3	9.9	7.0
Bosnia-H.	2.74	8.9	0.7	7.2	0.2	8.1	5.9
Croatia	2.97	12.9	1.0	10.6	0.4	12.0	8.5
Norway	1.23	9.5	0.5	8.9	0.3	9.7	6.2
R. Moldova	2.37	11.3	0.4	11.3	0.5	12.2	8.1
Russian F.	2.94	4.0	0.3	2.2	0.2	2.7	2.5
Serbia –M.	87.03	10.2	0.4	10.8	0.3	11.6	7.6
Switzerland	6.42	12.5	0.9	11.3	0.3	12.5	8.1
TFYROM	4.91	10.6	0.7	5.9	0.4	7.0	6.5
Ukraine	29.22	13.1	0.4	14.7	0.3	15.5	9.2
Non-EU	147.63		0.5	11.1	0.3	11.9	7.7
Total	472.43		0.8	9.1	0.6	10.5	8.3

4 Conclusions

In the early 2000s, the GAINS model used emerging epidemiological evidence to estimate premature mortality of the European population that can be attributed to the exposure to fine particulate matter and to identify cost-effective emission control strategies that reduce health impacts at least cost. Based on the review of available studies on the health effects of PM conducted by the UNECE Task Force on Health, the GAINS impact assessment employed the associations between ambient concentrations of PM2.5 and all-cause mortality of the American Cancer Society study (Pope et al., 2002).

In the meantime, a wealth of new epidemiological studies have sharpened the evidence about health effects of particulate matter and revealed more specific associations between exposure and health impacts (e.g., Pope et al., 2009). In particular, new studies establish robust relationships between outdoor concentrations of PM2.5 and specific causes of deaths. These new insights should facilitate a more specific estimate of the role of particular death causes that are associated with bad air quality, and a more precise estimate of the total mortality impacts in different countries as baseline death rates from different diseases vary over countries.

This background paper describes a revised approach of the health impact assessment in GAINS that employs cause-specific concentration-response relationships for lung cancer, cardio-vascular and respiratory diseases for the European countries.

Data on cause-specific deaths in the European countries have been extracted from the 2010 version of the WHO database on mortality indicators by 67 causes of death, age and sex (HFA-MDB) (WHO, 2010) for the latest available year. As a result, the cause-specific approach results in higher impact estimates than the former calculation for all-cause mortality. The difference depends on the relative shares of death causes in the various countries; for the EU-27, cause-specific calculations for the year 2000 result in 16% higher health effects, keeping all other factors constant (i.e., PM exposure, population, etc.). In the non-EU countries, the difference amounts to 54%, essentially due to the higher share of cardio-vascular deaths.

Further analysis will be required to explore the sensitivity of model results against uncertainties in the concentration-response functions, in the statistics about causes of death, and their extrapolation into the future.

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Annex: The GAINS methodology to calculate loss of life expectancy due to PM

Using the Cox proportional hazards model, a methodology was developed to calculate impacts of various scenarios of precursor emissions of fine particles on the life expectancy of the European population.

The methodology starts from the cohort- and country-specific mortality taken from the life tables and calculates for each cohort the survival function over time. The survival function is modified by exposure to PM pollution, and can then be converted into reduced life expectancy for an individual person. The calculation uses life-tables and applies an approximation method described in Vaupel and Yashin (1985) for the calculation of the change in life expectancy.

For an age cohort *c* of age *c* at starting time *s* (here 2010) in a grid cell, the change in life-expectancy can be calculated as follows:

The basis for the calculation of life expectancy is the so-called survival function *l(t)* that indicates the percentage of a cohort alive after time *t* has elapsed since starting time *s*. *l(t)* is an exponential function of the sum of the mortality rates $\mu_{a,b}$, which are derived from the life table with *a* as age and *b* as calendar time. As the relative risk function taken from Pope *et al.* (2002) applies only to cohorts that are at least 30 years old, younger cohorts were excluded from this analysis. Accordingly, for an age cohort aged *c* at start *s*, $l_c(t)$ is:

$$l_c(t) = e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}} \tag{5}$$

where c=30, 35,...,95.

Thereby, $l_{30}(t)$ signifies the cohort of age 30 at starting time 2010, μ(30,2010) is the mortality rate for this age cohort in 2010 and μ(35,2015) the mortality rate in 2015 for the same cohort, which will be by then five years older.

The remaining life expectancy e_c for a cohort aged *c* is the integral from *c* to w_1 over $l_c(t)$:

$$e_c = \int_c^{w_1} l_c(t)\, dt \tag{6}$$

where w_1 is the maximum age considered (in this study 95 years, this age group also contains persons older than 95).

Exposure to different PM concentrations changes the mortality rate and consequently life expectancy:

$$\overline{e_c} = \int_c^{w_1} \overline{l_c}(t)\, dt = \int_c^{w_1} e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}}\, dt = \int_c^{w_1} e^{-\sum_{z=c}^{t} RR(PM)\,\mu_{z,z-c+s}}\, dt \tag{7}$$

where $\bar{l}_c$ is the survival function with the modified mortality rates and RR a function of (the change in) PM concentrations following Equation (4):

$$RR(PM) = (\beta PM) + 1$$

The absolute change in life expectancy per person is

$$\begin{aligned}
\Delta e_c &= \bar{e}_c - e_c \\
&= \int_c^{w_1} \bar{l}_c(t)\,dt - \int_c^{w_1} l_c(t)\,dt \\
&= \int_c^{w_1} e^{-\sum_{z=c}^{t} (\beta PM + 1)\mu_{z,z-c+s}}\,dt - \int_c^{w_1} e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}}\,dt \\
&= \int_c^{w_1} \left(e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}} e^{-\sum_{z=c}^{t} \beta PM \mu_{z,z-c+s}}\right) dt - \int_c^{w_1} e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}}\,dt \qquad (8) \\
&= \int_c^{w_1} \left(e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}} \left[e^{-\sum_{z=c}^{t} \beta PM \mu_{z,z-c+s}} - 1\right]\right) dt \\
&= \int_c^{w_1} \left(l_c(t)\left[e^{-\sum_{z=c}^{t} \beta PM \mu_{z,z-c+s}} - 1\right]\right) dt
\end{aligned}$$

This specification has the disadvantage that the RR function is part of the exponent of the e-function. In order to simplify, with

$$l_c(t) = e^{-\sum_{z=c}^{t} \mu_{z,z-c+s}},$$

the following substitution is permissible :

$$-\sum_{z=c}^{t} \mu_{z,z-c+s} = \ln l_c(t) \qquad (9)$$

Substituting (9) in (8) leads to

$$\Delta e_c = \int_c^{w_1} l_c(t)\left[e^{\beta * PM * \ln l_c(t)} - 1\right] dt \qquad (9')$$

To simplify further, the following linear approximation of (9') by means of a Taylor-approximation of degree 1 around 0 is used. The quality of the fit of this approximation is discussed below.

$$e^{(\beta * PM) \ln l_c(t)} - 1 \approx (\beta * PM) \ln l_c(t) \qquad (10)$$

Thus the absolute change in life expectancy per person of a cohort *c* in year *s* is

$$\Delta e_c = (\beta * PM) \int_c^{w_1} l_c(t) \ln l_c(t) dt = (\beta * PM) H_c \quad (11)$$

where

$$H_c = \int_c^{w_1} l_c(t) \ln l_c(t) dt .$$

The change in life years for all persons of one cohort in grid cell *x,y* is obtained by multiplying Equation (11) by the size of the cohort $P_{c/x,y}$ and the length of the time interval for which demographic and mortality data are given. (For this study, data are available for five-years intervals.)

This leads to the change in life years lived for cohort *c* in grid cell *x,y*. As cohort data were obtained with reference to the aggregate national level, cohort size in a grid cell was calculated by weighting total population in a grid cell with the relative share of the given cohort in the national population:

$$\Delta L_c = P_{c/x,y} * \Delta e_t * i \quad (12)$$

where

$$P_{c/x,y} = P_{c/national} * \frac{P_{total/x,y}}{P_{total/national}} \quad (12')$$

where

ΔL_c	change in life years lived for cohort *c* in grid cell *x,y*
$P_{c/x,y}$	population in cohort *c* in grid cell *x,y*
$P_{c/national}$	national population in cohort *c*
$P_{total/x,y}$	total population in grid cell *x,y* (at least of age 30)
$P_{total/national}$	total national population (at least of age 30)
i	length of time interval

For all cohorts in a grid cell *x,y* the change in life years is expressed as the sum of the change in life years for the cohorts:

$$\Delta L_{x,y} = \sum_{c=w_0}^{w_1} \Delta L_c = i * (\beta * PM) * \frac{P_{total/x,y}}{P_{total/national}} \left(\sum_{c=w_0}^{w_1} H_c * P_{c/national} \right) \quad (13)$$

where

w_0 first cohort considered (here 30)

w_1 last cohort considered (here 95)

Dividing (13) by total population at least of age 30 in grid cell *x,y* leads to the average change in life expectancy in grid cell *x,y*.

$$\Delta E_{x,y} = \frac{\sum_{c=w_0}^{w_1} \Delta L_c}{P_{total\ /\ x,y}} = i * (\beta * PM\ ) \frac{\sum_{c=w_0}^{w_1} H_c * P_{c\ /\ national}}{P_{total\ /\ national}} \tag{14}$$

In order to calculate the average change in life expectancy for a country *A*, the change in life years in all grid cells of a country divided by total population is computed:

$$\begin{aligned} \Delta E_A &= \frac{\sum_x \sum_y \Delta L_{xy}}{P_{total\ /\ nat.}} \\ &= \frac{i}{P_{total\ /\ nat.}} * \sum_x \sum_y [(\beta * PM_{x,y}) * \frac{P_{total\ /\ x,y}}{P_{total\ /\ nat.}} \sum_{c=w_0}^{w_1} (H_c * P_{c\ /\ nat.})] \\ &= \frac{i}{P^2_{total\ /\ nat.}} * \sum_x \sum_y [(\beta * PM_{x,y}) * P_{total\ /\ x,y} (\sum_{c=w_0}^{w_1} H_c * P_{c\ /\ nat.})] \end{aligned} \tag{15}$$

where ΔE_A is the change in average life expectancy in country *A* expressed in years.