Economic valuation of the mortality benefits of a regulation on SO$_2$ in 20 European cities

Olivier Chanel$^1$, Susann Henschel$^2$, Patrick G. Goodman$^2$, Antonis Analitis$^3$, Richard W. Atkinson$^4$, Alain Le Tertre$^5$, Ariana Zeka$^6$ and Sylvia Medina$^5$ on behalf of the Aphekom group

1 Aix-Marseille School of Economics, Aix-Marseille University, CNRS & EHESS, GREQAM et IDEP, Marseilles, France
2 School of Physics, Dublin Institute of Technology, Dublin, Ireland
3 Department of Hygiene, Epidemiology and Medical Statistics, Medical School, University of Athens, Athens, Greece
4 St. George’s, University of London, London, UK
5 French Institute for Public Health Surveillance, InVS, Saint-Maurice, France
6 Institute for the environment, Brunel University, London, UK

Correspondence: Olivier Chanel, Aix-Marseille School of Economics, Aix-Marseille University, GREQAM, 2 rue de la Charité, 13236 Marseille cedex 02, France, Tel: +33 (0)4 91 14 07 80, Fax: +33 (0)4 91 90 02 27, e-mail: olivier.chanel@univ-amu.fr

Background: Since the 1970s, legislation has led to progress in tackling several air pollutants. We quantify the annual monetary benefits resulting from reductions in mortality from the year 2000 onwards following the implementation of three European Commission regulations to reduce the sulphur content in liquid fuels for vehicles.

Methods: We first compute premature deaths attributable to these implementations for 20 European cities in the Aphekom project by using a two-stage health impact assessment method. We then justify our choice to only consider mortality effects as short-term effects. We rely on European studies when selecting the central value of a life-year estimate ($€_{2005}$ 86 600) used to compute the monetary benefits for each of the cities. We also conduct an independent sensitivity analysis as well as an integrated uncertainty analysis that simultaneously accounts for uncertainties concerning epidemiology and economic valuation. Results: The implementation of these regulations is estimated to have postponed 2212 (95% confidence interval: 772–3663) deaths per year attributable to reductions in sulphur dioxide for the 20 European cities, from the year 2000 onwards. We obtained annual mortality benefits related to the implementation of the European regulation on sulphur dioxide of $€_{2005}$ 191.6 million (95% confidence interval: $€_{2005}$ 66.9–$€_{2005}$ 317.2). Conclusion: Our approach is conservative in restricting to mortality effects and to short-term benefits only, thus only providing the lower-bound estimate. Our findings underline the health and monetary benefits to be obtained from implementing effective European policies on air pollution and ensuring compliance with them over time.
certain gas oils and diesel fuels, excluding member states seeking derogation\textsuperscript{14}: 0.2% by weight as of 1 October 1994 and 0.05% by weight as of 1 October 1996. The maximum sulphur content of certain gas oil fuels for vehicles was further reduced by EC Directive 98/70/EC to 0.035% for diesel fuels and 0.015% for petrol as of 1 January 2000.\textsuperscript{15} Council Directive 99/32/EC extended the 93/12/EEC Directive to cover certain liquid fuels derived from petroleum and used by seagoing ships\textsuperscript{16} and specifies the following as the permitted maximum SO\textsubscript{2} content: 0.2% by mass as of 1 July 2000 and 0.1% by mass as of 1 January 2008.

Our study used data from 20 cities included in the Aphekom (Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe) project, a research programme involving 60 scientists from 12 countries across Europe. Aphekom’s objective was to provide new information and tools to enable decision-makers to set more effective European, national and local policies. To this end, it used traditional health impact assessment (HIA) techniques as well as innovative methods to explore the impact of air pollution on health in 25 European cities totalling nearly 39 million inhabitants.

\section*{Methods}

\subsection*{Background}

Because the implementation dates for the EC directives on SO\textsubscript{2} were 1994 (first stage), 1996 (second stage) and 2000 (third stage), city-specific daily data on urban background (UB) SO\textsubscript{2} concentrations, temperature and humidity measures and numbers of deaths [all-cause excluding external causes (ICD9: <800)] from 1990 to 2008 were collected using common guidelines based on the Aphekom project.\textsuperscript{17} Five cities were excluded due to missing data, leaving 20 cities from 11 countries in the analysis (see list in Table 1).

However, not all countries complied with the implementation dates as specified in the council directives, because of local derogations for instance. Hence, the number of stages implemented and their corresponding implementation dates were not the same for every city. The following 14 cities implemented all three stages of the council directives: Athens, Bordeaux, Brussels, Dublin, Le Havre, Lille, London, Lyon, Marseille, Paris, Rome, Rouen, Stockholm and Strasbourg. The other six cities (Barcelona, Bilbao, Budapest, Ljubljana, Toulouse and Vienna) only applied the last implementation stage, namely, Council Directive 99/32/EC. Our analysis assesses the number of deaths from year 2000 onwards (after third implementation stage) compared with the pre-1993 period in all 20 cities. The impacts of each of the three implementation stages on respiratory (ICD9: 460–519), cardiovascular (ICD9: 390–459) and total (ICD9: [I]800) mortality across the 20 cities have been reported in another study.\textsuperscript{4}

\subsection*{Computation of attributable premature deaths}

We used a two-stage hierarchical modelling approach to assess the mortality impact of the regulation up to implementation of the third stage. In the first stage, data of each city were analysed separately, whereas in the second stage, evidence across cities was combined using meta-regression techniques. Briefly, for the first stage, city-specific estimates were estimated from a Poisson regression model linking mortality to UB SO\textsubscript{2}, adjusting for temperature, day of the week, seasonality and time trend. Generalized additive models\textsuperscript{18} were used to control potential non-linearity between confounders and mortality. The exposure variable used for UB SO\textsubscript{2} was the average of lags 1 and 2 (i.e. 1 and 2 days prior to the mortality event).\textsuperscript{4} Additionally, dummy variables and their interaction with UB SO\textsubscript{2} were included in the model, depending on when council directives were successfully implemented in each city. The second stage of the modelling approach was designed to pool the city-specific estimates of air pollution effects on health, using meta-regression techniques.

SO\textsubscript{2} effects on mortality in each city were combined in a meta-analysis based on generalized least squares to provide overall estimates. Variables representing potential effect modifiers (yearly means of SO\textsubscript{2}, PM\textsubscript{10} and temperature) were included in the second-step regression models to account for city heterogeneity. Details on the whole methodology have been previously published,\textsuperscript{19} and models were run using R statistical software.\textsuperscript{20}

The combined estimate of SO\textsubscript{2} effect on mortality was then used in the HIA to estimate the attributable number of premature deaths (Table 1).

\section*{Monetary assessment}

\subsection*{Special features of the monetary assessment}

By reducing UB SO\textsubscript{2} levels in the 20 cities, the regulation has two potential effects on mortality: short-term and long-term.

For acute (or short-term, ST) mortality effects, the number of premature deaths avoided is generally computed through time-series analyses and proportional hazard models. The gains in life expectancy corresponding to each of these premature deaths can be considered to be in the range of a few months, certainly lower than 1 year.\textsuperscript{21}

For chronic (or long-term, LT) mortality effects, the number of premature deaths avoided is generally obtained via cohort studies that monitor populations exposed to different levels of pollution. One of the crucial issues is the magnitude of the gain in life expectancy related to these premature deaths. Although no definitive answer exists, a 10-year gain seems to be supported by three types of evidence: medical, epidemiological and empirical from past practice.\textsuperscript{21–24}

Depending on whether the mortality effects are acute or chronic, there are two possible ways to deal with the time that elapses between a reduction in air pollution exposure due to the implementation of a regulation and the achievement of full health benefits.

In the ‘steady-state’ approach, the mortality effects corresponding to two different levels of air pollution are assessed and the number of premature deaths attributed to a change in air pollution exposure is computed as the difference between the numbers of premature

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|}
\hline
City & UB SO\textsubscript{2} [\mu g m\textsuperscript{-3}] & SD of UB SO\textsubscript{2} & Mean SO\textsubscript{2} & SD of \textsubscript{SO2} & Number of cases \& 95 CI– & 95 CI+ \\
\hline
Athens (Greece) & 38.97 & 26.96 & 507 & 177 & 842 \\
Barcelona (Spain) & 5.23 & 5.94 & 35 & 12 & 58 \\
Bilbao (Spain) & 17.46 & 7.19 & 14 & 5 & 24 \\
Bordeaux (France) & 7.22 & 5.06 & 18 & 6 & 29 \\
Brussels (Belgium) & 10.04 & 8.73 & 54 & 19 & 90 \\
Budapest (Hungary) & 29.07 & 19.56 & 390 & 136 & 647 \\
Dublin (Ireland) & 19.56 & 11.07 & 37 & 13 & 61 \\
Le Havre (France) & 23.38 & 28.26 & 23 & 8 & 38 \\
Lille (France) & 13.86 & 14.75 & 66 & 23 & 108 \\
Ljubljana (Slovenia) & 8.19 & 6.32 & 31 & 11 & 52 \\
London (UK) & 18.72 & 23.71 & 240 & 84 & 396 \\
Lyon (France) & 11.63 & 14.75 & 62 & 22 & 103 \\
Marseille (France) & 13.48 & 9.08 & 66 & 23 & 108 \\
Paris (France) & 12.16 & 10.88 & 314 & 110 & 519 \\
Rome (Italy) & 9.76 & 7.81 & 115 & 40 & 191 \\
Rouen (France) & 17.21 & 15.76 & 46 & 16 & 76 \\
Stockholm (Sweden) & 4.31 & 3.28 & 20 & 7 & 33 \\
Strasbourg (France) & 11.48 & 9.56 & 19 & 7 & 31 \\
Toulouse (France) & 21.67 & 15.85 & 35 & 12 & 58 \\
Vienna (Austria) & 8.92 & 11.70 & 90 & 31 & 148 \\
Total & – & – & 2212 & 772 & 3663 \\
\hline
\end{tabular}
\caption{UB SO\textsubscript{2} mean and standard deviation (SD) concentration and number of attributable premature deaths for the 20 EU cities (upper and lower 95% CI bounds).}
\end{table}
deaths resulting from the respective steady states. This clear, simple and informative approach is accurate for acute (or ST) mortality effects, and provides an idea of the magnitude of the public health problem for chronic (or LT) health effects.

In the ‘marginal (benefit)’ approach, the impact of a reduction in today’s air pollution exposure on the future flow of mortality effects is estimated. Reducing air pollution exposure via the implementation of a regulation in a given year does not produce all its chronic (or LT) effects in the same year because these effects are cumulative.25–28 This approach is appropriate for cost–benefit analysis where chronic mortality effects are involved: the flow of discounted future benefits can be properly compared with the costs of the policy that generates these benefits.

Although the two approaches are similar for acute (ST) mortality effects, they differ for chronic (LT) mortality effects due to the latency period before the achievement of full mortality benefits and the additional impact of discounting future monetary benefits. In this paper, we consider mortality effects as ST effects only because the health data analysis relies on time-series studies and not on cohort studies. Because it takes a conservative standpoint, the economic evaluation thus constitutes a lower bound of the mortality effects of the regulation.

Economic values chosen

The valuation of mortality effects follows the standard valuation procedure adopted in ExternE,29 New-Ext30 or CAFE,31 which consists in using monetary values derived from stated preferences’ surveys, hence relying on preference-derived rather than market-derived values. However, the choice of a proper economic value is crucial because the gain in life expectancy related to a prevented premature death differs according to whether it concerns those affected by chronic or by acute effects (see previous text). Given that we consider ST effects only, the gain in life expectancy associated with each of the premature deaths is assumed to be ‘around 1 year’,21 so a value of a life year (VOLY) was chosen here instead of a value of a statistical life.

Because the regulation effects are assessed in European cities, we relied on European studies when selecting the VOLY. To allow for the uncertainty pertaining in the economic valuation, we use a low, a central and a high estimate of a VOLY. First, for the low estimate, we take the recent results from the New Energy Externalities Developments for Sustainability (NEEDS) program11 (based on a 3-month life expectancy gain with protesters and outliers deleted) conducted in 10 European countries: EUR

<table>
<thead>
<tr>
<th>Cities</th>
<th>VOLY Estimate (EUR/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilbao</td>
<td>86 600</td>
</tr>
<tr>
<td>Athens</td>
<td>15.3 million</td>
</tr>
<tr>
<td>Athens</td>
<td>191.6 million (95% CI: 143.9 million–217.2 million)</td>
</tr>
<tr>
<td>Bilbao</td>
<td>43.9 million (95% CI: 15.3 million–72.9 million)</td>
</tr>
</tbody>
</table>

We perform a sensitivity analysis specific to the economic valuation by applying the low (EUR40 000) and high (EUR133 200) estimates of the VOLY to the number of premature deaths provided by the epidemiological computations. Results are presented in table 2 and represent a range of monetary benefits (low and high) for the number of premature deaths as well as for the related upper and lower 95% CI bounds.

Uncertainty analysis

Uncertainty analysis simultaneously accounts for uncertainties concerning epidemiology and economic valuation through an integrated approach. The results of the HIA and the economic values are treated as random variables with specified distributions of probability. Monte Carlo simulations are used to propagate the

Results on HIA

Inference by eye36 did not provide evidence of changes in the slope of the SO2–mortality dose–response curve after implementation of the different legislations: 0.62 (95% CI: 0.3–0.95) before 1994, 0.71 (95% CI: 0.01–1.4) between 1994 and 1996, 0.64 (95% CI: 0.09–1.19) between 1996 and 2000 and 1.16 (95% CI: 0.67 to 3.02) after 2000. This is not altogether unexpected because it is consistent with a linear dose–response curve down to very low concentrations. Over the study period, a decrease of 10 μg m−3 in UB SO2 levels was associated with a (pooled) decrease in daily all-cause mortality of 0.53% (95% CI: 0.18–0.83). These findings were broadly comparable with results from the APHEA multi-city study in Europe: Katsouyanni et al.37 found that an increase of 50 μg m−3 in SO2 was associated with an approximate increase of 3% for all-cause mortality.

Applying the two-stage approach to city-specific mortality incidence and SO2 level increases from pre- to post-intervention period, the HIA analysis of the mortality data suggests an overall 2212 (95% CI: 772–3663) premature deaths avoided per year associated with decreases in SO2 for 20 cities from year 2000 onwards (after third implementation stage) compared with the pre-1993 period (see column labelled ‘Attributable premature deaths’ in table 1 for results by city with the corresponding 95% CI). The lowest number of postponed deaths attributable to the regulation is obtained in Bilbao (14) and the highest in Athens (507).

Mortality benefits

Results and sensitivity analysis

Based on the number of premature deaths computed in table 1 and the central estimate associated with a premature death avoided (EUR86 600), the annual economic benefit related to the implementation of the EC regulations on SO2 amounts to EUR191.6 million (95% CI: EUR66.9 million–EUR317.2 million). The detailed results as well as the upper and lower 95% CI bounds for each city are given in table 2. Bilbao obtains the lowest annual economic benefits, with EUR1.2 million (95% CI: EUR0.4 million–EUR2.1 million), and Athens obtains the highest, with EUR43.9 million (95% CI: EUR15.3 million–EUR72.9 million).

We perform a sensitivity analysis specific to the economic valuation by applying the low (EUR40 000) and high (EUR133 200) estimates of the VOLY to the number of premature deaths provided by the epidemiological computations. Results are presented in table 2 and represent a range of monetary benefits (low and high) for the number of premature deaths as well as for the related upper and lower 95% CI bounds.
uncertainty in the numbers of premature deaths and the Voly, by
drawing random samples from the distributions. Each draw
generates an estimate of the annual monetary benefits, and a
sufficient number of draws makes it possible to characterize the
distribution of these monetary benefits. 38

A normal distribution is used to characterize the spread of the
mortality data, defined in terms of its mean and standard deviation.
This choice relies on the assumptions and data obtained by the HIA.

A triangular distribution is used for the Voly, defined in terms of a
modal central value, a maximum and a minimum. The triangular
distribution is typically used when knowledge of the variable is more
subjective than objective.

Once these probability distributions are defined, the model is run
using 10,000 Monte Carlo samples and provides probabilized

---

**Table 2** Annual monetary benefits for the 20 EU from 2000 onwards compared with the pre-1993 period (central, low and high estimates of the number of premature deaths and of the upper and lower 95% CI bounds)

<table>
<thead>
<tr>
<th>City</th>
<th>Monetary valuation (million €2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central estimate (VOLy = €86,600)</td>
</tr>
<tr>
<td></td>
<td>Benefits</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Athens</td>
<td>43.9</td>
</tr>
<tr>
<td>Barcelona</td>
<td>3.0</td>
</tr>
<tr>
<td>Bilbao</td>
<td>1.2</td>
</tr>
<tr>
<td>Bordeaux</td>
<td>1.6</td>
</tr>
<tr>
<td>Brussels</td>
<td>4.7</td>
</tr>
<tr>
<td>Budapest</td>
<td>33.8</td>
</tr>
<tr>
<td>Dublin</td>
<td>3.2</td>
</tr>
<tr>
<td>Le Havre</td>
<td>2.0</td>
</tr>
<tr>
<td>Lille</td>
<td>8.3</td>
</tr>
<tr>
<td>Ljubljana</td>
<td>2.7</td>
</tr>
<tr>
<td>London</td>
<td>20.8</td>
</tr>
<tr>
<td>Lyon</td>
<td>5.4</td>
</tr>
<tr>
<td>Marseille</td>
<td>5.7</td>
</tr>
<tr>
<td>Paris</td>
<td>27.2</td>
</tr>
<tr>
<td>Rome</td>
<td>10.0</td>
</tr>
<tr>
<td>Rouen</td>
<td>4.0</td>
</tr>
<tr>
<td>Stockholm</td>
<td>1.7</td>
</tr>
<tr>
<td>Strasbourg</td>
<td>1.6</td>
</tr>
<tr>
<td>Toulouse</td>
<td>3.0</td>
</tr>
<tr>
<td>Vienna</td>
<td>7.8</td>
</tr>
<tr>
<td>Total</td>
<td>191.6</td>
</tr>
</tbody>
</table>
distributions of the product of the annual number of postponed deaths and the VOLY, representing the annual mortality benefits. Figure 2 shows the distribution of the annual mortality benefits for the 20 EU cities that implemented the third implementation stage. The mean is €191.44 million, and the empirical 95% CI is €57.5 million–€363.6 million. This range is slightly wider than the range obtained previously because it accounts jointly for epidemiological and economic uncertainties.

Discussion

Our findings underline the health and monetary benefits obtained from drafting and implementing effective EU policies on air pollution, and by ensuring compliance with them over time. They show a marked and sustained reduction in ambient SO\textsubscript{2} levels over time in the 20 cities. Some of this decrease is attributable to the implementation of Council Directive 93/12/EEC and its amended version, and we estimate that some 2200 premature deaths were prevented annually, valued at €192 million.

We should bear in mind that SO\textsubscript{2} emissions have long been acknowledged to also generate direct monetary effects on morbidity\textsuperscript{39} and crops,\textsuperscript{40,41} as well as more intangible effects on the environment\textsuperscript{42,43} that were not assessed in our study. Chestnut and Mills\textsuperscript{12} when assessing the US Acid Rain Program benefits, account for effects on ST and LT human health benefits as well as visibility, natural resources and deposition on materials. This paper thus only partially evaluates the full economic benefits of the regulation, as it limits itself to ST mortality effects.

Moreover, although the regulation on SO\textsubscript{2} has two potential effects on mortality, ST and LT, we take a conservative standpoint, restricting mortality effects to ST effects and consequently valuing them with a VOLY instead of a value of a statistical life. The economic evaluation thus constitutes a lower bound of the mortality gains of the regulation.

Finally, we should acknowledge that the benefits of SO\textsubscript{2} reduction may also have arisen from reductions in other pollutants. SO\textsubscript{2} was not the only pollutant to decrease over the period studied, black smoke, for instance, also decreases, and we cannot distinguish the separate effects of the various pollutants. Thus, care should be taken in future work not to double count by repeating the analysis on other pollutants and totalling the results. Moreover, the concentration–response functions used to assess the mortality impact are derived from observational studies that only provide evidence for associations, and causality cannot be inferred because other (non-pollution) factors cannot be ruled out.

Acknowledgements

The huge amount of work behind the Aphekom project is the fruit of generous and constructive input from all the members of the Aphekom network. The Aphekom project was co-funded by the European Commission’s Programme on Community Action in the Field of Public Health (2003–8) under Grant Agreement No. 2007105 and by the many national and local institutions that dedicated resources to the fulfilment of this project. We wish to mention our thanks and appreciation of all their contributions. The authors thank J.-P. Lacharme, A. Lefranc, M. Sweetko, J.-M. Thiolet and two anonymous reviewers for helpful suggestions on the manuscript.

Funding

This work was supported by the European Commission’s Programme on Community Action in the Field of Public Health (2003–8) [2007105].

Conflicts of interest: None declared.

Keypoints

- We quantify the monetary benefits resulting from reductions in mortality following the implementation of the European regulation to reduce the sulphur content in liquid fuels.
- We find a marked and sustained reduction in ambient SO\textsubscript{2} levels over time for 20 European cities, and we estimate that some 2200 premature deaths were prevented annually, valued at €192 million.
- We perform both sensitivity and uncertainty analyses and obtain a slightly wider range for the latter, as it jointly accounts for epidemiological and economic uncertainties.
• Our findings underline the health and monetary benefits obtained from drafting and implementing effective EU policies on air pollution, and by ensuring compliance with them over time.
• By assessing the effectiveness of past regulations in terms of both health impacts and avoided health costs, we provide useful input to future regulations.

References


40 Eyres NJ, Oezdemiroglu E, Pearce DW, Steele P. Fuel and location effects on the fuel and location effects on the value for health benefits in the UK. Am Econ Rev 1997;87:328–39.