OECD Environment Working Papers No. 124

The Rising Cost of Ambient
Air Pollution thus far
in the 21st Century: Results
from the BRIICS and the
OECD Countries

**Rana Roy,
Nils Axel Braathen**

<https://dx.doi.org/10.1787/d1b2b844-en>

ENVIRONMENT DIRECTORATE

**THE RISING COST OF AMBIENT AIR POLLUTION THUS FAR IN THE 21ST CENTURY:
RESULTS FROM THE BRIICS AND THE OECD COUNTRIES - ENVIRONMENT WORKING
PAPER No. 124**

Rana Roy, Nils Axel Braathen

OECD Working Papers should not be reported as representing the official views of the OECD or of its member countries. The opinions expressed and arguments employed are those of the authors.

Authorised for publication by Simon Upton, Director.

JEL Classification: Q53, Q51, D61.

Keywords: Air pollution, Mortality, Value of Statistical Life, Cost-Benefit Analysis.

OECD Environment Working Papers are available at www.oecd.org/environment/workingpapers.htm

JT03417335

Complete document available on OLIS in its original format

This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

OECD ENVIRONMENT WORKING PAPERS

OECD Working Papers should not be reported as representing the official views of the OECD or of its member countries. The opinions expressed and arguments employed are those of the author(s).

Working Papers describe preliminary results or research in progress by the author(s) and are published to stimulate discussion on a broad range of issues on which the OECD works.

This series is designed to make available to a wider readership selected studies on environmental issues prepared for use within the OECD. Authorship is usually collective, but principal author(s) are named. The papers are generally available only in their original language – English or French – with a summary in the other language.

Comments on Working Papers are welcomed, and may be sent to:
OECD Environment Directorate
2 rue André-Pascal, 75775 Paris Cedex 16, France
or by email: env.contact@oecd.org

OECD Environment Working Papers are published on
www.oecd.org/environment/workingpapers.htm

Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

© OECD (2017)

You can copy, download or print OECD content for your own use, and you can include excerpts from OECD publications, databases and multimedia products in your own documents, presentations, blogs, websites and teaching materials, provided that suitable acknowledgment of OECD as source and copyright owner is given.

All requests for commercial use and translation rights should be submitted to rights@oecd.org.

FOREWORD

The 2014 OECD publication *The Cost of Air Pollution: Health Impacts of Road Transport* presented evidence of air pollution costs in OECD countries, China and India in 2005 and 2010 being much larger than any previous estimate. The costs of air pollution were computed by multiplying estimates of mortalities caused by outdoor air pollution from the 2010 Global Burden of Disease (GBD) Study with estimated country-specific values of statistical lives, based on the 2012 OECD meta-analysis, *Mortality Risk Valuation in Environment, Health and Transport Policies*.

The present paper, written by Dr. Rana Roy in co-operation with Nils Axel Braathen¹ of the OECD Secretariat, updates the mortality and social cost estimates to 2015 and enlarges the geographical coverage compared to *The Cost of Air Pollution: Health Impacts of Road Transport* to include all the BRIICS countries.

1 . The authors thank Miguel Cardenas Rodrigues for helpful comments.

ABSTRACT

This paper presents updated results for the cost of ambient air pollution in 41 countries: the 6 major emerging economies known as the BRIICS – Brazil, Russia, India, Indonesia, China and South Africa – and the 35 member-countries of the OECD. It draws on the epidemiological evidence base assembled in the Global Burden of Disease Study 2015, in order to detail results for mortalities from ambient air pollution (AAP) – ambient particulate matter pollution (APMP) and ambient ozone pollution (AOP) – in each of these 41 countries, at successive five-year intervals from 2000 to 2015. Mortalities from AAP, from both APMP and AOP, increased over the fifteen-year period from 2000 to 2015, both in the BRIICS taken together and in the OECD countries taken together. So, too, did the economic cost of these mortalities. The burden of ambient air pollution in the 41 countries under study stood at a toll of around 3.2 million deaths and at a cost of around USD 5.1 trillion in 2015.

Keywords: Air pollution, Value of Statistical Life, Cost-Benefit Analysis.

JEL Classification: Q53, Q51, D61.

RÉSUMÉ

Ce document présente des données actualisées sur le coût de la pollution de l'air ambiant dans 41 pays : les six grandes économies émergentes désignées par le sigle BRIICS – Brésil, Russie, Inde, Indonésie, Chine et Afrique du Sud – et les 35 pays membres de l'OCDE. À partir des données épidémiologiques réunies dans le cadre de l'étude 2015 sur la charge mondiale de morbidité, il calcule de façon détaillée la mortalité imputable à la pollution de l'air ambiant – par les particules et par l'ozone – dans chacun de ces 41 pays à intervalles de cinq ans de 2000 à 2015. En l'occurrence, le nombre de décès attribuables à cette pollution a progressé en quinze ans, aussi bien dans le groupe des BRIICS que dans celui des pays de l'OCDE. Il en va de même pour le coût économique de cette mortalité. Dans les 41 pays étudiés, la pollution de l'air ambiant a provoqué en 2015 quelque 3.2 millions de décès, pour un coût d'environ 5 100 milliards USD.

Mots clés : Pollution de l'air, Valeur d'une vie statistique, Analyse coût-avantages.

Classification JEL : Q53, Q51, D61.

TABLE OF CONTENTS

FOREWORD.....	3
ABSTRACT	4
RÉSUMÉ.....	4
ABBREVIATIONS	6
1. Introduction	7
2. Calculating mortalities: procedures, objections and rejoinders	8
3. Mortalities from ambient air pollution	10
4. Calculating the cost of mortalities: the Value of Statistical Life	14
5. The cost of mortalities from ambient air pollution	20
6. Causes, conclusions and policy implications.....	25
REFERENCES	28

Tables

Table 1.	Premature deaths from APMP are rising	11
Table 2.	Premature deaths from AOP are on a fast rising trend	11
Table 3.	Sum of premature deaths from APMP and AOP	12
Table 4.	Premature deaths from APMP per 1 million inhabitants	12
Table 5.	Premature deaths by country from APMP per 1 million inhabitants.....	13
Table 6.	VSL values for BRIICS and OECD countries.....	18
Table 7.	Estimated share of mortality costs saved as a percentage of total benefits in CAAA CBA ..	21
Table 8.	Cost of premature deaths from APMP in the BRIICS and OECD countries	22
Table 9.	Cost of premature deaths from APMP + AOP in the BRIICS and OECD countries	24

Figures

Figure 1.	Mortalities from ambient PM pollution per 1 million inhabitants.....	14
Figure 2.	Cross-country variations in VSL values in 2015, measured in current USD ₂₀₁₅	19
Figure 3.	Per cent changes in VSL values over time measured in constant USD ₂₀₁₀	20
Figure 4.	Cross-country variations in the costs of ambient PM mortalities compared to GDP	23
Figure 5.	Changes in the costs of ambient PM mortalities compared to GDP.....	23
Figure 6.	The costs of ambient outdoor air pollution mortalities compared to GDP	25

ABBREVIATIONS

AAP	Ambient air pollution
AOP	Ambient ozone pollution
APMP	Ambient particular matter pollution
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
BRIICS	Brazil, Russia, India, Indonesia, China, South Africa
EEA	European Environment Agency
EC	European Commission
EU	European Union
GBD	Global Burden of Disease
GDP	Gross domestic product
HAP	Household air pollution
IHME	Institute for Health Metrics and Evaluation
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
PM	Particulate matter
PPP	Purchasing power parity
PV _b	Present value of benefits
PV _c	Present value of costs
USD	United States dollar
US EPA	United States Environmental Protection Agency
VSL	Value of a statistical life
WHO	World Health Organization
WTP	Willingness-to-pay

THE RISING COST OF AMBIENT AIR POLLUTION THUS FAR IN THE 21ST CENTURY: RESULTS FOR THE BRIICS AND THE OECD COUNTRIES

1. Introduction

This paper presents new and updated results for the cost of ambient air pollution in 41 countries: the six major emerging economies known as the BRIICS – Brazil, Russia, India, Indonesia, China and South Africa – and the 35 member-countries of the OECD.

It builds on the epidemiological evidence assembled in the Global Burden of Disease Study 2015 (hereafter, GBD 2015), published in October 2016 (GBD 2015 Global Risk Factors Collaborators, 2016, and IHME, 2016), and on the economic analyses developed by the authors and in a series of recent studies from 2012 onward (OECD, 2012; OECD, 2014; WHO Regional Office for Europe, OECD, 2015; OECD, 2016a; Roy, 2016).

Air pollution is, in the words of the World Health Organization, “the world’s largest single environmental health risk” (WHO, 2014a). It is a major risk factor in several diseases leading to disabilities and deaths, including cancers, lower respiratory infections, and cardiovascular and cerebrovascular diseases – in short, heart disease and strokes – with the two last-named accounting for the greater share of the deaths attributable to air pollution (WHO, 2014b).

The deaths and disabilities resulting from air pollution carry a quantifiable *economic cost to society*.² As documented in recent reports (OECD, 2014; WHO Regional Office for Europe, OECD, 2015): world-wide, air pollution claims an annual toll of *several million* premature deaths and imposes thereby an annual cost of *several trillion* US dollars.

The epidemiological scope of the present study has a specific and deliberate focus – as does its geographic and temporal scope. It is concerned with *ambient particulate matter pollution* (APMP), from fine particulate matter particles (PM_{2.5}), and *ambient ozone pollution* (AOP), from ground-level ozone (O₃) – the two types of *ambient air pollution* (AAP) that are an attendant feature of urbanised, industrialised and motorised societies. It therefore leaves aside the issue of household air pollution from solid fuels (HAP), which was once the main source of world-wide deaths from air pollution but is now a lesser problem in much of the world and with no more than a marginal presence in the most advanced economies.

Relatedly, its geographic scope is intended to cover the already advanced economies of the OECD area and the rapidly advancing economies of the BRIICS. Taken together, these 41 countries account for around 70% of the estimated global total of 4.5 million deaths from AAP. Arguably, their trajectory also represents a potential path for the remainder of the world.

Finally, the temporal scope of this study is restricted to the 21st century. This is not simply because the limitation of the space imposes a limitation of the scope of what can be reported; it is also because it is the period since year 2000 that has witnessed the broad-based industrialisation of the BRIICS as a whole and therewith a new global division of labour, which enables us to compare like for like at given intervals within this period.

2. Unless otherwise specified, all references to “costs” in this paper refer exclusively to the “economic cost to society”. In the relevant literature, this measure is also, and variously, called “social cost” or “welfare cost” or “welfare loss” or “loss in social welfare”: all these terms refers to the same thing. To keep it simple, we use the term “economic cost” – or yet more simply, “cost”. As has been discussed elsewhere (summarily in WHO Regional Office for Europe, OECD, 2015, and more comprehensively in OECD, 2016a), air pollution also has a quantifiable impact on GDP and other key macro-economic indicators: these macro-economic impacts are not addressed in the present paper.

In what follows, Section 2 sets out some key procedures used in calculating mortalities from air pollution, some often-raised objections and our rejoinders to these objections. Section 3 draws on the evidence-base in GBD 2015 to detail the results for mortalities from AAP – more specifically: APMP; AOP; and APMP + AOP – in each of these 41 countries, and at successive five-year intervals from year 2000 onward: 2000, 2005, 2010 and 2015. Section 4 explains the basis of our calculation of the cost of mortalities, based on recent OECD work on the value of statistical life (VSL), but differentiating more accurately between the advanced economies of the OECD and the emerging economies of the BRIICS. Section 5 presents the results for the cost of mortalities in each country. Section 6 notes some likely causal explanations of the results and draws out some key conclusions and implications for policy.

There is much to be noted in the detail of the pattern but the pattern itself is clear. Globally, the death toll from AAP – from both APMP and AOP as well as from the sum of the two – has increased in each of the selected successive intervals from 2000 onward. The OECD area experienced a steady if modest fall in the period to 2010 but a sharp rise thereafter, with the resulting death toll in 2015 being higher than in 2000. The BRIICS experienced a more or less continuous increase over this entire period. The sum of the BRIICS and the OECD countries – in other words, the enlarged centre of the new world economy – has held a constant share of the rising global death toll. And the economic cost of this toll has increased in each of these intervals, not only and obviously in the BRIICS but also in the OECD countries taken together: here, the increase in VSL values has outpaced any modest reduction in the number of deaths in those intervals in which any such reduction was achieved. In view of all this, it ought not to be controversial to suggest that something more than business-as-usual is required to address air pollution in the OECD area as well as in the BRIICS and the rest of the world.

2. Calculating mortalities: procedures, objections and rejoinders

It would be useful to begin by making a few preliminary, almost elementary, points on some of the key procedures used in calculating mortalities – and by answering some of the objections that are often raised in the larger public debate and commentary on the subject.

The first point to be made – and it does need to be made in a world where decision-makers still ask the question “but nobody actually dies from air pollution, do they?” – is to specify what exactly is being counted here as a relevant death.

Of course, individuals do not literally die from air pollution. But neither do they literally die from smoking. Epidemiology distinguishes between the *diseases* that are diagnosed as the cause of individual deaths – for example, heart disease – and the *risk factors* that contribute to such diseases – for example, air pollution of a specific type or tobacco smoking. With reliable data on a given population’s exposure to the various risk-factors, and reliable data on exposure-response functions in the case of each risk factor, it then becomes possible to “distribute” the total of deaths from a particular disease amongst these various risk factors – that is, to attribute a given percentage of these deaths to each of the relevant risk factors. These “attributed” deaths among the population from the various risk factors as defined in epidemiology should not be confused with the diagnosed deaths of particular individuals from the various disease causes as defined in clinical practice.

But it is important to stress that this distinction does not mean that air pollution is merely a contributory factor, one among several contributory factors, in the deaths attributed to it. Rather, it is a contributory factor to a death toll far larger than the millions tabled below – the numbers below being the best estimates attributable to this set of risk factors. It follows that the technical distinction between clinically diagnosed and epidemiologically attributed deaths does not affect the absolute and relative weight of air pollution in the global death toll.

The second point concerns the need to acknowledge uncertainty. The GBD database used in this paper provides a range as well as a mid-point estimate for the deaths attributed to each risk factor. For example, in the case of the main set of numbers used here, namely deaths from APMP, GBD 2015 provides in its estimate of the global death toll a range that stretches to around 15% on either side of the mid-point estimate (GBD 2015 Global Risk Factors Collaborators, 2016, Table 4). In all cases, the numbers presented below are the mid-point estimate only and need to be introduced here as such. And although it would be too burdensome to repeat this same caveat in introducing each set of numbers below, the reader is asked to bear in mind that the caveat itself applies to all that follows.

Moreover, there is a specific uncertainty in estimating the joint effect of the various types of air pollution. The whole is less than the sum of its parts since the effects of these individual risk factors are not fully independent of each other. As is argued in the GBD studies and elsewhere (including WHO 2014b; WHO Regional Office for Europe, OECD, 2015), the requisite adjustment is imprecise and estimates for joint effects need to be interpreted with caution. In what follows, there are no estimates for joint effects: rather, tabled below are the mid-point estimates for APMP, for AOP, and APMP + AOP, with the last explicitly identified as such.

Nonetheless, and notwithstanding the importance of uncertainty, at any given moment, every researcher is obliged to use the best estimates available. And the estimates used here are the best available.

The third preliminary point – and it is a point of importance, both objectively and as a motive informing this paper – concerns the epidemiology of air pollution rather than epidemiology *tout court*. As highlighted previously in OECD, 2014, and in WHO Regional Office for Europe and OECD, 2015, the estimated death toll from air pollution was revised upward very substantially in the Global Burden of Disease Study for 2010, published in December 2012 (see Lim et al., 2012 and IHME, 2013) – and available for use in OECD, 2014, and in WHO Regional Office for Europe, OECD, 2015. These estimates were modified in GBD 2013, published in September 2015, and again in GBD 2015, published in October 2016 – the last-named being the database for the present study. In *each* of these iterations, the estimates of the global death toll from air pollution remain well above those prevalent prior to GBD 2010.

Now the point to be made is that this substantial upward revision presented in the recent past is not an indicator of any supposed volatility or unreliability in epidemiological estimates but rather the result of a much-to-be-welcomed progress of knowledge in this field, in the form of several recent technological and methodological advances. These include:

- New, more advanced monitoring methods, including remote-sensing technology, to estimate emissions and ambient concentrations of pollutants (Brauer et al., 2012; Evans et al., 2012; Amann, Klimont and Wagner, 2013);
- A much-improved understanding of the relation between emissions/concentrations of pollutants and the exposure of populations thereto, and of the relation of population exposure and the health impacts thereof, resulting in the use of new integrated exposure-response functions, undergoing continuing refinement (WHO Regional Office for Europe, 2013a, b);
- A new understanding of the link between air pollution and lung cancer (Beelen et al., 2008; Silverman et al., 2012; Fajersztajn et al., 2013; Raaschau-Nielsen et al., 2013) – paving the way for the recent decisions by the International Agency for Research on Cancer (IARC) to classify diesel as a definite carcinogenic (IARC, 2012; Benbrahim-Tallaa et al., 2012) and outdoor air pollution as “a leading cause of cancer deaths” (IARC, 2013) – and a fuller understanding of the cardiovascular, cerebrovascular and respiratory health impacts of air pollution (see Shah et al., 2013; Wellenius et al., 2012; and Laumbach and Kipen, 2012, respectively);

- A more comprehensive and consistent methodology for assembling and analysing the epidemiological evidence, in order to establish the relative share of each relevant risk factor in deaths and disabilities for each relevant disease (see Lim et al., 2012).

It follows that further progress in knowledge may well result in further revisions to the estimates quoted below. Nonetheless, and as before, it remains the case that every researcher is obliged to use the best estimates available at any given moment.

A final and related point to note is that there is reason to suppose that future revisions to estimates of the toll from air pollution – and from APMP in particular – are likely to be in an upward rather than downward direction. Specifically, there are two reasons to suppose this.

The first is the likelihood of an expanded definition of the relevant risk factor or cluster of risk factors. Today, the effects of APMP are measured through the effects of PM_{2.5}. But it is increasingly accepted that the effects of the precursor gases to primary particulate matter and its secondary pollutants are not reducible to the PM_{2.5} effect alone (EEA, 2013; and European Commission, 2013). In particular, there is now an increasing focus on the independent, and independently harmful, impact of exposure to NO₂ (WHO, 2013b, Holland, 2014).

The second is the likely expansion of the list of diseases against which the relevant risk is paired. In the GBD studies to date, the deaths attributable to the air pollution risk factors have been restricted to four main disease groupings: cancers, cardiovascular, cerebrovascular and respiratory diseases. But there is evidence to suggest that air pollution may also play a part in a range of other diseases which are not paired to it in the current GBD count, including for example neo-natal and neuropsychological impairments (Guxens and Sunyer, 2012).

The likelihood of such a future upward revision to the toll from air pollution does not serve to diminish the present urgency of the issue but rather the reverse.

3. Mortalities from ambient air pollution

The 21st century has witnessed a more or less uninterrupted increase in mortalities from both APMP and AOP centred in the BRIICS and in the OECD area. As noted below, this is in part a function of factors such as population growth and economic development, though the relationships at work here are complex. But first, the aggregate numbers need to be tabled.

The global death toll from APMP has increased in each selected successive interval from year 2000, climbing above 4.2 million deaths by 2015, or a cumulative increase of 12% (Table 1). The OECD countries as a whole did succeed in reducing their own total of deaths from APMP between 2000 and 2010: some things have gone *right* here and these need to be recalled in any discussion of prospects and policy implications. But this reduction in deaths was relatively modest – and more than offset by the increase registered in the OECD countries subsequently, in the five years up to 2015. The story of the BRIICS is clearer still: a more or less uninterrupted increase in the total of deaths, albeit with a plateauing out in the five-year period from 2005 to 2010. The share of the rising global death toll registered by the BRIICS and the OECD countries, taken together, has been remarkably constant (Table1, last row).

Table 1. Premature deaths from APMP are rising

	2000	2005	2010	2015
Premature deaths from APMP				
Globally	3 793 975	3 934 335	3 944 727	4 241 096
Of which:				
BRIICS	2 195 951	2 339 580	2 331 686	2 491 163
<i>Share of global</i>	58%	59%	59%	59%
OECD	463 576	439 204	419 781	469 096
<i>Share of global</i>	12%	11%	11%	11%
BRIICS + OECD	2 659 527	2 778 784	2 751 468	2 960 258
<i>Share of global</i>	70%	71%	70%	70%

Source: Extracted from IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.

In the case of AOP, the pattern is not dis-similar but there are some important differences. The increase in the global death toll over the 15-year period to 2015, although starting from a much lower base, has been much more rapid than in the case of APMP: a cumulative increase of 28%. Moreover, as shown in Table 2, deaths from AOP have increased uninterruptedly, at each successive interval, everywhere – not only globally, and in the BRIICS taken together, but also in the OECD countries as a whole.

Table 2. Premature deaths from AOP are on a fast rising trend

	2000	2005	2010	2015
Premature deaths from AOP				
Globally	198 747	207 026	217 336	254 046
Of which:				
BRIICS	147 910	151 973	157 122	184 423
<i>Share of global</i>	74%	73%	72%	73%
OECD	26 576	27 969	29 021	31 692
<i>Share of global</i>	13%	14%	13%	12%
BRIICS + OECD	174 486	179 943	186 143	216 115
<i>Share of global</i>	88%	87%	86%	85%

Source: Extracted from IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.

Table 3 presents the simple sum of deaths from APMP and AOP and without attempting any adjustment for joint effects – globally, in the BRIICS and in the OECD countries. Thus, the first fifteen years of the 21st century have witnessed a cumulative increase of 13% in this sum of deaths at a global level. Over this period, the BRIICS taken together have registered an increase of 14%, the OECD countries taken together a more modest increase of 2%. The combined *share* of these two blocks in this global death toll has been remarkably constant, at 71% of the total, at *each* of the selected intervals from year 2000. As at 2015, the sum of deaths from APMP + AOP in these 41 countries, stood at around 3.2 million, out of a global total of around 4.5 million.

Table 3. Sum of premature deaths from APMP and AOP

	2000	2005	2010	2015
Premature deaths from APMP + AOP				
Globally	3 992 722	4 141 361	4 162 063	4 495 142
Of which:				
BRIICS	2 343 861	2 491 553	2 488 809	2 675 585
<i>Share of global</i>	59%	60%	60%	60%
OECD	490 152	467 173	448 680	500 788
<i>Share of global</i>	12%	11%	11%	11%
BRIICS + OECD	2 834 013	2 958 726	2 937 489	3 176 373
<i>Share of global</i>	71%	71%	71%	71%

Source: Extracted from IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.

There emerges a somewhat different picture of the change over time once the growth in population as well as the process of economic development is taken into account. Clearly, if “premature death” is defined in relation to the best global benchmark, population growth will tend to increase the sum of premature deaths until and unless the world has converged at that best benchmark. Moreover, as argued in greater length in OECD (2014), the natural course of economic development will tend to alter the distribution of risk factors in the sum of premature deaths. Industrialisation will tend to increase certain characteristic risk factors, such as air pollution, whilst reducing the characteristic risk factors of poverty, such as under-nutrition. And having completed their industrialisation, the advanced industrial economies should experience a reduction in these characteristic risk factors of development such as air pollution – whilst perhaps suffering an increase in the characteristic risk factors of affluence, such as obesity. In view of this, one would expect the worst results for mortalities from air pollution to be found in those countries experiencing rapid industrialisation as well as population growth, including especially the BRIICS. In this sense, these results are not necessarily a comment on these countries’ management of the problem of air pollution but rather a by-product of their stage of development relative to the rest of the world.

As shown in Table 4, deaths from APMP *per 1 million inhabitants* have registered a *reduction* over the fifteen-year period from 2000 – by 7% globally and by 8% in the OECD area though by less than 2% in the BRIICS. Population growth is indeed a key factor in the increase in the absolute number of premature deaths from air pollution. Moreover, and unsurprisingly, mortality rates from air pollution are indeed higher in the BRIICS than they are globally and twice as high as they are in the OECD countries taken together. Industrialisation is indeed a key factor in the relative weight of this particular risk factor.

Nonetheless, it is important to note that this progress in reducing mortality rates from air pollution appears now to have stalled everywhere. In the latest five-year period, from 2010 to 2015, deaths from APMP per 1 million inhabitants *increased* across the board: by 1% globally, by 2% in the BRIICS and by 9% in the OECD countries as a whole.

Table 4. Premature deaths from APMP per 1 million inhabitants

	2000	2005	2010	2015
Globally	619	603	569	577
BRIICS	757	765	727	744
OECD	401	367	338	367

Source: Extracted from IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.

Clearly, this increase in mortality *rates* cannot be attributed to population growth. Nor can the especially rapid increase in mortality rates in the OECD countries from 2010 to 2015 be attributed to any especially rapid economic growth in these particular countries over this particular period.

Drilling down to the data for the individual countries, one can see a greater complexity, with considerable inter-country variations in terms of both the level and the pace of change in mortality rates. Table 5 reports the results for each of these 41 countries.

Table 5. Premature deaths by country from APMP per 1 million inhabitants

	2000	2005	2010	2015
BRIICS:				
Brazil	280	249	217	252
China	818	873	819	805
India	814	783	777	832
Indonesia	304	314	296	305
Russia	1 075	1 098	965	955
South Africa	633	579	450	456
OECD:				
Australia	200	172	136	140
Austria	520	449	423	465
Belgium	586	518	485	494
Canada	231	222	188	197
Chile	278	283	305	329
Czech Republic	796	726	711	737
Denmark	482	406	378	376
Estonia	628	550	422	511
Finland	317	271	268	283
France	326	292	283	315
Germany	539	489	490	534
Greece	503	462	499	616
Hungary	992	930	928	869
Iceland	223	198	180	182
Ireland	336	260	223	243
Israel	289	257	238	265
Italy	462	420	422	564
Japan	333	379	399	479
Korea	284	276	281	361
Latvia	1 024	1 064	958	1 061
Luxembourg	440	385	331	309
Mexico	208	206	199	228
Netherlands	492	422	394	401
New Zealand	193	168	127	135
Norway	411	319	289	269
Poland	775	728	763	721
Portugal	422	385	339	355
Slovak Republic	791	753	713	647
Slovenia	496	466	429	503
Spain	352	320	274	291
Sweden	265	203	183	224
Switzerland	356	306	279	297
Turkey	437	348	303	339
United Kingdom	586	484	415	420
United States	375	338	269	275

Source: Extracted from IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.

Figure 1 tells the story graphically.

Figure 1. Mortalities from ambient PM pollution per 1 million inhabitants

Clearly, from the viewpoint of any given country – its responsible researchers, policy advisers and decision makers – its own-country results are of critical importance. From a wider viewpoint, however, it is important to restate that the varying detail of the pattern does not change the pattern itself: mortality rates have been rising across the board in the most recent period, with the main exceptions being amongst those already burdened with the very highest rates (China and Russia in the case of the BRIICS; Hungary, Poland and the Slovak Republic within the OECD area).

4. Calculating the cost of mortalities: the Value of Statistical Life

The basis of the present calculation of the cost of mortalities – the method used to translate the epidemiological data reported above into economic results – can be summarised as follows.³

Present-day economics possesses a standard method by which to measure the cost of mortalities at the level of society as a whole: the “value of statistical life” (VSL), as derived from aggregating individuals’ willingness-to-pay (WTP) to secure a marginal reduction in the risk of premature death.

The algebraic reasoning informing this method is elegant in its simplicity. Suppose that each individual has an expected utility function, EU , relating the utility of consumption over a given period, $U(y)$, and the risk of dying in that period, r , of the form:

3. For recent expositions on the subject, including its various complexities, see inter alia Biaisque (2012); Braathen (2012); Hunt and Ferguson (2010); Hunt (2011); OECD (2012); OECD (2014); WHO Regional Office for Europe and OECD (2015). The exposition here borrows heavily from previous expositions by one of the present co-authors in OECD (2014), WHO Regional Office for Europe, OECD (2015), and Roy (2016).

$$EU(y, r) = (1 - r) U(y).$$

The individual's WTP, to maintain the same expected utility in the event of a reduction in the level of risk from r to r' is the solution to the equation:

$$EU(y - WTP, r') = EU(y, r).$$

VSL is thus the marginal rate of substitution between these two valued items, consumption and the reduction in the risk of dying, such that:

$$VSL = \delta WTP / \delta r.$$

Now the simplest way to discover the relevant individuals' WTP is – of course – to ask them. A WTP survey is thus the starting point of the calculation. OECD, 2012, describes the basic process of deriving a VSL value from such a survey:

The survey finds an average WTP of USD 30 for a reduction in the annual risk of dying from air pollution from 3 in 100 000 to 2 in 100 000. This means that each individual is willing to pay USD 30 to have this 1 in 100 000 reduction in risk. In this example, for every 100 000 people, one death would be prevented with this risk reduction. Summing the individual WTP values of USD 30 over 100 000 people gives the VSL value – USD 3 million in this case. It is important to emphasise that the VSL is not the value of an identified person's life, but rather an aggregation of individual values for small changes in risk of death (OECD, 2012).

And this in turn yields a simple result permitting an assessment of the impact of a given problem and of proposals to mitigate it. The economic cost of the impact being studied becomes the VSL value multiplied by the number of premature deaths. The economic benefit of a mitigating action becomes the same VSL value multiplied by the number of lives saved.

Moreover, thanks to the multiyear research effort embodied in OECD (2012) – including its meta-analysis of VSLs starting with 1 095 values from 92 published studies – researchers and policy makers now possess a set of OECD-recommended values for average adult VSL. In units of 2005 United States dollars (USD), the recommended range for OECD countries is USD₂₀₁₅ 1.5 million – 4.5 million, the recommended base value in 2005 is USD₂₀₀₅ 3 million.

This in turn enables the computation of country-specific VSL values for countries both within and outside the OECD and for years beyond 2005 – and, with it, the opportunity for informed decision-making on major risk factors in a timely manner, without needing to conduct expensive, large-scale surveys in every location and on every occasion.

Now it may be objected that the use of *country-specific* VSL values necessarily reproduces the existing income inequalities between countries: the cost of 100 deaths in a relatively high-income country becomes higher than the cost of 100 deaths in a relatively lower-income country. But this is to misunderstand the context and purpose of the exercise.

As argued above, a VSL value is an aggregation of *individual* valuations: an aggregation of individuals' WTP, as communicated through WTP surveys, to secure a marginal reduction in the risk of premature death. But individuals are differentially endowed with the means with which to make such a trade-off. All societies have therefore sought to "socialise" these risks to a greater or lesser extent in the form of public goods: to share the burden of these risks at least partially through the collective treasury

rather than impose it exclusively on the individual's purse at the point of need. And it so happens that the level at which this socialisation of risks is executed today is, principally, the level of the nation-state.

The point here is not that the problem of air pollution in any given country is, in the nature of things, exclusively national: clearly, it is not. Rather, the point is that the burden of addressing the problem and of bearing the costs of any solution – that is, effecting the sacrifice of some value in consumption to secure the greater value of lives saved – is, for the present, principally the responsibility of national governments. Thus, the citizens of any given lower-income country are, in the main, obliged to execute their relevant trade-offs largely without reference to the resources of other and higher-income countries. It is this reality, rather than any normative judgement, that explains the choice of country-specific VSL values. To over-ride this reality by means of *assuming* a common VSL is, in effect, to demand a disproportionately high sacrifice of consumption on the part of the citizens of the lower-income countries.⁴

To recognise the present-day reality of the process of socialisation of risks does not in any way preclude envisaging (and indeed welcoming) a future reconfiguration of responsibilities that would permit the trade-off between consumption and risk reduction to be conducted at a supra-national level wherever it is appropriate – for example, on a Union-wide basis for the member-states of the European Union (see WHO Regional Office for Europe, OECD, 2015, Chapter 2.8, for a fuller discussion of the issue and a calculation of the costs of air pollution in EU member-states using a common VSL). But such explorations lie beyond the limits of the present exercise in updating the OECD estimate of the costs of air pollution.

There is, however, an important amendment to the formula used in previous OECD work that is appropriate for the purpose of the present exercise.

The OECD formula in its last published versions (see in particular OECD, 2014, and WHO Regional Office for Europe, OECD, 2015) includes these features *inter alia*:

- The OECD base value of USD 3 million in year 2005 is the starting point for the calculation of VSL values both for OECD countries and for other countries;
- The calculation is in purchasing power parity (PPP)-adjusted USD estimates of per-capita GDP in each country relative to the OECD average per capita GDP;
- The income elasticity beta applied is 0.8, being the mid-point of the best estimate of 0.7-0.9 established in OECD research;

4. The point is perhaps best made through a stylized example. Luxembourg and India are two of the most important centres of the world's steel industry. Luxembourg hosts the world's largest steel conglomerate; India is the world's third-largest steel producer and will soon become its second-largest. Suppose now that a risk-reducing process innovation were available for application both at ArcelorMittal Dordrecht in Luxembourg and at the Bokaro Steel Plant, Asia's largest steel plant, in the Indian state of Jharkhand, at an identical resource cost in USD. If the respective decision-makers were to apply an identical VSL value in both cases, this would entail an identical sacrifice of consumption in USD terms on the part of both Luxembourgish society and Indian society. But Luxembourg happens to be the richest member-state of the European Union and the second richest country in the world – whereas India, despite its rapid progress in recent times, remains poor (and Jharkhand remains one of the poorest states in the Indian Union). The relative sacrifice that would be required of the average Indian in this circumstance – the marginal utility of the consumption forgone – would thus be many multiples of that required of the average Luxembourgish.

- The income elasticity adjustment is applied not only to the 2005 level, but also to its growth in the post-2005 period.⁵

The result for any given country, C, for any given year, here 2015, is thus as follows:

$$\text{VSL } C_{2015} = \text{VSL OECD}_{2005} \times (Y C_{2005}/Y \text{ OECD}_{2005})^{\beta} \times (1 + \% \Delta P + \% \Delta Y)^{\beta}.$$

Now the assumption of an income-elasticity with a value of < 1 means this: as incomes rise, the willingness-to-pay for a marginal reduction in the risk of death from a given risk also rises but not quite in proportion to the rise in incomes. And this assumption is empirically well-grounded in the case of the advanced economies – as is the estimate of 0.8 (see OECD, 2012).

However, as has been argued in a number of recent papers (see in particular Hammitt and Robinson, 2011; and also Narain and Sall, 2016, and Roy, 2016), there are reasons to suppose that this assumption does not necessarily hold true for emerging economies.

Here, a step-change in life circumstances away from deep poverty alters the “willingness-to-pay” more sharply than does a gradual but modest rise in incomes in the already high-income countries. There is therefore a case for adopting the more common assumption in the development literature of an income elasticity of 1 for the non-OECD countries under study.

This means *inter alia* that the resulting VSL values and consequent cost estimates tabled for the BRIICS in this paper start from a lower base than would be the case under the assumption of an income elasticity of 0.8 – but also that these values and estimates will rise more rapidly over time, a feature that will show itself in *future* studies of the problem.

To facilitate comparisons over time, Table 6 reports the resulting VSL value measured in *constant* USD₂₀₁₀ – for each of the 41 countries under study and for each of the relevant years (2000, 2005, 2010 and 2015). The calculation in constant USD₂₀₁₀ begins with a recalculation of the 2005 OECD base value of USD₂₀₀₅ 3 million into a new base value – in this instance, a 2010 base value of USD₂₀₁₀ 3.368 million – and captures only the growth in real income and not the change in prices captured in the formula in Paragraph 50. But the algebraic operations required here are straight-forward and need not detain the present discussion. Moreover, since most of the results and commentary in what follows relates to the latest year, 2015, the final column in Table 6 also reports the 2015 VSL value of each of the 41 countries in *current* USD₂₀₁₅ – these being, thanks to price inflation, higher in each case than the 2015 value in constant USD₂₀₁₀ recorded in the penultimate column.

Clearly, there is a considerable divergence in VSL values among the 41 countries, reflecting the divergence in real per capita incomes. Nonetheless, this divergence should not be over-stated. As is seen most clearly in Figure 2: as at 2015, and apart from three outliers at one end (Ireland, Luxembourg and Norway) and only one at the other (India), across these countries, the spread of VSL values as measured in USD₂₀₁₅ is contained within a range from USD 1 million to USD 5 million.

5. See OECD (2014) and WHO Regional Office for Europe, OECD (2015) for a fuller discussion of the components of the OECD (2014) formula, including its use of PPP-adjusted estimates in USD, by-passing national currencies, and its treatment of inflation and real income growth. The discussion in the present text is limited to the change to the formula that is applied here: the differentiation in the income-elasticity, β .

Table 6. VSL values for BRIICS and OECD countriesFor 2000, 2005, 2010 and 2015 measured in constant USD₂₀₁₀ and for 2015 measured in current USD₂₀₁₅

	Constant USD ₂₀₁₀				Current USD ₂₀₁₅
	2000	2005	2010	2015	2015
OECD base value			3.368		
OECD average	3.117	3.317	3.368	3.523	3.770
BRIICS:					
Brazil	1.073	1.159	1.367	1.370	1.885
China	0.342	0.526	0.872	1.236	1.360
India	0.245	0.302	0.421	0.544	0.737
Indonesia	0.545	0.640	0.793	0.977	1.226
Russia	1.278	1.754	2.094	2.208	3.269
South Africa	0.898	1.015	1.119	1.170	1.501
OECD:					
Australia	3.459	3.777	3.919	4.101	4.452
Austria	3.543	3.725	3.863	3.928	4.236
Belgium	3.398	3.578	3.672	3.726	3.960
Canada	3.505	3.730	3.730	3.901	4.138
Chile	1.572	1.797	1.998	2.246	2.516
Czech Republic	2.161	2.527	2.723	2.884	3.032
Denmark	3.781	3.940	3.893	3.959	4.161
Estonia	1.666	2.247	2.242	2.598	2.783
Finland	3.243	3.553	3.612	3.546	3.783
France	3.338	3.489	3.516	3.586	3.725
Germany	3.465	3.538	3.745	3.956	4.141
Greece	2.510	2.891	2.824	2.439	2.447
Hungary	1.912	2.287	2.298	2.504	2.695
Iceland	3.252	3.664	3.619	3.938	4.417
Ireland	3.623	4.183	3.953	5.018	5.137
Israel	2.700	2.723	2.939	3.161	3.301
Italy	3.347	3.402	3.318	3.244	3.428
Japan	3.081	3.215	3.255	3.349	3.428
Korea	2.200	2.589	3.001	3.317	3.530
Latvia	1.290	1.851	1.908	2.307	2.406
Luxembourg	6.131	6.751	6.856	7.034	7.500
Mexico	1.622	1.660	1.683	1.777	2.022
Netherlands	3.816	3.937	4.079	4.152	4.429
New Zealand	2.721	3.011	3.060	3.258	3.434
Norway	4.806	5.123	5.093	5.173	5.496
Poland	1.617	1.833	2.210	2.495	2.622
Portugal	2.613	2.661	2.710	2.657	2.798
Slovak Republic	1.726	2.102	2.528	2.773	2.932
Slovenia	2.308	2.650	2.783	2.800	2.919
Spain	2.939	3.165	3.146	3.133	3.282
Sweden	3.422	3.743	3.866	4.066	4.158
Switzerland	4.228	4.368	4.564	4.614	4.528
Turkey	1.488	1.680	1.811	2.018	2.634
United Kingdom	3.206	3.519	3.434	3.622	3.923
United States	4.115	4.386	4.361	4.604	4.880

Note: All computations are based on a 2005 OECD base value of USD₂₀₀₅ 3 million, adjusted for differences in per capita GDP, and for changes in income over time, with an income elasticity of 1 for BRIICS and 0.8 for OECD countries.

Source: Primary data extracted from OECD (2016b), *OECD Stat* (<http://stats.oecd.org/>).

Figure 2. Cross-country variations in VSL values in 2015, measured in current USD₂₀₁₅

Importantly, there is also a *convergence* in values over time, as lower-income countries achieve a higher rate of productivity growth and therewith a higher rate of income growth – a convergence reinforced in recent years by the economic recession that commenced in 2008 and impacted many of the higher-income countries harder than many of the key emerging economies. As shown in Figure 3: perhaps the single-most striking feature of the change in VSL values over time is the pace of the increase in China – as a result of which China’s VSL value has risen from 11% of the OECD average in 2000 to 35% of the OECD average as at 2015.

Figure 3. Per cent changes in VSL values over time measured in constant USD₂₀₁₀

5. The cost of mortalities from ambient air pollution

It needs to be acknowledged that the economic cost to society of ambient air pollution is not reducible to the cost of mortalities alone. There is the cost of impacts on human health that fall short of mortality, that is, the cost of morbidities of greater or lesser severity (see in particular Hunt et al., 2016). There is the cost of impacts other than those on human health, for example, impacts on the built environment, on animal and plant health (with further consequential impacts on the productivity of agriculture and forest resources), and on larger ecological systems.

Nonetheless, there is good reason to suppose that the numbers tabled below capture the greater part of the relevant cost. Consider for example the recent comprehensive cost-benefit analysis (CBA) conducted by the United States Environmental Protection Agency of the Clean Air Act Amendments (CAAA) enacted in 1990 (see United States EPA, 2011).

US EPA (2011) provides a series of estimates of the “annual monetized benefits” of the CAAA – the benefits from the reduction in mortalities and morbidities as well as from the reduction in environmental impacts other than health – by target years and also cumulatively. The absolute USD estimates are not relevant here; what is relevant is the distribution of the economic benefits gained: that is to say, the distribution of the economic costs saved. The information below at Table 7 is extracted from the central estimate in the final analysis for year 2020.

Table 7. Estimated share of mortality costs saved as a percentage of total benefits in CAAA CBA

	%
PM Mortality as a percentage of health effects	89.5%
Ozone Mortality as a percentage of health effects	2.9%
Sum of PM Mortality and Ozone Mortality as a percentage of health effects	92.4%
Sum of health effects as a percentage of total effects	95.0%
Sum of PM Mortality and Ozone Mortality as a percentage of total effects	87.8%

Source: Extracted from results at Table 7-2 (given in USD), US EPA (2011).

It is evident that mortality has a dominant share in the health effects of air pollution: in this case, 92.4%. Indeed, since health effects have a dominant share in the total effects of air pollution, here at 95%, mortality alone has a dominant share in the latter, here at 87.8%. To focus on the calculation of the cost of mortalities, as has been done here, is indeed appropriate.

To begin with APMP: Table 8 sets out the results of the calculation of the cost of mortalities from APMP in year 2015, for each of the 41 individual countries under study, first in absolute terms in USD₂₀₁₅ and next compared to the country's GDP.⁶

It is appropriate to note the divergence in results between these countries but also the limits of that divergence. As is seen most clearly in Figure 4, the result in most OECD countries is within a relatively narrow range on either side of the OECD average of 3.5% of GDP – with none of these countries boasting estimated costs comparable to less than 1% of GDP and no more than five suffering estimated costs comparable to more than 6% (namely, the Czech Republic, Hungary, Latvia, Poland and the Slovak Republic). Moreover, three of the BRIICS, Brazil, Indonesia and South Africa, also fell within this range even if China, India and Russia remained outside it.

That said, and although these and other inter-country variations are noteworthy, it is important not to lose sight of this key aggregate result: the *absolute* cost in *trillions* of USD. As at 2015, APMP imposed a cost of USD 1.769 trillion on the OECD countries, USD 2.991 trillion on the BRIICS, and USD 4.76 trillion on these 41 countries taken together.

In terms of the change over time, the result is more complex. As noted earlier in discussion and documented in Table 1, the OECD countries, taken together, did succeed in reducing their own total of deaths from APMP in two of the three five-year intervals in the period from 2000 to 2015. Individually, some of the BRIICS also achieved such a reduction on one or two occasions. Nonetheless, as is shown in Figure 5, the calculated cost of deaths from APMP has increased in each of these five-year intervals not only in the BRIICS as a block but also in the OECD countries as a block. This is because the increase in VSL values has exceeded any reduction in the number of deaths. The pace of reduction in deaths, insofar as there has indeed been a reduction, has been too slow to prevent an increase in the burden of its cost.

6. It is emphasised that the estimated welfare costs are not a part of GDP in the respective countries, but a comparison to GDP can give a better understanding of the magnitude of the estimated welfare costs.

Table 8. Cost of premature deaths from APMP in the BRIICS and OECD countries

2015

	USD₂₀₁₅ millions	Compared to GDP
<i>BRIICS:</i>		
Brazil	98 551	3.1%
China	1 507 189	7.9%
India	803 538	10.6%
Indonesia	96 415	3.5%
Russia	447 658	12.5%
South Africa	37 314	5.2%
<i>OECD</i>		
Australia	14 935	1.4%
Austria	16 840	4.1%
Belgium	22 106	4.4%
Canada	29 277	1.8%
Chile	14 845	3.7%
Czech Republic	23 541	6.8%
Denmark	8 872	3.3%
Estonia	1 866	5.1%
Finland	5 887	2.6%
France	75 533	2.9%
Germany	178 558	4.6%
Greece	16 516	5.7%
Hungary	23 091	9.1%
Iceland	265	1.7%
Ireland	5 861	1.9%
Israel	7 043	2.3%
Italy	115 669	5.3%
Japan	207 795	4.4%
Korea	64 117	3.7%
Latvia	5 031	10.5%
Luxembourg	1 315	2.3%
Mexico	58 620	2.7%
Netherlands	30 047	3.7%
New Zealand	2 106	1.2%
Norway	7 699	2.4%
Poland	73 046	7.3%
Portugal	10 285	3.4%
Slovak Republic	10 300	6.5%
Slovenia	3 034	4.7%
Spain	44 075	2.8%
Sweden	9 117	2.0%
Switzerland	11 175	2.2%
Turkey	70 255	4.6%
United Kingdom	106 594	3.9%
United States	431 598	2.4%
Total for all 35 OECD countries in USD and compared to OECD GDP	1 768 666	3.5%

Source: Epidemiological data extracted from IHME (2016), Global Burden of Disease Study 2015 (GBD 2015), Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>, and economic data extracted from OECD (2016b), *OECD Stat* (<http://stats.oecd.org/>).

Figure 4. Cross-country variations in the costs of ambient PM mortalities compared to GDP
2015

Figure 5. Changes in the costs of ambient PM mortalities compared to GDP are larger for the BRIICS
2000-2015

As was shown earlier in Tables 2 and 3, the epidemiological trajectory of AOP has been slightly different to that of APMP in various ways but the numbers involved have not been large enough to alter the

pattern of results for the sum of these two, APMP + AOP. *Mutatis mutandis*, the same applies to the calculation made here of the economic cost.

Table 9. Cost of premature deaths from APMP + AOP in the BRIICS and OECD countries 2015

	USD ₂₀₁₅ millions	Compared to GDP
BRIICS:		
Brazil	104 412	3.3%
China	1 604 925	8.4%
India	882 957	11.6%
Indonesia	97 641	3.5%
Russia	447 658	12.5%
South Africa	38 348	5.3%
OECD:		
Australia	14 935	1.4%
Austria	17 659	4.3%
Belgium	23 304	4.7%
Canada	32 142	2.0%
Chile	15 099	3.8%
Czech Republic	24 028	7.0%
Denmark	9 454	3.5%
Estonia	1 866	5.1%
Finland	6 025	2.7%
France	79 374	3.0%
Germany	186 873	4.8%
Greece	17 841	6.2%
Hungary	23 921	9.4%
Iceland	272	1.7%
Ireland	6 113	2.0%
Israel	7 514	2.5%
Italy	125 662	5.7%
Japan	215 831	4.6%
Korea	66 961	3.8%
Latvia	5 031	10.5%
Luxembourg	1 381	2.4%
Mexico	62 380	2.9%
Netherlands	31 856	3.9%
New Zealand	2 106	1.2%
Norway	7 997	2.5%
Poland	74 534	7.5%
Portugal	10 955	3.6%
Slovak Republic	10 462	6.6%
Slovenia	3 171	4.9%
Spain	50 004	3.1%
Sweden	9 476	2.1%
Switzerland	11 864	2.3%
Turkey	74 528	4.8%
United Kingdom	111 890	4.1%
United States	488 515	2.7%
Total for all 35 OECD countries in USD and compared to OECD GDP	1 888 156	3.7%

Source: Epidemiological data extracted from IHME (2016), Global Burden of Disease Study 2015 (GBD 2015), Online database – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>, and economic data extracted from OECD (2016b), *OECD Stat* (<http://stats.oecd.org/>).

Table 9 sets out the results of this calculation of the cost of mortalities from APMP + AOP in year 2015, for each of the 41 individual countries under study, first in absolute terms in USD₂₀₁₅ and next compared to the country's GDP.

As before, it is important to note both the divergence in results between these countries and its limits. As is seen most clearly in Figure 6, the result in most OECD countries is within a relatively narrow range on either side of the OECD average of 3.7% of GDP. As before: in none of these countries were the estimated costs lower than 1% of GDP and in no more than six were they higher than 6% of GDP (thus, the Czech Republic, Greece, Hungary, Latvia, Poland and the Slovak Republic). As before: this range also contains within it three of the BRIICS; Brazil, Indonesia and South Africa – but not China, India or Russia.

Figure 6. Cross-country variations in the costs of ambient outdoor air pollution mortalities compared to GDP

And once again, it will not hurt to underline the key aggregate result: the *absolute* cost is in *trillions* of USD. As at 2015, ambient air pollution (APMP + AOP) imposed an estimated cost of USD 1.888 trillion on the OECD countries, USD 3.176 trillion on the BRIICS, and USD 5.064 trillion on these 41 countries taken together.

6. Causes, conclusions and policy implications

In the OECD area – and especially so in the European Union and the United States – there is a relative abundance of relevant data available to permit the nomination of some likely causal explanations of the results presented above.

In regard to the totality of deaths: there is evidence to suggest that the road transport sector is now the leading cause of air pollution-related deaths, both in the European Union and in the United States. In the case of the European Union, the evidence suggests that its share of responsibility is around 50% (see the detailed evidence in Yim and Barrett, 2012, in regard to one of its larger member-states, the United Kingdom, and see OECD, 2014, and WHO Regional Office for Europe, OECD, 2015, for a summary of the evidence for the Union as a whole). In the case of the United States, the evidence suggests that its share is less than 50% but larger than that of any other single sector (see Caiazzo et al., 2013, and Dedoussi, 2014, and the discussion of this evidence in OECD, 2014, and WHO Regional Office for Europe, OECD, 2015). Clearly, the rest of the economy – in particular, “other transport” such as aviation, maritime and rail; power generation; and “other sectors” such as industry and agriculture – also remains a significant contributor to the death toll in all these above-named studies.

In regard to the trajectory of movement: in the period from 2000 – and indeed over a longer period from 1990 – it is clear that, thanks in large measure to regulatory initiative and regulatory pressure, many OECD countries succeeded in reducing pollutant emissions and their consequent toll on human health (see inter alia EEA, 2013; United States EPA, 2013; Amann et al., 2013). But it is also clear that regulatory pressure can weaken over time, with a consequent weakening in the pace of reductions in emissions and, thereby, the pace of reductions in mortalities – and even a reversal of the downward trend in both emissions and mortalities.

This is evident in the detailed data available for particular sectors and in particular locations: for example, the road transport sector in the European Union, which has witnessed a failure to effect sustained emission reductions for diesel vehicles *pari passu* with a rapid increase in the market share of these more-polluting vehicles relative to petrol vehicles (see inter alia EEA, 2012; Rafaj, Amann and Siri, 2014; OECD, 2014; WHO Regional Office for Europe, OECD, 2015; see also OECD, 2016a, for a wider discussion of policy initiatives and their fading effects over time).

But it is also evident in the extraordinarily high benefit-cost ratios (BCRs) shown to be available from major regulatory proposals to mitigate air pollution. For example, the mitigation measures in the 1990 Clean Air Act Amendments in the United States were estimated in ex post evaluation to have delivered a BCR of 31:1 (see United States EPA, 2011, and WHO Regional Office for Europe, OECD, 2015). And the mitigation measures in the European Union’s recently proposed Clean Air Package were estimated in an ex ante evaluation to yield a BCR of 42:1 (see European Commission, 2013; Holland, 2014; and WHO Regional Office for Europe, OECD, 2015). Now the availability of proposals with such extraordinarily high BCRs suggests precisely a past failure to proceed with proposals with ordinarily high BCRs. That is to say, it suggests that the effectiveness of regulation, both in the United States as at 1990 and in the European Union as at 2013, was clearly insufficient.

In the BRIICS – and *a fortiori* so in the rest of the world⁷ – the availability of data to support judgements on sectoral contributions to the present toll and explanations of the trends over time is much more limited than in the OECD world. Nonetheless, a couple of points can be established without too much difficulty. On the one hand, it is evident that air pollution from both heavy industry and energy generation, particularly coal-fired power plants, plays a larger role in several of the BRIICS than is the case in OECD countries. On the other hand, it is also evident that motorisation is also an increasing driver of air pollution, with the shift to diesel being an oft-cited factor in the case of India in particular (see OECD, 2014, and the sources cited therein).

Finally, it is a matter of some concern that the share of the rising global death toll registered by the BRIICS and the OECD countries, taken together, has been so remarkably constant over this entire period –

7. And nowhere more so than in Africa: see Roy (2016) and the sources cited therein.

with the sometimes falling share of the latter almost exactly offset by the rising share of the former (see above, Tables 1-3). Available evidence suggests that the observable reduction in air pollution and its impacts in the OECD countries is primarily the result of the use of improved technique, often in response to regulatory requirements, rather than the result of a direct relocation of polluting industries to the BRIICS: see in particular Levinson (2015). Nonetheless, it is as if the workshops of the world, taken together, are always equilibrating at a point that generates an increasing level of pollution with an increasing level of mortalities. This is a matter that is surely in need of further and urgent investigation.

Some obvious conclusions follow from the results and analysis presented above.

The present burden of AAP in the 41 countries under study is, by any measure, large: a toll of around 3.2 million deaths and a cost of around USD 5.1 trillion.

Importantly, it is *not* on an unambiguously downward trend in the new century. The total of deaths from AAP stands at a higher level in 2015 than it did in year 2000 – globally, in the BRIICS, and in the OECD countries as a whole. So too does the burden of its cost. The OECD countries as a whole did register progress in reducing the total of deaths in the ten years to 2010; but the progress registered was relatively modest and more than offset by the regress in the five years to 2015.

In view of this, it seems clear that business-as-usual will not solve the problem of AAP. On the contrary: if the future is to witness the BRIICS following in the path of the OECD, and the rest of the world following in the path of the BRIICS, it will witness thereby an increase in the cost of AAP, not its progressive reduction.

Of the many potential implications for policy that follow from this, perhaps the most salient are these.

In the OECD countries, the limitations of knowledge do not constrain the ability of governments to act decisively. There is more than enough evidence to show that very high BCRs are available from proceeding with actions to mitigate air pollution and thereby reduce its toll.

And given the dominant role of road transport as a contributory factor to AAP in the OECD countries, it is clear that effective action to address AAP needs to make much fuller use of the full suite of measures that have proved to be effective in this sector (see Roy, 2008, and the evidence cited therein).

In the BRIICS, as well as in the rest of the world, there is indeed a critical need to address gaps in knowledge. But this does not reduce the urgency of the need to act or the possibility of effective action. The rising death toll from AAP in many of the BRIICS can be constrained in several ways, including by climbing more rapidly to the higher, if insufficient, standards of technique prevailing in OECD countries.⁸

A final implication for policy that has to be noted here is the need for the BRIICS and the OECD countries taken together – *to wit*, the enlarged centre of the new world economy – to begin to consider the problem of AAP as a collective problem, requiring an enhanced degree of co-ordination in research and policy. The tabling of the evidence above on the remarkably constant share in the death toll from AAP of these two groups of countries, taken together, ought to serve to generate a new constancy of purpose in addressing the problem.

8. As it happens, China and India in particular have indeed sought to impose nation-wide EU vehicle standards with a minimal time-lag: see Amann et al., 2013. Unfortunately, the insufficiency of these standards, when coupled with the explosive growth of car ownership in these countries, has thwarted the desired effect.

REFERENCES

- Amann, M., Z. Klimont and F. Wagner (2013), “Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios”, *Annual Review of Environment and Resources*, Vol. 38, pp. 31-55, www.annualreviews.org/doi/abs/10.1146/annurev-environ-052912-173303.
- Beelen, R. et al. (2008), “Long-Term Exposure to Traffic-Related Air Pollution and Lung Cancer Risk”, *Epidemiology*, Vol. 19(5), pp. 702-710, <http://dx.doi.org/10.1097/EDE.0b013e318181b3ca>.
- Benbrahim-Tallaa, L. et al. (2012), “Carcinogenicity of diesel-engine and gasoline-engine exhausts and some nitroarenes”, *The Lancet Oncology*, Vol. 13(7), pp. 663-664, [http://dx.doi.org/10.1016/S1470-2045\(12\)70280-2](http://dx.doi.org/10.1016/S1470-2045(12)70280-2).
- Biausque, V. (2012), *The Value of Statistical Life: A Meta-Analysis*, OECD, Paris, ENV/EPOC/WPNEP(2010)9/FINAL.
- Braathen, N. A. (2012), *Valuation of human lives*, presentation at an Informal Joint Workshop of the Regulatory Policy Committee and the Annual Meeting of Sustainable Development Experts on “The Role of Impact Assessments in Policy Making”, OECD, Paris, www.oecd.org/gov/regulatory-policy/49312406.pdf.
- Brauer, M. et al. (2012), “Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution”, *Environmental Science & Technology*, Vol. 46(2), pp. 652-660, <http://dx.doi.org/10.1021/es2025752>.
- Caiazzo, F. et al. (2013), “Air Pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005”, *Atmospheric Environment*, Vol. 79, pp. 198-208, <http://dx.doi.org/10.1016/j.atmosenv.2013.05.081>.
- Dedoussi, I. C. (2014), *Air pollution and early deaths in the United States: Attribution of PM_{2.5} exposure to emissions species, time, location and sector*, A MIT SM thesis supervised by Professor Steven Barrett, Massachusetts Institute of Technology, Cambridge, MA, http://lae.mit.edu/uploads/LAE_report_series/2014/LAE-2014-003-T.pdf.
- EEA (2012), The contribution of transport to air quality. TERM 2012: transport indicators tracking progress toward environmental targets in Europe. Luxembourg: Publications Office of the European Union, www.eea.europa.eu/publications/transport-and-air-quality-term-2012/download.
- EEA (2013), *Air Quality in Europe – 2013 Report*, EEA Report No. 9/2013, Publications Office of the European Union, Luxembourg, www.eea.europa.eu/publications/air-quality-in-europe-2013.
- European Commission (2013), *Commission Staff Document: Impact Assessment*, European Commission, Brussels, http://ec.europa.eu/governance/impact/ia_carried_out/docs/ia_2013/swd_2013_0531_en.pdf.
- Evans, J. et al. (2012), “Estimates of global mortality attributable to particulate air pollution using satellite imagery”, *Environmental Research*, Vol. 120, pp. 33-42, <http://dx.doi.org/10.1016/j.envres.2012.08.005>.
- Fajersztajn, L. et al. (2013), “Air pollution: A potentially modifiable risk factor for lung cancer”, *Nature Reviews Cancer*, Vol. 13, pp. 674-678, <http://dx.doi.org/10.1038/nrc3572>.

- GBD 2015 Risk Factors Collaborators (2016), "Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015", *The Lancet*, Vol. 388, pp. 1659-1724, [http://dx.doi.org/10.1016/S0140-6736\(16\)31679-8](http://dx.doi.org/10.1016/S0140-6736(16)31679-8).
- GBD 2013 Risk Factors Collaborators (2015), "Global, regional and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Diseases Study 2013", *The Lancet*, Vol. 386, pp. 2287-2323, [http://dx.doi.org/10.1016/S0140-6736\(15\)00128-2](http://dx.doi.org/10.1016/S0140-6736(15)00128-2).
- Guxens, M. and J. Sunyer (2012), "A review of epidemiological studies on neuropsychological effects of air pollution", *Swiss Medical Weekly*, Vol. 141, w13322, www.ncbi.nlm.nih.gov/pubmed/22252905.
- Hammitt, J. K. and L. A. Robinson (2011), "The Income Elasticity of the Value per Statistical Life: Transferring Estimates between High and Low Income Populations", *Journal of Benefit-Cost Analysis*, Vol. 2, Issue 1, Article 1, www.bepress.com/jbca/vol2/iss1/1.
- Holland, M. (2014), *Cost-benefit Analysis of Final Policy Scenarios for the EU Clean Air Package*, Version 2, Corresponding to IIASA TSAP Report #11, Version 1, International Institute for Applied Systems Analysis, Laxenburg, <http://ec.europa.eu/environment/air/pdf/TSAP%20CBA.pdf>.
- Hunt, A. (2011), "Policy Interventions to Address Health Impacts Associated with Air Pollution, Unsafe Water Supply and Sanitation, and Hazardous Chemicals", *OECD Environment Working Papers*, No. 35, OECD Publishing, Paris, <http://dx.doi.org/10.1787/5kg9qx8dsx43-en>.
- Hunt, A. and J. Ferguson (2010), *A review of recent policy-relevant findings from the environmental health literature*, OECD, Paris, [http://search.oecd.org/officialdocuments/displaydocumentpdf/?doclanguage=en&cote=env/epoc/wp-nep\(2009\)9/final](http://search.oecd.org/officialdocuments/displaydocumentpdf/?doclanguage=en&cote=env/epoc/wp-nep(2009)9/final).
- Hunt, A. et al. (2016), "Social Costs of Morbidity Impacts of Air Pollution", *OECD Environment Working Papers*, No. 99, OECD Publishing, Paris, <http://dx.doi.org/10.1787/5jm55j7cq0lv-en>.
- IARC (International Agency for Research on Cancer) (2013), *IARC: Outdoor air pollution a leading cause of cancer deaths* – Press Release No. 221, 17 October 2013, International Agency for Research on Cancer, Lyon, www.iarc.fr/en/media-centre/iarcnews/pdf/pr221_E.pdf.
- IARC (2012), *IARC: Diesel Engine Exhaust Carcinogenic* – Press Release No. 213, 12 June 2012, International Agency for Research on Cancer, Lyon, www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf.
- IHME (2016), *Global Burden of Disease Study 2015 (GBD 2015)*, On line data base – Viz Hub – GBD Compare, Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.
- IHME (2015), *Global Burden of Disease Study 2013 (GBD 2013) – Results by Risk Factor – Country Level* [on line data base – Viz Hub – GBD Compare], Institute for Health Metrics and Evaluation, University of Washington, Seattle, <http://vizhub.healthdata.org/gbd-compare/>.
- IHME (2013), *The Global Burden of Disease (GBD) Visualizations: GBD compare* [online database], Institute for Health Metrics and Evaluation, Seattle, <http://viz.healthmetricsandevaluation.org/gbd-compare/>.

- Laumbach, R. J. and H. M. Kipen (2012), “Respiratory Health effects of Air Pollution: Update on Biomass Smoke and Traffic Pollution”, *Journal of Allergy and Clinical Immunology*, Vol. 129(1), pp. 3-13, <http://dx.doi.org/10.1016/j.jaci.2011.11.021>.
- Levinson, A. (2015), “A Direct Estimate of the Technique Effect: Changes in the Pollution Intensity of US Manufacturing, 1990–2008”, *Journal of the Association of Environmental and Resource Economists*, Vol. 2(1), pp. 43-56.
- Lim, S. S. et al. (2012), “A comparative assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010”, *The Lancet*, Vol. 380, pp. 2224-60, [https://doi.org/10.1016/S0140-6736\(12\)61766-8](https://doi.org/10.1016/S0140-6736(12)61766-8).
- Narain, U. and C. Sall (2016), “Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions”, *World Bank working paper*, World Bank, Washington DC, <http://documents.worldbank.org/curated/pt/832141466999681767/pdf/106607-WP-ADD-AUTHORS-ABSTRACT-PUB-DATE-PUBLIC.pdf>.
- OECD (2016a), *The Economic Consequences of Outdoor Air Pollution*, OECD Publishing, Paris, <http://dx.doi.org/10.1787/9789264257474-en>.
- OECD (2016b), OECD Stat Extracts [online database], OECD, Paris, <http://stats.oecd.org/>.
- OECD (2014), *The Cost of Air Pollution: Health Impacts of Road Transport*, OECD Publishing, Paris, <http://dx.doi.org/10.1787/9789264210448-en>.
- OECD (2012), *Mortality Risk Valuation in Environment, Health and Transport Policies*, OECD Publishing, Paris, <http://dx.doi.org/10.1787/9789264130807-en>.
- Raaschou-Nielsen, O. et al. (2013), “Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE)”, *Lancet Oncology*, Vol. 14(9), pp. 813-22, www.sciencedirect.com/science/article/pii/S1470204513702791.
- Rafaj, P., M. Amann and J. G. Siri (2014), “Factorization of air pollutant emissions: Projections versus observed trends in Europe”, *Science of the Total Environment*, Vol. 494-495, pp. 272-282, <http://dx.doi.org/10.1016/j.scitotenv.2014.07.013>.
- Roy, R. (2016), “The Cost of Air Pollution in Africa”, *OECD Development Centre Working Paper* No. 333, OECD Publishing, Paris, <http://dx.doi.org/10.1787/5jlqzq77x6f8-en>.
- Roy, R. (2008), *Mind-forg'd Manacles – The Constraints to Optimising Urban Transport Policy*, OECD, Paris, www.oecd.org/dataoecd/14/39/41577863.pdf.
- Shah, A. S. V. et al. (2013), “Global Association of air pollution and heart failure: A systematic review and meta-analysis”, *The Lancet*, Vol. 382, pp. 1039-48, [https://doi.org/10.1016/S0140-6736\(13\)60898-3](https://doi.org/10.1016/S0140-6736(13)60898-3).
- Silverman, D. T. et al. (2012), “The diesel exhaust in miners study: A nested case-control study of lung cancer and diesel exhaust”, *Journal of the National Cancer Institute*, Vol. 104(11), pp. 855-868, <http://dx.doi.org/10.1093/jnci/djs034>.
- United States EPA (2013), *Air Quality Trends*, United States Environmental Protection Agency, Washington DC.

- United States EPA (2011), *The Benefits and Costs of the Clean Air Act from 1990 to 2020: Final Report – Rev A*, United States Environmental Protection Agency, Washington DC, www.epa.gov/cleanairactbenefits/feb11/fullreport_rev_a.pdf.
- Wellenius, G. A. et al. (2012), “Ambient Air Pollution and the Risk of Acute Ischemic Stroke”, *Archives of Internal Medicine*, Vol. 172(3), pp. 229-234, <http://archinte.jamanetwork.com/article.aspx?articleid=1108717>.
- WHO (2014a), *7 million premature deaths annually linked to air pollution*, Media Centre News release, World Health Organization, Geneva, www.who.int/mediacentre/news/releases/2014/air-pollution/en/.
- WHO (2014b), *Burden of disease from Household Air Pollution for 2012: Summary of results; Burden of disease from Ambient Air Pollution for 2012: Summary of results; Burden of disease from the joint effects of Household and Ambient Air Pollution for 2012: Summary of results; Burden of disease from Household Air Pollution for 2012: Description of method; Burden of disease from Ambient Air Pollution for 2012: Description of method; Burden of disease from the joint effects of Household and Ambient Air Pollution for 2012: Description of method*, World Health Organization, Geneva, www.who.int/phe/health_topics/outdoorair/en/
- WHO Regional Office for Europe and OECD (2015), *Economic cost of the health impact of air pollution in Europe: Clean air, health and wealth*, WHO Regional Office for Europe, Copenhagen, www.euro.who.int/_data/assets/pdf_file/0004/276772/Economic-cost-health-impact-air-pollution-en.pdf?ua=1.
- WHO Regional Office for Europe (2013a), *Review of evidence on health aspects of air pollution – REVIHAAP Project: Technical Report*, WHO Regional Office for Europe, Copenhagen, www.euro.who.int/_data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf?ua=1.
- WHO Regional Office for Europe (2013b), *Health risks of air pollution in Europe – HRAPIE project. Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen oxide*, WHO Regional Office for Europe, Copenhagen, www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project.-recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide.
- Yim, S. H. L and S. R. H. Barrett (2012), “Public Health Impacts of Consumption Emissions in the United Kingdom”, *Environmental Science & Technology*, Vol. 46(8), pp. 4291-4296, <http://pubs.acs.org/doi/abs/10.1021/es2040416>.