Kerry Krutilla*, David H. Good and John D. Graham

Uncertainty in the Cost-Effectiveness of Federal Air Quality Regulations

Abstract: In this study, we conduct a cost-effectiveness analysis of nine air quality regulations recently issued by the U.S. Environmental Protection Agency (EPA). Taking emission reductions in the Regulatory Impact Analyses (RIAs) for these regulations as given, we independently assess uncertainty about the compliance costs of the regulations and the lives the regulations are estimated to save. The latter evaluation is based on a formal uncertainty analysis that integrates expert judgments about the effects of fine particle exposures on mortality risks. These expert judgments were given in an EPA-sponsored elicitation study conducted in 2006. The integrated judgments are used to generate probability distributions for several types of cost-effectiveness ratios, including the gross and net cost per life saved, net cost per life year saved, and net cost per quality-adjusted life year (QALY) gained. The results show that the cost-effectiveness ratios exhibit considerable uncertainty individually and also vary widely across regulations. Within a simulated 90% confidence interval for the gross cost per life saved, for example, there is both the possibility that benefits from lifesavings alone are sufficient to cover the rules' costs and the possibility that no lives will be saved and cost-effectiveness ratios will be infinite. The wide ranges for the confidence intervals suggest the need for better information about the effects of fine particle exposures on mortality risks.

Keywords: air quality regulation; cost-effectiveness analysis; uncertainty analysis.

1 Introduction

In this study, we conduct a cost-effectiveness analysis of recent regulations issued by the Office of Air and Radiation of the U.S. Environmental Protection Agency (EPA). These regulations will reduce exposures to airborne concentrations of fine particles and other pollutants, reducing the risk of morbidity and premature mortal-

---

*Corresponding author: Kerry Krutilla, School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA, e-mail: krutilla@indiana.edu
David H. Good: School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA
John D. Graham: School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA

ity, and providing other benefits, such as improved visibility. The economic effect of such regulations is significant. Regulations issued exclusively by the EPA account for 63%–82% of the total monetized benefits of all federal regulations, and 45%–56% of their total costs, with regulations having a primary or significant goal to improve air quality accounting for 98%–99% of these benefits (Office of Management and Budget, 2014).

The cost and consequences of regulations that reduce mortality risks, including those targeting air pollution, have drawn the attention of academic researchers, policy makers, and stakeholders.[1] Two issues have been considered. The first is whether lifesaving regulations allocate resources cost-effectively.[2] A second question concerns the effects of exposures to fine particulate matter on mortality risks, and whether these uncertainties are adequately reflected in regulatory benefit estimates.[3] Reducing exposures to fine particulate matter often account for more than 90% of the monetized benefits of EPA's air regulations (Office of Management and Budget, 2014).

The second question has been the subject of an enormous literature, the implications of which will be discussed in a later section of the article that presents an uncertainty analysis of the mortality risk reductions associated with air regulations.[4] The first question has been addressed by a more limited literature which is useful to review here. In this regard, a study by John Morrall computed the cost-effectiveness of 76 federal regulations promulgated from 1967 to 2001, measured as net resource cost per statistical life saved (Morrall, 2003). The numerator of this ratio subtracts from compliance costs all of the benefits other than those related to

---

1 Regulations reduce the risk of premature mortality in large populations, without the affected individuals being known. The term "statistical lifesavings" has traditionally been used to denote this context, but usage such as "reduced mortality risk" or "avoided premature deaths" is now increasingly common. These characterizations are used interchangeably in this study. For semantic convenience, the qualifier "statistical" is also sometimes dropped from "statistical lifesavings" and "statistical lives saved," leaving just the terms "lives saved" and "lifesavings." When the "statistical" qualifier is omitted, its presence should be regarded as implicit.

2 A related discussion in the academic literature is the extent to which benefit-cost analysis is informative for making judgments about risk regulation. Heinzerling and Ackerman (2002) argue against the use of benefit-cost analysis for this purpose, while Graham (2008), Revesz and Livermore (2008), and Viscusi (2005−2006) advocate for the use of benefit-cost analysis. This article adopts the conventional economic evaluation perspective represented in the latter views, and in the analytical guidance offered to agencies from the Office of Management and Budget (OMB).

3 Fine particulate matter is defined as particles having diameters of 2.5 micrometers or less ("PM2.5"). Particles in this size range can penetrate deeply into the lungs and bloodstream, creating greater health risks than larger sized particles.

4 For recent research on the possible health effects of exposures to fine particulates see Krewski et al. (2009), Lepeule et al. (2012), and Fann et al. (2012*a*). For recent debate and discussion about the way uncertainties about the health effects of fine particle exposures are addressed in the evaluation of air quality regulations, see Cox (2012), Fann et al. (2012*b*), Fraas and Lutter (2013*a*,*b*), Fann, Lamson, Anenberg, and Hubbell (2013), Smith and Gans (2014), and Fann, Lamson, Luben, and Hubbell (2015).

mortality risk. Using this measure, a break-even ratio is defined at which the net resource cost of the regulation is equal to the value of a statistical life (VSL) it saves.[5] Cost-effectiveness ratios beneath this threshold will yield benefits greater than their costs. A "health–health" cutoff point is also identified. This is a cost-effectiveness ratio at which the regulation has no effect on aggregate mortality risks, owing to the opportunity cost of the resources the regulation diverts from other risk-reducing alternatives (see Lutter, Morrall & Viscusi, 1999). Regulations with cost-effectiveness ratios beneath this threshold will reduce mortality risks in society, on net. It turns out that 58% of the rules had a net cost per statistical life saved less than the VSL, giving positive net benefits, while 65% of the rules passed the health–health test, yielding societal mortality risk reductions, on net. There is wide variation in the cost-effectiveness ratios of the regulations, with a six order of magnitude difference between the minimum and maximum.

Tengs et al. (1995) conducted a cost-effectiveness analysis of 500 private and public interventions reducing the risk of premature mortality. They used a net resource cost measure in the numerator, but statistical life years rather than lives saved in the denominator.[6] Although the cost-effectiveness metric and sample used in Tengs et al. (1995) differed from that in Morrall (2003), the results were broadly consistent. Again, there were significant differences in cost-effectiveness among different interventions. In 2013 dollars, the median net cost per statistical life year saved was $61,981; with the median for medical interventions at $28,039 and those for toxin control of $4.1 million.[7] These discrepancies, and those found in Morrall (2003), are likely to be partially explained by the lumpy non-continuous nature of some of the investment options (making it difficult to equate incremental costs at the margin). But the magnitude of the differences are also likely to indicate significant inefficiencies in resource allocation (Tengs & Graham, 1996).

There has been limited cost-effectiveness analysis of regulations using the "quality-adjusted life year" (QALY) outcome measure commonly used in the health evaluation literature (Drummond, O'Brien, Stoddart & Torrance, 2005).[8]

---

5 The "value of a statistical life" (VSL) is the marginal rate of substitution between wealth and risk, and can be measured as individual willingness to pay for small reductions in one's own mortality risks in a defined period, divided by the risk reduction.

6 Life years are computed from lives saved by distributing the lives saved to the age classes in which they are expected to occur, and determining the expected years of life remaining – "life years" – in each age class based on age-class specific conditional life expectancies. The life years are then aggregated across age classes to give the total life years associated with the lives saved.

7 A number of the interventions in this study were not subsequently implemented, so the ratios include data from some proposed-only interventions.

8 The use of QALYs as an outcome measure in the environmental health context has been much debated, in part because restrictive assumptions about utility functions are needed for cost–utility analysis to be consistent with benefit-cost analysis (see Hubbell, 2006; Haninger & Hammitt, 2011; and Hammitt,

The QALY is based on a utility measure for morbidity outcomes that can be combined with mortality impacts into a single index. Over the past decade, published cost-effectiveness analyses in the health evaluation field using the QALY measure (known as "cost–utility" analysis) have grown rapidly (Thorat, Cangelosi & Neumann, 2012).[9] In 2003, the OMB recommended the use of cost–utility analysis for the assessment of federal health, environmental, and safety regulations (Office of Management and Budget, 2003).[10] In 2006 an expert panel of the Institute of Medicine of the National Academy of Sciences was commissioned to study the feasibility and relevance of cost-effectiveness analysis, including cost–utility analysis, for the assessment of regulatory interventions (Institute of Medicine, 2006). The panel concluded that cost-effectiveness analysis was feasible and potentially informative for regulatory evaluation, and the tool was illustrated in several case studies, including an application to EPA's off-road diesel rule (Robinson et al., 2005).[11] At the same time, EPA was assessing its experience with cost–utility analysis, begun in regulatory impact assessments in 2003, and studying how to adapt cost–utility analysis for the economic evaluation of air pollution regulations (U.S. EPA, 2006).[12] Cost–utility analysis has also seen some limited application in the academic literature on air pollution-reducing interventions, e.g., Cohen, Hammitt and Levy (2003).

The cost-effectiveness analysis in this study extends the literature in several ways. First, and consistent with the recommendations in the report by the Institute of Medicine, the analysis is based on multiple cost-effectiveness metrics. This framework allows an assessment of the sensitivity of results to the different measures, and comparisons to other studies of federal regulations using the different metrics. Our study is also the first to apply cost–utility analysis to a group of federal regulations.[13] This extension allows a comparison of the cost-effectiveness of the regulatory interventions studied to those evaluated in the health literature, where cost–utility analysis is standard practice. Third, the analysis focuses on recent air regulations. This application is particularly policy relevant given the cost and consequences of these regulations. Finally, because there are significant uncertainties associated with federal regulatory interventions (see Krupnick et al., 2006), and

---

2013). We use cost–utility analysis in this study to see how air regulations will compare with other public and private health care interventions that are based on the method.

9 See the Cost-Effectiveness Registry at https://research.tufts-nemc.org/cear4/Default.aspx.

10 Circular A-4 is the guidance document making this recommendation. It is the most recent OMB circular providing analytic guidance to agencies for preparing economic evaluations of federal regulations.

11 The recommendations of the Institute of Medicine report were never formally adopted by the OMB, and in some cases differ from the guidance in Circular A-4.

12 EPA has not performed a regulatory cost–utility analysis since 2008.

13 As noted, previous cost–utility analyses of federal regulations have been based on individual case studies.

in particular, regulations to reduce air pollution exposures, our study considers the major uncertainties in the analysis and conducts a formal uncertainty analysis of the concentration–response relationship between fine particle exposures and mortality risks. This formal analysis integrates the expert judgments derived from an elicitation study to compute 90% confidence intervals for the statistical lives that the regulations are expected to save. A 90% confidence interval is then computed for all of the cost-effectiveness measures for each of the regulations in the study.

We begin in the next section with a description of the criteria used to select the regulations, and offer some perspective about their characteristics and the regulatory program that includes them. The following section describes the data and methods used to construct the cost-effectiveness ratios. The results of the analysis are then presented, followed by a discussion of the methodology implications and suggestions for future research.

2 Sample selection and characteristics

This section describes the criteria used to select the rules in the study, and then describes some of their characteristics. We also report the range of estimated statistical lifesavings for each of the rules based on estimates for relative risk reduction commonly used in the Regulatory Impact Analyses (RIAs) of the regulations.[14] We also indicate cost-effectiveness ratios, defined as gross compliance costs per life saved, that correspond to these estimates. In combination, this information provides the context for understanding the air quality regulations in the study and their costs and effects as the EPA estimates them. This information provides the point of departure for the analysis that follows.

2.1 Sample selection

The analysis is based on a sample of EPA rules that meet two criteria. Rules had to target stationary source emitters, and have promulgation dates between 2011 and 2013. Additionally, rules had to be deemed "significant," and have a RIA completed sometime from August 2010 to December 2013. Table 1 shows the complete list of the rules included in the study.

---

14 "Regulatory Impact Analysis" is the terminology used to describe the benefit-cost analysis that the OMB requires for "significant regulations." "Significant regulations" are usually those that have an annual impact of at least $100 million – either on the cost or benefit side.

Table 1 Air quality regulations in the study.

Regulatory target	RIN	Rule	Federal register publication [*]	RIA [**]	Analytical reference year in RIA [***]
Electric Generating Units	2060-AP52 2060-AR31	Mercury and Air Toxic Standards (MATS)	February 16, 2012	December 2011	2016
	2060-AP50	Cross State Air Pollution Rule (CSAPR)	June 12, 2012	June 2011	2014
Boilers and Incinerators	2060-AR13	National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	January 31, 2013	December 2012	2015
	2060-AR13	National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Area Source Boilers	February 1, 2013	February 2011	2015
	2060-AR15 2050-AG44	NESHAP for Commercial and Industrial Solid Waste Incinerators	February 7, 2013	December 2012	2016
Portland Cement Plants	2060-AQ93	NESHAP for the Portland Cement Manufacturing Industry and Performance Standards for Portland Cement Plants	February 12, 2013	August 2010	2015
Reciprocating Internal Combustion Engines (RICE)	2060-AQ58	NESHAP for compression ignited RICE	January 30, 2013	January 2013	2015
	2060-AQ58	NESHAP for spark-ignited RICE	January 30, 2013	January 2013	2015
Petroleum Refineries	2060-AN72	Performance Standards (for refineries constructed or modified after May 14, 2007)	September 12, 2012	June 2012	2017

[*]Federal register citations indicated in Appendix A.
[**]RIA citations listed in Appendix B.
[***]The analytical reference year is the year in which the RIAs estimate annual lives saved, the annual benefits, and the annualized costs of the rules.

The time period was chosen for two reasons. First, the analysis is based on secondary sources, and most significantly, on the RIAs themselves. The methods for preparing RIAs continue to evolve, so basing the analysis on the relatively recent period offers a sample of RIAs reflecting reasonably current practices. Secondly, as Table 1 shows, this time frame coincides with a period of significant regulatory activity. This rulemaking reflects the somewhat fortuitous confluence of a series of administrative reconsiderations and legal actions largely resolving a backlog of contested and delayed rulemakings dating back over several administrations. These rulemakings principally, though not exclusively, regulate the emission of hazardous air pollutants (HAPs).[15]

The National Ambient Air Quality Standards (NAAQS) for fine particulate matter is a notable exclusion from our study. Characteristics of NAAQS limit the usefulness of their cost estimates for comparative analysis. States have the flexibility to choose different compliance strategies in multiple sectors to attain ambient standards, and this flexibility reduces the predictability of future costs. The RIA for the NAAQS for particulate matter describes the situation as follows:

> The setting of a NAAQS does not compel specific pollution reductions and as such does not directly result in costs and benefits. For this reason, NAAQS RIAs are merely illustrative. The NAAQS RIAs illustrate the potential costs and benefits of additional steps States could take to attain a revised air quality standard nationwide beyond the rules already on the books (U.S. EPA, 2012, pdf pp. 36).[16]

2.2 Characteristics of air regulations[17]

The rules in this study require national emission standards for hazardous air pollutants (NESHAPs) with just two exceptions: the regulation targeting petroleum refineries, and the Cross State Air Pollution Rule (CSAPR). New Source Performance Standards (NSPS) for the conventional criteria pollutants[18] are also required in the rulemakings with just two exceptions: the CSAPR and the rule that reduces hazardous pollutants from large boilers, known as the "Boiler MACT." In short,

---

15 Minor administrative reconsiderations and proposed changes have continued beyond the time frame illustrated in Table 1, and additional legal actions are likely.

16 Given this uncertainty about costs, NAAQS are also excluded from the EPA's ongoing retrospective studies of major rules (see Kopits et al., 2014).

17 Unless otherwise indicated, the Federal Register notices indicated in Appendix A and the RIAs listed in Appendix B provide the information and data for this section.

18 The "criteria pollutants" are the standard pollutants that are regulated in EPA regulations, i.e., ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, lead.

NESHAPs in conjunction with NSPS is the modal regulatory approach for the group of regulations in the study.[19]

The regulations target different sources of emissions (see Table 1). The stringency and scope of the regulations differs for these sources, reflecting differences in the size of regulated combustion units and the fuels they use. In general, the Clean Air Act requires major sources of hazardous air pollutants – boilers or process heaters used in electric generating units or in heavy industry – to install "Maximum Achievable Control Technology" (MACT).[20] Smaller boilers or sources defined as "area" sources, (for example, those used to provide heat in commercial establishments, schools, and hospitals), face less stringent standards consistent with the use of "Generally Available Control Technology" (GACT). Energy efficiency assessments and regular maintenance scheduling are the kinds of actions that might be taken to meet this category of standards.

Given this regulatory framework, the rulemakings targeting the utility sector are the most costly and are estimated to save the most lives, with Mercury and Air Toxic Standards (MATS) the most costly rule in the study. Indeed, the MATS is one of the most costly rules that the EPA has ever issued, having estimated compliance costs of around $11 billion, or 60% of the total costs of all of the rules in our study. The EPA also estimates that the controls installed to reduce emissions from utility generators will save between about 3,800 and 10,000 statistical lives annually, discounted at 3% (see Table 2). These control devices reduce fine particles as a side effect, and it is the effects of reducing fine particles that give rise to these estimates. The figures shown are from the coefficient estimates from reducing fine particles from two cohort-based epidemiological studies: the American Cancer Society Study and the Harvard Six Cities Study. These studies, which provide updated relative risk estimates with the passage of time, give the benchmark estimates for reduced mortality risks for all air regulations from the EPA.[21]

---

19 The Clean Air Act specifies a 3-year timetable for regulated sources to come into compliance with standards for hazardous pollutants, and allows states and local permitting authorities to grant up to an additional year on a case by case basis. Administrative reconsiderations by EPA can restart this timetable, and legal actions often delay the implementation schedule. As of the time of this writing, the compliance timetable for the standards for hazardous pollutants seems likely to occur sometime in the 2015–2018 period.

20 Maximum Achievable Control Technology (MACT) for hazardous air pollutants has a statutory definition under Section 112(d) of the Clean Air Act. For example, MACT for new sources is defined as a level of control at least as stringent as that achieved by the best controlled similar source.

21 These epidemiological studies follow the health status of a cohort of individuals though time, and statistically relate the cohort's health status to fine particle exposures and covariates. Pope et al. (2002) gives the estimates for the American Cancer Society Study shown in Table 2, while Laden et al. (2006) gives the estimates shown for the Harvard Six Cities Study. To provide additional perspective, EPA also uses an expert elicitation study giving twelve expert opinions on the mortality effects of fine particle exposures. We discuss the cohort studies and expert elicitations further in Section 3.2.

Table 2 EPA estimates of costs and discounted lives saved, air regulations in the study.

Rule	Compliance cost (Millions $2013)[*]	Mean estimate avoided adult mortality, from American Cancer Society Study (Pope et al., 2002), at 3%[**]	Mean estimate avoided adult mortality from Harvard Six Cities Study (Laden, Schwartz, Speizer & Dockery, 2006), at 3%[**]	$Cost/discounted life saved (3%), American Cancer Society Study (Millions $2013)	$Cost/discounted life saved (3%), Harvard Six Cities Study (Millions $2013)
Mercury and air toxic standards (MATS)	$11,000	3,800	10,000	$2.80	$1.10
Cross state air pollution rule (CSAPR)	$2,600	12,000	31,000	$0.20	$0.10
National emissions standards for hazardous air pollutants (NESHAP) for major boilers (Boiler MACT)	$1,700	2,800	7,200	$0.60	$0.20
National emissions standards for hazardous air pollutants (NESHAP) for area source boilers	$530	22	55	$24.00	$9.6
NESHAP for commercial and industrial solid waste incinerators	$280	43	110	$6.60	$2.60
NESHAP for the portland cement manufacturing industry and performance standards for Portland cement plants	$1,100	870	2,300	$1.30	$0.50

Table 2 (Continued).

Rule	Compliance cost (Millions $2013)[*]	Mean estimate avoided adult mortality, from American Cancer Society Study (Pope et al., 2002), at 3%[**]	Mean estimate avoided adult mortality from Harvard Six Cities Study (Laden, Schwartz, Speizer & Dockery, 2006), at 3%[**]	$Cost/discounted life saved (3%), American Cancer Society Study (Millions $2013)	$Cost/discounted life saved (3%), Harvard Six Cities Study (Millions $2013)
NESHAP for compression ignited reciprocating internal combustion engines (CIRICE)	$390	77	200	$5.10	$2.00
NESHAP for spark-ignited reciprocating internal combustion engines (SIRICE)	$120	6	16	$19.00	$7.40
New source performance standards (NSPS) for petroleum refineries	$110	24	60	$4.60	$1.80
Totals[***]	$18,000	19,000	51,000	$0.90	$0.30

All estimates in table rounded to two significant figures.

[*]Subtracts out energy savings, with the exception of the Petroleum Refinery Rule. Energy savings for the petroleum refinery rule are larger than the rule's compliance costs.

[**]EPA analyses assume that lifesavings are distributed in the periods following the implementation of the regulation according to a "cessation lag." The discount factor used to convert these future distributed lifesavings into a present value at a 3% discount rate (used here for illustrative purposes) is 0.9061. For the 7% discount rate, the factor is 0.8160. Multiplying the ratios in the table by 1.1036 will convert them to costs per undiscounted lives saved. Multiplying the ratios by 0.9006 will give cost per discounted lives saved at 7%.

[***]Totals may not equal summations due to rounding.

The CSAPR is the other rule that targets utilities. This rulemaking replaces the Clean State Air Pollution Rule (CAIR), regulating the cross state transport of ozone and fine particle precursors (SO_x and NO_x) from electric generating units in 28 states. The CSAPR costs in the neighborhood of \$2.6 billion per year and, according to the benchmark EPA estimates, saves 12,000 to 31,000 lives annually from reducing fine particle exposures (see Table 2). These estimates of discounted lives saved are three times larger than those for the MATS, and constitute 60% of the total estimated lives saved for all of the rules in the study.

Rules regulating major boilers (The Boiler MACT) and portland cement plants each cost over a one billion annually and save lives from the reduction of fine particles (again discounted at 3%) from around 2,800 to 7,200 (in the case of the Boiler MACT) and 870 to 2,300 (for the portland cement plants). The Boiler MACT targets larger industrial boilers, while the Portland Cement Rule regulates approximately 158 kilns at 100 facilities.

The regulation targeting hazardous pollutants from solid waste incinerators costs around \$280 million per year, and is estimated by EPA to save 43–110 lives annually. The remaining rules target smaller sources, with lower costs and lifesaving effects. They include a regulation targeting smaller "area source" boilers of the type that provide heat in commercial establishments, and the two rules regulating stationary reciprocating internal combustion engines (RICE). These engines are used to power pumps and compressors, and also to power backup generators.[22]

The final rule specifies NSPS for NO_x emitted from process heaters in refineries, and provides a flare management and monitoring plan designed to reduce hydrogen sulfide emissions. This is the smallest rule in the study, with an annual compliance cost of around \$110 million, and lifesavings from 24 to 60 per year.[23]

Table 2 combines the cost and lifesaving estimates indicated into cost-effectiveness ratios (columns (4) and (5)). These figures can be compared to the VSL for the analytical reference year of the rules. These VSLs range between \$9.0

---

22 Compression-ignited internal reciprocating combustion engines (CIRICE) use diesel as a fuel, while spark-ignited reciprocating internal combustion engines (SIRICE) are fueled with gasoline or natural gas.

23 The small scale of this rule is partially an artifact of the way it is evaluated. The analysis is based on the costs and effects of compliance of new sources in the analytical reference year 2017. An alternative approach would be to wait until refinery stock fully turns over, and to analyze the costs and effects of compliance to the NSPS by the entire industry. (This approach was used in the analysis of joint DOT–EPA rule promulgated in 2011 regulating CO_2 emissions and energy consumption in medium and heavy duty trucks.) While these different analytical methods will affect costs, lives saved estimates, and net benefits, they do not necessarily affect cost-effectiveness (or benefit-cost) ratios. Assuming that effects are proportional to market penetration, the scale difference between partial and total industry compliance – and the temporal differences involved, as reflected in discounting – will divide out in the ratio formats.

and $10.0 million in $2013.[24] Thus, the gross compliance cost per discounted statistical life saved is always less than the VSL for all of the rules in the study but two: the rule regulating Area Source Boilers, and the rule regulating Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE). This implies that, with the exception of these two rules, the benefits of reducing fine particles, estimated from either of the cohort epidemiological studies represented in Table 2, are large enough to cover compliance costs without considering any other benefits.

In sum, recent regulations to reduce the emission of hazardous air pollutants, as well as the criteria pollutants, cost around $18 billion per year in aggregate.[25] Using the estimation methods and data in EPA's regulatory impact assessments, the mean lifesaving estimates for these rules in combination are over 20,000 to over 55,000 lives per year, discounted at 3%. The benefit estimates associated with these lifesavings are larger than the compliance cost of the regulations for all of the rules but two.

3 Methods and data

This section describes the methods and information sources underlying the several cost-effectiveness metrics used in the study. We first consider the compliance costs of the rules, before turning to the uncertainty analysis of the lifesavings resulting from the regulations. Next we consider the sources and methods for computing net cost numerators, and then turn to an explanation of two additional denominators: life years and QALYs. In combination, this development provides the necessary information for computing probability distributions for the cost-effectiveness metrics.

There are many uncertainties associated with regulatory impact evaluation (see Krupnick et al., 2006). While it is not possible to address them fully in this analysis, it is important to consider the bigger picture briefly to provide some perspective on the scope of our study. One key uncertainty is the emissions baseline. Future emissions will be influenced by difficult-to-anticipate market conditions, including changes in the price of fuel and other inputs, rates of economic growth, and

---

24 The VSLs are based on the mean of the VSLs in 26 labor market and contingent valuation studies conducted form 1974 to 1991. The value is $6.3 million ($2000). This figure is adjusted for income growth to the analytical reference year, and then converted into $2013.

25 This aggregate figure must be viewed as an approximate ballpark because it does not adjust for differences in the timing associated with the different analytical reference years in which the annual costs are computed. The annual OMB reports to Congress on the benefits and costs of federal regulations do not make this adjustment either. If the analytical reference years are significantly different, combining costs and benefits from different years could lead to significant biases.

technology trends. The estimation of emissions reductions that the regulation brings about also has uncertainties. The degree of compliance and the scope of the rule's impact may not be known with certainty, and rulemaking delays and reconsiderations often end up changing the structure of the rule. Uncertainties in the emissions baseline and the effect of the regulation will affect both compliance costs and mortality risks; hence, both the numerator and denominators of the cost-effectiveness ratios.[26]

Modeling the chemical transport and dispersion processes that translate emission reductions into local concentration changes also has uncertainties. Air quality models are subject to extensive validation tests (see Fann et al., 2012*a*), but atmospheric chemistry is complex. Recent research, for example, has found that interactions between NO_x emissions and ozone and ammonia can give non-convexities in the formation of ozone and fine particulates – resulting in negative damages in some urban locations from increased nitrogen oxide emissions (Fraas & Lutter, 2011, 2012).

Once the effects of emissions changes on concentrations have been estimated, the concentration changes are mapped to demographic characteristics at particular locations, and concentration–response models are used to estimate health effects. There are likely to be uncertainties in future demographic conditions, but the main uncertainty discussed in the literature concerns concentration–response modeling.

To make the analysis tractable, we take the reductions in emissions and exposure risks represented in the RIAs as given, abstracting from many of the uncertainties just described. This approach has the important implication that uncertainties about costs and lives saved can be treated independently, and channels the uncertainty analysis into particular areas. On the cost side, the analysis has to focus on uncertainties around the compliance cost per emission or exposure risk reduced, or "unit cost" as described in the literature on retrospective evaluation (Harrington, Morgenstern & Nelson, 2000; Kopits et al., 2014). In terms of outcomes, the assumption that exposures can be taken as given implies that uncertainty about the mortality risks per unit of exposure reduction is the relevant issue. We abstract from possibly relevant demographic uncertainties, and focus on the concentration–response relationship. We now turn to the estimation of unit costs and the concentration–response relationship between exposures and mortality risks.

---

[26] See "Special Issue: Retrospective Analysis of the Costs of EPA Regulations," *Journal of Benefit-Cost Analysis*, 5, 2 (2014) for the way these uncertainties can cause ex post cost estimates to differ from ex ante estimates.

3.1 Uncertainty in unit compliance costs[27]

There are significant uncertainties associated with regulatory cost estimation. Owing to the difficulty in formally modeling cost distributions, however, we chose not to conduct a formal uncertainty analysis. Rather, we use the cost estimates in the RIAs as the basis for the cost-effectiveness measures, while providing some qualitative perspective about them.

It is important to recognize two categories of uncertainties around compliance costs. The first is uncertainty about compliance strategies, engineering cost components, or market conditions which are known to analysts, and therefore, are measured and represented in the RIAs. Initial assumptions about these factors often prove to be in error, and are reported in retrospective evaluations. As an example, initial assumptions about per unit compliance costs for the 1998 Locomotive Emissions Standard were found to be half of what the cost turned out to be, due to inaccurate assumptions about the usage rates of different control strategies, and rising fuel prices (Kopits, 2014). On the other hand, ex ante estimates of compliance costs for the "Cluster Rule" were subsequently found to be 30%–100% higher than actual costs (Morgan, Pasurka & Shadbegian, 2014).[28] Cleaner technology and flexible compliance options reduced costs beneath the level initially expected.

Another uncertainty concerns cost categories not generally recognized in the RIAs. Research in the energy conservation literature offers relevant insight. Individuals often do not undertake energy conservation investments that an outside assessment based on engineering cost estimates would show to be profitable (Gillingham & Palmer, 2014), suggesting that the engineering cost estimates are leaving out relevant information. In fact, this context arises in our study: the energy savings associated with the NSPS for petroleum refineries alone are larger than the regulatory compliance costs. A reason that compliance is not voluntary, given this fact, could be unrecognized transaction costs arising from organizational or managerial constraints, information barriers, or administrative burdens (Krutilla & Krause, 2011; Martin, Muuls, de Preux & Wagner, 2010). Not being identified in the RIAs, uncertainties about these types of costs will not be picked up in retrospective evaluations.

We briefly consider uncertainties of one or both of these types for the following: compliance strategies, engineering costs, the regulatory implementation schedule and cost allocation, political transaction costs, and modeling frameworks.

---

27 The term "compliance cost," as used in this study, denotes either engineering or partial equilibrium cost estimates. This usage differs than that in EPA documents. EPA uses the term "social cost" to refer to costs that are estimated through multi-market modeling, and reserves the term "compliance costs" for engineering costs (see U.S. EPA, 2014).
28 The "Cluster Rule" is a combined rulemaking that integrated water and air pollution control in the pulp and paper industry. It was promulgated on April 15, 1998.

3.1.1 Compliance strategies

Firms have choices about compliance options, and this flexibility reduces the certainty of unit cost estimations. The fact that compliance takes place over time adds uncertainty, as market conditions and technology that affect the relative cost of different compliance alternatives change over time. The recent declines in natural gas prices, for example, have encouraged significantly more fuel switching to natural gas in the utility sector than initially anticipated (Burtraw, Palmer, Paul & Woerman, 2012).

Compliance options are greatest for incentive-based instruments, like tradable permits, and as noted previously, for ambient standards. But even for performance standards based on technology benchmarks, firms have significant compliance flexibility. To comply with MACT-based standards prescribed in the MATS, for example, firms can retrofit pollution controls, switch from coal to natural gas at existing generating units, or accelerate the retirement of coal-fired units and the planning for new plant constructions. To the extent that these compliance options cannot be fully anticipated, ex post compliance costs are likely to be different than the initial cost estimates in the RIAs (McGarity & Ruttenberg, 2001; McCarthy & Copeland, 2011; McCarthy, 2012).

3.1.2 Engineering costs

If firms choose to install pollution controls, uncertainties about control costs become relevant for cost estimation. EPA must sometimes choose between higher estimates made by the regulated industry and lower cost estimates submitted by the suppliers of equipment and other inputs to the regulated industry. Unit charges are included in EPA's cost estimation manual, which indicates that cost estimates are accurate within ±30% (U.S. EPA, 2002). Assuming that estimation errors are randomly distributed, total industry compliance cost estimates should be relatively accurate. However, EPA's cost manual is significantly out of date. In response to the 2014 Omnibus Bill, the manual is being revised over the next three years to reflect the evolution of materials prices, the component costs of pollution control systems, and the price of labor.[29]

Installed costs must also be considered, and may not be fully reflected in compliance cost estimates in the RIAs. The enactment of the multiple overlapping rules that has recently taken place can make retrofitting additional pollution controls relatively difficult (Chicanowicz, 2011). On the other hand, compliance with multiple rules might also present opportunities for scale economies that would lower unit costs.

---

29 See http://www.epa.gov/ttncatc1/products.html#cccinfo.

3.1.3 Regulatory timing and cost allocation

All of the rules in the study have faced implementation delays, due to administrative reconsiderations and/or legal actions. Such delays can increase unit costs by altering the timing of capital investments. Interrupted implementation also makes it difficult to accurately discount the temporal path of investment, and to allocate costs and effects across rulemaking phases. The CSAPR provides a notable example. In 2008, the District of Columbia Circuit Court of Appeals vacated CSAPR's predecessor, the Clean Air Interstate Rule (CAIR), but the ruling allowed EPA to administer the CAIR pending future regulation. By EPA estimates, industry incurred $1.6 billion in annual costs to comply with the CAIR by the end of 2011. The replacement of the CAIR with the CSAPR added another $0.8 billion in compliance costs. EPA's RIA uses the $0.8 billion cost figure, but includes the lifesaving estimates from the incremental change in emissions from the 2005 emissions baseline. In contrast, the 2012 OMB report to Congress included 30% of the total benefits in the RIA for the CSAPR, an amount estimated to correspond with the incremental regulation of the CSAPR beyond the CAIR rule it replaced (Office of Management and Budget, 2012). Our study takes a third approach: both the lifesaving estimates and the compliance costs are taken as the difference between the 2005 baseline and 2013 analytical reference year.

3.1.4 Political costs

Contested regulatory implementation imposes resource costs that stakeholders incur to try to influence outcomes. These costs are not included in conventional economic cost estimates of regulatory actions, but can be tractably modeled and reflected in a modified benefit-cost standard that incorporates lobbying costs and regulatory uncertainty (Krutilla & Alexeev, 2012). The presence of transfer payments, such as pollution taxes or subsidies, also influences lobbying costs and regulatory outcomes (Krutilla & Alexeev, 2014). Lobbying costs over policies with the rights structure of regulatory standards can amount to as much as 68% of total compliance costs.

3.1.5 Modeling methods

Engineering cost estimation and partial equilibrium modeling are the methods used to determine compliance costs in the RIAs in our study. Economists often make arguments for general equilibrium modeling, or dynamic market models, to better

reflect the market adjustments associated with rulemakings. A well-known dynamic general equilibrium assessment of the Clean Water Act found that social cost estimates could be higher or lower than engineering cost estimates (Hazilla & Kopp, 1990). A recent dynamic econometric model of the effects of regulating hazardous pollutants in the portland cement industry found that social costs were significantly higher than engineering cost estimates (Ryan, 2012).[30] A caveat is that the welfare effects in these models are driven by adjustments in input usage, output, and consumption – owing to changes in the equilibria in factor and commodity markets that the regulation brings about. In both the models mentioned, for example, prices rise, and output and consumption drop. These market responses can cause emissions to drop; thus, increasing benefits. Without holding the benefit side constant, it is hard to cleanly attribute the welfare effects demonstrated in these models to the cost side of the equation.

3.1.6 Conclusions

There are a number of factors that can cause realized unit compliance costs to vary from the estimates given in the RIAs, and the difference between initial estimates and realized costs can be significant. It is not uncommon for retrospective evaluations to find unit costs to be less than 50% to more than double the estimates in RIAs. Although the retrospective evaluation literature is spotty, there does not seem to be a directional bias in unit cost estimates (Harrington et al., 2000; Kopits et al., 2014). However, transactions costs will impose a downward bias to unit cost estimates in the RIAs, and are not measured in retrospective evaluations. The significance of these costs in the measurement of regulatory opportunity costs has received only limited research.

3.2 Lives saved and uncertainty analysis

The core of EPA's analysis of mortality risks is based on two families of cohort studies. The first, using the ACS's Cancer Prevention Study II cohort ("ACS Study") involves approximately 500,000 adults. The second, the Harvard Six Cities Study ("SCS study"), develops its own cohort involving a little over 8,000 adults.[31] Both

---

30 This result is also shown in static partial equilibrium models of concentrated industries, owing to the wedge between marginal values and costs (see RIA in Appendix B for Portland Cement).
31 The family of studies from the ACS cohort include Pope et al., 1995, 2002; Krewski et al., 2009. The SCS cohort studies include Dockery et al., 1993; Laden et al., 2006; Lepeule et al., 2012.

the ACS and the SCS studies follow individuals over time, estimating the relative risk of dying prematurely based on a Cox proportional hazards model. Both the initial ACS and SCS studies are regarded as being well done but rely on somewhat different variation in fine particulate concentrations to identify their estimates.

The 2002 National Academies' National Research Council (NRC) review of EPA's uncertainty analysis recommended, among other things, that the EPA include expert judgment about the state of knowledge in its analysis (NRC, 2002). Other approaches to synthesize the state of knowledge include either meta-analysis of studies or integrated exposure response assessment (see for example, Fann, Gilmore & Walker, 2013). Recent research by Smith and Gans (2014) and Fraas and Lutter (2013a) suggests that EPA focuses only on aleatory uncertainty and should do more to address epistemic uncertainty. The debate and following comments (Fann, Lamson, Anenberg, and Hubbell 2013; Fraas & Lutter, 2013b; Fann, Lamson, Luben & Hubbell, 2015) suggest that the issue remains controversial.[32]

One way to address epistemic uncertainty is with expert elicitations. In 2006 EPA conducted an expert elicitation study on the mortality risks associated with exposure to fine particulates (Industrial Economics, Inc., 2006; Roman et al., 2008).[33] The central values of the benefit estimates that follow from these expert judgments are reported in every RIA. This expert elicitation study could also be used to address epistemic uncertainties about impacts for the concentration–response functions, including uncertainties about causality; uncertainties about thresholds or nonlinearity in the concentration–response function; and uncertainties about differential toxicity of the ambient mix of fine particulate constituents. In our study, we use expert elicitation studies to address the first two of these uncertainties. Assessment of the third uncertainty requires speciation of the fine particulate mix and source attribution of emissions and is beyond the scope of this article. The effects of differential toxicity of particles are not a small uncertainty and have been discussed qualitatively in Smith and Gans (2014).

To provide further context for this analysis, some background on uncertainty analysis in EPA RIAs is given, and we describe the way the information in expert elicitation studies can be used to shed additional light on uncertainties around life-saving estimates.

---

32 Essentially, aleatory uncertainty is associated with confidence intervals from statistical estimation examining how the estimates could be different based on the sample that was selected while epistemic uncertainty examines uncertainty about the estimates stemming from not being clear about what model should be estimated.

33 Three of the authors of the ACS and SCS studies were on the expert-judgment panel. Their inclusion can be justified on the basis of their strong knowledge of the relevant data, but it also raises questions about whether they might be inclined to see their study results as especially definitive or influential.

3.2.1 Background

In its RIAs, EPA addresses aleatory uncertainty (i.e., confidence intervals which captures uncertainties about the data), while treating epistemic uncertainties about the model in sensitivity analyses. The predominate approach is to include the latest coefficient estimate for mortality risk from the ACS studies (for example either Pope et al., 2002 or Krewski et al., 2009) and the latest estimate from the SCS studies (for example Laden et al., 2006 or Lepeule, Laden, Dockery & Schwartz, 2012), with their associated confidence intervals. These studies extend the sample, adding additional precision to estimates because of the increased sample sizes and more sophisticated techniques, but whatever biases, mismeasurements, and omitted variables there are in original studies tend to persist, as will the reliance on cross-sectional variation or temporal variation in exposure levels for the identification of estimates.

To address the broader question of epistemic uncertainty, results from the 2006 expert elicitation study are summarized in the following sections. These expert elicitations allow experts to examine the evidence and to use their "mental models" to combine and adjust that evidence. Researchers using expert elicitations must decide whether to provide anonymity to their experts. Anonymity can potentially elicit evidence that better reflects the experts' opinions. On the other hand, not providing anonymity might lead to a better understanding of the reasons for the experts' perceptions (e.g., toxicologists might view the evidence differently than epidemiologists). Ultimately, both of the expert studies used in our study opted for anonymity, making nuanced interpretations of meanings less possible. While some may question our approach of aggregating information over experts as opposed to leaving them separate, we think both approaches have merit. Given our objective of comparing multiple EPA rules and multiple measures of cost-effectiveness, however, leaving the expert opinions disaggregated is not useful.

3.2.2 Causality

The original report on the elicitation (Industrial Economics, Inc., 2006) provides rich detail about how the individual experts viewed the causality issue and their reasoning for their probability statements. All of the experts initially started off with ranges of estimates for the probability of causality, most quite wide. All experts ultimately ended with a point estimate near the top of their range for the probability of causality. Only the point estimates for this probability of causality appear in Roman et al. (2008).

In Roman et al. (2008), four of the twelve experts ultimately attached nontrivial probabilities to the hypothesis that the association between PM2.5 and mortality was not causal. Those four non-causal probability statements ranged from 65% to 10% at some exposure concentrations; three experts placed the probability of non-causality at 5%. The remaining five experts placed the probability of non-causality at 2–0%. Only one of the experts placed the probability of non-causality at 0. If a typical statistical hypothesis criteria based on a 95% confidence interval were used, seven out of twelve of the experts would not reject a null hypothesis of non-causality. The elicitation also allowed the experts to refine their assessments about causality to depend on concentration. The average assessment of non-causality at the lowest concentration below 7 μg/m^3 was 13% while the average non-causality assessment was 9% for concentrations above 16 μg/m^3.

EPA's BenMAP maps the air quality model concentrations to the demographics at a particular location and applies information about the concentration–response model to identify benefits. The BenMAP program incorporates these non-causality probabilities in the assessment of the benefits for each of the twelve experts.[34]

EPA's Particulate Matter Integrated Science Assessment (PM ISA) provides another approach for assessing the concentration–response function (U.S. EPA, 2009). Unlike the expert elicitation where the variation across experts can be preserved, this group's deliberation is designed to achieve consensus. The consensus opinion in the PM ISA is that a causal relationship between fine particulates and mortality exists at a high probability.

Based on their 2009 PM ISA, the EPA incorporates no adjustment for non-causality in the estimates from the ACS and SCS cohort studies, assuming causal relationships. Additionally, in those RIAs where EPA incorporates the uncertainty around the individual expert central values, it appears that EPA leaves the uncertainty associated with non-causality out of the confidence intervals.

The issue of non-causality should not necessarily be viewed as an all or nothing proposition. Indeed several of the experts chose not to separate the question about non-causality from the magnitude of the concentration–response impact. Clearly, the ACS and SCS families of studies cannot both be correct. When considering how to evaluate these studies the Industrial Economics, Inc. study (2006) provided details about what the experts viewed as weaknesses in the studies, suggesting

---

[34] Experts were requested to specify a full distribution for the impact of changes in fine particulate concentrations. Five of the experts chose to incorporate their causality probabilities directly into their probability distribution of impacts while the remaining seven chose to provide causality probabilities and conditional distributions for the impact of fine particulate reductions separately. We construct the information given to obtain the unconditional distribution for the concentration–response coefficient. This is consistent with the way that BenMAP (U.S. EPA, 2014) constructs the distributions in Appendix E of the user's manual.

departures from the true causal concentration–response relationship for each study. Chief among these were weaknesses in the measurement of fine particulate concentrations at specific locations, weak controls for smoking behavior and the tendency to include more highly educated individuals in cohorts. Fraas and Lutter (2013*a*) point out that the cohort studies do not control for systematically time varying variables such as advances in medical treatments. None of the experts raised this as an issue. This issue is potentially important for a number of reasons. Both medical advances and reductions in fine particulates tend to be correlated with time, suggesting that at least some of what the ACS and SCS attribute to fine particulate reductions could be due to this lack of control. And further, that because the SCS has less spatial variation than the ACS studies, it is more susceptible to spurious correlation bias.

On the basis of evaluating the causality judgment in the EPA expert elicitation, a 95% confidence interval for the mortality impact of reducing PM2.5 will include 0 for concentrations greater than 16 $\mu g/m^3$. For concentrations of less than 10 $\mu g/m^3$, a 90% confidence interval will also include 0.

3.3 Nonlinearity and thresholds

Starting with the RIA for the Portland Cement Rule in 2010, EPA stopped using a threshold value of 10 $\mu g/m^3$ in RIAs, and replaced it with their lowest measured level (LML) methodology.[35] This approach identifies the lowest measured fine particulate concentration level in the most recent of the ACS or SCS cohort studies and allows the reader to decide what fraction of benefits can be relied on when extrapolating impacts far from the sample means, and even beyond the limits of the sample. EPA notes that these out-of-sample benefit ranges have considerably more uncertainty associated with them than within sample ranges, but they include these extrapolations in their analysis without an uncertainty analysis beyond the aleatory uncertainty associated with the standard errors of ACS and SCS impact coefficients. In this latest set of air quality rules, benefit reductions at levels below 10 $\mu g/m^3$ constitute a much larger fraction of benefits compared to prior rules, and suggest a reliance on these more uncertain benefits.

---

35 This does not necessarily mean that EPA analysts ever believed that there was a 10 $\mu g/m^3$ threshold or that they have changed their opinion. Instead, they may have viewed benefits in the range below 10 $\mu g/m^3$ as being subject to more uncertainty and unnecessary to justify the regulation. EPA's inclusion of these benefits in subsequent RIAs is based on the conclusion of the fine particulate ISA in 2009 that the best evidence supports a no-threshold linear relationship between long-term fine particulate exposure and premature mortality.

No studies provide much information about low-concentration extrapolation of benefits. EPA's experts (Industrial Economics, Inc., 2006) were given the opportunity to evaluate the studies and express their judgments about causality and impact at low concentrations. To represent these nonlinearities, experts were given the opportunity to specify a break point greater than 4 μg/m^3 where they thought that the concentration–response function would be different. Four of the twelve experts expressed either a lower probability of causality or a lower health impact for exposures at the lower concentration levels. None expressed an expectation of a supralinear impact (the impact increases as the concentration is lowered). Some experts suggested that there was not much evidence for a threshold or nonlinearity but continued that it was unlikely that long-term exposure studies would be able to adequately estimate a threshold even if one existed.

We combine the expert judgments about nonlinearities and causality, weighting the judgments equally. The resulting distribution is shown in Figure 1.[36] The blue distribution (probability distribution for mortality effect per 1 μg/m^3 reduction in fine particulates) has a higher spike at 0 (indicating the judgments of noncausality) than the red distribution. The blue distribution represents the probability distribution for reductions less than 7 μg/m^3 while the red distribution represents the probability distribution for reductions at higher ambient levels over 16 μg/m^3. The experts, on the whole, expect some non-causality/nonlinearity at lower concentrations, but not large nonlinearities.[37]

3.4 Performance weighting and additional expert elicitations

The expert elicitation in Cooke et al. (2007) and Tuomisto, Wilson, Evans and Tainio (2007) provided six more expert judgments about health effects associated

---

36 In many cases the experts provided enough information about a parametric distribution, possibly truncated, that they specifically chose to fit the parameters to that distribution directly. In other cases, the experts chose nonparametric distributions that were more difficult for us to fit. Expert B chose a bimodal distribution that would not fit most parametric distributions that assume unimodality. We used a piecewise uniform distribution to fit it, preserving all the characteristics about quantiles. In other cases where no specific distribution was chosen we used a four parameter Johnson distribution. We simulated 100,000 draws from each expert distribution and then merged the data together to generate the combined distribution representing the synthesis of the unconditional distributions for all experts.

37 Some of the more recent studies such as Krewski et al. (2009) and Lepeule et al. (2012) hint at a potential supralinearity (that is, the concentration–response relationship is steeper at low concentrations than at high ones). Such a finding might also be the result of failures to adequately control for time varying confounding variables like medical advances. Over time, as the concentration of fine particulates is reduced by less each year, this reduction is related to the same improvement in medicine. This could make a sublinear relationship look more linear.
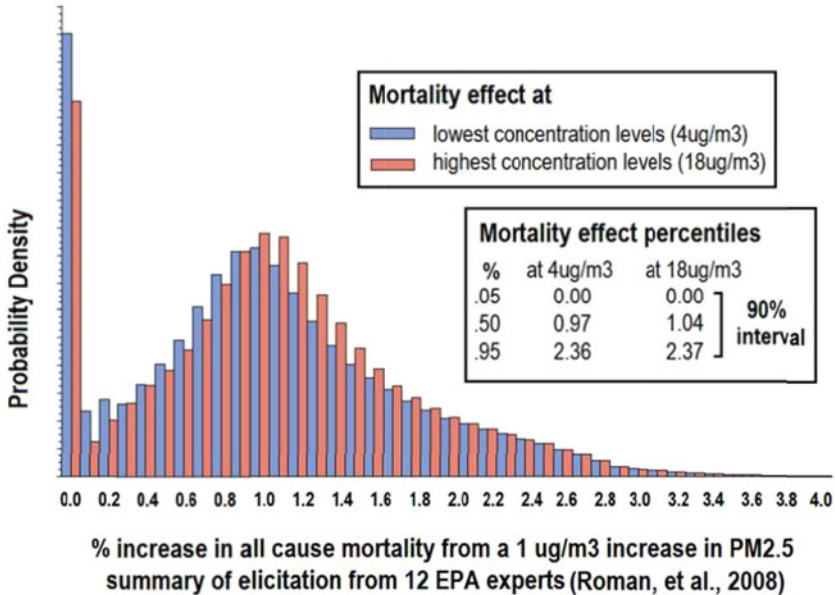
Figure 1 Simulated distribution of epistemic and aleatory uncertainty for 12 US experts on the impact of a 1 μg/m^3 increase in PM2.5 at high- and low-concentration levels.

with the American ambient mix of fine particulate species.[38] These judgments also addressed the possibility of differential toxicity and provided additional information about performance weighting of the judgments based on the experts' ability to answer 12 seed questions (see Cooke (1991) for the performance-weighting approach). To capture more detail about these distributions we fit a four parameter Johnson distribution to the percentiles for each of their distributions since there were no specific statements available about the parametric distribution that most represented the experts' perceptions of health effects of fine particulates. This distribution is based on the sinh transformation of the normal and has the ability to represent either positive or negative skewness or kurtosis that differs from the normal. Our distributions fit quite well for all six experts. As shown in Figure 2, these are aggregated using either equal weighting (blue) or performance weighting (red). In general, experts who supplied more informative answers on the seed questions tended to express lower central estimates of mortality impacts of fine particulates and a lower degree of dispersion.

Performance weighting can offer the potential to reduce epistemic uncertainty by placing more weight on the distributions from more knowledgeable experts. This

---

38 While the experts found the American and European species mix to have very comparable health effects, individual experts often noted very different toxicities associated with individual species.
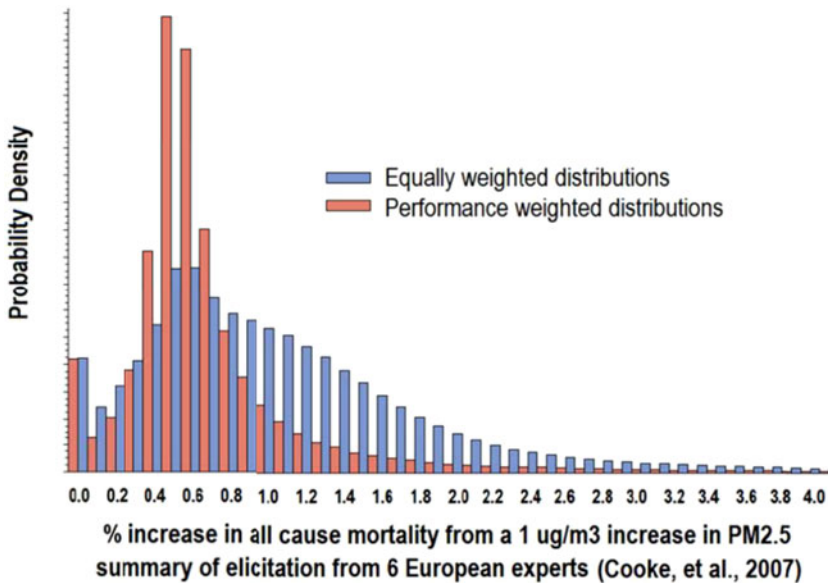
Figure 2 Performance weighting of simulated distributions for six European experts on the impact of a 1 $\mu g/m^3$ increase in PM2.5 concentrations in the United States.

is illustrated by the smaller variation in the red distribution (performance weighted) than the blue distribution (equally weighted) shown in Figure 2. While the inclusion of performance weighting was discussed in the Industrial Economics, Inc. (2006) elicitation, ultimately they decided not to use the procedure, and no seed questions are available for us to construct the weighting. Because the questions asked in the European study were somewhat different than in the EPA elicitation, the European study experts are not combined with the EPA experts. However, the equally weighted unconditional distributions are very comparable so that our results would not change importantly if all eighteen experts were integrated with equal weighting. Performance weighting of the experts does reduce the variation in the distribution, suppressing some perspectives and emphasizing others. Whether performance weighting is useful depends on the quality of the seed questions, which may be difficult to assess a priori.

The distributions from Figure 1, along with the intermediate distributions at concentrations between 7 and 16 $\mu g/m^3$ are used to generate a distribution of premature deaths avoided by each rule.[39] In turn, the distributions for lifesavings are

---

[39] In each RIA, EPA provides a distribution of benefits based on the initial concentration. For example, the RIA might state that 10% of the PM reductions were accrued when the initial concentration was

used to construct confidence intervals for the different cost-effectiveness metrics used in the study.

3.5 Cost-effectiveness measures

In this section, we discuss the cost-effectiveness ratios used in the study. Numerators are constructed by subtracting some of the benefits other than lifesavings from compliance costs, giving a "net cost," while denominators are represented as lives saved, life years saved, or QALYs gained. The methods used to derive the various cost-effectiveness measures follow the standard practice for cost-effectiveness analysis in the health evaluation field (Robinson & Hammitt, 2013), and in the extensions made to the assessment of air quality regulations (Robinson et al., 2005; U.S. EPA, 2006; Hubbell, 2006; Cohen, Hammitt & Levy, 2003).

The categories of health benefits that are typically monetized in EPA RIAs are shown in Table 3, with an example valuation based on central estimates from the CSAPR. The pattern displayed is typical for the rules in the study. Mortality benefits are significantly larger than morbidity benefits. For the morbidity category, chronic bronchitis and non-fatal heart attacks are the largest components.[40] The RIAs derive estimates of the effects of air regulations and their valuation from a variety of sources. Avoided cases of chronic bronchitis and non-fatal heart attacks are derived respectively from health impact functions from Abbey, Hwang, Burchette, Vancuren and Mills (1995) and Peters, Dockery, Muller and Mittleman (2001). A willingness to pay study by Viscusi, Magat and Huber (1991) is the starting point for the valuation of chronic bronchitis.[41] A cost of illness (COI) valuation with two components – medical costs and work productivity – is used to value non-fatal myocardial infarctions. A study by Wittels, Hay and Gotto Jr. (1990) provides the estimates for the medical costs, while Cropper and Krupnick (1990) is used to value lost earnings. A variety of mostly COI studies are used to determine values for the other morbidity categories shown in Table 3.

---

between 10–11 μg/m^3. Ideally, we would use a distribution of benefits associated with 11–10 μg/m^3 for the first unit of reduction, and 10–9 μg/m^3 for the second unit, and so on. However, since we do not know the distribution of reductions, this is not possible. Instead, we use the impact for 10–11 for all reductions that start at this concentration. The ultimate result is that this approach tends to overstate benefits slightly, particularly at locations where the magnitude of reductions is large.

40 EPA stopped monetizing the value of reducing chronic bronchitis starting with the RIA for the NAAQS for PM. But the RIAs for all of the rules in our sample monetize the value of reducing chronic bronchitis.

41 See the CSAPR RIA pdf pp. 119–120.

Table 3 Health endpoints and their evaluation for the Cross State Air Pollution Rule.

Morbidity	Health end point	Mean total value (Billions $2007)
Duration more than 1 year	Mortality	$100/$270[1]
	Chronic bronchitis	$4.2
	Non-fatal heart attacks	$1.7[2]
Duration less than 1 year	Hospital admissions-respiratory	$.04
	Hospital admissions-cardiovascular	$.09
	Hospital admissions asthma-related ER	$.003
	Acute bronchitis	$.008
	Upper respiratory symptoms	$.005
	Lower respiratory symptoms	$.004
	Asthma exacerbations	$.02
	Work loss	$.2
	School absence	$.01
	Minor restricted activity	$.7

[1]Estimates from American Cancer Society Study and Harvard Six Cities Study respectively.
[2]3% discount rate.

Energy savings and diminished carbon emissions are sometimes valued in the RIAs, and visibility benefits are monetized for the CSAPR. We use the central benefit estimates given in the RIAs for the monetary valuation of these categories, and also for the morbidity benefits.[42]

From the benefits monetized in the RIAs, two "net cost" numerators are constructed. The first subtracts all benefits from the rule's compliance costs other than the value of avoided mortality. We denote the result as the "low net cost boundary." It is possible for this subtraction to yield a negative number, implying that the non-mortality benefits alone are sufficient to cover the compliance costs of the rule. In this case, the regulation is denoted as "cost saving," and no further computation is conducted.

When QALYs are used to represent outcomes, a second net cost numerator is computed. Two adjustments are made to the first measure. The productivity part of

---

42 There has been some recent discussion about the appropriate accounting stance for valuing global climate benefits. Gayer and Viscusi (2014) argue that the accounting perspective should be national, which is consistent with the general recommendation in OMB Circular A-4. The national accounting stance reduces the Social Cost of Carbon to 7–10% of its total value if U.S. benefit estimates are derived directly from integrated assessment models, and to 23% if it is assumed that the U.S. share of climate benefits is proportional to the share of the U.S. economy in global GDP. However, for the rules in the study that estimate climate benefits, the benefits were relatively small. Given that it does not matter very much, we did not adjust the global warming benefit estimates in the RIAs to the U.S. accounting perspective.

the COI estimate for non-fatal heart attacks is excluded, rather than subtracted, in the numerator computation. This adjustment reflects the common point of view in the health evaluation literature that productivity is represented in the QALY measure in the denominator.[43] The morbidity estimate for chronic bronchitis is also excluded from the numerator. In theory, the medical cost part of the estimate should be subtracted from the compliance cost while the other components should be removed on the assumption that productivity and utility gains are represented by the QALY measure in the denominator (Institute of Medicine, 2006). However, there is no empirical basis to make this discrimination. Consequently, chronic bronchitis is fully excluded. This results in a high net cost boundary. These two net cost measures bracket the formats discussed in the literature on cost–utility analysis.

Table 4 shows the two net cost numerators. Two of the rules, the CSAPR and NSPS for Petroleum Refineries, are cost savings in all of the permutations. The visibility benefit and the value of avoided bronchitis for the CSAPR rule are each above $4 billion, while compliance costs are $2.6 billion. As noted before, the negative net cost for the Petroleum Refinery rule comes from energy savings. The Boiler MACT rule is also cost saving at 3% for the low-bound numerator. This rule significantly reduces chronic bronchitis and myocardial infarctions, and the associated benefits lower net costs. For the other rules, the benefits are less than the compliance costs, so they have positive net cost numerators.[44]

Turning to the outcome side, none of the RIAs in our study provided estimates of lives saved by age class. This information is necessary for estimating life years gained. Additionally, for the six rules in our study using the "benefit per ton" approach, there is no information on the fine level geographic detail that would show how pollutant concentrations might be correlated with age class. To deal with this informational constraint, we assume that age distributions are independent of concentrations and use fairly course state level information about mortality incidence rates to estimate life year savings. This approach may not lead to significant biases given the need for spatial aggregation for benefit analysis (see Smith & Gans, 2014). As a point of comparison, our estimates of undiscounted life years per life saved are 15.31, 15.49, and 15.31 using age-class mortality incidence data for the eastern states covered by the CSAPR, the 32 states covered by the NSPS for Petroleum refineries, and the entire United States. These figures compare with estimates given in the RIA for the NAAQS for PM of 15.0 using the ACS study and 16.0 using the SCS study. In short, our method gives life year estimates in

---

43 See Tilling et al. (2012) and U.S. EPA (2006) for a discussion of this issue.
44 A number of benefits are not monetized in EPA RIAs, e.g., the health and morbidity benefits associated with the reduction of other pollutants than PM2.5. Adding the monetary valuation of these omitted benefits would reduce the net cost ratios.

Table 4 Two net costs (gross compliance cost less benefits) for numerators.

Rule	Low Bound ($2013 000')[*] (Used in all ratios)		High Bound ($2013 000')[*] (Used only with QALY denominators)	
	3%	7%	3%	7%
Mercury and air toxic standards (MATS)	7,600,000	7,800,000	9,600,000	9,800,000
Cross state air pollution rule (CSAPR)	Cost saving	Cost saving	Cost saving	Cost saving
National emissions standards for hazardous air pollutants (NESHAP) for major boilers ("Boiler MACT")	Cost saving	$18,000	$970,000	$970,000
National emissions standards for hazardous air pollutants (NESHAP) for area source boilers	$520,000	$520,000	$520,000	$520,000
NESHAP for commercial and industrial solid waste incinerators	$250,000	$250,000	$270,000	$270,000
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$550,000	$560,000	$870,000	$870,000
NESHAP for compression ignited reciprocating internal combustion engines (CIRICE)	$350,000	$350,000	$370,000	$370,000
NESHAP for spark-ignited reciprocating internal combustion engines (SIRICE)	$120,000	$120,000	$120,000	$120,000
New source performance standards (NSPS) for petroleum refineries	Cost saving	Cost saving	Cost saving	Cost saving

[*]Estimates are rounded to two significant figures. The difference between the 3% and 7% discount rates is sometimes not apparent at two significant figures.

the neighborhood of those that EPA has estimated in an RIA based on air quality modeling.[45]

Following the Institute of Medicine (2006) and U.S. EPA (2006), QALYs were computed for the avoided incidences of chronic bronchitis and myocardial infarctions. Incidence of these morbidity categories by age group were taken from data compiled by the U.S. Department of Health and Human Services (2012, 2014) and the National Hospital Discharge Survey (Hall, DeFrances, Williams, Golosinskiy & Schwartzman, 2010). Following U.S. EPA (2006), individuals with chronic bronchitis were assumed to have normal lifespans.[46] For non-fatal heart attacks, assumptions about life spans and the probability of various health conditions after heart attacks were taken from U.S. EPA (2006, pdf pp. 20–24). With utility weights, this information gives the expected QALYs saved from reducing non-fatal heart attacks.

Preference-based EQ-5D scores are used for utility weights, as recommended by the Institute of Medicine (2006). These scores are taken from a regression study by Sullivan and Ghushchyan (2006), based on data from the Medical Expenditure Panel Survey. Coefficient estimates from this regression give the marginal changes in EQ-5D scores as a function of various health conditions. The Sullivan and Ghushchyan study also gives age-based EQ-5D utility weights for baseline health status. We adjust baseline health status to reflect age, as recommended by the Institute of Medicine (2006).

The weights used in our study are shown in Tables 5 and 6. Notice that the decline in utility associated with the change in health status from aging is larger than the decline in utility from the health state change associated with any one category of morbidity, holding all else constant.

4 Results

Cost-effectiveness ratios are displayed in Tables 7–11. For illustrative purposes, the ratios are shown for the 3% discount rate. With the exception of the Boiler MACT rule, the difference between the 3% and 7% rates does not significantly affect results. (Again see Table 4).

---

45 Data for mortality incidence by age class are from an online data base, CDC Wonder. We averaged the percentage of the age-specific mortality across 3 years (2004 through 2006). Once the age distributions were determined, discounted life years were computed for each age class based on the age-specific conditional lifespans. These discounted life years were then aggregated.
46 This assumption provides an upward biased estimate of the QALYS gained from avoiding chronic bronchitis if individuals with chronic bronchitis do not have normal lifespans.

Table 5 Age related EQ-5D score.

Age	Mean EQ-5D
18–29	0.922
30–39	0.901
40–49	0.871
50–59	0.842
60–69	0.823
70–79	0.790
⩾80	0.736

Source: Sullivan, P.W., & Ghushchyan, V. (2006).

Table 6 Mean change in EQ-5D score (holding other covariates constant).

Condition	Mean change in EQ-5D
Angina	−0.0409
Acute myocardial infarction	−0.049
Congestive heart failure	−0.065
Emphysema	−0.0667

Source: Sullivan, P.W., & Ghushchyan, V. (2006).

For comparative purposes, Table 7 reproduces the gross cost per discounted life saved ratios shown in Table 2 that correspond to those derived from the ACS cohort study, and also presents the mean and 90% confidence intervals for the cost per discounted life saved ratios from the simulation of expert judgments. The simulated mean estimates are always lower than the estimates derived from the ACS study, because the expert judgments on relative risk tend to lie between those in the ACS and SCS cohort studies. The simulated means for the cost per life saved ratios are therefore lowered by the expert judgments closer to the SCS estimates. The lower confidence limit for the cost per life saved ratios is pulled down further by the variability around the judgments about the risk coefficient estimates. The lower limit for the confidence interval are less than the VSL (again between $9.0 and $10.0 million in $2013 for the analytical reference years) for all of the rules in the study, indicating that lifesaving estimates alone are sufficient to cover the cost of the rules for this part of the cost-effectiveness distribution.

For the mean estimates, the cost-effectiveness ratios are less than the VSLs for all of the rules except for the Area Source Boiler Rule, and the SIRICE rule. On the other hand, the greater variability that comes from combining all of the information in the expert elicitations raises the cost-effectiveness ratios at the upper

Table 7 Gross cost per discounted life saved.

Rule	American Cancer Society Study mean estimate, 3% ($2013 millions)[*]	Simulated distribution from integrated expert elicitations, 3% ($2013 millions)[*]		
		0.05	Mean	0.95[**]
Mercury and Air Toxic Standards (MATS)	$2.80	$0.70	$1.60	∞
Cross State Air Pollution Rule (CSAPR)	$0.20	$0.10	$0.10	∞
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	$0.60	$0.20	$0.40	∞
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for area source boilers	$24.00	$6.00	$14.00	∞
NESHAP for commercial and industrial solid waste incinerators	$6.60	$1.70	$3.90	∞
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$1.30	$0.30	$0.80	∞
NESHAP for Compression Ignited Reciprocating Internal Combustion Engines (CIRICE)	$5.10	$1.30	$3.00	∞
NESHAP for Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE)	$19.00	$4.80	$11.00	∞
New Source Performance Standards (NSPS) for petroleum refineries	$4.60	$1.20	$2.70	∞

[*]Estimates rounded to two significant figures.
[**]Corresponds to no lives saved.

end of the confidence interval – to infinity. This upper 5% limit corresponds to the "no lives" saved part of the probability distribution for lifesavings. This outcome illustrates a stark dichotomy. Within a simulated 90% confidence interval, there is both the possibility that benefits from lifesavings alone are sufficient to cover the costs of all of the air quality regulations in the study, and the possibility that no lives will be saved and the cost-effectiveness ratios will be infinite for any of the regulations.

Table 8 shows the 90% confidence interval for the net cost per discounted life saved. Given the results in Table 7, it is not surprising that the ratios at the lower confidence limit are lower than the VSL for all the rules in the study. For the mean

Table 8 Net cost per discounted life saved.

Rule	American Cancer Society Study mean estimate, 3% ($2013 000')[*]	Simulated distribution from integrated expert elicitations, 3% ($2013 000')[*]		
		0.05	Mean	0.95[**]
Mercury and Air Toxic Standards (MATS)	$2,000	$510	$1,200	∞
Cross State Air Pollution Rule (CSAPR)	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for area source boilers	$22,000	$5500	$13,200	∞
NESHAP for commercial and industrial solid waste incinerators	$5,900	$1,500	$3,500	∞
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$630	$160	$370	∞
NESHAP for Compression Ignited Reciprocating Internal Combustion Engines (CIRICE)	$4,500	$1,100	$2,700	∞
NESHAP for Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE)	$18,000	$4,700	$11,000	∞
New Source Performance Standards (NSPS) for petroleum refineries	Cost saving	Cost saving	Cost saving	Cost saving

[*]Estimates rounded to two significant figures.
[**]Corresponds to no lives saved.

estimates, the ratios are less than the VSL with the exception of the Area Source Boiler Ruler and the SIRICE rule. These results are again consistent with those in Table 7, and are also consistent with the sign of the net benefits estimated for these

Table 9 Net cost per discounted life year saved.

Rule	American Cancer Society Study mean estimate, 3% ($2013 000')[*]	Simulated distribution from integrated expert elicitations, 3% ($2013 000')[*]		
		0.05	Mean	0.95[**]
Mercury and Air Toxic Standards (MATS)	$170	$43	$100	∞
Cross State Air Pollution Rule (CSAPR)	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for area source boilers	$1,870	$490	$1100	∞
NESHAP for commercial and industrial solid waste incinerators	$500	$130	$300	∞
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$54	$14	$32	∞
NESHAP for Compression Ignited Reciprocating Internal Combustion Engines (CIRICE)	$380	$97	$230	∞
NESHAP for Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE)	$1,600	$400	$930	∞
New Source Performance Standards (NSPS) for petroleum refineries	Cost saving	Cost saving	Cost saving	Cost saving

*Estimates rounded to two significant figures.
**Corresponds to no lives saved.

rules in the RIAs. The upper confidence interval for the net cost per lives saved again is infinity for the rules that are not cost saving.

Of course, the general pattern is similar when life years are represented in the denominator (see Table 9). For the rules that are not cost saving, the ratios at

Table 10 Net cost per discounted QALY saved, low-bound net cost (estimates rounded to two digits).

Rule	American Cancer Society Study mean estimate, 3% ($2013 000')	Simulated distribution from integrated expert elicitations, 3% ($2013 000')		
		0.05	Mean	0.95
Mercury and Air Toxic Standards (MATS)	$180	$52	$120	$1,400
Cross State Air Pollution Rule (CSAPR)	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for area source boilers	$2,100	$600	$1,300	$15,000
NESHAP for commercial and industrial solid waste incinerators	$530	$150	$330	$3,600
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$57	$16	$36	$390
NESHAP for Compression Ignited Reciprocating Internal Combustion Engines (CIRICE)	$410	$120	$260	$3,200
NESHAP for Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE)	$1,700	$470	$1,100	$13,000
New Source Performance Standards (NSPS) for petroleum refineries	Cost saving	Cost saving	Cost saving	Cost saving

*Estimates rounded to two significant figures.
**Corresponds to no lives saved.

the lower 5% confidence limit range from $14,000 for the Portland Cement Rule to $490,000 for the Area Source Boiler rule. The means for the corresponding cases vary from $32,000 per life year saved to $1,100,000 per life year saved.

Table 11 Net cost per discounted QALY saved, high-bound net cost.

Rule	American Cancer Society Study mean estimate, 3% ($2013 000')[*]	Simulated distribution from integrated expert elicitations, 3% ($2013 000')[*]		
		0.05	**Mean**	**0.95**[**]
Mercury and Air Toxic Standards (MATS)	$230	$65	$140	$1,800
Cross State Air Pollution Rule (CSAPR)	Cost saving	Cost saving	Cost saving	Cost saving
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for Major Boilers ("Boiler MACT")	$31	$9	$19	$220
National Emissions Standards for Hazardous Air Pollutants (NESHAP) for area source boilers	$2,100	$600	$1,300	$15,000
NESHAP for commercial and industrial solid waste incinerators	$560	$160	$350	$3,800
NESHAP for the portland cement manufacturing industry and performance standards for portland cement plants	$90	$25	$56	$610
NESHAP for Compression Ignited Reciprocating Internal Combustion Engines (CIRICE)	$450	$130	$280	$3,400
NESHAP for Spark-Ignited Reciprocating Internal Combustion Engines (SIRICE)	$1,700	$480	$1,100	$13,000
New Source Performance Standards (NSPS) for petroleum refineries	Cost saving	Cost saving	Cost saving	Cost saving

*Estimates rounded to two significant figures.
**Corresponds to no lives saved.

However, the cost-effectiveness ratios for the six rules that are not cost saving are infinite at the upper 5% confidence interval. Tengs et al. (1995) provides one benchmark against which to compare these results. As mentioned before, the median cost-effectiveness ratio in that study was $61,981, with the median for medical

interventions at \$28,039 and those for toxin control of \$4.1 million. It seems unlikely that the median estimates in our study would be less than the \$61,981 figure for any of the rules but for portland cement manufacturing (which has a mean estimate of \$32,000). Thus, if lower than the median in Tengs et al. (1995) is taken as a metric for relative cost-effectiveness, some regulations in our study having positive net benefits (having net cost per life saved less than the VSL) will not meet this standard – suggesting that different ratio formats can have different normative implications. Regardless, uncertainty about the lifesaving effects of the regulations reconciles the normative standards at the upper confidence limit in which no lives are saved and the regulations with positive net costs are not cost-effective by any measure.

Table 10 indicates the net cost per QALY saved by each of the rules using the low-bound numerator (Again see Table 4). At the lower 5% confidence limit, the net cost per QALY of all of the rules is less than \$200,000 except for the Area Source Boiler rule, and the SIRICE rule. At the mean, only the MATS and the Portland Cement Rule have net cost per QALY less than \$200,000. At the upper 5% limit, the net cost per QALY ratios are finite, reflecting the utility gains from reducing cases of chronic bronchitis and non-fatal heart attacks even without any lifesavings. But the net cost per QALY ratios at this point are relatively high. At the upper 5% limit, all of the rules with positive net cost ratios have net cost per QALY values above \$200,000.

Table 11 shows the boundary case for the high net cost numerator. In this case, the Boiler MACT rule is not cost saving, but it is the lowest cost rule of any of the rules that have positive net costs. The 90% confidence for the net cost per QALY for this rule runs from \$9,000 to \$220,000. For the group of other rules having positive net costs, the ratios are marginally higher than those reported for the high net cost bound in Table 10, with the overall pattern being consistent.

In the health evaluation literature, \$50,000–\$100,000 per QALY gained has been a traditional benchmark for gauging cost-effectiveness (Grosse, 2008). More recently, thresholds from \$100,000 to \$200,000 have been suggested (Neumann, Cohen & Weinstein, 2014). Although widely used, cost-effectiveness benchmarks have been criticized as arbitrary (Neumann et al., 2014), and for not reflecting relevant WTP measures very well (Grosse, 2008). Even with these criticisms, these benchmarks provide another reference point for how the cost-effectiveness of air regulations might be regarded in the health evaluation literature. The ratios that are cost savings are cost-effective by definition. For those regulations with positive net costs, the air quality interventions would not be regarded as cost-effective for ratios at the upper 5% limit. With the exception of the Boiler MACT for the low net cost boundary, none of the net cost per QALY figures is close to \$200,000 per

year at the upper 5% limit. This suggests that, without mortality risk reductions, the values now monetized in RIAs are not alone likely to make air regulations look cost-effective by the conventional standards of cost–utility analysis.

On the other hand, mortality risk reductions occurring at the mean and lower 5% confidence limits significantly lower the net cost per QALY figures. As noted above, all rules have net cost per QALY lower than $200,000 at the lower 5% confidence limit with the exception of the Area Source Boiler rule and the SIRICE rule. For the mean estimates, the picture is more mixed. The mixed picture at the mean again shows that the normative conclusions drawn from different cost-effectiveness metrics – cost–utility analysis in this case – may not dovetail with benefit-cost analysis. Specifically, while the mean estimates for net cost per QALY in Tables 10 and 11 do not necessarily fall under the $200,000 benchmark, the means for the ratios in Table 8 are less than the VSL – again with the exception of the SIRICE and Area Source Boiler rules – indicating that they pass the benefit-cost test.

5 Discussion and conclusion

We have studied recent EPA regulations targeting stationary source air emissions, and have simulated a 90% confidence interval for the premature deaths avoided by each regulation. These simulations are based on the combined judgments of experts concerning the relationship between airborne particulate exposures and mortality risks. Adding estimates for compliance cost and morbidity benefits gives 90% confidence intervals for cost-effectiveness ratios.

Two of the rules in the sample, the CSAPR and the NSPS for Petroleum Refineries, are "cost saving" in all permutations. That is, the non-mortality benefits that these rules provide are sufficient to pay off the compliance costs of the rules. The Boiler MACT is also cost saving for the 3% discount rate and lower bound estimate for its net cost numerator. Of the rules having positive net costs, the net cost-effectiveness ratios differ significantly between the lower and upper confidence limits. Most of the rules are cost-effective by most metrics at the lower 5% confidence bound, while most of the rules are not cost-effective measured by any metric at the upper 5% confidence limit. In particular, all rules with positive net costs have infinite cost-effectiveness ratios at the upper 5% limit when the denominators are lives or life years saved. At the mean, the picture is more varied.

Structural aspects of air regulation explain the width of the 90% confidence intervals for cost-effectiveness ratios. Air pollution creates exposure risks for virtually everyone. Small changes in the estimates of relative risk will therefore give large changes in estimated mortality risk reductions. The sensitivity of predictions

about total lives saved to minor differences in relative risk estimates suggests the importance of resolving informational uncertainty about the effects of fine particle exposures on mortality risks.

Our work has focused on particular aspects of epistemic and aleatory uncertainty in concentration–response models, but not on others such as the toxicity of different fine particulate species. To include these uncertainties would have widened the confidence intervals further. At the same time, it should be recognized that the existing expert elicitation studies are more than eight years old and could overstate, as well as understate, uncertainties about causality, magnitudes of impacts, and nonlinearities. As a result, updated elicitations should be conducted reflecting information from recent research, including extensions of the ACS and SCS cohort studies as well as the integrated science assessment sponsored by the EPA (U.S. EPA, 2009). Experience in the use of expert elicitations has increased, allowing for better assessments of uncertainty to more refined questions. An updated elicitation study could complement EPA's ongoing efforts to integrate scientific knowledge about the consequences of fine particulate mortality.

We believe our results also contain insights relevant for the larger cost-effectiveness literature. The confidence intervals for cost-effectiveness ratios around the rules in our study are substantially wider than the differences between the means. However, uncertainties for air regulations are highly correlated, reflecting lives saved estimates generated from the same relative risk coefficients. In the more common context of cost-effectiveness analysis, effects across interventions are not likely to be so strongly correlated. In that case, the results of our study serve as a reminder that confidence intervals are important for cost-effectiveness comparisons. Standard "league tables" that compare cost-effectiveness ratios usually contain point estimates. That begs the question of how much uncertainty there is in the estimates given in these tables, and suggests that interpretations about cost-effectiveness based on comparisons of point estimates be made cautiously. The presentation of confidence intervals for cost-effectiveness ratios would also allow an expanded analysis that compares trade-offs in means and variances for different interventions.

Elisabeth Gilmore, Kevin Boyle, James Barnes, and Dan Cole offered knowledgeable perspectives on various aspects of the work, while Ed Chicanowicz and Mark Menefee provided useful information about compliance costs. Yu Zhang, Gabriel Piña, Michelle Hoover, and Tyler Kerr provided capable research assistance. Finally, Glenn Blomquist and an anonymous reviewer provided perceptive and detailed comments on an initial submission of the article, and Mary Kokoski gave the article a necessary editing. While indebted to all of these individuals, the authors are entirely responsible for the execution of the study, its results and conclusions, and the final written article.

Appendix A. Federal register publication of the rules in the study

A.1 Utility rules

U.S. EPA, "National Emission Standards for Hazardous Air Pollutants From Coal- and Oil-Fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial- Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units; Final Rule," 77 Federal Register 9304, February 16, 2012. http://www.gpo.gov/fdsys/pkg/FR-2 012-02-16/pdf/2012-806.pdf

U.S. EPA, "Revisions to Federal Implementation Plans To Reduce Interstate Transport of Fine Particulate Matter and Ozone; Final Rule," 77 Federal Register 34830, June 12, 2012. http://www.gpo.gov/fdsys/pkg/FR-2012-06-12/pdf/2012-14 251.pdf

A.2 Boilers and incinerators

U.S. EPA, "National Emission Standards for Hazardous Air Pollutants for Major Sources: Industrial, Commercial, and Institutional Boilers and Process Heaters; Final Rule," 78 Federal Register 7138, January 31, 2013. http://www.gpo.gov/fd sys/pkg/FR-2013-01-31/pdf/2012-31646.pdf

U.S. EPA, "National Emission Standards for Hazardous Air Pollutants for Area Sources: Industrial, Commercial, and Institutional Boilers; Final Rule" 78 Federal Register 7488, February 1, 2013. http://www.gpo.gov/fdsys/pkg/FR-2013-02-01/p df/2012-31645.pdf

U.S. EPA, "Commercial and Industrial Solid Waste Incineration Units: Reconsideration and Final Amendments; Non-Hazardous Secondary Materials That Are Solid Waste; Final Rule," 78 Federal Register 9112, February 7, 2013. http://www.gpo.gov/fdsys/pkg/FR-2013-02-07/pdf/2012-31632.pdf

A.3 Portland cement

U.S. EPA, "National Emission Standards for Hazardous Air Pollutants for the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants; Final Rule," 78 Federal Register 10006, February 12, 2013. http://www.gpo.gov/fdsys/pkg/FR-2013-02-12/pdf/2012-31633.pdf

A.4 RICE rules

U.S. EPA, "National Emission Standards for Hazardous Air Pollutants for Reciprocating Internal Combustion Engines; New Source Performance Standards for Stationary Internal Combustion Engines; Final Rule," 78 Federal Register 6674, January 30, 2013. http://www.gpo.gov/fdsys/pkg/FR-2013-01-30/pdf/2013-01288.pdf

A.5 Petroleum refineries

U.S. EPA, "Standards of Performance for Petroleum Refineries for Which Construction, Reconstruction, or Modification Commenced After May 14, 2007; Final Rule," 77 Federal Register 56422, September 12, 2012. http://www.gpo.gov/fdsys/pkg/FR-2012-09-12/pdf/2012-20866.pdf

Appendix B. Regulatory impact analyses

B.1 Utility rules

U.S. EPA, "Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards," December 2011. http://www.epa.gov/ttnecas1/regdata/RIAs/matsriafinal.pdf

U.S. EPA, "Regulatory Impact Analysis for the Federal Implementation Plans to Reduce Interstate Transport of Fine Particulate Matter and Ozone in 27 States;

Correction of SIP Approvals for 22 States," June 2011. http://www.epa.gov/airtran
sport/pdfs/FinalRIA.pdf

B.2 Boilers and incinerators

U.S. EPA, "Regulatory Impact Results for Reconsideration Final Rule for National
Emission Standards for Hazardous Air Pollutants for Industrial, Commercial, and
Institutional Boilers and Process Heaters at Major Sources," December 2012. http:
//epa.gov/airquality/combustion/docs/boilerreconfinalria121220.pdf

U.S. EPA, "Regulatory Impact Results for the Reconsideration Final Rule for
Standards of Performance for New Stationary Sources and Emission Guidelines
for Existing Sources: Commercial and Industrial Solid Waste Incineration Units,"
December 2012. http://epa.gov/airquality/combustion/docs/boilerreconfinalria121
220.pdf

U.S. EPA, "Regulatory Impact Analysis: National Emission Standards for
Hazardous Air Pollutants for Industrial, Commercial, and Institutional Boilers and
Process Heaters," February 2011. http://epa.gov/airquality/combustion/docs/ciswir
econfinalria.pdf

B.3 Portland cement

U.S. EPA, "Regulatory Impact Analysis: Amendments to the National Emission
Standards for Hazardous Air Pollutants and New Source Performance Standards
(NSPS) for the Portland Cement Manufacturing Industry," August 2010. http://
www.epa.gov/ttnecas1/regdata/RIAs/portlandcementfinalria.pdf

B.4 RICE rules

U.S. EPA, "Regulatory Impact Analysis for Reconsideration of Existing Stationary
Spark Ignition Rice NESHAP," January 2013. http://www.epa.gov/ttnecas1/regdat
a/RIAs/NESHAP_RICE_Spark_Ignition_RIA_finalreconsideration2013_EPA.pdf

U.S. EPA, "Regulatory Impact Analysis for the Reconsideration of the Existing
Stationary Compression Ignition Engines NESHAP," January 2013. http://www.ep
a.gov/ttnecas1/regdata/RIAs/RICE_NESHAPreconsideration_Compression_Ignitio
n_Engines_RIA_final2013_EPA.pdf

B.5 Petroleum refineries

U.S. EPA, "Regulatory Impact Analysis Petroleum Refineries New Source Performance Standards," June 2012. http://www.epa.gov/ttnecas1/regdata/RIAs/refineries_nsps_ja_final_ria.pdf

References

Abbey, D. E., Hwang, B. L., Burchette, R. J., Vancuren, T. & Mills, P. K. (1995). Estimated Long-Term Ambient Concentrations of PM10 and Development of Respiratory Symptoms in a Nonsmoking Population. *Archives of Environmental Health: An International Journal*, *50*(2), 139–152.

Burtraw, D., Palmer, K., Paul, A. & Woerman, M. (2012). Secular Trends, Environmental Regulations, and Electricity Markets. *The Electricity Journal*, *25*(6), 35–47.

Chicanowicz, J. (2011). Factors Affecting the Timeline for Retrofit of Environmental Control Technologies to Coal-fired Power Stations: Testimony before the Subcommittee on Energy and Environment (Committee on Science, Space and Technology), United States House of Representatives, 113th Cong.

Cohen, J. T., Hammitt, J. K. & Levy, J. I. (2003). Fuels for Urban Transit Buses: A Cost-Effectiveness Analysis. *Environmental Science & Technology*, *37*(8), 1477–1484.

Cooke, R. M. (1991). *Experts in Uncertainty: Opinion and Subjective Probability in Science*. New York: Oxford University Press.

Cooke, R., Wilson, A., Tuomisto, J., Morales, O., Tainio, M. & Evans, J. (2007). A Probabilistic Characterization of the Relationship between Fine Particulate Matter and Mortality: Elicitation of European Experts. *Environmental Science & Technology*, *41*(18), 6598–6605.

Cox, L. (2012). Miscommunicating Risk, Uncertainty, and Causation: Fine Particulate Air Pollution and Mortality Risk as an Example. *Risk Analysis*, *32*(5), 765–767.

Cropper, M. L. & Krupnick, A. J. (1990). The Social Costs of Chronic Heart and Lung Disease. Resources for the Future. Washington, DC. Discussion Paper QE-89-16-REV.

Dockery, D. W., Pope, C. A., Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris, B. G. & Speizer, F. E. (1993). An Association Between Air Pollution and Mortality in Six US Cities. *New England Journal of Medicine*, *329*(24), 1753–1759.

Drummond, M. F., O'Brien, B., Stoddart, G. L. & Torrance, G. W. (2005). *Methods for Economic Evaluation of Health Care Programmes*. (3rd ed.). New York: Oxford Medical Publications, Oxford University Press.

Fann, N., Gilmore, E. & Walker, K. (2013). Characterizing the Long-term PM2.5 Concentration Response Function: Comparing Strengths and Weaknesses of Research Synthesis Approaches. Working Paper prepared for: Methods for Research Synthesis; A Cross-Disciplinary Workshop, Harvard Center for Risk Analysis.

Fann, N., Lamson, A. D., Anenberg, S. C. & Hubbell, B. J. (2013). Letter in Response to Fraas & Lutter Article: Uncertain Benefits Estimates for Reductions in Fine Particle Concentrations. *Risk Analysis*, *33*(5), 755–756.

Fann, N., Lamson, A. D., Anenberg, S. C., Wesson, K., Risley, D. & Hubbell, B. J. (2012*a*). Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone. *Risk Analysis*, *32*(1), 81–95.

Fann, N., Lamson, A. D., Anenberg, S. C., Wesson, K., Risley, D. & Hubbell, B. J. (2012*b*). Response to Cox Letter: "Miscommunicating Risk, Uncertainty, and Causation: Fine Particulate Air Pollution and Mortality Risk as an Example". *Risk Analysis*, *32*(5), 768.

Fann, N., Lamson, A., Luben, T. & Hubbell, B. (2015). Response To: "Enhancing the Characterization of Epistemic Uncertainties in PM2.5 Risk Analyses". *Risk Analysis*. Advance online publication. doi:10.1111/risa.12301.

Fraas, A. & Lutter, R. (2011). Do Some NO$_x$ Emissions Have Negative Environmental Damages? Evidence and Implications for Policy. *Environmental Science & Technology*, *45*(18), 7613–7614.

Fraas, A. & Lutter, R. (2012). Efficient Pollution Regulation: Getting the Prices Right: Comment. *American Economic Review*, *102*(1), 602–607.

Fraas, A. & Lutter, R. (2013*a*). Uncertain Benefits Estimates for Reductions in Fine Particle Concentrations. *Risk Analysis*, *33*(3), 434–449.

Fraas, A. & Lutter, R. (2013*b*). Reply to Letter by Fann, Lamson, Anenberg, and Hubbell, Regarding Fraas & Lutter Article: Uncertain Benefits Estimates for Reductions in Fine Particle Concentrations. *Risk Analysis*, *33*(5), 757–759.

Gayer, T. & Viscusi, W. K. (2014). Determining the Proper Scope of Climate Change Benefits. Vanderbilt Law and Economics Research Paper, (14–20). Retrieved from Brookings Institute website: http://www.brookings.edu/research/papers/2014/06/04-determining-proper-scope-climate-change-benefits-gayer.

Gillingham, K. & Palmer, K. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*, *8*(1), 18–38.

Graham, J. D. (2008). Saving Lives Through Administrative Law and Economics. *University of Pennsylvania Law Review*, *157*(2), 395–540.

Grosse, S. D. (2008). Assessing Cost-Effectiveness in Healthcare: History of the $50,000 per QALY Threshold. *Expert Review of Pharmacoeconomics & Outcomes Research*, *8*(2), 165–178.

Hall, M., DeFrances, C., Williams, S., Golosinskiy, A. & Schwartzman, A. (2010). *National Hospital Discharge Survey: 2007 Summary*, in National Health Statistics Reports. October 29, 2010.

Hammitt, J. K. (2013). Admissible Utility Functions for Health, Longevity, and Wealth: Integrating Monetary and Life-Year Measures. *Journal of Risk and Uncertainty*, *47*(3), 311–325.

Haninger, K. & Hammitt, J. K. (2011). Diminishing Willingness to Pay Per Quality-Adjusted Life Year: Valuing Acute Foodborne Illness. *Risk Analysis*, *31*(9), 1363–1380.

Harrington, W., Morgenstern, R. D. & Nelson, P. (2000). On the Accuracy of Regulatory Cost Estimates. *Journal of Policy Analysis and Management*, *19*(2), 297–322.

Hazilla, M. & Kopp, R. J. (1990). Social Cost of Environmental Quality Regulations: A General Equilibrium Analysis. *Journal of Political Economy*, 853–873.

Heinzerling, L. & Ackerman, F. (2002). The Humbugs of the Anti-Regulatory Movement. *Cornell Law Review*, *87*, 648–670.

Hubbell, B. J. (2006). Implementing QALYs in the Analysis of Air Pollution Regulations. *Environmental & Resource Economics*, *34*(3), 365–384.

Industrial Economics, Inc. (2006). *Expanded Expert Judgment Assessment of the Concentration-Response Relationship Between PM 2.5 Exposure and Mortality*. Prepared for the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency.

Institute of Medicine (2006). *Valuing Health for Regulatory Cost-Effectiveness Analysis*. Washington, DC: Institute of Medicine of the National Academies.

Kopits, E. (2014). A Retrospective Assessment of the Costs of EPA's 1998 Locomotive Emission Standards. *Journal of Benefit-Cost Analysis*, 5(2), 285–314.

Kopits, E., McGartland, A., Morgan, C., Pasurka, C., Shadbegian, R., Simon, N. B. & Wolverton, A. (2014). Retrospective Cost Analyses of EPA Regulations: A Case Study Approach. *Journal of Benefit-Cost Analysis*, 5(2), 173–193.

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E. & Shi, Y. et al. (2009). *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Health Effects Institute (HEI) Research Report*, (140).

Krupnick, A., Morgenstern, R., Batz, M., Nelson, P., Burtraw, D., Shih, J. S. & McWilliams, M. (2006). *Not a Sure Thing: Making Regulatory Choices Under Uncertainty*. Washington, DC: Resources for the Future.

Krutilla, K. & Alexeev, A. (2012). The Normative Implications of Political Decision-Making for Benefit-Cost Analysis. *Journal of Benefit-Cost Analysis*, 3(2), Article 2.

Krutilla, K. & Alexeev, A. (2014). The Political Transaction Costs and Uncertainties of Establishing Environmental Rights. *Ecological Economics*, 107, 299–309.

Krutilla, K. & Krause, R. (2011). Transaction Costs and Environmental Policy: An Assessment Framework and Literature Review. *International Review of Environmental and Resource Economics*, 4(3–4), 261–354.

Laden, F., Schwartz, J., Speizer, F. E. & Dockery, D. W. (2006). Reduction in Fine Particulate Air Pollution and Mortality. *American Journal of Respiratory and Critical Care Medicine*, 173(6), 667–672.

Lepeule, J., Laden, F., Dockery, D. & Schwartz, J. (2012). Chronic Exposure to Fine Particles and Mortality: An Extended Follow-Up of the Harvard Six Cities Study from 1974 to 2009. *Environmental Health Perspectives*, 120(7), 965–970.

Lutter, R., Morrall, J. & Viscusi, W. K. (1999). The Cost-Per-Life-Saved Cutoff for Safety-Enhancing Regulations. *Economic Inquiry*, 37(4), 599–608.

Martin, R., Muuls, M, de Preux, L. B. & Wagner, U. J. (2010). Anatomy of a Paradox: Management Practices, Organizational Structure and Energy Efficiency. Center for Economic Performance, Working Paper 1039.

McCarthy, J. (2012). EPA's Boiler MACT: Controlling Emissions of Hazardous Pollutants. Congressional Research Service Report, (R41459).

McCarthy, J. & Copeland, C. (2011). EPA's Regulation of Coal-fired Power: Is a "Train Wreck" Coming? Congressional Research Service Report, (R41914).

McGarity, T. O. & Ruttenberg, R. (2001). Counting the Cost of Health, Safety, and Environmental Regulation. *Tex. L. Rev.*, 80, 1997.

Morgan, C., Pasurka, C. & Shadbegian, R. (2014). Ex Ante and Ex Post Cost Estimates of the Cluster Rule and MACT II Rule. *Journal of Benefit-Cost Analysis*, 5(2), 195–224.

Morrall, J. F., III (2003). Saving Lives: A Review of the Record. *Journal of Risk and Uncertainty*, 27(3), 221–237.

National Research Council (2002). Estimating the Public Health Benefits of Proposed Air Pollution Regulations. Washington, DC: National Academies Press.

Neumann, P. J., Cohen, J. T. & Weinstein, M. C. (2014). Updating Cost-Effectiveness – the Curious Resilience of the $50,000-Per-QALY Threshold. *New England Journal of Medicine*, 371(9), 796–797.

Office of Management and Budget (2003). *Circular A-4: Regulatory Analysis*. Washington, DC: Office of Management and Budget.

Office of Management and Budget (2012). *Draft Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance with the Unfunded Mandates Reform Act*. Washington, DC: Office of Management and Budget. Retrieved from http://www.whitehouse.gov/sites/default/files/omb/inforeg/2012_cb/2012_cost_benefit_report.pdf.

Office of Management and Budget (2014). *Draft Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance with the Unfunded Mandates Reform Act*. Washington, DC: Office of Management and Budget. Retrieved from http://www.whitehouse.gov/sites/default/files/omb/inforeg/2013_cb/draft_2013_cost_benefit_report.pdf.

Peters, A., Dockery, D. W., Muller, J. E. & Mittleman, M. A. (2001). Increased Particulate Air Pollution and the Triggering of Myocardial Infarction. *Circulation*, *103*, 2810–2815.

Pope, C. A., III, Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E. & Heath, C. W., Jr. (1995). Particulate Air Pollution as A Predictor of Mortality in A Prospective Study of US Adults. *American Journal of Respiratory and Critical Care Medicine*, *151*(3_pt_1), 669–674.

Pope, C. A., III, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K. & Thurston, G. D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association*, *287*(9), 1132–1141.

Revesz, R. & Livermore, M. (2008). *Retaking Rationality: How Cost Benefit Analysis Can Better Protect the Environment and Our Health*. New York: Oxford University Press.

Robinson, L. A. & Hammitt, J. (2013). Skills of the Trade: Valuing Health Risk Reductions in Benefit-Cost Analysis. *Journal of Benefit-Cost Analysis*, *4*(1), 107–130.

Robinson, L. A., Black, R., Cropper, M., Burnett, R., Hammitt, J., Krupnick, A. & Williams, S. (2005). Alternative Approaches for Estimating Health Related Quality of Life Impacts: Nonroad Engine Air Emissions Regulation Case Study. In *Health, and Safety Regulation*. Institute of Medicine.

Roman, H. A., Walker, K. D., Walsh, T. L., Conner, L., Richmond, H. M., Hubbell, B. J. & Kinney, P. L. (2008). Expert Judgment Assessment of the Mortality Impact of Changes in Ambient Fine Particulate Matter in the US. *Environmental Science & Technology*, *42*(7), 2268–2274.

Ryan, S. P. (2012). The Costs of Environmental Regulation in a Concentrated Industry. *Econometrica*, *80*(3), 1019–1061.

Smith, A. E. & Gans, W. (2014). Enhancing the characterization of epistemic uncertainties in $PM_{2.5}$ risk analyses. *Risk Analysis*. Advance online publication. doi:10.1111/risa.12236.

Sullivan, P. W. & Ghushchyan, V. (2006). Preference-Based EQ-5D Index Scores for Chronic Conditions in the United States. *Medical Decision Making*, *26*(4), 410–420.

Tengs, T. O., Adams, M. E., Pliskin, J. S., Safran, D. G., Siegel, J. E., Weinstein, M. C. & Graham, J. D. (1995). Five-Hundred Life-Saving Interventions and their Cost-Effectiveness. *Risk Analysis*, *15*(3), 369–390.

Tengs, T. O. & Graham, J. D. (1996). The Opportunity Costs of Haphazard Social Investments in Life-Saving. In *Risks, Costs, and Lives Saved: Getting Better Results from Regulation* (Vol. 167, p. 172). Oxford University Press.

Thorat, T., Cangelosi, M. & Neumann, P. J. (2012). Skills of the Trade: The Tufts Cost-Effectiveness Analysis Registry. *Journal of Benefit-Cost Analysis*, *3*(01), 1–9.

Tilling, M. C., Kro, M., Tsuchiya, A., Brazier, J., van Exel, J. & Brouwer, W. (2012). Does The EQ-5D Reflect Lost Earnings? *Pharmaco Economics*, *30*(1), 47–61.

Tuomisto, J. T., Wilson, A., Evans, J. S. & Tainio, M. (2007). Uncertainty in Mortality Response to Airborne Fine Particulate Matter: Combining European Air Pollution Experts. *Reliability Engineering & System Safety*, *93*(5), 732–744.

U.S. Department of Health and Human Services Summary health statistics for U.S. adults: National Health Interview Survey, (2012), National Center for Health Statistics. *Vital and Health Statistics 10* (260). February 2014.

U.S. EPA (2002). *EPA Air Pollution Control Cost Manual* (6th ed.). EPA/452/B-02-001.

U.S. EPA (2006). *U.S. Environmental Protection Agency. Appendix G: Health-Based Cost-Effectiveness of Reductions in Ambient PM2.5 Associated with Illustrative PM NAAQS Attainment Strategies. 2006 National Ambient Air Quality Standards for Particle Pollution*. Washington, DC: U.S. EPA. Retrieved from http://www.epa.gov/ttnecas1/regdata /RIAs/Appendix%20G--Health%20Based%20Cost%20Effectiveness%20Analysis.pdf.

U.S. EPA (2009). *Integrated Science Assessment for Particulate Matter (Final Report). U.S. Environmental Protection Agency*, Washington, DC, EPA/600/R-08/139F.

U.S. EPA (2012). *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter*, December 2012. Retrieved from http://www.epa.gov/ttnecas1/regdata/RIAs/finalria.pdf.

U.S. EPA (2014). *Guidelines for Preparing Economic Analyses*. Washington, DC: U.S. EPA Office of Policy. (Original work published 2010.) Retrieved from http://yosemite.epa.g ov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf.

Viscusi, W. K. (2005 − 2006). Monetizing the Benefits of Risk and Environmental Regulation. *Fordham Urban Law Journal*, *33*(4), 101–143.

Viscusi, W. K., Magat, W. A. & Huber, J. (1991). Pricing Environmental Health Risks: Survey Assessments of Risk-Risk and Risk-Dollar Trade-Offs for Chronic Bronchitis. *Journal of Environmental Economics and Management*, *21*(1), 32–51.

Wittels, E. H., Hay, J. W. & Gotto, A. M., Jr. (1990). Medical Costs of Coronary Artery Disease in the United States. *American Journal of Cardiology*, *65*(7), 432–440.