# COSTS AND BENEFITS OF REDUCING AIR POLLUTANTS RELATED TO ACID RAIN

DALLAS BURTRAW, ALAN KRUPNICK, ERIN MANSUR, DAVID AUSTIN, and DEIRDRE FARRELL*

*The 1990 Clean Air Act Amendments initiated a dramatic reduction in emissions of sulfur dioxide and nitrogen oxides by electric power plants. This paper presents the results of an integrated assessment of the benefits and costs of the program. Dramatic uncertainties characterize the estimates especially with respect to the benefits of the program, many of which were modeled explicitly. The lion's share of benefits results from reduced risk of premature mortality, especially through reduced exposure to sulfates, and these expected benefits measure several times the expected costs of the program. Significant benefits also are estimated for improvements in health morbidity, recreational visibility, and residential visibility, each of which measures approximately equal to costs. Areas that were the focus of attention in the 1980s—including effects to soils, forests, and aquatic systems—still have not been modeled comprehensively, but evidence suggests that benefits in these areas are relatively small, at least with respect to "use values" for the environmental assets that are affected.* (*JEL* H43, Q2, Q4)

## I. INTRODUCTION

Control of $SO_2$ emissions under the 1990 Clean Air Act Amendments instituted two important innovations in U.S. environmental policy. The more widely acknowledged is the $SO_2$ emissions trading program. Firms are allowed to transfer allowances among facilities or to bank them for use in future years. Less widely acknowledged is the average annual cap on aggregate emissions by electric utilities, set at about one-half of the amount emitted in 1980. The cap represents a guarantee that emissions

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*Burtraw*: Fellow, Resources for the Future, Washington, D.C., Phone 1-202-328-5087, Fax 1-202-939-3460 E-mail burtraw@rff.org
*Krupnick*: Senior Fellow, Resources for the Future Washington, D.C., Phone 1-202-328-5107 Fax 1-202-939-3460, E-mail krupnick@rff.org
*Mansur*: Graduate Student, University of California, Berkeley, Phone 1-520-558-8360 E-mail mansur@econ.berkeley.edu
*Austin*: Fellow, Resources for the Future, Washington, D.C., Phone 1-202-328-5011, Fax 1-202-939-3460 E-mail austin@rff.org
*Farrell*: Staff Analyst, New York Metropolitan Transit Authority, New York, Phone 1-718-694-3248 Fax 1-718-722-4390, E-mail gabbay@erols.com

**ABBREVIATIONS**

ASI: Acid stress indexes
ASTRAP: Advanced Statistical Trajectory Regional Air Pollution
C-R: Concentration-response
CEUM: Coal and Electric Utilities Model
CPUE: Catch per unit effort
CV: Contingent valuation
EPA: U.S. Environmental Protection Agency
MAGIC: Model of Acidification of Groundwater in Catchments
NAAQS: National Ambient Air Quality Standards
$NO_X$: Nitrogen oxides
RADM: Regional Acid Deposition Model
RIA: Regulatory Impact Assessment
$SO_2$: Sulfur dioxide
TAF: Tracking and Analysis Framework
TSP: Total suspended particulates
VASM: Visibility Assessment Scoping Model
VSL: Value of a statistical life
WTP: Willingness to pay



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will not increase with economic growth. Title IV used a traditional approach in setting $NO_x$ emission rates for coal-fired electric utility units. Hence, there is no cap on emissions, but Title IV is expected to result in a 27% reduction from 1990 levels by the next decade.

This paper presents the first contemporary integrated analysis of the prospective costs and benefits of Title IV's Allowance Trading System for reducing sulfur dioxide ($SO_2$) emissions and mandated reductions in emissions of nitrogen oxides ($NO_x$). Previous studies, some of which are described below, have analyzed benefits and costs independently. Rubin (1991) provides an overview of the benefit-cost implications of the policy. This is the first analysis to compare benefits and costs under uniform assumptions.

## II. DESCRIPTION OF THE MODEL

The Tracking and Analysis Framework (TAF) is used to conduct the benefit-cost assessment.[1] TAF is a nonproprietary model constructed with the Analytica modeling software (Bloyd et al., 1996). TAF integrates models of electric utility emissions and costs, pollutant transport and deposition (including formation of secondary particulates but excluding ozone), visibility effects, effects on recreational lake fishing through changes in soil and aquatic chemistry, human health effects, and valuation of benefits. Each module of TAF was constructed and refined by a group of experts and draws primarily on peer reviewed literature to construct the integrated model. Thus, TAF is the work of a team of over 30 modelers and scientists from institutions around the country. As the framework integrating these literatures, TAF itself was subject to an extensive peer review in December 1995, which concluded that "TAF represent(s) a major advancement in our ability to perform integrated assessments" and that the model was ready for use by NAPAP (ORNL, 1995).

TAF characterizes emissions, emission transport, atmospheric concentrations of pollutants, and health effects at the state level. Changes outside the United States are not evaluated. The estimation of effects is amenable to modeling at a less centralized level, and the model uses probabilistic methods to represent variations in sources of emissions, geography, and population density within states. Recreational lake effects are characterized for a distribution of lakes in the Adirondacks. Recreational visibility effects are characterized at two parks and valued nationally. Residential visibility effects are characterized and valued for five metropolitan areas. These results are considered on a per capita basis. Regional issues are assessed through the regional pattern of health benefits. The considerable uncertainty in parameters in each of the modeled domains and in the underlying scientific and economic literature is at least partly captured through Monte Carlo simulation. Table 1 presents an overview of the model components described below.

### A. *The Benefits Valuation Module*

From an economic perspective, values are measured by how much of one asset or service individuals are willing to sacrifice in order to obtain or preserve another. This is referred to as an "opportunity cost approach." Values are expressed in monetary terms even though in principle they can be expressed in other metrics. The value or opportunity cost of goods and services that are readily traded in markets is reflected in their prices. For goods that are not traded in markets, the economics literature on monetizing benefits and costs is more developed in certain areas than in others, which is reflected in the characterization of uncertainty in the benefit models.

The Benefits Valuation Module provides an accounting of pathways and benefit endpoints. The module values effects on visibility (recreational and residential), Adirondack lake sport fish populations, and human health. These effects are valued only where physical effects have been modeled in TAF, so comprehensive geographic coverage is not provided. Other kinds of effects, such as forest, stream, and material damages, are not valued at this time, but they are represented in TAF in a qualitative manner.

### B. *Health Effects*

The Health Effects Module is designed to estimate the health impacts of changes in air pollution concentrations. Impacts are expressed as the number of days of acute mor-

1. The entire model is available at www.lumina.com\taflist.

**TABLE 1**

The Structure, Modules, Linkages and Origins of TAF

| Module[a] | Description | Links | Modeling Strategies | References[b] |
|---|---|---|---|---|
| Scenario Selector | User specifies electricity growth, plant retirement, and regulatory approach. | Links to the Emissions and Costs Module. | 18 built-in scenarios. Additional scenarios generated off-line. | |
| Emissions and Costs | Units scrub, switch, or blend fuels. Trading enables cost minimization. | Links to the Atmospheric Pathways Module, Costs. | Calculated off-line. | |
| Atmospheric Pathways | Concentrations of $SO_2$, $SO_4$, $NO_x$, and $NO_3$ and acid deposition calculated using linear coefficients and climatological variability. | Concentrations link to Health Effects and Visibility Effects Modules. Acid deposition links to the Soils and Aquatics Effects Module. | Based on ASTRAP, a regional transport model calibrated with 11 years of data. Climatological variability imported from ASTRAP. | Shannon (1985). |
| Health Effects | Model library with dozens of studies, with default probability distribution over values. | Mortality and morbidity effects link to the Health Valuation Submodule. | User can override selected defaults. | |
| Soils-Aquatics Effects | Acid deposition affects the soil and aquatic pH in the Adirondacks. | Acid stress index (ASI) is calculated for three fish species. Lake pH and ASI link to the Aquatic Valuation Submodule. | MAGIC was simplified for TAF. | Sullivan and Cosby (1995); Small et al. (1995). |
| Visibility Effects | Visual ranges are determined for two national parks, and 5 cities. | Links to Visibility Valuation. | VASM was simplified for TAF. | Shannon, Trexler and Sonnenblick (1997) |
| Health Valuation | Model library with dozens of studies on the value of morbidity and the value of a statistical life. | Links to Benefit calculations. | User can override selected defaults. | |
| Aquatic Valuation | Aquatic effects are valued in two ways: using a lake fishing "random utility" travel cost model. | Links to Benefit calculations. | Adaptation of Englin et al. | Englin (1991) |
| Visibility Valuation | Recreational visibility valued using a contingent valuation study. Residential visibility is valued using CV and hedonic property value studies. | Links to Benefit calculations. | Adaptation of Chestnut and Dennis for recreational visibility; probabilities assigned over residential valuation studies. | Chestnut and Rowe (1990) |

[a] In addition, TAF has a Public Index Library to ensure that all models use the same relevant indices. The Demographics Library includes state forecasts of total population, fractions of the population young and old, and income per capita. These estimates link electricity demand projections (and corresponding abatement costs), with benefits per capita.

[b] See Bloyd et al. (1996) for comprehensive documentation.

**TABLE 2**
Options for Assessing Mortality Effects

| | |
|---|---|
| Option 1 | Sulfates and nitrates treated as $PM_{10}$ |
| Option 2 | Sulfates and nitrates treated as $PM_{10}$, disaggregated by age |
| Option 3 (default) | Nitrates treated as $PM_{10}$, sulfates distinct and more potent |
| Option 4 | Sulfates and nitrates treated as sulfates |

bidity effects of various types, the number of chronic disease cases, and the number of statistical lives lost to premature death. The change in the annual number of impacts of each health endpoint is the output. Inputs consist of changes in ambient concentrations of $SO_2$ and $NO_x$, demographic information on the population of interest, and miscellaneous additional information such as background $PM_{10}$ levels for analysis of thresholds.

The module is based on concentration-response (C-R) functions found in the peer-reviewed literature. The C-R functions are taken, for the most part, from articles reviewed in the U.S. Environmental Protection Agency (EPA) Criteria Documents (see, for example, USEPA 1995). These documents are outcomes of a recurring comprehensive process initiated by the Clean Air Act and its Amendments for reviewing what is known about the health effects of the so-called "criteria" air pollutants.[2] Such information, and judgments about its quality, eventually help the Administrator of the EPA make decisions about National Ambient Air Quality Standards (NAAQS) that would "protect the public against adverse health effects with a margin of safety." These Criteria Documents contain thousands of pages evaluating toxicological, clinical, and epidemiological studies that relate particular criteria pollutants to a variety of health endpoints, including primarily acute cardiopulmonary and respiratory effects, chronic effects and prevalence of chronic illness, and premature mortality. The Health Effects Module contains C-R functions for $PM_{10}$, total suspended particulates (TSP), $SO_2$, sulfates ($SO_4$), $NO_2$, and nitrates ($NO_3$). Since nitrates are particulates and since no independent effect of nitrates on health has been established, they are treated as a component of $PM_{10}$.

The Health Effects Module calculates morbidity impacts from sulfates and nitrates, which are particulates created from of $SO_2$ and $NO_x$, respectively, and $SO_2$ and $NO_x$ as gases. Only mortality impacts resulting from the particulates are represented.

For the mortality endpoint, four plausible interpretations of the evidence on the effects of various particulate concentrations on mortality risk were examined (Table 2). Options 1 and 2 assume that sulfates and nitrates have the equivalent potency in causing health effects as any other particle 10 microns or less in diameter ($PM_{10}$), but option 2 addresses the age-disaggregated effects of air pollution on mortality. These reflect the fact that the over 65 population is more likely to die as a result of high particulate levels than is the under 65 population. Option 3 treats sulfates as distinct and associates them with relatively greater potency in comparison to other constituents of $PM_{10}$. Option 4 treats both sulfates and nitrates as relatively more potent than other components of $PM_{10}$. Option 3 is the most representative of the evidence at the time the work was completed.

The morbidity submodule aggregates $SO_2$, $PM_{10}$, and sulfate effects according to a scheme designed to avoid double-counting, such as symptom days and restricted activity days. Alternatively, $SO_4$ effects can be used as a proxy for particulate and $SO_2$ effects. $NO_x$ is included for eye irritation and phlegm days.

The Health Valuation Submodule of the Benefits Valuation Module assigns monetary values taken from the environmental economics literature (e.g., Lee et al., 1994) to the health effects estimates produced by the Health Effects Module. The benefits are totaled to obtain annual health benefits for each year modeled.

2. The Criteria Pollutants include ozone [$O_3$], nitrogen dioxide [$NO_2$], sulfur dioxide [$SO_2$], particulate matter less than 10 microns in diameter [$PM_{10}$], lead [Pb], and carbon monoxide [CO].

C. *Visibility*

The Visibility Effects module calculates changes in visual range for five cities (Albany, N.Y.; Atlantic City, N.J.; Charlottesville, Va.; Knoxville, Tenn.; and Washington, D.C.), and two national parks (the Grand Canyon and Shenandoah). Seasonal distributions of midday visual range are based on estimated atmospheric sulfate and nitrate concentrations from the Atmospheric Pathways module—a reduced-form model of the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model. Calculation of change in visual range is based on the Visibility Assessment Scoping Model (VASM), which uses Monte Carlo techniques to produce short-term variations of visual impairment based on seasonal lognormal distribution parameters of the six important particulate species (sulfate, nitrate, elemental carbon, organic carbon, fine-particle dust, and coarse-particle dust), relative humidity distribution statistics from climatology, and modeled changes in the seasonal means of the sulfate and nitrate concentrations.

The Visibility Valuation submodules examine both recreational and residential benefits. Chestnut and Rowe (1990) propose a functional form to value both recreational and residential visibility that takes into account the nonlinearity of willingness to pay (WTP) for a given change in visual range (i.e., the diminishing marginal utility for visibility enhancement). In the analysis here, WTP for improvements in recreational visibility were drawn from contingent valuation (CV) studies and involve both use and nonuse values for residents living in either park's state or another state ("out-of-state" residents). To value residential visibility improvements, the model employs a range of WTP coefficients from the Brookshire et al. (1979) Los Angeles study and from the McClelland et al. (1991) study of Atlanta and Chicago. Residential WTP is assumed positive only for local residents (e.g. only use values matter), so values are adjusted for "in-state" recreational visibility to avoid double counting with improvements in residential visibility.

D. *Recreational Lake Fishing*

The Recreational Lake Fishing module predicts changes in lake chemistry and soil chemistry caused by acid deposition. Using a set of "acid stress indexes" (ASIs) that describe the responses of specific species of fish to varying levels of acidity (pH) in the water, the module estimates economic benefits resulting from improvements in recreational fishing due to decreased acidification. Future surface-water and soil chemistry conditions in the watersheds are projected by reduced-form models based on the Model of Acidification of Groundwater in Catchments (MAGIC), which uses chemical equilibrium and mass balance equations to predict changes in lake and soil chemistry. The reduced-form models are applied to lakes in New York's Adirondack region, using a set of 33 lakes chosen to be representative of the target population of lakes in the region.

The Recreational Lake Fishing Benefits module estimates benefits both on the basis of benefits to recreational anglers and on avoided lake liming costs. It estimates changes in the catch rates (catch per unit effort, or CPUE) of anglers fishing for three species of fish in Adirondack Park. Values are assigned to these changes through the use of a "random utility" travel cost model. Benefits are calculated for the change in value of a single-day fishing trip (as opposed to an overnight or multi-day outing) as a result of changes in CPUE. The submodule also estimates the change in the annual number of single-day fishing trips the average Adirondack Park angler will take in the park, as a function of changes in CPUEs and other factors. The aquatics valuation literature focuses on single-day trips because it is thought that valuations for multi-day trips, which are far fewer, are intrinsically different. These "use values" for multi-day trips are not represented in the TAF analysis.

The submodule does not attempt to account for benefits enjoyed by new anglers attracted by improved conditions such as the health of the lakeside flora and fauna or for angler benefits other than improvements in catch rates. There are two reasons for this simplification. First, although no more than 10% of the population fishes for recreation, the use benefits enjoyed by non-anglers are probably of second order to the anglers' values for improved catch rates—even taken over nine-tenths of the population. Effects on swimming, boating, and shore usage are probably small relative to angling because those activities do not depend on aquatic life supported by the lakes. Second, there are no reliable estimates on which to base *non-use* valuations—in part because relative aesthetic effects are much smaller than the effects on fish populations. TAF does not include estimates of the nonuse or existence benefits that may be enjoyed by persons not visiting the affected lakes. Other parts of the country are not modeled currently. However, the potential magnitude of national benefits is illustrated by presenting benefits to Adirondack lake fishing in per capita terms for the affected population. However, extrapolating from the acid-sensitive Adirondack lake system will produce somewhat overstated national benefit estimates.

### E. *Costs and Emissions*

Estimates of costs and an algorithm for determining compliance activities at different facilities were developed by Argonne National Laboratory, and based on their unit inventory called GECOT. Compliance options for $SO_2$ reductions include scrubbing, fuel switching (including plant modifications), retirement, and replacement of plants. Decisions by utilities to install retrofit desulfurization equipment (scrubbers) at 21 units for compliance in Phase I of the $SO_2$ trading program are taken as given. The module ranks further compliance options on a unit cost ($/ton reduction) basis, with the most-cost-effective units being implemented first, until the emission reduction requirements are satisfied.

Many units are found to achieve cost savings through fuel switching and/or blending, consistent with other studies (Burtraw, 1996; Ellerman and Montero, 1998). In these cases the emission reductions are not included in the analysis of benefits because the model assumes the baseline (without Title IV) scenario also should reflect these emission reductions. However, the flexibility of the emission allowance trading program has allowed firms to take advantage of advantageous trends in fuel markets and to realize cost savings, while conventional regulatory approaches such as technology standards may have prohibited firms from doing so. Emission allowance trading is modeled implicitly by allocating compliance in a cost-effective way. $NO_x$ compliance is identified from among options facing individual facilities in order to achieve emission rate ceilings, absent the flexibility that characterizes $SO_2$ compliance. The total cost of compliance is expressed as the present value of revenue requirements to cover compliance costs summed over all units, and this is expressed as levelized annual costs (spread over the lesser of 35 years or the remaining life of the facility) for comparison with benefits.

The module predicts the industry will rely on fuel switching and blending as the primary means of $SO_2$ reductions, and that much of this switching will be implemented at low cost or cost savings to the affected firms. Scrubbing also is implemented, to a limited degree. This scenario appears robust to recent developments in the coal industry, and hence the analysis uses these estimates as a benchmark for compliance costs over the long run. The robustness of the module is explored through scenario analysis about plant lifetimes and future electricity demand, and through comparison with other recent studies.

### F. *Other Effects Not Modeled*

There are numerous other effects of Title IV that are not modeled quantitatively because of a lack of proper scientific and/or economic data and models. These include effects to material and cultural resources, nonuse of ecosystem health, recreational forests, agriculture and commercial forestry, and radiative forcing. Material and cultural resource valuation lacks a complete inventory of affected assets, data about the economic lives of affected assets, and information on behavioral responses. While nonuse values of ecosystem health are expected to be large, there is no characterization of ecosystem changes associated with Title IV or of a valuation framework for assessing benefits from improvements in ecological indicators, especially given the temporal aspects of ecological dynamics. Similarly, the link between primary pollutants and forest recreation effects that people care most about is not established. Exposure to ambient ozone is likely to be the most significant air pollutant causing significant effects on crops, but the studies examining these effects fail to account for behavioral responses in an adequate way, and the data on changes in ozone as a result of Title IV are not currently available. Lastly, atmospheric models predict changes in particulates and their effect on radiative forcing, but the economic methods for modeling damages of climate change are very uncertain, and data for valuation of local effects are not available.

## III. BASELINES AND SCENARIOS

The analysis requires an estimate of the time path of emissions of $SO_2$ and $NO_x$ (plus associated abatement costs) from 1995 to 2030 in the absence of Title IV—termed the baseline—and estimates of the emissions (and costs) associated with Title IV. Subtracting the emissions for the scenario from the baseline emissions provides emissions changes (which are fed into the atmospheric transport module) to estimate benefits of Title IV. These benefit estimates are compared with costs under a consistent set of assumptions, as well as "off-line" comparisons with alternative cost estimates.

Three baselines are developed, with one picked as the default. The baselines differ according to an estimate of plant lifetimes (60 versus 70 years) and the growth in electricity demand over the period (3%, termed "high growth," and 1%, termed "low growth"). Growth rates in electricity demand are weighted by state population growth. The 70-year-low-growth baseline is assumed the most likely, but also examine the effects of a 60-year-low-growth and 70-year-high-growth baseline.

The scenarios all involve Title IV with $SO_2$ trading and $NO_x$ reductions mandates. Specifically, the first phase of $SO_2$ reductions implemented in 1995 require average emission rates to be about 2.5 lb. sulfur per million Btu heat input. This rate applies to 431 units, including nearly 200 so-called "substitution and compensation" units that were voluntarily brought into Phase I to ease the cost of compliance on average. The second phase, taking effect in 2000, will lower the average emission rates to about 1.2, and will affect over 2,000 units. The first phase of $NO_x$ controls took effect in 1996 and reduced emission rates to 0.45 or 0.50 lb. per million Btu, affecting 239 units, all but 16 of which were also affected by Phase I $SO_2$ rules. The second phase of $NO_x$ controls are not yet final, but are expected to take effect in 2000.

### A. *Targeted Analysis of Health Benefits*

Since health benefits emerge as by far the most important of the benefits that are quantified, focus is placed on an exploration of the sensitivity of those benefits to various sets of assumptions. First the analysis tests the sensitivity of health benefits to two alternative baseline scenarios involving different life expectancies for power plants and different projections for growth in electricity demand.

Next, under the default baseline for power plant life expectancy and growth in electricity demand, the analysis explores four scenarios involving different assumptions involved in estimating health benefits that are compared with the default assumptions.

The default case health benefits estimates resulted from the authors' best judgment about the epidemiological and valuation literature at the time the work was completed. Our most important choice concerns the C-R functions for the mortality effects of reductions in sulfates and nitrates. For sulfates the analysis uses a weighted mean of the coefficient estimate of two benefit studies, giving both studies equal weight. This coefficient predicts the change in the number of incidents of mortality annually resulting from changes in total $PM_{10}$ (sulfate and nitrate) concentrations. The low estimate (0.1%), based on Plagiannakos and Parker (1988), assumes that sulfates are equally as potent as any $PM_{10}$ particle class, and estimates only daily mortality. The high estimate (0.7%), based on Pope et al. (1995), addresses the effects of cumulative exposure to fine particles, and probably captures much of the daily mortality risk. The high estimate implies that sulfates, which fall into the fine fraction of the particulate mass, are a relatively potent constituent of $PM_{10}$.

The analysis, unlike that of Hagler Bailly (1995), ignores the higher estimates of the particulate mortality coefficient (1.4%) found in Dockery et al. (1993) because it only examines mortality effects in six cities (i.e., using, effectively, six observations on particulate concentrations) and a sample of 8,111 people versus the 151 cities and 552,000 people covered by the Pope et al. (1995) study. Furthermore, recent, major benefit-cost analyses (USEPA, 1996) rely on the Pope et al. study over the Dockery et al. study.

For nitrates, the analysis assumes that they are no different in potency from any constituent of $PM_{10}$ based on Schwartz and Dockery (1992). Taken together, these choices imply that nitrates are, overall, less potent than sulfates, an assumption that reasonably reflects the state of the literature. For both functions there are assumed to be no thresholds, meaning health benefits from emissions reductions can be expected to occur irrespective of the baseline concentration of particulates.

The other key choice is the estimate of WTP for mortality risk reductions. In the base case, a lognormal distribution with mean of $3.1 million per statistical life (in $1990) is used along with a 90% confidence interval of $1.6 and $6 million. This distribution generally accords with the valuation literature but is somewhat on the low side, giving less weight to the labor market studies relative to the contingent valuation studies. The latter are marginally more appropriate for valuing mortality risks in the environmental health context and also capture age effects, based on Jones-Lee et al. (1985). The Jones-Lee study finds that the value of a statistical life for the 65 years and older group is about 75% of that of the average (40 year old) participant in their study.

As seen below, for the default case, benefits of reduced risk of health mortality alone far exceed the costs of emission reductions. For this reason, the analysis extensively explores downside sensitivities of the health benefits estimates that are designed to test whether there are plausible assumptions under which benefits no longer exceed costs. Three options are explored and compared individually to the default assumptions. Then the analysis explores a combined case.

*Impose threshold for $PM_{10}$.* This case assumes there is a threshold in effects at a 24-hour average concentration of 50 $\mu g/m^3$ $PM_{10}$. Days in which the baseline concentration of $PM_{10}$ in a county is below this amount will not register benefits of sulfate or nitrate reductions. This is a conservative assumption relative to Lee et al. (1995), who use a threshold of 30 $\mu g/m^3$ $PM_{10}$.

*Treat sulfates as $PM_{10}$.* This case assumes that nitrates have *no* effect on mortality rates, in line with the lack of any direct epidemiological evidence linking nitrates with such effects. This case assumes that sulfates are no more potent than any other $PM_{10}$ constituent and use the daily mortality studies only (equivalent to applying the base case mortality assumptions for nitrates to sulfates).

*Mortality Risk Valuation.* Even using the Jones-Lee et al. study to adjust the value of a statistical life (VSL), the benefits of mortality risk reductions from $PM_{10}$ are probably overestimated because this study (and nearly all of the VSL literature) provides estimates for reducing risks of accidental and immediate death primarily among the working-age population (averaging 40 years old).[3] Particulate matter exposure, on the other hand, may lead to higher probabilities of premature mortality in ways that disproportionately affect individuals when they are old. Data suggest that older people are at greater risk for premature mortality due to particulate matter, though not only the elderly are at risk. Several studies find substantially smaller, although sometimes statistically significant, risks for those under 65. For most of the population, then, the mortality benefits of *today's* $PM_{10}$ reduction may be very small. Said another way, the WTP for a risk reduction realized in the future is likely to be much lower if one has to pay today for benefits realized when one is much older. Unfortunately, the analysis cannot take this effect into account directly in the sensitivity analysis. Instead, it uses an approach to adjust the VSL downwards, based on life-years remaining, that, while providing a lower bound to the VSL estimates, may not provide a lower bound to an estimate of benefits based on the WTP to reduce mortality risks primarily late in life.[4]

*Combined Case.* This case assumes that there is a 50 $\mu g/m^3$ $PM_{10}$ threshold *and* that sulfates only have the potency of the average $PM_{10}$ particle.

3. There are additional reasons why WTP estimates in the "auto-death"-type context may over or underestimate risks in the PM-mortality context. The former may overestimate the latter if the older people at risk from PM have compromised health. The former may underestimate the latter if air pollution is thought to be an involuntary risk and auto-death risk is thought to be voluntary. Note, however, that increased incidence of chronic respiratory disease that might lead to increased death risks is captured by the chronic morbidity epidemiological and valuation studies included in our model.

4. This age-disaggregated estimate is based on a crude procedure that assumes each year of life is worth the default VSL divided by the life expectancy of a 40 year old, and that those over 65 are willing only to pay by the year for the number of years they can be expected to live. It results in the assignment of a VSL to the over 65 population of $0.9 million, about 1/3 that of the under 65 population, for which the VSL is assumed to be the default. For a review of alternative means of constructing life-years-based estimates of effects and benefits, see Krupnick et al., (1997).

### B. *The Hagler Bailly Study of Health Benefits from Sulfate Reductions*

The only other study examining the health benefits of Title IV is Hagler Bailly (HB, 1995). Incorporating their key inputs into our modeling framework reveals the nature of the uncertainties underlying benefits analyses. The HB study began with estimates of emissions changes made by ICF Resources using their Coal and Electric Utilities Model (CEUM) on behalf of the EPA's Acid Rain Division. The EPA tied those changes in emissions to their Regional Acid Deposition Model (RADM) to obtain changes in sulfate (fine particle) concentrations in the Eastern U.S., and used a particular set of health concentration-response and valuation functions to estimate the monetized health benefits of the emissions changes. The HB study places a value of a statistical life at \$3.17 million (1990\$) compared to a value of \$3.1 in TAF. Expected benefits are higher from the HB study than under our default health benefit estimates.

To reconcile the differences between these results, the analysis incorporated the HB study into TAF to compare results for 2010. Since EPA population estimates could not be easily attained, TAF population projections were used in all scenarios, so all results presented in this paper for HB reflect a small downward population adjustment. Mortality benefits per ton for $SO_2$ emission reduction are calculated. We did not have access to RADM for direct comparison with ASTRAP in TAF. However, by explicitly comparing the state-aggregated emission reductions forecast by TAF and HB and the predicted health effects and valuation functions, the analysis is able to impute the influence that the different atmospheric models had on benefit estimates.

### C. *The EPA's Regulatory Impact Assessment for Particulates*

As part of the Regulatory Impact Assessment (RIA) for the new proposed standards for particulates, the EPA has developed new health effect and valuation functions. The RIA examines mortality effects from $PM_{2.5}$ (which includes both sulfates and nitrates), using a value of a statistical life of \$4.8 million. As a further indication of the sensitivity of health benefits to key assumptions, the analysis incorporates these new functions and values into our model and compares results to those based on our defaults.

### D. *Alternative Cost and Emission Estimates*

To examine the sensitivity of our findings to changes in costs, the analysis compares the default cost estimates for $SO_2$ reductions with White et al. (1995), who compiled their estimates for the Electric Power Research Institute; ICF (1995), who compiled their estimates for the EPA; and GAO (1994). Carlson et al. (1997) provide econometric estimates of short-run and long-run costs. TAF default estimates of the cost of $NO_x$ control are compared with an ICF (1995) analysis of partial implementation of Title IV and with E. H. Pechan (1996).

The default estimates lead to emission estimates that are proximate to empirical measures based on the first two years of the program. In reporting results, focus is placed primarily on long-term estimates for the year 2010 and beyond, when the program will be in full swing. To consider an alternative emission scenario and its effects on benefits, the analysis compares the Argonne model with emissions and forecast by HB.

## IV. RESULTS

Figure 1 and Table 3 summarize the expected costs and benefits per capita for the included benefit pathways for our main run of the Monte Carlo simulation model.

Estimates in Table 3 are projected for the year 2010, when the second phase of the $SO_2$ program and the $NO_x$ programs are expected to be in full effect. (Note the vertical axis in Figure 1 is a log scale.) The dominant source of benefits is reduced human mortality risk, and taken singularly it results in a mean benefit estimate in 2010 that is nearly an order of magnitude greater than costs. Expected benefits from human morbidity, recreational visibility, and residential visibility each individually are approximately equal to the annualized expected cost per capita in 2010.

Health and recreational visibility benefits are presented as the average per capita benefits for all U.S. residents. Recreational visibility represents an estimate of average willingness-to-pay for modeled visibility improvements at just two parks—Grand Canyon and Shenandoah. Although there would be improvements at other park locations, problems of embedding

**FIGURE 1**
Costs and Benefits for Modeled Pathways for Affected Populations (Log-scale)

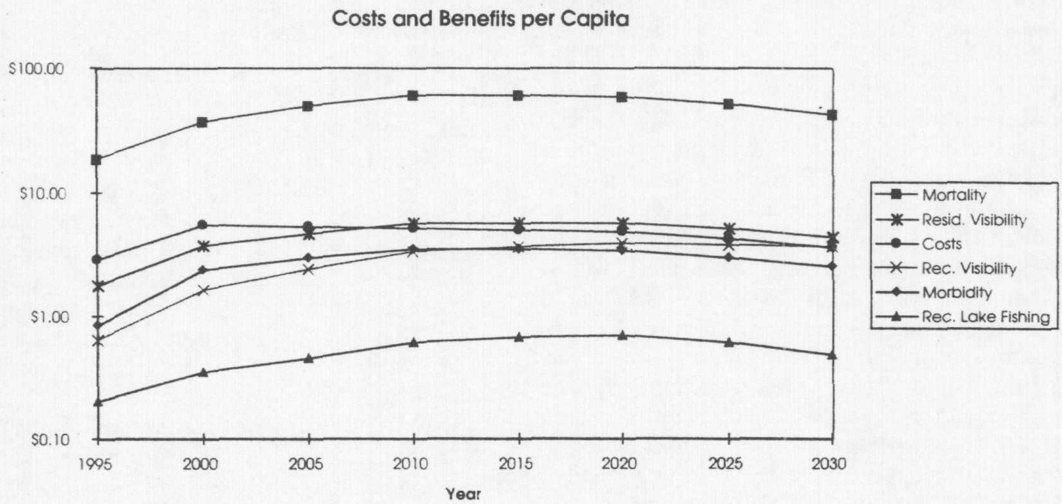


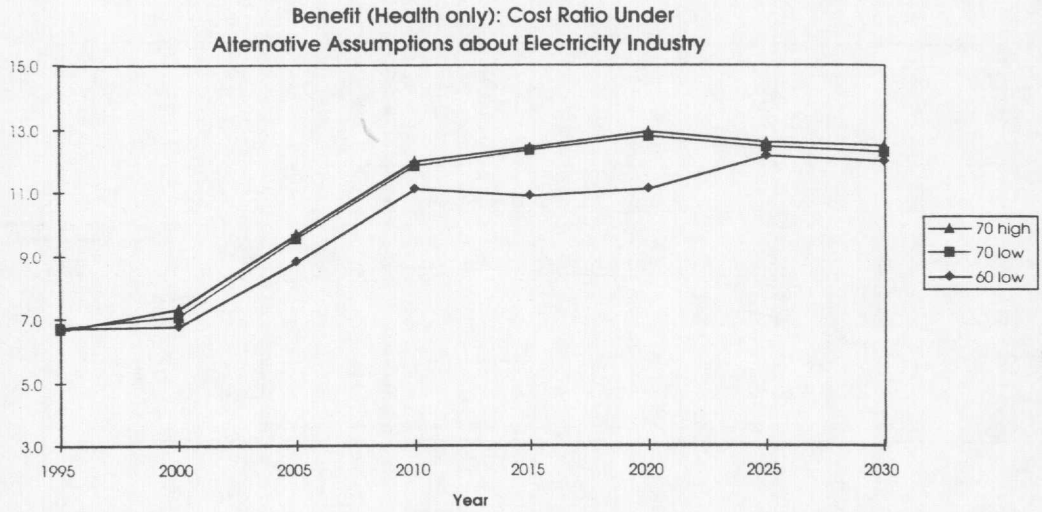

**TABLE 3**
Per Capita Benefits in 2010 for Affected Population

| Effect | Benefits per Capita (1990$) |
|---|---|
| Morbidity | 3.5 |
| Mortality | 59.3 |
| Aquatic | 0.6 |
| Rec. Visibility | 3.3 |
| Resid. Visibility | 5.8 |
| Costs | 5.3 |

benefit endpoints in the application of contingent valuation techniques to estimation of non-use benefits suggest that measures of WTP at other locations would not be additive to these, and indeed the analysis may capture most of the WTP for improvements across the entire nation with these locations (Chestnut and Rowe, 1990).

A virtue of a per capita comparison is that it allows inclusion of benefit pathways that are not modeled for the entire United States. The residential visibility benefits are those benefits that obtain for all residents in the five modeled cities of Washington, Atlantic City, Knoxville, Charlottesville, and Albany. The aquatic benefits are those that obtain for the portion of the population that is engaged in recreational fishing in Adirondack lakes. These benefits are expressed in per capita terms for each affected population in order to obtain a measure of the potential magnitude of such benefits at a national level. In the case of residential visibility, an extrapolation to the national level would likely overstate benefits because changes in sulfate and nitrate concentrations would be less in other parts of the country. In the case of aquatic effects, an extrapolation to the national level also would likely overstate bene-

**FIGURE 2**
Benefit-cost Ratio for Health Benefits under Alternative Assumptions about Electricity Industry

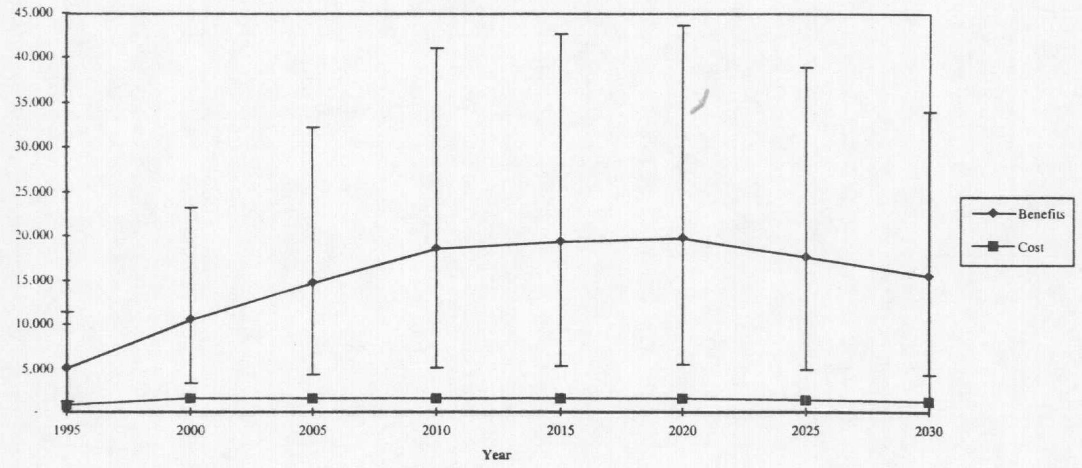



fits because a large portion of the population does not pursue recreational fishing, and again because the changes in lake chemistry would be less in most, if not all, parts of the country.

A potential point of confusion is the measure of tons reduced under the program, which depends importantly on the characterization of what would have happened to emissions in the absence of the program. To avoid confusion over the baseline emissions, benefits are calculated per ton of emission reductions. The location of emission reductions still matters importantly to the calculation of benefits per ton, and this is modeled explicitly in TAF. Measured in this way, health still plays a dominant role in the assessment of benefits. Median mortality benefits for the entire United States per ton $SO_2$ reduction under TAF's default scenario are $3,100. The 90% confidence interval around TAF's reference case estimate for $SO_2$ mortality benefits ranges from $1,700 to $9,600. The median value of human morbidity effects for TAF are $193 per ton of $SO_2$ reduction. The median estimate of benefits resulting from changes in $NO_x$ emissions in 2010 are $463 per ton for mortality (through the change in nitrate concentrations) and $137 for morbidity. These do not include the effects from changes in ozone concentrations. In contrast, annualized costs in 2010 are estimated to average $271 per ton of $SO_2$ emission reduction, and $382 per ton for $NO_x$ emission reduction.

Figure 2 displays the benefit-cost ratio, using health benefits only, under alternative baseline assumptions about plant lifetimes and growth in electricity demand. In the year 2020, annual costs (1990$) are $1.6 billion in the default case (low-growth-70-year retirements), while benefits are $20 billion. Costs drop to $1.2 billion in the low growth-60-year retirements case, while benefits drop to $13.2 billion. Costs are $1.6 billion in the high-growth-70-year retirements case, while benefits are $21 billion. For the high-growth-70-year retirement case, the benefit-cost ratio of Title IV is larger than for the default case. The reason is that changes in assumptions affect both benefits and costs in the same direction but to differing degrees. For instance, lower growth in electricity demand implies a lower opportunity cost to retiring older plants. It also suggests that emissions in the baseline would be lower, and hence emission reductions and program benefits would be lower. It is interesting that benefits in the low-growth-60-year retirement case are less than or equal to the default case in every year.

**FIGURE 3**
Annual Mean Total Health Benefits with 90% Confidence Intervals Compared with Expected Annualized Costs




Perhaps the most interesting aspect of this figure is that the benefit-cost ratio does not vary by a huge amount under the different assumptions, even though the measure of benefits or the measure of costs taken separately does vary significantly. This points out a virtue of an integrated assessment in that it allows us to explore benefits and costs under a consistent set of assumptions and sensitivity cases.

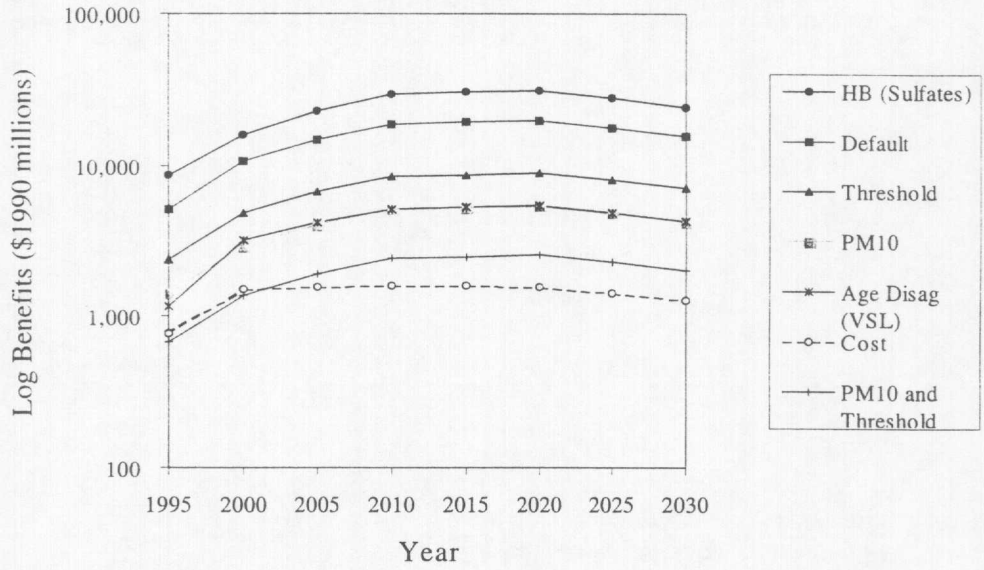
Because of the dominant role of health, a considerable part of the sensitivity analysis is devoted to whether the mortality and morbidity benefit estimates are robust. Figure 3 displays the annual health benefits alone for the default scenario, with associated uncertainty bars, in comparison with our default annualized expected cost estimates, in millions of dollars. Annualized costs for $SO_2$ and $NO_x$ reductions are about $760 million per year in 1995, increasing to $1.5 billion in 2000 and $1.6 billion in 2020. Expected benefits in the default scenario rise from $5 billion in 1995 to $20 billion in 2020, dropping back to $15.5 billion by 2030. The ramp up of benefits is attributable to meeting Title IV year 2000 goals as well as to population and income growth, while the drop after 2020 is attributable to plant retirements that occur in the baseline.

The main observation in Figure 3 is that the uncertainty bounds around the benefit estimates show that there is no year in which benefits (at the 5% confidence level) are less than expected annualized costs. About 94% of total health benefits result from mortality benefits in 2010. Only about 11% of total benefits are attributable to $NO_x$ reductions (the rest are attributable to sulfate reductions). Of morbidity benefits, $NO_x$ reductions account for closer to 27% of the benefits, according to our analysis.

Uncertainty in the cost estimates is explored through the three scenarios involving alternative assumptions about plant lifetimes and electricity demand growth described in Figure 2. However, these alternatives generate such a small range in costs, compared to uncertainty in benefits, that the range in estimates does not display in Figure 3. Uncertainties in costs are explored less systematically than uncertainties in benefits due to a limitation in our modeling. However, after considering the sensitivity analysis of cost uncertainties and comparison with other studies presented below, the analysis provides confidence that benefit un-

**FIGURE 4**

Annual Mean Total Health Benefits and Levelized Costs (log scale) by Scenario




certainty is considerably greater in absolute magnitude than cost uncertainty. Despite this uncertainty, the dominance of benefits over costs appears unchallenged.

Figure 4 reports the annual mean total health benefits and annualized expected costs for the TAF default case, the HB case for sulfates only, each of the three separate sensitivity analyses that are *designed* to reduce benefits, and for the combination case. The three separate analyses do not eliminate the gap between benefits and costs in any year when taken separately. The most dramatic reduction in benefits occurs with conservative assumptions to value statistical life. For instance, in 2020, expected total health benefits are $20 billion in the default scenario, but only $5.4 billion in this sensitivity case. Uncertainty analysis on the three sensitivity cases reveals that 5th percentile benefits are less than annualized costs up to, but not beyond, either 2000 or 2005, depending on the case, but that in no case do total costs exceed total health benefits. Only with a *combined* sensitivity analysis—assuming that sulfates affect mortality with the potency of the average component of $PM_{10}$ and that there is an effects threshold of 30 $\mu g/m^3$ $PM_{10}$—do total expected costs exceed total expected benefits.

Legislative debates about acid rain in the 1980s had a sharp regional character. Since acid deposition typically occurs far from the source of emissions, which were largely concentrated in the Ohio Valley, many observers claimed that emissions from these power plants were contributing to environmental degradation in the Northeast. Long range transport of emissions from the Ohio Valley do have an important effect outside the region. However, the regional decomposition of health benefits from reduced emissions is less parochially divisive because atmospheric concentrations are affected closer to the source of emissions. Table 4 illustrates that, expressed in per capita terms, those states providing 75% of the emission reductions accrue about 60% of total health benefits.

**TABLE 4**
Expected Total Health Benefits for 2010 and Percent of National $SO_2$ Emission Reductions by State

| State | Per Capita Health Benefits (1990$) | Percent of National Health Benefits | Percent of National $SO_2$ Emission Reductions |
|---|---|---|---|
| WV | $171 | 1.8% | 12.0% |
| OH | $160 | 10.2% | 23.3% |
| DC | $159 | 0.5% | 0.0% |
| PA | $158 | 11.0% | 9.8% |
| KY | $148 | 3.3% | 11.0% |
| VA | $135 | 5.5% | 0.4% |
| MD | $132 | 4.1% | 0.4% |
| IN | $131 | 4.4% | 16.0% |
| DE | $131 | 0.6% | 0.0% |
| NJ | $131 | 6.2% | 0.4% |
| NY | $115 | 11.6% | 2.2% |
| Other | $37 | 40.8% | 24.5% |

### A. *Comparison with HB Study*

Table 5 provides sulfate mortality benefit estimates comparing the HB model and our default values. This comparison was obtained through a different run of the model than the results reported previously and consequently the results for our default assumptions vary due to use of a different sample drawn with a different sampling procedure. A common sample was drawn for all examples in this comparison. This comparison is executed by substituting components of the HB analysis into TAF, enabling us to identify major sources of disagreement and areas of greatest uncertainty among the studies.

Because identical census population projections are used for both estimates, there are three margins along which TAF and HB estimates may differ: (i) the quantities and locations of emissions changes differ, (ii) the "source-receptor matrices" linking emissions to concentrations over space differ, and (iii) the concentration-mortality risk estimates and the estimates of the value of a statistical life differ. Each scenario in Table 5 is identified by the source for emission changes (EPA for the HB study, or TAF's default values), the atmospheric model (RADM for HB, or ASTRAP for TAF), and the health effects and valuation functions (HB or TAF).

Expected (mean) mortality benefits are higher from HB than TAF. Before any adjustments, HB found health benefits of $31 billion in 2010 (1990$) in the Eastern United States while TAF estimates benefits of $15 billion in this region.[5] Differences in population estimates are reconciled by using TAF's estimates in both scenarios. Under these assumptions, adjusted HB estimates are $30 billion (Table 5).

Although the analysis does not focus on uncertainty in this reconciliation, the adjusted HB estimates range from $5 to $67 billion for the 20th and 80th percentiles around the mean. TAF has tighter uncertainty bands, at $8-to-$24 billion for the same confidence interval. This uncertainty difference is driven primarily by our use of a narrower range of PM-mortality studies than those used by Hagler Bailly. Nevertheless, the two sets of estimates are not statistically different at any reasonable confidence level.

To reveal the effect of each of these differences in underlying assumptions, analysis begins with the HB analysis, and gradually replaces HB assumptions with default assumptions in TAF. First, the ASTRAP source-recep-

5. When including morbidity, total health benefits for HB are $35.5 billion, and for TAF they are $25 billion. Benefits in the Eastern United States make up the 98% of the benefits in TAF for the entire United States. Also note that in using RADM for atmospheric modeling, HB is using the median of several runs of the model rather than the mean.

**TABLE 5**
Comparison of HB and TAF Mortality Sulfate Benefits (billions $1990) for Eastern United States with Percent Changes over Previous Scenario, Year 2010

| **Scenario:** | **EPA/HB** | ***New Transport*** | ***New Emissions*** | ***New Health* TAF** |
|---|---|---|---|---|
| Emissions | EPA | EPA | TAF | TAF |
| Transport Model | RADM | ASTRAP-TAF | ASTRAP-TAF | ASTRAP-TAF |
| Health/Valuation | HB | HB | HB | TAF |
| Mean | | | | |
| Benefits (billion $) | 30 | 57 | 25 | 15 |
| Percent Change | | +88% | –56% | –39% |
| Benefits ($) per ton | 3,300 | 6,200 | 6,300 | 3,900 |
| Median | | | | |
| Benefits (billion $) | 19 | 35 | 15 | 13 |
| Percent Change | | +82% | –56% | –17% |
| Benefits ($) per ton | 2,100 | 3,700 | 3,800 | 3,200 |

tor coefficients used in the TAF analysis is substituted for RADM, which results in a large (87.8%) *increase* in the benefit estimates (from $30 billion to $57 billion). The difference appears to result from different treatment of meteorology by the two models, but for our purposes the difference highlights an important source of modeling uncertainty.[6]

Substituting EPA emissions forecasts with the TAF emissions forecasts *decreases* mortality benefits (which drop 56% from $57 billion to $25 billion). Although approximately equal average annual emissions should obtain in the long run, the EPA forecast suggests a higher baseline level of emissions and hence greater emission reductions under the program. EPA's higher baseline projects fewer units switching to coals with lower sulfur content than does the TAF model.

The reconciliation is completed by substituting TAF mortality coefficients and value of a statistical life for those in HB (recall only mortality effects are considered). This switch *decreases* the mean benefit estimate by 8.8% (from $25 to $15 billion). This change is primarily due to the inclusion by HB of the Dockery et al. (1993) "six city" study relating annual $PM_{2.5}$ concentrations to the probability an individual in the cities will die during the study period. HB assigns this study a weight of 25%. As noted above, the analysis provided in this paper gives it no weight.

## B. *Comparison with the Regulatory Impact Assessment*

For further analysis of heath effects, the analysis substitutes coefficients from the EPA's draft Regulatory Impact Assessment (RIA) for particulates into the health effects and health valuation modules. Compared with the EPA/HB analysis in Table 5, which reported mean annual mortality benefits from sulfate reductions in 2010 of $30 billion in the

6. Shannon et al. (1997) find the predictions of ASTRAP and RADM in reasonable agreement for predicting atmospheric sulfate concentrations in the eastern United States. However, weather patterns appear to be handled differently in a way that could account for much of the difference in benefits. In the HB application of RADM, the *median* of 30 episodes is used rather than a weighted average of episodes. In contrast, ASTRAP uses 11 years of daily meteorology to develop its source-receptor (S-R) matrices, which are constructed to represent average meteorology for each season. Given the lognormal distribution of meteorology (i.e., that most of the readings are clustered at the lower end of the distribution, with a small number of high readings accounting for much of the range of the distribution), the median could be far below the mean.

**TABLE 6**
Long-run (Phase II, Year 2010) Cost Estimates for $SO_2$ Reduction

| Study | Annual Cost (billion 1990 dollars) | Emission Reduction (million tons) | Average Cost per Ton $SO_2$ (1990 dollars) |
|---|---|---|---|
| TAF Default | 0.8 | 4.0 | 205 |
| ICF (1995) | 2.0 | 9.2 | 216 |
| White, et al. (1995) | 1.2–2.5 | 5.1–8.7 | 245–286 |
| GAO (1994) | 1.8–2.9 | 9.0 | 197–320 |
| Van Horn Consulting et al. (1993) | 2.0–3.2 | 6.9–8.6 | 289–373 |

Eastern United States, the RIA (using EPA emissions and RADM for atmospheric modeling) approach yields $25.6 billion. The RIA uses a higher value of a statistical life ($4.8 million) than does HB but predicts a smaller change in mortality for the same change in sulfate concentrations, despite including long-term mortality effects. The EPA/RADM/RIA analysis estimates are still larger than the mean estimates for TAF of $22.9 billion. However, with substitution of the RIA for TAF in measuring health effects and valuation, the expected benefits fall to $21.3 billion.

C. *Cost Comparisons*

The costs of $SO_2$ reductions have attracted attention because of the innovative allowance trading program. Projections from the middle 1980s based on command and control approaches, and projections of *marginal costs* under a market with an inadequate level of trading, ranged as high as $1500 per ton (Bohi and Burtraw, 1997). In 1990 the EPA projected costs in 2010 of $450–$620 per ton (ICF, 1990). Estimates have continued to decline, in large part because the program gives utilities the flexibility to exploit advantageous trends in coal markets and rail transport.

Table 6 reports a series of estimates for *average costs* (which are expected to be lower than marginal costs in Phase II), illustrating that various projections have continued to decrease as allowance trading has taken hold. Nonetheless, the TAF default costs are on the low end of this range. The ICF (1995) estimates are the final in a series of declining estimates provided for the EPA by ICF since 1989. ICF (1995) estimates were reported in the EPA's Regulatory Impact Assessment for Title IV. These estimates describe a considerably greater emissions reduction because of higher projected emissions in the baseline than assumed in TAF. The greater annual costs spread over greater emission reductions yield comparable average costs. It makes sense that the average costs per ton are greater in the TAF estimates since it assumes more switching to low sulfur coal for economic reasons in the baseline; a greater portion of this switching is accounted for as part of Title IV by ICF, and this brings down the average cost per ton in that study. Based on recent econometric estimates (Carlson et al., 1997) and on the recent trend in fuel markets, and also due to current trends toward increasing competition in the electric utility industry, the TAF estimates can be taken as central estimates. ICF (1995) suggests annual costs about 2.5 times those included in the TAF default case; however, the estimated average cost per ton reduction is just about equal to that for TAF.

Other reported estimates include White et al. (1995) and Van Horn Consulting et al. (1993), which were compiled for the Electric Power Research Institute. The range of estimates in White et al. is associated with the level of plant utilization, comparable to TAF's low and high electricity demand cases. Van Horn Consulting also was the contractor for the GAO (1994) estimates. The range of estimates for GAO pertain to variations in the liquidity of the allowance market, and the range

**TABLE 7**
Long-run (Phase II, Year 2010) Cost Estimates for $NO_x$ Reduction

| Study | Annual Cost (billion 1990 dollars) | Emission Reduction (million tons) | Average Cost per Ton $NO_x$ (1990 dollars) |
|---|---|---|---|
| TAF Default | 0.8 | 2.0 | 382 |
| ICF (1996) | 0.5 | 2.1 | 229 |
| E. H. Pechan (1996) | 1.6 | 3.7 | 438 |

in the Van Horn Consulting estimates cover a mix of scenarios.

Another aspect of regulatory costs that has only recently been investigated and estimated is the hidden social cost of imposing additional regulations in a second-best setting characterized by pre-existing regulations and taxes that already distort the economy away from economic efficiency. This issue has ignited colorful debate with respect to policies to address climate change. Goulder et al. (1997) addresses this issue in an analytical and computable general equilibrium model of the $SO_2$ program to estimate hidden social costs due to the second-best setting for Title IV. They estimate that the social costs stemming from interactions between the trading program and pre-existing taxes in the economy were $540 million per year. This social cost stems from the fact that the $SO_2$ program, like any regulation, imposes a cost that reduces the real wage of workers. This cost can be viewed as a virtual tax, and when imposed on top of pre-existing taxes, has large consequences for economic efficiency. Unfortunately, as far as this issue is concerned, the $SO_2$ trading program imposes particularly large costs because it encourages firms to internalize not only their abatement costs, but also the cost of residual emissions through the opportunity cost of $SO_2$ allowances. Were the program to raise revenues through the auction of permits, it could use these revenues to offset this tax-interaction effect by reducing other distortionary taxes. However, the $SO_2$ allowances are allocated without charge, so there is no revenue available for this purpose, and consequently the tax-interaction effect and resulting social cost is substantial. There also may be general equilibrium benefits beyond those measured directly here, for example, if labor productivity were to increase with improvements in public health.

Table 7 explores alternative cost estimates for the $NO_x$ portion of Title IV. TAF estimates these costs to be almost as great as the cost of $SO_2$ reductions. ICF (1995) considers only Phase I requirements for Group 1 boilers; however, E. H. Pechan (1996) considers full implementation of Title IV requirements. Compared to the former estimate, the TAF default case is on the high end. Again note that industry surveys suggest a secular downward trend in costs. Considering the alternative cost estimates, and also recognizing that costs stemming from the second-best setting of environmental regulation are excluded, TAF's more conservative default estimate is a reasonable midpoint. This perspective is especially justified because of the apparent magnitude of benefits compared to costs. If one were to double TAF's estimate, this difference would have an important effect on the benefit-cost comparisons illustrated in our previous examples; however, it would not by itself change the qualitative finding that benefits appear to outweigh costs by a significant margin.

### D. *Unmodeled Pathways and Research Priorities*

To varying degrees, members of the team of scientists and economists that contributed to construction of TAF initiated review and modeling of environmental pathways that were not part of our quantitative analysis. Based in part on these efforts, the analysis constructed a qualitative review of pathways that are not modeled, including a relative ranking of their expected magnitude, and a prioritization for further research according to our assessment of the value of additional information for each. This evaluation is reported in Table 8.

**TABLE 8**

Qualitative Evaluation of Expected Benefits and Value of Additional Information for Modeled and Nonmodeled Pathways

| *Categories* ● high **O** high-mid ◒ mid ⊙ low-mid ○ low | 1. Link Between Science and Economics: Are benefit endpoints well established? Does science provide infomation needed for economic analysis? | 2. Economic Methods: Are economic methods adequately developed? | 3. Data Availability: Is data available from science and from economics for an assessment of benefits? | 4. Expected Benefit: Are expected benefits large? | 5. Value of Additional Information: With the goal of improving benefit estimates, what is the relative short-term return on investment? |
|---|---|---|---|---|---|
| Health: Mortality | **O** | **O** | **O** | ● | ● |
| Health: Morbidity | **O** | **O** | **O** | **O** | **O** |
| Visibility | **O** | ◒ | ⊙ | **O** | **O** |
| Materials and Cultural Resources | ⊙ | ◒ | ○ | **O** | **O** |
| Nonuse Values: Ecosystem Health | ⊙ | ⊙ | ⊙ | ● | ◒ |
| Aquatics: Recreation | **O** | ● | ⊙ | ⊙ | ◒ |
| Forests: Recreation | ⊙ | **O** | ○ | ⊙ | ◒ |
| Agriculture and Commercial Forestry | **O** | ● | ◒ | ◒ | ⊙ |
| Radiative Forcing | ⊙ | ○ | ○ | ⊙ | ○ |

Short- and long-run research needs vary among the modeled and unmodeled pathways. Estimates of health and visibility benefits are uncertain; however, the cost of reducing uncertainty appears to be relatively less than for many other areas. It may be sufficient to focus efforts at assessing benefits from health and visibility, because these benefits alone appear to outweigh costs. Environmental areas including aquatics and forests stand to benefit in addition.

While there are many issues facing the health scientists and epidemiologists, economists should work to improve the basis for the valuation of small changes in mortality risks experienced late in life (see Johannesson and Johansson, 1996, for an example). For visibility, valuation needs to be more precise with respect to the endpoints that are important for assessment of benefits, and particular attention should be paid to the nature of preferences for changes in visibility, such as the trade-off between changes in the mean and extreme values of visual range. Benefits to materials and cultural resources also may be sizable. Rapid progress could be made through further work on the valuation of cultural resources, which should concentrate on the identification of the resources and the attributes of those resources that are meaningful endpoints to individuals. Assessment of benefits to commercial materials requires an improved inventory of affected materials and improved estimates of their economically useful lives.

Over a longer time frame, assessment of nonuse values for ecosystem health should be afforded high priority. However, a research emphasis in this area would require sustained levels of funding over several years in order to yield results that would be reliable. Also, agriculture and commercial forestry would receive a somewhat higher ranking in Table 8 were a sustained level of funding committed. One reason is that agriculture is undergoing structural change due to reforms passed by Congress in 1996 that may not be fully attained until the next decade. In addition, estimating rural ozone effects may be costly and time consuming, though such modeling also would contribute to an understanding of human health benefits and forest recreation.

The most important of the uncertainties and omissions in this analysis are summarized in Table 9, which appears as an appendix to this paper. This table provides a qualitative assessment of the direction of the bias for each of these shortcomings. A plus sign (+) indicates the uncertainty or omission imposes an upward bias in our benefit or cost estimate; a negative sign (–) indicates otherwise. Additional information about the uncertainties and limitations at each step in the TAF model is provided in the documentation for TAF (Bloyd et al., 1996).

## V. CONCLUSIONS

Although important limitations, caveats, and major uncertainties inhibit the comprehensiveness of this benefit-cost analysis, the clear conclusion that emerges is that the benefits of Title IV exceed the costs by a substantial margin and that even 5th percentile estimates of benefits do not dip below costs for any of the scenarios (but one) in any years after 2010. This assessment differs from the information that was available to policymakers at the time the program was enacted in 1990. At that time, Portney (1990) ventured to offer a comprehensive assessment of the Clean Air Act Amendments. Portney wrote that the expected benefits and costs appeared to be about equal for Title IV, in part because of the cost savings that were expected to result from the innovative allowance trading program. Benefits are now thought to be greater than expected, *and* compliance costs have fallen significantly compared to prior expectations, though compliance costs do not include all social costs of the program.

Expected benefits tend to be high in some areas that were not a primary focus of benefits assessment in the 1980s, particularly health and visibility. The dominant category of benefits is mortality, which is expected to be several times the costs of the program. Mortality benefits are found to be less than in previous estimates for the EPA (HB, 1995), partly because the EPA analysis is more pessimistic about $SO_2$ emissions in the absence of Title IV. Yet, the estimates of sulfate changes are actually lower than those of the HB analysis. Still, in this analysis there is no year in which health benefits alone at the 5% confidence level are less than the levelized expected costs. About 94% of the benefits are attributable to changes in $SO_2$ and 6% are attributable to changes in $NO_x$.

**TABLE 9**
Major Uncertainties and Omissions, and Direction of Bias

| Uncertainties and Omissions | Bias | Description |
|---|---|---|
| **Benefits** | | |
| *Aggregation to state level* | ? | Emissions, atmospheric transport and effects are modeled at state level. Probability distributions are used to represent variability within states in the simulations. |
| *Atmospheric model does not capture role of ammonia* | + | Ammonia may be a limiting factor in formation of secondary particulates. Reductions in one (e.g. sulfates) may allow increases in the other (e.g. nitrates). |
| *Aquatic effects capture limited recreational use, only at lakes* | – | The measure does not capture effects on other recreational uses. |
| *Aquatic effects limited to Adirondacks* | +/? | The Adirondack region has high participation rates compared to nation. Calculation of effects on "per affected capita" basis yields inflated values when extrapolated. |
| *Recreational visibility* | +/? | Only two parks included, but this may capture majority of benefits. Contingent valuation methods uncertain. Valuation is not precise with respect to the distribution of visibility improvements over time. |
| *Residential visibility* | ? | Only five cities evaluated; benefits represented on "affected per capita" basis. |
| *Morbidity measures* | – | Workplace productivity for small effects not captured. |
| *Mortality coefficient* | + | Use of mortality coefficients treats all mortality effects equally. A preferable approach would be life-years lost. |
| *Value of statistical life* | +/? | The VOSL approach does not value appropriately small changes in life expectancy realized late in life (+). Health status is not included. (+) However, VOSL ignores involuntary nature of exposure (–). |
| *Omitted environmental endpoints and nonuse values listed in Table 6* | – | Magnitude of use values for omitted pathways may be small as indicated by included aquatic endpoint. However, nonuse measures are not explored and may be significant. |
| *Benefits outside U.S. excluded* | – | The analysis is limited to the continental U.S. |
| **Costs** | | |
| *Perfect trading* | – | Regulatory incentives may hamper $SO_2$ allowance trading. |
| *$NO_x$ model does not reflect emissions averaging* | + | Implementation of $NO_x$ rules allows averaging among commonly owned and operated units which lowers costs. |
| *Electricity demand growth* | – | Our default analysis is conservative (low) on projected demand growth. Previous analysis has indicated demand growth and plant lifetime to be important variables in costs. |
| *Plant lifetime* | ? | Plant lifetime is treated parametrically. |
| *Partial equilibrium analysis* | – | General equilibrium effects indicate hidden efficiency costs. Also, failure of program to raise revenue. |

There are serious uncertainties in measuring and valuing mortality. Recent economic critiques have argued that the use of the value of a statistical life as the basis for valuing health risks from air pollution, instead of a more appropriate measure of quality adjusted life years lost, could grossly overestimate mortality benefits. In addition, economists have questioned the appropriateness of using labor studies of prime age men to value changes in life expectancy that occur among an older population. In the future one can expect these critiques to gain in credibility as more is learned about how to measure benefits. On the other hand, because environmental exposures are involuntary, compared with studies of labor market behavior, the latter may underestimate willingness to pay to avoid environmental exposures.

Mean values for three other modeled pathways—health morbidity, recreational visibility, and residential visibility—are each found to equal approximately the mean levelized costs of the program.

Public attention in the 1980s to air pollution from $SO_2$ and $NO_x$ emissions largely centered on the problem of acidification ("acid rain"), with particular concern for its affect on water and soil chemistry and ultimately ecological systems. It is surprising to many that relatively low benefits are estimated by economists for effects on aquatics (a finding supported by our study) or are expected to result from effects on forests and agriculture. One reason is that willingness to pay for environmental improvement depends on the availability of substitute assets. Economists would not expect changes in quality at one site to elicit large benefits if there are many sites available for comparable recreational opportunities. In contrast, individuals do not have the same kind of substitution possibilities with respect to health and visibility, which may help explain the relatively larger benefit estimates for these endpoints. Furthermore, one should note that the low values for aquatics stem from an assessment of *use* values, or *commodity* values in the case of agriculture. Environmental changes also may yield *nonuse* values, and estimates for nonuse values are not available. Nonetheless, the evidence, based on a small number of relatively narrow studies, suggests that these values may be significant.

The costs of compliance under Title IV have attracted attention because of the innovative allowance trading program. Many recent estimates find costs to be lower than anticipated for $SO_2$ reductions, in large part because of the flexibility the program gives firms to find least-cost ways to reduce emissions and to take advantage of advantageous trends in fuel and factor markets. Nonetheless, the TAF default costs are on the low end of previous estimates for $SO_2$ and on the high end for $NO_x$ control, and they do not take into account hidden social costs stemming from the second-best setting for environmental policy. These factors impart uncertainty around estimates of costs in this study.

In summary, this analysis finds that Title IV delivers net benefits to the United States. It is an open question how much tighter the emissions cap could be and still yield the same result. This issue is likely to take center stage in the near future as the country looks for ways to reduce sulfate and nitrate concentrations in order to meet EPA's new fine particle standard.

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