Appendix I: Valuation of Human Health and Welfare Effects of Criteria Pollutants

This appendix describes the derivations of the economic valuations for health and welfare endpoints considered in the benefits analysis. Valuation estimates were obtained from the literature and reported in dollars per case avoided for health effects, and dollars per unit of avoided damage for welfare effects. This appendix first introduces the method for monetizing improvements in health and welfare, followed by a summary of dollar estimates used to value benefits and detailed descriptions of the derivation of each estimate. These economic valuations are given both in terms of a central (point) estimate as well as a probability distribution which characterizes the uncertainty about the central estimate. All dollar values are rounded and are in 1990 dollars. Next, results of the economic benefits analysis are presented. Finally, uncertainties in valuing the benefits attributable to the CAA are explored.

Methods Used to Value Health and Welfare Effects

Willingness to pay (WTP) and willingness to accept (WTA) are the two measures commonly used to quantify the value an individual places on something, whether it is something that can be purchased in a market or not. Both WTP and WTA are measures of the amount of money such that the individual would be indifferent between having the good (or service) and having the money. Whether WTP or WTA is the appropriate measure depends largely on whether an increase or a decrease of the good is at issue. WTP is the amount of money an individual would be willing to pay to have a good (or a specific increase in the amount of the good) — i.e., the amount such that the individual would be indifferent between having the money and having the good (or having the specific increase in the good). WTA is the amount of money the individual would have to be compensated in order to be indifferent to the *loss* of the good (or a specific decrease in the amount of the good). WTP is the appropriate measure if the baseline case is that the individual does not have the good or when an increase in the amount of the good is at issue; WTA is the appropriate measure if the baseline case is that the individual has the good or when a decrease in the amount of the good is at issue. An important difference between WTP and WTA is that, in theory, WTP is limited by the individual's budget, whereas WTA is not. Nevertheless, while the underlying economic valuation literature is based on studies which elicited expressions of WTP and/or WTA, the remainder of this report refers to all valuation coefficients as WTP estimates. In some cases (e.g., stroke-related hospital admissions), neither WTA nor WTP estimates are available and WTP is approximated by cost of illness (COI) estimates, a clear underestimate of the true welfare change since important value components (e.g., pain and suffering associated with the stroke) are not reflected in the out-of-pocket costs for the hospital stay.

For both market and non-market goods, WTP reflects individuals' preferences. Because preferences are likely to vary from one individual to another, WTP for both market and non-market goods (e.g., health-related improvements in environmental quality) is likely to vary from one individual to another. In contrast to market goods, however, non-market goods such as environmental quality improvements are public goods, whose benefits are shared by many individuals. The individuals who benefit from the environmental quality improvement may have different WTPs for this non-market good. The total social value of the good is the sum of the WTPs of all individuals who "consume" (i.e., benefit from) the good.

In the case of health improvements related to pollution reduction, it is not certain specifically who will receive particular benefits of reduced pollution. For example, the analysis may predict 100 days of cough avoided in a given year resulting from CAA reductions of pollutant concentrations, but the analysis does not estimate which individuals will be spared those days of coughing. The health benefits conferred on individuals by a reduction in pollution concentrations are, then, actually *reductions in the probabilities* of having to endure certain health problems. These benefits (reductions in probabilities) may not be the same for all individuals (and could be zero for some individuals). Likewise, the WTP for a given benefit is likely to vary from one individual to another. In theory, the total social value associated with the decrease in risk of a given health problem resulting from a given reduction in pollution concentrations is

$$\sum_{i=1}^{N} WTP_i(B_i) \qquad (1)$$

where B_i is the benefit (i.e., the reduction in probability of having to endure the health problem) conferred on the ith individual (out of a total of N) by the reduction in pollution concentrations, and $WTP_i(B_i)$ is the ith individual's WTP for that benefit. If a reduction in pollution concentrations affects the risks of several health endpoints, the total health-related social value of the reduction in pollution concentrations is

$$\sum_{i=1}^{N}\sum_{j=1}^{J} WTP_i(B_{ij}) \qquad (2)$$

where B_{ij} is the benefit related to the jth health endpoint (i.e., the reduction in probability of having to endure the jth health problem) conferred on the ith individual by the reduction in pollution concentrations, and $WTP_i(B_{ij})$ is the ith individual's WTP for that benefit.

The reduction in probability of each health problem for each individual is not known, nor is each individual's WTP for each possible benefit he or she might receive known. Therefore, in practice, benefits analysis estimates the value of a *statistical* health problem avoided. For example, although a reduction in pollutant concentrations may save actual lives (i.e., avoid premature mortality), whose lives will be saved cannot be known *ex ante*. What is known is that the reduction in air pollutant concentrations results in a reduction in mortality risk. It is this reduction in mortality risk that is valued in a monetized benefit analysis. Individual WTPs for small reductions in mortality risk are summed over enough individuals to infer the value of a *statistical* life saved. This is different from the value of a particular, identified life saved. Rather than "WTP to avoid a death," then, it is more accurate to use the term "WTP to avoid a statistical death," or, equivalently, "the value of a statistical life."

Suppose, for example, that a given reduction in PM concentrations results in a decrease in mortality risk of 1/10,000. Then for every 10,000 individuals, one individual would be expected to die in the absence of the reduction in PM concentrations (who would not die in the presence of the reduction in PM concentrations). If WTP for this 1/10,000 decrease in mortality risk is $500 (assuming, for now, that all individuals' WTPs are the same), then the value of a statistical life is 10,000 x $500, or $5 million.

A given reduction in PM concentrations is unlikely, however, to confer the same risk reduction (e.g., mortality risk reduction) on all exposed individuals in the population. (In terms of the expressions above, B_i is not necessarily equal to B_j , for i j). In addition, different individuals may not be willing to pay the same amount for the same risk reduction. The above expression for the total social value associated with the decrease in risk of a given health problem resulting from a given reduction in pollution concentrations may be rewritten to more accurately convey this. Using mortality risk as an example, for a given unit risk reduction (e.g., 1/1,000,000), the total mortality-related benefit of a given pollution reduction can be written as

$$\sum_{i=1}^{N} \textit{(number of units of risk reduction)}_i \times \textit{(WTP per unit risk reduction)}_i \qquad (3)$$

where (number of units of risk reduction)$_i$ is the number of units of risk reduction conferred on the ith exposed individual as a result of the pollution reduction, (WTP per unit risk reduction)$_i$ is the ith individual's willingness to pay for a unit risk reduction, and N is the number of exposed individuals.

If different subgroups of the population have substantially different WTPs for a unit risk reduction and substantially different numbers of units of risk reduction conferred on them, then estimating the total social benefit by multiplying the population mean WTP to save a statistical life times the predicted number of statistical lives saved could yield a biased result. Suppose, for example, that older individuals' WTP per unit risk reduction is less than that of younger individuals (e.g., because they have fewer years of expected life to lose). Then the total benefit will be less than it would be if everyone's WTP were the same. In addition, if each older individual has a larger number of units of risk reduction conferred on him (because a given pollution reduction results in a greater absolute reduction in risk for older individuals than for younger individuals), this, in combination with smaller WTPs of older individuals, would further reduce the total benefit.

While the estimation of WTP for a market good (i.e., the estimation of a demand schedule) is not a simple matter, the estimation of WTP for a non-market good, such as a decrease in the risk of having a particular health problem, is substantially more difficult. Estimation of WTP for decreases in very specific health risks (e.g., WTP to decrease the risk of a day of coughing or WTP to decrease the risk of admission to the hospital for respiratory illness) is further limited by a paucity of information. Derivation of the dollar value estimates discussed below was often limited by available information.

Valuation of Specific Health Endpoints

Valuation of Premature Mortality Avoided

As noted above, it is actually reductions in mortality risk that are valued in a monetized benefit analysis. Individual WTPs for small reductions in mortality risk are summed over enough individuals to infer the value of a *statistical* life saved. This is different from the value of a particular, identified life saved. The "value of a premature death avoided," then, should be understood as shorthand for "the value of a *statistical* premature death avoided."

The value of a premature death avoided is based on an analysis of 26 policy-relevant value-of-life studies (see Table I-1). Five of the 26 studies are contingent valuation (CV) studies, which directly solicit WTP information from subjects; the rest are wage-risk studies, which base WTP estimates on estimates of the additional compensation demanded in the labor market for riskier jobs. Each of the 26 studies provided an estimate of the mean WTP to avoid a statistical premature death. Several plausible standard distributions were fit to the 26 estimates of mean WTP. A Weibull distribution, with a mean of $4.8 million and standard deviation of $3.24 million, provided the best fit to the 26 estimates. The central tendency estimate of the WTP to avoid a statistical premature death is the mean of this distribution, $4.8 million. The considerable uncertainty associated with this approach is discussed in detail below, in the subsection titled "The Economic Benefits Associated with Mortality," within the section titled "Uncertainties."

Table I-1. Summary of Mortality Valuation Estimates (millions of 1990 dollars).

Study	Type of Estimate	Valuation (millions 1990$)
Kneisner and Leeth (1991) (US)	Labor Market	0.6
Smith and Gilbert (1984)	Labor Market	0.7
Dillingham (1985)	Labor Market	0.9
Butler (1983)	Labor Market	1.1
Miller and Guria (1991)	Cont. Value	1.2
Moore and Viscusi (1988a)	Labor Market	2.5
Viscusi, Magat, and Huber (1991b)	Cont. Value	2.7
Gegax et al. (1985)	Cont. Value	3.3
Marin and Psacharopoulos (1982)	Labor Market	2.8
Kneisner and Leeth (1991) (Australia)	Labor Market	3.3
Gerking, de Haan, and Schulze (1988)	Cont. Value	3.4
Cousineau, Lacroix, and Girard (1988)	Labor Market	3.6
Jones-Lee (1989)	Cont. Value	3.8
Dillingham (1985)	Labor Market	3.9
Viscusi (1978, 1979)	Labor Market	4.1
R.S. Smith (1976)	Labor Market	4.6
V.K. Smith (1976)	Labor Market	4.7
Olson (1981)	Labor Market	5.2
Viscusi (1981)	Labor Market	6.5
R.S. Smith (1974)	Labor Market	7.2
Moore and Viscusi (1988a)	Labor Market	7.3
Kneisner and Leeth (1991) (Japan)	Labor Market	7.6
Herzog and Schlottman (1987)	Labor Market	9.1
Leigh and Folson (1984)	Labor Market	9.7
Leigh (1987)	Labor Market	10.4
Gaten (1988)	Labor Market	13.5
SOURCE: Viscusi, 1992		

Life-years lost is a possible alternative measure of the mortality-related effect of pollution, as discussed in Appendix D. If life-years lost is the measure used, then the value of a statistical life-year lost, rather than the value of a statistical life lost would be needed. Moore and Viscusi (1988) suggest one approach for determining the value of a statistical life-year lost. They assume that the willingness to pay to save a statistical life is the value of a single year of life times the expected number of years of life remaining for an individual. They suggest that a typical respondent in a mortal risk study may have a life expectancy of an additional 35 years. Using a mean estimate of $4.8 million to save a statistical life, their approach would yield an estimate of $137,000 per life-year lost or saved. If an individual discounts future additional years using a standard discounting procedure, the value of each life-year lost must be greater than the value assuming no discounting. Using a 35 year life expectancy, a $4.8 million value of a statistical life, and a 5 percent discount rate, the implied value of each life-year lost is $293,000. The Moore and Viscusi procedure is identical to this approach, but uses a zero discount rate.

Using the value of a life-year lost and the expected number of years remaining (obtained from life expectancy tables), and assuming a given discount rate, values of age-specific premature mortality can be derived. Examples of valuations of pollution-related mortality using the life-years lost approach are given below, in the subsection titled "The Economic Benefits Associated with Mortality," within the section titled "Uncertainties."

Valuation of Hospital Admissions Avoided

In the case of hospital admissions, cost-of-illness (COI), or "costs avoided," estimates were used in lieu of WTP because of the lack of other information regarding willingness to pay to avoid illnesses that necessitate hospital admissions. For those hospital admissions which were specified to be the *initial* hospital admission (in particular, hospital admissions for coronary heart disease (CHD) events and stroke), COI estimates include, where possible, all costs of the illness, including the present discounted value of the stream of medical expenditures related to the illness, as well as the present discounted value of the stream of lost earnings related to the illness. (While an estimate of present discounted value of both medical expenditures and lost earnings was available for stroke, the best available estimate for CHD did not include lost earnings. The derivations of the COI estimates for CHD and stroke, both lead-induced effects, are discussed in Appendix G.)

In those cases for which it is unspecified whether the hospital admission is the initial one or not (that is, for all hospital admissions endpoints other than CHD and stroke), it is unclear what portion of medical expenditures and lost earnings after hospital discharge can reasonably be attributed to pollution exposure and what portion might have resulted from an individual's pre-existing condition even in the absence of a particular pollution-related hospital admission. In such cases, the COI estimates include only those costs associated with the hospital stay, including the hospital charge, the associated physician charge, and the lost earnings while in the hospital. The derivations of these costs are discussed in Abt Associates Inc., 1996.

These COI estimates are likely to substantially understate total WTP to avoid an illness that began with a hospital admission or to avoid a particular hospital admission itself. First, most of the COI estimates fall short of being full COI estimates either because of insufficient information or because of ambiguities concerning what portion of post-hospital costs should be attributed to pollution exposure. Even full COI estimates will understate total WTP, however, because they do not include the value of avoiding the pain and suffering associated with the illness for which the individual entered the hospital.

Valuation of Chronic Bronchitis Avoided

Although the severity of cases of chronic bronchitis valued in some studies approaches that of chronic obstructive pulmonary disease, to maintain consistency with the existing literature we do not treat those cases separately for the purposes of this analysis. Chronic bronchitis is one of the only morbidity endpoints that may be expected to last from the initial onset of the illness throughout the rest of the individual's life. WTP to avoid chronic bronchitis would therefore be expected to incorporate the present discounted value of a potentially long stream of costs (e.g., medical expenditures and lost earnings) associated with the illness. Two studies, Viscusi et al. (1991) and Krupnick and Cropper (1992) provide estimates of WTP to avoid a case of chronic bronchitis. The study by Viscusi et al., however, uses a sample that is larger and more representative of the general population than the study by Krupnick and Cropper (which selects people who have a relative with the disease). The valuation of chronic bronchitis in this analysis is therefore based on the distribution of WTP responses from Viscusi et al. (1991).

Both Viscusi et al. (1991) and Krupnick and Cropper (1992), however, defined a case of severe chronic bronchitis. It is unclear what proportion of the cases of chronic bronchitis predicted to be associated with exposure to pollution would turn out to be severe cases. The incidence of pollution-related chronic bronchitis was based on Abbey et al. (1993), which considered only new cases of the illness.[1] While a new case may not start out being severe, chronic bronchitis is a chronic illness which may progress in severity from onset throughout the rest of the individual's life. It is the chronic illness which is being valued, rather than the illness at onset.

The WTP to avoid a case of pollution-related chronic bronchitis (CB) is derived by starting with the WTP to avoid a severe case of chronic bronchitis, as described by Viscusi et al. (1991), and adjusting it downward to reflect (1) the decrease in severity of a case of pollution-related CB relative to the severe case described in the Viscusi study, and (2) the elasticity of WTP with respect to severity. Because elasticity is a marginal concept and because it is a function of severity (as estimated from Krupnick and Cropper, 1992), WTP adjustments were made incrementally, in one percent steps. At each step, given a WTP to avoid a case of CB of severity level *sev*, the WTP to avoid a case of severity level 0.99**sev* was derived. This procedure was iterated until the desired severity level was reached and the corresponding WTP was derived. Because the elasticity of WTP with respect to severity is a function of severity, this elasticity changes at each iteration. If, for example, it is believed that a pollution-related case of CB is of average se-

[1] It is important that only new chronic bronchitis be considered in this analysis because WTP estimates reflect lifetime expenditures and/or losses associated with this chronic illness, and incidences are predicted separately for each year during the period 1970-1990. If the total prevalence of chronic bronchitis, rather than the incidence of only new chronic bronchitis were predicted each year, valuation estimates reflecting lifetime expenditures could be repeatedly applied to the same individual for many years, resulting in a severe overestimation of the value of avoiding pollution-related chronic bronchitis.

verity, that is, a 50 percent reduction in severity from the case described in the Viscusi study, then the iterative procedure would proceed until the severity level was half of what it started out to be.

The derivation of the WTP to avoid a case of pollution-related chronic bronchitis is based on three components, each of which is uncertain: (1) the WTP to avoid a case of severe CB, as described in the Viscusi study, (2) the severity level of an average pollution-related case of CB (relative to that of the case described by Viscusi), and (3) the elasticity of WTP with respect to severity of the illness. Because of these three sources of uncertainty, the WTP is uncertain. Based on assumptions about the distributions of each of the three uncertain components, a distribution of WTP to avoid a pollution-related case of CB was derived by Monte Carlo methods. The mean of this distribution, which was about $260,000, is taken as the central tendency estimate of WTP to avoid a pollution-related case of CB. Each of the three underlying distributions is described briefly below.

The distribution of WTP to avoid a severe case of CB was based on the distribution of WTP responses in the Viscusi study. Viscusi et al. derived respondents' implicit WTP to avoid a statistical case of chronic bronchitis from their WTP for a specified reduction in risk. The mean response implied a WTP of about $1,000,000 (1990 dollars)[2]; the median response implied a WTP of about $530,000 (1990 dollars). However, the extreme tails of distributions of WTP responses are usually considered unreliable. Because the mean is much more sensitive to extreme values, the median of WTP responses is often used rather than the mean. Viscusi et al. report not only the mean and median of their distribution of WTP responses, however, but the decile points as well. The distribution of reliable WTP responses from the Viscusi study could therefore be approximated by a discrete uniform distribution giving a probability of one ninth to each of the first nine decile points. This omits the first five and the last five percent of the responses (the extreme tails, considered unreliable). This trimmed distribution of WTP responses from the Viscusi study was assumed to be the distribution of WTPs to avoid a severe case of CB. The mean of this distribution is about $720,000 (1990 dollars).

The distribution of the severity level of an average case of pollution-related CB was modeled as a triangular distribution centered at 6.5, with endpoints at 1.0 and 12.0. These severity levels are based on the severity levels used in Krupnick and Cropper, 1992, which estimated with relationship between ln(WTP) and severity level, from which the elasticity is derived. The most severe case of CB in that study is assigned a severity level of 13. The mean of the triangular distribution is 6.5. This represents a 50 percent reduction in severity from a severe case.

The elasticity of WTP to avoid a case of CB with respect to the severity of that case of CB is a constant times the severity level. This constant was estimated by Krupnick and Cropper, 1992, in the regression of ln(WTP) on severity, discussed above. This estimated constant (regression coefficient) is normally distributed with mean = 0.18 and standard deviation = 0.0669 (obtained from Krupnick and Cropper, 1992).

The distribution of WTP to avoid a case of pollution-related CB was generated by Monte Carlo methods, drawing from the three distributions described above. On each of 16,000 iterations (1) a value was selected from each distribution, and (2) a value for WTP was generated by the iterative procedure described above, in which the severity level was decreased by one percent on each iteration, and the corresponding WTP was derived. The mean of the resulting distribution of WTP to avoid a case of pollution-related CB was $260,000.

This WTP estimate is reasonably consistent with full COI estimates derived for chronic bronchitis, using average annual lost earnings and average annual medical expenditures reported by Cropper and Krupnick, 1990. Using a 5 percent discount rate and assuming that (1) lost earnings continue until age 65, (2) medical expenditures are incurred until death, and (3) life expectancy is unchanged by chronic bronchitis, the present discounted value of the stream of medical expenditures and lost earnings associated with an average case of chronic bronchitis is estimated to be about $77,000 for a 30 year old, about $58,000 for a 40 year old, about $60,000 for a 50 year old, and about $41,000 for a 60 year old. A WTP estimate would be expected to be greater than a full COI estimate, reflecting the willingness to pay to avoid the pain and suffering associated with the illness. The WTP estimate of $260,000 is from 3.4 times the full COI estimate (for 30 year olds) to 6.3 times the full COI estimate (for 60 year olds).

[2] There is an indication in the Viscusi paper that the dollar values in the paper are in 1987 dollars. Under this assumption, the dollar values were converted to 1990 dollars.

Valuation of Other Morbidity Endpoints Avoided

WTP to avoid a day of specific morbidity endpoints, such as coughing or shortness of breath, has been estimated by only a small number of studies (two or three studies, for some endpoints; only one study for other endpoints). The estimates for health endpoints involving these morbidity endpoints are therefore similarly based on only a few studies. However, it is worth noting that the total benefit associated with any reduction in pollutant concentrations is determined largely by the benefit associated with the corresponding reduction in mortality risk because the dollar value associated with mortality is significantly greater than any other valuation estimate. More detailed explanations for valuation of specific morbidity endpoints is given in Table I-2.

Estimates of WTP may be understated for a couple of reasons. First, if exposure to pollution has any cumulative or lagged effects, then a given reduction in pollution concentrations in one year may confer benefits not only in that year but in future years as well. Benefits achieved in later years are not included. Second, the possible effects of altruism are not considered in any of the economic value derivations. Individuals' WTP for reductions in health risks for others are implicitly assumed to be zero.

Table I-2 summarizes the derivations of the economic values used in the analysis. More detailed descriptions of the derivations of lead-related endpoints (hospital admissions for CHD and stroke, Lost IQ points, IQ below 70, and hypertension) are discussed in Appendix G.

Valuation of Welfare Effects

With the exception of agricultural benefits, economic valuations for welfare effects quantified in the analysis (i.e., household soiling damage, visibility and worker productivity) are documented in Table I-2. For agricultural benefits, estimated changes in crop yields were evaluated with an agricultural sector model, AGSIM. This model incorporates agricultural price, farm policy, and other data for each year. Based on expected yields, the model estimates the production levels for each crop, the economic benefits to consumers, and the economic benefits to producers associated with these production levels. To the extent that alternative exposure-response relationships were available, a range of potential benefits was calculated. Appendix F documents the derivation of the monetary benefits associated with improved agricultural production. The derivation of the residential visibility valuation estimate is discussed further below.

Visibility Valuation

Residential visibility has historically been valued through the use of contingent valuation studies, which employ surveys and questionnaires to determine the economic value respondents place on specified changes in visibility. A number of such studies have been published in the economics literature since the late 1970s, and have reported a wide range of resulting values for visibility, expressed as household willingness to pay (WTP) for a hypothesized improvement in visibility. Those studies were carefully reviewed for their applicability to the retrospective analysis.

One limitation of many existing contingent valuation studies of visibility is that they are local or regional in scope, soliciting values for visibility from residents of only one or two cities in a single region of the country. Studies of visibility values from western cities, the most recent of which was published in 1981, have reported somewhat lower values than those from eastern cities, raising the question of whether eastern and western visibility are different commodities and should be valued differently in this analysis.

While the different visibility values reported in the literature may appear to imply that visibility is not valued equally by survey respondents in the eastern and western U.S., other evidence suggests that eastern and western visibility are not fundamentally different commodities, and that the retrospective benefits calculations should not be based on separate eastern and western visibility values. For example, NAPAP data indicate that California's South Coast Air Basin, which encompasses Los Angeles and extends northward to the vicinity of San Francisco, has median baseline visibility more characteristic of the eastern U.S. than of other areas of the west (NAPAP 1991; IEc 1992, 1993a), reflecting the influence of the higher humidity typical of coastal areas. While inland areas of the west will tend to have lower humidity, and hence greater baseline visibility than either the eastern region or the western coastal zone, such baseline visibility differences are accounted for in the conversion from the visual range metric to DeciView.

Perhaps the most compelling rationale for employing a single nationwide visibility valuation strategy in the retrospective benefits analysis, however, relates to the air quality modeling output used to calculate the control and no-control scenario visibility profiles, and its implications for the valuation of visibility as a commodity. The RADM model and linear scaling technique used for the retrospective analysis model visibility improvements nationwide as changes in regional atmospheric haze. In other words, although the magnitude of visibility effects may vary between regions, the model output does not distinguish between a change in eastern visibility and a change in western visibility as distinct phenomena. Thus, there is no clear reason to value those same visibility changes differently in calculating the benefits of visibility improvements. Consequently, a single, consistent valuation basis has been applied to residential visibility improvements nationwide for this analysis.

In light of advances in the state of the art of contingent valuation over the last decade, the age of many of the existing studies raised questions regarding their suitability to serve as the primary basis for the visibility benefits estimates. A review of the survey and data analysis methods used in the available studies indicated that a study conducted for EPA by McClelland et al. (1991) addressed many of the methodological flaws of earlier studies, employing survey methods and analytical techniques designed to minimize potential biases (IEc 1992). Although this study is unpublished, given its methodological improvements over earlier studies it was chosen as the basis for the central tendency of the visibility benefits estimate, yielding an estimated value of $14 per unit improvement in DeciView as the annual household WTP for visibility improvements (IEc 1997), as specified in Table I-2.

The difficulty of accurately defining the expected statistical distribution of WTP values for visibility improvements on the basis of published studies of uneven reliability, along with the considerable variation in reported visibility values, led to the selection of a hypothesized triangular distribution of values to characterize the uncertainty in the visibility benefits estimate. Reliance on any single study to estimate the uncertainty range would be unlikely to adequately characterize variations in visibility values that might exist across cities, and in any case would fail to capture the full variability of visibility values reported in the literature. Therefore, to ensure that the retrospective study characterizes the full range of uncertainty in visibility values nationwide, the upper and lower bounds of the triangular distribution were derived by combining results from appropriate eastern and western residential visibility valuation studies.

Most of the existing residential visibility valuation studies were found to suffer from part-whole bias, which results from the failure to differentiate values for visibility from those for other air quality amenities, such as reductions in adverse health effects. Of the studies reviewed for this analysis, only the McClelland study and Brookshire et al. (1979) have attempted to obtain bids explicitly for visibility improvements (IEc 1992). Since part-whole bias will tend to produce overstated values for visibility, reported values from all studies that do not correct for part-whole bias were adjusted prior to calculating the lower bound of the uncertainty range. The upper bound of the uncertainty range was calculated using the unadjusted values from all studies, which is equivalent to assuming that the entire value of respondents' stated WTP for improved air quality can be attributed to increased visibility.

The uncertainty range specified in Table I-2 calculated using a consensus function derived from a regression analysis, incorporates a 25 percent adjustment for part-whole bias (i.e., reported values were multiplied by 0.25) in calculating the lower bound. This represents an approximate midpoint of the range defined by the McClelland study's finding that respondents allocated, on average, 18.6 percent of their total WTP to improvements in visibility, and Chestnut and Rowe's (1989) conclusion that visibility improvement accounted for 34 percent of the total WTP reported in the Brookshire et al. study. Similarly, the "Denver Brown Cloud" study results indicate that respondents allocated 27.2 percent of their total WTP to visibility improvements (Irwin et al. 1990). Therefore, the application of a 25 percent adjustment for part-whole bias to all but the McClelland and Brookshire values would appear to be supported by the recent literature, with the resulting consensus value representing a plausible lower bound for the uncertainty range of visibility values. The consensus function approach, incorporating the part-whole bias adjustment, yields estimated upper and lower bound values of $21 and $8, respectively, for annual household WTP per unit improvement in DeciView.

Table I-2. Unit Values for Economically Valuing Health and Welfare Endpoints.

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
Mortality	$4.8 million per statistical life	Weibull distribution, mean = $4.8 million std. dev. = $3.24 million	Central Est: $ value is the mean of value-of-statistical-life estimates from 26 studies (5 contingent valuation and 21 labor market studies). Uncertainty: Best-fit distribution to the 26 sample means. The Weibull distribution prevents selection of negative WTP values.
	$293,000 per statistical life-year	Weibull distribution, mean = $293,000 std. dev. = $198,000	Central Est: $ value is the mean of the distribution of the value of a statistical life-year, derived from the distribution of the value of a statistical life (see below). Uncertainty: Assuming the discount rate is five percent, and assuming an expected 35 yrs. remaining to the avg. worker in the wage-risk studies (see above), the value of a statistical life-year is just a constant, 0.061, multiplied by the value of a statistical life. The distribution of the value of a life-year is derived from the distribution of the value of a statistical life. Given that this is a Weibull distribution, as indicated above, the value of a statistical life-year is also a Weibull distribution, with mean equal to 0.061 multiplied by the mean of the original Weibull distribution (0.061x$4.8 million = $293,000) and standard deviation equal to 0.061 multiplied by the standard deviation of the original distribution (0.061 x $3.24 = $198,000). (If the discount rate were considered to also be uncertain, then the distribution of a statistical life-year would depend on this distribution as well and would have to be generated by Monte Carlo methods.)

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
Chronic Bronchitis (CB)	$260,000	A Monte Carlo-generated distribution, based on three underlying distributions, as described more fully under "Derivation of Estimates" and in the text.	Central Est: $ value is the mean of a Monte Carlo distribution of WTP to avoid a case of pollution-related CB. WTP to avoid a case of pollution-related CB is derived by adjusting WTP to avoid a severe case of CB (as described in Viscusi et al., 1991) for the difference in severity and taking into account the elasticity of WTP with respect to severity of CB. The mean of the resulting distribution is $260,000. Uncertainty: The distribution of WTP to avoid a case of pollution-related CB was generated by Monte Carlo methods, drawing from each of three distributions: (1) WTP to avoid a severe case of CB is assigned a 1/9 probability of being each of the first nine deciles of the distribution of WTP responses in Viscusi et al., 1991; (2) the severity of a pollution-related case of CB (relative to the case described in the Viscusi study) is assumed to have a triangular distribution, centered at severity level 6.5 with endpoints at 1.0 and 12.0 (see text for further explanation); and (3) the constant in the elasticity of WTP with respect to severity is normally distribution with mean = 0.18 and standard deviation = 0.0669 (from Krupnick and Cropper, 1992). See text for further explanation.
IQ Changes			
1. Lost IQ Points	$3,000 per lost IQ point	none available	Central Est: $ value is the mean of estimates based on results of 2 studies. With an assumed 5% discount rate, the results in Schwartz (1994) yield an estimate of $2,500 per IQ point; the results of Salkever (1995) yield an estimate of $3,400. These estimates include the combined effects on lifetime earnings: (1) *directly* based on IQ decrement, and (2) *indirectly* based on lower educational attainment and reduced labor force participation (subtracting from indirect benefits the costs of additional education and associated opportunity cost).
2. Incidence of IQ < 70	$42,000	none available	Central Est: $ value measures reduction in education costs in terms of special needs for lower IQ students (in mainstream schools).

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
Hypertension	$680 per case per year	none available	Central Est: $ value quantifies costs associated with physician care, medications, and hospital charges, in addition to opportunity cost of lost work time due to the disability.
Hospital Admissions			
1. Strokes - initial cerebrovascular accidents (ICD code 436) - initial atherothrombotic brain infarctions (ICD code 434)	$200,000 for males; $150,000 for females	none available	Central Est: $ values for males and females are based on age- and gender-specific estimates of lifetime cost of stroke from Taylor et al., 1996. Estimates include both direct costs (medical expenditures) and indirect costs (reduced productivity) and assume a five percent discount rate. Uncertainty: Although there is uncertainty surrounding the central estimates presented, there is insufficient information to characterize this uncertainty.
2. Coronary Heart Disease (CHD)	$52,000	A Monte Carlo-generated distribution, based on the uncertainty about what proportion of pollution-related CHD events is acute myocardial infarction, what proportion is angina pectoris, and what proportion is unstable angina pectoris (see "Derivation of Estimates").	Central Est: $ value is the mean of the Monte Carlo-generated distribution of WTP to avoid a pollution-related case of CHD, described below. Uncertainty: The distribution was based on the estimates of the total medical costs within 5 years of diagnosis of each of three types of CHD events examined in the Framingham Study, including acute myocardial infarction, angina pectoris, and unstable angina pectoris (Wittels et al., 1990). It is unknown what proportion of pollution-related CHD events are of each type. On each iteration, three proportions were drawn from three continuous uniform distributions, such that the three proportions summed to 1.0. The $ value for an iteration is the weighted average of the $ values for the three types of CHD event (from Wittels et al., 1990), weighted by the corresponding proportions selected.

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
3. “Respiratory Illness”	$6,100	Normal distribution, mean = $6,100 std. dev. = $55	<u>Central Est</u>: $ value combines a cost-of-illness estimate, including the hospital charge, based on patients of all ages, and the cost of associated physician care, with the opportunity cost of time spent in the hospital. Source of hospital charge estimate: Elixhauser et al., 1993. Source of physician charge estimates: Abt Associates Inc., 1992. <u>Uncertainty</u>: variation about the central estimate based on the standard error reported for the hospital charge component (greater than the other two components by an order of magnitude).
4. COPD (ICD codes 490-496)	$8,100	Normal distribution, with mean = $8,100 std. dev. = $190	<u>Central Est</u>: $ value combines a cost-of-illness estimate, including the hospital charge, based on patients 65 and older, and the cost of associated physician care, with the opportunity cost of time spent in the hospital. Source of cost-of-illness estimates: Abt Associates Inc., 1992. <u>Uncertainty</u>: variation about the central estimate derived from a standard error estimated for the hospital charge component measured by another study (Elixhauser et al., 1993). The reported standard error for hospital charge was applied to the combined cost-of-illness and opportunity cost estimate by assuming that relative variabilities surrounding the respective means were similar (i.e., coefficients of variation are equal). The hospital charge represents the vast majority of the total value to avoid a hospital admission for COPD.
5. Pneumonia (ICD codes 480-487)	$7,900	Normal distribution, with mean = $7,900 std. dev. = $110	<u>Central Est</u>: $ value combines a cost-of-illness estimate, including the hospital charge, based on patients of all ages, and the cost of associated physician care, with the opportunity cost of time spent in the hospital. Source of hospital charge estimate: Elixhauser et al., 1993. Source of physician charge estimates: Abt Associates Inc., 1992. <u>Uncertainty</u>: Applied the standard error associated with the hospital charge component to the central estimate of $7,900. The hospital charge represents the vast majority of the total value to avoid a hospital admission for pneumonia.

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
6. Congestive Heart Failure (ICD code 428)	$8,300	Normal distribution, with mean = $8,300 std. dev. = $120	Central Est: $ value combines a cost-of-illness estimate, including the hospital charge, based on patients of all ages, and the cost of associated physician care, with the opportunity cost of time spent in the hospital. Source of hospital charge estimate: Elixhauser et al., 1993. Source of physician charge estimates: Abt Associates Inc., 1992. Uncertainty: Applied the standard error associated with the hospital charge component to the central estimate of $8,300. The hospital charge represents the vast majority of the total value to avoid a hospital admission for congestive heart failure.
7. Ischemic Heart Disease (ICD codes 410-414)	$10,300	Normal distribution, with mean = $10,300 std. dev. = $88	Central Est: $ value combines a cost-of-illness estimate, including the hospital charge, based on patients of all ages, and the cost of associated physician care, with the opportunity cost of time spent in the hospital. Source of hospital charge estimate: Elixhauser et al., 1993. Source of physician charge estimates: Abt Associates Inc., 1992. Uncertainty: Applied the standard error associated with the hospital charge component to the central estimate of $10,300. The hospital charge represents the vast majority of the total value to avoid a hospital admission for ischemic heart disease.
Respiratory Ailments Not Requiring Hospitalization			
1. Upper Resp. Symptoms (URS) (defined as one or more of the following: runny or stuffy nose, wet cough, burning, aching, or red eyes)	$19	Continuous uniform distribution over the interval [$7, $33]	Central Est: Combinations of the 3 symptoms for which WTP estimates are available that closely match those listed by Pope et al. result in 7 different "symptom clusters," each describing a "type" of URS. A $ value was derived for each type of URS, using IEc mid-range estimates of WTP to avoid each symptom in the cluster and assuming additivity of WTPs. The $ value for URS is the average of the $ values for the 7 different types of URS. Uncertainty: taken to be a continuous uniform distribution across the range of values described by the 7 URS types.

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
2. Lower Resp. Symptoms (LRS) (defined in the study as two or more of the following: cough, chest pain, phlegm, and wheeze.)	$12	Continuous uniform distribution over the interval [$5, $19]	Central Est: Combinations of the 4 symptoms for which WTP estimates are available that closely match those listed by Schwartz et al. result in 11 different "symptom clusters," each describing a "type" of LRS. A $ value was derived for each type of LRS, using IEc mid-range estimates of WTP to avoid each symptom in the cluster and assuming additivity of WTPs. The $ value for LRS is the average of the $ values for the 11 different types of LRS. Uncertainty: taken to be a continuous uniform distribution across the range of values described by the 11 LRS types.
3. Acute Bronchitis	$45	Continuous uniform distribution over the interval [$13, $77]	Central Est: Average of low and high values recommended by IEC for use in section 812 analysis (Neumann et al., 1994). Uncertainty: continuous distribution between low and high values (Neumann et al., 1994) assigns equal likelihood of occurrence of any value within the range.
4. Acute Respiratory Symptoms and Illnesses - Presence of any of 19 acute respiratory symptoms - Any Resp. Symptom - Increase in Resp. Illness	$18	1. URS, probability = 40% LRS, probability = 40% URS+LRS, prob. = 20% 2. If URS, use URS $ dist. If LRS, use LRS $ dist. If URS+LRS, randomly select one value each from URS and LRS $ distributions; sum the two	Central Est: Assuming that respiratory illness and symptoms can be characterized as some combination of URS and LRS, namely: URS with 40% probability, LRS with 40% probability, and both URS and LRS with 20% probability. The $ value for these endpoints is the weighted average (using the weights 0.40, 0.40, and 0.20) of the $ values derived for URS, LRS, and URS + LRS. Uncertainty: based on variability assumed for central estimate, and URS and LRS uncertainty distributions presented previously.

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
5. Asthma - Acute	$32	Continuous uniform distribution over the interval [$12, $54]	Central Est: Mean of average WTP estimates for the four severity definitions of a "bad asthma day." Source: Rowe and Chestnut (1986), a study which surveyed asthmatics to estimate WTP for avoidance of a "bad asthma day," as defined by the subjects. Uncertainty: based on the range of values estimated for each of the four severity definitions.
6. Shortness of breath	$5.30	Continuous uniform distribution over the interval [$0, $10.60]	Central Est: From Ostro et al., 1995. This is the mean of the median estimates from two studies of WTP to avoid a day of shortness of breath: Dickie et al., 1991 ($0.00), and Loehman et al., 1979 ($10.60). Uncertainty: taken to be a continuous uniform distribution across the range of values obtained from the two studies.
Restricted Activity and Work Loss Days			
1. WLDs	$83	none available	Central Est: Median weekly wage for 1990 divided by 5 (U.S. Department of Commerce, 1992) Uncertainty: Insufficient information to derive an uncertainty estimate.
2. RADs	not monetized[a]	--	--
3. MRADs	$38	triangular distribution centered at $38 on the interval [$16, $61]	Central Est: Median WTP estimate to avoid 1 MRRAD -- minor respiratory restricted activity day -- from Tolley et al. (1986) (recommended by IEc as the mid-range estimate). Uncertainty: range is based on assumption that value should exceed WTP for a single mild symptom (the highest estimate for a single symptom--for eye irritation--is $16.00) and be less than that for a WLD. The triangular distribution acknowledges that the actual value is likely to be closer to the point estimate than either extreme.
4. RRADs	not monetized[a]	--	--

Health or Welfare Endpoint	Estimated Value Per Incidence (1990$)		Derivation of Estimates
	Central Estimate	Uncertainty Distribution	
Welfare Effects			
Household Soiling Damage	$2.50 per household per μg/m^3 PM_{10} (annual cost)	Beta distribution with mean=$2.50, standard deviation=$1 on the interval [$1.30, $10.00]. The shape parameters of this distribution are α=1.2 and β=7.3.	Central Est: Source: ESEERCO (1994). ESEERCO uses $1.26 as its low estimate of annual cost of soiling and materials damage per household (assuming 2.63 persons per household), taken from Manuel et al. (1982). The Manuel study measured particulate matter as TSP rather than PM-10. Hypothesizing that at least half of the costs of household cleaning are for the time value of do-it-yourselfers, which was not included in the Manuel estimate, ESEERCO multiplied the Manuel estimate by 2 to get a point estimate of about $2.50, in 1990 $ (reported by ESEERCO as $2.70 in 1992 dollars). Uncertainty: The Beta distribution selected is a smooth, continuous function with its probability mass near the mean and it covers the range of reported estimates.
Visibility	Annual household WTP = $14 per unit decrease in DeciView (decrease in DeciView corresponds to increase in visibility)	Triangular distribution centered at $14 on the interval [$8, $21]	Central Est: Source: IEc 1997. Calculated by dividing the household WTP reported in the McClelland et al. study (1991) by the corresponding hypothesized change in DeciView. Uncertainty: Source: IEc 1997. Calculated by regressing reported household WTP values on the corresponding change in DeciView (converted from reported visual range changes) for all relevant city-scenario combinations posed to respondents in the original studies. The uncertainty range reflects the 25 percent adjustment for part-whole bias applied to reported values prior to calculating the lower bound.
Worker Productivity	change in daily wages: $1 per worker per 10% change in O_3	none available	Central Est: Based on the elasticity of income with respect to O_3 concentration derived from study of California citrus workers (Crocker and Horst, 1981 and U.S. EPA, 1994). Elasticity applied to the average daily income for workers engaged in strenuous outdoor labor, $73 (U.S. 1990 Census).

NOTES:
[a] This endpoint was not monetized because including it in the aggregation of economic benefits would result in double-counting (overlap with WLDs and MRADs).

Results of Valuation of Health and Welfare Effects

Table I-3 presents the results of combining the economic valuations described in this Appendix with the health and welfare effects results presented in Appendix D. As noted in Appendix D, there are alternative estimates for some health and welfare impacts, which form the basis of several alternative benefit estimates. Each of the health effects estimates also has quantified statistical uncertainty. The range of estimated health and welfare effects, along with the uncertain economic unit valuations, were combined to estimate a range of possible results. The combining of the health and economic information used the Monte Carlo method presented in Chapter 7. Table I-3 shows the mean estimate results, as well as the measured credible range (upper and lower five percentiles of the results distribution), of economic benefits for each of the quantified health and welfare categories.

The results for aggregate monetized benefits were also calculated using a Monte Carlo method. The results of the Monte Carlo simulations for the economic values for each of the major endpoint categories are presented in Table I-4. Note that for the upper and lower fifth percentiles the sum of the estimated benefits from the individual endpoints does not equal the estimated total. The Monte Carlo method used in the analysis assumes that each health and welfare endpoint is independent of the others. There is a very low probability that the aggregate benefits will equal the sum of the fifth percentile benefits from each of the ten endpoints.

Table I-5 shows the estimated total benefits ranges for the four modeled target years of this study: 1975, 1980, 1985, and 1990. The results of the Monte Carlo simulations of the aggregate economic benefits for these four target years are depicted in Figure I-1.

Table I-6 examines the impact of limiting the scope of the analysis to locations with more certain air quality estimates. The main analysis (as shown in Tables I-3 through I-5) covers almost the entire population of the 48 States.[3] However, the air quality information is less certain for locations far from a monitor. Table I-6 presents the results of limiting the analysis to people living within 50 km of an ozone, NO_2, SO_2, or CO monitor, or in counties with a PM monitor. The availability of monitors changes over time. Hence the proportion of the population included in this analysis changes over time as well. Table I-6 indicates that approximately a quarter of the total benefits estimated in the main analysis comes from areas with less certain air quality information.

The results of the "all U.S. population" analysis provides a more accurate depiction of the *pattern* of economic benefits across years. The accuracy of the *scale* of incidence is less certain. These results provide a better characterization of the total direct benefits of the Clean Air Act in the lower 48 states than do the "monitored area only" results because the latter completely omits historical air quality improvements for about 25 percent of the population. However, the "all U.S. population" results rely on uncertain extrapolations of pollution concentrations, and subsequent exposures, from distant monitoring sites to provide coverage for the 25 percent or so of the population living far from air quality monitors. Thus, the main results presented in Tables I-3 through I-5 include important uncertainties.

Uncertainties

The uncertainty ranges for the results on the present value of the aggregate measured monetary benefits reported in Table I-3 reflect two important sources of measured uncertainty:

- uncertainty about the avoided incidence of health and welfare effects deriving from the concentration-response functions, including both selection of scientific studies and statistical uncertainty from the original studies; and

- uncertainty about the economic value of each quantified health and welfare effect.

These aggregate uncertainty results incorporate many decisions about analytical procedures and specific assumptions discussed in the Appendices to this report.

In order to provide a more complete understanding of the economic benefit results in Table I-3, sensitivity analyses examine several additional important aspects of the main analysis. First, this section ex-

[3] Except for lead, two to five percent (depending on pollutant) of the population who live in sparsely populated areas are excluded from the main analysis to maximize computer efficiency. All of the population of the 48 states is included in the lead analysis.

Table I-3. Criteria Pollutants Health and Welfare Benefits -- Extrapolated to Entire 48 State Population Present Value (in 1990 using 5% discount rate) of Benefits from 1970 - 1990 (in billions of 1990 dollars).

		Present Value (billions of 1990$)		
Endpoint	**Pollutant(s)**	**5th %ile**	**Mean**	**95th %ile**
Mortality				
Mortality (long-term PM-10 exposure)	PM	$2,369	$16,632	$40,597
Mortality (Lead exposure)	Lead	$121	$1,339	$3,910
Chronic Bronchitis	PM	$409	$3,313	$10,401
Other Lead-induced Ailments				
Lost IQ Points	Lead	$248	$377	$528
IQ < 70	Lead	$15	$22	$29
Hypertension	Lead	$77	$98	$120
Coronary Heart Disease	Lead	$0	$13	$40
Atherothrombotic brain infarction	Lead	$1	$10	$30
Initial cerebrovascular accident	Lead	$2	$16	$45
Hospital Admissions				
*All Respiratory	PM & O3	$8	$9	$11
*COPD + Pneumonia	PM & O3	$8	$9	$10
Ischemic Heart Disease	PM	$1	$4	$6
Congestive Heart Failure	PM & CO	$3	$5	$7
Other Respiratory-Related Ailments				
Children				
Shortness of breath, days	PM	$0	$6	$17
**Acute Bronchitis	PM	$0	$7	$18
**Upper & Lower Respiratory Symptoms	PM	$1	$2	$4
Adults				
Any of 19 Acute Symptoms	PM & O3	$4	$46	$117
All				
Asthma Attacks	PM & O3	$0	$0	$1
Increase in Respiratory Illness	NO2	$1	$2	$4
Any Symptom	SO2	$0	$0	$0
Restricted Activity and Work Loss Days				
MRAD	PM & O3	$50	$85	$123
Work Loss Days (WLD)	PM	$30	$34	$39
Human Welfare				
Household Soiling Damage	PM	$6	$74	$192
Visibility - Eastern U.S.	particulates	$38	$54	$71
Decreased Worker Productivity	O3	$3	$3	$3
Agriculture (Net Surplus)	O3	$11	$23	$35

To avoid double-counting of benefits, the following endpoints were treated as alternatives:
*Hospital admissions for COPD combined with those for pneumonia are treated as an equally-weighted alternative to hospital admissions for all respiratory illnesses.
**The definitions of acute bronchitis and upper and lower respiratory illness overlap; both studies count trouble breathing, dry cough, and wheezing in their estimates. These two studies are treated as alternatives, which reflects the variability of pollution-induced respiratory effects in children.

Table I-4. Present Value of 1970 to 1990 Monetized Benefits by Endpoint Category for 48 State Population (billions of $1990, discounted to 1990 at 5 percent).

		Present Value		
Endpoint	**Pollutant(s)**	**5th %ile**	**Mean**	**95th %ile**
Mortality	PM	$2,369	$16,632	$40,597
Mortality	Pb	$121	$1,339	$3,910
Chronic Obstructive Pulmonary Disease	PM	$409	$3,313	$10,401
IQ (Lost IQ Pts. + Children w/ IQ<70)	Pb	$271	$399	$551
Hypertension	Pb	$77	$98	$120
Hospital Admissions	PM, O3, Pb, & CO	$27	$57	$120
Respiratory-Related Symptoms, Restricted Activity, & Decreased Productivity	PM, O3, NO2, & SO2	$123	$182	$261
Soiling Damage	PM	$6	$74	$192
Visibility	particulates	$38	$54	$71
Agriculture (Net Surplus)	O3	$11	$23	$35

Table I-5. Monte Carlo Simulation Model Results for Target Years, Plus Present Value in 1990 Terms of Total Monetized Benefits for Entire 1970 to 1990 Period (in billions of 1990-value dollars).

Total Benefits By Year ($Billions)	1975	1980	1985	1990	Present Value (5%)
5th percentile	$87	$235	$293	$329	**$5,600**
Mean	$355	$930	$1,155	$1,248	**$22,200**
95th percentile	$799	$2,063	$2,569	$2,762	**$49,400**

Notes:

Present value reflects compounding of benefits from 1971 to 1990.

"Uncertainty Estimates" are results of Monte Carlo analysis combining economic and physical effects uncertainty (i.e., using both between- and within-study variability).

Full uncertainty analysis done only for years shown. Uncertainty estimates for intermediate years computed based on ratios of 5th to 50th percentile and 95th to 50th percentile for years shown. Ratios interpolated between years shown and applied to point estimates for intermediate years.

Figure I-1. Monte Carlo Simulation Model Results for Target Years (in billions of 1990 dollars).

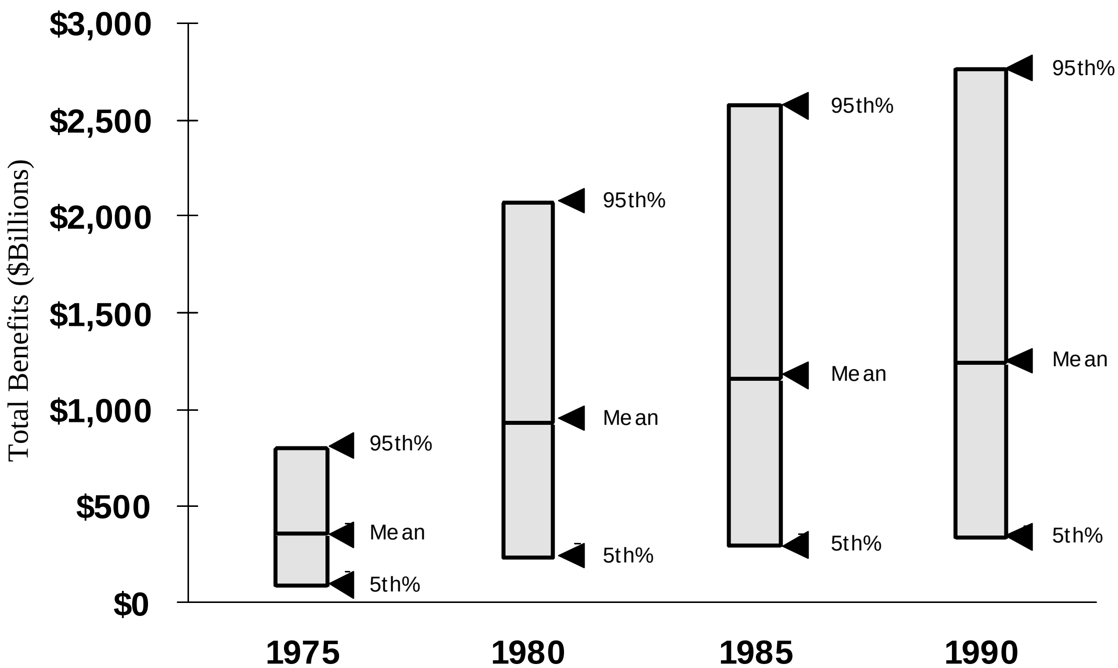


Table I-6. Comparison of 1990 (Single Year) Monetized Benefits by Endpoint for 48 State Population and Monitored Areas (in millions of 1990 dollars).

Endpoint	Pollutant(s)	Mean Estimate of Monetized Benefits (millions of 1990-dollars) 48 State Pop.	Monitored Areas*
Mortality	PM	$892,390	$580,299
Mortality	Pb	$111,741	$111,741
Chronic Bronchitis	PM	$179,755	$120,053
IQ (Lost IQ Points + Children with IQ < 70)	Pb	$32,381	$32,381
Hypertension	Pb	$8,584	$8,584
Hospital Admissions	PM, O3, Pb, & CO	$4,281	$3,994
Respiratory-Related Symptoms, Restricted Activity, & Decreased Productivity	PM, O3, NO2, & SO2	$10,249	$7,089
Soiling Damage	PM	$3,964	$2,709
Visibility	particulates	$3,382	$3,382
Agriculture (Net Surplus)	O3	$986	$986
	TOTAL ($Millions)	$1,247,713	$871,218

* Monitored areas are those within 50 km of an O3, NO2, SO2, or CO monitor or a PM-monitored county. The "48 State Population" modeling estimate captures benefits for populations in unmonitored areas. Air pollution concentrations in these areas are assigned based on concentrations measured at the closest monitor, for O3, NO2, SO2, and CO. PM concentrations in unmonitored counties are derived by extrapolating those in monitored counties.

plores the effect of selecting alternative discount rates on the aggregate present value benefits estimation. Second, this section examines the sources of the measured aggregate uncertainty, identifying which of the measured uncertainty components of incidence and valuation for individual health effects categories drive the overall uncertainty results. Third, this section examines several issues involving the estimated economic benefits of mortality.

The Effect of Discount Rates

The main analysis reflected in present value results shown in Table I-3 uses a five percent discount rate. The discount rate primarily enters the calculations when compounding the economic benefits estimates from individual years between 1970 and 1990 to estimate the present value of the benefits in 1990. The discount rate also directly enters in the calculations of the economic values of an IQ point and an initial case of coronary heart disease.[4] There is considerable controversy in the economics and policy literature about the appropriate discount rate to use in different settings. Major alternatives recommended by various authors include a discount rate based on the social discount rate (typical estimates are in the 2 to 3 percent range), and a discount rate based on the risk-free rate of return on capital (typically in the 7 to 10 percent range). Table I-7 presents the aggregate uncertainty results using three different discount rates: 3 percent, 5 percent and 7 percent. While the aggregate benefits estimates are sensitive to the discount rate, selecting one of these alternative discount rates affects the aggregate benefits estimates by only about 15 percent.

The Relative Importance of Different Components of Uncertainty

The estimated uncertainty ranges in Table I-3 reflect the measured uncertainty associated with both avoided incidence and economic valuation. A better understanding of the relative influence of individual uncertain variables on the overall uncertainty in the analysis can be gained by isolating the individual effects of important variables on the range of estimated benefits. This can be accomplished by holding all the inputs to the Monte Carlo uncertainty analysis constant (at their mean values), and allowing only one variable -- for example, the economic valuation of mortality -- to vary across the range of that variable's uncertainty. The sensitivity analysis then isolates how this single source of variability contributes to the variation in estimated total benefits. The results are summarized in Figure I-2. The nine individual uncertainty factors that contribute the most to the overall uncertainty are shown in Figure I-2, ordered by the relative significance of their contribution to overall uncertainty. Each of the additional sources of quantified uncertainty in the overall analysis not shown contribute a smaller amount of uncertainty to the estimates of monetized benefits than the sources that are shown.

Table I-7. Effect of Alternative Discount Rates on Present Value of Total Monetized Benefits for 1970 to 1990 (in trillions of 1990 dollars).

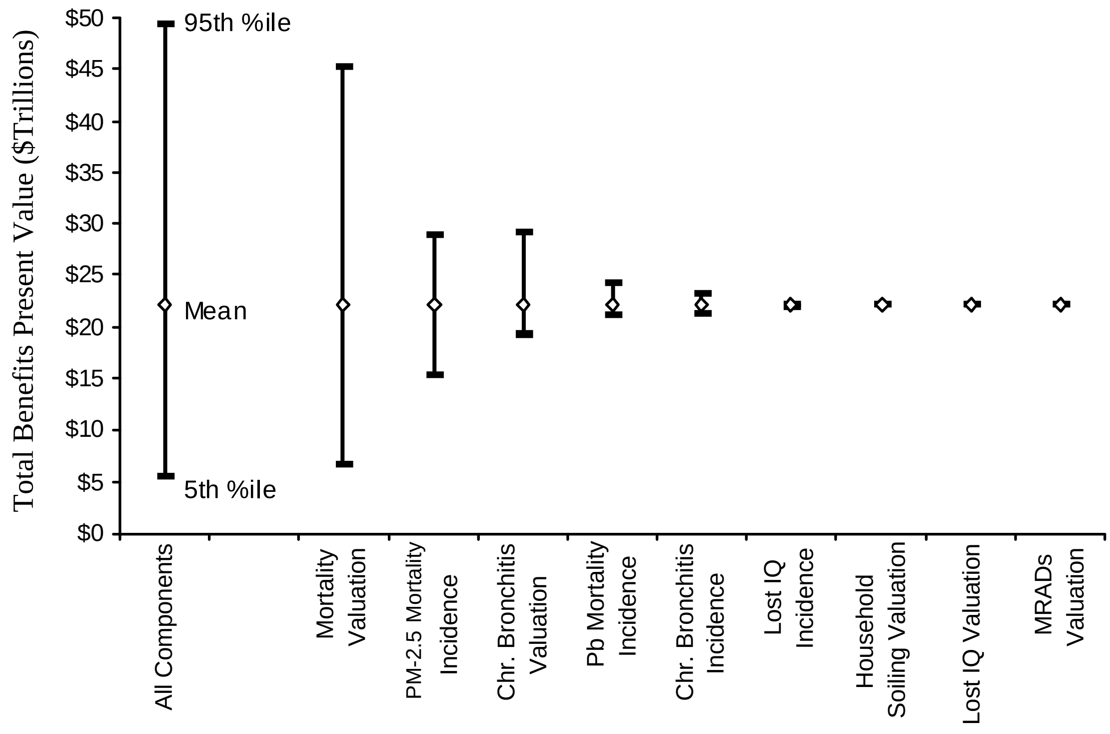
Present Value in 1990 of Total Benefits (Trillions of 1990 Dollars)	3%	5%	7%
5th percentile	$4.9	$5.6	$6.5
Mean	$19.2	$22.2	$25.8
95th percentile	$42.7	$49.4	$57.5

Notes:

Present value reflects compounding of benefits from 1971 to 1990.

[4] The estimated economic value of lost IQ points due to lead exposure is based on the present value of the impact on lifetime earnings. A discount rate is required to calculate that present value. The impact on income primarily occurs during adulthood, which is 20 to 70 years after the initial lead exposure. This significant lag results in the discount rate having a significant impact on the estimated economic benefits of the IQ loss. Similarly, the cost of illness estimate for an initial case of CHD includes the present value of the annual stream of medical costs incurred after the event, the calculation of which requires an estimate of the discount rate.

Figure I-2. Uncertainty Ranges Deriving From Individual Uncertainty Factors.



Because of the multiple uncertainties in the benefits estimation, the total estimated present value of the monetary benefits of the 1970 to 1990 Clean Air Act range from a low of about $5.6 trillion to a high of about $49.4 trillion (in 1990 dollars, discounted at five percent). Most of the uncertainty in the total estimated benefit levels comes from uncertainty in the estimate of the economic valuation of mortality, followed by the uncertainty in the incidence of mortality from PM (as a surrogate for all non-lead air pollution). The incidence of lead-induced mortality also has a significant influence on the overall uncertainty. The importance of mortality is not surprising, because the benefits associated with reduced mortality are such a large share of overall monetized benefits.

The uncertainty in both the incidence and valuation of chronic bronchitis are the two other significant factors driving the overall uncertainty range. The modeled uncertainty in the other remaining health and welfare endpoints in the analysis contribute relatively small amounts to the overall uncertainty in the estimate of total monetary benefits of the Clean Air Act. Most of these other endpoints account for a relatively small proportion of the overall benefits estimates, making it unlikely that they could contribute significantly to the overall uncertainty. Estimates of either the mean values or standard errors of these variables are generally very small relative to estimated total monetary benefits.

Economic Benefits Associated with Reducing Premature Mortality

Because the economic benefits associated with premature mortality are the largest source of monetized benefits in the analysis, and because the uncertainties in both the incidence and value of premature mortality are the most important sources of uncertainty in the overall analysis, it is useful to examine the mortality benefits estimation in greater detail.

The analytical procedure used in the main analysis to estimate the monetary benefits of avoided premature mortality assumes that the appropriate economic value for each incidence is a value from the currently accepted range of the value of a statistical life. As discussed above, the estimated value per predicted incidence of excess premature mortality is modeled as a Weibull distribution, with a mean value of $4.8 million and a standard deviation of $3.2 million. This estimate is based on 26 studies of the value of mortal risks.

There is considerable uncertainty as to whether the 26 studies on the value of a statistical life provide adequate estimates of the value of a statistical life saved by air pollution reduction. Although there is considerable variation in the analytical designs and data used in the 26 underlying studies, the majority of the studies involve the value of risks to a middle-aged working population. Most of the studies examine differences in wages of risky occupations, using a wage-hedonic approach. Certain characteristics of both the population affected and the mortality risk facing that population are believed to affect the average willingness to pay (WTP) to reduce the risk. The appropriateness of a distribution of WTP estimates from the 26 studies for valuing the mortality-related benefits of reductions in air pollution concentrations therefore depends not only on the quality of the studies (i.e., how well they measure what they are trying to measure), but also on (1) the extent to which the subjects in the studies are similar to the population affected by changes in pollution concentrations, and (2) the extent to which the risks being valued are similar. As discussed below, there are possible sources of both upward and downward bias in the estimates provided by the 26 studies when applied to the population and risk being considered in this analysis.

If the individuals who die prematurely from air pollution are consistently older than the population in the valuation studies, the mortality valuations based on middle-aged people may provide a biased estimate of the willingness to pay of older individuals to reduce mortal risk. There is some evidence to suggest that the people who die prematurely from exposure to ambient particulate matter tend to be older than the populations in the valuation studies. In the general U.S. population far more older people die than younger people; 88 percent of the deaths are among people over 64 years old. It is difficult to establish the proportion of the pollution-related deaths that are among the older population because it is impossible to isolate individual cases where one can say with even reasonable certainty that a specific individual died because of air pollution.

There is considerable uncertainty whether older people will have a greater willingness to pay to avoid risks than younger people. There is reason to believe that those over 65 are, in general, more risk averse than the general population, while workers in wage-risk studies are likely to be less risk averse than the general population. More risk averse people would have a greater willingness to pay to avoid risk than less risk averse people. Although the list of recommended studies excludes studies that consider only much-higher-than- average occupational risks, there is nevertheless likely to be some selection bias in the remaining studies -- that is, these studies are likely to be based on samples of workers who are, on average, more risk-loving than the general population. In contrast, older people as a group exhibit more risk averse behavior.

In addition, it might be argued that because the elderly have greater average wealth than those younger, the affected population is also wealthier, on average, than wage-risk study subjects, who tend to be blue collar workers. It is possible, however, that among the elderly it is largely the poor elderly who are most vulnerable to pollution-related mortality risk (e.g., because of generally poorer health care). If this is the case, the average wealth of those affected by a pollution reduction relative to that of subjects in wage-risk studies is uncertain. In addition, the workers in the wage-risk studies will have potentially more years remaining in which to acquire streams of income from future earnings.

Although there may be several ways in which job-related mortality risks differ from air pollution-related mortality risks, the most important difference may be that job-related risks are incurred voluntarily whereas air pollution-related risks are incurred involuntarily. There is some evidence (see, for example, Violette and Chestnut, 1983) that people will pay more to reduce involuntarily incurred risks than risks incurred voluntarily. If this is the case, WTP estimates based on wage-risk studies may be downward biased estimates of WTP to reduce involuntarily incurred air pollution-related mortality risks.

Finally, another possible difference related to the nature of the risk may be that some workplace mortality risks tend to involve sudden, catastrophic events (e.g., workplace accidents), whereas air pollution-related risks tend to involve longer periods of disease and suffering prior to death. Some evidence suggests that WTP to avoid a risk of a protracted death involving prolonged suffering and loss of dignity and personal control is greater than the WTP to avoid a risk (of identical magnitude) of sudden death. Some workplace risks, such as risks from exposure to toxic chemicals, may be more similar to pollution-related risks. It is not clear, however, what proportion of the workplace risks in the wage-risk studies were related to workplace accidents and what proportion were risks from exposure to toxic chemicals. To the extent that the mortality risks addressed in this assessment are associated with longer periods of illness or greater pain and suffering than are the risks addressed in the valuation literature, the WTP measurements employed in the present analysis would reflect a downward bias.

The direction of bias resulting from the age difference is unclear, particularly because age is confounded by risk aversion (relative to the general population). It could be argued that, because an older person has fewer expected years left to lose, his WTP to reduce mortality risk would be less than that of a younger person. This hypothesis is supported by one empirical study, Jones-Lee et al. (1985), that found the value of a statistical life at age 65 to be about 90 percent of what it is at age 40. Citing the evidence provided by Jones-Lee et al. (1985), a recent sulfate-related health benefits study conducted for EPA (U.S. EPA, 1995) assumes that the value of a statistical life for those 65 and over is 75 percent of what it is for those under 65.

There is substantial evidence that the income elasticity of WTP for health risk reductions is positive (see, for example, Alberini et al., 1994; Mitchell and Carson, 1986; Loehman and Vo Hu De, 1982; Gerking et al., 1988; and Jones-Lee et al., 1985), although there is uncertainty about the exact value of this elasticity. Individuals with higher incomes (or greater wealth) should, then, be willing to pay more to reduce risk, all else equal, than individuals with lower incomes or wealth. Whether the average income or level of wealth of the population affected by PM reductions is likely to be significantly different from that of subjects in wage-risk studies, however, is unclear, as discussed above.

The need to adjust wage-risk-based WTP estimates downward because of the likely upward bias introduced by the age discrepancy has received significant attention (see Chestnut, 1995; IEc, 1992). If the age difference were the only difference between the population affected by pollution changes and the subjects in the wage-risk studies, there might be some justification for trying to adjust the point estimate of $4.8 million downward. Even in this case, however, the degree of the adjustment would be unclear. There is good reason to suspect, however, that there are biases in both directions. Because in each case the extent of the bias is unknown, the overall direction of bias in the mortality values is similarly unknown. Adjusting the estimate upward or downward to compensate for any one source of bias could therefore increase the degree of bias. Therefore, the range of values from the 26 studies is used in the primary analysis without adjustment.

Examining the sensitivity of the overall results to the mortality values can help illuminate the potential impacts of alternative mortality valuations. As mentioned above, a contractor study performed for EPA used one approach to evaluate the economic value of sulfate-related human health improvements resulting from 1990 Clean Air Act Amendments Title IV acid rain controls. That study assumed that 85 percent of the people dying from sulfates (an important component of particulate matter) were over 65, and that people over 65 have a willingness to pay to avoid a mortal risk that is 75 percent of the values that middle-aged people have. Using this approach, the value of an average statistical life (using a weighted average) is reduced to 79 percent of the previous value.

If statistical life-years lost are used as the unit of measure, rather than statistical lives lost, the benefit attributed to avoiding a premature death depends directly on how premature it is. One way to estimate the value of a statistical life-year assumes that the value of a statistical life is directly related to remaining life expectancy and a constant value for each life-year. Such an approach results in smaller values of a statistical life for older people, who have shorter life expectancies, and larger values for younger people. For example, if the $4.8 million mean value of avoiding death for people with a 35 year life expectancy is assumed to be the discounted present value of 35 equal-valued statistical life-years, the implied value of each statistical life-year is $293,000 (using a 5% discount rate). The average number of life-years lost by individuals dying prematurely from exposure to PM is 14 years. This average is obtained by multiplying the predicted number of PM-related premature deaths in each age category by the life expectancy for that age category and dividing by the total number of PM-related premature deaths.) Using $293,000 per life-year, the discounted present value of a statistical life for a person with 14 years of expected life remaining (e.g., a 70 year old) is $2.9 million). If statistical life-years lost are used to value fatal risks, however, other sources of uncertainty are introduced in the valuation process.

If statistical life-years lost is the unit of measure, the value of a statistical life lost depends on (1) how many years of expected life are lost, (2) the individual's discount rate, and (3) whether the value of an undiscounted statistical life-year is the same no matter which life-year it is (e.g., the undiscounted value of the seventy-fifth year of life is the same as the undiscounted value of the fortieth year of life). Each of these is uncertain. The uncertainty surrounding the expected years of life lost by an individual involves the uncertainty about whether individuals who die from exposure to air pollution are average individuals in the demographic (e.g., age-gender-race) classification to which they belong. The uncertainty surrounding individuals' discount rates is well documented. Finally, even if it is assumed that all life-years are valued the same (apart from differences due to discounting), the value of a statistical life-year is derived from the value of a statistical life (of a 40 year old) and the discount rate, each of which is uncertain.

Using life-years lost as the unit of measure means that, rather than estimating a single value of a statistical life lost (applicable to all ages), the analysis would instead estimate age-specific values of statistical lives lost. It is unclear whether the variability of estimates of age-specific values of statistical lives lost (in particular, for ages greater than the average age of workers in the wage-risk studies) would be less than or greater than the variability of the original estimate of the value of a statistical life lost from which they would be derived. If there is an age-related upward bias in the central tendency value of a statistical life that is larger than any downward bias, then valuing life-years rather than lives lost may decrease the bias. Even this, however, is uncertain.

In spite of the substantial uncertainties and paucity of available information, this section presents an example of a preliminary estimate of the present value of avoided premature mortality using the life-years lost approach. The basic approach is to (1) estimate the number of pollution-related premature deaths in each age category, (2) estimate the average number of life-years lost by an individual in a given age category dying prematurely, and (3) using the value of a statistical life-year of $293,000, described above (assuming that the undiscounted value of a life-year is the same no matter when in an individual's life it is) and assuming a five percent discount rate, calculate the value of a statistical life lost in each age category.

To obtain estimates of the number of air pollution-related deaths in each age cohort, it is preferable to have age-specific relative risks. Many of the epidemiological studies, however, do not provide any estimate of such age-specific risks. In this case, the age-specific relative risks must be assumed to be identical.

Some epidemiology studies on PM do provide some estimates of relative risks specific to certain age categories. The limited information that is available suggests that relative risks of mortality associated with exposure to PM are greater for older people. Most of the available information comes from short-term exposure studies. There is considerable uncertainty in applying the evidence from short-term exposure studies to results from long-term (chronic exposure) studies. However, using the available information on the relative magnitudes of the relative risks, it is possible to form a preliminary assessment of the relative risks by different age classes.

The analysis presented below uses two alternative assumptions about age-specific risks: (1) there is a constant relative risk (obtained directly from the health literature) that is applicable to all age cohorts, and (2) the relative risks differ by age, as estimated from the available literature. Estimates of age-specific PM coefficients (and, from these, age-specific relative risks) were derived from the few age-specific PM coefficients reported in the epidemiological literature. These estimates in the literature were used to estimate the ratio of each age-specific coefficient to a coefficient for "all ages" in such a way that consistency among the age-specific coefficients is preserved — that is, that the sum of the health effects incidences in the separate, non-overlapping age categories equals the health effects incidence for "all ages." These ratios were then applied to the coefficient from Pope et al. (1995). Details of this approach are provided in Post and Deck (1996). Because Pope et al. considered only individuals age 30 and older (instead of all ages), the resulting age-specific PM coefficients may be slightly different from what they would have been if the ratios had been applied to an "all ages" coefficient. The differences, however, are likely to be minimal and well within the error bounds of this exercise. The age-specific relative risks used in the example below assume that the relative risks for people under 65 are only 16 percent of the population-wide average relative risk, the risks for people from 65 to 74 are 83 percent of the population-wide risk, and people

75 and older have a relative risk 55 percent greater than the population average. Details of this approach are provided in Post and Deck (1996).

The life-years lost approach also requires an estimate of the number of life-years lost by a person dying prematurely at each given age. The average number of life-years lost will depend not only on whether relative risks are age-specific or uniform across all age groups, but also on the distribution of ages in the population in a location. As noted above, using the same relative risk for all age categories, the average number of life-years lost in PM-related premature deaths in the United States was estimated to be 14 years. Using the age-specific relative risk estimates developed for this analysis, the average number of life-years lost becomes 9.8 years. In a location with a population that is younger than average in the United States, the same age-specific relative risks will produce a larger estimated average number of life-years lost. For example, using the same age-specific relative risks, the average number of life-years lost in PM-related premature deaths in Los Angeles County, which has a younger population, is estimated to be 15.6 years.

The present value benefits estimates for PM-related mortality using the alternative approaches discussed above are shown in Table I-8. Table I-8 is based on a single health study: Pope et al., 1995. Alternative studies, or the uncertainty approach used in the primary analysis, would result in a similar pattern of the relationship between valuation approaches. The pattern of monetized mortality benefits across the different valuation procedures shown in Table I-8 is essentially invariant to the particular relative risk and the particular dollar value used.

As noted above, the life-years lost approach used here assumes that people who die from air pollution are typical of people in their age group. The estimated value of the quantity of life lost assumes that the people who die from exposure to air pollution had an average life expectancy. However, it is possible that the people who die from air pollution are already in ill health, and that their life expectancy is less than a typical person of their age. If this is true, then the number of life years lost per PM-related death would be lower than calculated here, and the economic value would be smaller.

The extent to which adverse effects of particulate matter exposure are differentially imposed on people of advanced age and/or poor health is one of the most important current uncertainties in air pollution-related health studies. There is limited information, primarily from the short-term exposure studies, which suggests that at least some of the estimated premature mortality is imposed disproportionately on people who are elderly and/or of poor health. The Criteria Document for Particulate Matter (U.S. EPA, 1996) identifies only two studies which attempt to evaluate this disproportionality. Spix et al. (1994) suggests that a small portion of the PM-associated mortality occurs in individuals who would have died in a short time anyway. Cifuentes and Lave (1996) found that 37 to 87 percent of the deaths from short-term exposure could have been premature by only a few days, although their evidence is inconclusive.

Table I-8. Alternative Estimates of the Present Value of Mortality Associated With PM (based on Pope et al., 1996, in trillions of 1990 dollars).

Valuation Procedure	Present Value of PM Mortality Benefits
Primary Analysis Method ($4.8 million per statistical life saved)	$16.6
Life Years Lost approaches	
Single relative risk, valuation using 5% discounting	$9.1
Approximate age-specific relative risk, valuation using 5% discounting	$8.3

Notes:

Present value reflects compounding of benefits from 1971 to 1990, using a 5 percent discount rate.

Prematurity of death on the order of only a few days is likely to occur largely among individuals with pre-existing illnesses. Such individuals might be particularly susceptible to a high PM day. To the extent that the pre-existing illness is itself caused by or exacerbated by chronic exposure to elevated levels of PM, however, it would be misleading to define the prematurity of death as only a few days. In the absence of chronic exposure to elevated levels of PM, the illness would either not exist (if it was caused by the chronic exposure to elevated PM) or might be at a less advanced stage of development (if it was not caused by but exacerbated by elevated PM levels). The prematurity of death should be calculated as the difference between when the individual died in the "elevated PM" scenario and when he would have died in the "low PM" scenario. If the pre-existing illness was entirely unconnected with chronic exposure to PM in the "elevated PM" scenario, and if the individual who dies prematurely because of a peak PM day would have lived only a few more days, then the prematurity of that PM-related death is only those few days. If, however, in the absence of chronic exposure to elevated levels of PM, the individual's illness would have progressed more slowly, so that, in the absence of a particular peak PM day the individual would have lived several years longer, the prematurity of that PM-related death would be those several years.

Long-term studies provide evidence that a portion of the loss of life associated with long-term exposure is independent of the death from short-term exposures, and that the loss of life-years measured in the long-term studies could be on the order of years. If much of the premature mortality associated with PM represents short term prematurity of death imposed on people who are elderly and/or of ill health, the estimates of the monetary benefits of avoided mortality may overestimate society's total willingness to pay to avoid particulate matter-related premature mortality. On the other hand, if the premature mortality measured in the chronic exposure studies is detecting excess premature deaths which are largely independent of the deaths predicted from the short term studies, and the disproportionate effect on the elderly and/or sick is modest, the benefits measured in this report could be underestimates of the total value. At this time there is insufficient information from both the medical and economic sciences to satisfactorily resolve these issues from a theoretical/analytical standpoint. Until there is evidence from the physical and social sciences which is sufficiently compelling to encourage broad support of age-specific values for reducing premature mortality, EPA will continue to use for its primary analyses a range of values for mortality risk reduction which assumes society values reductions in pollution-related premature mortality equally regardless of who receives the benefit of such protection.

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Appendix J: Future Directions

Research Implications

In virtually any benefit analysis of environmental issues, the state of scientific information limits the degree of coverage possible and the confidence in benefit estimation. For most benefit categories, further scientific research would allow for a better quantification of benefits. One of the major outcomes of the retrospective analysis is a clear delineation of the major limitations in the scientific and economics literature in carrying out an analysis of this scope. Often, a list of research needs is generated in studies such as this, but there is no clear internal mechanism to address these needs. With this study (and the ongoing section 812 program), a process has been initiated where identified research needs are to be integrated into EPA's overall extramural research grants program, administered by the Office of Research and Development. It is hoped that the research projects that flow from this process will enable future analyses to be less uncertain and more comprehensive.

Certain of the limitations in the retrospective analysis are directly related to the historical nature of the analysis, such as sparse information about air quality in the early 1970's in many areas in the country. Other important limitations are related to the effects of elevated airborne lead concentrations, which has been virtually eliminated by the removal of lead from gasoline. A better understanding of these relationships would improve our understanding of the historical impact of the Clean Air Act, but would only indirectly contribute to developing future air pollution policy. However, most of the research that will reduce the major gaps and uncertainties needed to improve the section 812 analyses will be directly relevant to EPA's primary ongoing mission of developing and implementing sound environmental policies to meet the national goals established in the Clean Air Act and other legislation.

There are a number of biological, physical and economic research areas which the EPA Project Team identified as particularly important for improving future section 812 analyses. These research topics can be divided into two principal categories: (1) those which might reduce uncertainties in cost and benefit estimates with significant potential for influencing estimated net benefits of the Clean Air Act, and (2) those which might improve the comprehensiveness of section 812 assessments by facilitating quantification and/or monetization of currently excluded cost or benefit endpoints. The following subsections provide examples of research topics which, if pursued, might improve the certainty and/or comprehensiveness of future section 812 studies.

Research Topics to Reduce Uncertainty

Scientific information about the effects of long-term exposure to air pollutants is just beginning to emerge, but continues to be the subject of intense scientific inquiry. The relationship between chronic PM exposure and excess premature mortality included in the quantified results of the present analysis is one example of such research. However, many other potential chronic effects that are both biologically plausible and suggested by existing research are not included. Research to identify the relationship linking certain known or hypothesized physical effects (e.g., ozone's effects on lung function or fibrosis) with the development of serious health effects (e.g., cardiopulmonary diseases or premature mortality), and the appropriate economic valuation of the willingness to pay to avoid the risks of such diseases, would reduce the uncertainty caused by a major category of excluded health effects which could have a significant impact on the aggregate benefits estimates.

As described in Chapter 7 and Appendix I, premature mortality is both the largest source of benefits and the major source of quantified uncertainty in the retrospective analysis. In addition to the quantified uncertainty, there is considerable additional unquantified uncertainty about premature mortality associated with air pollution. Much of the information base about these relationships is relatively new, more is coming out virtually daily, and there is substantial disagreement in the scientific community about many of the key issues. EPA's Research Strategy and Research Needs document for particulate matter, currently under development, will address many of these scientific issues as they relate to PM. The following selection of highly uncertain issues could have a significant impact on both the aggregate mortality benefits estimates and the measured uncertainty range:

- the relationship of specific pollutants in the overall premature mortality effect, including the individual or interactive relationships between specific chemicals (e.g., ozone, sulfates, nitrates, and acid aerosols), and particle sizes (i.e., coarse, fine and ultra-fine particles);
- the degree of overlap (if any) between the measured relationships between effects associated with short term exposures and effects from long term exposure;
- the confounding effect of changes in historic air pollution, including changes over time in both pollution levels and the composition of the pollutant mix;
- the extent to which life spans are shortened by exposure to the pollutants, and the distribution of ages at the time of death;
- the willingness to pay to avoid the risks of shortened life spans; and
- the extent to which total $PM_{2.5}$ exposure incrementally augments the variability of outdoor $PM_{2.5}$ and increases the dose that would cause excess morbidity or mortality.

After premature mortality, chronic bronchitis is the next largest health effect benefit category included in the retrospective analysis. There is considerable measured uncertainty about both the incidence estimation and the economic valuation. Additional research could reduce uncertainties about the level of the pollutants associated with the observed effects, the baseline incidence used to model the changes in the number of new cases, and the correspondence between the definition of chronic bronchitis used in the health effects studies and the economic valuation studies.

Another area of potentially useful research would be further examination of the effects of criteria pollutants on cardiovascular disease incidence and mortality. Considering available epidemiological evidence and the potential economic cost of cardiovascular disease, the value of avoiding these outcomes may significantly influence the overall benefit estimates generated in future assessments.

Further research on the willingness to pay to avoid the risk of hospital admissions for specific conditions would reduce a potentially significant source of nonmeasured uncertainty. The Project Team used "avoided costs" for the value of an avoided hospital admission, based on the avoided direct medical cost of hospitalization (including lost wages for the employed portion of the hospitalized population). Avoided costs are likely to be a substantial underestimate of the appropriate willingness to pay, especially for such serious health effects as hospitalization for strokes and congestive heart failure, particularly because they omit the value of avoided pain, suffering, and inconvenience. Furthermore, in addition to hospitalization, there is evidence that some people seek medical assistance as outpatients. It is also likely that there are additional people adversely affected by short-term air pollution levels who seek physician services (but stop short of hospital admissions). Revised estimates of the appropriate economic value of avoided hospitalization and other primary care medical services could increase the total economic benefits of this cluster of health effects sufficiently that it could be a much larger portion of the aggregate benefit total.

Finally, one of the challenges in preparing the retrospective analysis was modeling the integrated relationships between emissions of many different chemicals, the subsequent mixture of pollutants in the ambient air, and the resulting health and welfare effects of simultaneous exposure to multiple pollutants. One element of the uncertainty in the analysis derives from the limited current understanding of any interactive (synergistic or antagonistic) effects of multiple pollutants. The need to better understand these complex issues is not a limited scientific question to improve section 812 analyses, but is the primary focus of EPA's current activities, organized under the Federal Advisory Council Act (FACA) process, to develop an integrated set of attainment policies dealing with ozone, particulate matter, sulfur and nitrogen oxides, and visibility. Further research on multi-pollutant issues may both (a) reduce a source of unmeasured uncertainty in the section 812 analyses and (b) allow for effective apportionment of endpoint reduction benefits to specific pollutants or pollutant mixes.

Research Topics to Improve Comprehensiveness

Even though research efforts falling in this category may not result in significant changes in net monetary benefit estimates, one of the goals of the section 812 studies is to provide comprehensive information about Clean Air Act programs. For example, programs to control hazardous air pollutants (HAPs) tend to impose costs and yield benefits which are relatively small compared to programs of pervasive national applicability such as those aimed at meeting National Ambient Air Quality Standards. Nevertheless, there are significant social, political, financial, individual human health, and specific ecosystem effects associated with emissions of HAPs and the programs implemented to control them. Under these circumstances, continued efforts to understand these consequences and evaluate their significance in relation to other programmatic and research investment opportunities might be considered reasonable, particularly in the context of comprehensive program assessments such as the present study.

Some cost and benefit effects could not be fully assessed and incorporated in the net monetary benefit estimate developed for the present study for a variety of reasons. Various effects were excluded due to (a) inadequate historical data (e.g., lack of data on historical ambient concentrations of HAPs), (b) inadequate scientific knowledge (e.g., lack of concentration-response information for ecological effects of criteria and hazardous air pollutants), or (c) resource-intensity or limited availability of analytical tools needed to assess specific endpoints (e.g., indirect effects resulting from deposition and subsequent exposure to HAPs). Other specific examples of presently omitted or underrepresented effect categories include health effects of hazardous air pollutants, ecosystem effects, any long-term impact of displaced capital on productivity slowdown, and redirected technological innovation.

Although the primary focus of 1970 to 1990 CAA programs was reduction of criteria pollutants to achieve attainment of national ambient air quality standards, emissions of air toxics were also substantially reduced. Some air toxics were deliberately controlled because of their known or suspected carcinogenicity, while other toxic emissions were reduced indirectly due to control procedures aimed at other pollutants, particularly ozone and particulate matter. The current analysis was able to present only limited information on the effects of changes in air toxic emissions. These knowledge gaps may be more serious for future section 812 analyses, however, since the upcoming prospective study will include evaluation of the effects of an expanded air toxic program under the CAA Title III. Existing knowledge gaps that prevented a more complete consideration of toxics in the present study include (a) methods to estimate changes in acute and chronic ambient exposure conditions nationwide, (b) concentration-response relationships linking exposure and health or ecological outcomes, (c) economic valuation methods for a broad array of potential serious health effects such as renal damage, reproductive effects and non-fatal cancers, and (d) potential ecological effects of air toxics.

In addition to research to improve the understanding of the consequences of changes in air pollution on human health and well-being, further research on non-health effects could further improve the comprehensiveness of future assessments. Improvements in air quality have likely resulted in improvements in the health of aquatic and terrestrial ecosystems and the myriad of ecological services they provide, but knowledge gaps prevented them from being included in the current analysis. Additional research in both scientific understanding and appropriate modeling procedures could facilitate inclusion of additional benefits such as improvements in water quality stemming from a reduction in acid deposition-related air pollutants. Water quality improvements would benefit human welfare through enhancements in certain consumptive services such as commercial and recreational fishing, in addition to non-consumptive services such as wildlife viewing, maintenance of biodiversity, and nutrient cycling. Similarly, increased growth, productivity and overall health of U.S. forests could occur from reducing ozone, resulting in benefits from increased timber production, greater opportunities for recreational services such as hunting, camping, wildlife observation, and nonuse benefits such as nutrient cycling, temporary CO_2 sequestration, and existence value. Finally, additional research using a watershed approach to examine the potential for ecological service benefits which emerge only at the watershed scale might be useful and appropriate given the broad geographic scale of the section 812 assessments.

While there are insufficient data and/or analytical resources to adequately model the short-run ecological and ecosystem effects of air pollution reduction, even less is known about the long-run effects of prolonged exposure. Permanent species displacement or altered forest composition are examples of potential ecosystem effects that are not reflected in the current monetized benefit analysis, and could be a source of additional benefits. In addition to these ecological research needs, an equally large, or larger, gap in the benefit-cost analysis is the lack of adequate tools to monetize the benefits of such ecosystem services.

Future Section 812 Analyses

This retrospective study of the benefits and costs of the Clean Air Act was developed pursuant to section 812 of the 1990 Clean Air Act Amendments. Section 812 also requires EPA to generate an ongoing series of prospective studies of the benefits and costs of the Act, to be delivered as Reports to Congress every two years.

Design of the first section 812 prospective study commenced in 1993. The EPA Project Team developed a list of key analytical design issues and a "strawman" analytical design reflecting notional decisions with respect to each of these design issues.[1] The analytical issues list and strawman design were presented to the Science Advisory Board Advisory Council on Clean Air Compliance Analysis (Council), the same SAB review group which has provided review of the retrospective study. Subsequently, the EPA Project Team developed a preliminary design for the first prospective study. Due to resource limitations, however, full-scale efforts to implement the first prospective study did not begin until 1995 when expenditures for retrospective study work began to decline as major components of that study were completed.

As for the retrospective, the first prospective study is designed to contrast two alternative scenarios; however, in the prospective study the comparison will be between a scenario which reflects full implementation of the CAAA90 and a scenario which reflects continued implementation only of those air pollution control programs and standards which were in place as of passage of the CAAA90. This means that the first prospective study will provide an estimate of the incremental benefits and costs of the CAAA90.

The first prospective study is being implemented in two phases. The first phase involves development of a screening study, and the second phase will involve a more detailed and refined analysis which will culminate in the first prospective study Report to Congress. The screening study compiles currently available information on the costs and benefits of the implementation of CAAA90 programs, and is intended to assist the Project Team in the design of the more detailed analysis by providing insights regarding the quality of available data sources and analytical models, and the relative importance of specific program areas; emitting sectors; pollutants; health, welfare, and ecological endpoints; and other important factors and variables.

In developing and implementing the retrospective study, the Project Team developed a number of important modeling systems, analytical resources, and techniques which will be directly applicable and useful for the ongoing series of section 812 Prospective Studies. Principal among these are the Criteria Air Pollutant Modeling System (CAPMS) model developed to translate air quality profile data into quantitative measures of physical outcomes; and the economic valuation models, coefficients, and approaches developed to translate those physical outcomes to economic terms.

The Project Team also learned valuable lessons regarding analytical approaches or methods which were not as productive or useful. In particular, the Project Team plans not to perform macroeconomic modeling as an integral part of the first prospective analysis. In fact, there are currently no plans to conduct a macroeconomic analysis at all. Essentially, the Project Team concluded, with confirmation by the SAB Council, that the substantial investment of time and resources necessary to perform macroeconomic modeling would be better invested in developing high quality data on the likely effects of the CAA on key emitting sectors, such as utilities, on-highway vehicles, refineries, etc. While the intended products of a mac-

[1] Copies of the prospective study planning briefing materials are available from EPA.

roeconomic modeling exercise – such as overall effects on productivity, aggregate employment effects, indirect economic effects– are of theoretical interest, the practical results of such exercises in the context of evaluating environmental programs may be disappointing for several reasons.

First, the CAA has certainly had a significant effect on several industrial sectors. However, the coarse structure of a model geared toward simulating effects across the entire economy requires crude and potentially inaccurate matching of these polluting sectors to macroeconomic model sectors. For example, the J/W model used for the retrospective study has only 35 sectors, with electric utilities comprising a single sector. In reality, a well-structured analysis of the broader economic effects of the CAA would provide for separate and distinct treatment of coal-fired utility plants, oil-fired plants, and so on. Furthermore, the outputs of the macroeconomic model are too aggregated to provide useful and accurate input information for the sector-specific emission models used to project the emissions consequences of CAA programs. Again, the critical flaw is the inability to project important details about differential effects on utilities burning alternative fuels.

The second critical problem with organizing a comprehensive analysis of the CAA around a macroeconomic modeling approach is that the effect information produced by the macroeconomic model is relatively unimportant with respect to answering the fundamental, target variable: "*How do the overall health, welfare, ecological, and economic benefits of Clean Air Act programs compare to the costs of these programs?"* The Project Team believes that any adverse effect, no matter how small in a global context, should not be deemed "insignificant" if even one individual is seriously harmed. However, the retrospective study results themselves have shown that, when analytical resources are limited, the resources invested in the macroeconomic modeling would have been better spent to provide a more complete and less uncertain assessment of the benefit side of the equation. Even on the cost side of the equation, it is far more important to invest in developing accurate and reliable estimates of sector-specific compliance strategies and the direct cost implications of those strategies. This will be even more true in the prospective study context when the Project Team will be faced with forecasting compliance strategies and costs rather than simply compiling survey data on actual, historical compliance expenditures.

The third and most important limitation of macroeconomic modeling analysis of environmental programs is that, unlike the economic costs of protection programs, the economic benefits are not allowed to propagate through the economy. For example, while productivity losses associated with reduced capital investment due to environmental regulation are counted, the productivity gains resulting from reduced pollution-related illness and absenteeism of workers are not counted. The resulting imbalance in the treatment of regulatory consequences raises serious concerns about the value of the macroeconomic modeling evaluation of environmental programs. In the future, macroeconomic models which address this and other concerns may be developed; however, until such time EPA is likely to have limited confidence in the value of macroeconomic analysis of even broad-scale environmental protection programs.

Based on these findings and other factors, the design of the first prospective study differs in important ways from the retrospective study design. First, rather than relying on broad-scale, hypothetical, macroeconomic model-based scenario development and analysis, the first prospective study will make greater use of existing information from EPA and other analyses which assess compliance strategies and costs, and the emission and air quality effects of those strategies. After developing as comprehensive a data set as possible of regulatory requirements, compliance strategies, compliance costs, and emissions consequences, the data set will be reviewed, refined, and extended as feasible and appropriate. In particular, a number of in-depth sector studies will be conducted to develop up-to-date, detailed projections of the effects of new CAA requirements on key emitting sectors. Candidate sectors for in-depth review include, among others, utilities, refineries, and on-highway vehicles.

The first prospective study will also differ from the retrospective study in that analytical resources will be directed toward development of a more complete assessment of benefits. Efforts will be made to address the deficiencies which prevailed in the retrospective study relating to assessment of the benefits of air toxics control. In addition, the Project Team will endeavor to provide a more complete and effective assessment of the ecological effects of air pollution control.