

THE COST OF REDUCED VISIBILITY DUE TO PARTICULATE AIR POLLUTION FROM MOTOR VEHICLES

Report #13 in the series: *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data*

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- Report 13:** The Cost of Reduced Visibility Due to Particulate Air Pollution from Motor Vehicles (M. Delucchi, J. Murphy, D. McCubbin, and J. Kim)

- Report 14:** The External Damage Cost of Direct Noise from Motor Vehicles (M. Delucchi and S. Hsu) (with separate 100-page data Appendix)
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LIST OF ACRONYMS AND ABBREVIATIONS AND OTHER NAMES

The following are used throughout all the reports of the series, although not necessarily in this particular report

AER = *Annual Energy Review* (Energy Information Administration)
AHS = *American Housing Survey* (Bureau of the Census and others)
ARB = Air Resources Board
BLS = Bureau of Labor Statistics (U. S. Department of Labor)
BEA = Bureau of Economic Analysis (U. S. Department of Commerce)
BTS = Bureau of Transportation Statistics (U. S. Department of Transportation)
CARB = California Air Resources Board
CMB = chemical mass-balance [model]
CO = carbon monoxide
dB = decibel
DOE = Department of Energy
DOT = Department of Transportation
EIA = Energy Information Administration (U. S. Department of Energy)
EPA = United States Environmental Protection Agency
EMFAC = California's emission-factor model
FHWA = Federal Highway Administration (U. S. Department of Transportation)
FTA = Federal Transit Administration (U. S. Department of Transportation)
GNP = Gross National Product
GSA = General Services Administration
HC = hydrocarbon
HDDT = heavy-duty diesel truck
HDDV = heavy-duty diesel vehicle
HDGT = heavy-duty gasoline truck
HDGV = heavy-duty gasoline vehicle
HDT = heavy-duty truck
HDV = heavy-duty vehicle
HU = housing unit
IEA = International Energy Agency
IMPC = Institutional and Municipal Parking Congress
LDDT = light-duty diesel truck
LDDV = light-duty diesel vehicle
LDGT = light-duty gasoline truck
LDGV = light-duty gasoline vehicle
LDT = light-duty truck
LDV = light-duty vehicle
MC = marginal cost
MOBILE5 = EPA's mobile-source emission-factor model.
MSC = marginal social cost

MV = motor vehicle
NIPA = National Income Product Accounts
NO_x = nitrogen oxides
NPTS = Nationwide Personal Transportation Survey
OECD = Organization for Economic Cooperation and Development
O₃ = ozone
OTA = Office of Technology Assessment (U. S. Congress; now defunct)
PART5 = EPA's mobile-source particulate emission-factor model
PCE = Personal Consumption Expenditures (in the National Income Product Accounts)
PM = particulate matter
PM₁₀ = particulate matter of 10 micrometers or less aerodynamic diameter
PM_{2.5} = particulate matter of 2.5 micrometers or less aerodynamic diameter
PMT = person-miles of travel
RECS = Residential Energy Consumption Survey
SIC = standard industrial classification
SO_x = sulfur oxides
TIA = *Transportation in America*
TSP = total suspended particulate matter
TIUS = *Truck Inventory and Use Survey* (U. S. Bureau of the Census)
USDOE = U. S. Department of Energy
USDOL = U. S. Department of Labor
USDOT = U. S. Department of Transportation
VMT = vehicle-miles of travel
VOC = volatile organic compound
WTP = willingness-to-pay

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13. THE COST OF REDUCED VISIBILITY DUE TO PARTICULATE AIR POLLUTION FROM MOTOR VEHICLES

13.1 INTRODUCTION

Particles and gases in the atmosphere scatter and absorb light, and thereby reduce visibility (Watson and Chow, 1994; Richards et al., 1990; Ozkaynak et al., 1985). Although natural sources of particles, such as volcanoes, can significantly degrade visibility, it generally is true that “when visibility is poor...most particles are found to be of human origin, from sources such as power plants, vehicle exhaust, biomass burning, suspended dust, and industrial activities” (Watson and Chow, 1994, p.244). Poor visibility diminishes the enjoyment of scenic vistas and makes travel hazardous¹. Statistical analyses of property values (discussed below) reveal that people are willing to pay extra for houses in areas with good visibility and good air quality.

The particles that are most efficient at scattering light are roughly the same size as the wavelength of visible light -- about 0.5 μm (Watson and Chow, 1994; Richards et al., 1990; Ozkaynak et al., 1985). Because most particles emitted by the combustion of diesel fuel, and some particles of re-entrained road dust, are 0.5 $\mu\text{m} \pm 0.4 \mu\text{m}$, emissions related to motor-vehicle use can significantly degrade visibility. In support of this, Trijonis (1984) has estimated that direct emissions from heavy-duty diesel vehicles in California cause 10% to 20% of the light extinction.

In this report, we review some of the literature on the cost of visibility, and then develop our own estimates of the national cost of visibility degradation due to air pollution. For our own estimate, we select a simple hedonic model, from the meta-analysis of Smith and Huang (1995), of the relationship between the asset value of homes, levels of total suspended particulate matter (TSP), and per-capita income. Because the hedonic price of TSP undoubtedly comprises the price of visibility (as well as the price of other effects of TSP, such as bad health), and because we can relate TSP emissions to visibility, we can use this hedonic model to estimate the visibility cost of TSP emissions. Specifically, we will apply this hedonic meta-model to estimate the visibility cost of all anthropogenic TSP pollution, and of motor-vehicle TSP pollution, in every county in the U. S. in 1990.

¹Mensah and Osei-Adjei (1992) estimated that a 10% improvement in visibility reduces non-fatal accidents by 15.6 units per day, and reduces travel time, but actually increases the probability of a fatal accident by 0.023 per day, apparently because people drive faster when they can see better.

13.2 LITERATURE REVIEW

13.2.1 General estimation methods

There are two ways to estimate the cost of impaired outdoor visibility. With *contingent valuation*, researchers survey people and ask them to make explicit, but hypothetical, tradeoffs between visibility and dollars or things with a known dollar value. In *hedonic price analysis*, researchers analyze the value of visibility that is implicit in the prices that people pay for houses in regions that have different average annual levels of visibility. These two methods have complementary strengths and weaknesses (Cropper and Oates, 1992).

Contingent valuation. The main strength of contingent valuation (CV) is that it is explicit: the item to be valued (in our case, visibility) is identified and described and “marketed” explicitly. In principle, one can perform a CV study of any nonmarket good. One can value separately items that otherwise are difficult to disentangle: for example, the aesthetic effects and the health effects of polluted air. Because they are hypothetical, CV studies are not limited by the availability of data from real markets. And because they explicitly ask for individual willingness to pay for specific goods or services, in principle they tell the cost-benefit analyst precisely what she or he needs to know.

However, the obvious and potentially grave weakness of CV is that the valuation is hypothetical, and therefore reliable only insofar as people respond realistically to the hypothetical market. Unfortunately, this difficulty becomes most serious in precisely those situations in which CV in principle is the most useful: the valuation of nonmarket goods and services that people apparently care about but have no experience valuing or trading. With CV studies, the challenge then is to design a credible scenario and market mechanism, to induce people to behave as realistically as possible. (See McClelland et al., [1991] and Chestnut and Rowe [1990b] for further discussion.)

Hedonic price analysis. By contrast, the strength of hedonic price analysis is that it is based on real, “revealed” behavior in the market place. In this approach, developed theoretically by Rosen (1974), one estimates a marginal willingness-to-pay function, or demand function, for visibility or air quality, on the basis of an estimated relationship between housing price and housing attributes including visibility or air quality². This

²There are two stages in the hedonic method. First, one regresses observed housing prices against observed housing attributes, including air quality. The resulting functional relationship between air quality and housing prices can be used to estimate the capitalized housing value of small changes in air quality, for households similar to those used in the regression. However, this hedonic function is not valid for large changes in air quality, or for households with significantly different characteristics, if household marginal willingness-to-pay (MWTP) for air quality depends on the level of air quality or the characteristics of households. In this case, one must estimate MWTP for air quality as a function of air quality and household characteristics such as income. To estimate this MWTP (demand) function (the second stage of the analysis), one differentiates the first-stage hedonic function with respect to the air quality attribute, to produce the MWTP for (or price of) air quality for each household, and then regresses the MWTP (price) against air pollution and household characteristics, to obtain the MWTP

approach thus attempts to capture the actual value that people place on visibility or air quality as revealed by their willingness to pay more for homes with better visibility or air quality, all else equal.

However, hedonic price analyses have several weaknesses. First, the individual items being valued, such as air quality or visibility, of course are not actually marketed explicitly as separate items, but rather are marketed implicitly, as part of a bundle of many attributes. An analyst can identify an implicit relationship between housing price and air quality or visibility, but because nobody buys and sells air quality or visibility, the analyst cannot be sure that his measure of air quality or visibility is the one that people actually use. More importantly, even if he has the right measure of air quality or visibility, he cannot on the basis of the hedonic analysis alone determine the “components” of the implicit value of air quality -- health, visibility, soiling, etc. -- because air quality and visibility are so highly correlated, in reality and in people’s minds. (By contrast, in a CV study, one can isolate these components explicitly.) (We discuss this more below.)

Moreover, analyses of housing values tell us only what people are willing to pay for visibility at home; they do not tell us, necessarily, what they are willing to pay for visibility at work or on vacation. Although it is possible to apply the hedonic price technique to commercial and industrial property and to wages, little work has been done in these areas.

13.3.2 Review of contingent valuation studies of visibility³

1). Rowe et al. (1980) attempted to establish the economic value of visibility over long distances in the Four Corners region in New Mexico. This study was the first bidding method in which the scenarios were developed to link physical measures of visibility levels with emission rates. Three alternative scenarios showed decreasing levels of visibility. The first (A) depicted a visual range of about 120 km, which was described as being marginally better than the current “typical” conditions. The second (B) represented a visual range of about 80 km, and the third (C) represented a visual range of about 40 km. The questionnaire attempted to break down the total benefits into separate benefits for visibility, acute health, and chronic health values.

Respondents were given variations on the typical iterative bidding procedure for proposed degradation in air quality from the highest level (A) to the lower levels (B or C). The results were annual bids for residents of \$82 (level A to level C) and \$57 (level B to level C).

2). Brookshire et al. (1979, 1982) used a contingent market approach to examine benefits from air-pollution control in the South Coast Air Basin of California. Three

function. With this, one calculates the value of a large change in air pollution by integrating the MWTP function between the before and after pollution levels.

³Chestnut and Rowe (1990a; updated but abridged in Chestnut and Dennis, 1997) provide an excellent review of the economic valuation of changes in visibility.

scenarios were developed. The A scenario depicted “poor” air quality with a visual range of about two miles. The B scenario represented “fair” air quality with a visual range of around 12 miles. The C scenario depicted “good” air quality with a visual range of about 28 miles. In communities with poor air quality, households bid \$11 to \$22 per month (mean of \$14.54/month) to obtain fair air quality. In communities with fair air quality, households bid \$5.55 to \$28.18 per month to improve local conditions to good, with an overall average bid of \$20.21. On average, for all proposed changes, the aesthetic, acute health, and chronic health components constituted about 34 percent, 40 percent and 26 percent, respectively, of the total mean bids.

3). Schulze et al. (1983) report the results of an experimental study designed to measure the economic value of visibility in the National Parks of the Southwestern United States. The purpose of the study was to estimate the visibility benefits of controls on SO₂ emissions from power plants, as part of a cost-benefit analysis of the emissions regulations. To derive their estimate, Schulze et al. (1983) used a study of visibility perception in which participants were shown photographs of vistas in different National Parks. For each vista, there were photographs with five different visibility ranges. Participants then were asked questions about their willingness to pay for the different visibility levels, as depicted by the five photographs.

The survey was designed to elicit the existence or option values of people who wouldn't use the park, as well as the values of people who would. To estimate user values, one-third of the participants were asked about their willingness to pay higher park entrance fees to: (1) improve visibility in the Grand Canyon, (2) prevent a deterioration of visibility from the current average in the Southwest National Parks, and (3) prevent plume blight in the Grand Canyon. The remaining two thirds of the participants, the hypothetical non-users, were asked about their willingness to pay for increased electricity rates, rather than increased park-entrance fees.⁴ The survey was conducted in 1980, with over 600 households in Denver, Los Angeles, Chicago, and Albuquerque participating.

The study found that it was worth about \$3.5 billion to control SO₂ emissions from power plants in order to preserve visibility in the Grand Canyon, and \$6.2 billion to preserve visibility in all National Parks in the Southwest (1980 dollars). Non-user benefits were about two-thirds of the total.

4). Chestnut and Rowe (1990b) administered a comprehensive survey of WTP to preserve visibility in National Parks, mainly in the southwestern U. S. They were especially concerned with a number of methodological issues, including: the impact of the kind of information given in the survey; the relationship between WTP and the number of regions or parks being considered; the respondents' uncertainty; the estimation of option value, bequest value, and existence value; and the separation of visibility from other impacts (such as on health) of air pollution.

⁴ Much of the visibility degradation in the Southwest parks is due to SO₂ emissions from coal-fired electricity plants.

They found that over 90% of the respondents were willing to pay something to protect visibility at National Parks, and that non-use values were at least as important as use values (the WTP comprised 32% option price, 37% bequest value, and 31% existence value). On average, households were willing to pay \$40 to \$60 per year to improve visibility from the 50th to the 90th percentile, or prevent a decline from the 50th to the 10th percentile. The mean WTP for Preventing the degradation of visibility was slightly more important than obtaining improvements. Over 80% of the respondents felt that their answers were either “very accurate” or “in the ball park”. However, in spite of clear instructions to value only visibility, respondents in fact valued non-visibility impacts as well: answers to a follow-up question revealed that 62% of the stated WTP was for visibility alone. Finally, Chestnut and Rowe (1990b) found that “if individuals had to simultaneously pay their stated WTP for all three regions, rather than for just one region, it is uncertain whether the total WTP would decrease as compared to the sum of the bids for all three regions” (p. 5-5).

5). Crocker and Shogren (1991) used contingent valuation to estimate the policy-relevant components of economic valuation of visibility at a wilderness location and an urban location in Oregon. The participants were given a questionnaire with computer-generated haze levels superimposed on a photograph of a vista from a wilderness site in the Central Oregon Cascades. The simulated haze represented visual ranges of 53, 88, 121, and 309 km. The participants were asked how much extra they would pay to enter the wilderness under each of the visibility conditions. They also were asked about their willingness to pay (WTP) even if they could not visit the site ever (i.e., WTP for “existence” value), and their WTP to obtain the visibility benefits at different times. Crocker and Shogren (1991) found that: i) existence value was about 10% of total WTP; ii) the implicit subjective discount rates were relatively high (about 10% to 40%/year), and iii) it was not clear if WTP for visibility at a specific site represented the WTP for that site only, or rather represented WTP for visibility throughout a much larger region.

6). McClelland et al. (1991) used the CVM method to assess WTP for improved air quality in Chicago and Atlanta. They were particularly concerned to “address and overcome the shortcomings of previous benefits estimations for improved visibility that have used the contingent valuation method” (p. 1). The survey carefully distinguished several different impacts of air pollution, and found that 19% of the total WTP for improved air quality was for visibility per se, 49% was for health, 22% was for soiling, and 11% was for “other” impacts. Chestnut and Dennis (1997) argue that the McClelland et al. (1991) study was “well designed, and addressed many of the criticisms raised about previous contingent valuation studies for residential use values related to visibility” (p. 398), and use results from McClelland et al. (1991) to estimate the value of the visibility coefficient in their own model of household WTP for improved visibility (discussed more below).

7). Recently, Loehman et al (1994) compared two different willingness-to-pay (WTP) measures: WTP to avoid a loss of air quality, and WTP to obtain gains in air quality. They obtained their data from a contingent valuation survey in the San Francisco Bay Area during the spring of 1980. These data were then used to estimate

bid functions for the two WTP measures for both visibility and health. They found that WTP to avoid losses in visibility and health exceeded WTP to obtain gains, especially for large changes, and that the average person was willing to pay more to avoid a health loss than a visibility loss.

13.2.3 Review of hedonic price analyses

1). Brookshire et al. (1979, 1982)⁵ analyzed residential property values in the South Coast Air Basin of Southern California in order to relate WTP with NO₂ or TSP levels and community average household incomes. They used 1977-1978 data on housing price and characteristics, 1975 average daily maximum levels of NO₂ and TSP, and community-level income data (household income was not available).

WTP was found to be positively correlated with pollution and income levels. They estimated that each household valued a 25% to 30% reduction in air pollution at \$528 (NO₂ equation) to \$588 (TSP equation) per year. Note, though, that this is the value of reducing pollution, which probably comprises more than just visibility improvement.

2). Trijonis et al. (1985) analyzed the relationship between housing values and horizontal visibility (expressed in terms of light extinction) in Los Angeles and San Francisco, from 1973-1974 and 1978-1979. The second-stage equation in their hedonic analysis is the demand curve for visibility: WTP for a home as a function of light extinction (which is inversely related to visual range) and community average household incomes. The equation indicates that a 10% improvement in visual range was worth \$99/year/household.

The Trijonis et al. (1985) model, which is shown in the Appendix to this report, is appealing because it relates a specific visibility variable -- light extinction -- with WTP. However, for several reasons, we decided not to use their equation as the basis of our national analysis.

First, it is a stretch to extrapolate to the entire U. S. an equation estimated for Los Angeles and San Francisco.

Second, in order to estimate the visibility benefit of eliminating motor-vehicle emissions, one must know the relationship between emissions and the visual-range variable. Although this is not especially difficult to estimate, it is an additional complication.

Third, there is no reason to believe that the "visibility" variable really is any different from an "air-quality" variable. As noted above, visibility levels are closely correlated with -- and indeed are known to be physically related to -- levels of some kinds of air pollutants, primarily particulate matter. This raises the possibility that *in peoples' minds* "visual range" is a proxy for air pollution. We -- and perhaps most people -- know that the pollutants that cause haze and reduce visibility also damage people,

⁵As reviewed above, Brookshire et al. (1979, 1982) also conducted a contingent valuation survey to estimate the value of air quality. The 1982 article compares the two approaches.

other animals, plants, and materials. Thus, the analytical problem is that we cannot be sure that the value of “visibility” implicit in the hedonic price analyses really is the value of visibility *only*, and not the value of at least some of the other bad effects of pollution as well. We cannot be sure because we believe not only that most people know that the pollution that impairs visibility also has other undesirable effects, but that most people in fact measure pollution by visibility⁶.

Finally, in Los Angeles, which contributed the majority of the observations in the combined regression, the light-extinction coefficient might have the wrong sign. Because light-extinction is a “bad,” in the economic sense of the word, intuition tells us that the sign of the coefficient for light-extinction should be positive -- that people should be willing to pay more per unit of extinction as extinction increases (i.e., as visibility, the “good”, decreases). However, all of the functional forms tested by Trijonis et al. (1985) yielded a negative coefficient, which seems to suggest non-convex preferences, and increasing marginal utility for the visibility good. Although Trijonis et al. (1985) acknowledge that these results are peculiar, they cite an unpublished paper that claims that this is a “mute issue because the non-linearity of the hedonic equation prevents a priori prediction of the sign of the pollution variable. Thus, although the negative sign seems to suggest non-convex preferences, there is really insufficient evidence to make such a conclusion” (page 90).

For these reasons, we have not used the Trijonis et al. (1985) equation for our official model and estimates. (We note, though, that with the model that we do use, which we discuss next, we in essence still face the third problem above.) However, we do present and apply their model in the Appendix to this report.

3). Smith and Huang (1995) performed a meta-analysis of prior hedonic price analyses of the marginal willingness-to-pay (MWTP) to reduce particulate matter levels. They reviewed over 50 studies developed between 1967 and 1988, 37 of which had some empirical estimates involving hedonic price functions with some measure of air pollution. From the 167 hedonic models in these studies, Smith and Huang (1995) were able to reconstruct 86 estimates of the MWTP for reducing total suspended particulates (TSP). They then estimated the relationship between MWTP in each study, expressed as the change in the asset value of a house per $\mu\text{g}/\text{m}^3$ of TSP pollution, and several independent variables, including: the level of pollution in each city in the year closest to the date of the sample, real per-capita income in each city in the year closest to the date for the housing prices, the vacancy rate for the year closest to the date of the housing sales, and qualitative variables describing the characteristics of each study, such as the number of variables used to describe neighborhood quality.

Smith and Huang (1995) used two different estimators in their meta-analysis: minimum absolute deviation (MAD) and ordinary least squares (OLS).

⁶For example, in the WTP survey by the Brookshire et al. (1979, 1982), air quality was represented by visual range.

For each of the two estimators, they specified a simple model, in which TSP levels and per-capita income are the only independent variables, and a more comprehensive model, which included the vacancy rate, characteristics of the original studies, and other variables as well as pollution and income.

Smith and Huang (1995) found that “the interquartile range for these estimated marginal values, measured as a change in asset (i.e. house) prices lies between zero and \$98.52 (in 1982-84 dollars) for a one-unit reduction in total suspended particulates (in micrograms per cubic meter). The mean MWTP is nearly five times the median (\$109.90 versus \$22.40), suggesting that outliers are important influences to any summary statistics for the estimates.”⁷

We have chosen Smith and Huang’s (1995) meta-analysis over other studies because a meta-analysis, being a synthesis of many different studies from many different regions, is a better basis for estimating national damages. As Smith and Huang note, it is better to use a model that relates MWTP to pollution and income in each city than to pick a single “best-guess” MWTP for every city⁸. We choose their simple MAD model because we have data on income and TSP levels in every county in the U. S., and because in the two-independent-variable MAD model the coefficients were significant, whereas in the two-independent-variable OLS model they were not. (Also, MAD is less sensitive to outlying observations, which were a serious problem in Smith and Huang’s meta-analysis.) Also, we can establish a simple relationship between TSP and visibility, and in essence weight TSP emissions according to their effect on visibility. This will allow us to estimate the *visibility* cost of TSP emissions from a particular source, such as motor -vehicles. (Different components of TSP have different effects on visibility, and hence any particular source of particulate emissions might contribute more or less to visibility degradation than do all particulate sources on average.)⁹ Finally, it will be interesting to compare the results of this hedonic-price analysis with the damage-function estimates of the health cost of air pollution.

Of course, we still must determine the portion of the estimated WTP that can be attributed to visibility per se, apart from any simultaneously perceived, or “coproduced,” health benefits. We discuss this problem more below.

⁷MAD tends to be less sensitive to outlying observations, but does not explicitly adjust for heteroscedasticity. OLS with adjusted estimates for coefficient variance takes heteroscedasticity into account, but tends to be influenced by outlying observations.

⁸Smith and Huang (1995) also note that “the MWTP estimates [from a meta-analysis] offer a crude average of the marginal values estimated under specific circumstances...[meta-analysis] is best interpreted as a statistical summary of the role of economic factors and modeling decisions for the *average* measures of MWTP for a set of individual single markets.” (p. 211, italics added)

⁹This actually is easier than estimating the relationship between emissions and visual range, which is what would have been required with the Trijonis et al. (1985) equation.

13.3 METHODS AND DATA OF OUR ANALYSIS

We model the net visibility benefits of three pollution-reduction scenarios:

- I) eliminate all anthropogenic air pollution;
- IIA) eliminate 10% of emissions attributable to motor-vehicle use;
- IIB) eliminate 100% of emissions attributable to motor-vehicle use.

Occasionally, we will for simplicity refer to scenarios IIA and IIB together as scenario II. We will model 1990 conditions (air quality, emissions, income, and population), and express our results in 1991 dollars.

13.3.1 The visibility cost of pollution, as reflected in housing prices

To estimate the visibility cost of pollution in the U. S., we begin with the simple MAD air-quality demand equation, developed by Smith and Huang (1995), and discussed above. This equation estimates the marginal willingness-to-pay per household, in 1982-1984\$, per $\mu\text{g}/\text{m}^3$ of TSP, as a function of the per-capita income and the TSP level:

$$V_{83} = \alpha + \beta_1 \cdot P + \beta_2 \cdot Y_{83} \quad [1]$$

where:

V_{83} = the shadow price of visibility: the change in the asset value of the house per unit of pollution ($\$/\text{house}/[\mu\text{g}/\text{m}^3]$), at TSP level T, in 1982-1984 prices (we take 1983 as the base year)

α = intercept (-49.31 in the simple MAD model)

β_1 = coefficient on TSP (-0.23 in the simple MAD model)

β_2 = coefficient on income (0.01) in the simple MAD model)

P = total suspended particulates (in micrograms per cubic meter)¹⁰

Y_{83} = average per-capita income in 1982-1984 (we take 1983 as the base year)

¹⁰Smith and Huang (1995) state the “the data are taken from table 5-6 in the *1992 Metropolitan Statistical Area Air Quality Factbook Peak Statistics for Selected Pollutants*, by metropolitan area. They relate the highest second maximum 24-hour concentration in PM₁₀ (in micrograms per cubic meter). This was the closest measuring format available for the data used in our summaries. The source was the U.S. Environmental Protection Agency (1993)” (p. 220). The EPA document referred to is the *National Air Quality and Emissions Trends Report 1992*, a more recent version of which goes through 1994 (EPA, 1995a). Smith and Huang (1995) convert PM₁₀ to TSP assuming the former is 55% of the latter.

As mentioned above, we will use 1990 data on income and TSP pollution, but will express the results in 1991\$. To do this, we first must estimate 1990 income in 1983 dollars, and then convert the calculated V_{83} , which will be in 1983 dollars, to 1991 dollars:

$$V_{91} = V_{83} \cdot K1$$

$$Y_{90} = Y_{83} \cdot K2$$

$$V_{91} = \alpha \cdot K1 + \beta1 \cdot P \cdot K1 + \frac{K1 \cdot \beta2 \cdot Y_{90}}{K2}$$

where:

V_{91} = the shadow price of visibility: the change in the asset value of the house per unit of pollution (\$/house/[$\mu\text{g}/\text{m}^3$]), at TSP level T, at 1991 prices

P = total suspended particulates ($\mu\text{g}/\text{m}^3$)

Y_{90} = average per-capita income in 1990

K1 = Price deflator to estimate 1991 WTP given 1983 prices (GNP implicit price deflator = 1.322)

K2 = Price deflator to estimate 1990 income given 1983 prices (GNP implicit price deflator = 1.264)¹¹

¹¹Smith and Huang's (1995) model is estimated with 1982-1984 (we assume 1983) data. Given this, we have two choices. First, we can use actual 1983 per-capita income, calculate the MWTP results in 1983 dollars, and then convert the 1983-dollar results to 1991-dollar results. However, this approach ipso facto tells us about MWTP at 1983 real income, not at 1990 real income, and presumably we wish to know about MWTP given the world as it was in the more recent year. Real average per-capita income actually increased between 1983 and 1990 (i.e., the ratio of nominal 1990 income to nominal 1983 income exceeds the CPI ratio for these two years), and as a result, according to the Smith and Huang (1995) equation, real MWTP for improved air quality increased. If we use 1983 income data we ignore the increase in real income and thus underestimate more recent real MWTP.

The second approach, which we adopt here, is to capture the effect of the increase in real per-capita income. To do this, we use actual 1990 income, but deflated to what it would be at 1983 price levels. The deflated 1983-price-level income is the amount of income, given 1983 rather than 1990 prices, with which we could have bought the same amount of goods and services as was or could have been bought with actual 1990 income and prices.

Now, given this, there are in general two ways to deflate 1990 income: with a fixed-weight index like the CPI, or with the GNP implicit price deflators. The CPI tracks price changes in a fixed basket of goods. Thus, if we deflate with the CPI, we derive the amount of income, given 1983 rather than 1990 prices, with which we could have bought the same amount of the *fixed basket* as could have been bought with actual 1990 income and prices.

The GNP implicit price deflators are a weighted average of the detailed price indexes used in deflating the GNP, combined according to the actual composition of GNP in each period. They thus differ from the CPI in two respects: they are "broader," and they are based on the current mix of products rather than a fixed mix (or basket). Thus, if we deflate with the GNP implicit price deflators, we derive

(From here on we will drop the 1991 (\$) and 1990 (TSP, income) subscripts.)

We treat equation [1] as the household demand function for TSP reductions. To calculate how much households in the U. S. are willing to pay for an improvement in TSP (VT), we integrate the household demand function between the two TSP levels, and multiply by all households in the U. S. We will estimate the cost of all anthropogenic visibility pollution, and the cost of motor-vehicle visibility pollution:

$$\begin{aligned}
 VT &= \sum_c \left(H_c \cdot \int_{PP_c}^{PI_c} \left(\alpha \cdot K1 + \beta1 \cdot P_c \cdot K1 + \frac{K1}{K2} \cdot \beta2 \cdot Y_c \right) dP_c \right) = \\
 &\sum_c \left(H_c \cdot \left[\alpha \cdot K1 \cdot P_c + \frac{\beta1 \cdot K1 \cdot P_c^2}{2} + \frac{K1}{K2} \cdot \beta2 \cdot Y_c \cdot P_c \right] \right) = \\
 &\sum_c \left(H_c \cdot \left(\alpha \cdot K1 \cdot (PI_c - PP_c) + \frac{\beta1}{2} \cdot K1 \cdot (PI_c^2 - PP_c^2) + \frac{K1}{K2} \cdot \beta2 \cdot Y_c \cdot (PI_c - PP_c) \right) \right)
 \end{aligned}$$

[2]

where:

subscript c = counties in the U. S.

α , $\beta1$, $\beta2$, K1, and K2 are as defined above

VT = the total amount extra that all households in the U. S. would have been willing to pay for their homes, if they had bought their homes outright in 1991, if TSP in each county were at the level represented by PP instead of the level represented by PI

H_c = the number of households in county c in the U. S. in 1990 (Bureau of the Census, 1994)

PP_c = what the TSP level in county c would have been in 1990 given no anthropogenic (case I) or motor-vehicle-related (case II) emissions (discussed below)

PI_c = the actual TSP level in county c in 1990 (discussed below)

something like the amount of income, given 1983 rather than 1990 prices, with which we could have bought the actual goods and services that were bought with 1990 income and prices.

In essence, the GNP price deflators tell us real income given the real mix of goods and services in 1990, rather than the fixed-basket mix. We believe that this is the appropriate deflator for our purposes.

Y_c = average annual per capita income in county c in 1990 (\$/year) (Bureau of the Census, 1994)

Equation [2] is our cost model. Note that the estimated total willingness to pay, VT, represents a one-time payment for a commodity (a home) that lasts many years. Thus, to calculate an annual WTP, the one-time total WTP, VT, must be amortized, or annualized, over the economic life of the home. This is discussed more below.

Note too that equation [2] uses TSP, not visibility, as an explanatory variable. However, not only are TSP and visibility highly correlated, they in fact are physically related -- as mentioned above, particulate matter scatters light and thereby reduces visibility -- which means that we can estimate how TSP affects visibility. The real difficulty will be to determine how much of the WTP to reduce TSP is WTP for visibility per se, as opposed to WTP to reduce the health and other effects of air pollution. We will analyze this below.

13.3.2 Annualizing the cost over the life of the home

One must translate the one-time willingness-to-pay for a home (VT) into an annualized payment (VA). An annualized payment is equal to full asset value (or one-time payment) multiplied by an annualization factor, AF:

$$VA = VT \cdot AF$$

$$AF = \frac{i}{1 - (1+i)^{-t}} \quad [3]$$

where:

VA = the annualized WTP of households

VT = as defined above

AF = the annualization factor

i = the annual interest rate for investment in homes (4% [low] or 7% [high]; Report #2 of this social-cost series)

t = the term of the investment in homes (40 [low] or 30 [high] years; our assumption; see also Report #14 of this social-cost series, which also uses a hedonic price model)

With these assumptions, the annualization factor AF is 0.0505 in the low case, and 0.0806 in the high-cost case.

13.3.3 The portion of the total WTP that is for visibility per se.

Hedonic price analyses relate differences in house values to differences in some measure of air quality. Given any such estimated relationship, and keeping in mind that our objective is to estimate the cost of visibility degradation, we are faced with two questions: First, is the TSP measure of air quality in the meta-analysis model of Smith and Huang (1995) the right one? Second, what is it about air quality that people value?

The right air-quality measure? Ideally, one would use as an explanatory variable the measure of air quality that people actually have in mind when they buy a house. To the extent that the air-quality explanatory variable in a hedonic model is *not* correlated with the real air-quality variables in people's minds, the model will mis-estimate the relationship between housing value and air quality

Most likely, prospective home buyers do not actually consult statistics from air-quality monitors, but rather judge air quality on the basis of whether or not the air appears polluted, and what people and the media say about the local air pollution. If this is so, then visual range, or some close proxy, probably represents reasonably well "air quality" as perceived and evaluated by people. Because TSP is closely correlated with visibility, we assume that it adequately represents the air quality that people actually are evaluating.

What do people value about good air quality? Even if we have the right measure of air quality, we still need to identify the "components" of air quality that people care about. When people pay more for a house in an area with cleaner [clearer] air, what benefits do they think that they are buying? Better health? Reduced soiling of clothes and materials? Or just better visibility?

The question is important to us because our goal here is to measure the value of visibility or aesthetics per se. (In separate reports, we estimate the other effects of air pollution.)¹² It might be tempting to assume that, because people most likely *assess* air quality on the basis of visibility, they most likely *value* improved air quality mainly because it means improved visibility. If this assumption were correct, then we could interpret the MWTP for "air quality", as estimated from the hedonic model, as the MWTP for visibility per se, apart from MWTP for anything else, such as health. However, the assumption probably is not correct, and consequently we must separate the pure visibility component of the total WTP for improved air quality¹³.

¹²Cropper and Oates (1992) make the same point, observing that "it is difficult to note what the pollution (or visibility) coefficient captures and, therefore, difficult to aggregate benefit estimates obtained from these studies with those obtained from other approaches" (p. 718)

¹³Even in CV studies that ask respondents to value changes in "visibility", some respondents may value other changes, such as in the unhealthiness of the air, that they assume are related to the change in visibility. Chestnut and Rowe (1990b) asked for the WTP for improvements in visibility at the Grand Canyon, as illustrated in photographs. The instruction at the top of the survey form emphasized that they were interested in visibility only, not in human health and vegetation. Nevertheless, respondents *still* considered impacts other than visibility in their stated WTP: a follow-up question, which specifically asked what percentage of the WTP was for visibility alone, revealed that 62% of the WTP was for visibility per se, and 38% for other impacts (summarized in Chestnut and Rowe, 1989).

Most likely, the visibility benefit is not the bulk of the total air quality benefit. Smith and Huang (1995) argue that the “hedonic models...reflect aesthetics, materials, and soiling effects, and, to some degree, perhaps perceived health effects, although the latter may well be incomplete” (p. 223)¹⁴. We think that this is broadly correct. Certainly, we cannot assume that the “air quality” measured in the hedonic model that we use is valued *only* with respect to visibility or aesthetics per se, and not at all with respect to human health, soiling, and so on -- even if people are judging air quality on the basis of visibility, which seems likely. People undoubtedly know that the pollutants that cause haze and reduce visibility also harm persons, plants, animals, and materials. We suspect that most people use visibility as an indicator for a variety of effects.

But which effects, with what importance?

As discussed in the literature review above, Brookshire et al. (1979, 1982) found that, of the estimated total willingness-to-pay for improved air quality in the South Coast Air Basin, about 34% was for improved aesthetics, which we would call visibility per se. The remaining 66% was for improved health. Similarly, Loehman et al. (1994) found that for the average person in the western San Francisco Bay area, the bid to avoid a loss of nonpolluted visibility days was about 2/3 of the bid to avoid a loss of good health days, and the bid to obtain an increase in nonpolluted visibility days was about 10% of the bid to obtain an increase in good health days. Thus, in the Loehman et al. (1994) study, the value of visibility was 10% to 40% of the total health+visibility value of air quality.

Finally, in their survey of WTP to improve air quality in the eastern U. S., McClelland et al. (1991), found that 19% of the total WTP was for visibility per se, 49% was for health, 22% was for soiling, and 11% was for “other” impacts.

If home buyers nationally are similar to the persons who responded to the surveys of Brookshire et al. (1979, 1982), McClelland et al. (1991), and Loehman et al. (1994), and if the evaluation of air quality explicit in these surveys is similar to the evaluation implicit in the choice of a home, then we may apply these survey findings to the hedonic study of Smith and Huang (1995). Thus, we assume that value of visibility per se constitutes 15% to 35% of the total value of “air quality” estimated by the Smith and Huang (1995) hedonic model.

13.3.4 The value of visibility outside of the local housing market.

Another shortcoming of the hedonic-price approach is that it captures the value of air quality, or visibility, in housing markets only; it does not capture any visibility

¹⁴Harrison and Rubinfeld (1978) agree that individuals typically do not perceive all of the health damages of pollution: “We stress that housing market studies of this type can only ascertain those benefits which are perceived by households. It is clear that individuals are not aware of all potential health hazards associated with air pollution and are often ignorant of the degree to which the air they breathe is polluted” (p. 82).

value in other markets (Chestnut and Dennis, 1997; Cropper and Oates, 1992; Chestnut and Rowe, 1990a).

When people assess visibility when they shop for a home, they assess the differences in the “visibility experiences” that will result from choosing one home over another. For example, they certainly will compare visibility in and around the candidate houses, because those local visibility experiences will depend on which home they buy. But buyers will not consider visibility in areas that they will visit (or, more generally, that they will care about) *regardless* of which home they buy. For example, if a person shopping for a home in Arizona intends to visit the Grand Canyon and Los Angeles once a year, regardless of which home he or she buys in Arizona, then visibility conditions in the Grand Canyon and Los Angeles -- although of value to the person -- will not affect his or her choice of home in Arizona, and will not affect prices in the Arizona housing market -- and, therefore, will not be included in the MWTP for visibility or air quality estimated from a database that includes the housing market in Arizona.

In general, people might positively value many “visibility experiences” but not consider them when choosing a home, because the experiences will not be affected by the choice of home. This means that the hedonic-price method, which captures the implicit value of visibility in a particular housing market or set of markets, does not capture the value of visibility *independent* of that housing market. Thus, to the extent that persons care about visibility outside of their home region (or housing market), the hedonic-price estimate, used by itself, will underestimate the total value of visibility *everywhere*.

It seems clear to us that people and environmental regulators care about visibility in wildernesses, National Parks, scenic areas, and urban areas outside of their home region or housing market. For example, the Prevention of Significant Deterioration amendments of the Clean Air Act have a specific goal of protecting air quality in special natural areas, and the EPA has identified 156 Class 1 (national parks, scenic wilderness) as areas in which good visibility is necessary and must be protected.

But how *much* do they care? Several studies suggest that people care a lot about visibility in parks and wildernesses. As noted in the literature review above, Schulze et al. (1983) found that non-users were willing to pay \$4 billion, and users \$2 billion, to preserve visibility in all National Parks in the Southwest (1980 dollars). Chestnut and Dennis (1997) use results from a 1990 of the value of visibility in national parks (Chestnut and Rowe, 1990b) to estimate that visibility changes at national parks in the Southeast of the U. S., brought about by the Title IV “Acid Rain” provisions of the 1990 Clean Air Act Amendments, would be worth about \$3.4 billion annually to residents of the eastern U. S. Less relevantly, Peterson et al. (1989) report that more than half of the respondents to a survey about WTP for forest quality stated that they cared mainly about the “existence value” of the forest. (However, this is less relevant for our purposes because it pertains to “existence value” rather than just “visibility value”.) On other hand, in a CV study of WTP for improved visibility in an Oregon wilderness,

Crocker and Shogren (1991) found that existence value was only 10% of the total WTP for visibility.

Obviously, it is difficult to use this information to extrapolate the hedonic results to include visibility values not captured in housing markets. We know nothing about the value of visibility in scenic areas outside of national parks, or in urban areas outside of particular local housing markets (i.e., as per the example above, we don't know the value to an Arizonan of visibility in Los Angeles). Chestnut and Rowe (1990a; more qualitatively on Chestnut and Dennis [1997]), faced with the same problem, draw on their considerable expertise and judge that total benefit of reducing haze in the eastern U. S. can be broken down as follows:

- about 2/3 residential use values (as captured in hedonic price analysis)
- about 1/4 recreational use and non-use values (mainly non-use values)
- the remainder residential "non-use" values.

These figures seem reasonable to us. We speculate that in the West, which has much more open space, and many more national parks and wilderness areas than does the East, the share of residential-use values is smaller, perhaps on the order of 50% of the total. Therefore, if as a national average hedonic price analysis of housing markets captures, say, 60-70% of the total national visibility improvement benefit, then the visibility value not captured by housing markets is about 40-70% of the value estimated by the hedonic model. Thus, we multiply the household (hedonic-model) results by 1.4 to 1.7 to get total national results.

13.3.5 Other problems with our application of the hedonic model

There are yet other difficulties in our application of the Smith and Huang (1995) meta-model.

1). First, with some combination of parameter values -- high TSP, low income, and low share of pollution due to motor vehicles -- the model estimates a negative WTP for reductions in light-scattering pollution from motor vehicles. Given that these problematic combinations of parameter values probably are *not* outside the range of values in the original database from which Smith and Huang (1995) built their model, we may assume that Smith and Huang (1995) model simply does not fit the outlying data well. Consequently, we discard all of the negative WTP estimates from the model, and in Case II make the following adjustment to account for the real, positive WTP in the counties for which the model estimates negative WTP:

$$VA_{TA} = VA \cdot \frac{\sum_c Y_c \cdot H_c}{\sum_c Y_c \cdot H_c - \sum_{cn} Y_{cn} \cdot H_{cn}}$$

$$\sum_c Y_c \cdot H_c = \$1715.30 \cdot 10^9 \quad [4]$$

$$\sum_{cn} Y_{cn} \cdot H_{cn} = \$31.14 \cdot 10^9$$

where:

- VA_{TA} = total adjusted willingness-to-pay for visibility improvements, with results for negative-WTP counties scaled up
- VA , Y_c , and H_c are as defined above (note that VA is positive willingness to pay estimated by the model -- i.e., model results, with negative WTP zeroed out)
- H_{cn} = number of households in a county for which the model estimates a negative WTP
- Y_{cn} = average annual per-capita income in a county for which the model estimates a negative WTP

This method simply scales up the estimated positive WTP in proportion to the total wealth (households multiplied by per-capita income) in the areas for which the model estimates a negative WTP. We scale with respect to total wealth because WTP for visibility is proportional to total wealth (the product of income and households -- see equation [2]).

Note that the problem of negative WTP arises only in Cases IIA and IIB. In Case I, in which the visibility cost of all anthropogenic emissions is estimated, the estimated negative WTP is so small -- about 0.1% of the total -- that we ignore it.

2). Second, the sample of home buyers whose purchase decisions are the raw data of the analysis might not be representative of the whole population to which the results are generalized. For example, the WTP function ($WTP = f(TSP, income)$) for renters might not be the same as the WTP function for homeowners, perhaps because renters in general care less about amenities of home, all else equal. Nevertheless, we apply the household-WTP function, which is derived from the choices of home buyers, to renting as well as to home-owning households.

3). Third, the estimated TSP-value function really is valid only over the range of TSP experiences in the housing areas studied in the original hedonic-price analyses. Therefore, if some housing areas experience significantly different TSP levels than did the residential areas analyzed in the hedonic-price analyses, the TSP-value function

might not accurately represent the dollar value of TSP levels in these other areas. We recognize this possibility but do not adjust for it.

4). Finally, the use of property-value differences to estimate the benefits of air quality usually assumes that prices and quantities of other things are not affected by changes in air quality. If this assumption is violated, the change in property values may not reflect the household's full WTP for air quality. People may respond to changes in air quality in ways that do not affect the value of their residences but affect the value of other goods. For example, the demand for some outdoor activities, such as golfing and jogging, may be affected by changes in air quality and cause changes in the prices of goods associated with these activities. If this occurs to any great extent, property value studies can capture only part of the benefits of a change in air quality.

13.3.6 Estimating TSP levels: actual 1990 levels, and levels without anthropogenic pollution or motor-vehicle related pollution

The WTP model derived above (equation [2]) estimates the total annual household WTP for a change in TSP from PI to PP, where PI is the TSP level in 1990, and PP is the TSP level after all anthropogenic emissions (case I) or all motor-vehicle related emissions (case II) have been eliminated. In this section we explain how we estimate PI and PP for each county *c* in the U. S. in 1990.

We specify the initial pollution level, PI, to be the actual ambient air quality in each county in the U. S. in 1990. These data are discussed below. We estimate PP, in each county, on the assumption that the ratio of PP to PI is equal to the ratio of the *modeled* PP to *modeled* PI:

$$\text{Assume : } \frac{PP}{PI} = \frac{PP^*}{PI^*} \tag{5}$$

$$PP = PI \cdot \frac{PP^*}{PI^*}$$

where:

PP = the estimated actual TSP level after the change in emissions (eliminate all anthropogenic emissions, or eliminate 10% or 100% of motor-vehicle-related emissions)

PI = the actual ambient TSP level (data from air-quality monitors [EPA, 1993]; discussed below)

PP* = the modeled level of TSP after the change in emissions (summarized below; see Report #16 for details)

PI* = the modeled level of ambient TSP (Report #16)

We model three different TSP-reduction scenarios (i.e., three different values of PP):

- I) TSP reduced from 1990 levels to the natural background levels, with no anthropogenic emissions, and
- II) TSP reduced from 1990 levels to the levels that would have resulted had
 - A) 10% of motor-vehicle related emissions had been eliminated, or
 - B) 100% of motor-vehicle related emissions had been eliminated.

In Report #16, we develop our model of the ratio PP^*/PI^* .

Note that, when we estimate the TSP level after removing motor-vehicle related emissions, we estimate the effects of a specific, “marginal” change in pollution: the difference between actual TSP (PI) and, what TSP levels would have been had motor-vehicle-related emissions been reduced by 10% or 100% (PP).

Current (1990) TSP levels. (PI) As noted above, the pollution variable in Smith and Huang’s (1995) hedonic model (our equation [2]) is the so-called “highest second maximum” 24-hour concentration of TSP, in $\mu\text{g}/\text{m}^3$. The “highest second maximum” in a particular region is the highest value out of the set of readings that comprises the second-highest value in the year for each air-quality monitor in the region.

The EPA (1993) measures 24-hour concentrations of TSP and PM_{10} at some of its ambient air-quality monitors throughout the country. We use these measurements to estimate the highest second maximum 24-hour concentration of TSP for each county in the U. S. in 1990. For each TSP monitoring site that has at least ten 24-hour readings in 1990¹⁵, we note the second-highest reading for the year, and then select the highest of all these second-highest site readings in the county. This is the so-called highest second maximum.

If a county does not have TSP measurements, but does have PM_{10} measurements, we assume that TSP is 1.72 times PM_{10} ,¹⁶ and then proceed to estimate the highest second maximum as above. If a county has neither TSP nor PM_{10} data (and most counties have neither), we first designate it as an urban or a rural county, and then identify all of the other urban or rural counties in the same EPA region as the county in question. (There are 10 EPA regions in the U. S.) Then, we assume for the county in question (which lacks TSP or PM_{10} data of its own) the *lowest* of the highest second maximum readings from the other urban or rural counties in the same EPA region as the county in question.

PP Case I: natural background TSP level. In case I, we estimate the visibility cost of all anthropogenic TSP pollution, which is the difference between current levels and the natural, or “background,” level. The natural level of TSP is a function of natural

¹⁵We required that a site have at least 10 readings so as to avoid including unrepresentative readings in our sample.

¹⁶We chose 1.72 because it is the average ratio of TSP to PM_{10} in all counties of the U.S. for which we have data on both pollutants. Smith and Huang (1995) assumed a ratio of 1.82.

(geogenic) emissions of TSP. We model the natural background TSP level (PP*) in each county c as:

$$PP_{TSP,N,c}^* = C_{P' \rightarrow TSP} \left(\begin{array}{l} (E_{P1',N,c} \cdot D_{P1',N,c} + E_{P1',N,oc} \cdot D_{P1',N,oc}), \\ (E_{P2',N,c} \cdot D_{P2',N,c} + E_{P2',N,oc} \cdot D_{P2',N,oc}) \dots \end{array} \right) \quad [6]$$

where:

subscript TSP = TSP air pollution

subscripts P1', P2' = the emitted TSP precursors: particulate matter less than 10 μm in aerodynamic diameter (PM10), particulate matter less than 2.5 μm in aerodynamic diameter (PM2.5), sulfur oxides (SO_x) nitrogen oxides (NO_x), volatile organic compounds (VOCs), and ammonia (NH₃)¹⁷

subscript N = natural (geogenic) sources

subscript C = the county of interest (i.e., the county for which air quality is modeled and the cost of visibility reduction is estimated)

subscript OC = all counties other than county C in the same Air Quality Control Region (AQCR) as C

* = modeled as opposed to measured air quality

PP_{TSP,N,c}^{*} = the modeled level of total ambient TSP received or formed at air-quality monitors in county C, in a year, due only to natural emissions

C_{P'→TSP} = the chemical transformation of precursor pollutants P' to ambient TSP (discussed in Report #16)

E_{P1',N,c}, E_{P2',N,c}... = yearly emissions of P1', P2'.. from natural (geogenic) sources in county C (EPA, 1995b, 1995c)

E_{P1',N,oc}, E_{P2',N,oc}... = yearly emissions of P1', P2'.. from natural (geogenic) sources in all counties except C, in the AQCR of county C (EPA, 1995b, 1995c)

D_{P1',N,c}, D_{P2',N,c}... = the fraction of emissions of P1', P2'...from natural sources in county C that reaches the ambient air-quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

D_{P1',N,oc}, D_{P2',N,oc}... = the fraction of emissions of P1', P2'...from natural sources in all counties except C, in the AQCR of C, that reaches the ambient air-

¹⁷We do not have data on emissions of particles coarser than PM₁₀. Hence, we estimate TSP levels on the basis of PM₁₀ emissions. We assume that the ratio PP*/PI* based on the available PM₁₀ emissions data is similar to the ratio PP*/PI* that would be derived based on TSP emissions were the TSP data available.

quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

We model PI^* (in equation [5]) similarly. See Report #16 for details.

PP Case II: TSP levels with 100% or 10% of motor-vehicle-related emissions eliminated. In case II, we estimate the visibility cost of motor-vehicle related TSP pollution. We use a simple model of emissions, dispersion, and atmospheric chemistry, developed in Report #16. In this model, we estimate PP^* as follows:

$$PP_{TSP,c}^* = C_{P' \rightarrow TSP}(P1', P2' \dots)$$

$$P' = \sum_i EC_{P',i} \cdot (1 - MS_{P',i}) \cdot \left(D_{P',i,c} \cdot OEI_{P',i,c} + D_{P',i,oc} \cdot \sum_{o \in R_c} OEI_{P',i,o} \right) \quad [7]$$

where:

subscripts TSP, P', C, and OC are as defined above

subscript i = sources of emissions of P' (includes all sources in the emissions inventory: motor vehicles, power plants, industries, businesses, farms, and so on).

subscript o = any county other than C in AQCR R

subscript R = AQCR R

$PP_{TSP,c}^*$ = the modeled level of total ambient TSP received or formed at air-quality monitors in county C, in a year

$C_{P' \rightarrow TSP}$ = the chemical transformation of precursor pollutants P' to TSP (discussed in Report #16)

$OEI_{P',i,c}$ = the EPA's official emission-inventory estimates of emissions of P' from source i in county C (EPA, 1995b, 1995c)

$OEI_{P',i,o}$ = the EPA's official emission-inventory estimates of emissions of P' from source i in county O (EPA, 1995b, 1995c)

$EC_{P',i}$ = our emissions-inventory correction factor, equal to the ratio of our estimate of true emissions of P' from source i to the EPA's official estimate (discussed in Report #16; this factor is 1.0 for most sources i, and is assumed to be the same in every county).

$MS_{P',i}$ = the motor-vehicle-related fraction of emissions of P' from emissions source i; that is, of the emissions of P' from source i, MS is the fraction that is related to motor-vehicle use (e.g., all tailpipe emissions from motor-vehicles are related to motor-vehicle use; some fraction of refinery emissions is related to motor-vehicle use, and no fraction of emissions from agricultural tillage is related to motor-vehicle use) (estimated in Report #10; in case IIA, we count 10% of this fraction; in case IIB, we count 100%)

$D_{P',i,C}$ = the fraction of emissions of P' from source i in county C that reaches the ambient air-quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

$D_{P',i,OC}$ = the fraction of emissions of VOCs and NO_x from source i in all counties except C , in the AQCR of C , that reaches the ambient air-quality monitor in county C (estimated on the basis of simple dispersion modeling, presented in Report #16)

We use this model to estimate the contribution of motor-vehicles to TSP air pollution. We specify this model (specifically, the parameters that determine the $D_{P',i,C}$) to represent urban and suburban situations, because the hedonic price model presented above estimates the WTP for reductions in TSP levels in areas where people buy property¹⁸.

13.3.7 Weighting TSP emissions by the contribution to light extinction

TSP consists of a wide range of particulate matter: fine particles, coarse particles, sulfates, nitrates, organic aerosols, carbon particles, and more. These different kinds of particles scatter and absorb light differently, and so contribute differently to the degradation of visibility. For example, fine particles scatter light more than do coarse particles, and so reduce visibility more. Because different sources of particulate pollution emit different mixtures of the various classes of particulates, a given amount of TSP from, say motor vehicles, will have a different effect on visibility than will the same amount of TSP, emitted at the same time and place, from, say, power plants. And because we care about visibility, and not TSP levels per se, we need to account for the differences in effect on visibility of different particle classes when we estimate the change, due to motor-vehicle emissions, in TSP as a proxy for visibility.

We can account for the differential visibility effects of particle classes by multiplying emissions of each class by a factor that represents the contribution of the particle class to light extinction. This factor is the “light-extinction efficiency,” a theoretical or empirical expression of the relationship between the atmospheric

¹⁸We assume that most people buy homes in urban and suburban areas. Of course, this is not the end of the story. In the first place, some housing markets are in rural areas. Beyond that, the hedonic model, as discussed in section 1.3.4, does not capture WTP for visibility (air quality) outside of housing markets. The motor-vehicle contribution to those visibility damages that are *not* captured by the hedonic model might be different from the motor-vehicle contribution to the largely urban and suburban visibility damages that *are* estimated by the hedonic model. If so, then it might be inappropriate to apply an urban and suburban air-quality model to estimate the contribution of motor vehicles to visibility damages everywhere. It would be better, in this case, to estimate separate motor-vehicle contributions for, say, urban and rural areas. However, it turns out that, at least according to our simple model, the motor-vehicle contribution to rural air quality is not greatly different from the motor-vehicle contribution to urban and suburban air quality, and so for simplicity, we use one set of parameter values, and generate one set of $D_{P',i,C}$ to estimate the contribution of motor vehicles everywhere.

concentration of a chemical compound and the extinction of light due to scattering and absorption (Lowenthal et al., 1995; Watson and Chow, 1994; Richards et al., 1990).

The extinction efficiency can be affected strongly by relative humidity. For example, Richards et al. (1990) estimated that the scattering efficiency (in $1/\mu\text{m}$ per $\mu\text{g}/\text{m}^3$, or m^2/g) of fine particles is equal to $0.25 + 0.052\text{RH}$, where RH is the percent relative humidity. Trijonis (1982) shows similar equations. On the basis of estimates and data in Trijonis (1982), Ozkaynak et al. (1985), Richards et al. (1990), the National Research Council (1991), Watson and Chow (1994), and Lowenthal et al. (1995), we assume the following total light-extinction efficiencies (m^2/g):

Pollutant	Total extinction efficiency (m^2/g)
NO_2	0.17 (absorption)
Very coarse PM (greater than $10\mu\text{m}$) ¹⁹	0.0
Coarse PM (between $2.5\mu\text{m}$ and $10\mu\text{m}$)	0.2 to 1.0 (mainly scattering)
Fine PM (less than $2.5\mu\text{m}$) (primary emissions)	1.0 to 5.0 (mainly scattering)
secondary ammonium nitrate and secondary organic aerosols	2.0 to 8.0 (mainly scattering)
secondary ammonium sulfate	3.0 to 10.0 (mainly scattering)
elemental carbon ²⁰	9.0 (absorption) + 1.0 (scattering) = 10.0

In the calculation of $\text{PP}_{\text{TSP},\text{N},\text{C}^*}$ and $\text{PP}_{\text{TSP},\text{C}^*}$ above we multiply the quantity of particles in each class by these extinction efficiencies. Where a range is shown, we use the numerically lower value in our low-cost case, the other value in our high-cost case.

Notice that the product of the extinction coefficient (m^2/g) and the quantity of pollutant (in grams) is m^2 , which is not a measure of concentration. However, as shown by equation [5] and discussed in Report #16, we estimate the new pollution level, PP by modeling the ratio PP^*/PI^* and multiplying this ratio by the actual 1990 pollution level, PI. That is, what we actually model is the *ratio* of PP^*/PI^* , not the absolute concentration. In the calculation of the ratio PP^*/PI^* of equation [5], the product of extinction weights (m^2/grams) and emissions (grams) appears in both the

¹⁹Although we did not find estimates of the extinction coefficient for $\text{PM}>10\mu\text{m}$, it is likely that the coefficient is less than the coefficient for coarse PM, and hence close to zero. In any event, we do not have data on emissions of $\text{PM}>10\mu\text{m}$.

²⁰In the present analysis, we do not actually use the coefficient for elemental carbon, because we do not estimate emissions of elemental carbon.

numerator and the denominator, so that we are left with a dimensionless ratio. This dimensionless ratio then is multiplied by the actual measured ambient concentration, PI, in 1990, in $\mu\text{g}/\text{m}^3$. Hence, the extinction coefficients are used to weight emissions from different sources in the calculation of the share of ambient pollution attributable to different sources.

13.4 RESULTS OF THE ANALYSIS

The results of the analysis for cases I, IIA, and IIB are presented in Tables 13-1 to 13-3. Costs are presented for four pollutants, six vehicle types, and for upstream and road-dust emission categories.

We estimate that the cost of light extinction due to emissions attributable to motor-vehicle use ranges from about \$4 to \$30 billion per year (Table 13-2c). The uncertainty in this estimate is due in large part to uncertainty regarding the visibility fraction of the total damages estimated by the hedonic model. Considering that the \$4 to \$30 billion is an estimate of the value of visibility per se, exclusive of the value of all of the other effects of air pollution, we believe that the upper bound of \$30/billion per year is implausible.

Table 13-1 shows the effect of the nonlinearity of the WTP function: the visibility value of each of the pollutants removed one-by-one is less than the visibility value of all of the pollutants removed simultaneously.

Table 13-1 shows that the total cost of anthropogenic TSP pollution in residential areas, according to the hedonic property-value model used here, is on the order of \$50 to \$90 billion in 1990 (but 1991 \$). The Trijonis et al. (1985) equation, shown in Appendix A, gives similar results. Table 13-1 also shows that the total annual cost of visibility degradation due to anthropogenic pollution in residential areas is \$7 to \$31 billion. A simple meta-function of household WTP for visibility changes, posited by Chestnut and Rowe (1990a) and Chestnut and Dennis (1997), estimates that the total annual cost of visibility degradation in residential areas is around \$19 billion. (See the Appendix.) Hence, our estimates are broadly consistent with those of two other independent models.

If, as we assume, 15% to 35% of the total TSP cost shown in Table 13-1 is the cost of visibility degradation specifically, then 65% to 85%, or \$30 to \$80 billion, pertains to other costs -- most likely, health costs. However, as mentioned in section 13.3.3, it is likely that the housing market does not capture the full cost of the health effects of air pollution, primarily because people are not aware of all of the health effects of air pollution. Thus, we expect our damage-function estimate (in Report #11) of the cost of the health effects of air pollution to be equal to or greater than the \$30 to \$80 billion health cost implied here by the hedonic model. This expectation is borne out by the analysis in Report #11, in which we use damage functions to estimate that the health cost of anthropogenic air pollution is \$50 to \$700 billion per year. Thus, the health-cost

portion of the total pollution cost estimated by the hedonic model does indeed lie at the low end of the range of health costs estimated by the damage-function approach²¹.

As can be seen by comparing the results of Table 13-1 with the results of 13-2c, our model estimates that motor vehicles, including upstream emissions and road dust, are responsible for about one half of all anthropogenic visibility damages. In turn, light-duty gasoline autos (passenger cars and associated upstream and road-dust emissions) account for roughly half of all motor-vehicle-related visibility damages (13-2a vs. 13-2c). Tailpipe emissions from motor vehicles account for a bit more than half of the total motor-vehicle-related damages (Table 13-2c), and road-dust emission for somewhat less than half (Table 13-2c). (There are two opposing factors here: road-dust mass emissions greatly exceed tailpipe mass emissions, but cause less light-extinction per unit of mass.) Upstream emissions related to motor-vehicle use occasion insignificant visibility costs (Table 13-2c).

Table 13-3 indicates that, per kilogram of emission, direct PM and SO_x emissions have the largest visibility costs. The \$/kg cost of SO_x exceeds the \$/kg cost of NO_x because the fraction of SO_x that becomes particulate sulfate (which causes the reduction in visibility) exceeds the fraction of NO_x that becomes particulate nitrate (which causes the reduction in visibility) (see Report #16). The \$/kg cost of VOCs is so small because such a small fraction of VOC emissions becomes organic aerosol (which causes the reduction in visibility).

The \$/kg cost including emissions from paved and unpaved roads is much smaller than the \$/kg cost of vehicular tailpipe emissions only (or tailpipe plus upstream emissions), because particulate matter from vehicles and upstream sources generally is fine, whereas most road dust PM is coarse, and the light-extinction coefficient for coarse particles is much less than the coefficient for fine particles (section 13.3.7).

²¹Note that the hedonic model estimates damages captured by the housing market -- i.e., in the home region -- only, whereas the damage-function model estimates damages everywhere, nationally. Thus, the hedonic model does not account for the cost, to a person in housing-market region R, of air pollution *outside* of region R -- for example, in scenic rural areas. However, while this omission undoubtedly matters greatly in the analysis of visibility, it probably matters little in the analysis of health. To a first approximation, the probability of being made ill by air pollution is proportional to the time of exposure. Since most people probably spend at least 90% of their time in the air basin of their home, pollution outside of their air basin will have relatively little effect on their health. Hence, the hedonic property-value model probably captures at least 90% of the health costs *that people recognize*. (We emphasize "that people recognize" because, as mentioned in the text, most people probably are not aware of all of the health effects of air pollution.) By contrast, vista-marring pollution can ruin the aesthetic enjoyment of those few days a year that people vacation outside of their home region -- for example, in pristine, scenic areas such as the Grand Canyon. Thus, the hedonic property-value model does not account for some significant visibility costs of pollution.

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TABLE 13-1. THE NATIONAL VISIBILITY COST OF ANTHROPOGENIC EMISSIONS (BILLION 1991\$ IN THE YEAR 1990)

	Residential areas, TSP cost ^a		Residential areas, visibility cost ^b		All areas, visibility cost ^c	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
PM ₁₀ (d)	25.5	47.1	3.8	16.5	5.4	28.0
NO _x (e)	9.8	19.4	1.5	6.8	2.1	11.5
SO _x (f)	10.5	10.0	1.6	3.5	2.2	5.9
VOC(g)	0.7	1.1	0.1	0.4	0.1	0.7
<i>All pollutants simultaneously^h</i>	<i>52.5</i>	<i>87.7</i>	<i>7.9</i>	<i>30.7</i>	<i>11.0</i>	<i>52.2</i>
<i>Sum of pollutants individuallyⁱ</i>	<i>46.4</i>	<i>77.6</i>	<i>7.0</i>	<i>27.2</i>	<i>9.7</i>	<i>46.2</i>

Note that the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991. See the text for further details.

^aThis is the total annualized WTP to eliminate anthropogenic TSP pollution -- VA in equation (3). It is *not* the WTP for visibility only, and does *not* include any adjustment for pollution outside of the home area.

^bThis is the annualized household (residential-area) visibility cost of anthropogenic emissions, equal to VA_{TA} (equation [4]) multiplied by the visibility share of total costs (section 13.3.3).

^cThis is the total, national, adjusted, annualized visibility cost of anthropogenic emissions, equal to VA_{TA} (equation [4]) multiplied by the visibility share of total costs (section 13.3.3) and the factor for visibility costs outside the home area (section 13.3.4).

^dIncludes fine PM (less than 2.5 μm) and coarse PM (between 2.5 μm and 10 μm).

^eIncludes NO₂ weighted by its relative light-absorption effect, and particulate nitrate weighted by its relative light-scattering effect.

^fParticulate sulfate weighted by its relative light-scattering effect.

^gSecondary organic aerosol weighted by its relative light-scattering effect.

^hThe effect of removing all pollutants at once.

ⁱThe sum of the effects of removing pollutants one by one. This is not the same as the effect of removing all of them at once, because the damage function is nonlinear. The difference, however, is not great.

TABLE 13-2A. THE NATIONAL VISIBILITY COST OF EMISSIONS ATTRIBUTABLE TO GASOLINE VEHICLES (YEAR 1990; 1991 \$)

Emissions source	Case IIA: 10% reduction in emissions attributable to motor vehicles				Case IIB: 100% reduction in emissions attributable to motor vehicles			
	10 ⁹ \$		\$/1000-VMT		10 ⁹ \$		\$/1000-VMT	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
LDGAs	0.110	0.663	0.70	4.25	1.12	6.81	0.72	4.37
LDGAs + U	0.123	0.705	0.79	4.52	1.26	7.24	0.81	4.64
LDGAs + U + RDP	0.146	1.070	0.94	6.86	1.50	11.01	0.96	7.06
LDGAs + U + RDP +RDU	0.174	1.194	1.11	7.66	1.77	12.31	1.14	7.89
LDGTs	0.040	0.245	1.03	6.27	0.41	2.48	1.04	6.32
LDGTs + U	0.047	0.263	1.19	6.71	0.47	2.65	1.20	6.77
LDGTs + U + RDP	0.055	0.385	1.39	9.83	0.55	3.89	1.40	9.93
LDGTs + U + RDP +RDU	0.064	0.427	1.62	10.90	0.64	4.31	1.64	11.01
HDGVs	0.005	0.041	1.98	16.27	0.05	0.41	1.98	16.29
HDGVs + U	0.006	0.043	2.23	16.94	0.06	0.43	2.23	16.96
HDGVs + U + RDP	0.007	0.062	2.70	24.48	0.07	0.62	2.71	24.52
HDGVs + U + RDP +RDU	0.008	0.069	3.27	27.05	0.08	0.69	3.27	27.09
All GVs	0.155	0.952	0.79	4.81	1.60	9.88	0.81	5.00
All GVs + U	0.176	1.013	0.89	5.12	1.82	10.50	0.92	5.31
All GVs + U + RDP	0.208	1.520	1.05	7.69	2.14	15.83	1.08	8.01
All GVs + U + RDP +RDU	0.246	1.693	1.24	8.57	2.53	17.67	1.28	8.94

LDGA = light-duty gasoline automobile; LDGT = light-duty gasoline truck; HDGV = heavy-duty gasoline vehicle; GV = gasoline vehicle; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

See the text for further details.

TABLE 13-2B THE NATIONAL VISIBILITY COST OF EMISSIONS ATTRIBUTABLE TO DIESEL VEHICLES (YEAR 1990; 1991 \$)

Emissions source	Case IIA: 10% reduction in emissions attributable to motor vehicles				Case IIB: 100% reduction in emissions attributable to motor vehicles			
	10⁹ \$		\$/1000-VMT		10⁹ \$		\$/1000-VMT	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
LDDAs	0.003	0.019	1.28	7.59	0.03	0.19	1.28	7.60
LDDAs + U	0.003	0.019	1.32	7.71	0.03	0.19	1.32	7.72
LDDAs + U + RDP	0.004	0.023	1.43	9.52	0.04	0.23	1.43	9.53
LDDAs + U + RDP +RDU	0.004	0.025	1.57	10.14	0.04	0.25	1.57	10.15
LDDTs	0.001	0.003	0.42	2.41	0.01	0.03	0.42	2.41
LDDTs + U	0.001	0.004	0.49	2.62	0.01	0.04	0.49	2.62
LDDTs + U + RDP	0.001	0.008	0.66	5.33	0.01	0.08	0.66	5.33
LDDTs + U + RDP +RDU	0.001	0.009	0.86	6.25	0.01	0.09	0.86	6.25
HDDVs	0.054	0.465	4.12	35.22	0.55	4.70	4.14	35.58
HDDVs + U	0.058	0.475	4.40	35.99	0.59	4.80	4.43	36.36
HDDVs + U + RDP	0.075	0.744	5.68	56.31	0.76	7.60	5.73	57.53
HDDVs + U + RDP +RDU	0.095	0.835	7.20	63.24	0.96	8.55	7.27	64.76
All DVs	0.058	0.487	3.40	28.49	0.59	4.93	3.42	28.80
All DVs + U	0.062	0.498	3.63	29.12	0.63	5.04	3.65	29.43
All DVs + U + RDP	0.080	0.775	4.65	45.30	0.80	7.93	4.69	46.32
All DVs + U + RDP +RDU	0.100	0.870	5.85	50.82	1.01	8.91	5.92	52.09

LDDA = light-duty diesel automobile; LDDT = light-duty diesel truck; HDDV = heavy-duty diesel vehicle; DV = diesel vehicle; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads.

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

See the text for further details.

TABLE 13-2C. THE NATIONAL VISIBILITY COST OF EMISSIONS ATTRIBUTABLE TO ALL MOTOR VEHICLES (YEAR 1990; 1991 \$)

Emissions source	Case IIA: 10% reduction in emissions attributable to motor vehicles				Case IIB: 100% reduction in emissions attributable to motor vehicles			
	10 ⁹ \$		\$/1000-VMT		10 ⁹ \$		\$/1000-VMT	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
MVs	0.214	1.442	0.99	6.71	2.22	15.06	1.03	7.01
MVs + U	0.238	1.513	1.11	7.05	2.47	15.81	1.15	7.36
MVs + U + RDP	0.288	2.301	1.34	10.71	2.99	24.44	1.39	11.38
MVs + U + RDP +RDU	0.347	2.571	1.61	11.97	3.60	27.43	1.68	12.77

MVs = motor vehicles; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads; PM₁₀ = particulate matter of aerodynamic diameter of 10 microns or less; NO_x = nitrogen oxides; SO_x = sulfur oxides; VOCs = volatile organic compounds.

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

See the text for further details.

TABLE 13-3A. THE NATIONAL VISIBILITY COST OF A KILOGRAM OF EMISSIONS ATTRIBUTABLE TO GASOLINE VEHICLES, GIVEN A 10% REDUCTION IN EMISSIONS RELATED TO GASOLINE VEHICLES (YEAR 1990; 1991 \$/KG-EMITTED)

Emissions source	\$/kg-PM ₁₀ ^a		\$/kg-NO _x ^(b)		\$/kg-SO _x ^(c)		\$/kg-VOCs ^d	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
LDGAs	0.58	4.09	0.22	1.21	1.35	5.00	0.01	0.04
LDGAs + U	0.46	3.04	0.21	1.13	0.34	1.08	0.01	0.04
LDGAs + U + RDP	0.33	1.92	0.21	1.13	0.34	1.08	0.01	0.04
LDGAs + U + RDP +RDU	0.09	0.74	0.21	1.13	0.34	1.08	0.01	0.04
LDGTs	0.55	3.97	0.21	1.11	1.25	4.62	0.01	0.04
LDGTs + U	0.43	2.98	0.19	1.02	0.27	0.82	0.01	0.04
LDGTs + U + RDP	0.33	1.94	0.19	1.02	0.27	0.82	0.01	0.04
LDGTs + U + RDP +RDU	0.10	0.76	0.19	1.02	0.27	0.82	0.01	0.04
HDGVs	0.31	3.28	0.12	0.95	0.69	3.74	0.01	0.06
HDGVs + U	0.29	3.01	0.12	0.91	0.28	1.16	0.01	0.05
HDGVs + U + RDP	0.30	2.01	0.12	0.91	0.28	1.16	0.01	0.05
HDGVs + U + RDP +RDU	0.09	0.80	0.12	0.91	0.28	1.16	0.01	0.05
All GV _s	0.55	3.97	0.21	1.17	1.29	4.83	0.01	0.04
All GV _s + U	0.44	3.02	0.20	1.09	0.32	1.00	0.01	0.04
All GV _s + U + RDP	0.33	1.93	0.20	1.09	0.32	1.00	0.01	0.04
All GV _s + U + RDP +RDU	0.09	0.75	0.20	1.09	0.32	1.00	0.01	0.04

LDGA = light-duty diesel automobile; LGDT = light-duty diesel truck; HDGV = heavy-duty diesel vehicle; GV = diesel vehicle; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads; PM₁₀ = particulate matter of aerodynamic diameter of 10 microns or less; NO_x = nitrogen oxides; SO_x = sulfur oxides; VOCs = volatile organic compounds.

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

^aEqual to the dollar cost of 10% of the primary ambient PM₁₀ (weighted by its relative light extinction) attributable to motor vehicles, divided by 10% of PM₁₀ emissions attributable to motor vehicles. Primary or direct PM is PM that is emitted as such, as distinguished from PM that is formed in the atmosphere.

^bNO_x emissions can become ambient NO₂ or form particulate nitrate aerosols. The \$/kg estimate is equal to the dollar cost of by 10% of the ambient NO₂ and 10% of the ambient particulate nitrate (weighted by their relative light extinction) attributable to motor vehicles, divided by 10% of NO_x emissions attributable to motor vehicles.

^cSO_x emissions can form particulate sulfate aerosols, which scatter light and reduce visibility. The \$/kg estimate is equal to the dollar cost of 10% of the ambient particulate sulfate (weighted by its relative light extinction) attributable to motor vehicles, divided by 10% of SO_x emissions attributable to motor vehicles.

^dVOC emissions can form secondary organic aerosols, which scatter light and reduce visibility. The \$/kg estimate is equal to the dollar cost of 10% of the ambient organic aerosol (weighted by its relative light extinction) attributed to motor vehicles, divided by 10% of VOC emissions attributable to motor vehicles.

TABLE 13-3B. THE VISIBILITY COST OF A KILOGRAM OF EMISSIONS ATTRIBUTABLE TO DIESEL VEHICLES, GIVEN A 10% REDUCTION IN EMISSIONS RELATED TO DIESEL VEHICLES (YEAR 1990; 1991 \$/KG-EMITTED)

Emissions source	\$/kg-PM ₁₀ ^a		\$/kg-NO _x ^(b)		\$/kg-SO _x ^(c)		\$/kg-VOCs ^d	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
LDDAs	0.69	5.46	0.23	1.24	1.35	5.00	0.01	0.06
LDDAs + U	0.68	5.33	0.22	1.19	1.10	4.00	0.01	0.05
LDDAs + U + RDP	0.52	3.22	0.22	1.19	1.10	4.00	0.01	0.05
LDDAs + U + RDP +RDU	0.17	1.41	0.22	1.19	1.10	4.00	0.01	0.05
LDDTs	0.64	5.04	0.21	1.14	1.24	4.60	0.01	0.05
LDDTs + U	0.59	4.52	0.16	0.87	0.51	1.76	0.01	0.04
LDDTs + U + RDP	0.37	2.19	0.16	0.87	0.51	1.76	0.01	0.04
LDDTs + U + RDP +RDU	0.10	0.84	0.16	0.87	0.51	1.76	0.01	0.04
HDDVs	0.32	3.79	0.11	0.90	0.62	3.38	0.02	0.17
HDDVs + U	0.31	3.69	0.11	0.87	0.43	2.15	0.01	0.10
HDDVs + U + RDP	0.31	2.25	0.11	0.87	0.43	2.15	0.01	0.10
HDDVs + U + RDP +RDU	0.10	0.91	0.11	0.87	0.43	2.15	0.01	0.10
All DVs	0.34	3.86	0.12	0.91	0.65	3.45	0.02	0.16
All DVs + U	0.33	3.75	0.11	0.87	0.45	2.19	0.01	0.10
All DVs + U + RDP	0.31	2.27	0.11	0.87	0.45	2.19	0.01	0.10
All DVs + U + RDP +RDU	0.10	0.92	0.11	0.87	0.45	2.19	0.01	0.10

LDDA = light-duty diesel automobile; LDDT = light-duty diesel truck; HDDV = heavy-duty diesel vehicle; DV = diesel vehicle; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads; PM₁₀ = particulate matter of aerodynamic diameter of 10 microns or less; NO_x = nitrogen oxides; SO_x = sulfur oxides; VOCs = volatile organic compounds.

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

a,b,c,d See notes to Table 13-3a.

TABLE 13-3C. THE VISIBILITY COST OF A KILOGRAM OF EMISSIONS ATTRIBUTABLE TO ALL MOTOR VEHICLES, GIVEN A 10% REDUCTION IN EMISSIONS RELATED TO ALL MOTOR VEHICLES (YEAR 1990; 1991 \$/KG-EMITTED)

Emissions source	\$/kg-PM ₁₀ ^a		\$/kg-NO _x ^(b)		\$/kg-SO _x ^(c)		\$/kg-VOCs ^d	
	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>	<i>Low</i>	<i>High</i>
MVs	0.40	3.90	0.19	1.11	0.89	3.97	0.01	0.05
MVs + U	0.37	3.47	0.17	1.04	0.36	1.35	0.01	0.04
MVs + U + RDP	0.32	2.07	0.17	1.04	0.36	1.35	0.01	0.04
MVs + U + RDP +RDU	0.10	0.81	0.17	1.04	0.36	1.35	0.01	0.04

MVs = motor vehicles; U = upstream; RDP = road dust from paved roads; RDU = road dust from unpaved roads; PM₁₀ = particulate matter of aerodynamic diameter of 10 microns or less; NO_x = nitrogen oxides; SO_x = sulfur oxides; VOCs = volatile organic compounds.

Note that in all cases, the year of the analysis is 1990 (i.e., 1990 data for emissions, air quality, and income), but the year of the dollars is 1991.

a,b,c,d See notes to Table 13-3a.

APPENDIX: OTHER ESTIMATES OF HOUSEHOLD WTP FOR VISIBILITY

13.A.1 TRIJONIS ET AL. (1985)

As mentioned in the text, Trijonis et al. (1985) analyzed the relationship between housing values and horizontal visibility (expressed in terms of light extinction) in Los Angeles and San Francisco, from 1973-1974 and 1978-1979. The second-stage equation in their hedonic analysis is the demand curve for visibility: WTP for a home as a function of light extinction (which is inversely related to visual range) and community average household incomes:

$$V_h = 11139 - 6006L + 0.178Y$$

$$L = \frac{KM}{V}$$

[A1]

where:

V_h = the amount extra that a household is willing to pay for a home, per unit of light-extinction L , at the particular visibility level represented by L (1978-1979\$)

L = median light-extinction coefficient

Y = average annual household income (\$)

V = the visual range (miles)

KM = Koschmeider constant (18.65 miles; for airport visibility data)

The light-extinction coefficient L is the fraction of light that is attenuated per unit distance as a light beam traverses the atmosphere. In a uniform atmosphere, the extinction coefficient is inversely proportional to the visual range, according to the Koschmeider formula given here.

Equation (A1) is the household demand function for visibility. The area under this demand curve, between light-extinction level 1 and light-extinction level 2, is the total dollar cost per household of the difference between the two light-extinction (visibility) levels. The cost per household multiplied by the number of households gives the grand total for the region of households.

Because equation A1 here has the same functional form as equation 1 in the text, the integration and evaluation of A1 (willingness-to-pay with respect to light extinction) results in the following analog of equation 2 in the text:

$$VT = \sum_c \left(H_c \cdot \left(11139 \cdot K1 \cdot (L_{1c} - L_{2c}) - \frac{6006}{2} \cdot K1 \cdot (L_{1c}^2 - L_{2c}^2) + \frac{K1}{K2} \cdot 0.178 \cdot Y_c \cdot (L_{1c} - L_{2c}) \right) \right)$$

$$L_{1c} = \frac{KM}{V_{1c}} \text{ and } L_{2c} = \frac{KM}{V_{2c}}$$

$$94.3 \cdot 10^6 \cdot \left(20161.6 \cdot (L_{1c} - L_{2c}) - 5435.43 \cdot (L_{1c}^2 - L_{2c}^2) + 6965.6 \cdot (L_{1c} - L_{2c}) \right)$$

$$L_{1c} = \frac{18.65}{15} = 1.243 \text{ and } L_{2c} = \frac{18.65}{100} = 0.1865(\text{high})$$

$$L_{1c} = \frac{18.65}{25} = 0.746 \text{ and } L_{2c} = \frac{18.65}{80} = 0.233(\text{low})$$

[A2]

$$AF = 0.0505(\text{low}), 0.0806(\text{high})$$

where:

subscript c = counties in the U. S.

VT = the total amount extra that all households in the U. S. would have been willing to pay for their homes, if light extinction in each county were at the level represented by L₂ instead of the level represented by L₁ (1991 \$)

H_c = the number of households in county c in the U. S. in 1990

L_{1c} = the actual light extinction in county c in 1990

L_{2c} = the hypothetical new light extinction in county c in 1990

Y_c = average annual household income in county c in 1990 (\$/year)

V_{1c} = the actual visual range in county c in 1990 (miles; data discussed below)

V_{2c} = the hypothetical new visual range in county c in 1990

K1 = price deflator to estimate 1991 WTP given 1978-79 prices (GNP implicit price deflator = 1.81 [interpolate between 1978 and 1979 values])

K2 = price deflator to estimate 1990 income given 1978-79 prices (GNP implicit price deflator = 1.73 [interpolate between 1978 and 1979 values])

Visual range. The National Climatic Data Center (1991), provides hourly horizontal visual range for 187 sites in the U. S. in 1990, on 3 CD-ROMs. Visual range is the median of the 365 calculated daily visibility values, in miles, where the daily visibility is calculated as the average of the visibility readings at 10:00 AM, 1:00 PM, and 4:00 PM each day. Visual range typically is between 10 and 100 miles, and generally less than 50 miles.

Illustrative calculation. In order to compare the results of equation [A2] with the results of equation [2], we calculate national willingness-to-pay, VT (equation [A2]), for national parameter values:

- H = total households in the U. S. in 1990 ($94.3 \cdot 10^6$; Bureau of the Census, 1992)
- Y = average household income in 1990 (\$37,403; Bureau of the Census, 1992)
- V₁ = typical visual ranges in 1990 (15 miles [high-cost case] to 25 [low-cost case] miles; Trijonis, 1982; Ozkaynak et al., 1985; National Climatic Data Center, 1991; Watson and Chow, 1994)
- V₂ = visual range in clean air (assume 80 to 100 miles; EPA, 1998; Watson and Chow, 1994)

We then use equation [4] to annualize the calculated total VT. The result is an annual cost of \$53 to \$155 billion (1991 \$) per year. (Note that this does not include costs outside the home area.) However, as we note above, this may include WTP to reduce air pollution impacts other than visibility. To allow for this, we compare the Trijonis et al. result with our independent estimate of the cost of all TSP pollution (based on the hedonic model of eq. [2]) as well as with our independent estimate of the cost of pollution impairment of visibility. As shown in Table 13-1, we estimate that the cost of TSP pollution, on the basis of the hedonic model of equation [2], is about \$50-\$90 billion/year -- similar to the range estimated with the Trijonis et al. (1985) model (eq. [A2]). However, our estimate of the cost of visibility alone is quite a bit lower than the range estimated with the Trijonis et al. model.

13.A.2 CHESTNUT AND DENNIS (1997)

Chestnut and Rowe (1990a) review the results of CVM studies of household WTP for visibility, and, “in a beginning effort to examine for consistent values and patterns across studies, [develop] the following function to put these WTP mean results from the different studies into a common metric” (p. 27-163):

$$VAHH_i = b \cdot \ln\left(\frac{V_{2i}}{V_{1i}}\right) \quad [A3]$$

where:

subscript i = geographic area i

VAHH_i = the annual WTP per household in area i for visibility changes in that year

V_{1i} = the actual average annual visual range in area i (miles)

V_{2c} = the hypothetical alternative average annual visual range in area i (miles)

ln = natural log
b = estimated coefficient

Chestnut and Dennis (1997) select a value of 160 for the coefficient b (in 1994 \$), on the basis of the fully adjusted results of McClelland et al. (1991), whose work Chestnut and Dennis (1997) feel is particularly sound. (This coefficient value of 160 corresponds to the McClelland et al. [1991] best estimate of the value of visibility *only*, after correcting for non-response and “high-end” bias.) In 1991 \$, the coefficient is 149. Note that equation [A3], unlike equations [1] and [A1], already is the *annual* household WTP for the *entire* change in visibility, not the change in house value per unit of pollution or visibility. Hence, we do not need to integrate this equation between visibility levels, and then annualize the results; rather, we simply can plug in the appropriate visual range values. If, following our assumptions above in the application of the Trijonis et al. (1985) model, we assume $V_1 = 15\text{-}25$ miles, and $V_2 = 80\text{-}100$ miles, then national annual WTP of households to improve visibility in their residential area from presumed actual conditions to “clear-sky,” zero-degradation conditions is \$16-27 billion. This does not include WTP to improve visibility outside of residential areas.

This estimate of \$16-27 billion is in the middle of our independently estimated range of \$7 to \$31 billion for residential areas (Table 13-1).