FEATURES

AIR POLLUTION AND BUILDINGS: AN ESTIMATION OF DAMAGE COSTS IN FRANCE

Ari Rabl
Ecole des Mines

The total damage cost is the sum of renovation cost and amenity loss. We show that amenity loss can be inferred from renovation expenditures without carrying out a contingent valuation; the amenity loss is approximately equal to the renovation cost. We review the methodologies for calculating air pollution damage to buildings, as well as the data available for their implementation in France. There are no inventories of building materials and surface areas for France, but we have been able to obtain data for frequencies and costs of renovation activities. By regressing these data we derive a "combined dose-response function" for the renovation cost as a function of pollution. We find that the most important variables are income and concentration of particles, whereas a correlation with SO_2 is not clear. This could be understood if most renovation expenditures in France are occasioned by soiling (primarily due to particles) rather than corrosion (primarily due to SO_2). For historical buildings and monuments we have been able to find only data for total national expenditures; they imply that the cost of pollution damage is somewhat smaller than for utilitarian buildings. Based on detailed models for atmospheric dispersion and for the geographical distribution of buildings, we calculate the damage cost caused by individual sources of pollution. We compare our results with other estimates in the literature, and we discuss the uncertainties. We also find that, compared to the cost of health damage, the cost of damage to buildings is smaller by about two orders of magnitude. © 1999 Elsevier Science Inc.

Address requests for reprints to: A. Rabl, Ecole des Mines, 60 boul. St.-Michel, F-75272 Paris Cedex 06, France. E-mail: RABL@CENERG.ENSMP.FR

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1. Introduction

Air pollution can damage materials, especially those used in buildings because of their long life. Damage to other objects tends to be less important: most cars, for instance, are replaced long before air pollution damage has become significant. The phenomena of the degradation of buildings are complex due to the numerous factors that intervene. There are factors of natural origin such as sun, rain, and the freeze/thaw cycle, in addition to manmade atmospheric pollution. It is often difficult to distinguish the share of each factor. However, there is a general consensus that manmade pollutants have greatly increased the degradation rate of buildings. Of particular importance are soiling caused by particles (especially soot) and corrosion or erosion caused by acid rain (especially due to SO_2).

For rational policy decisions about pollution control, one needs to know the cost of damage to buildings by pollution. The goal of the present article is to estimate damage costs for buildings in France. Ideally, one should do this by calculating the ambient concentrations of pollutants due to each pollution source, using atmospheric transport models, combined with dose-response functions that quantify the physical damage as a function of pollutant concentration. Unfortunately, despite all the detailed studies that have identified the physicochemical effects of air pollution on buildings, the quantification of damage costs remains problematic because of insufficient knowledge about building data and about interaction with human behavior. In many countries, particularly France, there is no inventory of building materials and surface areas.

In view of this situation, we explore an alternative approach, by working directly with observed data for frequencies and costs of cleaning and repair activities. In France, such data are available because expenditures for renovation of buildings are tax deductible. The data do not distinguish cleaning and repair, and they do not identify whether the cause is erosion or soiling. By regression of the data we derive a "combined dose-response function" for the renovation cost as a function of pollution. We designate it as concentration-response (C-R) function because it yields the impact directly as a function of the ambient concentration of a pollutant. We find that the most important variables in the C-R function are income and concentration of particulate matter. Coupled with data for the dispersion of atmospheric pollutants, this allows the calculation of damage costs due to individual pollution sources, as we illustrate by calculating the damage per kilogram of particles emitted by typical combustion equipment in France.

We also present a comparison of renovation costs with other studies, and we provide an estimate for the damage cost to historical buildings. In addition, we find that the cost of damage to buildings, per kilogram of particles, is small compared to the cost of health impacts. An analysis of the uncertainties suggests that our estimates are correct within an order of magnitude.

We begin by examining the relation between the two components of the total damage cost: expenditures made to mitigate or repair the damage, and the loss of amenity, i.e., impairment of utilization or esthetic enjoyment of a building. We prove that the amenity loss is equal to the cost of renovation, if the amenity loss increases linearly with time and the decision to renovate is made by the person(s) who suffer(s) the amenity loss (for rational decision-makers and zero discount rate). We argue that this result is a good approximation in practice. This leads us to recommend as general rule that the total damage cost is approximately twice the renovation cost.

2. Damage Cost

2.1. Cost Components

There is a general consensus that the economic valuation should be based on willingness to pay to avoid damage. In general, one can distinguish three cost components:

- Expenditures to restore the original condition of the damaged object, e.g., by cleaning,
- Preventive measures, e.g., the extra cost of paint with enhanced resistance to pollution,
- Loss of amenity.

The total cost is the sum.

The first of these is the most straightforward, because cleaning and repair of buildings involve market transactions that are relatively easy to measure, as we illustrate for the case of France.

In contrast, the cost of preventive measures is very difficult to determine. There is ongoing development of materials, technologies, and management, with such a variety of costs and benefits that it would be difficult, if not impossible, to keep account. For instance, wire fence used to be made of galvanized steel and would rust away quite rapidly. Now it is steel coated with plastic, which is far more resistant to air pollution. What is the extra cost, if any, and what are the benefits in addition to protection from corrosion? Often the cost of protective measures, e.g., the extra cost of better paint, is included in the cost of repair; trying to separate the protective component seems neither easy nor necessary.

Finally, there is a loss of amenity, such as the esthetic loss as a building becomes dirty. This cost category involves subjective perception and therefore might appear to necessitate contingent valuation (Mitchell and Carson 1989). However, this subjective valuation is reflected in market decisions about cleaning and repair, and, as we show later, the amenity loss can be inferred by a simple rule from the cleaning and repair costs. We will refer to the sum of cleaning and repair costs as renovation cost.

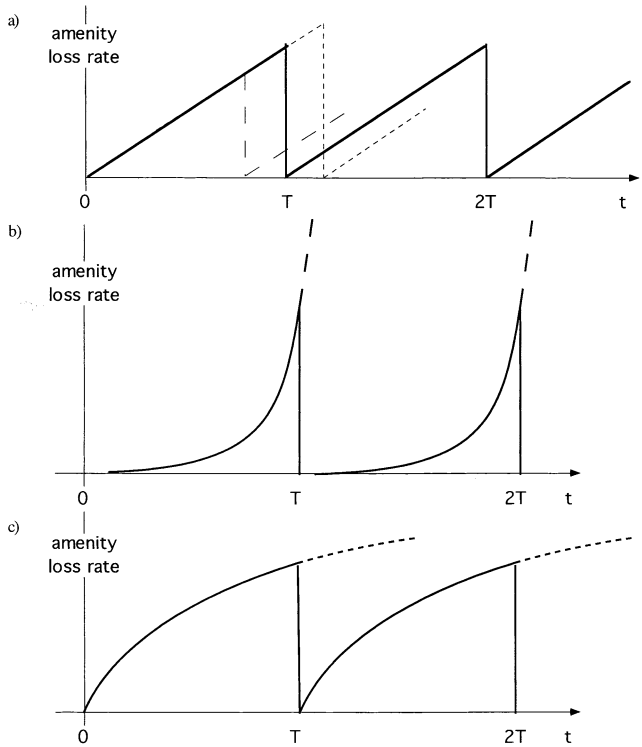

FIGURE 1. Amenity loss rate as function of time t. (a) Linear increase with time. Solid line = renovation period T; dashed lines = renovation period shorter or longer than T. (b) Amenity loss due to corrosion. (c) Amenity loss due to soiling.

2.2. Renovation Costs and Amenity Loss

During the time between the renovation actions, there is a loss of amenity as the appearance of the building degrades, even if renovation will restore the original condition of the building. As a first approximation, consider the case where the instantaneous amenity loss increases linearly with the time t since the last renovation; let us also neglect discounting for now. If T is the time between renovation actions, the total amenity loss during one period T is given by Eq. 1:

$$L = \int_0^T \alpha t dt = \frac{\alpha}{2} T^2 \quad (1)$$

where α is a constant of proportionality. This is illustrated in Figure 1a.

The total cost during the period is the sum of amenity loss L and renovation cost R. Of the parameters of this model, the only one over which a building owner has control is the length of the period T. A rational owner will chose T so as to minimize total cost. This is equivalent to minimizing the total average cost c_{av} during one period T given by Eq. 2:

$$c_{av} = \frac{L}{T} + \frac{R}{T}. \tag{2}$$

Inserting Eq. 1 and taking the derivative of c_{av} with respect to T, we obtain the condition for the optimal period T_o given by Eq. 3:

$$0 = \frac{\alpha}{2} - \frac{R}{T_o^2} \tag{3}$$

or, rewritten as in Eq. 4:

$$T_o = \sqrt{\frac{2R}{\alpha}}. \tag{4}$$

Inserted into Eq. 1, this implies a very simple result given in Eq. 5:

$$L = R \tag{5}$$

where the amenity loss L is equal to the renovation cost R.

As a simple generalization of the linear increase in Figure 1a, let us consider a power law of the form given in Eq. 6:

$$L = \int_0^T \alpha t^n dt = \frac{\alpha}{n+1} T^{n+1}. \tag{6}$$

With $n > 1$ as shown in Figure 1b, this could be a reasonable approximation for corrosion damage, because in many cases the need for repair does not become visible until the damage is quite substantial and the need for repair becomes evident. For example, a tin roof that is corroding away may entail negligible amenity loss until it begins to leak. For soiling, on the other hand, $n < 1$ seems more relevant, because the loss of reflectance is rapid at first but slows as dirt builds up (Figure 1c). Now, the above optimization leads to a generalization of Eq. 5 given by Eq. 7:

$$L = \frac{R}{n} \quad \text{for zero discount rate.} \tag{7}$$

The amenity loss L is smaller than the expenditure R for $n > 1$ (corrosion) and larger than R for $n < 1$ (soiling).

2.3. Discounting

Discounting reduces the weight of future costs relative to present costs and likewise for benefits. The decision when to renovate is based on discounted costs and benefits. A rational building owner chooses the period T between renovations so as to minimize the present value P of the total lifecycle cost. Using continuous discounting with rate r, one finds that P is given by Eq. 8:

$$P = R + Re^{-rT} + Re^{-2rT} + Re^{-3rt} + \ldots + \int_0^T \alpha t e^{-rt} dt + \int_T^{2T} \alpha(t - T)e^{-rt}\, dt + \int_{2T}^{3T} \alpha(t - 2T)e^{-rt} dt + \ldots \quad (8)$$

for the case where the amenity loss rate increases linearly with time t. Summing the geometric series and designating the amenity loss during the first period by L in Eq. 9:

$$L = \int_0^T \alpha t e^{-rt} dt = \frac{\alpha}{r^2}[1 - (1 + rT)e^{-rT}] \quad (9)$$

one can write P in the form given in Eq. 10:

$$P = \frac{R + L}{1 - e^{-rT}}. \quad (10)$$

Analogous to the derivation of the optimal period T_o in Eq. 4, we now take the derivative of P with respect to T and set this derivative equal to zero. This yields T_o as the solution of the equation given in Eq. 11:

$$\frac{rR}{\alpha} = T_o + \frac{1}{r}(e^{-rT_o} - 1). \quad (11)$$

Here we do not need to solve this transcendental equation. All we want is the relation between L and R, and that is readily found by using Eq. 9 (evaluated at $T = T_o$) to eliminate α. The result is given by Eq. 12:

$$L = R\,\frac{1 - (1 + r\,T_o)e^{-rT_o}}{rT_o + e^{-rT_o} - 1}. \quad (12)$$

Plausible values of rT_o range from 0 (at $r = 0\%$) to 3 (at $r = 10\%$ and $T_o = 30$ years). The corresponding ratio L/R varies from 1 to 0.4, and a typical value might be around 0.7 for $r\,T_o = 1$ (at $r = 5\%$ and $T_o = 20$ years). Thus, discounting has the effect of reducing the amenity loss L relative to the zero discount rate result of Eq. 7.

2.4. A Simple Rule for Amenity Cost

To sum up this section, we have shown that amenity loss due to building damage can be inferred from renovation expenditures. The key assumptions are:

1. The amenity loss is restored by renovation;
2. People minimize total cost; and
3. The decision to clean or repair is made by the people who suffer the amenity loss.

For assumption 2 we note that most building owners are acutely aware of costs, and budget constraints impose strong pressures to minimize costs; there may be errors of judgment or inability to obtain the necessary information, but being random such errors tend to cancel and, on average, the period T is chosen more or less correctly. The third assumption may seem questionable in cities where the majority of people who get to see a building are not the owner. There is, however, a certain collective pressure that forces the owners to internalize the amenity loss of the public. Such collective pressure is particularly strong in cities such as Paris, where the appearance of the buildings has a direct effect on tourism (a crucial industry for France), and where legislation has been passed to enforce a minimal renovation frequency (see Section 4.2).

On the other hand, Eq. 5 is likely to be an underestimate for the amenity loss if:

- The victim does not have the means to affect a repair or the damage is irreversible, or
- The victim chooses another way of coping with the damage (e.g., selling a house and moving to a less polluted area).

Of course, it is difficult to guess the magnitude of this underestimate, even with contingent valuation. As a practical compromise, it is perhaps best to adopt the simple rule that amenity loss is approximately equal to renovation cost and that, according to Eq. 13:

$$\text{Total damage cost} = 2 \times \text{renovation cost}. \tag{13}$$

As suggested by Eqs. 6 and 7, with zero discount rate the factor may be larger than 2 for soiling and smaller than 2 for corrosion. Discounting tends to reduce the factor. On balance, we find a factor of 2 reasonable, because soiling appears to be more directly correlated with renovation actions than corrosion, as implied by our data for France in Section 4.1.

These arguments also apply to historical monuments and buildings, in the sense of collective decision-making: public expenditures for the restoration of historical buildings are a reflection of our collective willingness to pay. We argue that it is meaningful to look at restoration costs, despite the often-heard opinion that historical monuments are "priceless" (similar to the widespread refusal of a monetary value for mortality risks). The purpose of quantifying such costs is pragmatic: to establish consistent reference values for the efficient allocation of limited financial resources; it is not the purpose to pass judgment on the intrinsic value of the damaged objects. Thus, we take the expenditures for the renovation of historical buildings as de facto expression of society's valuation, and we use Eq. 13 to account for loss of amenity.

To close this section, we note that only part of the expenditures for renovation can be attributed to pollution; the rest are due to various natural factors. Of course, only the part due to pollution is to be counted in Eq. 13.

3. Methodologies for Estimating Renovation Costs

3.1. Damage Mechanisms

The two main types of damage induced by atmospheric pollution are:

- *Corrosion* or *erosion* of construction materials and of coatings; and
- *Soiling.*

Corrosion and erosion are mainly due to acidity, especially from SO_2. Humidity of the air and rain play an important role. Other damaging factors include ozone (O_3), NO_x, as well as dust and soot. Different pollutants can interact; for example, particles or oxidants can affect the transformation of SO_2 to sulfuric acid. A large number of studies has been carried out to quantify the effects of air pollution on corrosion and erosion. For several important building materials explicit dose-response functions have been reported; for details see Kucera (1990), Haneef et al. (1992), Butlin et al. (1992), and Lipfert (1987). The most important pollutant for corrosion and erosion is SO_2.

Soiling is generally due to the deposition of airborne particulate matter, especially soot, onto the building surface (Ball 1989). Soiling can be measured as a change in light reflectance in areas where the particulate deposition is low [<20 g/(m^2·month)] or using a mass-based method for highly polluted sites [>20 g/(m^2·month)] (Terrat and Joumard 1990). There are relatively few studies on soiling due to air pollution. Few dose-response functions have been established, expressing the loss of reflectance as a function of time and concentration of particles (Hamilton and Mansfield 1992).

3.2. Bottom-Up Analysis: Dose-Response Functions and Repair Frequency

Typically, the dose-response functions for building materials yield the erosion rate (in μm/year). If one knows the relation between erosion rate and repair frequency, and if one has data for the inventory of building surfaces and repair costs, one can calculate the total repair cost according to Eq. 14:

$$\text{Total repair cost} = \sum_i \text{Surface area}_i \times \text{Repair frequency}_i \times \text{Repair cost}_i \qquad (14)$$

the sum running over all surface types in the inventory. The repair frequency is calculated at each building site by using an atmospheric dispersion model for the air pollutant(s) and applying the appropriate dose-response function. This approach could be called bottom-up because it is based on very detailed data.

For example, ExternE (1995) followed this approach for damage to buildings in the UK, using an inventory derived from a detailed survey of buildings in Birmingham, the second largest city in the UK (Ecotec 1986). On the basis of this survey, a building materials "identikit" was prepared for five major building types and combined with data for the geographical distribution of these building types. The relation between repair frequency and erosion rate was estimated by expert judgment. Repair costs were based on Ecotec (1986) and Lipfert (1987).

However, the relation between repair frequency and erosion rate is uncertain. It is not customary to monitor the thickness of building façades to determine when they should be renovated. Rather, owners tend to decide on the basis of the general appearance of a building. This can result from soiling and from corrosion. For stone buildings, the predominant type in France, soiling seems more likely than corrosion to be the prime driver for renovation.

3.3. Top-Down Analysis: Renovation Cost Data

Trying to apply the bottom-up methodology in France, we face a serious problem because there is no inventory of construction materials. The only available data in this domain are limited to floor areas for different building types; there is no information on the façade areas or construction materials. All we know, from general observation, is that most building façades are made of stone, concrete, brick, cement, or plaster, and the thickness of the façade material ranges from several centimeters to meters. Some are painted, in which case the relevant thickness is measured in millimeters.

Given the scarcity of data for France and the uncertainties when using the bottom-up method, we decided to base our study directly on observed data of renovation frequencies and costs, a top-down approach similar to that of Newby et al. (1991). As it happens, in France there are fairly detailed data on renovation costs, because these costs can be deducted from the income tax, and certain aggregated data on tax returns are accessible to the public. For the city of Paris, we also were able to obtain data on cleaning frequencies and costs. These data allow us to determine a "combined dose-response function," yielding directly the cost as a function of the concentration of a pollutant.

4. Renovation Costs in France

4.1. Data from Tax Deductions

From the income tax service of France we have been able to obtain data on deductions for building renovation expenditures in 1994, per taxpayer and aggregated over administrative regions such as cities or Départements (mainland France consists of 95 Départements). We have also obtained data for ambient pollutant concentrations in some of the corresponding urban areas (ADEME 1992; Stroebel et al. 1995). Unfortunately, the data for cities are rather limited, and only for 15 cities were we been able to get complete data for renovation expenditures, particle concentrations, and SO_2 concentrations; for an additional 2 cities we have renovation expenditures and particle concentrations. One reason for the data limitation stems

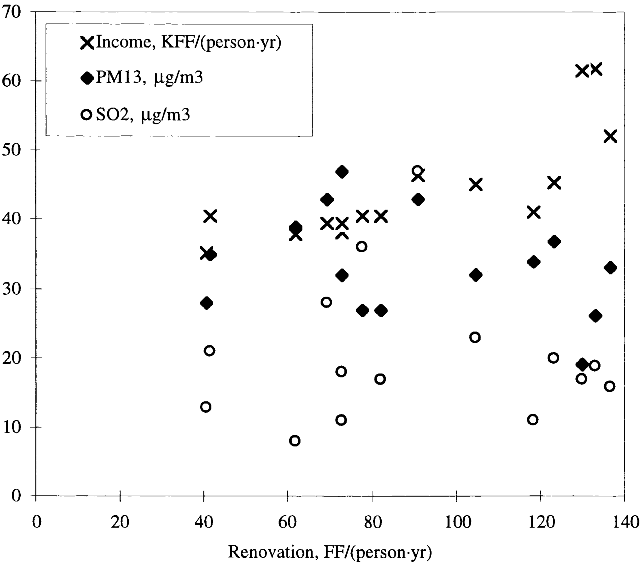

FIGURE 2. Data for renovation expenditures, income, and concentrations of particles (PM_{13}) and SO_2, for 15 cities in France. For each city, renovation expenditures are shown on the x-axis, and the corresponding income and concentrations are shown on the y-axis. ($1.00 = 5 to 6 FF).

from the fact that two different instruments have been used in France for measuring particle concentrations; one measures "black smoke" and the other PM_{13}. Most urban areas have chosen only one or the other. Because there is no site-independent conversion factor, we chose the PM_{13} data because they are closer to the TSP (total suspended particles) measure commonly used for emissions data and to PM_{10}, the standard international measure for ambient concentrations.

The data are plotted in Figure 2. One sees that the renovation expenditures increase with income. They appear to decrease with pollution, a surprising result that is due to the negative correlation between income and pollution in these cities. In fact, the correlation coefficient between income and PM_{13} is -0.5, whereas the correlation coefficient between income and SO_2 is $+0.1$, of opposite sign but much smaller magnitude. Clearly the income effect is very important.

A linear regression of renovation expenditures against income, PM_{13} and SO_2 yields the results listed in Table 1. The coefficient of PM_{13} is positive, as it should be. However, the one of SO_2 is negative. Also, the uncertainty of the coefficients for pollution is large, as shown by the small t (=coefficient/standard error of coefficient), which is 0.8 for PM_{13} and -0.7 for SO_2.

TABLE 1. Linear Regression of Renovation Expenditures in FF/(person·year) versus Income in KFF/(person·year) and Concentrations in μg/m^3 of Particles (PM_{13}) and SO_2 for the Data Shown in Figure 2

	Coefficient	Units	t Statistic
β_0 = Intercept	−82	FF/(person·year)	−1.5
β_{Inc} = coefficient of Income	3.52	FF/KFF	4.3
β_{PM} = coefficient of PM_{13}	0.72	FF/(person·year·μg/m^3)	0.8
β_{SO2} = coefficient of SO_2	−0.39	FF/(person·year·μg/m^3)	−0.7

$R^2 = 0.66$.

Actually, if income is so important, one would expect a model where the coefficient(s) for pollution varies with income. Thus, one should include in the regression the product of income and pollution variable(s). Indeed, this improves the results in the sense of higher t statistics. An example is shown in Table 2. This is a regression against Income and Income × PM_{13}, for 17 cities (those of Figure 2 plus two for which we have only PM_{13} but no SO_2).

We tried several other regressions, but the main features remain unchanged: the correlation of renovation with income is dominant and highly significant, whereas the correlation with pollution is difficult to identify. The coefficient of PM_{13} or Income × PM_{13} is positive, the one for SO_2 or Income × SO_2 is negative, and all have large standard errors ($|t| \leq 1$). The most reasonable model for the renovation cost R appears to be the one with the β coefficients listed in Table 2 (Eq. 15):

$$R = \beta_0 + \beta_{Inc}\ \text{Income} + \beta_{Inc*PM}\ \text{Income} \times c_{PM} \quad (15)$$

where Income is in KFF/(person·year), c_{PM} is the concentration of PM_{13} in μg/m^3, and R has units of FF/(person·year). This equation is, in effect, a concentration-response function and the coefficient of PM_{13} is the slope, apart from a correction factor to be discussed in Section 7. At a mean income of 43.5 KFF/(person·year), the coefficient is given in Eq. 16 as:

TABLE 2. Linear Regression of Renovation Expenditures versus Income and Income × Concentration of PM_{13} for the Data Shown in Figure 2 plus Two Additional Cities with PM_{13} Data

	Coefficient	Units	t Statistic
β_0 = Intercept	−67.1	FF/(person·year)	−2.0
β_{Inc} = coefficient of Income	3.02	FF/KFF	4.9
β_{Inc*PM} = coefficient of Income × PM_{13}	0.0158	FF/(KFF·μg/m^3)	1.0

$R^2 = 0.65$.

$$\frac{\partial R}{\partial c_{PM}} = \beta_{Inc*PM} \times \text{Income} = 0.69 \text{ FF/(person·year·}\mu\text{g/m}^3\text{)}. \quad (16)$$

For Paris, the city with the highest per capita income in France, the coefficient is $0.0158 \times 61.9 = 0.98$ FF/(person·year·μg/m^3).

The data leave much to be desired and the results are not very satisfying. A major source of uncertainties lies in the environmental data which have been changing over the years. Generally the concentrations of PM_{13} or SO_2 in France have been decreasing (by as much as a factor of two in Paris) since the early eighties due to a massive shift to nuclear power, but such reduction has not been uniform and in some of the cities the concentrations have even increased. Unfortunately we do not have a sufficiently detailed record for all the cities to carry out systematic regressions against weighted averages of past concentrations. We have tried additional regressions against data earlier than 1994 but they do not substantially change our results.

The lack of a positive correlation with SO_2 is disturbing, because numerous studies have established that SO_2 damages building materials. However, it is plausible that renovation expenditures in France may be driven more by soiling than by corrosion. Also, in our data the SO_2 damage may be covered up by the correlations among PM_{13}, SO_2, and income.

That particles emitted by combustion of fossil fuels drive up cleaning costs is as obvious as the blackness of soot. Therefore, we find the positive correlation of renovation costs with PM_{13} entirely plausible, despite the low t statistic. The only question concerns the magnitude of the effect.

The average renovation expenditure for the data shown in Figure 2 is 83.7 FF/(person·year). If all of that were due to particles (with average PM_{13} concentration 32.4 μg/m^3), the slope of the concentration-response function would be as given in Eq. 17:

$$\frac{83.7 \text{ FF/(person·year)}}{32.4 \ \mu\text{g/m}^3} = 2.60 \text{ FF/(person·year·}\mu\text{g/m}^3\text{)}. \quad (17)$$

The coefficient of PM_{13} (Eq. 16) is much smaller, 0.69 FF/(person·year·μg/m^3). This suggests that only about one-quarter of the renovation expenditures (given in Eq. 18):

$$\text{Fraction attributable to pollution} = \frac{0.69}{2.60} = 26\% \quad (18)$$

is attributable to particles. Of course, this fraction is very uncertain in view of the low t in Table 2. The value of 2.60 FF/(person·year·μg/m^3) is certainly an upper bound.

Incidentally the income tax service has also given us data for the number of renovation actions per year; they imply a renovation frequency per tax payer. With reasonable assumptions about the number of buildings per tax

TABLE 3. Data for the Cleaning of Buildings in Paris

Number of buildings in Paris	110,588
Number of renovation permits/year	2,714
Cleaning frequency, once per	41 years

Sources: Council of the City of Paris, and N. Roy. Sous-Direction du Permis de Construire, Mairie de Paris.

payer, this implies an average frequency of about once per 50 years for France and once per 30 years for Paris.

4.2. *Cleaning Data for Paris*

For verification it is interesting to look at independent data that we have been able to obtain for Paris.

4.2.1. Legislation. In 1852 Napoléon III passed a law that required all building owners in Paris to clean the façades exposed to the street at least once every 10 years. This measure was extended, in June 1904, to all the façades (Brandela 1992). During the 20th century, application of the law has been somewhat irregular. The legal requirement of a 10-year cleaning frequency remains in effect, although it is enforced only if a building is considered too dirty. The city can take legal action against recalcitrant owners, with fines from 1000 to 20,000 FF. A survey of cities in France realized by Virolleaud and Laurent (1990) indicates that 30 of a sample of 100 impose a renovation obligation similar to Paris.

4.2.2. Building renovation statistics for Paris. Table 3 shows the key data we were able to obtain. More detailed information on individual renovation actions is generally not available, e.g., exposed surface, type of construction, type of work done, and cost. If we assume that the cleaning frequency is 10 years, as implied by the law, more than 11,000 buildings must be cleaned per year. The actual frequency, averaged over 1990 to 1994, is only about a quarter of that value.

4.2.3. Cleaning cost. Data for the costs of façade cleaning or renovation are presented in Table 4. They are based on the "Publications du Moniteur," which publishes each year a statement of prices for the construction industry. We obtained some additional cost data by telephone inquiry of six firms, as indicated by the references in Table 4. The numbers suggest a total cost of about 250 FF per m^2 of façade ($45 per m^2).

4.2.4. Annual cost of façade renovation in Paris. Usually only the side facing the street is cleaned. The major cause of pollution in Paris is exhaust from diesel vehicles (between one-third and one-half of all passen-

TABLE 4. Price List for Cleaning of Façades (Without Taxes)

Operation	Price (FF/m^2)
Cleaning	
Dry scrubbing	30[a]
Gumming	95–115[b]
Sand jet	79[a]
Jet and brush cleaning	74[a]
Steam cleaning	96[a]
High-pressure cleaning with detergents	60[a]
Chemical removal of paint	89[a]
Surface treatment	
Painting	150[c]
Waterproof coating	60–80[b,c]
Plaster	104[a]
Lime	134[a]
Cement	164[a]
Other	
Scaffolding (rental, including set-up and removal)	74–166[a,b,d]
Protective covering (rental, including set-up and removal)	20–40[a,d]

$1.00 = 5 to 6 FF.
Sources:
[a] Publications du Moniteur (1994).
[b] C.P.P., St. Ouen; Mr. Katalinic, personal communication.
[c] Sarpie, St. Michel-sur-Orge; Mr. Antoine, personal communication.
[d] Technie Puts, St. Ouen; Mr. Garnalec, personal communication.

ger cars are diesel, and buses and taxis, the vehicles with the greatest utilization, are diesel). We might point out a clear demonstration of this effect in the very building where we work: one side of the Ecole des Mines faces a large park, the other a busy street; the street side is much dirtier even though it was cleaned more recently. This is one of the reasons why we believe that soiling due to particles is the major cause of air pollution-induced renovation expenses in France.

If we assume, for the sake of illustration, an average building height of 20 m and an average width of 20 m as typical for buildings in Paris, we find an area of 400 m^2. For the cost per area, Table 4 suggests a value around 250 FF/m^2. Together with the number of buildings cleaned per year (Table 3), we find the cost per year as given in Eq. 19:

$$\begin{aligned}\text{Cost/year} &= \frac{\text{Cost}}{\text{Area}} \times \frac{\text{Area of façade}}{\text{Building}} \\ &\quad \times \text{Number of buildings cleaned/year} \\ &= 400\ \text{m}^2/\text{building} \times 250\ \text{FF/m}^2 \times 2714\ \text{buildings/year} \\ &= 271\ \text{MFF/year.} \qquad (19)\end{aligned}$$

Because the population of the city of Paris is 2.15 million, this implies 126

FF/(person·year). This is close to the data point of 133 FF/(person·year) for Paris shown in Figure 2.

5. Comparison with Other Studies

It is interesting to compare these results with those of other studies. In Table 5 we list those that appear most comparable. Two of these studies, in Germany and in three European cities (Stockholm, Prague, and Sarpsborg), determined the cost of building renovation and the share of the atmospheric pollution.

The German study (Isecke et al. 1991) analyzes the case of the city of Dortmund, then extrapolates the results to evaluate the cost for West Germany. Frequencies of renovation are determined from an inquiry among property managers and construction firms. Two cases are distinguished: polluted areas (annual average concentration of $SO_2 > 30\ \mu g/m^3$) and non-polluted areas (annual average concentration of $SO_2 < 30\ \mu g/m^3$). The cost is calculated only in areas where $SO_2 > 30\ \mu g/m^3$, as the author considered the SO_2 impact negligible below this concentration. Results are presented in Table 5, converted with the exchange rate of 1991 and corrected for inflation in France since 1991.

The Scandinavian study (Kucera et al. 1993) looked at three cities: Prague (Czech Republic), Stockholm (Sweden), and Sarpsborg (small industrial city of Norway), to determine the cost of the corrosion on buildings. Four pollution intervals were distinguished:

- Concentration of $SO_2 < 20\mu g/m^3$,
- $20\mu g/m^3 <$ Concentration of $SO_2 < 60\mu g/m^3$,
- $60\mu g/m^3 <$ Concentration of $SO_2 < 90\mu g/m^3$
- Concentration of $SO_2 > 90\mu g/m^3$.

Renovation frequencies were determined mainly by field inspection and/or different sources of published or well-documented guidelines for renovation of buildings (Kucera et al. 1993). As model for the additional cost of corrosion in polluted areas they used (Eq. 20):

$$K_a = KS\left(\frac{1}{L_p} - \frac{1}{L_c}\right) \tag{20}$$

where K_a = additional cost for renovation, K = cost of renovation per area, S = exposed material surface, L_p = interval between renovations in polluted zones, and L_c = interval between renovations in unpolluted zones.

This permits determination of the gain that could be made if the pollution were decreased to the lowest SO_2 pollution level ($<20\ \mu g/m^3$). Results are presented in Table 5, together with data from other studies.

Unfortunately Isecke et al. (1991) and Kucera et al. (1993) give no information on the ambient concentration of particles. Instead, they used

TABLE 5. Results of Several Studies for the Cost of Building Renovation due to Pollution

	Exposed Surface per Inhabitant (m^2/person)	Renovation Cost per Inhabitant FF/(person·year)	Renovation Cost per Exposed Surface FF/(m^2·year)	Pollution (μg/m^3 SO_2)	Pollution (μg/m^3 PM_{13})
Germany[a]	55.6	370	6.65	>30	
Prague[b]	83	757	9.12	70	
Sarpsborg[b]	165	358	2.17	20–60	
Stockholm[b]	132	138	1.04	<20	
UK[c]		17			
Paris[d]	21[e]	35	6.14[e]	19	26

Notes:
[a] Isecke et al. (1991): corrosion and soiling; survey of real estate owners and managers.
[b] Kucera et al. (1993): corrosion; survey of real estate owners and consultation of construction guides, with calculated repair frequencies, and assuming Swedish prices for all three cities.
[c] Newby et al. (1991): soiling; survey of the stone cleaning market.
[d] Present study: real renovation costs from tax records, estimated surface area; assuming 26% of the total renovation cost of 133 FF/(person·year) attributable to pollution.
[e] In Paris, most renovation activities concern only the façade and we count only façade area.
Source: From Pons et al. (1995).

concentration of SO_2, a parameter for corrosion but less good as an indicator for soiling, although areas with high SO_2 levels usually have a high concentration of particles as well.

In the Scandinavian study, costs are determined by using a price list for Swedish builders in 1991 for all three cities. Thus, by comparing the values of the annual cost by square meter of exposed material, it is possible to judge the importance of pollution, because at the assumed constant prices it is the main parameter responsible for the variation of the cost.

However, the high cost for the city of Prague is due not only to the high pollution level but also to the fact that 24% of the materials exposed is plaster and 40% metals. The cost of repairing plaster is three times the cost of that of any other construction material in this study, and the cost of metal renovation also is high. Therefore, the cost of renovation is not only influenced by the level of pollution but also by the type of material. Thus, much of the factor three between the annual renovation cost per surface in West Germany and in Sarpsborg, despite an equivalent pollution level, is due to the different material. The surfaces in Sarpsborg are mostly painted wood, whereas West Germany has many buildings with façades of stone, mortar, or plaster.

The German study is closer to real costs because it is based on the renovation intervals practiced by the building owners, whereas the Scandinavian study estimates these intervals from data of construction guides whose rules are not necessarily applied.

The costs in Isecke et al. (1991) and Kucera et al. (1993) are an order of magnitude higher than the 17 FF/(person·year) obtained by Newby et al. (1991) in their economic evaluation of the soiling of English buildings, based on the cleaning market in the UK. Our result of 35 FF/(person·year) is much closer to the latter than the former, especially when one recalls that expenditures in Paris are about 50% higher than in the rest of France.

6. Costs of Renovation of Historical Monuments

It is difficult to obtain a generic price for the cleaning of a square meter of a historical monument façade, because each monument will require a specific treatment due to its characteristics, such as shape, age, material, location, and exposure. Also, the cleaning of a historical monument is only one operation among several typically carried out during a restoration project, and we do not know what fraction of the total cost can be attributed to pollution.

The budgets invested by the Ministry of Culture for restoration and renovation of the national heritage were 1199 MFF/year from 1988 to 1992 and 1570 MFF/year from 1994 to 1998 (Ministère de Culture 1994). The contribution of the Government covers only 40% to 50% of the expenses. Therefore, the total annual expenditure is approximately 3.0×10^9 FF/year, which corresponds to 52 F/(person·year).

TABLE 6. Expenditures for Restoration of Historical Monuments

Number of historical monuments	12,500
Total expenditures for restoration	Approximately 3000 MFF/year (private + public)
Population of France	58 million
Total expenditure/(person·year)	Approximately 52 FF/(person·year)
Contribution of air pollution, if 26% total	Approximately 13 FF/(person·year) [2.36 $/(person·year)]

Source: From Ministère de Culture (1994).

This includes historical monuments but also historical objects, furniture, and gardens. Only a fraction of the expenditure can be attributed to air pollution. If we estimate the share of air pollution to be 26%, by analogy to what we found for utilitarian buildings in Section 4.1, we find that the damage to historical monuments is around 13 F/(person·year). These numbers are summarized in Table 6. Comparing the total expenditures for renovation, 52 FF/(person·year) in Table 6 with the previous value of 83.7 FF/(person·year) for utilitarian buildings (Eq. 17), suggests that air pollution damage to historical monuments in France is smaller. In the following, we will assume that damage to historical monuments in France can be estimated by applying the ratio given in Eq. 21:

$$\frac{\text{Damage to historical monuments}}{\text{Damage to utilitarian buildings}} = \frac{52\ \text{FF/(person·year)}}{83.7\ \text{FF/(person·year)}} = 0.62 \text{ in France.} \tag{21}$$

to the damage estimate for utilitarian buildings.

7. Damage per Kilogram of Particulate Emission

In Eq. 15 we have a linear C-R function for damage cost as a function of PM_{13} in ambient air. For the calculation of damage costs due to particle emissions, one needs a correction factor because there is a difference in composition between the primary particles emitted by combustion equipment and the particles in the ambient air. Only a portion of the latter, perhaps 20% to 50%, is due to primary particles from combustion; the rest is composed of soil particles and nitrate and sulfate aerosols (Harrison and Jones 1995). Most soil particles are less black than soot, and the contribution of nitrate and sulfate aerosols is white. For these reasons, the coefficient of PM_{13} (Eqs.15 and 16) probably should by multiplied by a factor of 2 to 4 when it is used for damage calculations per kilogram of emitted combustion particles. Here we will take 3 as a typical value. In addition, we multiply by a factor of 2 to account for amenity loss as per Eq. 13. Thus, the C-R function for the total damage cost to utilitarian buildings in France has the slope given in Eq. 22:

$$\begin{aligned} f_{CR} &= \frac{\partial R}{\partial c_{PM}} \times 3 \times 2 \\ &= 0.69 \text{ FF/(person·year·}\mu\text{g/m}^3) \times 6 \\ &= 4.14 \text{ FF/(person·year·}\mu\text{g/m}^3). \end{aligned} \tag{22}$$

This is the value for the average income, and for simplicity we will use it without attempting to account for different incomes in different regions of France.

During the ExternE ("External Costs of Energy") Project (ExternE 1995, 1998) of the European Commission, software was developed for calculating the damage cost for impacts caused by particles, NO_x and SO_2, if the dose-response function is known. The dispersion modeling is based on the ISC Gaussian plume model (Wackter and Foster 1987) in the local range up to about 50 km from the source and the Harwell Trajectory Model beyond. These dispersion models, together with databases for population, etc., covering all of Europe, have been integrated into the ECOSENSE software (Krewitt et al. 1995). A large number of site-specific calculations of damage costs have been carried out.

For impacts of particles with linear C-R functions, the results can be summarized conveniently in terms of the so-called "uniform world model" (Curtiss and Rabl 1996), which estimates the damage as given in Eq. 23:

$$D_{uni} = \frac{f_{CR}\rho_{uni}}{k_{uni}} Q \tag{23}$$

where Q = emission rate of particles, f_{CR} = slope of the C-R function, ρ_{uni} = average of receptor density in region, and k_{uni} = deposition velocity (sum of wet and dry deposition).

This equation follows if receptor density and deposition velocity are assumed constant throughout the region over which impacts are significant (radius of about 500 km). For impacts to buildings according to the C-R function slope of Eq. 22, the receptor density is the population density, just as for health impacts. By means of many detailed site-specific calculations, we verified that Eq. 23 is remarkably relevant (Spadaro and Rabl 1997). For example, it reproduces within a few percent the results of detailed calculations of the average health damage costs for the coal- and oil-fired electric power plants in France. The variation with emission site is particularly strong for primary pollutants such as particles. For sources in rural sites, the damage is a factor two to three smaller than D_{uni}, and for sources in large cities the damage can be up to an order of magnitude larger than D_{uni} if the emission takes place at ground level (air pollution from cars)

(Table 7). To understand why the damage for sources in or near Paris is so large, one has to note that the population of greater Paris is about 11 million, 20% of the total population of France.

In France, the average population density is ρ_{uni} = 105 persons/km^2. By detailed fits to ECOSENSE dispersion results, we found that the average deposition velocity for particles is approximately k_{uni} = 0.01 m/s. The slope f_{CR} of the C-R function of Eq. 22 has units of FF/(person·year·μg/m^3), which represents the damage accruing during 1 year due of exposure to a given concentration of PM_{13}. Therefore, the damage due to an incremental emission of 1 kg of PM_{13} is calculated by assuming that this 1 kg is emitted at a uniform rate during the course of 1 year, i.e., one takes Q = 1 kg/1 year = 10^9 μg/365 × 24 × 3600 s = 31.7 μg/s (for most combustion equipment, the emitted particles are smaller than 13 μm; hence, TSP = PM_{13}). Thus, we obtain (Eq. 24):

$$
\begin{aligned}
D_{uni} &= \frac{f_{CR}\rho_{uni}}{k_{uni}} Q \\
&= \frac{4.14 \text{ FF/(person·year·}\mu\text{g/m}^3) \times 1.05 \times 10^{-4} \text{ persons/m}^2}{0.01 \text{ m/s}} 31.7 \ \mu\text{g/s} \\
&= 1.38 \text{ FF/year} \qquad (24)
\end{aligned}
$$

for the total damage to utilitarian buildings due to an emission rate of 1 kg/1 year. Therefore, this is also the damage per kilogram of particulate emissions (Eq. 25):

$$D_{uni} = 1.38 \text{ FF/kg} = 0.21 \text{ Euro/kg} = \$0.25\text{/kg}. \qquad (25)$$

For historical buildings and monuments we apply the ratio in Eq. 21 to find (Eq. 26):

$$
\begin{aligned}
D_{uni} &= 1.38 \times 0.62 \text{ FF/kg} = 0.86 \text{ FF/kg} = 0.13 \text{ Euro/kg} \\
&= \$0.16\text{/kg}. \qquad (26)
\end{aligned}
$$

Of course, this estimate is only for typical combustion installations, such as power plants in France. Table 7 indicates how these numbers might change for other emission sources.

For comparison, the damage due to health impacts is (Eq. 27):

$$D_{uni} = 89.9 \text{ FF/kg} = 13.6 \text{ Euro/kg} = \$16.3\text{/kg}. \qquad (27)$$

under the same conditions (Rabl et al. 1998; Spadaro and Rabl 1997); it is two orders of magnitude larger than the damage to buildings.

Of course, one must not forget that the uncertainties of damage cost estimates are very large. Rabl and Spadaro (1999) analyzed the various sources of uncertainty in the calculation and their effect on the uncertainty of the result. They found that, for most health costs due to air pollution,

TABLE 7. Damage as Multiple of D_{uni} for Different Sites of Emission of a Primary Pollutant

Site	Stack Height	Damage
Rural	40–200 m	0.3–0.5 D_{uni}
Urban, except Paris	40–200 m	0.7–1.5 D_{uni}
Suburb of Paris	40–200 m	2–4 D_{uni}
Center of Paris	100 m	4–6 D_{uni}
Center of Paris	Ground level (cars)	14 D_{uni}

Source: Based on Spadaro and Rabl (1997).

the uncertainty corresponds to a geometric standard deviation σ_g of 3 to 5. The geometric standard deviation has a simple interpretation in terms of approximate multiplicative confidence intervals about the geometric mean μ_g ($\approx$ median), e.g., $[\mu_g/\sigma_g, \mu_g.\sigma_g]$ for 68% and $[\mu_g/\sigma_g^2, \mu_g.\sigma_g^2]$ for 95% confidence. For damage costs to buildings, the uncertainties of the steps of the calculation, particularly the C-R function, are comparable to those of health. Thus, we have reason to believe that our estimates are correct within an order of magnitude, and we are confident in our conclusion that damage costs to buildings are small compared to the costs of health damage.

8. Conclusion

With a simple theoretical argument we have shown that amenity loss can be inferred from observed renovation expenditures. Because the amenity loss turns out to be comparable to the renovation expenditure, the total damage cost is approximately twice the renovation expenditure.

We reviewed the methodologies for calculating air pollution damage to buildings, as well as the data available for their implementation in France. We were able to obtain data for frequencies and expenditures of cleaning and repair activities. By regression of the data we derived a "combined dose-response function" for the renovation cost as a function of pollution. We find that the most important variables are income and concentration of particles, but, surprisingly, a correlation with SO_2 is not clear. This could be understood if most renovation expenditures in France are occasioned by soiling (primarily due to particles) rather than corrosion (primarily due to SO_2).

For historical buildings and monuments, a category of great importance in France, we have been able to find only data for total national expenditures for renovation. They imply that the cost of pollution damage is somewhat smaller than for utilitarian buildings, if one assumes that the fraction of renovation expenditures attributable to pollution is the same (26%).

We compared our results with values that have been cited for other cities in Europe (Isecke et al. 1991; Kucera et al. 1993; Newby et al. 1991); our

TABLE 8. Summary of Damage Costs According to D_{uni} of Eq. 23 for Particle Emissions from Power Plants in France

Impact Category	FF/kg	Euro/kg	$/kg
Utilitarian buildings	1.38	0.21	0.25
Historical buildings and monuments	0.86	0.13	0.16
Health	89.9	13.6	16.3

Note: For other particle sources, see Table 7. Health damage according to estimates by ExternE (1998) and Rabl et al. (1998). Damage to buildings and monuments includes amenity loss.

numbers are compatible with those of Newby et al. (1991), but much lower than those of Isecke et al. (1991) and Kucera et al. (1993). Of course, differences are to be expected because of differences in materials in different countries.

Our damage cost estimates are summarized in Table 8 for typical particle emissions from power plants (for other combustion equipment, see Table 7). They include the amenity loss. For comparison we also show the cost of health damages due to particles, as estimated by Rabl et al. (1998) for the ExternE Project. Even though the uncertainties are large, about a factor of 4 in either direction (Rabl and Spadaro 1998), one can certainly conclude that the cost of damage to buildings, including historical buildings and monuments, is smaller by at least one, probably two, orders of magnitude than the cost of health damage.

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Appendix

Glossary

All costs in this article are expressed in FF of 1994, correcting for inflation as appropriate. Foreign costs have been converted at the exchange rate of the year for which they are given and then corrected by the inflation rate of France. During the past decade, the exchange rate for the dollar has been mostly in the range of 5 to 6 FF/$; here we take 5.50 FF = US $1.00.

c = concentration
C-R function = concentration-response function
D = damage cost

EC = European Commission
Euro = European currency unit (1 Euro = 6.60 FF ≈ \$1.00 to \$1.25)
EU = European Union (EU15 = the current 15 member countries)
External costs = costs that arise when the social or economic activities of one group of people have an impact on another for which the first group does not fully account, e.g., when a polluter does not compensate others for the damage imposed on them
f_{CR} = slope of concentration-response function [cases/(person·year·μg/m^3)]
FF = French franc
k = deposition velocity (m/s)
KFF = 1000 FF
L = amenity loss
MFF = million FF
NO_x = unspecified mixture of nitrogen oxides, especially NO and NO_2
PM_d = particulate matter with aerodynamic diameter smaller than d μm
Q = emission rate of a pollutant (kg/s)
R = renovation cost
r = discount rate = rate that allows comparison of monetary values incurred at different times, defined such that an amount P_n in year n has the same utility as an amount $P_0 = P_n (1 + r)^{-n}$ in year 0
SO_x = unspecified mixture of sulfur oxides, especially SO_2 and SO_3
T = period between renovation actions
TSP = total suspended particles
ρ = receptor density.