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Project Summary

Damage Cost Models for Pollution Effects on Material

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Two damage cost models were developed to quantify the effects of ambient air pollutants on manmade materials exposed in urban environments. The models use existing physical damage functions, estimates of material in place and average repair or replacement costs to calculate the use life maintenance costs as a function of air pollutant concentration.

The first model, called the "prevailing practice model", assumes that existing maintenance practices represent a rational response to current levels of pollution and material properties. Information on the frequency of maintenance actions and the rate of damage predicted by existing physical damage functions is used to derive a "critical damage level". This critical damage level, defined as the amount of damage that is usually accepted before remedial action is taken, is assumed to be constant. The change in the rate of damage with changes in pollutant concentration can then be used to calculate a change in maintenance schedule, which, in turn, is converted to a change in maintenance costs over the use life of the material system under study.

The second model, called the "least cost model" does not make any assumptions about the appropriateness of current maintenance practices. Instead, the critical damage levels and maintenance criteria are directly specified by the user. The model then calculates the system use life costs for maintenance schedules based on these criteria for different pollution levels.

Each model has its advantages and disadvantages. The prevailing practice model is easy to use but is highly dependent on the accuracy of information on existing maintenance practices and the appropriateness of the assumption that such practices represent the most rational response to existing conditions. The least cost model is more versatile in that it can be applied to conditions that are not representative of the existing situation, but it requires more detailed input and assumptions. Both models are highly dependent on the accuracy of existing physical damage functions.

This report presents both approaches and demonstrates their application to calculating the cost of sulfur dioxide damage to steel, zinc and paint, total suspended particulate matter damage (soiling) of clean surfaces, and ozone damage to elastomers.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The physical effects of air pollution on manmade materials have long been recognized and a considerable amount of knowledge on physical effects has been accumulated. Economic estimates of the cost of damage have been made based on this knowledge, but there is little confidence in these estimates because of questions concerning the accuracy of key input data and the lack of sophistication of the techniques used. The importance of accuracy in making economic assessments for cost-benefit comparisons and consideration of secondary air quality standards is obvious.

The damage costs due to an air pollutant must be calculated in light of natural limits to the useful life of the material affected and options for repair, replacement or substitution. Lifetime is distinguished from the use life of the system as being the time of exposure experienced until a critical damage level is reached at which action is taken and/or real costs are incurred. Use life is defined as the time period over which the material system is expected or needed to be used. For example, children's shoes usually have a lifetime significantly longer than their typical use life. That is, they are usually discarded long before they have physically deteriorated to the point at which they can no longer be worn. Therefore, little attention is paid to repairing children's shoes. A painted house, on the other hand, has a use life far in excess of the lifetime of the paint. Accordingly, maintenance of the house paint is usually performed.

The incremental cost of pollution damage, that is, the cost associated with damage above that expected from normal wear or use in an unpolluted ("clean") environment, is the most important factor in the consideration of the costs and benefits of pollution control. More specifically, the damage to a material by a given pollutant must be assessed if the benefit to be gained by reducing that pollutant is to be calculated.

Accurate estimates of the disbenefit of air pollution damage to materials, (conversely, the benefits of avoiding such damage), are difficult to derive. Such estimates must not only take into account many important physical and chemical interactions, but must also consider socioeconomic factors. Aesthetic judgment, an awareness of alternatives and the cost of capital are only a few of the factors which can strongly influence incurred costs.

In order to determine the costs associated with the exposure of materials to ambient pollutant levels, several types of information are necessary. This includes the distribution and exposure of the materials of interest, the rate at which damage is incurred under actual exposure conditions, the amount of damage which necessitates remedial or preventive action (critical damage level), and finally, the type and cost of remedial or preventive action actually taken.

The objective of this work was to develop a relatively simple method for estimating the damage cost of air pollution with regard to its effects on nonliving materials, and to establish a framework by which the estimates may be improved when additional information becomes available. To meet this goal two methods for estimating the damage cost of air pollution were developed. The first method is a simple approach in which current maintenance practices, determined from surveys, are coupled with existing pollutant levels and physical damage functions and are extrapolated into general rules or functions. These rules or functions can then be applied in hypothetical situations where factors such as the pollutant level are varied over a limited range and the resulting change in maintenance and replacement costs can be calculated.

The second method is a more complex model which uses available pollutant damage functions and specific critical damage levels to calculate damage costs directly. The complex model is somewhat more theoretical but it allows consideration of alternative maintenance strategies that may be significantly different from those currently influencing actual practice. The complex model can thus be used to derive an estimate of costs for conditions or maintenance strategies not currently in use, including a theoretical ideal or least economic cost approach.

Damage Cost Model

General Concepts

There are two fundamental approaches to estimating the economic impact of air pollutants on materials. The first is a direct, empirical comparison of total expenditures and/or a loss of amenity due to materials damage under different atmospheric pollutant conditions, followed by the direct development of quantitative relationships between cost and pollution.

The second approach is based on the calculation of the physical damage from a given atmospheric pollutant concentration by means of physical damage functions and the quantification of the economic and aesthetic responses to that damage, through economic damage functions. The cost versus pollution relationships are thus derived from calculated effects, and are not based solely on observation. Although less direct, this analytical approach has the advantage that it is less sensitive to common sources of error such as regional differences in climate, population, income, mix of materials and spurious correlation, than the comparative approach.

Two models employing the second approach have been developed. The first model, called the prevailing practice model, reflects current maintenance and replacement practices. It is assumed in this model that such prevailing practice is the result of well-informed decisions and represents the best possible response to local conditions. The second model, or least cost model, uses pollutant damage functions, current ambient pollutant concentrations, specific critical damage levels and a maintenance or replacement decision matrix to determine a least cost economic strategy independent of the prevailing practice.

Prevailing Practice Model

The prevailing practice model is based on several key assumptions. First, it is assumed that the current strategies for the use of material systems incorporate decisions based on accurate information of both physical and socioeconomic factors. This assumption may be of limited validity due to the rapid introduction of new materials and the relatively recent changes in ambient air quality which have drastically changed material/environment interactions. Strategies that are used today may not yet reflect these changes since the consequences of the changes are not yet apparent. This simple model is still a useful tool, however, because it automatically includes a number of variables which are difficult, if not impossible, to define precisely. Several of these variables are socioeconomic as well as physical in nature, such as the level of damage which prompts repair and replacement. It is also a model which may be applied with reasonable accuracy and without extensive (and expensive) data gathering.

A schematic outline of the prevailing practice model approach is presented in Figure 1. The prevailing practice model requires information on the lifetime of materials systems in the ambient environment which can usually be derived from a survey of currently practiced maintenance strategies. Physical damage functions, which relate the concentration of a given pollutant to the rate of physical damage are then selected. The current pollutant level and other environmental factors are then used in the physical damage function to define a critical damage level that is consistent with the prevailing lifetime of the material. The damage function and defined critical damage level are then applied with the projected pollutant levels of interest and a projected lifetime of the material is calculated. The projected lifetimes are then used to determine the costs attributable to pollutant damage at each level of pollution.

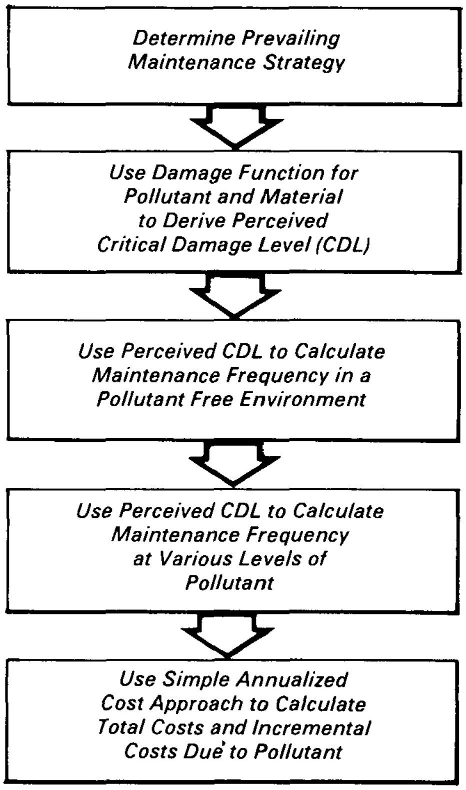

Figure 1. *Prevailing practice model.*

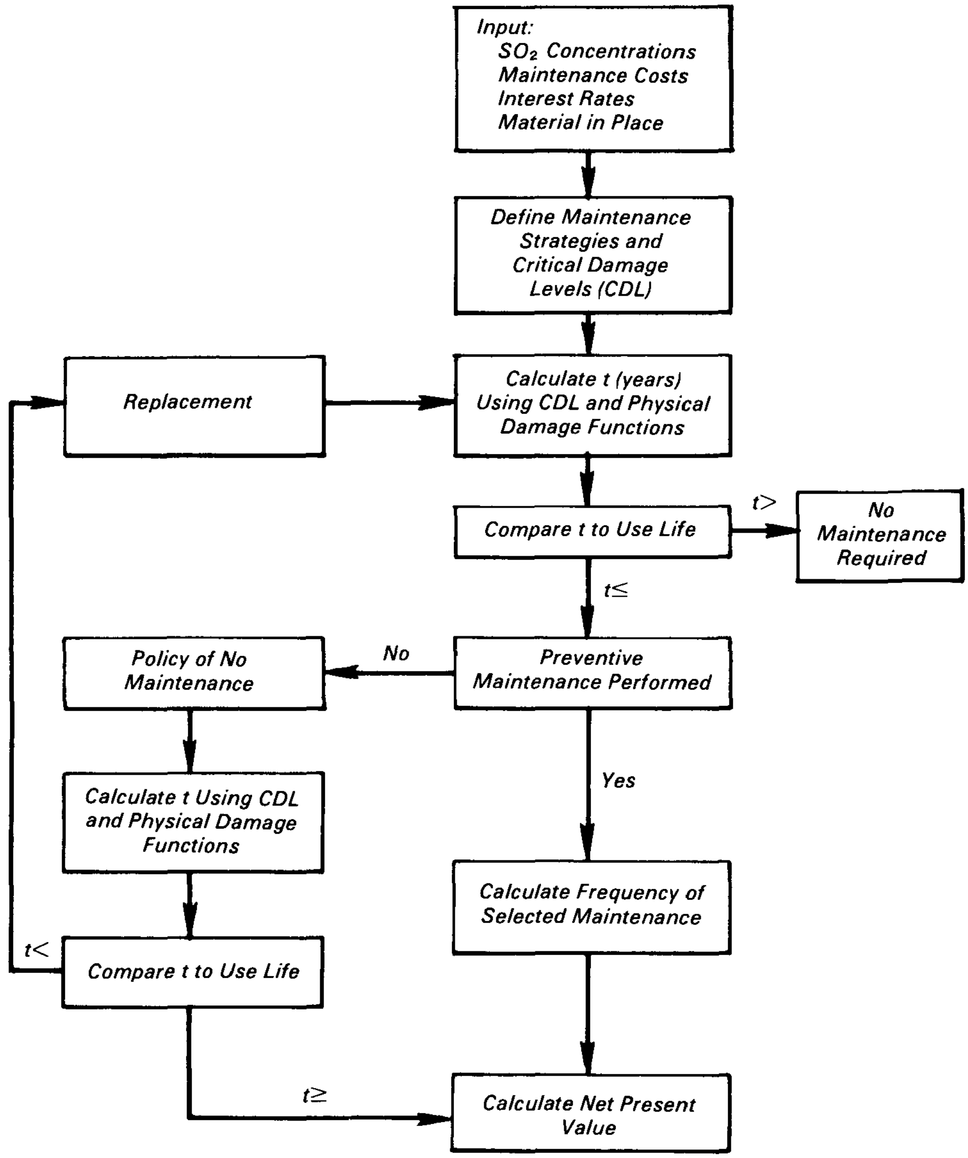

Figure 2. *Least cost model flow diagram.*

Least Cost Model

The least cost model is much more complex than the prevailing practice model described above. Instead of simply accepting the typical period between maintenance activities as the lifetime of the material, this model is used to calculate the maintenance schedule most appropriate for minimizing total cost. These calculations are based on physical damage functions, externally derived critical damage levels and information on economic factors such as the cost of capital (discount rate) as a function of income for various groups.

As in the simple prevailing practice model, the first step is to define the nature of the materials system and pollutant interactions of interest. However, unlike the simple model, the progressive changes in the rate at which both physical and economic damage accumulates as a function of previous history must be included. The least cost model accounts for these changes by allowing the definition of the material subsystem to change as described by critical damage levels. The rate of accumulation of both physical and economic damage is also changed as the definition of the material subsystem is varied. Since critical damage levels are usually defined in terms of either changes in the rate of accumulation of economic damage or changes in system utility, the method is not as complex as it initially appears.

In practice the critical damage levels are specified in the model. The appropriate physical damage functions are used to define the length of time required to reach each critical damage level for a given set of environmental conditions. A cost factor is associated with the maintenance performed within the period between changes in critical damage level. The model then calculates the use life costs for different maintenance schedules and adjusts the costs to account for the cost of capital.

The impact of a change in pollutant level is determined by the total minimized costs of maintenance at different levels of pollutant concentration.

A schematic diagram of the least cost practice model is illustrated in Figure 2.

Model Application

Prevailing Practice

The prevailing practice model was used to determine incremental damage costs associated with changes in annual average SO_2 and TSP concentrations for bare galvanized steel and painted steel exposed in an urban environment. Normal maintenence practices for the repair and replacement of these materials were determined in a limited local survey of the Boston area. The maintenance practices reviewed include those for highway stuctures (bridges, signs, poles, guardrails), chain-link fencing, and electric transmission towers. One interesting result of the survey was the discovery that the majority of galvanized materials are not routinely maintained. Only a relatively small percentage of the total stock of bare galvanized steel products has deteriorated to the point where maintenance has been required, although much of it has been removed for other reasons (aesthetic appearance, damage by impact or physical wear).

Accordingly, although damage to structures such as chain link fencing and electric transmission towers could be significant, there is not enough current maintenance history to judge the degree of significance through the prevailing practice model.

In another application, the amount of painted surface in an urban area was estimated, the prevailing maintenance practice was determined through a survey of residential house painting practices in the Boston area and the incremental damage costs attributable to annual average pollutants was calculated. Application of this model with the existing mathematical damage function for paint indicates that only a small portion of the costs of painting is attributable to SO_2 damage.

The evaluation of the damage costs associated with total suspended particulate matter (TSP) and soiling was limited by the available pollutant-material damage functions and a lack of data on normal practice and critical damage levels. For soiling the potential disbenefits are primarily in the form of aesthetic costs rather than direct costs associated with changes in maintenance practices. The economic impact of soiling, therefore, could not be determined accurately with the prevailing practice model.

The relationship between ozone and damage to rubber tires was analyzed and two areas of disbenefit were identified. On a regional basis, reduction in ozone concentration would result in small benefits to the retread industry in the form of an increased number of available casings. Benefits from reduction in ozone on a national level could occur as the amount of antiozonant added to tires by manufacturers was reduced to provide the same level of protection currently afforded, resulting in lower costs. However the benefits associated with changes at either the national or regional level were calculated to be relatively small.

The results of the prevailing practice model applications are presented in Table 1.

Least Cost

The least cost model combines physical damage functions and an economic approach using the net present value technique (NPV) to predict the least cost approach to addressing damage to materials exposed outdoors. A variety of maintenance strategies (including no maintenance); the cost associated with each maintenance strategy; and various ambient concentrations of air pollutants were considered. Other factors included in the analysis were:

- The use life of the material, defined as the period of time that the system of which the material is a part is expected to perform a particular function.
- The value of the material in place reflected by the cost of total repair or replacement.
- The critical damage levels, defined as the amount of damage which prompts a decision for maintenance or replacement of the material.
- The interest rates for use in calculating the net present value.

The least cost model was configured to calculate the damage costs associated with various annual average SO_2 concentrations (0, 20, 40, 60, 80, 100 $\mu g/m^3$) and interest rates of 5 percent, 10 percent and 15 percent.

An example of the results of the least cost model are presented in Table 2. In this application, damage to painted wood residential structures from exposure to ambient SO_2 was evaluated using three maintenance strategies. The model was also applied to study bare galvanized steel chain link fence and painted metal reactions with ambient SO_2.

The most dramatic result of the analysis presented in Table 2 is the importance of the discount rate used to calculate net present value costs. High discount rates put a heavy emphasis on near term expenditures, and this fact is reflected in the relatively small influence of both maintenance strategies and pollutant levels on calculated maintenance costs. The time-to-first maintenance has a powerful effect on total costs. Since damage by pollutants to most materials used in permanent construction takes several years to become evident, the use of the net present value method of cost accounting tends to reduce substantially the apparent economic impact.

Conclusions

The development of these two damage cost models demonstrated that there are several key areas where additional information is essential to develop more accurate estimates. The basic economic approaches of using prevailing practice and least cost analyses to develop costs are basically sound. However, uncertainties as to the amounts of exposed material in place on a nationwide scale; the lack of knowledge of the response of the industrial and private sectors to the effects of air pollution; and the failure of several of the physical damage functions together to address the major factors leading to maintenance actions, undermine the accuracy of economic estimates made using these models.

Additional information must be obtained on normal or prevailing practice to determine how the public and private sectors respond to conditions prompting maintenance and replacement and the estimation techniques for quantifying the amount of susceptible materials in place must be improved. These data would be used as primary input to the estimation of material damage nationwide. The damage functions for steel and zinc in the

Table 1. *Example of Applications of the Prevailing Practice Model*

Pollution/Material	*Pollutant Concentration ($\mu g/m^3$)* *Incremental Per Capita Annual Cost (1981 $)*			
SO_2/Bare Galvinized Steel	*NA[a]*			
TSP/Clean Surfaces	*NA[b]*			
SO_2/Painted Wood	*0*	*20*	*40*	*100*
	0	*9.07[c]*	*9.07[c]*	*28.49*
O_3/Rubber (national)	*40*	*60*	*80*	*100*
	.14	*.36*	*.54*	*.59*

[a] *Insufficient maintenance history to apply prevailing practice model.*
[b] *Inadequate damage functions to apply prevailing practice model.*
[c] *Cost calculated for changes in lifetime of integer years.*

Table 2. *An Example of the Application of the Least Cost Model to Analysis of SO_2 Damage to Painted Wood Residential Structures*

Structure Use Life. 75 yrs.
Maintenance Strategy· Repaint on first sign of damage.

SO_2 Level ($\mu g/m^3$)	Number of Maintenance Actions Over Use Life	Net Present Value Maintenance Cost per Structure at Discount Rate of:		
		5%	10%	15%
0	8	3800	1600	900
20	9	4100	1800	1000
40	9	4400	1900	1100
60	10	4700	2100	1200
80	11	5000	2200	1300
100	11	5200	2300	1400

Structure Use Life: 75 yrs.
Maintenance Strategy: Repaint only after wood rot appears.

SO_2 Level ($\mu g/m^3$)	Number of Maintenance Actions Over Use Life	Net Present Value Maintenance Cost per Structure at Discount Rate of:		
		5%	10%	15%
0	5	5000	1800	800
20	5	5300	1900	900
40	5	5500	2000	900
60	5	5700	2100	1000
80	5	5900	2200	1100
100	6	6200	2300	1100

Structure Use Life: 75 yrs.
Maintenance Strategy: Replace structure on collapse.

SO_2 Level ($\mu g/m^3$)	Number of Maintenance Actions Over Use Life	Net Present Value Maintenance Cost per Structure at Discount Rate of:		
		5%	10%	15%
0	1	7800	1000	200
20	1	8000	1100	200
40	1	8200	1100	200
60	1	8300	1200	200
80	1	8500	1200	200
100	1	8600	1200	200

presence of SO_2 are fairly well defined. Unfortunately neither the physical damage function for paint nor the physical damage functions for soiling are adequate to characterize damage. Information gathered in these areas will improve the accuracy on reliability of estimating the potential benefits and costs due to changes in ambient concentrations of atmospheric pollutants.

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The complete report, entitled "Damage Cost Models for Pollution Effects on Material," (Order No. PB 84-140 342; Cost: $14.50, subject to change) will be available only from:
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