EPA-600/5-76-011
September 1976

PHYSICAL AND ECONOMIC DAMAGE FUNCTIONS FOR AIR POLLUTANTS BY RECEPTOR

by

Ben-chieh Liu, Ph.D.
Eden Siu-hung Yu, Ph. D.
Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

MRI Project No. 4004-D
EPA Contract No. 68-01-2968

Project Officer

John Jaksch
Criteria and Assessment Branch
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

CORVALLIS ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF DEVELOPMENT AND RESEARCH
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97330

DISCLAIMER

This report has been reviewed by the Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Clean Air Act of 1970 requires substantial reduction in air pollution. Under the authority of this and subsequent Acts, the Environmental Protection Agency has promulgated national ambient air quality standards for several pollutants. In geographic regions where ambient standards are exceeded, the states have been required to undertake action to comply with the standards.

The current energy crisis has resulted in a closer look by society and the Agency at the tradeoffs between energy conservation and improved environmental quality. Specifically, the crisis has resulted in the air quality standards coming under closer scrutiny. The standards in many instances are viewed by industry as impediments to the use of alternative fuels which could alleviate the current energy situation.

In order to effectively evaluate the environmental tradeoffs, the decision maker must have information on the costs and benefits of alternative environmental control strategies. Providing such information involves difficult issues of measuring and evaluating the diverse effects of pollution abatement. One of the results of the energy crisis has been a renewed call for a reevaluation of and increased emphasis on the delineation and quantification of the benefits and costs attributable to air pollution reduction.

As most economists who are familiar with the methodology know, benefit/cost analysis has its limitations in practical application to decision making problems. The primary limitations are the difficulties encountered in placing an economic value on some effect responses, and/or the derivation of adequate effect responses. While dependable, systematic estimates of damages resulting from the effects of air pollution are still quite rare, progress is being made. Within the past decade, several studies have been completed estimating property and material costs of air pollution and the effects of air pollution on property values and human health. However, many of these studies are too specific, and, as a result, do not lend themselves well for use in formulating decisions having national implications. The purpose of this study was to see, using existing studies, whether this limitation could be overcome.

More specifically, the purpose of this study was to examine past economic, and other related environmental studies, to determine whether the results could be utilized in estimating composite parametric damage functions. The functions, while providing ballpark estimates, could be used in evaluating the outcomes of implementing alternative environmental policies. In the meantime it was hoped that additional economic-environmental studies would be undertaken which would mitigate the shortcomings and permit a reestimation of more precise damage functions.

This report estimates economic, parametric damage function by receptor (human health, household soiling, materials, and vegetation) for the stationary source pollutants - sulfur dioxide and suspended particulates. The damage functions are based on existing research results. The socio-economic data used in formulating the damage functions for the different metropolitan areas are derived from the 1970 census.

The research results have been extensively reviewed by environmental economists, whose suggestions and comments have been incorporated into the study. The results should be used with appropriate caution. Some of the assumptions employed in the study, by necessity, are uncertain. Some of the methodological-statistical techniques employed are in their infancy and have not been tested elsewhere. Despite the existence of these difficulties, it is the general consensus of the reviewers that the study represents an important step forward in evaluating alternative pollution control options. Peer review of the study results by other environmental economists are welcome, and should be sent to the project officer at the Corvallis Laboratory.

This study was initiated by the Washington Environmental Research Center, Office of Research and Development, Washington, D.C., and completed at the Corvallis Environmental Research Laboratory (CERL), Office of Research and Development, Corvallis, Oregon.

A. F. Bartsch
Director, CERL

PREFACE

This is the Final Report for the project entitled "Physical and Economic Damage Functions for Air Pollutants by Receptor," for U.S. Environmental Protection Agency, EPA Contract 68-01-2968 and MRI Project NO. 4004-D.

The primary objective of this project is to generate some physical and economic damage functions by receptor for sulfur dioxide and suspended particulates for the U.S. urban areas so that marginal benefit and marginal cost principal can be applied to air pollution control decision making Based on existing literature and available data on U.S. metropolitan areas, 1970, average functions are developed for air pollution damages on human health, household soiling, materials and vegetation. Various types of air pollution damages are also estimated on a cross section basis for the metropolitan areas included. It should be noted that the geographic damage estimates are tentative not only because the assumptions employed in the study are uncertain but also because the methodology used is in its infant stage of development.

This project was completed under the general supervision of Mr. Bruce Macy, Assistant Director of Economics and Management Science Division and the project director was Dr. Ben-chieh Liu, Principal Economist. Research assistance and data process were provided, respectively, by Miss Mary Kies, and Mr. Jim Miller. Valuable assistance and comments from Dr. Chatten Cowherd, Messrs. Paul Gorman and Richard Salmon of MRI, Drs. Donald Gillette, Michael Hay and John Jaksch of EPA, Dr. Fred Able of Energy Research and Development Administration, Dr. William Watson of Resource for the Future and Dr. Eugene Seskin at Urban Institute are gratefully acknowledged. Editorial service was provided by Mrs. Doris Nagel, Mrs. Sharon Wolverton efficiently performed the report typing and computer work was carried out at MRI's Computation Center. Nevertheless, the views expressed in this study are those of the authors. They do not necessarily reflect the opinions of the sponsoring agency.

CONTENTS

CONTENTS (concluded)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (concluded)

EXECUTIVE SUMMARY

The research delineated in this report is primarily concerned with evaluating regional economic damages to human health, material, and vegetation and of property soiling resulting from air pollution. This research also attempts to develop a more plausible exponential physical dose-response function for premature mortality and morbidity. The comparable and consistent damage loss estimates for a variety of receptors developed in this research are expected to provide a data base useful for designing national and regional pollution control strategies.

The report comprises seven sections. A brief summary of the highlights from each section follows:

SECTION I - INTRODUCTION

The project involving the determination of regional air pollution damage losses for mortality, morbidity, household soiling, material and vegetation can be divided into four distinct phases: (1) problem discussion and refinement; (2) information and data gathering; (3) damage loss assessment; and (4) physical and/or economic damage function estimation. Static analyses are performed on the basis of 1970 data for many metropolitan areas and regions in the United States.

SECTION II - MORTALITY AND AIR POLLUTION

A two-step econometric model was developed for estimating a nonlinear mortality physical damage function and net damage costs of premature deaths resulting from excess air pollution for the 40 Standard Metropolitan Statistical Areas (SMSA'S) which had a sulfur dioxide level above 25 $\mu g/m^3$ between 1968 and 1970. The model circumvents partially the often recognized but largely ignored econometric problems such as heteroscedasticity and multicolinearity and, hence, gives credence to our damage loss estimate. In addition, an "average" economic damage function was developed which relates premature mortality damage losses in dollar terms to socioeconomic, demographic, climatological and air pollution variables--sulfur dioxide (SO_2) and total suspended particulate (TSP). The estimated mortality damage due to SO_2 for 1970 varies from less than $0.1 million in Charleston, West Virginia to $329 million in New York City, whereas mortality damage attributable to TSP ranges from $1.4 million in Lawrence, Massachusetts to $155 million in New York City. On a per capita basis, the highest damage due to SO_2 and TSP is $28.4 in New York City and $27.6 in Detroit, respectively.

SECTION III - MORBIDITY AND AIR POLLUTION

The damage costs and physical and economic damage functions were developed and estimated. Regional physical damage functions on adult morbidity were derived by resorting to the classical least-squares linear regression. A Monte Carlo technique was then used to derive an "average" nonlinear morbidity physical damage function for adults. Low estimates for total annual morbidity costs due to SO_2 range from less than $1,000 in Cincinnati to a maximum of $22 million in New York City. Low estimates on morbidity damages attributable to TSP, however, range from $152,000 in Bridgeport to more than $21 million in Chicago. On a per capita basis, the highest damage due to SO_2 and TSP is respectively $1.9 in Chicago and $3.7 in Cleveland.

SECTION IV - HOUSEHOLD SOILING AND AIR POLLUTION

A system of soiling physical damage functions relating various types of cleaning frequencies to air pollution was developed. Net and gross soiling damage costs for the 148 SMSA's were estimated. Finally, national "average" economic damage functions for household soiling were developed by relating soiling damages to air pollution, demographic, socioeconomic, and climatological variables. Total net soiling costs for 1970 attributable to air pollution over the 148 SMSA's were estimated to be more than $5 billion, while total gross soiling costs were about $17 billion over the 148 SMSA's.

SECTION V - MATERIAL AND AIR POLLUTION

This section develops economic damage estimates on the two most economically important materials, i.e., zinc and paint, for the 148 SMSA's in the United States. Economic damage functions relating material damages to air pollution and other socioeconomic and climatological variables were derived. The state of the art regarding the physical damage functions on materials was also reviewed and summarized. The soiling damage costs‘of zinc for 1970 range from less than $0.5 million in Dayton, Ohio to $1.7 billion in Chicago, whereas the deteriorating damage costs of zinc range from less than $0.5 million in Dayton to $57 million in Chicago. The soiling damage costs of paint for 1970 range from $19 million in Fayetteville, North Carolina, to $2.3 billion in New York City, while the deteriorating damage cost of paint is $0.7 million in Fayetteville and $79 million in New York City.

SECTION VI - VEGETATION AND AIR POLLUTION

Dose-response relationships for vegetation were reviewed. A set of national "average" economic damage functions for 10 economically important crops in the United States and regional economic damages to vegetation were derived. The economic damage functions will be useful to policymakers for forecasting possible gains as a result of pollution control programs.

SECTION VII - AGGREGATE DAMAGE LOSSES AND DAMAGE FUNCTIONS: AN OVERALL VIEW

Range estimates of economic damage losses over some broader categories of receptors were derived. A number of aggregate economic damage functions were also developed and summarized for the major pollutants. The aggregate as well as the disaggregate damage functions developed in the previous sections can be useful to national and regional policymakers in their quest for obtaining estimates of possible benefits brought about by various pollution abatement strategies.

The numerically large values of aggregate damage estimates provided by the experts in this area point to the need for effective control of pollutant emissions. The question naturally arises as to what constitutes economically optimal and politically feasible pollution control programs. As an effort in providing some useful clues for understanding the above question, this study attempts to estimate net as well as gross economic damages to human health, material, vegetation and household soiling attributable to and in the presence of air pollution for the urban areas in the United States. Economic and physical damage functions relating economic (physical) damages to air pollution, demographic, socioeconomic, and climatological variables were also developed for the United States urban areas. It is hoped that the generalized economic damage functions in this report are informative and useful for predicting possible marginal (average) benefits resulting from various air pollution abatement programs.

Any study of this nature is bound to have a few inherent limitations. The notable limitations are the uncertainty associated with estimating the physical damage function and in translating it into economic terms, and the uncertainty of selecting the most relevant measure of air pollution and the "correct" form of relating damages to pollution.

To provide the reader an overall view of the economic damages of various receptors due to air pollution, a summary of the damage estimates for the effect categories of human health, material deterioration, and household soiling is presented in Table S-1. The selected 40 SMSA's which had an SO_2 level equal to or greater than the threshold 25 $\mu g/m^3$ are listed in Column 1. The low and high damage estimates of human health are presented respectively in Column 2 (HNC1) and Column 3 (HNC2). Column 4 (MDC) presents the material deteriorating damage estimates of both zinc and paint; Column 5 (TNSCO) contains the aggregate net household soiling damages. On the basis of the low and high damage estimates of human health presented,respectively,in Columns 2 and 3, two sets of low and high aggregate damage estimates for the three effect categories, i.e., human health, material deterioration and household soiling, were derived and summarized in Column 6 (TNC1) and Column 7 (TNC2), respectively. The further details on the estimations of the economic damages of each of the effect categories are contained in the subsequent Sections II, III, IV, V and VI. The formulas used for deriving the estimates presented in Table S-1 will be discussed in Section VII.

TABLE S-1 . ECONOMIC DAMAGES DUE TO AIR POLLUTION, BY RECEPTORS FOR SELECTED SMSA's
(in $ million, 1970)

(1) SMSA's	(2) HNC1	(3) HNC2	(4) MDC	(5) TNSCO	(6) TNC1	(7) TNC2
1. Akron, OH	10	18	7	16	33	41
2. Allentown, PA	8	15	3	16	27	34
3. Baltimore, MD	48	80	17	137	202	234
4. Boston, MA	49	52	26	117	192	195
5. Bridgeport, CT	3	5	6	3	12	14
6. Canton, OH	6	6	11	14	31	25
7. Charleston, WV	3	3	4	10	17	17
8. Chicago, IL	191	360	105	516	812	981
9. Cincinnati, OH	22	22	12	57	91	91
10. Cleveland, OH	55	93	49	216	320	358
11. Dayton, OH	18	18	9	39	66	66
12. Detroit, MI	129	161	55	294	478	510
13. Evansville, IN	2	2	2	5	9	9
14. Gary, IN	12	24	8	24	44	56
15. Hartford, CT	12	19	5	16	33	40
16. Jersey City, NJ	11	17	8	17	36	4.2
17. Johnstown, PA	4	4	1	10	15	15
18. Lawrence, MA	3	5	7	3	13	15
19. Los Angeles, CA	123	147	76	388	587	611
20. Minneapolis, MN	21	32	12	37	70	81
21. New Haven, CT	3	5	4	4	11	13
22. New York, NY	352	527	111	418	881	1,056
23. Newark, NJ	39	48	14	112	165	174
24. Norfolk, VA	13	13	3	29	45	45
25. Paterson, NJ	7	7	13	9	29	29
26. Peoria, IL	4	4	9	8	21	21
27. Philadelphia, PA	107	158	33	104	244	295
28. Pittsburgh, PA	45	79	30	147	222	256
29. Portland, OR	13	13	8	30	51	51
30. Providence, RI	16	25	9	20	45	54
31. Reading, PA	5	5	4	15	24	24
32. Rochester, NY	13	15	7	27	47	49
33. St. Louis, MO	44	61	24	119	187	204
34. Scranton, PA	5	5	2	23	30	30
35. Springfield, MA	12	15	3	7	22	25
36. Trenton, NJ	3	3	2	5	10	10
37. Washington, DC	48	88	21	86	155	195
38. Worcester, MA	3	4	8	6	17	18
39. York, PA	4	4	2	9	15	15
40. Youngstown, OH	9	10	8	23	40	41
Total	1,475	2,166	736	3,134	5,349	6,040

Table S-1 reveals that the largest aggregate air pollution damage, in the order of $1 billion, occurred in New York and Chicago SMSA's in 1970. The smallest air pollution damage occurred in Johnstown and York, both SMSA's in Pennsylvania. The damages were in the magnitude of $15 million in 1970. Human health damage estimates (mortality and morbidity) ranged from $1.5 to $2.2 billion for the 40 SMSA's. Total material deterioration damages were about 0.7 billion, and total household soiling costs were about 3 billion for the 40 SMSA's under study.

The implication of our study for pollution abatement strategies is obvious. Any effort to reduce the current pollution level appears to have a varyingly significant impact on the economic damages resulting from the harmful effects of air pollution. Admittedly, the implication of this study must be qualified by several theoretical and empirical factors. The major difficulties often encountered in estimating air pollution damages involve the lack of knowledge regarding the shapes of functions describing the relationship between air pollution and various receptors, and the lack of a satisfactory theoretical model specifying the way air pollution affects various receptors. The impossibility of accounting for all major factors which might affect various receptors, the lack of reliable formulations used for translating physical damages into monetary terms, and the presence of numerous econometric problems have also caused concern to investigators.

Despite the existence of these difficulties, this study represents a step forward in our knowledge of pollution damages. It seems to be the first attempt to construct essential frameworks of the physical and economic damage functions which can be used for calculating comparable regional damage estimates for the several important receptors--human health, material, and household soiling--however tentative the damage estimates may appear to be. More importantly, aggregate economic damage functions instrumental for transforming the multifarious aspects of the pollution problem into a single, homogeneous monetary unit are tentatively derived and illustrated. It is hoped that these results will be of some use to guide policymakers as they make decisions on the implementation of programs to achieve "optimal" pollution levels for this country. Given the experimental nature of the methodological and statistical procedures and the degree of uncertainty associated with the study results, a great deal of caution should be exercised in using the products of this research.

Finally, it should be noted that although the availability of information on average or marginal damages is instrumental in determining the optimal national or regional pollution control strategies, the current problem is far more complex than the question of balancing the benefits to polluters with damages inflicted on the receptors. The issues are pressing and not yet well specified. The basic difficulty in applying the recent research findings to accurately estimate the air pollution damage cost stems from our ignorance about the receptors at risk to air pollution. So far, few attempts have been made to identify who suffers, to what extent, from which sources, and in what regions. At this moment, updating and expansion of the available crude estimates, which are

generally restricted to certain regions, are urgently needed. To identify the population at risk to air pollution, and to measure the damage specifically for polluted regions are apparently the most logical steps in the area of future research.

MAJOR NOTATIONS AND VARIABLES

A	Air pollutants
C	Conventional mortality rate
CC	Computed conventional mortality rate
CMR	Computed mortality rate
CRMR	Computed residual mortality rate
CROPL	Economic loss of a particular type of crop
CROPV	The output value of a particular type of crop
DTS	Number of days with thunderstorms
DDCZ	Deteriorating damage cost of zinc
DDCP	Deteriorating damage cost of paint
EXP or e	Exponential
E_{ij}	Elasticity of variable i with respect to variable j
GSCO	Gross household soiling damage cost
MR	Mortality rate
MB	Morbidity rate
MBC	Morbidity cost
MDC	Material deteriorating cost
NSCO	Net household soiling damage cost
OXID	Oxidant relative severity index
PAGE	Percentage of population 65 or older
PYAP	Percentage of population with income above poverty level
PCOL	Percent of persons 25 or older who have completed 4 years of college
PWOP	Percentage of white to total population
POP	Population in the area
PDS	Population density
RHM	Relative humidity
RMR	Residual mortality rate
SDCP	Soiling damage cost of paint
SDCZ	Soiling damage cost of zinc
SMSA	Standard Metropolitan Statistical Areas
SO_2	Sulfur dioxide
SUN	Possible annual sunshine days (percent)
TSP	Total suspended particulates
$TMBCSO_2$	Total morbidity cost due to SO_2
TMBCTSP	Total morbidity cost due to TSP
TEMB	Number of days in a year with temperature below 33° F
TEMA	Number of days in a year with temperature above 89° F
U	The disturbance term

SECTION I

INTRODUCTION

Deterioration in urban air quality constitutes one of the major problems confronting most American cities today. Air pollution has inflicted a multitude of damaging effects on human health, material, vegetation, animals, household and industrial property. In the past decades, numerous research studies have been conducted to ascertain and to quantify, if possible, the physical and monetary damage losses to the various receptors due to the presence of excessive concentration levels of the major air pollutants, e.g., sulfur dioxide, total suspended particulate matter, oxidants, carbon monoxide and other substances in the urban areas. 1/

The numerical values of aggregate damage estimates provided by the experts in this area point to the need for effective control of pollutant emissions. 2/ The question naturally arises as to what constitutes economically optimal and politically feasible pollution control programs. The issues surrounding the control strategies have been hotly argued and debated. Implementation of some of the proposed control programs has been postponed for either political or economic reasons.

According to estimates prepared by the Bureau of Economic Analysis, (Cremeans and Segel, 1975) a total of $18.7 billion was spent on domestic air, water, solid waste and other pollution abatement and control programs in 1972. The expenditure was about 1.6 percent of our GNP in that year. Of the total figure, 35 percent was accounted for by control and abatement activities of air pollution. This expenditure figure is indicative of the magnitude of sacrifice the society has made for the purpose of reducing the problem of air degradation.

Is this amount of expenditure sufficient, from an economic point of view, to attain optimal air quality for this country? The inquiry into this question is handicapped without information about the corresponding benefit accruable to the society because of the existing pollution control programs.

From economic theory, it is well-known that the control policy is optimal if the marginal benefit due to pollution abatement is matched by the marginal expenditure incurred to implement the control. In the absence of national marginal or "average" damage functions of air pollution by receptors and the marginal (average) damage estimate for each effect category, it is difficult, if not totally impossible, to estimate the marginal (average) benefits stemming from the abatement of the last unit of air pollution in each metropolitan area and the nation as a whole.

1/ For a background information on the cost of air pollution damage, see Barrett and Waddell (1973) and Waddell (1974).

2/ For details on the damage estimates and the references, see the beginning paragraphs of each of the later sections.

For purposes of analysis the effects of air pollution are customarily classified into six broad categories: (1) detrimental effects on human health; (2) damage to vegetation; (3) deterioration of materials; (4) soiling of households and business establishments; (5) injury to animals; and (6) reduction of visibility and other atmospheric effects of an aesthetic nature. Since each of these categories has direct and indirect economic value, whenever one's ability and opportunity to enjoy these benefits is reduced, economic damages result. It is unfortunate that the magnitude and measurement of the resulting economic damages is probably the most controversial point in the entire pollution control issue.

The basic objectives of this study were to estimate net as well as gross economic damages to human health, material, vegetation and household soiling attributable to and in the presence of air pollution for the urban areas in the United States. Economic and physical damage functions relating economic (physical) damages to air pollution, demographic, socioeconomic, and climato-Logical variables were also developed for the United States urban areas. It is hoped that the generalized economic damage functions in this report are informative and useful for predicting possible marginal (average) benefits resulting from various air pollution abatement programs.

Any study of this nature is bound to have a few inherent Limitations. The notable Limitations are the uncertainty associated with estimating the physical damage function and in translating it into economic terms, and the uncertainty of selecting the most relevant measure of air pollution and the "correct" form of relating damages to pollution.

Since this study is primarily concerned with the estimation of the economic damages of air pollution in the United States urban areas, a brief, but critical, review of the economic effects of air pollution is in order. Accumulating evidence suggests that air pollution results in a number of noticeable and substantial economic effects. Some of the more obvious of these effects include the soiling of materials by dustfall, necessitating additional expenditures for cleaning; corrosion of materials, requiring replacement and application of protective coatings; atmospheric haze, reducing visibility and causing aesthetic blight; and various respiratory and other health problems associated with the inhalation of noxious fumes and particles from the atmosphere.

DAMAGING EFFECTS OF AIR POLLUTION

Effects on Human Health

According to the 1974 National Academy of Sciences reports, two major pollutants, i.e., total suspended particulates and sulfur dioxide, are responsible for the bulk of the deleterious effects on human health. Other pollutants, Like carbon monoxide, nitrogen oxides and photochemical oxidants and ozone also exert damaging effects. Exposure to high concentrations of carbon monoxide damages the function of oxygen-dependent tissues and exposure to Low concentrations of carbon monoxide results in adverse effects both in normal people

and in patients with heart disease. Acute exposure to low concentrations of nitrogen oxide can cause visual and olfactory abnormalities. Tentative evidences indicate that long term exposure to photochemical oxidants can result in eye irritation and a decrease in lung tissue elasticity. At any one time, several pollutants are present in the air. Thus, it is difficult to determine the interaction of pollutants and the specific health damages caused by a single pollutant. Nevertheless, it has been established that air pollutants can accelerate disease and death, even at levels generally considered safe and used as the basis for setting standards. Each of the major air pollutants presents a health hazard in itself, and harmful effects may be greatly amplified when they occur in combination. Unfortunately, the degree of the synergistic effects among the pollutants is not clearly known.

Particulate emissions include a wide variety of pollutants, each of which may exert different effects on human health. Carbon or soot particles are the most commonly emitted kinds of particles. However, even when these are the only particulates emitted--such as in coal combustion--there are indications that the toxic effects of sulfur dioxide (also released in the coal combustion process) are enhanced by their association with the particulate matter. Other contaminants can absorb on the surface of the particles, thereby coming into contact with the inner surfaces of the lungs and mucous membranes in far greater concentrations than would otherwise be possible. The site and extent of particle deposition in the respiratory tract, and therefore its ultimate effect on human health, depend upon both physical and physiological factors.

Sulfur dioxide is highly soluble in body fluids. The principal effect of this gas is irritation of the tissues lining the upper respiratory tract. This results in bronchial constriction which, in turn, produces an increase in respiratory flow resistance. Persons suffering from respiratory or cardiac diseases may be unable to withstand the increased body burden caused by this respiratory flow resistance. Adverse effects on ciliary activity and mucous flow may also result from prolonged exposure to sulfur dioxide. Sulfur dioxide and other oxides of sulfur can, under certain conditions, combine with water, soot particles and other aerosols in the atmosphere to produce toxic acid aerosols and other contaminants far more dangerous than any of the individual ingredients.

The damage to human health depends not only on the concentration level of pollutants, but also on the physical conditions of each individual. There is virtually no single threshold of pollutant concentration below which health damages will not occur. At every level of a pollutant concentration, someone could be adversely affected. In view of a wide range of physical conditions of human beings the threshold of pollutants may be viewed as a symmetrical distribution. The "mean" level of this distribution is used in the present study to calculate the economic damages resulting from air pollution.

While the exact role of air pollution in causing illnesses is not known, there is substantial evidence that air pollution does aggravate existing illnesses, even to the point of causing premature death. 1/ While high rates of asthma attacks have been reported on days with high air pollution surface concentrations, greatly increased mortality rates from influenza, bronchitis, and pneumonia have been noted during periods of high sulfur dioxide and particulate levels.

In estimating the damage cost of morbidity, it should be noted that the direct, out-of-pocket cost of treating an illness or disease is probably far less than the value of avoiding the necessity for treatment. When someone suffers from a pollution-related chronic illness, the cost of pollution to him is almost infinite; the value of avoiding the pollution-induced discomfort is, for this person, immeasurably high. For this reason, it should be cautioned that the health damage of air pollution estimated in this study, like other major studies on the basis of the health costs of treating pollution-related illnesses, may understate the true economic costs or benefits of reducing the responsible pollutants. Sections II and III present a thorough analysis of the air pollution effects on human health, i.e., mortality and morbidity, respectively.

Effects on Materials

Many external factors influence the reaction rate between pollutants and materials, with moisture the most important in accelerating corrosion. 2/ Inorganic gases are likely to cause tarnishing and corrosion of metals; can attack various building materials such as stone, marble, slate, and mortar; and may deteriorate a variety of natural and synthetic fibers.

The most noticeable effect of particulate pollutants is soiling of the surfaces on which they are deposited. They may also act as catalysts increasing the corrosive reactions between metals and acid gases. Additional damages to surfaces and textiles are incurred by the wear and tear imposed by the extra cleanings made necessary because of particulate soiling.

The true economic damage to materials caused by air pollution is difficult to ascertain. First, it is difficult to scientifically distinguish between natural deterioration and deterioration caused by air pollution. Secondly, it is uncertain regarding indirect costs of early replacement of materials worn out by pollutant soiling.

The most comprehensive analysis of the economic effects of air pollution on materials was conducted by Midwest Research Institute (Salmon 1969). In that study, the damages caused by interactions between specific pollutants and specific materials were identified. The estimated economic loss resulting from the various pollutant-material interactions totaled $3.8 billion in 1968.

1/ For details, see Section III.

2/ See Section V for further details.

Detailed analyses of soiling costs and material damages by region are contained in Sections IV and V, respectively.

Effects on Vegetation

The air pollutants having the greatest deleterious effects on vegetation are sulfur dioxide, hydrogen fluoride, photochemical smog and oxidants, ethylene, and herbicides and fungicides. Sulfur dioxide enters a leaf through the stoma, causing injury to the blade of the leaf in the form of intervenal collapsed areas. Fluorides may be absorbed from the surface of the leaf and can be toxic to some plants at extremely low concentrations. Other pollutants may damage only certain susceptible types of plants.

Based upon a Stanford Research Institute study (Benedict et al., 1973), the national damage cost of air pollution on vegetation is estimated to be $150 million. This damage cost amounts to approximately more than one-half of 1 percent of the total value of crops produced in the United States in 1970. This figure represents mainly the visible damage to agricultural crops, and does not fully recognize the real economic losses due to growth suppression, delayed maturity, reduced yields, and increased costs of crop production.

Section VI describes and estimates the air pollution damages on vegetation on a regional basis for different types of crops.

Other Damaging Effects

Aesthetic damage caused by air pollution is the most difficult to quantify; yet, intuitively at least, it represents one of the important categories of economic loss suffered as a result of degraded air quality. The aesthetic category encompasses a number of different effects ranging from impaired atmospheric visibility to decreased property values resulting from the presence of air pollutants.

Reduction in visibility creates a heavy economic burden on most communities. Some of the community operations which are most affected by pollution-related visibility problems include airports, highways, and homes. When an airport's traffic pattern is slowed due to delays in take-offs and landings caused by reduced atmospheric visibility, operational costs are increased, additional safety hazards are imposed, passengers are inconvenienced, and businesses may be indirectly affected. Similar effects occur on highways where reduced visibility slows traffic, causes congestion, and increases the likelihood of injurious and expensive accidents. Additional lighting--both on the streets and in the home--is required when the sunlight is unable to penetrate a polluted atmosphere.

Aesthetic damage can sometimes be partially measured indirectly, such as by comparing property values in comparable residential neighborhoods having different air pollution levels. In other cases, aesthetic damages may be reflected in the costs that are incurred in connection with their prevention or avoidance, such as special precautions taken to protect certain values from aesthetic damage

by air pollutants. Still other cases may require a willingness-to-pay approach, estimating the amount that individuals would be willing to pay in order to prevent or avoid the threatened aesthetic damages due to the soiling effect or, conversely, how much additional they would have to be paid to willingly endure the aesthetic blight.

Due to data deficiency, air pollution effects on aesthetics are not studied.

Considerable damage to animals caused by air pollution has been noted. However, most cases are localized, the sources are easily identified, and the economic consequences are relatively minor. Poisoning of livestock from heavy metals--arsenic, lead, and molybdenum--has been reported on numerous occasions, and cattle and sheep are particularly susceptible to fluorine poisoning. In addition to the direct economic losses resulting from animal mortality, significant losses may come from such effects as decreased reproductivity, decreased growth, and lower output of milk, eggs and wool.

No studies of the economic impact of air pollution on animals have been reported in the literature. The value of all livestock and livestock products produced during 1968 was $21 billion; out of this total, perhaps $10 million could reasonably be attributed to losses of all kinds from air pollution damage (Park, 1974).

Due to data deficiency, air pollution effects on animals are not studied.

In summary, this air pollution damage function project involves four distinct phases common to each of the five studies regarding the damaging effects of air pollution on mortality, morbidity, household soiling, materials and vegetation. The four phases are as follows: (1) problem refinement; (2) data and information gathering; (3) estimation of regional economic damages; and (4) development of physical and economic damage functions.

Data on air pollution, demographic, socioeconomic and climatological variables were collected by a thorough literature search. Most of the data utilized for developing the economic damage functions were attained from a comprehensive quality of life study for the United States Standard Metropolitan Statistical Areas (SMSA'S) recently completed by Liu (1975).

Following the selection of the needed data, regression models were developed to determine the physical and economic damage functions for all these major air pollutants as well as the various categories of the damaging effects. Econometric problems and technical difficulties are discussed and dealt with as much as possible during the process of damage estimation. Furthermore, several methodologies were developed to evaluate the economic damages by air pollutants and effect categories for the SMSA's in the United States.

SECTION II

MORTALITY AND AIR POLLUTION

INTRODUCTION: THE PROBLEMS AND THE OBJECTIVES

Two issues in the area of pollution control have attracted much attention recently. The first problem is to evaluate from the control efficiency viewpoint the appropriate governmental policies for handling pollution abatement. While Kneese (1972), Peltzman and Tideman (1972), and Lerner (1974) opted for regional regulation of pollution, Stein (1974) stressed the role of the federal government for controlling various pollution. Another problem involves the determination of the optimal level of pollution abatement at which the marginal benefits are matched by the marginal expenditures incurred to implement the control. Estimation of the marginal benefits of pollution control at regional levels, however, requires information on damage functions and damage estimates for the various regions in the United States.

Empirical works in this area for the United States have been advanced substantially by Ridker (1967), Lave and Seskin (1970, 1973), Jaksch and Stoevener (1974), R. K. and M. Koshal (1974), among others. They confirmed the existence of a close association between health and air pollution.[1,2] The conventional ordinary least squares, linear or log-linear regression method has been employed to quantify the damaging effect of air pollution on mortality. However, often the major difficulties encountered in estimating such a physical damage function involve the problems of errors in variables, nonnormality, heteroscedasticity, and multicolinearity among air pollution and other explanatory socioeconomic, demographic and climatological variables, and the lack of knowledge regarding the shape of the function which depicts the relationship between air pollution and health.

Two major approaches have been suggested in the literature for estimating a pollution damage function.[3] The first approach involves the assumption that consumers are explicitly or implicitly knowledgeable about the potential benefit of pollution control. Therefore, the estimation problem boils down to one of inducing the consumers to reveal their "true" preferences about abatement. Often, unsatisfactory results were obtained in this approach because consumers generally are not willing to pay their share of cost for abatement, and, hence, tend to provide misleading information about the benefit accruable to them if air quality is improved.

1/ These and earlier studies are subject to a number of limitations. For a detailed discussion see, for example, J. R. Goldsmith (1969).

2/ Contrary results have also been obtained, for example, by Toyama (1964) and Petrilli, Agnese and Kanitz (1966). There were no controls for socioeconomic factors in their studies. Hence, their results are subject to bias.

3/ See, for example, Lave (1972), p. 213, for a detailed exposition of the two approaches.

The second method, on the other hand, involves explicit quantification of the physical damage function and translation of the physical damage into monetary terms. The advantage of this explicit approach is that it requires no interpersonal utility comparison and cooperation from the consumers. However, the considerable extent of uncertainty present in estimating the physical damage function and in converting it into an economic damage function casts doubt on the reliability of the damage estimates.

The damaging effects on human health by air pollution in New York City have been well documented by Glasser et al. (1967), Greenburg et al. (1962a, 1962b), Hodgson (1970), and McCarroll and Bradley (1966). Recently, Schimmel and Greenburg (1972) performed a time-series study based on mortality rate and pollution for New York City covering the period between January 1, 1963, to December 31, 1968. The excess mortality rate was regressed on two daily mean pollution variates, SO_2 and smoke shade, for both the same and previous day. They showed that approximately 80 percent of the excess deaths were attributed to the effects of smoke shade while only 20 percent were attributed to SO_2. Again, methodological problems encountered in national estimates are also prevailing in these regional estimates.

Damage costs of premature death and morbidity due to air pollution have been estimated for the whole nation previously. Ridker (1965) estimated the tota1 costs of a specific disease and then attributed 20 percent of these *costs* to air pollution. Lave and Seskin (1970, 1973) related the amount of mortality for specific diseases to air pollution and some socioeconomic variables. They found that the association between air pollution and mortality is significant and of substantial magnitude; e.g., a 10 percent decrease in the biweekly minimum level of sulfates is associated with a 0.3 percent decrease in mortality rate per 10,000 live births. Koshal (1974) established a quantitative relationship between respiratory mortality rates and the level of air pollution and *two* climatic variables. They estimated a reduction of about 50 percent in the air pollution would imply a social saving on the order of about $1.9 to $2.2 billion per year in terms of respiratory disease alone.

It is noteworthy that although most of these air pollution damage studies draw tentative conclusions, they suffer from a certain inherent difficulty in evaluating their results. Difficulty arises because either the statistical procedures employed are less than perfect or the results obtained are inadequate for generating statistical inferences needed. With the exception, perhaps, of those of Lave and Seskin and the Koshals, most of the studies are time-series analyses with sample observations restricted to a specific area or a small number of areas. As a result, little information can be deduced from the existing studies for designing a general air pollution control policy which requires the knowledge of an "average" damage function expressed in both physical and economic terms and applicable to all metropolitan areas in the nation. From economic theory, it is well known that the control policy is optimal if the marginal benefits resulting from pollution abatement are matched by the marginal expenditures incurred to implement the control. In the absence of national average damage functions by pollutants and the marginal damages for each pollutant, it is

difficult to estimate the marginal benefits stemming from the abatement of the last unit of air pollution in each metropolitan area and the nation as a whole.

Lave and Seskin (1973 p. 290) in a well-known article, noted possible specification errors in the empirical estimates of mortality and air pollution relation. They cautioned the reader that "[their] analysis is beset by a vast number of problems including little a priori knowledge of the true specification of the relations, omitted variables, and errors of measurement in the variables." This observation has been recently verified by Smith (1975) by reestimating a set of mortality air pollution relationships with a new data base. The Ramsey tests were utilized with the data on mortality rates and suspended particulates for 50 SMSA's. 1/ The research findings indicate that the errors in specification and heteroscedasticity could constitute technical problems in estimation.

While the multicolinearity problem between air pollution and other independent variables in the damage function makes it difficult, if not totally impossible, to disentangle their influences so as to obtain reasonably precise estimates of their separate independent effects on mortality, the presence of the heteroscedasticity problem violating one of the assumptions used in the normal linear regression model (i.e., the disturbances were independently distributed with constant variances) renders the ordinary least-squares estimates inefficient .2/ Despite the fact that these specification errors were observed by have and Seskin, the econometric problems remain largely unexplored in the prior studies.

This section attempts to achieve two basic objectives. First, a stepwise econometric model will be developed to estimate a dose-response relation for mortality and pollution. Second, "average" economic and physical damage functions for the United States Metropolitan Areas will be constructed by relating mortality economic damages and mortality rates, respectively, to air pollution, demographic, socioeconomic, and climatological variables. Although the methodological and statistical procedures used are experimental, and the statistical results are subject to a great deal of uncertainty, it is hoped that the generalized economic damage function and the cost estimates presented in this section are informative. They can be useful for predicting possible benefits in the urban areas resulting from various air pollution abatement programs and to shed light on the major issues in current and future air pollution research.

Technically, the heteroscedasticity and multicolinearity problems that emerged in estimating the relationships between mortality and pollution damage are partially circumvented via the two-step econometric model. In the first step, observed mortality rates are regressed on several relevant socioeconomic, demographic and climatological variables. In the second step, the residual mortality rates obtained by subtracting the computed mortality rates from the observed

---

1/ The logic underlying the Ramsey tests was succinctly outlined in Smith (1975), pp. 341-342. For a detailed discussion on the tests, see Ramsey (1969, 1970, 1974).

2/ See, for example, Johnston (1963), pp. 207-211, and Goldberger (1964), pp. 192-194.

mortality rates are again regressed nonlinearly on air pollution variable only to derive the physical damage function. The estimated dose-response relation is then utilized to derive net damage costs of premature deaths due to excessive air pollution for 40 Standard Metropolitan Statistical Areas (SMSA'S) in the United States.

In order to estimate physical and economic damages associated with air pollution the effects of air pollution on human health are classified as: (1) mortality effect; (2) morbidity effect; and (3) combination effect.1/ The mortality effect refers to the increase in the excess deaths resulting from increased contamination in the air, or the decrease in the survival probability of all ages. The premature mortality affects an individual's probability of being accessible to future earning opportunities and nonmarket leisure activities, but it will not alter the nature of the existing economic and leisure activities. The morbidity effect, which will be dealt with in the next section, however, directly changes the nature of economic and leisure activities. The combination effect can be viewed as earlier mortality because of increased severity in morbidity. In this case, both the survival probability and the nature of activities of the victim are affected. Schrimper (1975) has shown that this interaction effect can be conveniently ignored because of its small magnitude.

It may be worth pointing out, at the outset, that the physical dose-response relation derived in the present study is probably the first of its kind ever estimated in the pollution effect studies. Four distinguishing features in the dose-response relation differentiate our study from the earlier studies, say, Lave and Seskin (1970, 1972, 1973) and Koshals (1974). First, the technique of residualizing the dependent variable (mortality rates) is used in estimating the dose-response function. Second, the pollution variable is the sole explanatory variable included in the dose-response relation. Third, the dose-response function is specified as a nonlinear relation in accord with both a priori judgment and empirical results regarding human responses to increased pollution doses. Fourth, a threshold level is adopted before damages are estimated.

This section, which represents a preliminary effort to estimate empirically a nonlinear dose-response function and a linear "average" pollution damage function, is presented in the following subsections: Estimation of Physical Damage Functions, A Linear General Physical Damage Function, Values of Air Pollution Damages and Economic Damage Functions, Premature Mortality Damages and Suspended Particulates, and Implications and Concluding Remarks.

1/ For a detailed discussion on the effect of air pollution on human health, see Schrimper (1975).

ESTIMATION OF PHYSICAL DAMAGE FUNCTIONS

For analytical purposes, two types of physical damage functions can be posited: (1) dose-response or stimulus-effect relations; (2) general physical damage functions which relate mortality not only to pollution, but also to other relevant socioeconomic, demographic and climatological variables.

A long-term, generalized physical damage function has been specified, for example, by Lave and Seskin (1970), Goldsmith (1965), and Ferris and Whittenberger (1966) as

$$MR = F(D, S, E, W, A; e) \qquad \text{(II-1)}$$

where MR is mortality rate per 10,000 population and is related to D (demographic factors such as age, sex, racial and genetic), S (the social factor such as individual's exercise and other habits, nutrition, occupational structure; population density, and housing conditions), E (the economic variables such as income and the level and quality of medical care received), W (weather), A (the air pollutants), and e (the disturbance term). To measure the damage effect of air pollution and other independent variables on mortality, the conventional least-squares linear regression has been the common technique.

If the objective is to estimate a short-term, day-to-day, physical damage function for a given study region, demographic, social and economic factors can then be reasonably assumed to be stable. Hence, the short-term physical damage function can be specified as

$$MR = f(W, A; e) \qquad \text{(II-1)}$$

Lave and Seskin (1972) utilized (II-1) to derive acute, day-to-day mortality-pollution relationships. Lags up to 5 days in the pollution variables were incorporated into the regression equations. Results obtained in their study were generally negative because no discernible, consistent pattern of statistically significant coefficients was observed. One of the several questions examined by Lave and Seskin which has bearing on policymaking is whether deaths are merely shifted by a few days by pollution episodes. Their finding indicates that the reallocation of mortality extends over a period longer than 10 days.

Nonlinear Dose-Response Function

A dose-response relation which includes the pollution variables as the sole explanatory variable can be written as

$$MR = g(A; e) \qquad \text{(II-2)}$$

The dose-response functions may be estimated via controlled laboratory experiments on human bodies. However, ethical and legal considerations prohibit the use of human bodies for experimental purposes. Because of this, epidemiological studies so far have not been fruitful in identifying the true cause-effect relationship underlying mortality and air pollution.

The clinical, laboratory, and experimental studies at relatively high concentration levels of sulfur dioxide or other pollutants suggest that tentative dose-response relationships are available. However, information on such relationships is largely lacking at concentration levels in the range of current standards. The best available tentative dose-response function ever produced by epidemiological studies is presented in Buechley (1971). The function can be approximated by a nonlinear, flat "S" shape curve, as shown in Figure II-1 The relation indicates that while the air pollutant SO_2 is a contributing factor of premature mortality, the damaging effect is nonproportional. As the SO_2 concentration level increases, the excess mortality rate increases initially at an increasing rate and continues to increase, but at a decreasing rate after a certain inflection level.

It is generally the opinion of medical experts that the true a priori dose-response is nonlinear. This hypothesis is also recently used by Leung (1974) who studied the exposure-effect relation between human health and mobile source air pollution best described by a nonlinear curve as shown in Figure II-1.

On the basis of a priori judgment of medical experts and the two empirical results produced respectively by Buechley and Leung concerning the human health damage responses to pollutant doses, the exposure-effect function relating mortality rate (MR) to sulfur dioxide SO_2 in the present study is hypothesized as an exponential function alternativley specified as follows:

$$MR = C + e^{(a-b/SO_2)} \qquad \text{(II-3)}$$

$$MR - C = e^{(a-b/SO_2)} \qquad \text{(II-3')}$$

$$\ln (MR - C) = a - b/SO_2 \qquad \text{(II-4)}$$

where C is the "conventional" mortality rate in that the mortality rate is independent of the pollutants and a and b are parameters determining the shape of the nonlinear function. Since both coefficients a and b can take any real values, the semilog, reciprocal equation (II-3) covers a wide range of nonlinear functions with positive first derivatives.

The conventional mortality rate (C) is determined by a host of socioeconomic, demographic, climatological and personal factors. It is recognized that many of the factors known to affect mortality are not amenable to quantification. Factors such as nutrition, exercise, personal habits, etc., are difficult to measure conceptually, while data on smoking habits have not been collected and on medical care are poorly measured. The exclusion of these relevant factors from the regression equation because of insufficient data may result in specification errors and, hence, biased estimates. Thus, careful interpretation of the regression results is warranted.

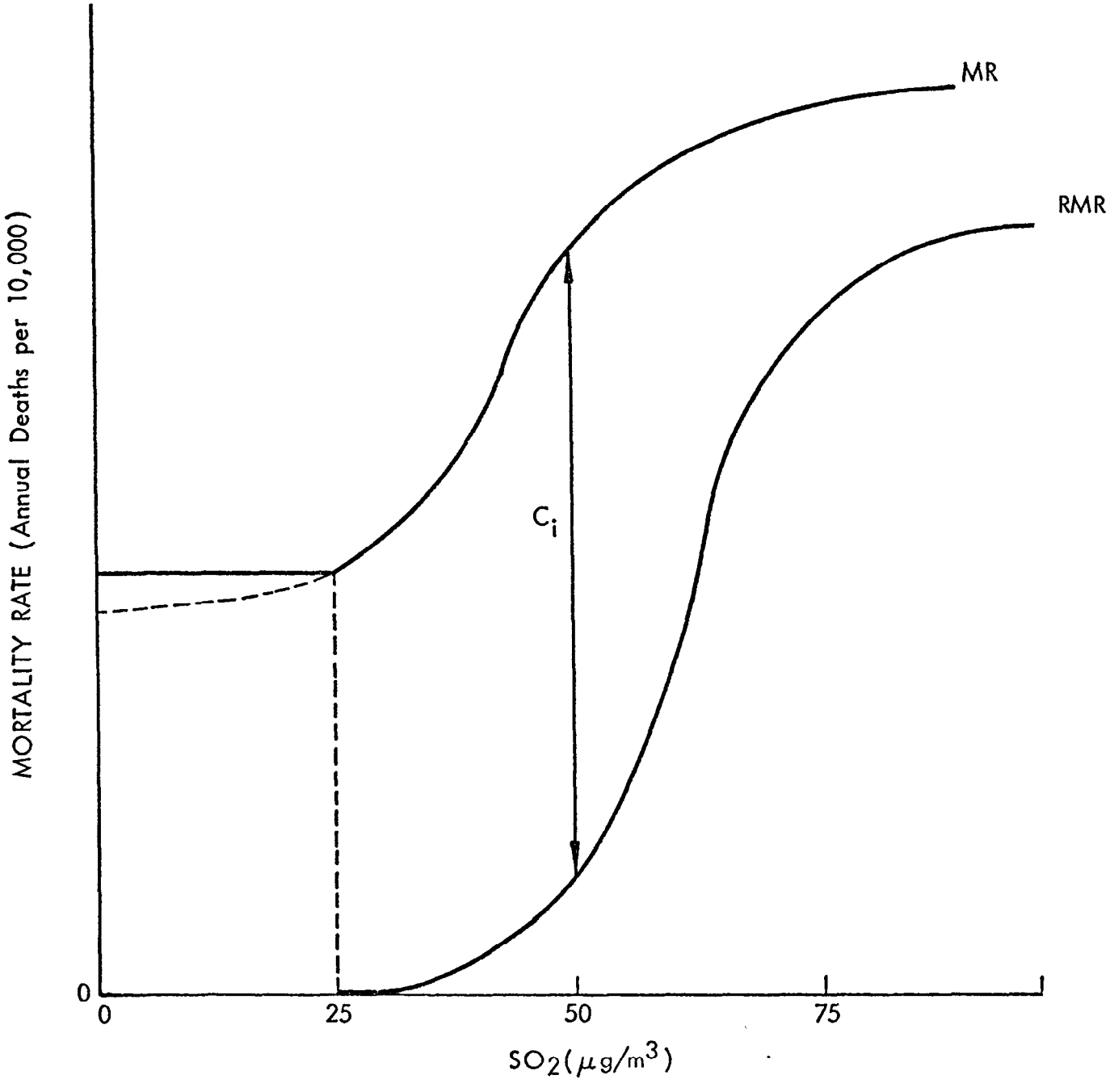

Figure II-1. Hypothetical relationship between mortality rate and SO_2 concentration.

A number of regressions with data on more than 25 potential explanatory variables collected from the 40 SMSA's which had a sulfur dioxide level equal to or greater than 25 $\mu g/m^3$ between 1968 and 1970 were run during the course of this study. The selection of 25 $\mu g/m^3$ as the threshold is based on two considerations: First, this concentration level is the average level prevailing in rural areas. Second, this level is considered to be the "mean" of the tolerable threshold distribution of all individuals in the SMSA. Available evidence suggests that no matter how small the concentration is, adverse health effects may still occur (National Academy of Science, 1974). Thus, threshold in a strict sense should be zero concentration. However, the threshold levels with respect to all individuals in a given region could be reasonably viewed as a symmetrical distribution with a mean level possibly at 25 $\mu g/m^3$. The use of this mean level of thresholds will probably result in more accurate damage estimates than using zero or other threshold levels.

It should be noted that damage estimates cited previously in other pollution studies were derived on the basis of a zero threshold. The use of a zero threshold level tends to overstate the damages.

It is noteworthy that many of the determinants of mortality are difficult to quantify, and data are not readily available for some of the variables.1/ The data for the above mentioned variables for 40 SMSA's which had a sulfur dioxide level equal to or greater than 25 $\mu g/m^3$ between 1968 and 1970 were taken from a comprehensive quality of life study about U.S. SMSA's recently completed by Liu (1975). Variables of no statistical significance or with wrong signs were accordingly eliminated, and the best regression results with the remaining seven independent variables were obtained as follows:

$$\begin{array}{l} CC = 229.6 + 741.8\ PAGE - 119.7\ PYAP - 0.12\ PCOL - 76.58\ PWPO \\ \qquad\quad (50.5)^* \quad (96.4)^* \qquad (62.8)^{**} \quad (0.04)^* \quad (21.6)^* \\ \qquad\qquad - 0.54\ SUN + 0.23\ RHM + 0.04\ DTS \\ \qquad\qquad\quad (0.24)^* \quad (0.22) \quad (0.07) \end{array} \qquad \text{(II-5)}$$

$$R = 0.82$$

1/ In the studies of Lave and Seskin (1970, 1973) and the Koshals (1974), a portion of the explanatory variables was used to estimate a general physical damage. Lave and Seskin regressed mortality rates against air pollutions--particulates and sulfates--population density, proportions of nonwhite, proportions of people over age 64, and proportion of poor families. The Koshals selected the population density, the percentage of relative humidity and the pollutants-suspended particulate matter and benzene soluble organic matter as the explanatory variables in their mortality equation.

where CC denotes the computed conventional mortality rates, PAGE the percentage of population 65 or older, PYAP percentage of population with income above poverty level, PCOL percent of persons 25 or older who have completed 4 years of college, PWPO percentage of white to total population, SUN possible annual sunshine days, RHM relative humidity, and DTS number of days with thunderstorms. The figures in the parentheses are standard errors of the estimates. The estimated coefficients shown in the equation have the correct signs, and with * and * to indicate that they are statistically significant at the 1 and 5 percent level.

The dose-response function embodying the effect of the threshold level of 25 $\mu g/m^3$ is expressed as:

$$(MR - CC) = EXP\ (a - b/(SO_2 - 25))$$

or

$$RMR = EXP\ (a - b/(SO_2 - 25)) \qquad \text{(II-6)}$$

where CC is the computed value of conventional mortality rate from equation (II-5), and RMR = MR - CC is the residual mortality rate.

The residuals, i.e., MR - CC = RMR, take both positive and negative values. Since the logarithm of a negative number is undefined, RMR was squared prior to its logarithmic transformation. The resultant regression equation was then adjusted by dividing the coefficients by 2. This adjustment is demonstrated as follows:

The regression equation takes the form

$$In\ (RMR)2 = 2a - 2b/SO_2$$

By virtue of a property of logarithm, we also obtain

$$2\ In\ (RMR) = 2a - 2b/SO_2 \qquad \text{(II-7)}$$

or

$$In\ (RMR) = a - b/SO_2$$

Note that the coefficients in equation (II-7) are twice as large as those in equation (11-4) which is the initially specified nonlinear dose-response function.

The regression result for equation (II-4) is shown as follows:

$$RMR^2 = \underset{(1.34)}{EXP\ (2.50} \underset{(4.22)*}{-\ 51.04/SO_2)}$$

or (II-8)

$$RMR = EXP\ (1.25 - 25.52/SO_2)$$

$$R^2 = 0.03$$

The figures below the coefficients are standard errors with * indicating that the coefficient of SO_2 is significant at the 1 percent level. Though SO_2 explains only 3 percent of the residual mortality rate, the nonlinear fit showed an explanatory power 150 times larger than the linear fit. Generally comparison of R^2 when the dependent variables are different may not be meaningful. However, the purpose of comparing R^2 associated with RMR and In (RMR) equations here is to determine which of the two specifications is more suitable for the estimation of the physical damage function. For comparison purposes, such a linear regression equation is presented as follows:

$$\underset{(20.28)}{RMR = 29.65} \underset{(0.35)}{-\ 0.034\ SO_2} \qquad \text{(II-9)}$$

$$R^2 = 0.0002$$

The linear fit showed not only very low explanatory power, but also an incorrect sign for SO_2. Thus, the nonlinear specification of the dose-response relation seems to be superior and tends to support the *a priori* judgment regarding human responses to pollution dose variations.

To recapitulate, the methodological procedures for estimating the function between mortality rate and SO_2 are summarized as follows:

1. A linear multiple regression model represented by equation (II-5) was developed for estimating the effects of the socioeconomic, demographic, and climatological factors with the exclusion of air pollution on the conventional mortality rate, C, expressed in deaths per 10,000 population.

2. The computed values of C, i.e., CC, were subtracted from the observed gross mortality rate. The residual, RMR = MR - CC, was then regressed on SO_2 alone according to the specification in equation (II-4). The regression result was shown in equation (II-8). The nonlinear, exponential dose-response function was transformed into a linear function with logarithm on RMR and reciprocal on SO_2 for empirical estimation.

The nonlinear physical dose-response function between residual mortality and SO_2 derived from this stepwise econometric technique is characterized by the following features:

1. The nonlinear dose-response function is consistent with the a priori judgment about dose-response relationship between air pollution and mortality rate. It can also be easily adjusted with whatever is the threshold level of the SO_2 concentration when estimating the economic damages.

2. For the purpose of predicting and computing the marginal mortality damages due to SO_2, this nonlinear equation has the right sign and higher explanatory power than its counterpart linear equation in view of its goodness of fit.

3. The nonlinear specification circumvents at least partially some of the econometric problems such as multicolinearity and heteroscedasticity which are to be discussed next.

Technical Problems in Estimation--

Although detecting and treating econometric problems which are often encountered in the pollution effect studies are not the main purpose of this study, the problem of multicolinearity and heteroscedasticity are examined during the course of research.

Multicolinearity--1/It is well known that multicolinearity problems occur when some or all of the explanatory variables are highly correlated and that it becomes difficult; if not totally impossible, to disentangle their separate influences. Of the nine explanatory variables used in this study, PWPO is correlated with the pollution variables, SO_2 and TSP. RHM is correlated with PAGE, PYAP, PWPO, and SUN. The correlation coefficients are presented in Table II-1. On the basis of this correlation coefficient table, one may be led to conclude that not too "strong" multicolinearity appear to be present in this study; However, it should be noted that the usefulness of partial correlation coefficients as a diagnosis of multicolinearity is questionable. Withers (1975) has recently shown that a given value of partial correlation coefficient may be compatible with two very different multicolinearity patterns. Less obtusely stated, a simple correlation coefficient may not be the appropriate measure of multicolinearity.

1/ For a detailed discussion on multicolinearity see Johnston (1963), p. 207, Goldberger (1964), pp. 192-193, Farrar and Glauber (1967), and Haitovsky (1969). The three-stage test for the detection of multicolinearity patterns in the classical regression model was criticized by Kumar (1975), Withers (1975), and O'Hagen and McCabe (1975). Kumar cast doubt on the x^2 test suggested by Farrar and Glauber for the existence of multicolinearity and on the F and t tests to localize the problem. Withers showed that the third stage of the Farrar-Glauber test is ineffective. O'Hagan and McCabe pointed out a fundamental error which renders meaningless the contribution of Farrar-Glauber to multicolinearity as a sample problem.

TABLE II-1. CORRELATION COEFFICIENTS[a/]

PAGE	0.74								
PYAP	-0.26	-0.12							
PCOL	0.61	-0.41	0.25						
PWPO	0.36	0.72	0.33	-0.38					
SUN	-0.25	-0.09	-0.01	0.18	-0.26				
RHM	0.23	0.35	0.45	-0.04	0.42	-0.36			
DTS	0.05	-0.20	-0.19	-0.19	-0.13	-0.17	0.00		
S02	0.13	0.05	-0.10	0.08	-0.27	0.08	-0.08	-0.04	
TSP	0.24	-0.09	-0.23	-0.15	-0.33	-0.23	-0.01	0.06	0.04
	MR	PAGE	PYAP	l PCOL	PWPO	SUN	RHM	DTS	SO_2

a/ Correlation coefficients are statistically significant at 5 percent level if $r \geq 0.32$ for 40 observations.

Thus, diagnosis of multicolinearity could be guided by a priori judgment with respect to the interactions among the explanatory variables. Furthermore, the existence of multicolinearity poses little problem if the model is correctly specified, because in such a case least-squares estimates will be unbiased regardless of the extent of multicolinearity. The estimates will be biased if a relevant variable is omitted and inefficient if a nonrelevant variable is included in the regression analysis. The extent of the biases is dependent on the degree of correlation between the misspecified variable and the variables with significant coefficient.

In the presence of multicolinearity, no cut-and-dried technique has been discovered to treat the problem. The residualization technique was first used by Ridker (1965, p. 127-135) in a study of property value and pollution to alleviate the multicolinearity problem by attributing to all the nonpollution variables the covariance between them and the pollution variable. The two-stage estimation procedure is known to bias the pollution coefficients toward zero and reduce their significance in the presence of multicolinearity.

Residualization technique was later employed by Lave and Seskin (1973) to examine the multicolinearity problem. However, the estimated results obtained by Lave and Seskin indicate that the estimated coefficients of the air pollutants retain their significance and the parameter estimates are similar to those in the one-stage regression equation.

Following Ridker and Lave and Seskin, the residuals rather than the gross mortality rates were regressed on the air pollution variables. In doing so, not only the nonlinear dose-response function can be estimated, but also the

possible multicolinearity problem existing among the explanatory variables can be alleviated. The low R for the dose-response function is expected from using this two-stage residualization technique. However, the important result is that the nonlinearity of dose-response function represents a better fit than the linear specification as pointed out previously.

Heteroscedasticity- The violation of the condition of a constant variance in the disturbance term in any regression analysis is called heteroscedasticity. The effect of heteroscedasticity is not on the biasness of the estimated regression coefficient itself, but rather on efficiency of the variance of the coefficient estimated. It is recognized that the existence of heteroscedasticity often occurs in the cross-section data. In the present study, heteroscedasticity is detected by using the eyeballing method. In terms of Figure II-2, the residuals are plotted against the dependent variables. The shape of the residual distribution pattern suggests that the variance of the error term is variable, i.e., there is likely a problem of heteroscedasticity. Glejser (1969) and Park (1966) discussed alternative methods for detecting heteroscedasticity. These methods have been applied by Smith and Deyak (1975) for testing heteroscedasticity in estimating air pollution and property value relation.

The common treatment for heteroscedasticity is to use the weighted regression method designed to reduce the nonhomogeneity of the variance. The use of semilog on the dependent variable in this study is a sort of the weighted regression method. The semilog transformation reduces the nonhomogeneous spread of the variance in the error term (e.g., along the mortality rate axis in Figure II-2, on page 27), and, hence, partially alleviates the heteroscedasticity problem.

A LINEAR GENERAL PHYSICAL DAMAGE FUNCTION

As noted earlier, reliable and useful average damage functions on mortality rate and air pollution for the United States metropolitan areas are still lacking. To close this gap in the air pollution damage investigation, a generalized average damage function is developed by regressing jointly, in a linear form, the sum of the estimated mortality rates from both equations (II-5) and (II-8) on the four socioeconomic and demographic variables, the three climatological variables and the SO_2. It should be stressed that the results of this generalized average damage function should only be used for prediction purposes, and any statistical interpretations would be meaningless. Otherwise stated, this damage function so derived serves to yield a more accurate prediction with respect to the changes in the mortality rates in response to a ceretis paribus change in any of its determinants. Based on the data of the 40 SMSA's with SO_2 exceeding 25 $\mu g/m^3$ between 1968 and 1970, the linear regression analysis was conducted to ascertain the generalized average damage function, estimated as:

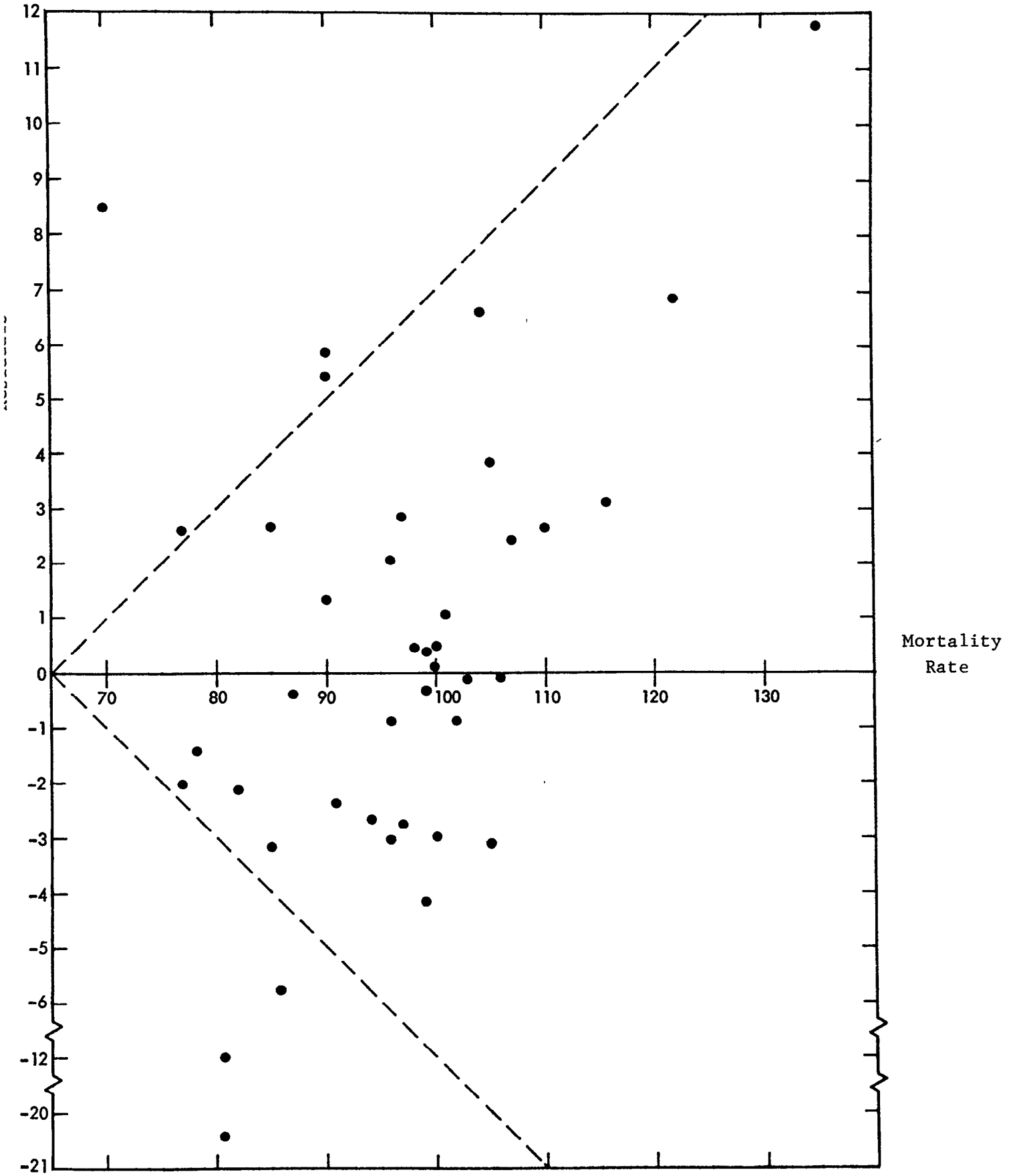

Figure II-2. Heteroscedastic distribution of the residuals.

$$CMR = CC + CRMR$$

$$= 226.2 + 735.4\ PAGE - 113.8\ PYAP - 0.12\ PCOL - 77.5\ PWPO$$
$$(3.4)^{*} \quad (8.7)^{*} \quad (5.3)^{*} \quad (0.003)^{*} \quad (2.0)^{*}$$

$$- 0.55\ SUN + 0.23\ RHM + 0.03\ DTS + 0.023\ SO_2 \qquad \text{(II-10)}$$
$$(0.02)^{*} \quad (0.02)^{*} \quad (0.006)^{*} \quad (0.003)^{*}$$

where CMR is the computed mortality rate, which is the sum of the computed conventional mortality rate (CC) and the computed residual mortality rate (CRMR) from equations (II-5) and (II-8), respectively. All independent variables on the right-hand side of equation (II-10) were defined previously.

Admittedly, a usual statistical interpretation for the generalized damage function summarized by equation (II-10) is not meaningful. However, the purpose of deriving this equation is to demonstrate that the stepwise econometric model ameliorates some technical problems of estimation. The advantage of this approach is clear if equation (II-10) is compared with the similar physical damage function using the actual rather than computed mortality rates as the dependent variable. Such a physical damage function is summarized as follows:

$$MR = 230.1 + 746.4\ PAGE - 119.3\ PYAP - 0.12\ PCOL - 77.7\ PWPO$$
$$(51.5) \quad (10.59) \quad (63.9) \quad (0.035) \quad (24.3)$$

$$- 0.54\ SUN + 0.23\ RHM + 0.04\ DTS - 0.004\ SO_2 \qquad \text{(11-11)}$$
$$(0.25) \quad (0.22) \quad (0.07) \quad (0.033)$$

It is noteworthy that the coefficient of SO_2 in equation (II-11) is negative despite the fact that the simple correlation coefficient between MR and SO is positive and equal to 0.13. The negativity of the S02 coefficient is probably due to multicolinearity and other econometric problems discussed earlier. The two-step econometric method seems to have partially overcome these technical problems and yields, if not coincidentally, the expected positive coefficient of SO_2 in equation (II-10).

VALUES OF AIR POLLUTION DAMAGES AND ECONOMIC DAMAGE FUNCTIONS

Air pollution damage to human health in this country has been roughly estimated by Ridker (1965), Lave and Seskin (1970, 1973), Jaksch and Stoevener (1974), Koshal and Koshal (1974), Park (1974), and others. However, their estimates vary considerably; from $443 million by Ridker to $2.4 billion by Lave and Seskin, and $6.8 billion by Park, partially because their study scopes and period are not commensurate with each other. In order to estimate an average economic damage function for the United States urban areas, it is not meaningful to borrow the national damages estimated by the above authors not only

because of this great disparity but also the different methods of estimation. A method will be developed to quantify regional damage separately for each metropolitan area so that regional control costs and benefits can be evaluated. Since we considered 25 $\mu g/m^3$ as the threshold of SO_2, only those SMSA's with average annual SO_2 levels equal to or greater than 25 pg/m^3 between 1968 and 1970 and with data on other relevant factors were selected.

Air pollution has caused high morbidity rates in addition to premature mortality in this country. This section, however, is mainly concerned with the mortality damages. The morbidity damages due to air pollution will be discussed in Section III. To estimate the mortality damages of SO_2 and the percentage of pollution-caused damage to total mortality losses, an expected average permanent income method was developed. Specifically, we computed via equations (II-5) and (II-8) the conventional and the residual mortality rate for the selected SMSA's. Assume that each individual in any of the SMSA's is equally affected by air pollution and that the growth in median earnings from 1960 to 1970 represents an expected normal income rate. The expected future income streams are computed by a simple formula computed for the conventional and air pollution victims in the labor force--between 18 and 64 years of age. The present value of the economic damages was derived by discounting the future incomes at a rate of 4 percent which is the long-term bond rate. Finally, we regressed the computed economic losses of both conventional and pollution victims on the demographic, socioeconomic, and weather variables, and SO_2 for the selected SMSA's to derive the so-called "average" economic damage function.

In functional form, this part of the work for each SMSA can be succinctly expressed as follows:[1/]

$$V = \bar{Y} \cdot \left[\sum_{t=1}^{n} (1 + r)^t / (1 + i)^t \right] \cdot L \cdot [CC + CRMR] \qquad \text{(II-12)}$$

$$V' = \bar{Y} \left[\sum_{t=1}^{n} (1 + r)^t / (1 + i)^t \right] \cdot L \cdot CC \qquad \text{(II-12')}$$

1/ A somewhat different formula was developed and employed by Ridker for estimating damage costs due to premature death. A drawback of his method, as noted by Ridker himself, is the lack of adjustment for increase in labor productivity over time. A similar framework was also used by Schrimper (1975) to calculate mortality costs for Chicago. The expected income formula developed here considers the improvement in labor productivity, though all workers are assumed to live through and be employed until the age of 65. The bias in the resulting estimates is believed to be negligible.

where V and V' are, respectively, the computed value of regional economic damages with or without air pollution;

Y is the weighted median income of 1970 between males and females with the weights being their respective share in the labor force;

r is the expected family income growth rate which partially reflects the growth in labor productivity assumed to be equal to the average from 1960 to 1970;

i is the discount rate, set at 4 percent per year, a rather conservative rate;

L is the labor force or population between 18 and 64 years of age;

CRMR and CC are the computed excess mortality rates and the computed conventional mortality rate, respectively;

n is the difference between regional median age and 64; this assumes that the number of deaths due to air pollution with age younger than the median age is offset by those who fall short of reaching the age of 64.

The damage costs without and with air pollution and the per capita damage costs for 1970 by SMSA are estimated using equations (II-8), (II-12), and (II-12') and are contained in Table II-2. All dollars reported in the table are in 1970 value. Under the heading of mortality damage due to SO_2, total and per capita mortality cost for each SMSA can be found in Columns 1 and 2. Mortality damages in the absence of air pollution is presented in Column 3, and Column 4 presents the ratio or the relative magnitude of total mortality cost attributable to SO_2 and the mortality damage with and without SO_2. The higher the ratio, the more serious is the pollution damage.

It should be noted that the damage estimates presented in the table depend vitally on the assumptions made in this study. The most critical assumptions are the threshold levels of SO_2 the natural mortality rate, the growth in income and the discount rates. Change in any of these assumptions would result in modification in the damage estimate.

As readily revealed in the table, total mortality costs in the presence of SO_2 amounted to $887 million for the 40 SMSA's which had average annual SO_2 concentration beyond 25 $\mu g/m^3$ between 1968 and 1970. Given that total mortality cost in the absence of air pollution in the 40 SMSA's is $60.2 billion, as measured, the air pollution damage accounted for 1.4 percent of the total. Among the 40 SMSA's, New York City had the highest total and per capita mortality air pollution damage, about $329 million and $28.4 respectively, partially because it had the highest SO_2 concentration level between 1968 and 1970, i.e., 210 $\mu g/m^3$. The highest percentage of air pollution damage was found in Chicago and New York City; 2.7 percent of total gross mortality values in these areas could

TABLE II-2. MORTALITY COSTS WITH SO_2 BY SMSA's, 1970

SMSA	SO_2 ($\mu g/m^3$)	Mortality Damage Due to SO_2		Mortality Damage Without Air Pollution	Ratio
		Total (in 10^6)	Per Capita	(in 10^2)	(1)÷((1)+(3)
		(1)	(2)	(3)	(4)
1. Akron, OH	51	8.4	12.4	570.6	0.0145
2. Allentown, PA	57	7.5	13.8	462.5	0.0160
3. Baltimore, MD	54	28.4	13.7	1891.6	0.0148
4. Boston, MA	31	1.3	0.5	2398.7	0.0005
5. Bridgeport, CT	40	2.6	6.7	353.4	0.0073
6. Canton, OH	30	0.1	0.3	330.9	0.0003
7. Charleston, WV	27	--	--	159.0	--
8. Chicago, IL	120	178.0	25.5	6292.0	0.0275
9. Cincinnati, OH	25	--	--	1160.0	--
10. Cleveland, OH	64	34.3	16.6	1875.7	0.0180
11. Dayton, OH	25	--	--	398.0	--
12. Detroit, MI	38	26.0	6.2	4884.0	0.0053
13. Evansville, IN	25	--	--	214.0	--
14. Gary, IN	58	10.6	16.7	555.4	0.0187
15. Hartford, CT	57	10.5	15.8	552.5	0.0187
16. Jersey City, NJ	75	9.6	15.8	529.4	0.0178
17. Johnstown, PA	25	--	--	263.0	
18. Lawrence, MA	52	2.7	11.6	204.3	0.0130
19. Los Angeles, CA	35	15.9	2.3	4964.1	0.0032
20. Minneapolis, MN	38	9.1	5.0	1380.9	0.0065
21. New Haven, CT	40	2.2	6.2	341.8	0.0064
22. New York, NY	210	329.0	28.4	11671.0	0.0274
23. Newark, NJ	37	7.0	3.8	1633.0	0.0043
24. Norfolk, VA	26	a-	--	511.0	--
25. Paterson, NJ	28	--	--	1150.0	--
26. Peoria, IL	26	--	--	295.0	--
27. Philadelphia, PA	84	97.9	20.3	4322.1	0.0221
28. Pittsburgh, PA	57	30.0	12.5	2000.0	0.0148
29. Portland, OR	26	--	--	922.0	--
30. Providence, RI	67	14.6	16.0	777.4	0.0184
31. Reading, PA	30	0.1	0.3	257.9	0.0004
32. Rochester, NY	32	0.8	0.9	784.2	0.0010
33. St. Louis, MO	40	13.3	5.6	2156.7	0.0061
34. Scranton, PA	30	--	0.01	185.0	--
35. Springfield, MA	87	10.6	20.0	458.4	0.0226
36. Trenton, NJ	32	0.2	0.7	254.8	0.0008
37. Washington, D.C.	47	35.5	12.4	1194.5	0.0175
38. Worchester, MA	31	0.2	0.6	319.8	0.0006
39. York, PA	31	0.1	0.3	263.9	0.0004
40. Youngstown, OH	30	0.1	0.2	482.9	0.0002
Total		886.6		60,221.4	

Note: -- denotes less than $0.1 million.

be attributed to SO_2. In order of magnitude, New York City, Chicago, and Philadelphia all had air pollution damages of more than $50 million. In terms of the ratio of net mortality damage to gross mortality damage, i.e., Column 4, again New York and Chicago which had ratio values of 2.7 percent lead all the other SMSA's. As noted earlier, the degree of the pollution damage is partially reflected by the magnitude of this ratio.

Although the economic damage costs derived in this section are more detailed than prior estimates, they are still crude information and should be used with caution under the stated conditions. In order to develop a marginal economic damage function useful for prediction and control purposes, the "total of economic costs of mortality" is related not only to SO_2, but also to various socio-economic, demographic, and climatological characteristics of different regions. The stepwise regression technique was used with inputs from the 40 sample observations to estimate the economic damage function. The regression results are shown as follows:

$$V = \underset{(11,023)}{10,295} + \underset{(6.97)^*}{47.02\ SO_2} - \underset{(5,195.9)}{8,128.4\ PWPO} + \underset{(46.9)^*}{98.5\ RHM} + \underset{(53.4)}{72.3\ SUN}$$

$$- \underset{(15.99)}{15.98\ DTS} - \underset{(13,659.9)}{16,191.8\ PYAP} + \underset{(7.6)}{7.7\ PCOL} + \underset{(22,650)}{3,772\ PAGE} \qquad \text{(II-13)}$$

$$R^2 = 0.74$$

where V is total mortality cost obtained from equation (II-12) and all the explanatory variables are defined earlier.

The coefficients and standard errors in (II-13) are reduced by a factor of 106. The values of standard error are presented below the coefficients, with * to indicate that the coefficient is significant at the 1 percent level.

The economic damage function derived can be useful to policymakers in estimating the marginal and average damages (benefits) resulting from a pollution control program. To serve as an illustration, an example involving the computation of the partial elasticity of an explanatory variable and the associated marginal benefit due to the changes in that variable is presented. Suppose the federal government is considering the implementation of a pollution abatement program which is expected to reduce the average SO_2 level in the urban areas by, say, 10 percent. What will then be the dollar worth benefit of the reduced premature mortality rate as a result of the pollution abatement program? Since the average total damage cost due to premature mortality is $1,530.8 million and the average SO level is 47.95 $\mu g/m^3$ among the 40 SMSA's, the partial elasticity of the damage cost with respect to SO_2 is derived by using the formula that

$$E_{c,SO_2} = (\partial c/\partial(SO_2)) \times (\overline{SO_2}/\bar{c}) = 47.02 \times (47.95/1{,}530.8) = 1.45.$$

Note $(\partial c/\partial(SO_2))$ in the formula denotes the coefficient of SO_2 in the economic damage function; $\overline{SO_2}$ and $\bar{c}$ are, respectively, the mean values of SO_2 and the total damage cost for the 40 SMSA's included in the sample.

The distinguishing property of the concept of elasticity is that it is a unit-free measure of the percentage change in the dependent variable with respect to the percentage change in any of the explanatory variables while holding other things equal. Given the computed elasticity of damage cost with respect to SO_2, $E_{c,SO_2} = 1.45$, it is in general expected that a 10 percent decrease in the SO_2 concentration level will result in a 14.5 percent reduction in the premature mortality damage cost. Since the mean value of the regional damage cost for the 40 SMSA's is \$1,531 million, when the SO_2 level decreases from 47.95 $\mu g/m^3$ to 43.15 $\mu g/m^3$, it is expected that on the average the damage cost will be reduced by the amount of \$1,530.8 x 14.5 percent = \$221.9 million. Likewise, the elasticities for the other explanatory variables can be analogously computed and interpreted.

PREMATURE MORTALITY DAMAGES AND SUSPENDED PARTICULATES

Earlier studies have established a positive qualitative relationship between mortality and suspended particulates. Recently Lave and Seskin (1970, 1973), and the Koshals (1974) further confirmed the existence of a quantitative association between mortality and the particulates. As discussed earlier, the threshold effects of the air pollutant and the heteroscedasticity problems in the empirical estimation of the relation were, by and large, ignored in the prior studies. A two-step residualization technique was, however, developed earlier to cope with these problems in estimating a nonlinear dose-response function. The same methodology is used in this section to establish a dose-response function relating mortality to suspended particulates.

The nonlinear dose-response relation (II-3) was used for regressing the residual mortality rate (MR-C) on total suspended particulates (TSP). To be consistent with earlier SO_2 estimates, the particulate level is also adjusted by a threshold of 25 $\mu g/m^3$ in computing the physical damage. As noted earlier, although 25 $\mu g/m^3$ is a reasonable level for capturing the threshold effect, alternative thresholds may also be considered. Changes in the threshold will cause modifications in the damage estimates. It is conceivable that, other things being equal, a lower threshold level implies higher damage cost.

The least-squares regression yields the following nonlinear physical damage functions for suspended particulates:

$$RMR = EXP\ \underset{(0.83)}{[1.30} - \underset{(70.84)}{65.75/TSP]} \qquad \text{(II-14)}$$

$$R^2 = 0.02$$

The values below the coefficients are standard errors. The explanatory variable TSP is not statistically significant. With the availability of the physical damage function, the methodological procedures used earlier for estimating the postulated function relating mortality rate to SO_2 can be employed to estimate the economic damages and the associated economic damage function for suspended particulates.

Economic Damage Functions

For policymakers, economic damage functions may be more relevant than physical damage functions. An economic damage function, or a monetary damage function, relates levels of pollution to the amount of compensation which would be needed in order that the society is not worse off than before the deterioration of the air quality. The economic damage function is useful to decision makers since the multiple dimensions of the decision problem are reduced into one dimension only, i.e., money. It should be noted, however, that transformation of a physical damage function into an economic damage function often involves value judgment on the part of the policymaker. A related question as to the degree of conformity of the values of the policymaker with those of the consumer sovereignty is largely unresolved.

The expected permanent income method delineated earlier was employed to estimate premature mortality damages due to total suspended particulates. The damage costs associated with total suspended particulates are presented in Table II-3. Columns (1) and (2) present total and per capita mortality damage attributable to TSP. Mortality damage without air pollution is presented in Column (3). Column (4) presents ratio of total mortality damage due to TSP to total mortality damage with TSP. This ratio reflects the relative magnitude of the damage attribute TSP to total mortality damage. An examination of the table reveals that the mortality damages range from $1.4 million in Lawrence, Masssachusetts, to $155 million in New York City. The air pollution damage in Lawrence is 0.7 percent of the total gross mortality damage, while in New York City suspended particulate causes about 1.3 percent of total mortality damage. The highest ratio of pollution damage to total mortality damage of the magnitude of 4.0 percent is observed for Dayton, Ohio.

Generalized economic damage functions were derived by regressing the premature mortality damage costs associated with TSP (TMRCT) which is the sum of Columns (1) and (3) in Table II-2 on the demographic, socioeconomic, and

TABLE II-3. MORTALITY COSTS WITH TSP BY SMSA's, 1970
(in dollars)

	SMSA	TSP ($\mu g/m^3$)	Mortality Damage Due to TSP: Total (in 10^6) (1)	Mortality Damage Due to TSP: Per Capita (2)	Mortality Damage Without Air Pollution (in 10^6) (3)	Ratio (1)÷((1)+(3)) (4)
1.	Akron, OH	80	7.2	10.6	570.6	0.0125
2.	Allentown, PA	87	6.0	11.0	462.5	0.0128
3.	Baltimore, MD	147	42.0	20.3	1891.6	0.0217
4.	Boston, MA	108	42.9	15.6	2398.7	0.0176
5.	Bridgeport, CT	57	2.0	5.1	353.4	0.0056
6.	Canton, OH	103	5.3	14.2	330.9	0.0158
7.	Charleston, WV	105	2.5	10.9	159.0	0.0155
8.	Chicago, IL	155	147.0	21.1	6292.0	0.0228
9.	Cincinnati, OH	106	18.9	13.6	1160.0	0.0160
10.	Cleveland, OH	201	47.8	23.2	1875.7	0.0249
11.	Dayton, OH	114	16.4	19.3	398.0	0.0396
12.	Detroit, MI	153	116.0	27.6	4884.0	0.0232
13.	Evansville, IN	75	2.0	8.6	214.0	0.0093
14.	Gary, IN	105	10.6	16.7	555.4	0.0187
15.	Hartford, CT	74	6.4	9.6	552.5	0.0115
16.	Jersey City, NJ	83	5.4	8.9	529.4	0.0101
17.	Johnston, PA	103	3.7	14.1	263.0	0.0139
18.	Lawrence, MA	65	1.4	6.0	204.3	0.0068
19.	Los Angeles, CA	118	106.0	15.1	4964.1	0.0209
20.	Minneapolis, MN	76	18.8	10.4	1380.9	0.0134
21.	New Haven, CT	60	1.9	5.3	341.8	0.0055
22.	New York, NY	95	155.0	13.4	11671.0	0.0131
23.	Newark, NJ	134	33.6	18.1	1633.0	0.0202
24.	Norfolk, VA	113	11.2	16.5	511.0	0.0214
25.	Paterson, NJ	56	6.0	4.4	1150.0	0.0052
26.	Peoria, IL	78	3.3	9.6	295.0	0.0111
27.	Philadelphia, PA	78	45.8	9.5	4322.1	0.0105
28.	Pittsburgh, PA	135	38.5	16.0	2000.0	0.0189
29.	Portland, OR	86	11.1	11.0	922.0	0.0119
30.	Providence, RI	77	8.0	8.8	777.4	0.0102
31.	Reading, PA	117	4.3	14.5	257.9	0.0164
32.	Rochester, NY	90	11.7	13.3	784.2	0.0147
33.	St. Louis, MO	120	38.5	16.3	2156.7	0.0175
34.	Scranton, PA	189	3.7	15.8	185.0	0.0196
35.	Springfield, MA	64	3.1	5.9	458.4	0.0067
36.	Trenton, NJ	71	2.4	7.9	254.8	0.0093
37.	Washington, D.C.	90	43.3	15.1	1994.5	0.0212
38.	Worchester, MA	72	2.8	8.1	319.8	0.0087
39.	York, PA	85	3.3	10.0	263.9	0.0124
40.	Youngstown, OH	110	8.2	15.3	482.9	0.0167
	Total		1044.0		60,221.4	

climatological variables and the suspended particulate level for the 40 SMSA's. The stepwise regression result for the generalized economic damage function is summarized below:

$$\begin{aligned} TMRCT = {} & 13{,}109 + 7.63\ TSP - 20{,}225\ PWPO + 85.05\ RUM + 6.85\ SUN \\ & (18{,}034)\ (11.68)\quad (8{,}339)^{*}\quad (72.85)\quad (87.49) \\ & - 14.88\ DTS - 10{,}554\ PYAP + 11.39\ PCOL + 54{,}606\ PAGE \\ & (24.89)\quad (21{,}076)\quad (12.25)\quad (33{,}019) \end{aligned}$$

$$R^2 = 0.38 \qquad \text{(II-14)}$$

The values below the coefficients are standard errors. The symbol * indicates that the coefficient is significant at the 1 percent level. The coefficients and standard errors are reduced by a factor of 10^6. The explanatory variables are the same as those appearing in the sulfur dioxide economic damage function and explain about 38 percent of the variations in the dependent variables.

Given the mean values of total damage cost and total suspended particulate level are \$1,543.5 million and 100.9 $\mu g/m^3$, respectively, the partial elasticity of damage cost with respect to total suspended particulate is:

$$E_{C,TSP} = 7.63 \times (100.9/1{,}543) = 0.49$$

Thus, a 10 percent decrease in the average TSP level as a result of pollution control programs will cause a reduction of 4.9 percent in the premature mortality damage cost. That is, when the TSP is reduced from 100.9 $\mu g/m^3$ to 89.81 $\mu g/m^3$ the damage cost, on the average, will be reduced by the amount of \$1,543 x 4.9 percent = \$75.6 million.

IMPLICATIONS AND CONCLUDING REMARKS

This study is the first attempt to estimate a physical nonlinear damage function between excess mortality rates and the SO_2 concentration with considerations of circumventing certain econometric problems such as multicolinearity and heteroscedasticity, and accounting for the effects of the threshold levels. Through a two-step adjustment procedure, the average physical mortality function was generalized with a rather complete specification. That is, the generalized average mortality model includes not only the major demographic, socioeconomic, and climatological determinants but also air pollution variables. The two-step econometric model developed here represents a constructive response to the call recently made by Lave and Seskin (1973) and Ferris (1970) in connection with the urgent need to improve on the existing studies in the area of air pollution and human health.

This study is also the first attempt to present comparable estimates for premature mortality damages due to "excessive" air pollution--sulfur dioxide and total suspended particulates--for individual urban areas in the United States. To assist the policymakers in estimating possible marginal damage (benefit) resulting from a given pollution control strategy, "average" economic damage functions which transform the multiaspect of the problems into a single, homogeneous monetary unit were also developed separately for the two major pollutants.

It should be noted that the present federal standards were derived on the assumption that threshold levels for various pollutants exist. These threshold levels are considered to be the safe levels below which essentially no person is hurt. This threshold level concept has been attacked by many medical experts on the grounds that evidence has failed to support a genuine clear-cut lower limit. It is our contention that the threshold model of health effects, however, should not be taken literally, as some experts suggested.

The threshold of 25 $\mu g/m^3$ was used in this study in deriving the damage estimates because it is viewed as the mean level of the underlying distribution of tolerable threshold levels of all the individuals in a given SMSA. Furthermore, it is also the average concentration level in the rural areas where little air pollution damage on human health is observed. Thus, while the annual average concentration level is below the threshold level, the majority of the population in the rural areas is assumed not hurt from the presence of air pollution. In order to derive more accurate "average" damages of pollution in a given region, it is imperative to establish threshold level which is the mean level of the actual threshold distribution. Our model is easily adaptable for any threshold levels that one would like to consider as tolerable.

Another issue which merits discussion is the possible chemical interactions among the pollutants. It is generally recognized that the total effect of several pollutants present at the same time in the air may be greater or less than the sum of their individual effects. In other words, the interaction effect may be additive, synergistic or even antagonistic. Two types of interactions should be noted: (1) physiological, and (2) chemical. Both types of interactions are expected to occur. The crucial question is how and to what extent air pollutants interact with each other. Stated differently, the question is whether the interaction effects are of sufficient magnitude to negate the present method of establishing the air quality standards. All panel experts, according to a recent National Academy of Sciences study (1974), found that synergistic effects are not important enough to invalidate the current methods which set air quality standards for each major pollutant.

Since the synergism occurs when SO_2 and TSP are present at the same time, the independency assumptions employed in this study may result in underestimating the damages. However, it has been well recognized that both SO_2 and TSP may be merely convenient indexes of all major damaging pollutants. This measurement problem of the pollutants contributes to overestimating the damages. In view of these two opposing factors, we are unable to judge whether our procedure tends to result in upward or downward biased estimates.

Other conceptual and empirical problems often encountered in estimating air pollution damage also should be noted. The major difficulties include the lack of knowledge regarding the shape of the function which describes the relationship between air pollution and health, the lack of a theoretical model specifying the way air pollution affects health, the virtual impossibility of accounting for all factors that might affect human health, and errors of observations in the data. Some of these problems, however, have been tackled in the present paper. For example, the nonlinear dose-response relation was specified for the excess mortality rate and the pollutant concentration level. The specification of this more plausible physical dose-response function would partially account for the credibility in our air pollution damage estimates. The semi log transformation reduces the heteroscedasticity while the use of the residuals ameliorates the multicolinearity problem.

Although the income foregone or productivity models have been employed by economists, their application to mortality or deaths in individual metropolitan areas due to SO_2, TSP, and other causes opens up another avenue for air pollution damage quantification which seems to be much more desirable than earlier studies unveiling only some aggregate figures for the nation as a whole. Furthermore, the average air pollution damage functions derived in this study with observations from a selected set of SMSA's with pollution level above the threshold are conceivably more meaningful than prior studies which included all SMSA's as sample observations regardless of the concentration level of air pollution.

This section presents a set of more recent estimates of air pollution damage for each of the 40 SMSA's with concentration levels higher than 25 $\mu g/m^3$. Based on the conservative assumption employed, it is found that while SO_2 alone in 1970 costs approximately $887 million, or about 1.4 percent of total mortality costs in these areas, TSP imposes about $1,047 million damages, or about 1.7 percent on the total mortality costs in the same areas.

The mortality damages due to SO_2 and TSP and the mortality damages without air pollution from Tables II-2 and II-3 are reproduced in Table II-4. Column 4 of Table II-4 presents the total mortality damage costs which are the sum of the three component damages listed in Columns 1, 2, and 3. The SO_2 damage estimates derived in this section should replace the earlier estimates reported by Liu (1975).

The results presented in this section are only suggestive and tentative. Given the tentativeness and experimental nature of the methodological and statistical procedures, and the degree of uncertainty associated with the study results, a great deal of caution should be exercised in using the products of this research. However, the availability of average or marginal damages is instrumental in determining the optimal national or regional pollution control strategies.

The current problem seems far more complex than the question of balancing the benefits to polluters against damages inflicted on the receptors. The issues are pressing and not yet well specified. The basic difficulty in applying the

TABLE II-4. MORTALITY COSTS BY SMSA's, 1970

	SMSA	Total Mortality Damage Due to SO_2 (10^6) (1)	Total Mortality Damage Due to TSP (in 10^6) (2)	Mortality Damage Without Air Pollution (in 10^6) (3)	Total Mortality Damage (in 10^6)
1.	Akron, OH	8.4	7.2	570.6	586.2
2.	Allentown, PA	7.5	6.0	462.5	476.0
3.	Baltimore, MD	28.4	42.0	1891.6	1962.0
4.	Boston, MA	1.3	42.9	2398.7	2442.9
5.	Bridgeport, CT	2.6	2.0	353.4	358.0
6.	Canton, OH	0.1	5.3	330.9	336.3
7.	Charleston, WV	--	2.5	159.0	161.5
8.	Chicago, IL	178.0	147.0	6292.0	6617.0
9.	Cincinnati, OH	--	18.9	1160.0	1178.9
10.	Cleveland, OH	34.3	47.8	1875.7	1957.8
11.	Dayton, OH	--	16.4	398.0	414.4
12.	Detroit, MI	26.0	116.0	4884.0	5026.0
13.	Evansville, IN	--	2.0	214.0	216.0
14.	Gary, IN	10.6	10.6	555.4	576.6
15.	Hartford, CT	10.5	6.4	552.5	569.4
16.	Jersey City, NJ	9.6	5.4	529.4	544.4
17.	Johnstown, PA	--	3.7	263.0	266.7
18.	Lawrence, MA	2.7	1.4	204.3	208.4
19.	Los Angeles, CA	15.9	106.0	4964.1	5086.0
20.	Minneapolis, MN	9.1	18.8	1380.9	1408.8
21.	New Haven, CT	2.2	1.9	341.8	345.9
22.	New York, NY	329.0	155.0	11671.0	12155.0
23.	Newark, NJ	7.0	33.6	1633.0	1673.6
24.	Norfolk, VA	--	11.2	511.0	522.2
25.	Paterson, NJ	--	6.0	1150.0	1156.0
26.	Peoria, IL	--	3.3	295.0	298.3
27.	Philadelphia, PA	97.9	45.8	4322.1	4465.8
28.	Pittsburgh, PA	30.0	38.5	2000.0	2068.5
29.	Portland, OR	--	11.1	922.0	933.1
30.	Providence, RI	14.6	8.0	777.4	800.0
31.	Reading, PA	0.1	4.3	257.9	262.3
32.	Rochester, NY	0.8	11.7	784.2	796.7
33.	St. Louis, MO	13.3	38.5	2156.7	2208.5
34.	Scranton, PA	--	3.7	185.0	188.7
35.	Springfield, MA	10.6	3.1	458.4	472.1
36.	Trenton, NJ	0.2	2.4	254.8	257.4
37.	Washington, D.C.	35.5	43.3	1994.5	2073.3
38.	Worchester, MA	0.2	2.8	319.8	322.8
39.	York, PA	0.1	3.3	263.9	267.3
40.	Youngstown, OH	0.1	8.2	482.9	491.2
	Total	886.6	1044.0	60,221.4	62,152.0

Note: -- denotes less than $0.1 million.

recent research findings to accurately estimate the air pollution damage cost stems from our ignorance about the populations at risk to air pollution. So far, few attempts have been made to identify who suffers, to what extent, from which sources, and in what regions. At this moment, updating and expanding the available crude estimates which are generally restricted to certain regions are urgently needed.