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Setting Priorities for Control of Fugitive Particulate Emissions from Open Sources

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Setting Priorities for Control of Fugitive Particulate Emissions from Open Sources

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ABSTRACT

Emission rate estimates of suspended particulates from open sources in the United States were obtained from emission factors and source extents in the literature. The major open sources, with their estimated total emission rates (in millions of tons per year), are: unpaved roads, 3×10^2; construction activities, 3×10^1; wind erosion of cropland, 4×10^1; paved roads, 8; wild fires, agricultural tilling, and mineral extraction, each 3. (For comparison, point sources of particulates in the U.S. are estimated to emit about 20 million tons per year.) Open source emission rates are estimated for each state. Correlations among these rates (and with state area and population) show that most open source rates are correlated with each other and that state population is strongly correlated with the total rate and with most of the source types. The use of cost-effectiveness is defended. It is shown that the paving of unpaved roads should reduce emissions at an average of less than $0.01 per pound for such states as RI and DE (for rural roads) and AK, AZ, CA, DE, MI, NV, PA, CO, FL, IL, IN, KY, MD, MA, NJ, NM, OH, RI, TN, TX, UT, VA, WA, WV (for remaining unpaved municipal roads). These cost figures are estimates, and particular situations may differ greatly from the conditions assumed. Linear regression of state-by-state annual geometric mean TSP values versus open and point source emissions rates showed that variations in open sources emissions contributed less to variations in TSP readings (per ton of material emitted) than did variations in point source emissions. Particle toxicity and transport characteristics deserve consideration, too, but the literature indicates that the predominant contribution to total suspended particulates (TSP) measurements is soil-like material. The control of unpaved road emissions (generally by paving), especially in cities, and the control of emissions from construction activities are concluded to deserve high priority in the effort to reduce TSP levels.

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SECTION 1

INTRODUCTION AND SUMMARY

Of the 3215 counties in the U.S., 424 are not meeting the current EPA standards for particulates, and this is true of the majority of the country's urbanized areas with populations greater than 200,000.[1] Our research goal was to investigate setting priorities for the reduction of particulate emissions from open sources, following a systems analysis approach: goal definition, problem identification, formulation of assessment criteria, comparison of alternatives. As the work progressed, it became evident to us that the first three steps of such an analysis were not sufficiently advanced that we would be able to compare all the major alternatives for control of open sources. Instead, having settled on cost-effectiveness as our criterion for comparison of alternatives, we performed a cost-effectiveness analysis on the source we estimated to have the greatest emission rate of suspended particulates: emissions from unpaved roads.

BACKGROUND

One reason open sources have received increased attention is that the steady improvement in total suspended particulate (TSP) concentrations in the early 1970's was at least temporarily reversed in 1976. Figure 1.1 (from reference 2) shows a box plot of the national geometric mean daily TSP readings from 1970 to 1976. (The upper and lower edges of the boxes are the 75th and 25th percentiles; the triangle is the average; the point in the box is the median; the dark squares connected by lines to the box are the 90th and 10 percentiles.) In 1976, TSP values increased rather than decreased. Analysis of the events associated with 1976 indicated:[2] "Large areas of the country experienced drought during 1976, and these extremely dry soil conditions increased the likelihood of wind-blown dust contributing to ambient TSP levels.....dry soil conditions existed in those general areas that had TSP increases." Further, the results of an assessment of the particulate material captured on filters in 14 major cities in the U.S. indicated that mineral matter (mostly soil-like material) predominated over other types of particulate material, including combustion products.[3]

Figure 1.2 (from reference 6) shows the Air Quality Control Regions (AQCR's) having violations in the first half of 1976 of the EPA TSP primary standards. (In some instances, only a few of the sampling locations, such as in a major city, within an AQCR may exceed the standard yet the entire AQCR has been shaded.) The violations in the West are surprising if only point sources are considered. The pattern is more easily understood when the effects of emissions from open sources - roads, agricultural areas - are considered.

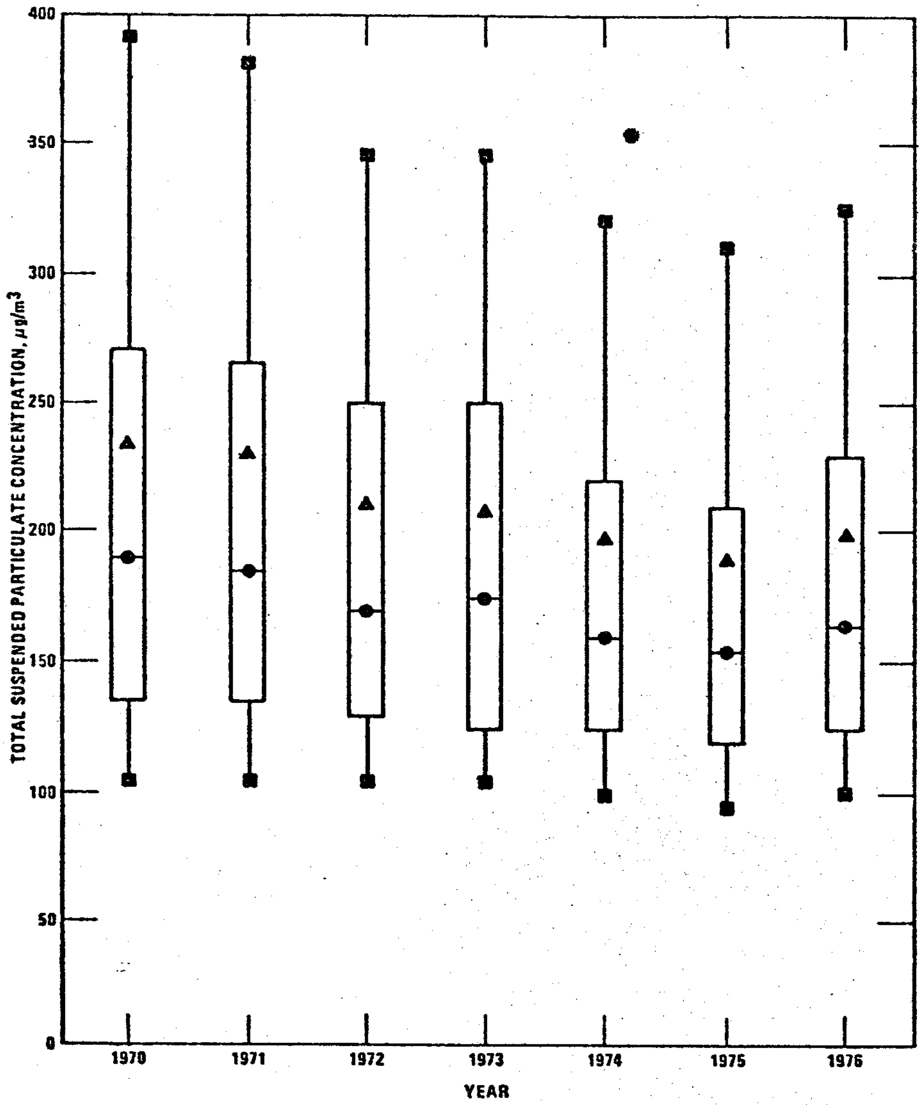

Figure 1.1. Trends of peak daily total suspended particulate concentrations from 1970 to 1976 at 2,350 sampling sites.[2]

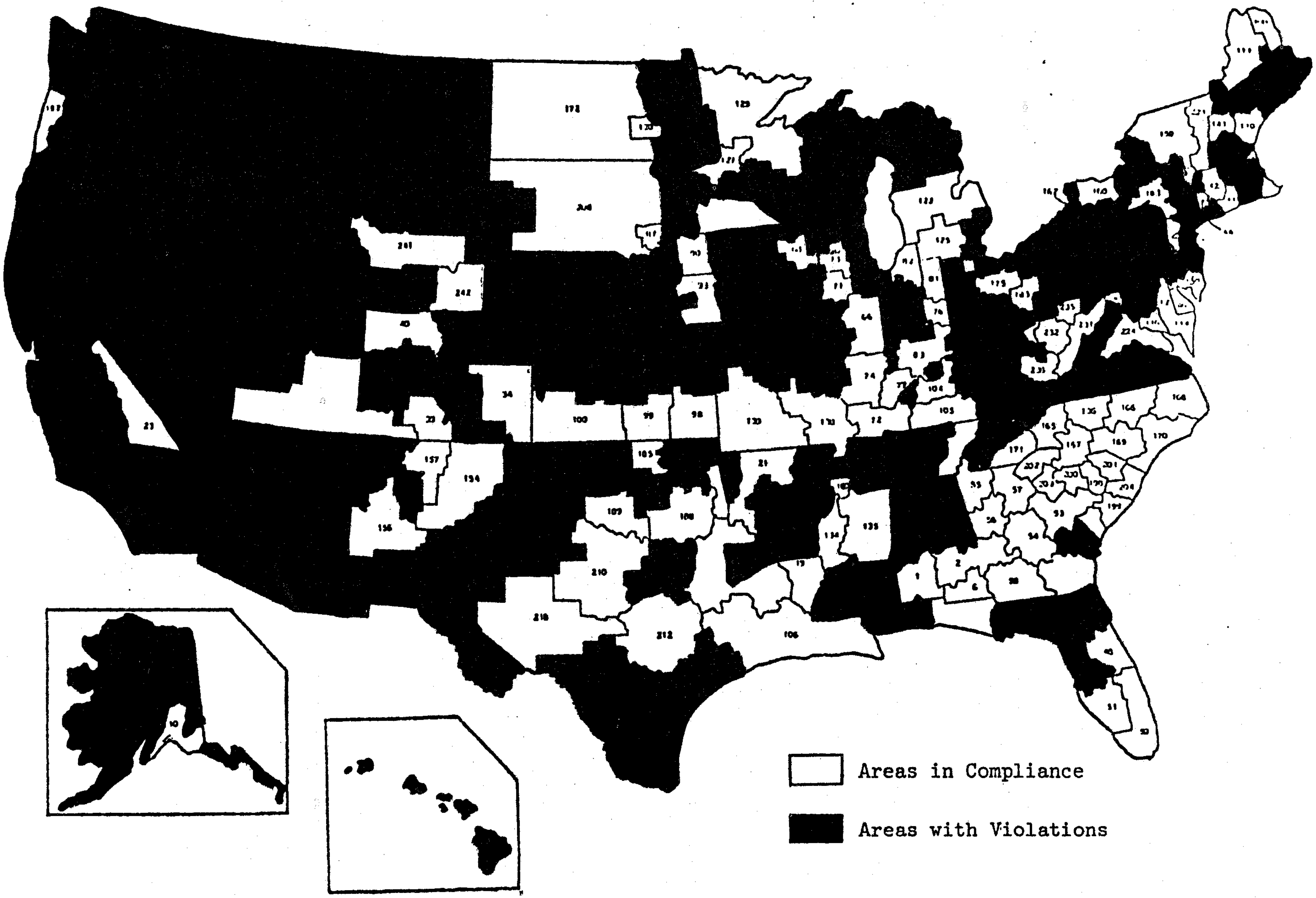

Figure 1.2. AQCR status of compliance with ambient air quality standards for suspended particulates.[6]

GOAL DEFINITION

A proper goal would be the equitable minimization of the costs of pollution control and the costs of pollution damage. The difficulties in finding such an equitable minimization are discussed in Chapter 2. Essentially, one requires some agreed-upon measure of equity and accurate information on the emissions, emissions control, and the connection between the reduction of emissions and the reduction of pollution damage in terms of costs. Such an equitable minimization is probably impossible to determine.

PROBLEM IDENTIFICATION

One way of stating the problem is that emissions from open sources contribute to failures to meet the E.P.A. standards for particulate concentrations in many localities nationwide. Determining which sources contribute most would require a knowledge of the connection between emission rates and concentration measurements. At least an initial understanding of the problem could be obtained by determining which open sources contributed most (as mass rate emitted). The results of our using emission factors and source extents from the literature to calculate emission rates are given in Table 1.1. More details are presented in Chapter 3 and in Appendices A, C, D, E, and G.

Unpaved roads are estimated to have the largest emission rates of the major open sources. Total emissions of particulates from point sources have been less than 20 million tons per year for several years. In contrast, our unpaved road emission estimate is fifteen times this, and construction emissions and wind erosion of cropland are also estimated by us to exceed the point source emissions. Admittedly, the estimates of open source emissions are crude, but it is unlikely they are wrong by an order of magnitude; such sources are certainly greater in magnitude than point sources. Whether or not their impact on particulate concentrations in populated areas is as important as those from point sources depends upon particle transport and relative toxicities, matters that deserve further study. Results of air sampling in cities suggests that soil-like particles are the major contributors to suspended particulate concentrations, as discussed below.

Our emission estimates were aggregated to the state-wide level, as it is generally on this level that governmental control decisions will be made. Chapter 3 presents frequencies and correlations by state for the various types of open sources of particulates and also identifies those states with the greatest and least mass rates of emission in each category.

ASSESSMENT CRITERIA

In Chapter 4, it is argued that cost-effectiveness—achieving the maximum reduction in emissions (or in concentrations or in doses) for a given expenditure—is the appropriate criterion to apply to evaluate con-

TABLE 1.1. ESTIMATED TOTALS OF ANTHROPOGENIC OPEN SOURCE PARTICULATE EMISSION RATES FOR THE UNITED STATES

EMISSIONS TYPE	ESTIMATED EMISSION RATE (10^6 tons per year)	RANK
agricultural tilling	3.2	6
wind erosion of cropland	44.	2
construction	27.	3
wild fires	3.4	5
prescribed fires	0.43	10
minerals: extraction		
-coal	0.4	9
-other	2.8	7
minerals: tailings	0.8	8
paved roads	7.9	4
unpaved roads	320.	1
TOTAL	409.	
TOTAL, NON-ROAD	81.	

trol alternatives, in conjunction with equity considerations.

Initially, we intended to use a cost-benefit approach to optimize control of open sources. The costs of control were to be determined as well as the benefits. The benefits would be estimated by the procedure outlined in Figure 1.3. Having obtained emission rates (from emission factors and source extents), we would use a (simple) dispersion model to predict mean concentrations, then factor in population distributions and dose-response information to predict health effects. Health costs and values assigned to person-years of healthy or sick life would then be used to estimate the benefits to be obtained from changes in emissions. Recently, the relationships between total suspended particulate concentrations and health effects have been summarized by Lave and Seskin.[7] Medical costs and lost earnings are not adequate for estimating the value of lost years of life, as we discussed in a progress report for this project, and as Howard[8] has argued in a recent paper on the proper methodology for estimating the value an individual places on a small incremental probability of premature death. Almost as good a measure would be the cost of alternative ways of saving lives. Lacking proper information for evaluating the benefits of pollution control, we have chosen to investigate the least-cost reduction of emissions.

COMPARISON OF ALTERNATIVES: UNPAVED ROADS

In Chapter 5, cost-effectiveness is applied to the control of unpaved road emissions. The least-cost technique is judged to be paving of roads, and states are ranked from those for which paving would produce the greatest reduction in emissions per dollar to those for which the reductions would be least. (Rural and municipal roads are distinguished.) The statewide average costs per pound of particulates prevented from being emitted are estimated to range from $\leq$ \$0.005/lb. (DE, CA, MD, NJ) to about \$0.06/lb. (SC).

CONCLUSIONS

The conclusions in Chapter 6 relate primarily to the areas in which more investigation is warranted. The conclusions others will draw from the results in Chapters 3 and 5 and Appendices C, D, and G will depend on their perspectives and responsibilities. It seems incontestible, however, that open sources are major contributors of particulate material which is measured as total suspended particulates, both in urban and in rural areas, and that control of such particulates in many areas can be much less costly than control of some industrial emissions in those areas.

DISCUSSION

This analysis indicates that open sources may well contribute more primary particulate material than do point sources and may be less expensive to control, at least in one important case, unpaved roads. The emission inventory approach used in this report estimates mass rates of emissions as

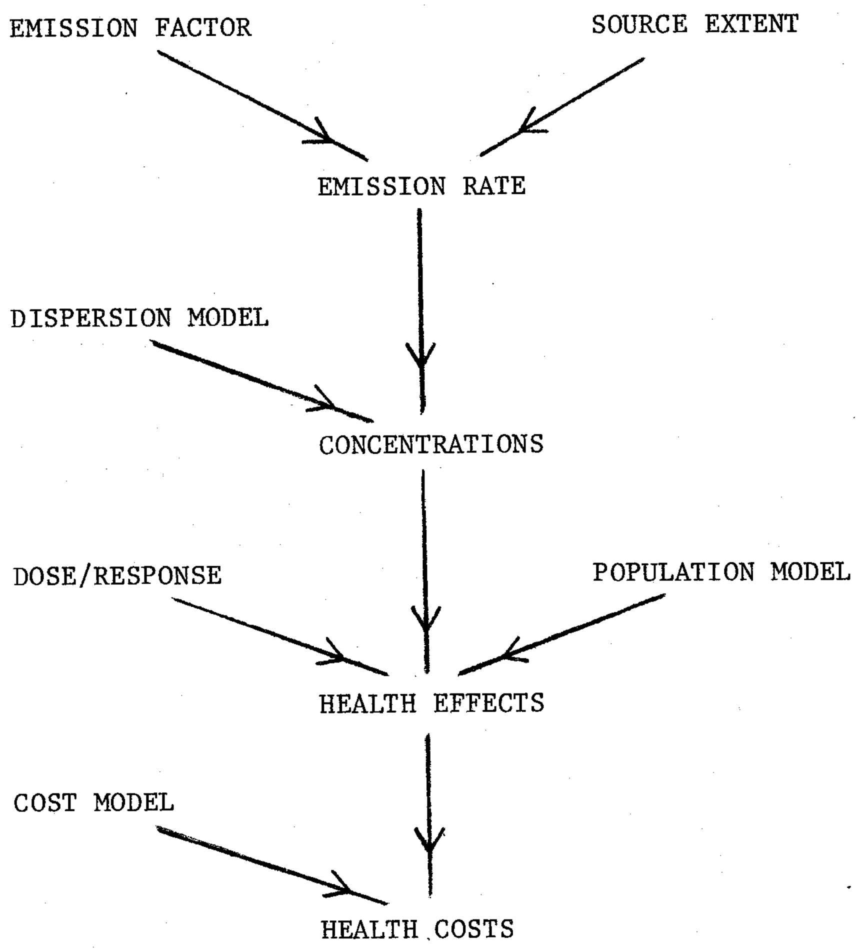

Figure 1.3. Flow chart: estimation of source impact.

a means of assessing the relative impact of different source types on air quality. This necessarily neglects transport. A complementary approach is that of using air sampling and analysis to determine the sources of particulate materials that are airborne in populated areas. The results of several such sampling and analysis studies corroborate our conclusion that sources of soil-like particles, such as unpaved roads, construction, wind erosion, and paved roads are primary contributors to measured TSP levels.

Lynn et al.[3] selected fourteen cities in the contiguous United States and analyzed 300 filters from high-volume samplers in these cities. They used these analyses to determine the major contributors to measured TSP concentrations. They concluded that the traditionally-studied point sources are sometimes dominant, especially in heavily industrialized areas, and they estimated such sources contributed to about 15 $\mu g/m^3$ in residential areas and over 60 $\mu g/m^3$ in heavily industrialized areas. Non-traditional sources, primarily those open sources which are the subjects of this report, were estimated to contribute about 25 to 35 $\mu g/m^3$ to citywide TSP levels. Lynn et al.[3] found that the particulates, by mass, had an average of about 65 percent mineral matter versus about 25 percent combustion products. Denver and Oklahoma City, "both areas of dry climate with acknowledged fugitive dust problems," had averages of over 80 percent minerals. They concluded, "Even the cleanest cities (with respect to traditional sources) will be 30 to 40 $\mu g/m^3$ above the local nonurban levels due to nontraditional sources."

With respect to reentrained dust from paved roads, Lynn et al.[3] concluded, "The average impact on monitors reviewed in this study was about 10 to 15 $\mu g/m^3$ in residential areas and 15 to 20 $\mu g/m^3$ in commercial and industrial areas...."

Lynn et al.[3] found it difficult to specify the contribution of dust from unpaved roads: "...the current emission factors given in AP-42 provide emission estimates that can be up to 30 times the emissions from traditional sources." Table 1.2[3] shows emission inventory (not air sample analysis) estimates of emissions from unpaved roads and from traditional sources for fourteen major counties in the United States. Unpaved road emission estimates ranged from much larger than to much smaller than those of traditional sources, from city to city. It was noted that unpaved road emissions and traditional emissions have different particle sizes and release heights and therefore may not make the same contribution to airborne concentrations per mass emitted.

Lynn et al. also concluded that construction activities can be important:[3] "Monitors within half a mile of construction may have annual geometric means 10 to 15 $\mu g/m^3$ higher than normal. On an annual basis, the effect on the citywide TSP level is expected to be only 1 to 3 $\mu g/m^3$ .... As with reentrained dust from unpaved roads, the currently available emission factors for construction activity provide estimates of fugitive dust emissions well above what would appear logical in terms of the TSP

TABLE 1.2. COMPARISON OF FUGITIVE DUST EMISSIONS FROM UNPAVED ROADS WITH TRADITIONAL SOURCE EMISSIONS IN MAJOR COUNTIES OF 14 AQCR'S [3]

AQCR	Major county	Emissions from unpaved roads, tons per year	Emissions from traditional sources, tons per year	Ratio
Baltimore	Baltimore City[a]	510	7,000	0.07
Birmingham	Jefferson	193,000	110,000	1.75
Chattanooga	Hamilton	N.A.	10,300	—
Cincinnati	Hamilton	76,990	56,100	1.37
Cleveland	Cuyahoga[a]	18,800	210,000	0.09
Denver	Denver[a]	1,270	9,700	0.13
Miami	Dade	70,940	8,000	8.88
Oklahoma City	Oklahoma	85,920	2,600	33.55
Philadelphia	Philadelphia[a]	2,660	31,600	0.08
Providence	Providence	139,830	7,800	17.88
San Francisco	San Francisco[a]	660	4,800	0.14
Seattle	King	197,770	7,300	27.17
St. Louis	St. Louis City[a]	1,220[b]	15,600	0.08
Washington, D.C.	District of Columbia[a]	100	5,600	0.02

[a]These counties are almost totally urbanized so the travel on unpaved roads is expected to be minimal.

[b]This represents the emissions from St. Louis County, a much larger, less urbanized area; actual reported emissions for St. Louis City were 159,900 tons/year suggesting a coding error confusion with the county.

levels actually observed."

Figure 1.4 and Table 1.3 summarize the estimates by Lynn *et al.*[3] of the impact of non-traditional sources on air quality. (They cited a figure of 0.66 million tons of vehicle tire tread wear per year, which is a much smaller mass rate than those of the major open sources we have identified; these particles were generally the largest found on the filters and there is some question as to their true contribution to the mass concentration.) Table 1.3[3] gives particle size information on minerals, combusion products, biological material, and rubber from the 300-filter analysis.

Confirmatory evidence that soil-like particulates are major contributors to the TSP levels in cities as well as rural areas came from work recently published by Klappenbach and Goranson[5]. Noting that 15 October 1976 had many reported TSP values (24-hour samples) exceeding secondary (150 μg/m^3) standards, they analyzed by microscope material caught that day on the filters of hi-vol samplers for six sites: Fish Creek, WI; Madison, WI; Milwaukee, WI; Chicago, IL; Moline, IL; Peoria, IL. The particles were examined and identified as to chemical type (such as quartz, fly ash, spores, salt) and the percentages (by count) were listed by the detailed descriptions under four rather general categories: minerals, combustion products, biological materials, miscellaneous. The minimum detectable particle size was estimated to be 1-2 μm. The percentages attributed to minerals (the kind of material emitted by open sources) ranged from 72 percent (Fish Creek, WI) to 91 percent (Moline, IL; Milwaukee, WI); the Chicago value was 84 percent. The authors conjectured that agricultural activity was responsible, but their evidence was inconclusive. It was, however, a period in the area which was more dry and more windy than average, which would increase emissions from agriculture, roads, and construction.

Almost all open sources are at ground level. If, as we believe, they contribute substantially to the ambient concentrations of particulates in the cities as well as in rural areas, then one would expect that urban concentrations would decrease from the ground level up. This is exactly what Pace *et al.*[4] found in a study of the concentrations measured by 31 high-volume air samplers in 7 urban commercial areas. Subtracting estimated nonurban and secondary particulate contributions, the residual concentrations were found to decrease with high height, following a relationship well-fitted (r^2=0.947) by the equation:

$$c(z) = b + a/z \qquad (10 \text{ ft} \leq z \leq 100 \text{ ft})$$

where

c(z) = adjusted concentration at z, μg/m^3

z = height of monitor above ground level, ft

b = 23.5 μg/m^3

a = 381.6 ft-μg/m^3.

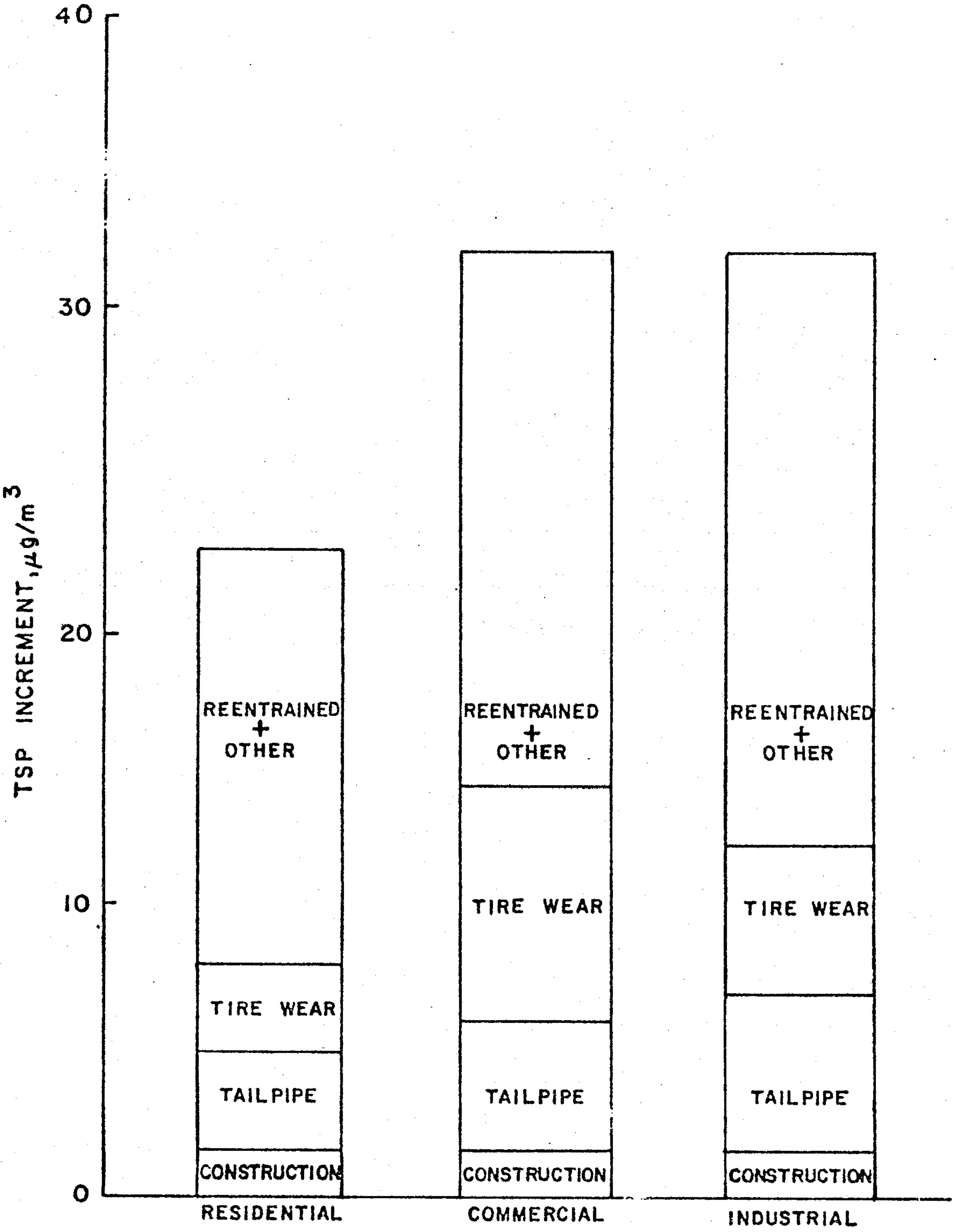

Figure 1.4. Nontraditional source increments at different site types.[3]

TABLE 1.3. ESTIMATES OF AVERAGE FILTER LOADINGS BY SITE CLASSIFICATION[a][3]

Components	Average loading, $\mu g/m^3$			
	Commercial	Residential	Industrial	Undeveloped
Mineral	64	51	87	66
Combustion products	27	19	42	6
Biological material	2	3	3	<1
Misc. (mostly rubber)	9	5	9	<1
Assumed < 1 μm	19	14	25	13
Total	120	92	166	86

[a]Based on a total of 300 filters analyzed.

TABLE 1.4. COMPOSITE SUMMARY OF PARTICLE SIZE BY COMPONENTS[a][3]

Component	Average size, μm	Average size range, μm	No. of filters included in averaging
Minerals	(8)	<1-62	153
Quartz	11	2-65	154
Calcite	9	1-45	148
Hematite	3	<1-39	89
Combustion Products	(5)	<1-58	92
Oil soot	13	4-106	107
Coal soot	30	6-66	52
Glassy fly ash	12	2-38	35
Biological Material	(24)	5-82	13
Pollen	35	13-39	15
Rubber	(43)	13-135	94

[a]Based on a total of 300 filters analyzed.

Pace *et al.* also analyzed data taken in other cities at different heights at the same sites. They concluded,[4] "roughly 12 to 20 $\mu g/m^3$ may be added to the concentrations at typical hi-volume sites due to the influence of nearby ground-level sources...."

Major open sources within the cities would include paved roads, unpaved roads, and construction. As Table 1.2 demonstrates, there are urban areas where the expected emissions from unpaved roads exceed those estimated to be emitted from "traditional" sources.

CONCLUSIONS

Emissions from unpaved roads greatly exceed those from point sources. In relatively dry regions of relatively high traffic density, they can be controlled for as little as $0.01/lb. Other open sources which rival point sources in magnitude are: construction emissions, wind erosion of cropland, and emissions from paved roads. Controlling such sources may be more cost-effective in reducing TSP concentrations than controlling point sources further. Whether such a strategy would also be optimal in a cost-benefit sense depends upon factors yet to be determined: transport of particulates and their relative toxicities, the value of increased life expectancy, the costs of alternative methods of saving lives.

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SECTION 2

DEFINING GOALS

INTRODUCTION

To set priorities, one first needs to identify one's goals. In air pollution control these are the reduction of air pollution damages in an economical and equitable manner. Because of the complexity of the source-transport-receptor-effects-valuation chain in air pollution control, often the criteria for choosing one approach over another represent rather imperfect surrogates for the optimally economic and equitable reduction of damage. This is discussed at greater length next.

DECISION FRAMEWORK

Figure 2.1 (from Deininger[1]) presents a general decision framework for decisions about control technology and regulations. This information would be required for determining whether the added cost of the controls/regulations was justified by the added benefits. Considerations of equity would also enter into such a decision. The major aspects of the decision framework are:

1. sources - emissions types, sizes, locations, future growth;
2. transport - concentrations created in time and space;
3. receptors - population magnitude and distribution;
4. effects - dose-response relationships;
5. impact - value and implications of effects and controls.

An approach to optimal control would be to use cost and benefit estimates for each alternative. Benefit estimation is quite difficult, however, and should involve equity considerations, which are unfortunately still subjective. A cost-effectiveness approach is less complete, but more tractable: this indicates the minimum cost to reach any particular set of conditions. For example, it could be determined what the minimum necessary cost was for achieving the National Ambient Air Quality Standards for a city like New York through a linear programming analysis.[1] Another cost-effectiveness example would be the determination of the maximum reduction of unpaved road emissions which could be obtained for one (or several) level(s) of expenditure; this we have done in Section 5.

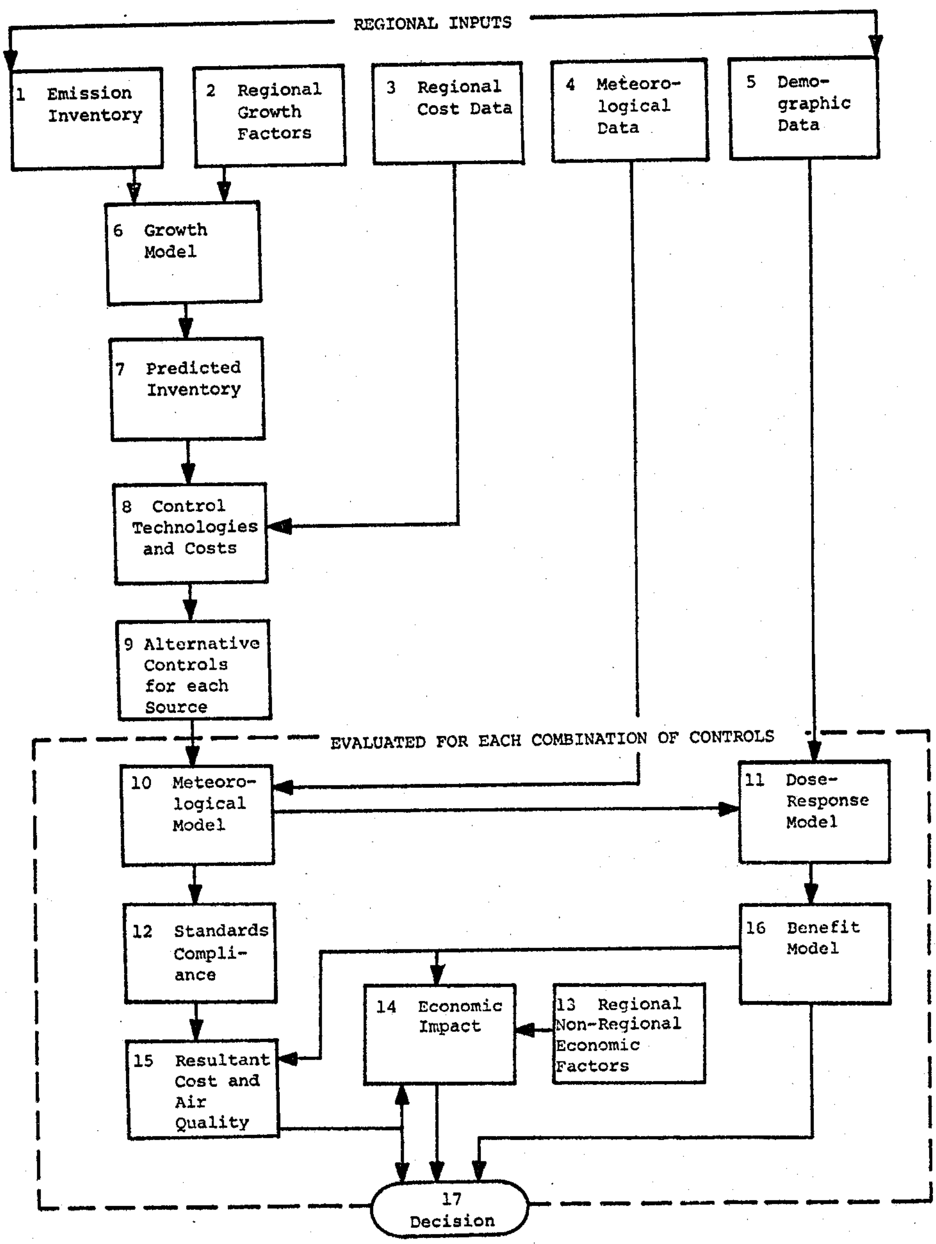

Figure 2.1. General decision framework for air pollution control.[1]

Ideally, then, we would like information about the reduction of damages from various policies. Short of that we would prefer, in descending order:

-reduction of doses

-reduction of concentrations

-reduction of emission rates.

The cost-effectiveness approach, which we use here, would then ask for the maximum reduction achievable at various expenditures.

The sources and the costs of controlling them vary greatly geographically. It may be much more cost-effective to control unpaved road emissions in one region than another, for example. In some sense, the more detailed information we could provide about open sources, the better for those who have to make control decisions, but this is offset by information limitations as well as by the financial and manpower resources available for this project. We have chosen to aggregate to the state level; the states have primary responsibility in pollution control, so that those making the decisions based partly upon information in this document may well have responsibility at the state level, and the state-wide figures may be of most use.

CONCLUDING REMARKS

This investigation of the setting of priorities in open source control has led to the identification, state by state, of open sources contributing most to the total emission emission rate of the state. Further analysis is required to approximate the costs and benefits of control to make an optimal decision. For the overwhelmingly largest of these emitters, unpaved roads, we have performed a cost-effectiveness analysis (Section 5) to set priorities among the states for control and to serve as an illustration of the cost-effectiveness approach we recommend.

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SECTION 3

PROBLEM IDENTIFICATION

INTRODUCTION

One approach to systematic problem solving involves determination of goals, identification of problems, specification of criteria, evaluation of alternatives, implementation of the alternative selected, and monitoring of the performance of that alternative. This section is directed to characterizing some aspects of the problem of open sources of particulate emissions.

Three elements of air pollution are the sources, the transport of the material, and the effects on receptors. An optimizing approach to air pollution control would involve minimizing the effects (weighted for value) at a given budgetary level, or --- better yet --- continuing to add to control until the marginal cost of additional control just matched the marginal benefits of that control. Because of the complexity of evaluation of dose-response relationships and even of predicting dose given the sources, the approach taken in this study has been to focus on reduction of the emissions rather than reduction of the concentrations, the effects, or the cost of the effects.

We do not think that priorities for pollution control should be set solely on the basis of emission rates. Information on control costs and benefits and other impacts is clearly needed. However, to decide on which of the open sources we should first gather such additional information, we were strongly influenced by the dominant emission rate from unpaved roads, so that our cost-effectiveness investigation focused on this source.

We have divided emissions into those which are particularly harmful ("toxic") and those which are not particularly harmful, though not necessarily harmless. Industrial hygienists, for example, distinguish between "nuisance dusts" and those that are more toxic. We have adhered to the same distinction. Toxic substances are discussed in Appendix D. In this section, we deal with emissions which are not especially toxic, akin to "nuisance dusts" though not necessarily synonymous with them.

Emission rates are the masses of material emitted per period of time. Emission factors give the emission rates per unit of source extent. The determination of emission factors and source extents done for this study is described in Appendices A and E, and more information will be made available on request. This section presents emission rates by state for the major anthropogenic open sources of particulate emissions.

EMISSION FACTORS

The derivation of these is outlined in Appendix A, and they are presented by state in Table 1 of that appendix.

SOURCE EXTENTS

These, too, are explained in Appendix A; they are listed in Table 2 of that appendix.

EMISSION RATES

In Table 1.1 are presented the emission rate totals for the major open sources we identified. A partial listing of the state-by state emission rates appears in Table 3 of Appendix A. The general categories are: agriculture, construction, fires, mineral industries, and roads. As indicated in Table 1.1, unpaved road emissions were an order of magnitude larger than those from any other source, but the estimation of their magnitude is quite difficult (see Appendix A), thus suspect. Next largest were the rates from agriculture and from construction, followed by emissions from paved roads, wild fires, and the extraction of minerals. Relatively small contributions came from mineral tailings piles and from prescribed burning.

The national totals are less useful for control implementation than are the state totals, on which we concentrate in this section. The Clean Air Act of 1970 requires the states to develop State Implementation Plans to meet the National Ambient Air Quality Standards for criteria pollutants, including "total suspended particulates" (TSP). Therefore, much of the control decision-making takes place at the state level. Furthermore, as will be seen, the states differ greatly one from another, so that a major source in one state may well be minor in another.

To facilitate the presentation of the emission rate estimates by computer, we present in Table 3.1 an explanation of the lables used in the four succeeding tables. The emission estimates are for the masses of particulates smaller than about 30 μm in diameter and of specific gravity 2.5, which is equivalent to particles smaller than about 48 μm in aerodynamic diameter. Although these are thought to be the correct criteria for describing particles captured in the standard Hi-Vol used for measuring total suspended particulates, only particles smaller than about 10 μm aerodynamic diameter are respirable and capable of being transported miles or more under usual atmospheric conditions. Thus, a substantial portion of the mass of particulates emitted by open sources as indicated in these tables may not make an important contribution to the hazards of air pollution or even to the measures of total suspended particulates miles away from where they are generated.

Table 3.2 gives the emission rates for tilling, wind erosion, construction, wild fires, and prescribed fires. Table 3.3 continues these

TABLE 3.1. TERMS USED IN TABLES 3.2 to 3.6

AREA: State area, land and water, in thousands of square miles.

CONSTRUCTION: Emissions due to construction activities.[a]

EXTRACTION: Emissions from overburden removed to facilitate surface mining.

NON-ROAD: TOTAL minus the sum of PAVED and UNPAVED ROADS; in other words, the non-transportation contribution.

PAVED ROADS: Emissions from transportation over paved roads, due to re-entrainment of surface dirt.

POPULATION: State population, in millions.

PRESCRIBED FIRES: Emissions due to fires set for agricultural or silvacultural reasons.

TAILINGS: Emissions due to the re-entrainment of dust from tailings piles.

TILLING: Emissions due to tilling cropland.

TOTAL: Sum of the emission rate estimates from all major anthropogenic open sources of particulates.

UNPAVED ROADS: Emissions due to transportation over, and wind erosion of, unpaved roads due to re-entrainment of surface material.

WIND EROSION: Emissions due to wind erosion of cropland.

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a. Note: all emission rates are in thousands of tons per year (909 x 10^3 kg per year).

TABLE 3.2. STATE EMISSION RATES: TILLING, WIND EROSION, CONSTRUCTION, WILD FIRES AND PRESCRIBED FIRES

State	Tilling	Wind Erosion	Construction	Wild Fires	Prescribed Fires
AL	5.30	47.5	273.	102.00	15.60
AK	0.10	0.0	59.	646.80	0.00
AZ	117.00	713.1	139.	28.50	5.20
AR	14.60	159.3	141.	94.50	4.10
CA	126.00	3945.8	4854.	218.80	21.20
CO	158.00	881.6	117.	25.00	0.50
CT	0.50	4.1	333.	1.00	0.00
DE	0.60	8.6	10.	0.05	0.04
FL	5.00	92.2	766.	316.60	71.90
GA	8.45	91.5	455.	41.30	54.30
HI	2.30	0.0	62.	0.00	0.00
ID	88.80	987.8	24.	544.00	45.40
IL	151.00	1721.4	1415.	11.40	0.00
IN	52.40	842.6	773.	8.90	0.00
IA	142.00	2077.7	253.	1.90	0.00
KS	239.00	4769.0	245.	65.80	0.00
KY	15.10	122.1	270.	62.50	0.00
LA	14.40	90.7	870.	73.00	16.60
ME	1.20	10.4	87.	2.50	0.00
MD	2.10	44.6	128.	1.40	0.00
MA	0.50	6.4	1260.	8.40	0.00
MI	21.20	410.7	743.	7.70	0.30
MN	99.30	1610.6	452.	30.80	0.00
MS	12.90	71.9	138.	78.60	12.70
MO	61.70	858.8	346.	119.80	0.00
MT	200.00	1264.1	31.	99.60	52.90
NE	306.00	5218.9	197.	20.00	0.00
NV	68.00	1157.1	22.	14.80	0.00
NH	0.40	0.5	69.	0.46	0.00
NJ	1.60	15.7	844.	23.50	1.50
NM	50.30	842.3	61.	19.90	1.40
NY	20.10	149.6	1462.	6.00	0.00
NC	6.30	118.2	640.	75.10	8.80
ND	292.00	3553.3	80.	0 47	0.10
OH	44.20	822.8	1365.	5.20	0.00
OK	89.00	1177.9	332.	115.80	0.00
OR	39.40	48.2	212.	196.50	21.60
PA	21.60	81.6	2090.	12.90	0.00
RI	0.10	0.9	82.	0.70	0.00
SC	4.30	54.0	177.	43.60	29.10
SD	210.00	3119.6	39.	4.80	0.00
TN	10.90	41.2	333.	27.70	0.00
TX	386.00	5000.7	3760.	19.10	6.20
UT	78.40	653.4	203.	10.00	0.00
VT	1.90	8.1	17.	0.20	0.00
VA	5.30	71.0	212.	5.60	3.90
WA	14.60	64.3	447.	164.30	56.80
WV	2.84	5.6	215.	74.20	0.00
WI	49.00	663.1	218.	6.90	0.00
WY	56.30	638.8	59.	8.30	0.00

TABLE 3.3. STATE EMISSION RATES: MINERAL EXTRACTION: COAL AND OTHER, TAILINGS, PAVED AND UNPAVED ROADS

State	Extraction: Coal	Extraction: Other	Tailings	Paved Roads	Unpaved Roads
AL	16.9	39.3	1.1	149.	3760.
AK	0.6	127.0	0.0	11.	1990.
AZ	0.2	187.0	156.7	92.	9740.
AR	0.4	38.0	1.0	73.	9340.
CA	0.0	171.0	141.5	803.	27530.
CO	0.2	33.8	17.0	89.	10080.
CT	0.0	15.1	0.4	117.	320.
DE	0.0	2.4	0.0	23.	70.
FL	0.0	235.0	2.6	386.	7010.
GA	0.0	54.6	1.3	212.	7010.
HI	0.0	9.0	0.0	26.	80.
ID	0.0	17.8	30.9	30.	4120.
IL	49.5	104.0	5.5	370.	7960.
IN	20.2	58.1	2.6	229.	6450.
IA	0.5	49.4	4.8	104.	11310.
KS	0.6	28.5	22.5	78.	14330.
KY	116.6	36.6	2.1	146.	4380.
LA	0.0	24.5	0.4	121.	3790.
ME	0.0	5.4	0.2	43.	710.
MD	2.0	30.5	0.8	154.	710.
MA	0.0	25.7	0.5	182.	680.
MI	0.0	139.0	6.7	345.	8830.
MN	0.0	216.0	20.4	139.	11560.
MS	0.0	18.2	0.2	81.	4260.
MO	3.9	56.1	19.3	175.	10330.
MT	0.4	33.9	11.6	28.	773.
NE	0.0	16.9	2.8	56.	10610.
NV	0.0	36.8	142.2	21.	4890.
NH	0.0	6.8	0.0	32.	1250.
NJ	0.0	44.9	1.8	304.	1950.
NM	0.3	42.5	44.0	48.	10640.
NY	0.0	75.6	10.0	414.	5160.
NC	0.0	57.1	2.0	220.	3860.
ND	0.0	5.1	1.5	17.	8800.
OH	38.6	95.9	6.3	403.	3820.
OK	2.0	32.0	6.5	123.	11860.
OR	0.0	45.0	1.4	83.	12110.
PA	68.4	90.7	4.0	424.	10100.
RI	0.0	3.2	0.1	36.	390.
SC	0.0	24.3	0.6	126.	1350.
SD	0.0	12.4	5.3	24.	6370.
TN	6.4	56.0	1.5	191.	4380.
TX	0.0	116.0	25.9	476.	28640.
UT	0.2	55.8	118.0	42.	5410.
VT	0.0	5.3	0.7	18.	1180.
VA	29.2	58.7	3.9	214.	2340.
WA	0.1	38.1	0.7	137.	6710.
WV	87.1	14.6	1.2	60.	3920.
WI	0.0	53.9	2.9	176.	3310.
WY	0.6	17.9	5.9	19.	2440.

TABLE 3.4. STATE EMISSION RATES: TOTAL OPEN SOURCE EMISSIONS AND TOTAL NON-ROAD OPEN SOURCE EMISSIONS

States	Total	Non-Road
AL	4409.7	500.70
AK	2834.5	833.50
AZ	11178.7	1346.70
AR	9865.9	452.90
CA	37811.3	9478.30
CO	11402.1	1233.10
CT	791.1	354.10
DE	114.7	21.69
FL	8885.3	1489.30
GA	7928.4	706.45
HI	179.3	73.30
ID	5888.7	1738.70
IL	11787.8	3457.80
IN	8436.8	1757.80
IA	13943.3	2529.30
KS	19778.4	5370.40
KY	5151.0	625.00
LA	5000.6	1089.60
ME	859.7	106.70
MD	1073.4	209.40
MA	2163.5	1301.50
MI	10503.6	1328.60
MN	14128.1	2429.10
MS	4773.5	332.50
MO	11970.6	1465.60
MT	2494.5	1693.50
NE	16427.6	5761.60
NV	6351.9	1440.90
NH	1359.2	77.16
NJ	3187.0	933.00
NM	11749.7	1061.70
NY	7297.3	1723.30
NC	4987.5	907.50
ND	12749.5	3932.47
OH	6601.0	2378.00
OK	13738.2	1755.20
OR	12757.1	564.10
PA	12893.2	2369.20
RI	513.0	87.00
SC	1808.9	332.90
SD	9785.1	3391.10
TN	5047.7	476.70
TX	38429.9	9313.90
UT	6570.8	1118.80
VT	1231.2	33.20
VA	2943.6	389.60
WA	7632.9	785.90
WV	4380.5	400.54
WI	4479.8	993.80
WY	3245.8	786.80

TABLE 3.5. STATE POPULATIONS, AREAS, EMISSION RATES: TOTAL PER AREA, NON-ROAD PER AREA, TOTAL PER POPULATION, NON-ROAD PER POPULATION

STATES	POPULATION	AREA	TOTAL PER AREA	NON-ROAD PER AREA	TOTAL PER POPULATION	NON-ROAD PER POPULATION
AL	3.44	51.600	85.459	9.703	1281.9	145.55
AK	0.30	586.000	4.837	1.422	9448.3	2778.33
AZ	1.77	114.000	98.059	11.813	6315.6	760.85
AR	1.92	53.100	185.799	8.529	5138.5	235.89
CA	19.95	159.000	237.807	59.612	1895.3	475.10
CO	2.21	104.000	109.636	11.857	5159.3	557.96
CT	3.03	5.010	157.904	70.679	261.1	116.86
DE	0.55	2.060	55.675	10.529	208.5	39.44
FL	6.79	58.600	151.626	25.415	1308.6	219.34
GA	4.59	58.900	134.609	11.994	1727.3	153.91
HI	0.77	6.450	27.798	11.364	232.9	95.19
ID	0.71	83.600	70.439	20.798	8293.9	2448.87
IL	11.11	56.400	209.004	61.309	1061.0	311.23
IN	5.19	36.300	232.419	48.424	1625.6	338.69
IA	2.83	56.300	247.661	44.925	4927.0	893.75
KS	2.25	82.200	240.613	65.333	8790.4	2386.84
KY	3.22	40.400	127.500	15.470	1599.7	194.10
LA	3.64	48.500	103.105	22.466	1373.8	299.34
ME	0.99	33.200	25.895	3.214	868.4	107.78
MD	3.92	10.600	101.264	19.755	273.8	53.42
MA	5.69	8.260	261.925	157.567	380.2	228.73
MI	8.88	58.200	180.474	22.828	1182.8	149.62
MN	3.81	84.100	167.992	28.883	3708.2	637.56
MS	2.22	47.700	100.073	6.971	2150.2	149.77
MO	4.68	69.700	171.745	21.027	2557.8	313.16
MT	0.69	147.000	16.969	11.520	3615.2	2454.35
NE	1.48	77.200	212.793	74.632	11099.7	3892.97
NV	0.49	111.000	57.224	12.981	12963.1	2940.61
NH	0.74	9.300	146.146	8.297	1836.7	104.27
NJ	7.17	7.840	406.505	119.005	444.5	130.13
NM	1.02	122.000	96.309	8.702	11519.3	1040.88
NY	18.24	49.600	147.123	34.744	400.1	94.48
NC	5.08	52.600	94.819	17.253	981.8	178.64
ND	0.62	70.700	180.332	55.622	20563.7	6342.69
OH	10.65	41.200	160.218	57.718	619.8	223.29
OK	2.56	69.900	196.541	25.110	5366.5	685.63
OR	2.09	97.000	131.516	5.815	6103.9	269.90
PA	11.79	45.300	284.618	52.300	1093.6	200.95
RI	0.95	1.210	423.967	71.901	540.0	91.58
SC	2.51	31.100	58.164	10.704	720.7	132.63
SD	0.67	77.000	127.079	44.040	14604.6	5061.34
TN	3.92	42.200	119.614	11.296	1287.7	121.61
TX	11.20	267.000	143.932	34.884	3431.2	831.60
UT	1.06	84.900	77.395	13.178	6198.9	1055.47
VT	0.44	9.610	128.117	3.455	2798.2	75.45
VA	4.65	40.800	72.147	9.549	633.0	83.78
WA	3.41	68.200	111.919	11.523	2238.4	230.47
WV	1.74	24.200	181.014	16.551	2517.6	230.20
WI	4.42	56.200	79.712	17.683	1013.5	224.84
WY	0.33	97.900	33.154	8.037	9835.8	2384.24

emission rate estimates for mineral extraction and beneficiation (mill tailings) and for roads (paved and unpaved, including wind erosion of unpaved roads).

Table 3.4 presents the total anthropogenic open source emission rates of particulates and the non-road contribution to that total. Table 3.5 presents the 1970 populations of the states, their total areas, and emissions per population and per area. The material in Tables 3.2-3.5 is discussed next.

Total Emissions

Total emissions by state ranged from 115 thousand tons per year (Delaware) to 38,400 thousand tons per year (Texas), with the median value being 6,460. Figure 3.1 shows the histogram derived from these data. The intervals are 1000 thousand tons per year. Note that Texas and California together contribute 19 percent of the total emissions.

Emissions per area (tons per square mile per year) is another useful measure. If one were to formulate a simple box model for the air above the state, the concentrations would be proportional to the rate of emissions per area (of material which stayed suspended). These values ranged from 4.8 to 424 tons/sq. mi./yr. A measure of the relative dispersion of the values is the coefficient of variation (COV), the standard deviation divided by the mean. For the state total emissions, the COV was 0.95. If a major factor in the emissions were the area of the state, we would expect that total emissions per area would have a smaller COV, which it does, 0.60. The comparative coefficients of variation show that the states are more alike in their emissions per area than they are in their total emissions, not unsurprisingly. Figure 3.2 is a histogram of total emissions per area. The two largest values are for Rhode Island and New Jersey.

States differ greatly in population. Emissions per person indicate not only something about the relative contribution of individuals between states to the air pollution problem, but also the relative doses, to the degree to which concentrations correlate with emission rates. Figure 3.3 shows a histogram of emissions per population, which range from 208 to 20,500 tons/year/thousand, with a mean value of 3,884. The COV is 1.14. The three highest states are North Dakota, South Dakota, and Nevada, principally due to their unpaved road emissions and relatively small populations.

On a state-by-state basis, as well as on an aggregated national basis, the dominant contributor to our emission rate estimates is unpaved road emissions. Figure 3.4 shows total emissions versus unpaved road emissions, for the states. The correlation is evident; in fact, the correlation coefficient is $r=0.99$ and the coefficient of determination is $r^2=0.98$, indicating that 98 percent of the state-to-state variation can be "explained" by the variation in unpaved road emissions. The regression equation is

$$c12 = -107 + 1.30\ c10$$

where

c12 = total state open source emissions, 10^3 tons/yr

middle of interval	number of observations	
1000.	9	*********
3000.	6	******
5000.	9	*********
7000.	6	******
9000.	4	****
11000.	6	******
13000.	5	*****
15000.	1	*
17000.	1	*
19000.	1	*
21000.	0	
23000.	0	
25000.	0	
27000.	0	
29000.	0	
31000.	0	
33000.	0	
35000.	0	
37000.	1	*
39000.	1	*

Figure 3.1. Histogram: total emissions.

```
middle of   number of
interval    observations
    10.        2     **
    30.        3     ***
    50.        3     ***
    70.        4     ****
    90.        4     ****
   110.        6     ******
   130.        5     *****
   150.        5     *****
   170.        3     ***
   190.        5     *****
   210.        2     **
   230.        2     **
   250.        2     **
   270.        1     *
   290.        1     *
   310.        0
   330.        0
   350.        0
   370.        0
   390.        0
   410.        1     *
   430.        1     *
```

Figure 3.2. Histogram of state total emissions per area.

middle of interval	number of observations	
500.	13	*************
1500.	13	*************
2500.	5	*****
3500.	3	***
4500.	1	*
5500.	3	***
6500.	3	***
7500.	0	
8500.	2	**
9500.	2	**
10500.	0	
11500.	2	**
12500.	1	*
13500.	0	
14500.	1	*
15500.	0	
16500.	0	
17500.	0	
18500.	0	
19500.	0	
20500.	1	*

Figure 3.3. Histogram of state total emissions per population.

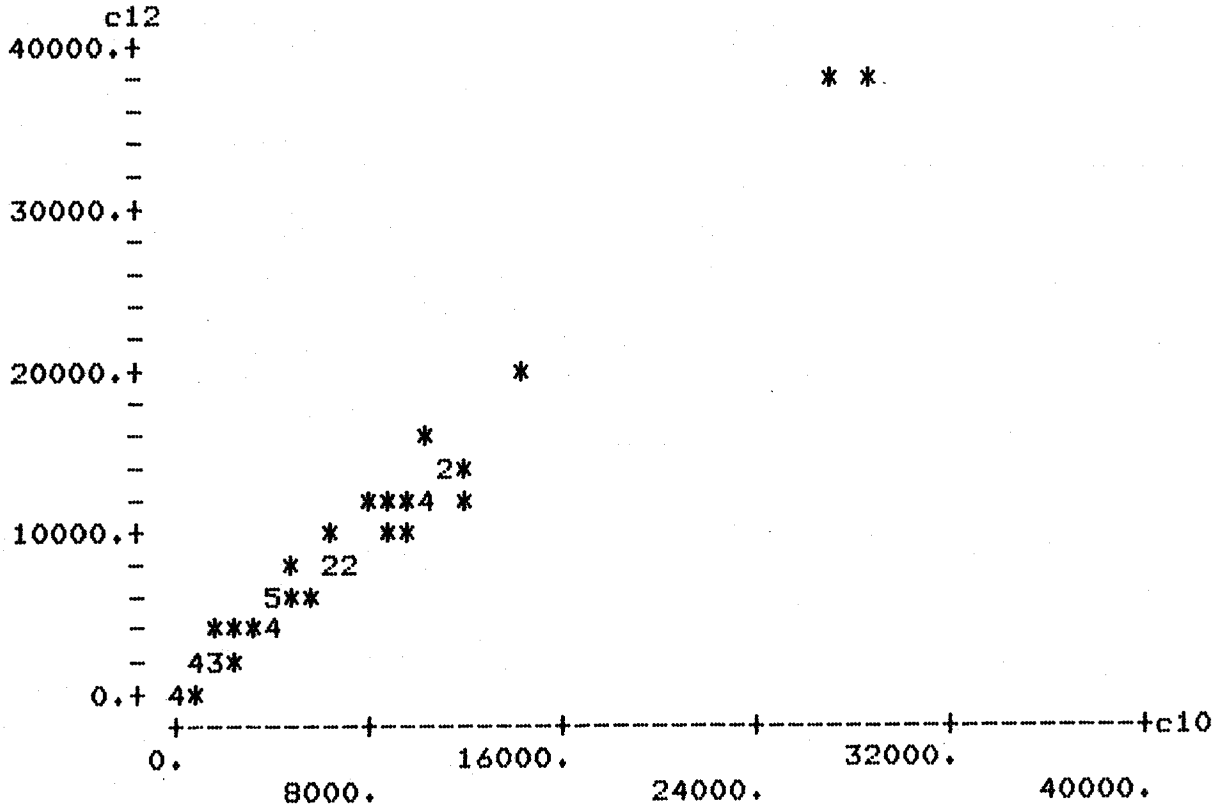

Figure 3.4. Total emissions by state (c12) versus unpaved road emissions (c10).

c10 = state unpaved road emissions, 10^3 tons/yr.

The intercept is not statistically significantly different from 0.0. Not only are unpaved roads the dominant source, but they tend to increase in rate when agricultural tilling and wind erosion increase, due to the climatic determinants the emission factors have in common. (See Appendix E.)

Paved roads also contribute substantially. The correlation coefficient for total emissions versus paved road emissions is r = 0.58. In turn, paved road emissions are strongly correlated with population (r = 0.95). Note that population and the emission rates for construction (r = 0.86) and unpaved roads (r = 0.48) have high correlation coefficient values. For example, $r^2 \geq 0.25$ means that the influence of population "explains" at least 25 percent of the variation among the states. A predictive linear equation for total emissions based just upon population and area accounted for 45 percent of the variation among the states ($r^2 = 0.37$).

Thus, unpaved roads are the dominant contribution to state emission rates, as estimated here. Along with paved roads, they contribute 84 percent of the estimated total emissions.

Non-Road Total Emissions

There is value in separating the total into transportation and non-transportation contributions. For one thing, if the emission rate estimates for unpaved roads are later shown to be greatly in error, the non-road estimates here would not be affected. Agricultural emissions, construction emissions, fires, and emissions from the mineral industries all are related to climatic conditions, although the relations differ. Where measures to reduce transportation emissions are infeasible, proposals for action might center on this broad group.

Figure 3.5 is a histogram of non-road emissions. They range from 21 to 9478 thousand tons per year, with a median of 1075 and a coefficient of variation of 1.23. These values and the histogram show that the emissions rates have great variation. In decreasing order, the states with the largest non-road rates are: California, Texas, Illinois, and Nebraska. In these states, the contributions are primarily from wind erosion of cropland and from construction. Accounting for irrigation would substantially lessen the California rate (Appendix F).

Wind erosion, the second largest source, is highly correlated with non-road emissions. We regressed the non-road emission rates (c15) versus the wind erosion emission rates (c4). The slope and the intercept of the following regression equation were both statistically significant ($P < 0.05$):

$$c15 = 488 + 1.32\ c3$$

where

c15 = non-road emissions rates, 10^3 tons/yr
c3 = wind erosion emissions rates, 10^3 tons/yr

middle of interval	number of observations	
250.	14	**************
750.	10	**********
1250.	10	**********
1750.	5	*****
2250.	3	***
2750.	1	*
3250.	2	**
3750.	1	*
4250.	0	
4750.	0	
5250.	1	*
5750.	1	*
6250.	0	
6750.	0	
7250.	0	
7750.	0	
8250.	0	
8750.	0	
9250.	2	**

Figure 3.5. Histogram of state non-road emissions rates.

The correlation coefficient was r = 0.81. It is this high partly because wind erosion emissions contribute heavily to the non-road emissions, partly because they covary with other important emissions.

The non-road emission rates are better correlated with the simple measures of extent, state area and state population, than were the total emission rates. For the non-road sources the regression equation for total emissions:

$$c15 = 154 + 241\ c13 + 7.33\ c14$$

where

c13 = state population, millions
c14 = state area, millions of square miles,

had a coefficient of determination $r^2 = 0.37$ (meaning it accounted for 76 percent of the variation). The intercept and the slopes were all statistically significant with the population being the most significant.

Having looked at the totals and the non-transportation totals, we next examine briefly the individual emission rates.

Agricultural Tilling

These rates depend primarily on soil type, climatic conditions, and acres of cropland harvested yearly. The five states with the largest emission rates (in decreasing order) are: Texas, Nebraska, North Dakota, Kansas, and South Dakota. The two states with the smallest are Alaska and Rhode Island.

Wind Erosion of Cropland

Wind erosion depends upon soil type, climatic factors, crop type and crop acreage, among other factors. The states with the five largest emission rates are (decreasing order): Nebraska, Texas, Kansas, California, and North Dakota. Accounting for irrigation would substantially reduce the rates for California (Appendix F).

Construction

These emissions were estimated from very approximate emission factors for the states, adjusted for type of construction, with source extents taken from construction activity types and expenditures. The top five state rates were (decreasing order): California, Texas, Pennsylvania, New York, and Illinois. The two smallest: Vermont and Delaware.

Paved Roads

As noted above, paved road emissions were very highly correlated with population. Thus the top five states are about as expected: California, Texas, Pennsylvania, New York, and Ohio. The rate for New York, the second most populous state, would be expected to be higher; Figure 3.5 shows paved road emission rates by state versus population, and it can be seen that New York's value lies well below the trend. This suggests there is relatively less driving per capita there than in most other states, due to demographic and socio-economic factors. The states with the least paved road emissions were Alaska and North Dakota.

Unpaved Roads

Texas produced only slightly more unpaved road emissions by our estimates than did California, followed by Kansas, Oregon, and Oklahoma. The least were produced by Delaware and Hawaii.

Wild Fires

The top five states are: Alaska, Indiana, Florida, California, and Oregon. The smallest two are Vermont and Delaware.

Prescribed Fires

The biggest five emission rate estimates were for: Florida, Washington, Georgia, Missouri, and Indiana; many states had negligible rates.

Minerals: Coal

Kentucky is estimated to have the greatest emissions rate due to coal mining, followed by West Virginia, Pennsylvania, Illinois, and Ohio. Many states had negligible coal mining emissions.

Minerals: Other Than Coal

Phosphate rock extraction helped make Florida the leader in this emission rate category, with the next highest being Minnesota (iron ore), then Arizona, California, and Michigan. The smallest are Rhode Island and Delaware.

Minerals: Tailings

The biggest five are: Arizona, Nevada, California, Utah, and New Mexico, all in the Southwest. The smallest two are Rhode Island and Maine.

Correlation Matrix

Table 3.6 contains all the correlation coefficients for the various possible combinations of emission rates. The first column is a list of the variables. The first row contains a similar list. The rest of the table gives the correlation coefficients. The first column of numbers has correlation coefficient values for the emission rates, etc., versus the "state numbers," the alphabetical rank of the state (Alabama=1, Wyoming=50). These state numbers should be essentially randomly associated with any of the other variables, but one of the numbers in the first column of coefficients would be significant at $P<0.05$ ($r>0.28$), which shows that if you test enough random

TABLE 3.6. MATRIX OF CORRELATION COEFFICIENTS

	State No.	Tilling	Wind Erosion	Construction	Wild Fires	Prescribed Fires
Tilling	0.053					
Wind Erosion	0.012	0.922				
Construction	-0.039	0.267	0.394			
Wild Fires	-0.319	-0.085	-0.055	0.022		
Prescribed Fires	-0.130	-0.059	-0.106	0.049	0.458	
Extraction: Coal	0.096	-0.137	-0.140	0.099	-0.080	-0.168
Extraction: Other	-0.257	0.083	0.123	0.469	0.271	0.217
Paved Roads	-0.067	0.056	0.192	0.889	0.001	0.131
Unpaved Roads	-0.067	0.630	0.707	0.688	0.072	0.029
Tailings	-0.139	0.203	0.246	0.275	0.035	-0.023
Total	-0.061	0.686	0.775	0.735	0.066	0.022
Population	-0.040	0.052	0.173	0.855	-0.051	0.029
Area	-0.169	0.286	0.254	0.186	0.643	0.049
Non-Road	-0.036	0.792	0.901	0.746	0.042	-0.012
Total per Area	0.037	0.098	0.208	0.325	-0.220	-0.200
Non-Road per Area	-0.044	0.205	0.301	0.351	-0.191	-0.199
Total per Population	0.093	0.578	0.531	-0.251	0.158	-0.109
Non-Road per Population	0.086	0.654	0.609	-0.185	0.161	-0.043

TABLE 3.6. (cont'd)

	Extraction: Coal	Extraction: Other	Paved Roads	Unpaved Roads	Tailings	Total
Extraction: Other	0.008					
Paved Roads	0.167	0.593				
Unpaved Roads	-0.053	0.468	0.542			
Tailings	-0.135	0.367	0.164	0.386		
Total	-0.051	0.458	0.575	0.989	0.382	
Population	0.170	0.517	0.953	0.478	0.137	0.517
Area	-0.134	0.360	0.028	0.322	0.207	0.329
Non-Road	-0.055	0.349	0.551	0.841	0.328	0.910
Total per Area	0.133	0.077	0.354	0.259	-0.095	0.276
Non-Road per Area	0.012	0.004	0.309	0.089	-0.066	0.167
Total per Population	-0.202	-0.131	-0.423	0.229	0.269	0.239
Non-Road per Population	-0.179	-0.157	-0.349	0.121	0.135	0.181

TABLE 3.6. (cont'd)

	Population	Area	Non-Road	Total Per Area	Non-Road Per Area	Total Per Population
Area	0.010					
Non-Road	0.516	0.322				
Total per Area	0.354	-0.291	0.277			
Non-Road per Area	0.340	-0.197	0.356	0.748		
Total Per Population	-0.401	0.366	0.285	-0.133	-0.044	
Non-Road Per Population	-0.318	0.347	0.369	-0.109	0.105	0.909

correlations, chance will produce some "significant" ones. In the remainder of the table, correlation coefficients greater than r = 0.5 have been underlined, not because they are statistically significant (though they are, at $P < 0.01$), but because the relationship is strong enough that it "explains" 25 percent or more of the variation in the two variates compared.

Inspecting the matrix, we find the following to have high correlations ($r \geq 0.5$):

1. Agricultural tilling emissions and: emissions from wind erosion, unpaved roads, total emissions, total per population, non-road and non-road per population.
2. Wind erosion emissions and: emissions from tilling, unpaved roads, total emissions, non-road emissions.
3. Construction emissions and: emissions from paved roads, from unpaved roads, total emissions, total per population, non-road, and non-road per population.
4. Wild fires and area.
5. Prescribed fires and none.
6. Coal extraction emissions and none.
7. Emissions from extraction of minerals other than coal and: emissions from paved roads, total emissions, and population.
8. Paved road emissions and: unpaved road emissions, total and non-road emissions, and population (as well, of course, as those named above: wind erosion, construction, and mineral extraction other than coal.)
9. Unpaved road emissions and: emissions from tilling, wind erosion, construction, paved roads, non-road emissions, and total emissions.
10. Mineral tailings and none.
11. Total emissions and: agricultural tilling, wind erosion of cropland, construction, mineral extraction other than coal, both paved and unpaved roads, population, and non-road emissions.
12. Non-road emissions and: all the same factors as for total emissions, except for wind erosion of cropland.
13. Population and: wind erosion of cropland, construction, paved and unpaved road emissions, and non-road and total emisssions.
14. Area and: wild fires.
15. Non-road total and: wind erosion of cropland, construction, paved and unpaved road emissions, tailings, and total emissions.

The large number of correlations and the fact that all those having r = 0.50 or larger are positive indicate that states with one open source emission problem have others as well.

CONCLUDING REMARKS

The state-by-state emission rate estimates presented here can be useful in setting priorities for control. Many of the emissions are correlated with other emissions as well, suggesting that those states with any open sources problem probably have several. The major emission sources were generally unpaved roads, wind erosion of cropland, construction, and paved roads.

SECTION 4

FIGURES OF MERIT

INTRODUCTION

Particles impair health, increase rates of weathering and corrosion of materials, contribute to the damage of vegetation, and decrease visibility. The decision to control open sources of emissions, and the selection of a strategy of control, affect society in two ways: the amount, type, and location of damage done by particles is altered, and resources are diverted from other uses to control open sources of emissions. In an ideal world, the optimal level of control would be easily determined. Control expenditures would be increased to the point at which the marginal social benefit (associated with emission reductions) was exactly equal to the marginal social cost (of reducing emissions). In this ideal world costs and benefits would be measured in units of social welfare, i.e., the system of measurement would incorporate simultaneous consideration of equity and economic efficiency. In the real world imperfect information prevents us from knowing how close our actual decisions are to these optimal decisions, and even with such information it might be impossible to achieve an ideal solution. Nonetheless, consideration of these abstract models may help us avoid grossly inefficient or inquitable social policies.

DOSE-RESPONSE RELATIONSHIPS

In order to develop an open source model useful in the selection of an optimal control policy, we would first consider the physical system's behavior, and later translate measures of physical performance into measures of social desirability. The elements of the physical system are: source, control system, transport system, and receptor. A control policy consists simply of the specification of which sources to control, the selection of a control method (and possibly, degree of control for each source requiring control)*.

*In a systems model we hope to relate measures of output (here, air pollution damages) to parameters of the system which we can vary (control system expenditures). To complete a systems model, it must be possible to mathematically describe the behavior of each component of the system.

As the value of any control policy is directly contingent upon reduction in physical damages to receptors, we feel that a brief discussion of the response of various receptors to particles is in order.†

As air is such a prevasive medium, it would be difficult to make a comprehensive listing of receptors. It is conceivable that certain organisms and/or materials benefit by the changes in air quality induced by man's activities. However, traditionally discussions of the "receptors" of "air pollution" have been limited to those materials and/or organisms which are thought to be adversely affected by air pollution, e.g.:

i. humans
ii. vegetation
iii. materials

Although a large number of crops (including potatoes, corn, tomatoes, green beans, lima beans, soy beans, grapes, oranges, tobacco, spinach, peanuts, and alfalfa) and many other plants are known to be injured by air pollution, oxidants (e.g.,ozone, nitrogen dioxide, and peroxyacetyl nitrate) and sulfur dioxide are most frequently implicated. Similarly, although Yocum and McCaldin[1] have identified damage to metals, building materials, paint, leather, paper, textiles, dyes, natural and synthetic rubber, glass, ceramics, and electrical equipment as a portion of the social costs of air pollution, sulfur dioxide, acid gases, and oxidants are the most frequently cited causes of damage.

In contrast, physiologists have identified three mechanisms by which exposure to particles could affect human health:

i. direct chemical or toxic action of the particle, per se; e.g., arsenic, lead, beryllium;

ii. indirect effects which are mediated by the physical properties of the particle; e.g., mucous flow, slowed ciliary beat, overloading macrophages, or penetration of the alveolar membrane;

iii. adsorption or absorption of gases or solutes, thereby increasing their effect by holding them more focally in the deeper portions of the lungs for longer periods of time.

Exposure to air pollution is thought to influence the rates of incidence and prevalence of disease, and to affect its severity. Asthma, emphysema, chronic bronchitis, respiratory infections, lung cancer, angina pectoris, arteriosclerosis, myocardial infarction, and conjunctivitis are diseases which are currently suspected of being induced (either directly, or indirectly by increasing susceptibility to a causal factor) or aggra-

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†Even if we were able to complete the physical systems model, a full social model would include evaluation of the social desirability of alternative policies. Currently there are both theoretical and practical limitations to attempts to place a value on reductions of mortality and morbidity, effects of great significance in any air pollution model.

vated by community air pollutants. This increased incidence, prevalence, and severity of disease is thought to indirectly contribute to reductions in life expectancy.

Although much effort of epidemiologists, toxicologists, physicians, biochemists, and physiologists has been devoted to the analysis of these relationships, many questions remain largely unanswered. These would include:

i. At the levels of air pollution which currently prevail in the U.S., how much (if any) additional life shortening is produced by each incremental unit of air pollution exposure?

ii. Which pollutants are responsible for any reductions in life expectancy or increments in morbidity?

iii. Are the observed effects due to chronic exposure to annual mean levels of pollution, or are all effects due to the occasional periods of peak exposure?

Until these issues are clarified, we are left simply speculating about the appropriate form of weighted human dose function. A few hypothetical weighted human dose functions are outlined here simply to illustrate the wide range of intuitively attractive alternatives.

FORM 1: $D_T = \int_o^T C_{TSP}\, dt$

FORM 2: $D_T = \int_o^T C_{mrp}\, dt$

FORM 3: $D_T = \int_o^T [C_{mrp} - K_{mrp}]dt$

FORM 4: $D_T = \int_o^T [C_{TSP} - K_{mrp}]^P dt$

FORM 5: $D_T = a_{cd} \int_o^T [C_{cd} - K_{cd}]dt + a_{B\alpha P} \int_o^T [C_{B\alpha P} - K_{B\alpha P}]dt + \ldots$

where

D_T = dose received in the interval t = 0 to t = T.

C_{TSP} = concentration of total suspended particulates

C_{mrp} = concentration of mass respirable particulates

C_{cd} = concentration of cadmium

$C_{B\alpha P}$ = concentration of benzo-α-pyrene

P = an unspecified exponent

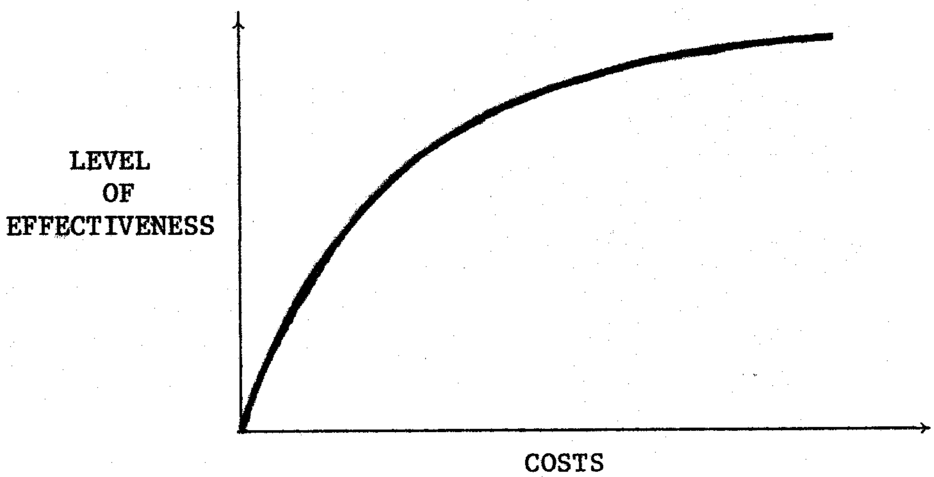
a = relative toxicity factor

K = a threshold for given pollutant

Clearly, more complex measures of dose (*e.g.*, including synergisms and antagonisms, non-linear relationships with concentration) may be required to adequately reflect human physiological response to particles in the atmosphere.

COST-EFFECTIVENESS CRITERION

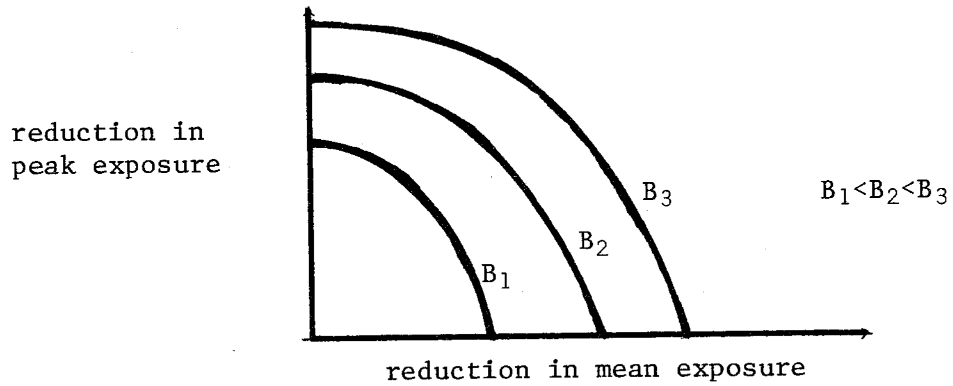
This uncertainty as to the response of the system to increased ambient concentrations of particles limits our ability to carry out a full cost-benefit analysis. We must be content with an analysis of the cost-effectiveness of alternative control strategies. In a cost-effectiveness analysis we seek to minimize the costs associated with achievement of a specified level of effectiveness. By combining several cost-effectiveness analyses, we can determine the minimum cost associated with any specified level of effectiveness. Alternatively stated, for any level of control expenditure we will know how to achieve the maximum level of effectiveness:



Many measures of effectiveness might be suggested: reduction of mean annual TSP concentrations, reduction of peak TSP concentrations, reduction of population-weighted TSP levels, reduction of inhalable particulate levels, reduction of respirable lead levels, reduction of asbestos emissions, reduction of frequency of exceeding a threshold TSP concentration, reduction of mass emissions of soil-like particles, reduction of emissions of particles with aerodynamic diameters less than 10 μm, or a weighted sum of these. In the selection of a criterion we balance two factors: the degree to which we believe the criterion is correlated with human response, and the amount of effort required to complete an analysis involving the criterion.* Relatively complex criteria are likely to be highly correlated with human response, but may require considerable computational efforts.

CONCLUSIONS

We recommend a sequential analysis of the open source problem. Attractive alternatives could be identified in a preliminary cost-effectiveness analysis using reduction of mass emissions of particles not significantly more toxic than soil as the criterion of efficiency.† In the second stage of analysis, promising alternatives could be more thoroughly investigated using a more sophisticated criterion, such as a weighted sum of reductions in population-weighted annual mean TSP exposures and peak TSP exposures. By allowing the weights to vary, a "production possibility frontier" could be sketched for each budgetary level (B_i):



In the following section, we apply the cost-effectiveness approach to the largest source of soil-like particles, reentrainment of road dust from unpaved roads.

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*In this balancing we must bear in mind that policies based on distant surrogates for human response may involve socially inefficient expenditures of control resources.

†This could be accompanied by a qualitative analysis of the feasibility of control and estimation of control costs for sources emitting potentially toxic particles, e.g., asbestos, lead, cadmium....

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SECTION 5

EVALUATION OF CONTROL STRATEGIES: COST-EFFECTIVENESS OF THE CONTROL OF UNPAVED ROADS

INTRODUCTION

Dust arises from unpaved roads through three mechanisms: wind erosion of the unpaved surface, action of the tires, and surface disturbance by the aerodynamic wake behind the vehicle. Heinsohn, Birnie, and Cuscino[20] note that estimates of crude emission factors range from 0.04 to 55.9 pounds per vehicle mile and postulate that the extreme variability in these estimates stems from underlying variability in:

1. speed and shape of the vehicle,
2. physical characteristics of the road surface,
3. meteorological conditions,
4. size distribution of the aerosol, and
5. uncertainty in sampling and estimation methods.

By parameterizing the emission factor, uncertainty can be separated from true variation. The emission factor currently sanctioned by the EPA includes such parameterization:[1]

$$E_o = (0.60)(0.81)(S_r)(\frac{S}{30})(1 - \frac{w}{365})$$

where

E_o = emission factor (lbs/veh-mi)
S_r = road surface silt content (percentage $\leq$ 75 μm diameter)
S = average vehicle speed (mph)
w = number of days per year with $\geq$ .01 inch of rain, or snow cover.

Considering the wide fluctuations in climate and soil types across the nation, it should not be surprising that the average emission factors for states vary from 3.9 pounds per vehicle mile in South Carolina to 13.2 pounds per vehicle mile in California.[2]

Generic methods of pollution control include alteration of the source, the transport mechanism or the receptor. In air pollution control, efforts have been concentrated on source control. Open source control is no exception. Widely-used methods of road dust control include paving, oiling, watering, and the application of calcium chloride. Speed reduction is often suggested as an emission control method, since emission factors increase at least proportionally with vehicle speed. Although many methods of chemical stabilization have been tested (and appear to be more effective than oiling), not enough data is available to permit evaluation of their cost efficiency. Briefly, we summarize the estimates of control cost and efficiency for each of the feasible control methods below.

CONTROL COSTS AND EFFICIENCIES

Paving

The term "paving" is very ambiguous. Paved surfaces vary from what is referred to by the industry as a "single chip seal" to portland cement surfaces over several inches of bituminous material. The costs of paving and the life of the paved surface will clearly depend not only upon the surface type, but also on the condition of the existing surface, traffic density, severity of climate, and regional costs of aggregate and labor. The estimates of initial cost and expected surface life which we have compiled are presented in Table 5.1. In order to facilitate comparison of these cost estimates we have inflated capital costs to equivalent mid-1977 levels using the "bituminous surface cost index," and have made similar adjustments in the annual operations and maintenance figures on the basis of the "highway operating and maintenance price index."[8,9] These estimated 1977 equivalent costs are shown in brackets.

The efficiency of paving as a control method depends very directly upon the characteristics of the unpaved surface being considered for treatment. By simply comparing the range of emission factors for paved and unpaved roads developed by Chatten Cowherd et al. at Midwest Research Institute, we can begin to estimate the range of control efficiency:[2,10]

	paved emissions		
	industrial	residential	commercial
unpaved emissions	.0243 lb/veh-mi	.0108 lb/veh-mi	.0026 lb/veh-mi
South Carolina: 3.9 lb/veh-mi	99.38%	99.72%	99.93%
California: 13.2 lb/veh-mi	99.82%	99.92%	99.98%

In his M.S.E. thesis, J.W.Roberts presented emission factors for:[3]

- a gravel road	6.0-8.1	lbs/veh-mi
- a paved road without curbs	0.83	lbs/veh-mi
- a paved road with curbs-flushed weekly and swept bi-weekly	0.14	lbs/veh-mi

These data indicate that simple paving of the main road surface might yield 86 percent or more reduction of emissions, and that the addition of curbs in combination with periodic cleaning could bring the efficiency above 98%.

Watering

High rates of infiltration and evaporation combine to limit the general effectiveness of watering as a long-term means of dust supression. Nonetheless, it may be an appropriate control method for short-term supression of nuisance dust, such as during highway construction. Support for these beliefs is

TABLE 5.1. COST ESTIMATES FOR PAVING UNPAVED ROADS

Surface Type	Initial Cost ($/mile)	Life (yrs)	Change in Operating and Maintenance Costs ($/mile/yr)	Year	Source
1. 3" asphalt	26,400 [40,890]*	20	-2665[-3627]gravel	1973	Roberts[3]
2. low-type bituminous	-	5-12	-124[-267]gravel +219[+471]macadam	1965	Winfrey[4]
3. high-type bituminous	-	12-20	+195[+419]gravel +538[+1158]macadam	1965	Winfrey[4]
4. double bituminous	-	-	-1365 gravel	1977	Mississippi[5]
5. asphalt bituminous	-	-	-1020 gravel	1977	Mississippi[5]
6. 2" hot bituminous	19,000	3	-	1978	North Dakota[6]
7. "hot mix"	15,134[15,470]+6278[6417] per mi paved	-	-	1975	Vermont[7]

*Figures in brackets are the corresponding dollar value in mid-1977 dollars.

found in both the open literature and the correspondence we received from the state highway departments:

> "...watering is not a feasible method of effective dust control on public roads because of the high frequency of treatment required. However it may be used advantageously on unpaved roads under special circumstances..." - Jutze and Axetell[11]

> "Water, as a means of controlling dust is too costly, time consuming, and ineffective to use when dealing with the many miles of non-hard surfaced roads we have. This is due to the quick evaporation of water, therefore necessitating many applications..." - State of Virginia[12]

To provide some quantitative basis for comparison of watering with other control methods, we cite the 1978 estimate of the State of North Dakota, "The average cost of water is $200/mile/day and, rating effectiveness, on a scale of 1-10 rates about 4."[6] Using this daily cost, and assuming that is used as a permanent control watering would be required on each dry day of the year, we find annual costs ranging from $41,400/mile in West Virginia to $62,800/mile in Arizona. Regional variations in water prices, which are not considered here, would be expected to increase the geographic variation in these annual costs.

Oiling

Oil may either be sprayed onto the road surface, or it can be mixed into the top few inches of surface material. Recycled oils, standard commercial oils, or specially formulated dust control oils, which typically are petroleum resins cut back with light hydrocarbon solvents, may all be used for dust control. Although oiling may intuitively seem an attractive intermediate between watering and paving, practice does not seem to support intuition:[11]

> "Application of a surface chemical treatment for dust suppression is a relatively inexpensive control method. However, in tests on public roads conducted by several different highway departments, no commercial material has been found which retains its effectiveness over a reasonable period of time (e.g., two months) under traffic conditions.... An alternative intermediate in cost and effectiveness between paving and surface treatment is working the stabilization chemicals into the roadbed to a depth of two to six inches. This construction technique has been used extensively in the San Joaquin Valley, where locally available petroleum by-products provide a cheap material for oiled earth roads... the results so far are not encouraging. The construction cost approaches that of a single bituminous chip seal surface, and the resulting road has a shorter lifespan with comparable maintenance..."

From our correspondence with state highway departments, it appears that oiling is not even particularly attractive for short-term control of dust:

"On construction projects where temporary gravel roads are being maintained, watering seems to be the most cost-effective. Normally a contractor is given the option to either water or oil the road and he usually elects the watering option." - State of Michigan[13]

"Very little dust oil has been used in our State...we require watering during construction..." - State of South Dakota[14]

Estimates of the cost and effectiveness of various methods of oiling for dust control are presented in Table 5.2.

The costs in brackets in Table 5.2 were adjusted to mid-1977 price levels using the "refined petroleum products index" to adjust materials costs, and the "general index of hourly and weekly earnings" to adjust applications costs.[17] Estimates of the required frequency of application necessary to maintain desirable surface properties and continuous control of dust are sparse, and highly varied. Whereas Roberts's estimate[3] of the average life of an oiled surface is four to six years, Sultan states that oil controls dust effectively for at most 25 days. An estimate of the difference in annual maintenance costs for gravel and oiled road surfaces is provided by Roberts[3]: gravel, $2910/mile; oiled, $1106/mile.

The control efficiency of oiling has been reported to be between 50 and 90 percent, as indicated in Table 5.2 presented below. Although we have not seen data reported in this form, it would seem clear that for any material and method of application the average efficiency of control is a function of the frequency of application.

Calcium Chloride

Calcium chloride has a deliquescent effect. At any relative humidity above 29 percent it will absorb moisture into the road surface from the atmosphere. In addition to the direct reduction of emissions due to this increased soil moisture, soil stability is increased as a result of compaction of clays. In arid and semi-arid regions it has found widespread application, as it is relatively effective and inexpensive. In regions which undergo frequent wetting and drying, it is impractical since calcium chloride is readily leached from the treated road surface.

The information which we obtained in correspondence from the state highway departments permits estimation of the cost and effectiveness of this control method:

"...Calcium chloride is used in special cases and works best when the humidity is high. It costs $400/mile/week [1978] and rates 6 [on a scale of 10]. Calcium chloride is considered one of the best and most economical methods of dust control...." - State of North Dakota[6]

"Presently the bulk of our dust control is done with calcium chloride... A calcium chloride treatment of one pound per square yard costs approximately 5¢...." - State of Virginia[12]

TABLE 5.2 COST ESTIMATES FOR OILING UNPAVED ROADS

Material	Method of application	Control efficiency	Cost ($/mile/application)	Year	Source
1. PS 300 oil	not specified(n/s)	n/s	2000[3202]	1973	Roberts[3]
2. Standard® Dust Control Oil	0.5 gal./sq. yd. - sprayed	(98%)	1100-3153[2650-7597]	1974	Sultan[15]
			+1492[1930]cost of application	1973	Roberts[3]
3. oil	not specified	n/s	5950	1978	
4. emulsified asphalt	not specified	(80%)	2000	1978	
5. Standard® Dust Control Roil	0.5 gal./sq. yd. - mixed 3 inches followed by 0.1 gal./sq. yd. spray	(88-91%)	1320-3784[3181-9117]	1974	Sultan[15]
			* +1472[>1930] application	1973	Roberts[3]
6. not specified	a. applied to prepared surface	(50%)	2000-3000[3322-4164]	1974	Jutze and Axetell[11]
	b. applied to unprepared surface	(50%)	1000-2000[1661-3322]	1974	"
	c. worked into the roadbed	(50%)	5000-12000[8305-19932]	1974	"

If these treatments were repeated weekly, the annual costs of application per mile treated would be $20,800 in North Dakota and $38,116 in Virginia.

A commercially available material, known as Soil-Lok, combines the properties of calcium chloride with those of sodium silicate. Experiments in arid regions demonstrated that sodium silicate is a very good dust-proofing agent. Sodium silicate is a good inorganic cementing material capable of bonding or hardening the soil. In combination, the two chemicals react within the sand pores to form an impervious gel which hardens, binding the sand particles into a solid mass. Although Sultan reported that Soil-Lok showed no damage after six months and that it affords good protection against wind erosion, he did not provide any information on costs or resistance to traffic and rain.[15]

Speed Control

As emission factors vary at least proportionally with vehicle speed, speed control is often suggested as a means of reducing dust emissions from unpaved roads. Although some have naively suggested that the only costs associated with speed control are the costs of administration and enforcement, we believe that social costs are imposed in the form of increased travel times.

The increased travel times are easily calculated. Using 40 mph as a reference, we can see that 0.5 minutes per mile will be added to travel times by a reduction to 30 mph, and 3.0 minutes per mile by a reduction to 20 mph. In order to estimate the social costs associated with these increases, we must consider traffic densities and the economic value of this "lost time."

Winfrey[4] in 1969 recommended valuing generalized passenger car travel between $1.00 [$1.68] and $4.00 [$6.67] per car hour. The Interstate Commerce Commission (1965) estimated that the value of time losses for commerical vehicles varied from $3.65 [7.66] to $8.29 [17.39] per hour.[4] These values have been adjusted to mid-1977 price levels using the "index of general hourly and weekly earnings."[17]

The control efficiency which we attribute to various degrees of speed reduction follows directly from the functional form of the relationship between average vehicle speed and emissions. On the basis of proportional relationships developed by Cowherd et al. we would expect a 25 percent reduction in emissions with a decrease from 40 to 30 mph, and a 50 percent reduction if average speeds were reduced from 40 to 20 mph.[2] Other researchers have suggested non-linear relationships:

1. Jutze, Axetell, and Parker of PEDCo Environmental Specialists developed emission factors for six AQCR's in New Mexico, Nevada, Arizona, California, and Texas.[11] Their equation of best fit for vehicle-generated dust was:

$$E = 0.27 \times (1.068)^S$$

where: E = emission factor (lb/veh-mi)
S = average vehicle speed (mph)

To this must be added a term accounting for wind erosion of the unpaved surface. This second term was derived from the empirical wind erosion equation of Woodruff and Siddoway[18]. Using a wind erosion rate of 3 tons/acre/year, or 9 tons/mile/year, we have combined wind and vehicle generated emissions of:

$$E = [0.27 \times (1.068)^S] + \frac{49.3}{ADT}$$

where: ADT = average daily traffic (veh/day)
and all other terms are defined above.

2. Roberts, Watters, Mangold, and Russano in Seattle, Washington developed the following emission factors for gravel roads:[2]

speed (mph)	observed emission factor (lb/veh.-mi)	estimated emission factor (lb/veh.-mi)
10	3.5	3.3
20	7.0	8.2
30	22.0	20.7
40	-	52.3

We have fit these data to the equation:

$$E = 1.29 \times (1.097)^S$$

Exploring these relationships, we see that Robert's data would suggest a 60 percent reduction in emissions accompanying a speed reduction from 40 to 30 mph, and a 84% emissions reduction with a reduction to 20 mph. The PEDCo data demonstrate the dependency of emissions reduction efficiency on traffic density:[11]

Speed Reduction	Average Daily Traffic		
	50	500	∞
40→30 mph	38%	47%	48%
40→20 mph	58%	71%	73%

Intuitively it might seem that speed reductions should be credited with reduction of the frequency and severity of accidents. However, we have not been able to find reliable data on accident frequency or severity as a function of average vehicle speed, applicable to unpaved roads.

COST-EFFECTIVENESS RATIO

From this basic information on the components of cost and anticipated efficiency of control we can compute a single number which characterizes the relative cost-efficiencies of the various control methods. Let us arbitrarily select a mile of unpaved road as the unit of interest.

First, we must adjust all costs to the same price levels. We have chosen to adjust to the levels which prevailed in mid-1977. Then we must combine the costs of capital investments with the recurring costs associated with maintenance. To combine costs which occur at different points in time, one can compute annualized cost. The total annualized cost is the average yearly cost of items which involve repeated yearly expenditures, such as maintenance, plus a yearly pro-rating of costs which do not, in fact, occur yearly, such as initial capital investment. To calculate the total annualized cost we add the average annual cost of operation and maintenance, AC, to the product of the capital recovery factor, CRF, and the initial capital investment, K. (The capital recovery factor is the percentage of the initial investment which one would pay yearly on a loan or mortgage, at an interest rate, i, for the life of the loan, n years.) The relevant equations are:

$$TAC = AC + (CRF)K$$

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

In Table 5.3 we summarize the range of estimates of the total annual costs of application of each of the feasible control methods to one mile of unpaved road. The figures in the table are based upon a discount rate, i, of 10 percent per year. Without further computation, it is clear that any method which has both higher annualized costs and lower control efficiency than some other method, can be culled. Similarly if one method has both lower annualized costs and higher control efficiencies than the others, it clearly dominates. Generally, however, it will be helpful to calculate a single index of relative cost-efficiency. In Table 5.4 we have divided the total annualized costs by the control efficiency of each method to derive such a measure. The wide ranges in these cost estimates reflect two influences: regional variation in the costs, lifetimes and efficiencies of control; and imprecision and uncertainty in the estimates of these parameters. In the face of uncertainty, an initial selection of the dominant control technology may be made by examining the mid-ranges of the cost estimates.

Although speed control from 40 mph to 30 mph appears to be economical for roads with low traffic density ($\leq$ 80 vehicles/day), for permanent or continuous reduction of emissions from roads with more typical traffic densities, paving appears to dominate, with a standardized total annual unit cost of $88.98/yr-mile-percent control, or $7653/yr-mile at 86 percent control efficiency. This analysis suggests that regardless of location or existing road surface type, by paving we can reduce mass emissions more for each dollar spent on control than through the application of any other control technique.

Now, if we are interested in maximizing the nation-wide reduction of dust emissions for various levels of national control expenditure, we must account for regional variations in emissions factors and traffic densities. For example, it is clear that paving a road in California (average statewide emission factor = 13.2 lbs/veh-mi) will reduce national dust emissions more than paving a road with similar traffic density in South Carolina (average

TABLE 5.3. ESTIMATED COSTS AND DUST EMISSION REDUCTIONS OF VARIOUS TREATMENTS FOR UNPAVED ROADS.

Control Method	Total Annualized Cost Estimates ($/yr /mile @ i=10%)		Range of Efficiencies (% reduction)
	low	high	
paving	-1,810	+16,861	86-99.98
oiling	-1,423	+291,413	50-98
watering	41,400	62,800	40
calcium chloride	20,800	38,116	60
speed control: 40 to 30 mph	5.08 x ADT	52.68 x ADT	25-60
speed control: 40 to 20 mph	30.60 x ADT	317.35 x ADT	50-84