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A Cost Evaluation of Alternative Air Quality Control Strategies

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A COST EVALUATION OF ALTERNATIVE AIR QUALITY CONTROL STRATEGIES

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ABSTRACT

A computer simulation is employed to evaluate three alternative particulate air pollution control strategies utilizing St. Louis as a model region with the following objectives:

(i) Quantification of the cost savings of two least-cost strategies based on alternative linear programming (LP) formulations -- an air pollutant emissions least-cost (ELC) strategy and an ambient air quality least-cost (ALC) strategy, and comparison of these minimum cost strategies with a third strategy suggested in the State Implementation Plan (SIP) Guidelines (typical of the strategies included in the plans submitted to EPA by the states).

(ii) Evaluation of the relative importance of two important characteristics of the regional air pollution problem -- the variation in marginal control costs from source-to-source and the variation in the impact a source may have as a function of location, stack height, etc.

(iii) Evaluation of the impact on total regional costs of increasingly stringent ambient air quality standards, with ambient quality levels ranging approximately from the primary to the secondary standard.

(iv) Derivation of the costs of alternative emissions tax strategies, based on the ELC and ALC solutions, which achieve the primary and secondary standards.

(v) Comparison of marginal costs and benefits of control at the primary standard.

The ELC strategy assumes a linear relationship between air quality and total regional emissions (i.e., that a given percentage reduction

in total regional emissions will give the same percentage improvement in air quality) and allocates the control burden on the basis of marginal control costs only. This assumption leads to the least-cost method of attaining a given reduction in total regional emissions. The ALC strategy produces the least-cost method of attaining prescribed regional air quality by considering individual source-receptor transfer coefficients (i.e., geographical location), as well as marginal control costs. These two degrees-of-freedom are found to be of roughly equal importance in determining least-cost solutions. That is, the ELC strategy captures only one-half of the total potential savings achieved by ALC in attaining a given air quality standard. In addition, the ALC strategy requires as little as one-tenth the expenditure of the SIP strategy which ignores both degrees-of-freedom. A policy which employs a single emissions tax based on mass emissions, rather than implementing the ALC solution to attain a desired air quality, sacrifices substantial savings since the emissions tax strategy can be no cheaper than the ELC solution. The inclusion of area sources and costs of standards enforcement may erode some advantage of the least-cost strategies over the SIP strategy, and of the ALC over the ELC approach.

A comparison of marginal costs and preliminary marginal benefit figures for health and welfare at the primary standard indicates that stricter control is economically justified. Marginal control costs for the entire region at the level of the secondary ambient air quality standard are found to be four times the marginal costs at the level of the primary standard.

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SECTION I

CONCLUSIONS

Particulate air pollution control strategies of the type included in the State Implementation Plan (SIP) Guidelines are six to ten times as costly in achieving a given level of air quality as an ambient least-cost (ALC) strategy which allocates the control burden on the basis of both individual source marginal control costs and source-receptor transfer coefficients (derived from dispersion parameters such as location, stack height, and other meteorological parameters). The ALC strategy, based on a linear programming (LP) solution, is the least-costly method of attaining ambient air quality standards.

A second LP solution, an emissions least-cost (ELC) strategy, allocates the control burden only on the basis of marginal control costs without considering the impact of variations in transfer coefficients, realizing approximately half of the cost savings of the ALC strategy. The ELC method produces the required reduction in regional emissions (as computed assuming ambient quality and total regional emissions are linearly related) at minimum cost, but only in the trivial case yields the minimum cost to achieve the corresponding ambient air quality standard. The cost of a single emissions tax based on mass emissions would approach that of the ELC strategy. Consideration of area source control costs, which make up 20% of the regional emissions, and strategy enforcement costs may reduce the advantage of the least-cost strategies over the SIP strategy and of ALC over ELC.

Comparison of marginal costs and preliminary marginal benefit figures for health and welfare at the primary standard indicate that stricter levels of control are economically defensible. Moving from the primary to the secondary standard, total regional control costs increase by a factor of four.

The problem-solving technique used in this analysis could be improved in several ways. An ideal formulation would be one which meets technical feasibility requirements and resource constraints, while including the intermedia and multipollutant impacts of control devices, i.e., marginal control costs, transfer coefficients, and several discrete control alternatives for each pollutant and source would ideally be included in a mixed-integer optimization program. However, the large number of source-device combinations would require years of computer effort if conventional techniques (e.g., branch-and-bound) were used. A heuristic approach could be adopted with the caveat that the solution is only an approximation (though hopefully a close one) to the optimum.

SECTION II

RECOMMENDATIONS

A number of recommendations can be made for future work in developing least-cost air pollution control strategies so that cost-benefit accounting will be more complete:

(1) Considerable reduction in the total cost of control can be achieved by utilizing the assimilative capacity of the ambient air.

(2) More research attention should be given to estimating the appropriate level for the secondary standard, since marginal benefits to health and welfare appear to exceed marginal costs at the primary standard, i.e., it appears that a cost-benefit analysis would support a more stringent standard. In particular, this will require more information on the costs of fine-particulate control and the resulting benefits.

(3) Because some control measures generate significant multiple-pollutant effects, least-cost solutions should be developed which simultaneously meet air quality standards for the five primary pollutants.

(4) The other-media effects of air pollution control, especially water quality degradation, may also be important and should be introduced.

(5) Techniques for including area source control costs should be incorporated into the least-cost solution. This will be especially important as mobile sources of pollution (represented as area sources) are included in the analysis.

(6) The informational requirements as well as administrative and enforcement costs (transaction costs) associated with the implementation

of least-cost solutions should be investigated. Because each source has a unique emission level in a least-cost strategy, transaction costs will almost certainly be higher than they are for the SIP strategies and will partially offset the cost advantages of the least-cost strategies.

SECTION III

INTRODUCTION

In accordance with the Clean Air Act of 1970, each state has submitted to the Federal Government a State Implementation Plan (SIP), which describes their basic air pollution control strategy for achieving the Federally set ambient air quality standards. This strategy has essentially the same structure for all states, usually consisting of a set of three emission standards, each of which defines the allowable emission rate for all point sources in a broadly defined category. Typically, plant size is the only variable in the function describing allowable emissions within each category. Larger plants are allowed greater emissions in all cases, even though some standards require a decrease in emissions per unit of plant input or output as plant size increases. Allowable emissions for each SIP control strategy are determined by adjusting the level of the standard, e.g., the number of pounds of particulates allowed per million BTU heat input, until the resulting air quality, predicted by a meteorological model or rollback calculation, is equal to or less than the Federal standard. The rollback calculation, which assumes that air quality is improved by the same percentage that emissions are reduced, is explained below in greater detail. (See also [21].)

In determining the allowable emissions for each SIP strategy, two important variables are omitted:

(1) transfer coefficients -- some sources degrade air quality more than others because of different location, stack height, average mixing height, stack exit conditions, stability wind rose (speed, direction, and stability class) and pollutant decay rates -- factors referred to as dispersion parameters throughout this paper. Transfer coefficients are derived from dispersion parameters and are employed to transform individual source emissions into ambient air quality at specific receptors.

(2) control costs -- marginal control costs not only rise rapidly with increasing abatement, they also vary considerably from one source to the next.

The work described in this report is a first step in attempting to quantify the typical penalty in economic efficiency associated with the current SIP air pollution control strategies, i.e., to identify the least-cost solutions, and to investigate ways of modifying the SIP strategies to move them closer to the least-cost solutions. One of these solutions, the emissions least-cost (ELC) strategy, is the least-cost method of achieving a regional mass emissions standard and utilizes only the information in (2) above. The other, the ambient least-cost (ALC) strategy, employs both (1) and (2) and is the least-cost method of achieving a specified ambient air quality standard. However, the ALC solutions as developed in this paper will not quite be the true least-cost solutions, since area source control costs and strategy enforcement costs are not included in the analysis.

Since the ALC program makes use of more information than the ELC routine in minimizing costs, the latter must be at least as expensive as the former in achieving a specified air quality. To make clearer the importance of optimization subject to constraints employing transfer coefficients, consider the case of a large modern suburban power plant which incurs lower marginal control costs than a smaller antiquated city plant. In the ELC solution the suburban plant would probably be controlled more than the central city source, since the latter has older, less efficient abatement equipment. Levels of control will differ, however, in the ALC solution, if the large suburban source contributes less to degradation of ambient air quality measured at monitoring sites (generally located in or near the urban core) than does the central-city source. The greatest abatement would be required of the source which achieves the largest improvement in ambient air quality per dollar spent on particulate control. The ELC-based level of emission control for the suburban source might be unnecessarily costly. The use of additional information relating individual emissions to ambient air quality will reduce ALC total cost below the ELC level or leave cost unchanged in the unlikely case that all individual transfer coefficients are identical.

The thrust of this paper is that the omission of both variables produces SIP control strategies that are more expensive than necessary to achieve a given level of air quality. If the view is taken that the assimilative capacity of the atmosphere is a scarce resource which can be rationed by standards and that environmental goals should be achieved at minimum cost, both of these variables must be considered.

This study utilized emissions data based on the 27 largest point sources of particulate emissions in the St. Louis Air Quality Control Region (AQCR), plus an added constant to account for natural (i.e., uncontrollable) background groundlevel concentration. However, the model should give realistic results, since the 27 sources account for approximately 80% of the particulate emissions in the St. Louis AQCR.

This analysis included the following steps:

(1) Development of the ALC and ELC linear programming (LP) strategies and the SIP strategy for achieving particulate air quality standards, using the same meteorological model, emissions data, and cost coefficients to predict the impact of each strategy; (2) Determination of the loss in economic efficiency associated with the SIP strategy as a function of ambient air quality for the AQCR by comparing the SIP strategy costs with those of the two least-cost solutions; (3) Comparison of the costs of an emission tax strategy to the costs of the ALC and ELC solutions; (4) Comparison of marginal benefit and cost figures at the primary standard; and (5) Analysis of alternative problem formulations used by various investigators in the field, making recommendations for future research.

In this last effort, interest was focused on alternative ways of defining the objective function and independent variables in the LP algorithm used to find the least-cost solutions. Alternative problem formulations were judged by their solutions' engineering feasibility and the handling of synergistic effects of multiple-pollutant control measures, both within and between media. Ultimately, it is hoped that it will be possible to compare cost data with highly refined benefit numbers to determine the appropriate standard.

SECTION IV

REVIEW OF THE LITERATURE

Many least-cost models have been formulated in which direct regional control costs are minimized subject to ambient air quality constraints. Kohn [6, 7, 8] employs an LP model for the St. Louis region to minimize control costs while satisfying certain production and consumption constraints and ambient air quality standards for five pollutants. His decision variables are levels of control activities, and he assumes a linear relationship between total regional emissions of each pollutant and regional air quality. This linear mapping means that only source-to-source variations in marginal control costs are used to structure the LP solution, i.e., the effects of individual source transfer coefficients are ignored. This approach is defined above as the ELC strategy and is usually considerably more costly than the ALC strategy, as demonstrated below.

The engineering feasibility of Kohn's work comes into question when divisibility is considered. A solution may call for the use of two or more design efficiencies whose joint utilization might be incompatible. In addition, Kohn's decision variables are defined so that marginal costs are constant at all activity levels, regardless of the control measure throughout. More is said on the importance of these assumptions later.

The approach of Seinfield and Kyan [16] will not guarantee attainment of ambient air quality goals at minimum cost since they also employ an ELC program. Individual transfer coefficients are omitted during the least-cost solution of the Seinfield-Kyan program, and are only employed to map mass emissions into regional ambient air quality after the cost-minimization problem has been solved.

In an approach similar to Kohn's, Teller [17, 18] minimizes the total cost of low- and high-sulfur fuel for all sources subject to ambient air quality constraints for SO_x. He finds that the ALC solution is considerably cheaper than the ELC, and that abatement only when pollution episodes are forecast is much less costly than constant abatement. Teller utilizes Turner's somewhat rudimentary diffusion model and allows only fuel substitution as a control measure. Despite this, he avoids the shortcomings of Kohn's ELC solutions (which optimize subject to mass emission constraints).

Norsworthy and Teller [13] extend Teller's analysis [17, 18] by suggesting an LP approach in which the benefits as well as costs of pollution abatement are directly evaluated in the objective function. They suggest a separable programming approach to handle the non-linearities in total benefit and cost functions. The objective function is defined as net social benefits, i.e., the difference between total pollution control costs (including regional impacts) and total savings from reduced mortality, morbidity, and structural damage. Although not quantitatively estimable because benefit functions are poorly developed, the solution to this formulation would be socially optimal.

Burton and Sanjour [1] and the Consad Corporation [2] employ integer programming to compare three strategies for SO_x and particulate control for the Kansas City area. Individual source transfer coefficients are employed in the constraint equations. The integer program first ranks the alternative control methods for each source according to annualized cost. The algorithm then examines an initial case involving the least-costly control methods for each source and heuristically searches through the other source-control combinations for a least-costly solution that satisfies the air quality constraints. The solution converges toward the global optimum (assuming it avoids local optima) but rarely reaches it, in contrast to linear and separable programming. However, an advantage of heuristic integer programming is that solutions are in terms of discrete control levels with no more than one device per source. Certain problems of device incompatibility and interpretation (explained in more detail below) are avoided. Comparison of the three Kansas City strategies, a strategy of maximum control for each source, equiproportional particulate emission rollback of at least 20% for all sources, and the ALC least-cost solution, indicate savings from the latter strategy are quite substantial. Total costs are $26, $16, and $7.5 million, respectively, to achieve an air quality of about 85 $\mu g/m^3$ particulate matter and .025 ppm SO_x. The maximum-control strategy requires substantial abatement of many large sources which degrade air quality very little (because of suburban location) and other expensive-to-control plants. Thus, an equiproportional strategy should be less expensive than maximum control in meeting given ambient standards but not as cheap as the ALC least-cost method.

Russell and Spofford [15] employ an LP model to maximize social welfare subject to constraints on levels of production and consumption as well as requirements for transport, treatment, and discharge of residuals, rather than ambient air and water quality standards. The quantities of generated residuals are input to diffusion models which determine ambient concentrations. These in turn are input to damage functions, whose cost figures enter the objective function on successive iterations as shadow values. Standards (with their implicit cost-benefit comparisons) are not required in the LP model, since damage functions are explicitly introduced into the objective function.

Plotkin and Lewis [14] have followed an approach similar to that of Teller [17, 18] in utilizing an LP routine with transfer coefficients in the constraints to determine least-cost emissions consistent with given particulate air quality goals. The authors employ data for twenty-seven point sources and nine receptors using St. Louis as a model region. They employ the cost model of the Implementation Planning Program (IPP) [19] to determine piecewise linear cost functions for particulate control. A Gaussian plume-rise diffusion model developed by Martin and Tikvart [12] is also utilized. The ALC particulate control strategy is compared to two alternative emission control programs: an ELC strategy and an SIP strategy representative of those currently being implemented by the states. The latter two strategies are found to be two to five times as expensive as the ALC approach in achieving one particular air quality goal.

The study presented in this paper utilizes the work of Plotkin and Lewis as a starting point and is similar to their work in that:

(1) The ALC and ELC strategies are compared to a strategy representative of those currently employed in the SIP's;

(2) The cost of each strategy is related to the achievement of ambient air quality standards.

However, the present paper differs from previous studies in that:

(1) The costs of all strategies are compared over a range of ambient air quality standards;

(2) The implications of an emissions tax are considered and preliminary comparisons of marginal control costs and damages to health and welfare are made at the primary standard.

SECTION V

PROBLEM FORMULATION

DIFFUSION MODEL AND COST DATA

This section describes the general data requirements for the derivation of the control costs and transfer coefficients employed in this paper. These requirements are discussed in greater detail in the Operator's Manual for the IPP Model [19].

Transfer coefficients, employed in the constraint equations, are derived using a Gaussian diffusion model developed by Martin and Tikvart [12]. The meteorological input data required for the model are referred to in Section III as dispersion parameters.* The output consists of a matrix which gives the contribution of each of m sources to the predicted annual arithmetic average pollutant ground level concentrations at each of n receptors. Transfer coefficients, with units of micrograms per cubic meter per ton per day are obtained by dividing the concentration at the i^{th} receptor due to the j^{th} source by the number of tons emitted by the j^{th} source (usually written as a matrix a_{ij}, $i = 1, \ldots, n; \; j = 1, \ldots, m$).

To determine costs three basic types of data are required: source information, regional information, and control cost data. The first category includes sources identified by Standard Industrial Classification code and source type. Source data describes the important point and area sources, although the latter were excluded from the present analysis. Point sources include major stationary fuel combustion plants (primarily industrial and steam-electric power plant boilers), industrial process

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*For a more complete discussion see [19].

sources, and solid waste disposal sources (incineration and open burning). The twenty-seven largest point sources were included in the present analysis and they accounted for 80% of total particulate emissions in the St. Louis area. All mobile sources and any other sources too small or too numerous to categorize as point sources were treated as part of the background.

Additional required source input data includes temperature and volume of the effluent gas stream, type and efficiency of existing pollution controls (since new ones must be compatible with them), plant operating schedules (for use in deriving device operating costs), fuel usage requirements (to determine the applicability and effectiveness of fuel substitution), and the maximum process rate (to again determine device applicability).

Regional information consists of data on wage and interest rates, the availability, costs, and ash content of fuel, and utility costs.

To develop control cost data, the applicability of control measures to each source was considered. A number of devices were examined: wet scrubbers (low, medium, and high efficiency); mechanical collectors (gravity and centrifugal with low, medium, and high efficiency); electrostatic precipitators (low, medium, and high efficiency); mist eliminators (low and high velocity); fabric filters (low, medium, and high temperature); afterburners (catalytic and direct flame, both with and without heat exchanger); and fuel substitution (elimination of coal, use of low sulfur coal and fuel oil, or a change of all fuel to natural gas).

The compatibility of control devices for each point source within a region was then determined. A number of restrictions on device usage are built into the IPP, e.g., gravity collectors are too ineffective to be employed, cyclone collectors are not applicable for control of fuel combustion sources burning fuel oil or gas, electrostatic precipitators must be high efficiency with oil or gas fuel sources, and only one of the three alternative baghouses may be applied to each source and cannot be used in conjunction with wet scrubbers. Other particulate control devices can be utilized with few restrictions.

The expected pollutant reduction efficiency is calculated for each device. Corrections for reduction in pollutant-collection efficiency over time have also been incorporated.

The costs of each device are obtained from the Control Technique Documents prepared by EPA [22]. The total annual cost of a control device includes annualized capital and installation cost (based on a rate of interest and rated life of the device) as well as annual operating and maintenance costs. Capital costs are principally a function of the source's size, with installation costs assumed to be a given percentage of capital costs. Operating and maintenance costs are based on the quantity of power, labor, and fuel used by the control device, and the cost or credit from disposal of the collected pollutant. Once computed, the same control cost figures were employed in all control strategies examined in this paper.

A number of costs were ignored, however. These included the administrative costs of enforcing the three control strategies and any dislocation of workers or alteration of output caused by the purchase of control devices, as well as any dynamic adjustment in costs. The usage of "cost of control" and "least-cost" must be understood in this restricted sense.

AIR QUALITY CONTROL STRATEGIES

The control strategy portion of an SIP consists of a listing of emission regulations, sufficient to cover all stationary sources of air pollution in the given region, as well as a demonstration that the allowable emission levels included in these regulations will achieve the Federal ambient air quality standards. The similarity of these plans from state-to-state is surprising and is probably due to the fact that emission regulations developed by a few of the more progressive states were used as models by the others. Virtually every control strategy is based on a grouping of all stationary air pollution sources into fuel combustion, industrial process, and solid waste categories, with an emissions regulation for each category.

For purposes of this study, a representative set of emission regulations suggested in the SIP Guidelines [21] has been selected to form the SIP control strategy. The particulate standards include a heat input standard for fuel combustion sources (.30 pounds particulate matter per million BTU), a process weight standard for industrial process sources (46.72 lbs/hr of particulates per million lbs/hr process weight), and a refuse-charged emission standard for solid waste disposal sources (.20 pounds particulate per 100 pounds of refuse charged).

The total cost of applying the SIP strategy to the St. Louis area was determined from the cost of control data by reducing particulate emissions to the SIP strategy levels for all twenty-seven sources. Emissions remaining from the controlled sources were then run through a diffusion model which predicted ambient particulate ground-level concentrations, termed "achieved" air quality, at nine receptors.

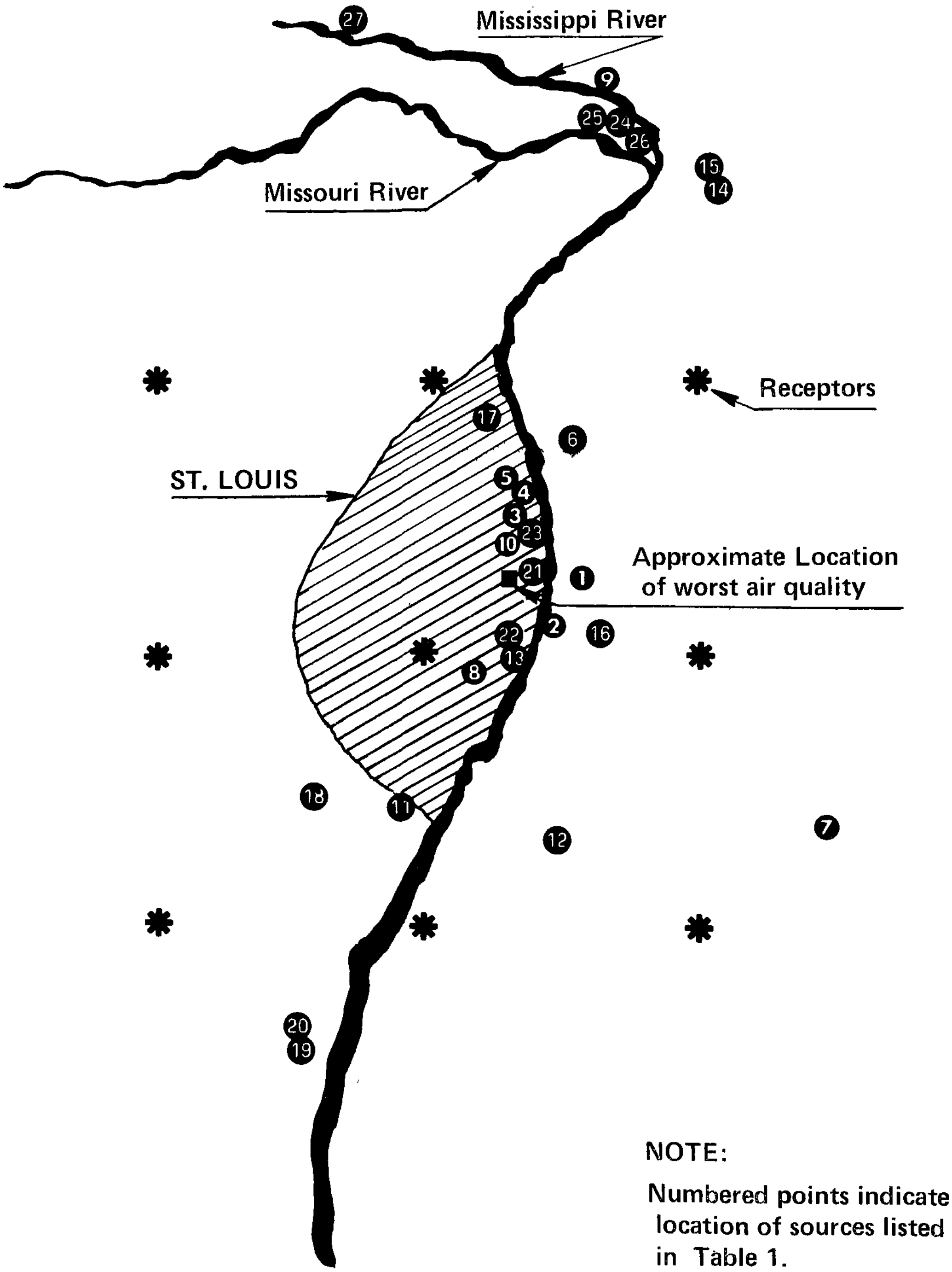
For each of the twenty-seven particulate sources, the source type, pre-control emissions level, and control cost data are listed in Table 1, and their approximate location relative to the major features of the St. Louis region is depicted in Figure 1. The locations of the nine receptors for which air quality predictions are made are also indicated in Figure 1. This source-receptor pattern was used for all computations.

Simulation of the ambient air quality resulting from the SIP strategy gives a single point on the curve relating regional air quality to total control cost. Each point on this curve is the maximum of the predicted ground-level concentrations for the nine receptors. In order to generate

Table 1. INPUT DATA FOR SOURCES CONTROLLED UNDER ALL STRATEGIES

Source No.	Standard Industrial Classification	Site No.	Pre-control Emission Rate (T/D)	Control Cost Data: First Node Cost, $/Ton	First Node Emission Reduction	Second Node Cost, $/Ton	Second Node Emission Reduction
1	2010; Meat Packing, Boiler	001	6.25	16.	75.	73.75	99.
2	2041; Feed and Grain Mill	001	5.70	16.	80.	57.68	99.
3	2041; Feed and Grain Mill	009	11.37	11.	75.	184.25	99.
4	2041; Feed and Grain Mill	010	17.15	15.	75.	279.0	99.
5	2041; Feed and Grain Mill	012	5.09	341.	52.	1830.2	99.
6	2046; Wet Corn Milling, Boiler	001	4.21	19.	75.	97.38	99.
7	2082; Brewer, Boiler	001	2.95	13.	75.	41.88	99.
8	2082; Brewery, Boiler	002	2.67	600.	76.	2114.02	95.
9	2600; Paper Products, Boiler	002	21.22	4.	75.	20.5	99.
10	2800; Chemical PH., Boiler	002	3.42	34.	75.	1172.5	99.
11	2816; Inorg. Pigments, Boiler	002	7.30	63.	52.	79.85	99.
12	2819; Inorg. Ind. Chem Plant	003	6.00	32.	68.	111.84	99.
13	2819; Inorg. Ind. Chem Plt., Boiler	007	10.70	4.	75.	32.88	99.
14	2911; Petro. Refinery	001	6.00	128.	75.	1064.38	99.
15	2911; Petro. Refinery	002	4.72	58.	52.	72.75	99.
16	2952; Asphalt Batch., Boiler	001	2.90	15.	75.	321.77	99.7
17	3241; Cement Plant, Dry Process	001	3.28	2.	75.	10.25	99.
18	3241; Cement Plant, Dry Process	003	3.68	118.	97.	464.5	99.
19	4911; Powerplant	001	3.72	214.	93.	1138.0	99.
20	4911; Powerplant	002	7.60	251.	63.	311.5	99.
21	4911; Powerplant	003	5.00	86.	66.	173.0	99.
22	4911; Powerplant	004	5.10	909.	74.	3138.65	92.4
23	4911; Powerplant	005	11.90	75.	81.	201.5	99.
24	4911; Powerplant	006	80.00	5.	75.	17.38	99.
25	4911; Powerplant	008	6.90	104.	75.	4469.77	89.2
26	4911; Powerplant	009	32.50	39.	75.	96.75	99.
27	4911; Powerplant	010	5.60	240.	93.	1312.5	99.

Figure 1. MAP OF RECEPTORS AND SOURCES FOR ST. LOUIS REGION



a functional relationship between total regional control costs and various air quality levels, a number of SIP strategies were developed by scaling up and down the levels of the suggested SIP emission regulations.

As indicated above, the guidelines issued by EPA for the preparation of implementation plans allow the states to use either a diffusion model or a simple proportional model to demonstrate that their proposed emission standards would achieve the Federal ambient air quality standards. Most of the states elect to use the proportional model, which is based on a linear relationship between regional emissions and air quality. In effect, a given percentage improvement in air quality is assumed to require the same percentage reduction in emissions. This approach, known widely as the "rollback" technique, requires calculation of the percentage improvement in air quality required to meet the ambient standard at the receptor with the worst air quality. This percentage improvement in air quality or reduction in emissions for the i^{th} pollutant, R_i, is defined as:

$$R_i = \frac{X_{max(i)} - X_{std(i)}}{X_{max(i)} - X_{back(i)}} \quad (100)$$

where: $X_{max(i)}$ = existing concentration of the i^{th} pollutant at the location having the highest measured or estimated concentration in the region,

$X_{std(i)}$ = air quality standard for the i^{th} pollutant,

$X_{back(i)}$ = background concentration for the i^{th} pollutant.

The actual ambient air quality impact of a given reduction in regional emissions will depend upon the exact pattern of individual source controls. Since the level of emission reduction dictated by the SIP's for an individual plant is generally determined by its source category in conjunction with plant size, required regional emission reductions may be achieved by heavy control of rural sources, such as outlying power plants. In this case, ambient air quality in the urban core where concentrations were initially highest may not be improved the same percentage as regional emissions are reduced. Consequently, the rollback approach will not necessarily achieve the desired air quality in the core area. (See [24] for a more complete discussion.)

The SIP strategy does not take advantage of marginal control costs or transfer coefficients. Rather, it places prime importance on equity which is to be achieved when all sources of a particular type and size are treated equally, regardless of cost and transfer coefficients.

The complete functional relationship between total regional costs and ambient air quality was generated for the ELC and ALC as well as SIP strategies. Since the ALC strategy includes the appropriate source-receptor relationships (i.e., transfer coefficients) in the constraints, output from each run of the ALC strategy directly provides a point on the function relating air quality to regional control costs. Because the constraints in the ELC approach guarantee only that a given emission reduction has been reached, derivation of this air quality vs. cost function for the ELC strategy requires the additional step of mapping the post-control ELC pattern of regional emissions into ambient air quality using a diffusion model. As shown below, the rollback technique is an integral part of the ELC strategy, and leads to the required air quality only under the most fortuitous of circumstances.

The ELC strategy minimizes the total cost of control for all sources subject to a set of equations which include only one constraint representing the emissions reduction required as computed by applying the rollback assumption to the receptor with the poorest air quality.* The reduction in regional emissions required to meet the ambient standard

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*The other constraints are bookkeeping equations for the separable variables (see Appendix B).

at the eight other receptors must be less than that for the receptor with the greatest required improvement in air quality. (See Appendix A for a proof of this assertion.) The constraint is generally stated in terms of air quality improvement, which, for ELC, is simply a constant times the emission improvement (reduction) required.

The ELC problem may be stated mathematically as:

$$\text{minimize} \quad c^T x$$

$$\text{subject to:} \quad a^{0T} x \geq b^0,$$

$$\text{where} \quad x \geq 0.$$

b^0 = scalar equal to the greatest reduction in particulate concentration ($\mu g/m^3$) needed to achieve the standard among the i receptors (i=1, ..., 9),

x = (27x1) vector whose element, x_j, (j=1, ..., 27) is tons of particulate matter required to be removed per day from the j^{th} source,

c = (27x1) vector whose element, c_j, (j=1, ..., 27) is the cost of removal of one ton per day of particulate matter by the j^{th} source,

a^0 = (27x1) vector whose elements, a^0, are equal to the coefficient (in this model, .1214) which relates total regional emissions to air quality, computed using the rollback technique.

The ELC constraint, $a^{0T}x \geq b^0$, embodies the rollback calculation, which determines the required percentage reduction in emissions as:

$$\frac{X_{max} - X_{std}}{X_{max} - X_{back}} .$$

This is easily proven. The transfer coefficient a^0 is defined in terms of $\mu g/m^3$/tons/day as:

$$\frac{X_{max} - X_{back}}{RE} ,$$

where RE is regional emissions/day. The term b^0 is the maximum required improvement in ambient air quality (MIA) measured in $\mu g/m^3$ and is defined as $X_{max} - X_{std}$. Since $\sum x_j$ is the amount of regional emissions which must be removed (RER) to satisfy the ELC constraint, and since a^0 is a constant, it can be factored out of the constraint, so that $a^0 \sum x_j = b^0$. Thus, this constraint can be written as:

$$\frac{(X_{max} - X_{back})}{RE} (RER) = MIA$$

or

$$\frac{RER}{RE} = \frac{MIA}{X_{max} - X_{back}} = \frac{X_{max} - X_{std}}{X_{max} - X_{back}} .$$

The ALC model minimizes the total cost of control for all sources subject to nine particulate air quality constraints. Since the ALC strategy considers the effect of each source on individual receptors, it requires one constraint for each receptor, rather than the constraint corresponding to the receptor with the worst air quality employed in the ELC strategy. In addition, ALC employs a unique transfer coefficient for each source, while ELC utilizes only one transfer coefficient to map mass emissions into ambient air quality.* An important assumption of the ALC solution is that the contribution of each source's emissions to air quality degradation is independent of the contributions from other sources and additive in effect at each receptor.

The separable ALC model can be expressed algebraically as follows:

minimize $c^T x$

subject to: $Ax \geq b$,

$x \geq 0$,

where b = (9x1) vector whose element, b_i, (i=1, ..., 9) represents the required ambient air quality improvement for particulate matter at the i^{th} receptor.

x = (27x1) vector whose element, x_j, (j=1, ..., 27) is the number of tons of particulate matter required to be removed per day by the j^{th} source.

c = (27x1) vector whose element, c_j, (j=1, ..., 27) is the cost of removal of one ton per day by the j^{th} source. The c vector is identical to that of the ELC model.

A = (9x27) matrix of coefficients whose element, a_{ij}, (i=1, ..., 9; j=1, ..., 27) is the transfer coefficient relating tons of pollutant to be removed from the j^{th} source to the incremental improvement of air quality at the i^{th} receptor.

*With all three strategies, the assumption that the worst air quality is actually measured is critical to the validity of the solutions.

Rapidly increasing costs for each additional unit of control (i.e., increasing marginal cost) is a significant characteristic of pollution abatement, and it is important that this characteristic be adequately represented in both the ELC and ALC solutions. In fact, total cost curves may approach a vertical asymptote, reflecting infinite costs for 100% pollutant removal. These convex cost functions are represented by a series of piecewise linear segments and, based on a set of special assumptions, separable convex programming is employed. The interpretation of solutions obtained using this technique is discussed in the next section.

INTERPRETATION OF THE PIECEWISE OBJECTIVE FUNCTION AND ALTERNATIVE FORMULATIONS

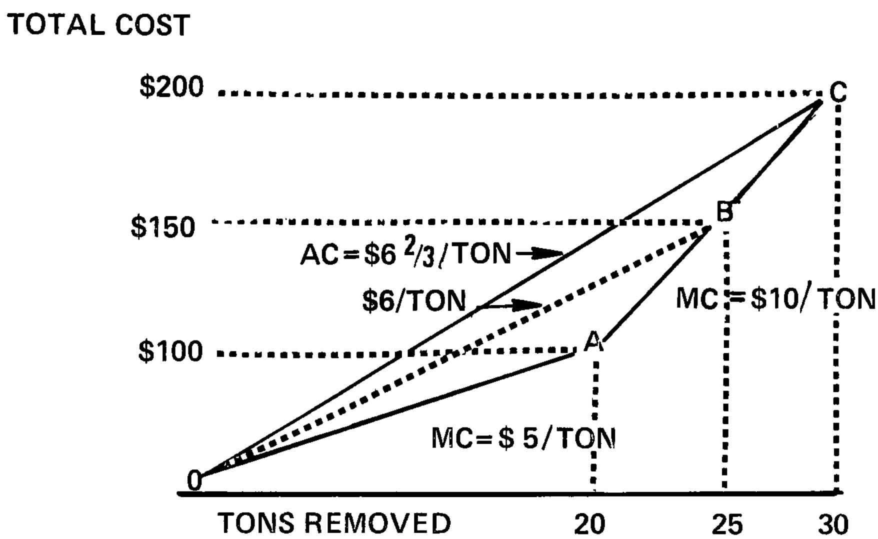
Twenty-seven piecewise linear cost curves, one for each source, are used to compute the objective function.* Each curve traces out an approximation to the lower bound of points representing the total cost of the particulate control devices technologically applicable to each source; there may be a dozen or more control measures contained in this set of points. Each curve is convex to the origin and consists of two straight-line segments. These curves were drawn such that the break-points (nodes) in the straight-line segments represent physically realizable control measures (e.g., a high voltage precipitator). Since all the constraints are linear, a local optimum will be global.

If the solution calls for a level of control (in terms of tons of particulate removed per day) at a node point (in Figure 2, either 0, A, or C), the control device to be employed, the number of tons to be removed, and the total cost can easily be determined.

If the solution for the source is at point 0, the source is completely uncontrolled. If the solution is A, 20 tons per day are

*For more details on the formulation of the separable program see Appendix B.

Figure 2. HYPOTHETICAL EXAMPLE OF TOTAL COST AS FUNCTION OF TONS REMOVED FOR GIVEN SOURCE AND APPLICABLE CONTROL DEVICES



removed at a total cost of $100. The control method employed and its removal efficiency are represented by point A. Removal efficiency of this device (operated at full power) is calculated as the ratio of tons removed to uncontrolled tons emitted by the source times 100. Point C has a similar interpretation.

Solution points between 0 and A and between A and C require a different interpretation. Since decision variables are in terms of tons removed per source at a specified cost, they must be translated into a corresponding optimal control device or combination of devices. However, since there are only a discrete number of applicable control devices, a unique corresponding device may not exist. In this case the closest device, or a convex combination of two devices which bound the theoretically optimal (but nonexistent) device, will have to be chosen. Any point B is a convex combination of devices A and C if $B = aA + (1-a)C$, $0 \leq a \leq 1$. In addition, B can be expressed as a convex combination of any devices which bound B and lie between A and C. Such convex combinations would be optimal, i.e., they would correspond to the solution point called for by the LP algorithm. Although these convex combinations can be interpreted as requiring that the gas stream be split and routed through the nodal devices in the proportions a and (1-a) (in the case of point B, 50% of the gas stream would pass through device A and 50% would pass through device C), this is not likely to be a practical engineering solution. Thus, the greater the number of non-nodal solutions, the less the engineering feasibility of the result.

The LP algorithm selects solution points along the segments OA and AC on the basis of the marginal control costs for the devices which lie on these segments. For any device between points 0 and A, the marginal control cost is simply the slope of a ray from the origin to point A. To evaluate the impact of bringing devices on segment AC into the solution, the LP algorithm again uses the marginal cost, which is no longer the slope of a ray through the origin, but is rather the slope of the segment from A to C. For points on segment AC, the slope of rays from the origin represent average, rather than marginal, costs. The marginal cost is \$5/TON between 0 and A, \$10/TON between A and C, while the average cost is \$5/TON on segment 0A and \$6 2/3/TON on AC.

Two alternative formulations would eliminate the need to consider convex combinations. The first alternative would define variables in terms of tons removed by a specific control device or units of consumption and production activities (e.g., tons of high grade steel produced with 1.6% sulfur coal or kilowatts of electricity produced in a steam-electric powerplant with a wet scrubber installed). This approach is utilized by Kohn [6].

The second alternative is integer programming, with explicit consideration given to each discrete control measure alternative. However, this would require consideration of the marginal cost of each control device within the set bounded by segments OA and AC, at considerably greater programming and computational costs. It ten devices were included for each of twenty-seven sources, 10^{27} possible combinations of control devices would have to be considered. The machine time required for a typical, say, branch-and-bound, solution would be measured in years, although a heuristic integer program could be employed to approach an optimum (usually very closely) at a much lower cost. In contrast, the separable programming formulation actually attains an optimum. However, an integer program could consider the synergistic and multi-media effects of control devices much more easily than the present approach.

On the other hand, the present formulation allows consideration of a number of control alternatives for each source, yet is much simpler to program and cheaper to run than approaches which use activity levels as independent variables or are based on integer programming techniques. Only two node points and the slopes of lines between them are input data for each source in the present approach. In addition, control variables are formulated directly in terms of tons removed, an advantage in computing regional aggregates and possibly in enforcing control strategies.

SECTION VI

DISCUSSION OF RESULTS

CAVEATS

In reviewing the results presented in this section, the following assumptions and conditions must be kept in mind:

1) Annual concentrations are in terms of arithmetic rather than geometric averages.

2) Only the cost of particulate control is considered. Synergistic effects of particulate and SO_x control and multi-media effects are ignored.

3) Area source control costs, dynamic adjustments to control costs, and externalities are not measured or considered.

4) Since the ALC strategy considers only a few sources and receptors, it is probably not the true optimal solution for the St. Louis AQCR. The use of a different or larger source-receptor set would most likely alter the solutions for the three strategies considered, although differences should be small.

5) The control cost segments must be carefully interpreted as explained above. Problems of technological feasibility may be encountered and marginal control costs may vary at different utilization rates.

6) Constraints on production activities are omitted from the problem. Such constraints insure that the region considered consumes only the available supply of resources and generates no surpluses. A short supply of eastern low-sulfur coal, for example, is an important limitation to SO_x control efforts. Resource constraints were omitted

from this paper since particulate control would not impinge on scarce resources to a significant degree. If control of other pollutants were considered, resource constraints would probably be required.

GENERAL COST ANALYSIS

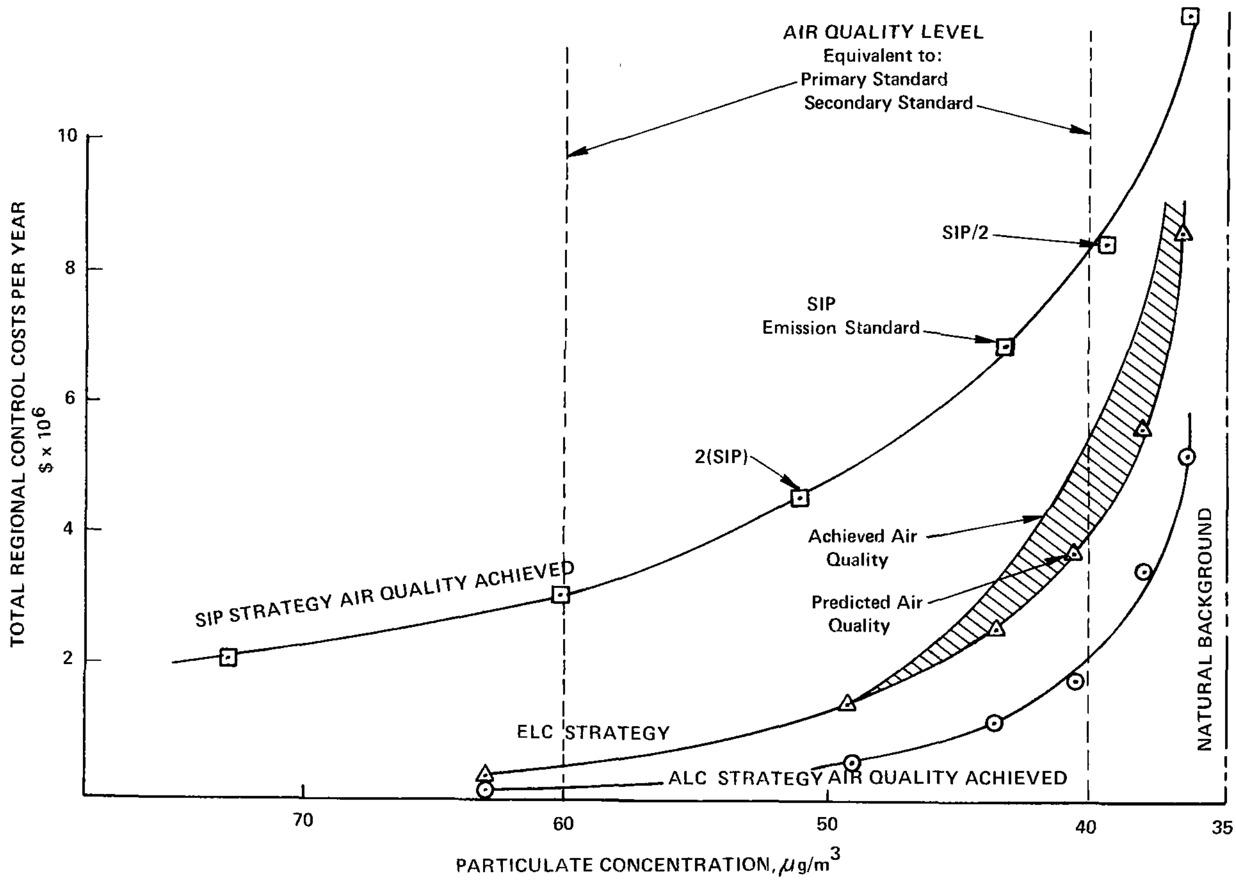
Figure 3, which contains the principal results of this study, presents total regional control costs for three control strategies as a function of air quality.* The functions for the SIP and ALC strategies relate costs to "achieved" air quality as explained above. Two ELC curves are presented -- one for "achieved", and one for "predicted" ambient quality. The predicted level is that which is employed in the ELC constraint equation (representing the greatest improvement required in ambient quality). The achieved level is obtained by feeding the controlled emission levels from all sources into the diffusion model and selecting the highest receptor concentration.

The control costs for the SIP strategy in Figure 3 are seen to be as much as one order-of-magnitude larger than those for the ALC strategy. Over the range of interest, 60 to 40 $\mu g/m^3$, in this figure, the ratio never drops below six, indicating a very substantial penalty for using the SIP strategy.

The range of interest was determined by assuming that controlled area sources and remaining point sources, which account for 20% of regional emissions, contribute approximately 25 $\mu g/m^3$ to the maximum receptor. The Federal ambient air quality standards for particulates are stated as geometric averages (75 and 60 $\mu g/m^3$), while the results of this paper are stated in terms of annual arithmetic averages. Given a standard geometric deviation for the region, it is possible to relate these two quantities, but they may vary considerably. Assuming a moderate

*Total costs, as explained above, only include control costs.

Figure 3. TOTAL REGIONAL CONTROL COSTS PER YEAR AS A FUNCTION OF AIR QUALITY



standard geometric deviation, the Federal standards become 85 and 65 $\mu g/m^3$ annual arithmetic average (primary and secondary, respectively).* The 60 and 40 $\mu g/m^3$ concentrations in Figure 3 correspond roughly to these primary and secondary ambient particulate standards when the 25 $\mu g/m^3$ increment for omitted sources is added.

The difference between the cost functions for ALC and ELC quantifies the importance of the location variable (i.e., transfer functions), since ALC includes this variable plus variations in marginal costs, while ELC considers only marginal costs. Over the 60 to 40 $\mu g/m^3$ range, ELC requires at least twice the expenditure required by ALC in achieving the same ambient quality level. This result is not surprising in view of the fact that source-to-source variations in the magnitudes of the transfer coefficients and marginal costs are about the source (each varies by as much as a factor of 100), i.e., these two variables are of roughly equal importance. Note that the emphasis in the ALC/ELC comparison above is on achieved air quality, and that, because of use of the roll-back calculation, ELC performance falls short of predicted levels for air quality better than 50 $\mu g/m^3$.

Despite the considerable cost savings of the ALC strategy over ELC, the latter still possesses a substantial cost advantage over the SIP strategy. The ratio of SIP to ELC control costs is as high as six to one at 60 $\mu g/m^3$, but drops to about eight to six at the secondary standard. Regardless, a substantial cost differential exists for a wide range of air quality.

An alternative way of looking at control strategy efficiency is to consider air quality as a function of tons of pollutant removed as in

*Based on Larsen [11], the annual geometric average of 75 $\mu g/m^3$ translates into an annual arithmetic average of 77 or 96 $\mu g/m^3$, depending upon whether the standard geometric deviation for the region has a very low or a very high value. Annual geometric standards of 75 and 60 $\mu g/m^3$, assuming a moderate standard geometric deviation of 1.50, correspond to arithmetic standards of 85 and 65 $\mu g/m^3$, respectively.

Figure 4. Here the assimilative capacities of landfill sites as well as the atmosphere are regarded as scarce resources; the more efficient the allocation, the smaller the number of tons which must be removed to achieve a given level of ambient air quality. The ALC strategy not only achieves air quality goals at minimum cost, but minimizes the tons of particulate matter to be disposed of in land-fill or on-site locations. This strategy, therefore, poses the fewest inter-media pollutant-transfer problems. From Figure 4, the ALC strategy achieves an ambient quality of 50 $\mu g/m^3$ by removing 100 tons/day of particulate matter, while both the SIP and ELC strategies must remove almost twice this amount to achieve the same result.

However, by removing far more tons per day than the ALC strategy, ELC does buy cleaner air. That is, the air quality under ELC not only meets the standard at the worst receptor but is substantially cleaner at most other receptors than ALC, which tends to improve air quality to the minimum extent required. The same improvement in air quality is produced by the SIP strategy vis-a-vis ELC and ALC. These relationships are illustrated in Figure 5.

The cross sectional profiles of regional air quality shown in this figure are, of course, illustrative only. The upper curve shows existing (uncontrolled) air quality, with the receptor recording the maximum particulate concentration located in the Central Business District (CBD). Implementation of the SIP strategy brings the air quality at this receptor down to the level of the standard, and at the same time, improves air quality at all other receptors in the region (bottom curve, labeled "SIP"). The ALC strategy also meets the standard, but, because maximum use is made of atmospheric assimilative capacity, air quality is improved only as much as it needs to be, generating the "plateau" appearance shown in Figure 5 (dotted line labeled "ALC"). The ELC strategy lies midway between the ALC and SIP -- note that it has been assumed that this ELC strategy achieves the air quality standard. The cross hatched areas illustrate the increments of clean air associated with the higher cost ELC and SIP strategies.

Figure 4. TOTAL REGIONAL TONS REMOVED PER DAY AS A FUNCTION OF AIR QUALITY

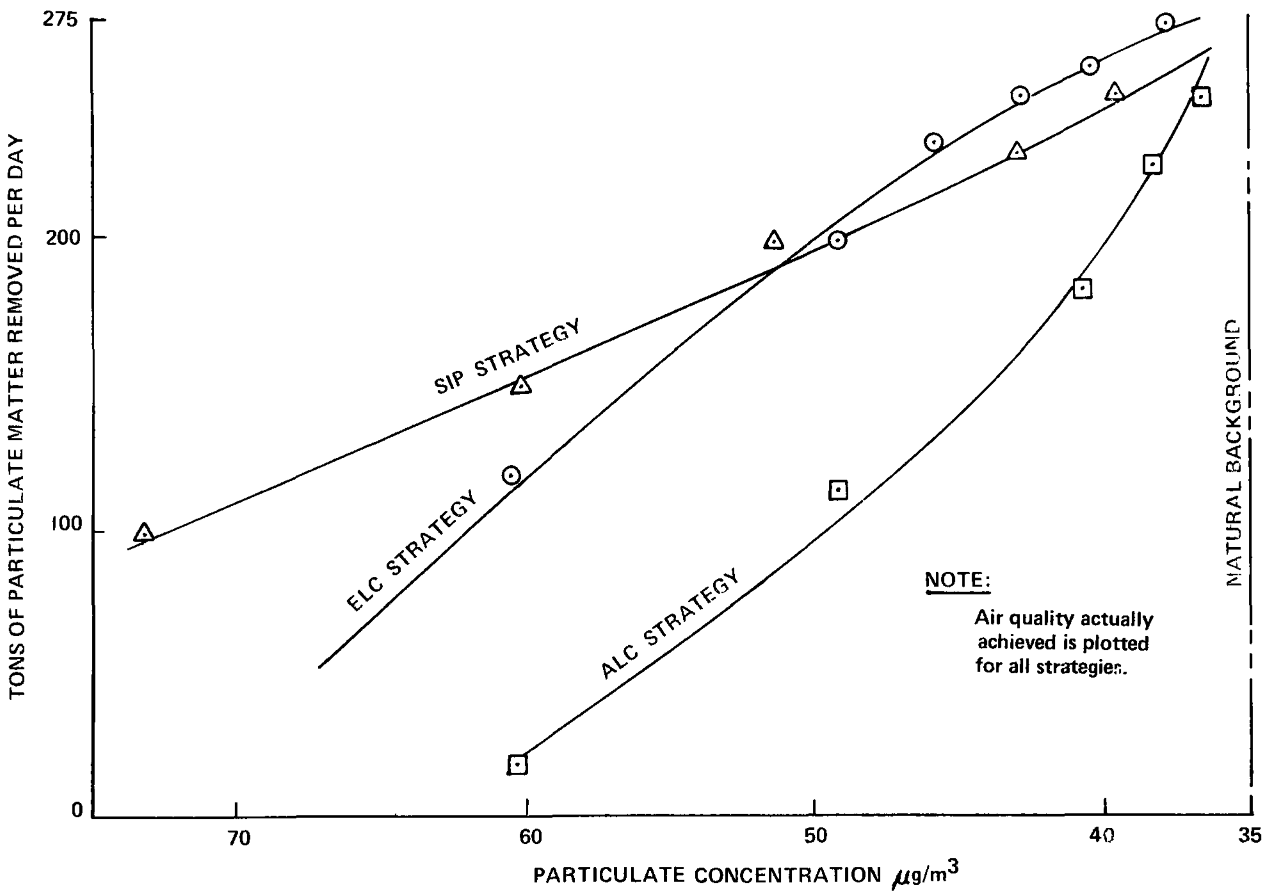
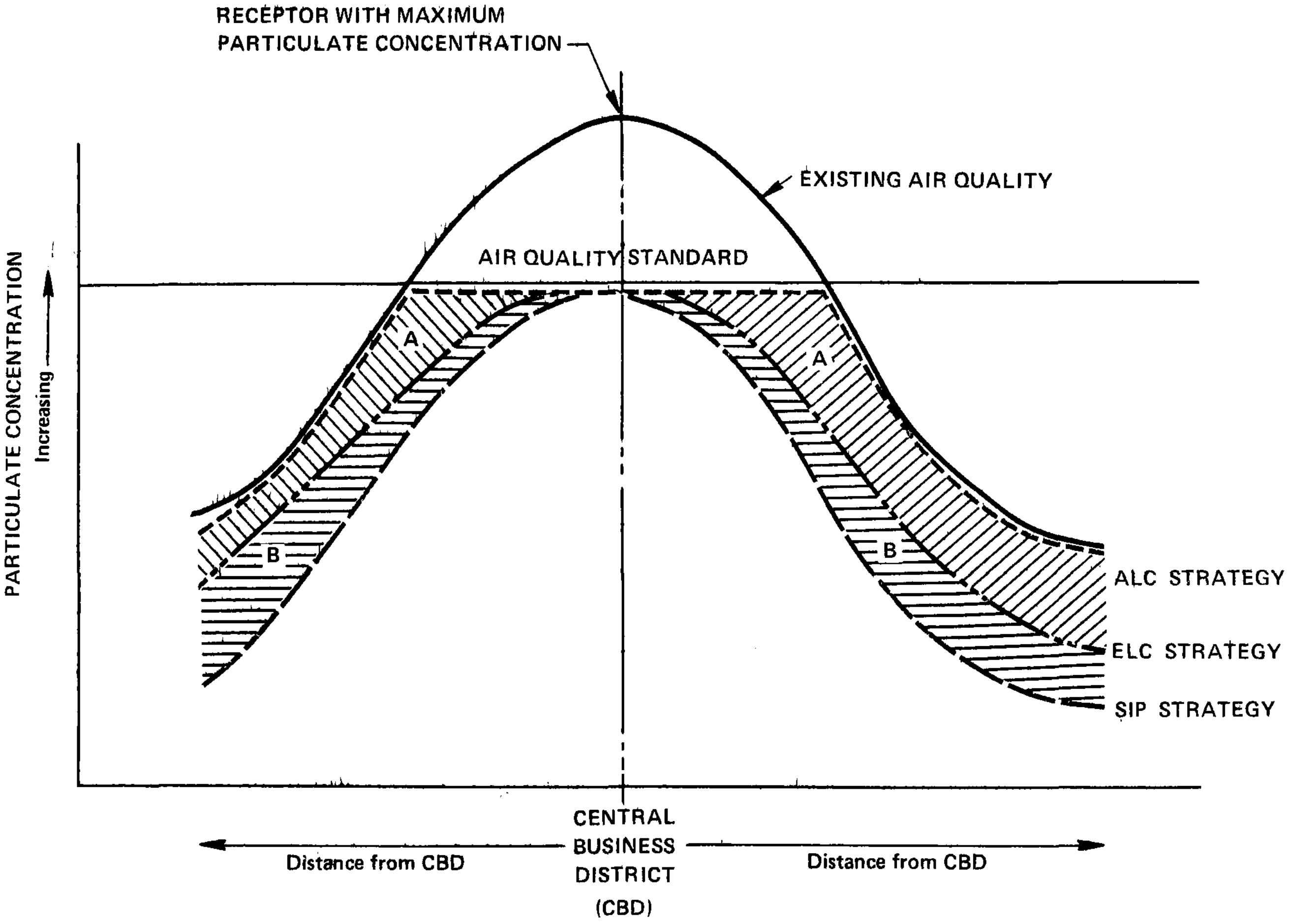


Figure 5. REGIONAL AIR QUALITY AS A FUNCTION OF LOCATION -- CROSS SECTIONAL VIEW



Area A shows the air quality improvement gained in going from ALC to ELC and Area B shows that gained in going from ELC to SIP. As shown above, each of these jumps (from ALC to ELC, and from ELC to SIP) may increase costs by a factor of 2 or more.

The substantial cost differences between the three strategies is again demonstrated in Figure 6, where cost is a function of tons removed. The ELC strategy removes the required 200 tons/day at only one-fourth the cost incurred by the SIP strategy, for example. Figure 6 also clearly illustrates that the ELC strategy minimizes costs to achieve a given emission reduction, not a given ambient air quality.

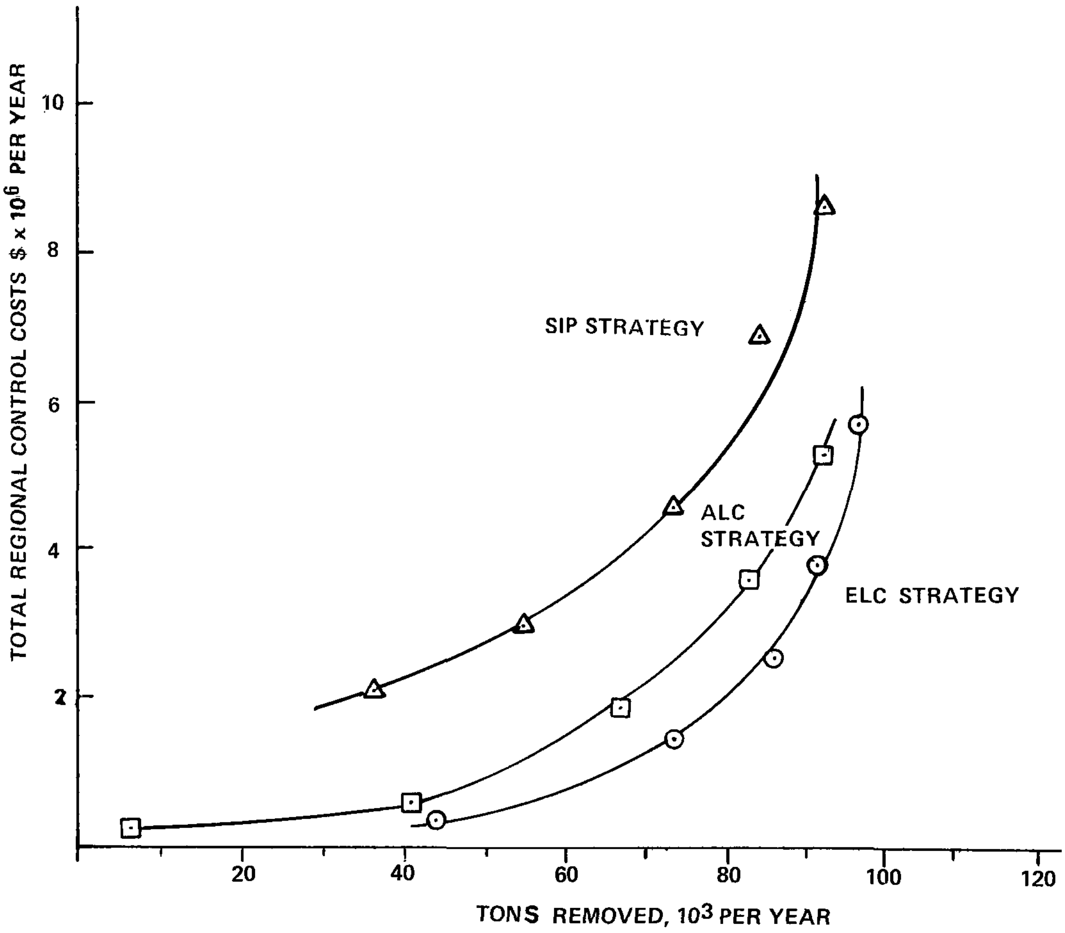
Although the foregoing analysis indicates what to expect as the primary standard is attained and the states begin to move toward the secondary standard, the impact of area source control costs must be included before a definitive result can be obtained. However, it is highly probable that the cost ratios among strategies will basically remain unaltered.

EQUITY, TAX STRATEGIES, AND EFFICIENCY

A number of alternatives exist to the discriminatory emission regulations described above. These alternatives involve imposing taxes, either uniform or discriminatory: a set of positive and negative tax payments to equalize the net control costs to each firm while enforcing the ALC solution; a discriminatory emissions tax to obtain the ALC solution; a single emissions tax to obtain the ELC solution; and a single emissions tax derived from the ELC solution with a tax on remaining emissions.

Least-cost solutions of the ALC type are often criticized on grounds that they require unequal and therefore inequitable expenditure on control as well as lead to non-optimal solutions over time. Sources in a given process and size category which operate different vintage control devices and have different control costs would be required to remove different

Figure 6. TOTAL REGIONAL CONTROL COSTS PER YEAR AS A FUNCTION OF TONS REMOVED



percentages of emissions, even if there were no variation in dispersion parameters. In a dynamic context, the ALC strategy may create disincentives to improving emission control technology. For example, a new sewage treatment plant may be required to bear a larger control burden than an older plant of equal size but with higher marginal control costs. This penalizes the use of more efficient devices, retards technological development, and may adversely affect plant location and expansion.

Equality of inter-plant control costs could be achieved without abandoning the ALC solution of differential emission control. After calculating this solution and enforcing the computed levels of control, positive and negative taxes could be levied against all plants in a given size and process classification so that the control costs for each plant are the same. This would reduce some of the disincentive to utilize newer control technology while still minimizing the cost of control summed over all firms to achieve ambient standards. Credit could even be given for implementation of more cost-effective control devices in order to stimulate technological development. The sum of this expense and the total cost of ALC would still probably be less than the total cost of the ELC or SIP strategy.

However, equal payment for unequal environmental degradation may not be any fairer than differential payment based on the ALC solution. With the latter, polluters pay in relation to environmental degradation.

Thus, in keeping with the concept of marginal cost pricing and as an alternative to directly controlling emissions based on the ALC solution, the shadow values of the ALC solution (one for each receptor) can be employed to determine tax rates which will reproduce the emissions, ambient quality, and total cost of this strategy. Since shadow values are the marginal costs of degrading air quality at each receptor, sources can then be left to decide on the least-costly course for themselves -- whether to abate or pay a pollution tax (which will likely be unique for each source). The tax for the j^{th} source would equal the sum over the i receptors of the shadow value of each receptor, s_i, times the transfer coefficient, a_{ij}, which is the degradation of air quality at the i^{th} receptor per ton emitted by the j^{th} source.[9] For this source, the pollution tax per ton emitted would equal $\sum_{i=1} a_{ij} s_i$.

An emissions tax based on the ALC solution requires that the agency levying the tax know the levels of control required under this solution and announce either the appropriate tax rate or number of tons which must be removed. A tax would be announced simply to motivate firms to undertake the required level of control, and once the ALC solution is attained, remaining emissions would not be taxed.

The minimization problem for the ALC solution as defined above is:

$$\text{minimize} \quad c^T x,$$

$$\text{subject to:} \quad Ax \geq b,$$

The dual problem is:

$$\text{maximize} \quad s^T b,$$

$$\text{subject to:} \quad A^T s \leq c,$$

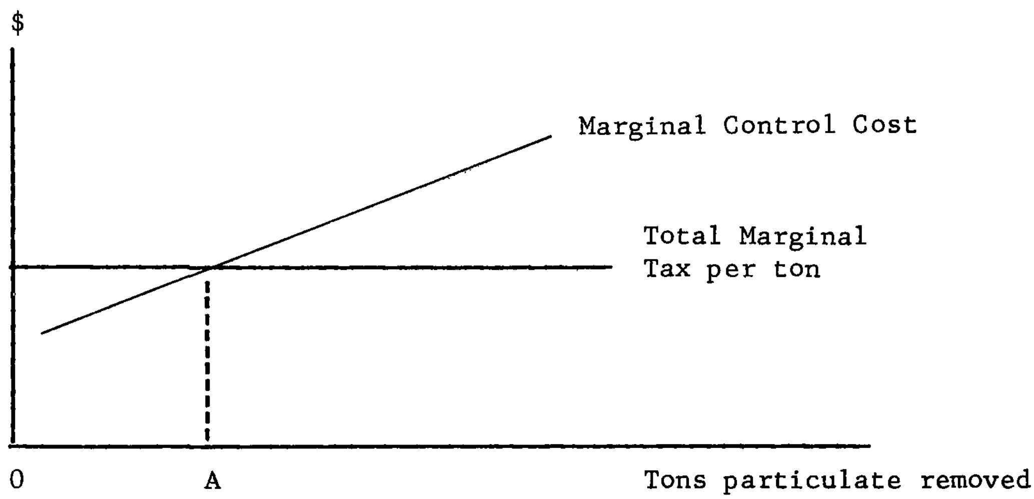
$$s \geq 0.$$

The dual maximizes the value of air quality subject to j constraints which require that the total marginal tax paid by the j^{th} source $\sum_i a_{ij} s_i$, must be less than or equal to the marginal cost of control for the j^{th} source.* Any source which is required to control emissions must

*In the separable programming algorithm, this marginal cost is one of two possible values which is applicable for the level of control determined in the primal problem.

abate until the total marginal tax equals the marginal cost. For a typical source, this level is represented by point A in Figure 7. To control to a lower level would mean paying more per ton in taxes than the marginal cost of control, violating the constraint. Control beyond A would imply $\sum a_{ij} s_i < c_j$, which requires that $x_j = 0$. That is, the source need not abate at all.

Figure 7. MARGINAL TAX VS. MARGINAL CONTROL COST FOR A TYPICAL SOURCE*



In terms of Figure 7, the tax is announced to inform firms of the appropriate marginal tax rate. Once they know this, they will control to point A, where the total marginal tax rate equals the marginal control cost, under threat of having to pay the more expensive total marginal tax. To reiterate, a tax need only be collected when firms are uncooperative; normally no tax needs to be collected beyond the optimal level (point A). Rather than risk miscalculation by firms, the control agency

*The marginal cost of control curve for the separable program would consist of two discontinuous horizontal segments. A smooth upward-sloping curve is employed here for simplicity.

may prefer to simply announce the level of control required by each source. With perfect knowledge, the result would be the same with either method.

Analysis for the ELC strategy is analogous and is not presented here. One major difference is that the ELC strategy involves only one meaningful shadow value, which means a uniform marginal tax rate for all sources. Table 2 contains the emissions tax specified for each source as calculated from the ALC solution based on the air quality level represented by the 63 $\mu g/m^3$ concentrations (approximately the primary standard) and 40 $\mu g/m^3$ (approximately the secondary standard) in Figure 3. For the former, the range is from $4.21 to $643.21 and for the latter from $.11 to $51.03 per ton of particulate matter. The single emissions tax for the 63 and 40 $\mu g/m^3$ predicted concentrations calculated from the ELC solution are $16.00 and $239.99 per ton, respectively.

The foregoing analysis produces important implications about a pollution control strategy based solely on a uniform emissions tax not calculated from individual cost and transfer coefficient data, as were the ALC- and ELC-based emission tax strategies. Such a uniform tax will probably be revised in an iterative fashion as air quality improves, and is fittingly termed an iterative emissions tax (IET). An IET such as a sulfur tax, based on the rollback calculation, will probably result in far more costly control to meet a given ambient standard than the ALC tax strategy, but would approach the cost of the ELC-based tax as a lower bound as the variation among individual cost coefficients approaches zero. Since the IET ignores individual source transfer coefficients and costs of control, which produce different tax rates per ton for each source in the ALC solution, an IET must be more costly than an ALC-based strategy. The difference should be very large, based on the cost savings attainable with the ALC strategy.

If the agency administering the IET first calculated the ELC solution (for an achieved air quality) and announced its single shadow value as the uniform tax per ton, the IET and ELC solutions would coincide.

Table 2. ALC EMISSIONS TAX - $/TON

SOURCE	ALC SOLUTION	
	40 $\mu g/m^3$	63 $\mu g/m^3$
1	261.08	4.33
2	517.54	18.38
3	184.29	2.26
4	84.54	1.06
5	73.03	.87
6	249.73	3.04
7	136.16	3.27
8	600.04	51.03
9	66.08	1.20
10	465.55	11.85
11	189.00	13.08
12	177.92	5.57
13	579.39	32.87
14	133.48	2.92
15	31.41	.55
16	643.21	15.00
17	156.62	6.54
18	6.51	.25
19	14.26	.48
20	6.75	.20
21	86.00	1.28
22	90.73	3.25
23	25.90	.29
24	25.82	.45
25	23.26	.41
26	25.89	.46
27	4.21	.11

Otherwise, the agency must rely on its ingenuity or successive iterations of air quality monitoring and tax revision. However, since legislating an IET would be difficult, efforts to revise it would probably be even harder.

Those who propose the IET strategy quickly point toward modification of a strict emission-based tax to overcome its shortcomings. One suggestion involves the use of geographical zones to help determine differential IET rates, since suburban sources will probably degrade ambient quality less than urban ones. But since location is only one dispersion parameter, a method for handling the other parameters must be devised. For example, a strategy for dealing with two sources with greatly unequal stack height must be devised. In addition, problems of equity, enforceability, and prevention of collusion -- if emission rights purchased with taxes are transferrable -- cannot be lightly dismissed.

As mentioned above, the ALC- and ELC-based emissions taxes will create disincentives to develop new control technology. A possible solution to this problem would involve modification of these strategies by announcing the tax as previously calculated in either of these strategies, and then collecting the tax on all uncontrolled emissions. A dynamic stimulus would be provided to lower the marginal cost curve over time by introducing more cost-effective devices, even though the immediate solution would be the same with or without the additional tax.

Under this modified system the sum of control costs and the collected emissions tax would comprise "total firm costs." For each plant this will exceed the ALC or ELC strategy costs by the amount of the emissions tax actually paid. At an achieved air quality of 63 $\mu g/m^3$, the total annual emissions tax is $963,191 and total annual firm costs are $1,270,050 for the ELC strategy. Again for this strategy, at the 40 $\mu g/m^3$ level of predicted air quality (about 43 $\mu g/m^3$ achieved air quality), the total annual emissions tax is $2,887,806 and total annual firm costs are $6,733,654. In comparison, the ALC total annual emissions tax is $226,354 and total annual firm costs are $292,686 at 63 $\mu g/m^3$, while at the 40 $\mu g/m^3$ level the total emissions tax is $1,625,199 and the total annual firm costs are $3,534,337. Both strategies, however, produce total firm costs substantially below total costs of control for the SIP strategy at both levels of air quality.*

MARGINAL BENEFITS AND COSTS

The optimal level of control occurs where the marginal cost of control equals the marginal benefit, since total pollution damages and the costs of pollution control are minimized.** Based on [20], estimates can be made of nationwide average benefits to health, plant life, and property obtained by reducing particulate concentration from the present level to the primary standard.*** Only fuel combustion, industrial process and solid waste sources are considered. The average benefit estimates range from a low of $135/ton to a high of $421/ton,

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*The above discussion did not consider payments rather than taxes to induce abatement. The immediate effect on resource allocation from either scheme should be the same, assuming perfect knowledge of potential source emissions.

**In all the following analysis, it is assumed that the parties which suffer damages from particulate matter cannot bargain with the polluters. If this were not the case, the optimal level of control would be lower. See [20] for a detailed discussion.

***National benefit figures can be reasonably employed to generate average and marginal benefit data for the St. Louis area. This region is large and heterogeneous enough to produce a good approximation to a random sample of nationwide exposure to pollutants, age distribution, racial classification, population density, and other variables employed in the calculation of aggregate benefit figures.

with a mid-range estimate of $280/ton in 1967 dollars.* At the level of the primary standard, most investigators assume that the function relating total damages to air quality is strictly concave to the origin, and marginal damages will be less than average damages. However, the exact shape of the function is unknown. In addition, since total and average damages are only estimated at one point -- approximately the primary standard -- marginal damages cannot be directly calculated.

Nonetheless, certain a priori restrictions can be placed on the relationship between marginal and average damages. Control technology data indicates that the level of abatement required to achieve the primary standard principally involves removing large particles, so that remaining particulate matter must be predominately less than 10 microns. Health experts feel that these fine particles are most injurious to human health.

A reasonable assumption, therefore, is that the total benefit function continues to rise steeply from the primary to the secondary standard and beyond, so that marginal benefits are not substantially less than average benefits. That is, some factor k exists such that average benefits times k equals marginal benefits, $0 < k < 1$. Based on

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*These figures were obtained by first assuming that 8 million tons of particulates are miscellaneous, background, or non-urban. Of the 19 million tons remaining, removal of 17 million of them implies about 90% control of all emissions, and would bring air quality from the present level to a point very near the primary standard. The low, middle, and high estimates of total benefits from this reduction are $2.57, $5.11, and $7.67 billion. However, only the benefits from control of fuel combustion, industrial process and solid waste sources are desired. The percentage of total air quality degradation weighted by population exposure due to these sources (84%) is expressed as a ratio of the total percentage removed (90%). This ratio is multiplied by each total benefit figure before dividing by total tons removed to obtain average benefits. All benefit data is in 1967 dollars so it can be compared with the 1967-based cost data. Certain factors operate to make these figures both under- and over-estimates of the true benefits. (See [23] for a complete discussion.)

the above argument, it is reasonable to assume that k is close to 1.

From Figure 3, marginal control costs can be derived for the SIP, ELC, and ALC strategies. At the 60 $\mu g/m^3$ level (corresponding approximately to the primary standard), marginal costs per $\mu g/m^3$ decrease from $122,500 for the SIP strategy to $55,000 for the ELC strategy and $15,000 for the ALC strategy. Marginal costs increase rapidly for all strategies as the secondary standard is approached, rising, e.g., to about $560,000 per $\mu g/m^3$ for the SIP strategy at the secondary standard.

The cost of control per ton of particulate matter can be obtained by multiplying the derivative of the cost versus air quality curve (Figure 3) by the reciprocal of the derivative of the tons versus air quality curve (Figure 4) and adjusting tons/day to tons/year, or by simply taking the derivatives in Figure 6 and making the same adjustment in units. At the primary standard the cost per ton is $5.67, $23.18, and $64.70 for the ALC, ELC, and SIP strategies, respectively.

A comparison can then be made of average benefits and marginal costs at the approximate level of the primary standard so the value of k which equates the product of k times average benefits to marginal costs can be determined.* At the approximate level of the primary standard, the marginal cost of $64.70/ton for the SIP strategy is about one-half the low estimate of average benefits of $135/ton and about one-seventh the high estimate of $421/ton. If marginal benefits are more than one-half or one-seventh average benefits, i.e., k is greater than these values, marginal benefits will exceed marginal costs. These magnitudes seem very reasonable based on the above reasoning.

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*The particulate standard does not specify allowable particle size, so that at a given $\mu g/m^3$ concentration, costs may refer to concentrations composed of different sized particles than do benefits.

For the ELC strategy, the marginal cost of $23.18/ton is about one-sixth the low estimate of average benefits and about one-eighteenth the high estimate. For the ALC strategy, the marginal cost of $5.67/ton is about 1/24 the low estimate of average benefits and about 1/74 the high estimate. That is, if marginal benefits are at least 1/24 or 1/74 the size of average benefits, then marginal benefits exceed marginal costs. Ratios of at least this magnitude for the ELC and ALC strategies seem almost certain.

REFINEMENTS

One of the major objectives of this research was to develop an understanding of alternative ways of formulating least-cost pollutant control strategies and to make recommendations for future analysis.

Two alternate ways of defining independent variables have been utilized in the literature -- the one employed in this paper, where a single decision variable represents the controlled emissions at each source, and the other employed by Kohn [6], where several possible activity levels for each source describe the quantity of output produced using various fuel-switching or add-on control measures. In the first case it is necessary to assume either constant marginal costs, or represent costs by a convex function and use a separable programming technique (rather than the normal LP). In the second approach, because there are several variables per source, the only required assumption is constant costs per unit of output produced under a given control alternative. Despite the larger number of independent variables required by this approach, it is still basically equivalent to the first one, since special variables have been introduced to define the convex cost function used with this technique.

Divisibility problems exist with either approach. In the single-variable-per-source approach, the solution may occur at a point on the cost-versus-control-efficiency curve where no device exists, requiring a convex combination of two devices, while the solution under the multiple-variable approach, for example, may call for production of half of the output using a 99.7% precipitator and half with uncontrolled emissions. In the real world either of these would mean splitting the gas stream and running each portion through one or more devices -- something which could be done, but is certainly not common practice. In addition, devices may be incompatible, e.g., when a solution calls for production with low sulfur fuel and control with flue gas desulfurization. Despite these criticisms of the multiple-variable approach, it does satisfy constraints on scarce resources and guarantee required output.

A mixed-integer program, which would select only one control device per source, could be employed to avoid these kinds of problems. However, as discussed above, computational costs rise considerably. The tradeoff must be carefully weighed.

The fact that this paper has dealt with only one pollutant means that another important difference between the single and multiple-variable approach has been ignored. When considering the impact of simultaneously controlling several pollutants with a single control measure, the single-variable approach would require a separate cost-versus-efficiency-of-control function for each pollutant and each source. The multiple-variable formulation makes the cost of each control device explicit and allows for much easier tracing of their multi-media impact.

SECTION VII

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SECTION VIII

APPENDICES

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A. ELC CONSTRAINT

The purpose of this appendix is to prove that the use in the ELC program of only the one constraint whose receptor requires the greatest improvement in air quality will produce the largest necessary reduction in regional emissions. This proof will be made for a two-constraint (two-receptor) case.

Define

(1) $$\Delta E_i = E_T - E_{si} \qquad i = 1, 2$$

where ΔE_i is the required reduction in regional emissions so that the ambient standard is met at receptor i, E_T is total regional emissions, and E_{si} is the level of regional emissions which would satisfy the air quality standard at the i^{th} receptor.

Using a standard formulation (see Kohn [6]) let

(2) $$a_i = \frac{q_i - b}{E_T} \qquad i = 1, 2$$

where q_i is the air quality at the i^{th} receptor, b the background at all receptors, while E is regional emissions.

Then define

(3) $$E_{si} = \frac{q_s - b}{a_i} \qquad i = 1, 2$$

where q_s is the air quality standard for the region and a_i is defined in (2).

Then from (1) - (3)

$$\frac{\Delta E_1}{\Delta E_2} = \frac{E_T - E_{s1}}{E_T - E_{s2}}$$

which simplifies to

(4) $$\frac{\Delta E_1}{\Delta E_2} = \frac{q_1 - q_s}{q_1 - b} \bigg/ \frac{q_2 - q_s}{q_2 - b} .$$

Assuming that the standard exceeds the background,

(5) $$q_s - \epsilon = b,$$

where ϵ is some positive constant,

substituting (5) into (4) yields

(6) $$\frac{\Delta E_1}{\Delta E_2} = \frac{q_1 - q_s}{q_1 - q_s + \epsilon} \bigg/ \frac{q_2 - q_s}{q_2 - q_s + \epsilon} .$$

Thus $$\frac{\Delta E_1}{\Delta E_2} = \left[\frac{(q_2 - q_s) + \epsilon}{(q_1 - q_s) + \epsilon}\right] \frac{(q_1 - q_s)}{(q_2 - q_s)}$$

or

(7) $$\frac{\Delta E_1}{\Delta E_2} = \frac{1 + \dfrac{\epsilon}{q_2 - q_s}}{1 + \dfrac{\epsilon}{q_1 - q_s}} .$$

Three cases exist for (7):

(a) if $q_2 = q_1$, $\dfrac{\Delta E_1}{\Delta E_2} = 1$;

(b) if $q_1 > q_2$, $\dfrac{\Delta E_1}{\Delta E_2} > 1$;

(c) if $q_1 < q_2$, $\dfrac{\Delta E_1}{\Delta E_2} < 1$.

Therefore, the constraint with the highest air quality concentration and therefore the greatest required improvement in air quality will require the greatest regional emissions reduction.

B. SEPARABLE LINEAR PROGRAM

The optimization technique employed is the IBM MPS/360 separable linear program which employs the "delta method," described in detail in [4]. This algorithm allows approximation of a continuous non-linear function (e.g., a cost function) of more than one variable provided the function is separable, i.e., contains no cross-product terms.*

The separable program represents a non-linear objective function and any non-linear constraints as piecewise approximations defined by a set of special variables. The use of more linear segments improves the degree of approximation of the non-linear function. Additional accuracy is then traded-off against programming and computational expense.

Let the original non-linear minimization problem be

$$\text{minimize } z = \sum_{j=1}^{m} f_j(x_j),$$

(1) subject to:

$$\sum_{j=1}^{n} g_{ij}(x_j) \geq b_i, \qquad i = 1, \ldots, m,$$

$$x_j \geq 0, \qquad j = 1, \ldots, n.$$

---

*Cross-product terms can be separated with a procedure described in [3].

The piecewise approximation is then

$$\text{minimize } z = \sum_{j=1}^{n} \sum_{k=0}^{r_j} f_{kj}\, l_{kj},$$

(2) subject to:

$$\sum_{j=1}^{n} \sum_{k=0}^{r_j} g_{k_{ij}}\, l_{k_j} - b_i, \qquad i = 1, \ldots, m,$$

$$\sum_{k=0}^{r_j} l_{k_j} = 1, \qquad j = 1, \ldots, n,$$

$$l_{k_j} \geq 0, \qquad \text{for all } k, j.$$

Equation set (2) can be written in matrix form as

$$\text{minimize } f^T l,$$

(3) subject to:

$$G^T l \geq b,$$

$$l \geq 0,$$

where f and l are column vectors of cost coefficients and special variables, respectively, and G is a matrix containing m + n rows and $\sum_j r_j + n$ columns. (The delta method actually involves approximating (1) by the introduction of variables somewhat different from those employed in (2).)

Each additional j^{th} original variable requires one new row and $r_j + 1$ new columns for the G matrix. Additional resolution attained, for example, by adding another special variable for one original variable requires no more rows, but one more column.

The solution to (2) is a global as well as local minimum if the feasible set is convex and the objective function is convex to the origin.

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