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A Cost-Effectiveness Analysis of Alternative Air Quality Control Strategies[1]

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A number of linear programming models purport to minimize the costs of emission control to achieve ambient air quality standards. Many of the simulations incorporate the simplifying assumption that improvements in ambient air quality are proportional to reductions in regional emissions. This approach minimizes the cost of mass emission reduction, but not the cost to achieve a prescribed ambient air quality. The costs of this emissions least-cost strategy are compared to an ambient least-cost strategy which does achieve prescribed ambient air quality at minimum cost. The cost saving achieved by this strategy relative to the emissions least-cost strategy is as much as 50%. In addition, both are compared to a strategy typical of those currently used by the states, which is found to be as much as ten times as expensive as the ambient least-cost strategy.

I. INTRODUCTION

Considerable linear programming effort has been devoted to estimating models which purport to achieve ambient air quality standards at least cost. Most of this effort has focused on two alternative approaches, differing in the structure of the constraint relationships. One formulation, termed the ambient least-cost (ALC) model, employs individual source marginal control costs and individual emission dispersion characteristics to compute the allowable source emissions which will achieve ambient air quality standards at least cost. The second formulation, which also uses individual source marginal control costs but assumes that a unit emission will have the same impact on ambient air quality regardless of source, is called the emission least-cost (ELC) model.

[1] This paper was presented at the ORSA/TIMS April 1974 Meetings, and is an abbreviated version of an Environmental Protection Agency, Office of Research and Development Report [1]. The research underlying the report was performed while both authors were on the staff of the Office of Research and Development. This report has been reviewed by EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the EPA or the FEO.

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One conclusion resulting from the analysis described below is that the cost of control under the ELC strategy is substantially greater than that under the ALC strategy, because of the simplifying assumption that all unit emissions have the same impact on air quality, regardless of source. This is equivalent to assuming that a given percentage reduction in regional emissions will produce the same percentage improvement in ambient air quality. Therefore, the ELC model describes the least-costly control strategy to achieve a required reduction in regional mass emissions, but not necessarily a required level of ambient air quality.

A second conclusion of this analysis is that a third air quality control strategy, representative of those developed by the states in preparing their State Implementation Plans (SIP) [23], is far more costly than either of the least-cost strategies. This result holds true over a wide range of air quality, and is the result of ignoring both individual marginal control costs and emission dispersion characteristics in developing the SIP strategy.

Although the least-cost solutions developed in this paper do not include area source control costs and strategy enforcement costs, and are therefore not true least-cost strategies, the relative costs of the three strategies should be basically invariant to their inclusion.

Numerous ALC and ELC air pollution control models have been formulated and estimated. Kohn [7–9] employs St Louis data to minimize control costs, while satisfying certain production and consumption constraints and ambient air quality standards for five pollutants. However, he produces an ELC solution by assuming a linear relationship between total regional emissions of each pollutant and regional air quality. Seinfeld and Kyan [17] also generate an ELC solution, since individual transfer coefficients are omitted during the least-cost optimization, and are only employed to map mass emissions into regional ambient air quality after the cost minimization has been completed.

Teller [18, 19] finds that the ALC solution is considerably cheaper than equiproportional abatement and that abatement only when pollution episodes are forecast is much less costly than constant abatement. Norsworthy and Teller [14] extend this analysis by suggesting an ALC approach in which benefits as well as costs of pollution abatement are directly evaluated in the objective function. The model cannot be estimated, however, because benefit functions are poorly developed.

Burton and Sanjour [2] and the CONSAD Research Corporation [3] compare three strategies—maximum control for each source, equiproportional control, and the ALC solution—over three levels of air quality and indicate that savings from the latter strategy are substantial.

Plotkin and Lewis [15] have followed an approach similar to Teller's [18, 19] by comparing the SIP, ELC, and ALC strategies for one level of ambient air quality for the St. Louis region.

In a more general systems framework, Russell and Spofford [16] employ a linear programming 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.

Although the estimation of ALC and ELC models is by no means new, this paper differs from previous research by comparing cost functions for the ALC, ELC, and SIP strategies over a wide range of relevant ambient air quality levels. In so doing, the cost implications of enforcing the current SIP strategy or alternatively assuming that improvements in ambient air quality can be adequately represented by proportional reductions in regional emissions are quantified. In addition, differences among strategies in terms of quantity of removed emissions and overall air quality are analyzed.

II. MODEL FORMULATION

This study analyzes a model region based on the 27 largest point sources of particulate emissions in the St. Louis Air Quality Control Region (AQCR), accounting for approximately 80% of total particulate emissions.

A. Diffusion Model and Cost Data

Source-receptor transfer coefficients, employed in the constraint equations to describe the emission dispersion characteristics of individual sources, are derived using a Gaussian diffusion model developed by Martin and Tikvart [13]. The meteorological input data required for the model are referred to above as pollution dispersion characteristics.[3] They include location, stack height, average mixing height, stack exit conditions, stability wind rose (speed, direction, and stability class), and pollutant decay rates. 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 $\mu g/m^3$/ton/day, are obtained by dividing the concentration at the ith receptor due to the jth source by the number of tons emitted by the jth source; the coefficients are 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 includes important point sources identified by Standard Industrial Classification code and source type. All area sources were excluded from the present analysis. Point sources include major stationary fuel combustion plants (primarily industrial and steam-electric power-plant boilers), industrial process sources, and solid-waste disposal sources (incineration and open burning). 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 include 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 (to derive 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.

Prior to developing control cost data, the applicability of control measures to each source was considered. A number of measures (devices and input changes) 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 flames, 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).

In order to determine the compatiblity of control devices with each source, consideration must be given to the temperature and volume of the effluent gas stream, type

[3] For a more complete discussion see Ref. [20].

and efficiency of existing pollution controls, fuel usage requirements, and the maximum process rate. A number of restrictions on device usage are built into the model. 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 limitations.

Substantial synergistic effects of particulate control on sulfur oxide (SO_x) emissions and possible multi-media effects connected with the disposal of particulate matter were not considered in this analysis. The first should reduce particulate control costs, if part of total cost is allocated to SO_x control, while the latter should raise them somewhat. The net effect is unclear, but particulate control costs would probably decline overall.

The costs of each device are obtained from the Control Technique Documents prepared by EPA [22] and are the same for each control strategy. The total annual cost 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 for disposal of the collected pollutant. Corrections for reduction in pollutant-collection efficiency of control devices over time have also been incorporated.

A number of costs were ignored, however, in addition to area source control costs. These included the administrative costs of enforcing the three control strategies, and any unemployment or reduction of output caused by the purchase and operation 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.

B. The SIP Strategy

In accordance with the Clean Air Act of 1970, each state has submitted to the Federal Government an SIP which describes its basic air pollution control strategy for achieving the federally-set ambient air quality standards. The control strategy portion of an SIP consists of a listing of emission regulations, sufficient to cover all sources of air pollution in a given region, as well as a demonstration that the allowable emission levels included in these regulations will achieve the Federal ambient air quality standards.[4] More specifically, an SIP usually consists of a set of three emission standards, each of which defines the allowable emission rate for all point sources in a broadly-defined category: fuel combustion, industrial process, and solid waste. Typically, plant size is the only variable in the function describing allowable emissions within each category. Larger plants are allowed greater total 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

[4] 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.

TABLE I

INPUT DATA FOR SOURCES CONTROLLED UNDER ALL STRATEGIES

Source no.	Standard industrial classification	Precontrol emission rate (T/D)	Control cost data			
			First node		Second node	
			Cost ($/ton)	Emission reduction (%)	Cost ($/ton)	Emission reduction (%)
1	2010; Meat packing, boiler	6.25	16.00	75.0	73.75	99.0
2	2041; Feed and grain mill	5.70	16.00	80.0	57.68	99.0
3	2041; Feed and grain mill	11.37	11.00	75.0	184.25	99.0
4	2041; Feed and grain mill	17.15	15.00	75.0	279.00	99.0
5	2041; Feed and grain mill	5.09	341.00	52.0	1830.20	99.0
6	2046; Wet corn milling, boiler	4.21	19.00	75.0	97.38	99.0
7	2082; Brewery, boiler	2.95	13.00	75.0	41.88	99.0
8	2082; Brewery, boiler	2.67	600.00	76.0	2114.02	95.0
9	2600; Paper products, boiler	21.22	4.00	75.0	20.50	99.0
10	2800; Chemical plant, boiler	3.42	34.00	75.0	1172.50	99.0
11	2816; Inorganic pigments, boiler	7.30	63.00	52.0	79.85	99.0
12	2819; Inorganic industrial chemical plant	6.00	32.00	68.0	111.84	99.0
13	2819; Inorganic Industrial chemical plant, boiler	10.70	4.00	75.0	32.88	99.0
14	2911; Petroleum refinery	6.00	128.00	75.0	1064.38	99.0
15	2911; Petroleum refinery	4.72	58.00	52.0	72.75	99.0
16	2952; Asphalt batching, boiler	2.90	15.00	75.0	321.77	99.7
17	3241; Cement plant, dry process	3.28	2.00	75.0	10.25	99.0
18	3241; Cement plant, dry process	3.68	118.00	97.0	464.50	99.0
19	4911; Powerplant	3.72	214.00	93.0	1138.00	99.0
20	4911; Powerplant	7.60	251.00	63.0	311.50	99.0
21	4911; Powerplant	5.00	86.00	66.0	173.00	99.0
22	4911; Powerplant	5.10	909.00	74.0	3138.65	92.4
23	4911; Powerplant	11.90	75.00	81.0	201.50	99.0
24	4911; Powerplant	80.00	5.00	75.0	17.38	99.0
25	4911; Powerplant	6.90	104.00	75.0	4469.77	89.2
26	4911; Powerplant	32.50	39.00	75.0	96.75	99.0
27	4911; Powerplant	5.60	240.00	93.0	1312.50	99.0

meteorological model or rollback calculation (explained below), is equal to or better than the Federal standard.

For purposes of this study, a representative set of emission regulations suggested in the SIP guidelines [23] has been selected to form the SIP control strategy. The particulate standards include a heat input standard for fuel combustion sources (0.30 lb. particulate matter/million Btu), a process weight standard for industrial process sources (46.72 lb/hr of particulates/million lb/hr process weight), and a refuse-charged emission standard for solid waste disposal sources (0.20 lb particulate/100 lb of refuse charged).

The type, precontrol emissions rate, and costs of achievable particulate control of each of the 27 plants considered in the St. Louis region are listed in Table I. The approximate location of each source and the nine receptors for which air quality predic-

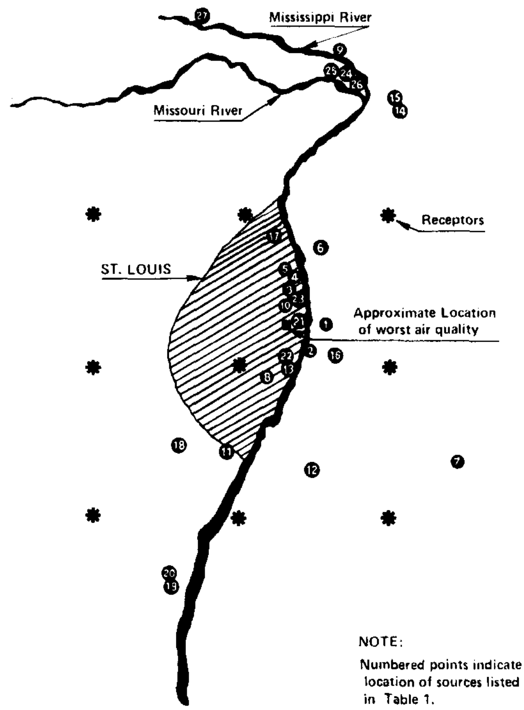

FIG. 1. Map of receptors and sources for St. Louis region.

tions are made are shown in Fig. 1. The same control information and source-receptor pattern were used for the cost comparisons of all strategies.

The total cost of applying the SIP strategy to the St. Louis model region was determined from the cost of control data by reducing particulate emissions to the SIP strategy levels for all 27 sources. Remaining emissions from the controlled sources were then run through the Gaussian diffusion model which generates ambient ground-level concentrations, termed actual or "achieved" air quality, at each of the nine receptors. The highest reading was selected for purposes of comparison among strategies, since Federal standards require that this reading meets the standard. Simulation of the ambient air quality resulting from each SIP strategy gives a single point of the function relating regional air quality to control cost. In order to generate 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.

Although each state can employ either a diffusion model or a simple rollback model to demonstrate the adequacy of its SIP, most elect to use the latter, 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. The rollback technique requires calculating the percentage improvement in air quality (reduction in emissions) necessary to meet the ambient standard at the receptor with the worst air quality. This percentage for the ith pollutant, R_i, is defined as:

$$R_i = [(B_{\max(i)} - B_{\mathrm{std}(i)})/(B_{\max(i)} - B_{\mathrm{back}(i)})](100), \tag{1}$$

where

$B_{\max(i)}$ existing concentration of the ith pollutant at the location having the highest measured or estimated concentration in the region,

$B_{\mathrm{std}(i)}$ air quality standard for the ith pollutant,

$B_{\mathrm{back}(i)}$ background concentration for the ith pollutant.

The actual impact on ambient air quality of a given reduction in regional emissions will depend on the pattern of individual source control. Since the level of emission reduction dictated by the SIPs for an individual plant is generally determined by its source category in conjunction with plant size, required regional emission reductions may be achieved by strict control of rural sources, such as outlying power plants. In this case, ambient air quality in the urban core where concentrations were probably initially highest may not be improved by the same percentage as regional emissions are reduced. If this occurs, the rollback approach will not achieve the required improvement in air quality. At the root of the problem is the orientation of the SIP strategy which places prime importance on equity, presumably achieved when all sources of a specific type and size are treated equally, regardless of individual control costs or contribution to the degradation of air quality.

C. The ELC and ALC Strategies

A separable linear program is formulated for both the ELC and ALC strategies, since control costs are highly nonlinear.[5] Marginal control costs rise rapidly with increasing levels of control, appearing to approach a vertical asymptote at complete pollutant removal.

For each of 27 sources, a two-segment piecewise cost function is constructed by tracing out the lower bound of the total cost of the particulate control devices technologically applicable to each source. The objective function for the ELC and ALC strategies employs the marginal costs (equal to the slope) of each source's piecewise segments. Since each separable function is convex to the origin and all constraints are linear, the local optimum will be global. To facilitate cost-effectiveness comparisons among strategies, costs of control are computed in terms of tons removed per day at each source. The corresponding control device can then be determined.[6]

The ELC strategy minimizes the total cost of control for all sources subject to a set of equations which includes only one air quality constraint representing the greatest required improvement in air quality and bookkeeping equations for the special variables.[7] None of the strategies employs constraints on production activities utilized by

[5] All computations were carried out using an IBM MPS/360 separable linear programming package [5]. For more details concerning this algorithm see Ref. [4].

[6] However, a single control device which removes the optimal tonnage may not exist for all sources. A convex combination of two control devices which border the optimal but nonexistent device must then be determined. This, however, may introduce technological incompatibility. Far more complex and expensive alternatives define variables in terms of specific control devices [9] and utilize integer programming [2]. There are no theoretical differences in total cost and only insignificant computational discrepancies between the formulation in Ref. [9] and that employed here, *ceteris paribus*. However, the cost of the present approach may be considerably cheaper than an integer programming solution and will form its lower bound.

[7] The reduction in regional emissions required to meet the ambient standard at the eight other receptors must be less than that for the receptor with the greatest required improvement in air quality, therefore obviating the need to utilize the other constraint equations (see Ref. [1]).

Kohn [7–9]. These constraints insure that a region 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 sulfur oxide control efforts. Resource constraints were omitted since particulate control would not impinge on scarce resources to a significant degree. If additional control of other pollutants were considered, resource constraints would be required.

The ELC model is expressed as follows:

minimize

$$z = \sum_{j=1}^{27} \{c_{1j}x_{1j}\lambda_{1j} + (\sum_{k=1}^{2} c_{kj}x_{kj})\lambda_{2j}\} \tag{2}$$

subject to

$$a^* \sum_{j=1}^{27} (x_{1j}\lambda_{1j} + \sum_{k=1}^{2} x_{kj}\lambda_{2j}) \geqq b^*,$$

$$\sum_{k=0}^{2} \lambda_{kj} = 1, \quad j = 1, \ldots, 27,$$

$$\lambda_{kj} \geqq 0, \quad \text{for each } k, j,$$

$$x_{kj} \geqq 0, \quad \text{for each } k, j,$$

where

$$x_{1j}\lambda_{1j} + \sum_{k=1}^{2} x_{kj}\lambda_{2j} = x_j \quad (j = 1, \ldots, 27)$$

and for a given j, no more than two λ_{kj} can be positive, and this pair must be adjacent.

The variables are defined as:

- b^* scalar equal to the greatest reduction in particulate concentration (μg/m^3) needed to achieve the standard among the i receptors ($i = 1, \ldots, 9$),
- c_{kj} the marginal cost of control per day for the kth segment ($k = 0, 1, 2$) of the jth source,
- x_{kj} the number of tons of particulate matter which can be removed per day from the jth source at corresponding cost c_{kj},
- a^* the scalar transfer coefficient (equal in this model to 0.1214) which relates total regional emissions to air quality, computed using the rollback technique,
- λ_{kj} the special variables (weights) for the x_{kj},
- x_j the actual tonnage removed per day by the jth source.

In this formulation, the c_{kj} and x_{kj} are constants as are a^* and b^*. The λ_{kj} are the special variables which determine for each source the convex combination of the total cost at the origin, $c_{0j}\, x_{0j}$, the node of the first and second segments, $c_{1j}\, x_{1j}$, and the point of total achievable pollutant removal, i.e., at the termination of the second segment,

$$\sum_{k=1}^{2} c_{kj}x_{kj}.$$

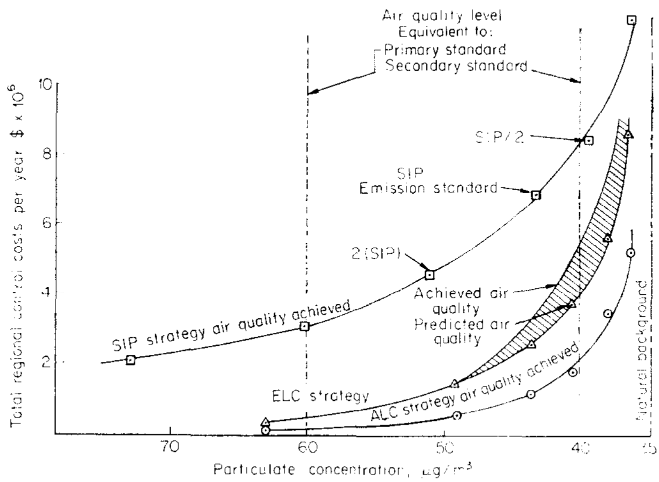

FIG. 2. Total regional control costs per year as a function of air quality.

Similarly, the λ_{kj} are used to determine the convex combination of

$$x_{0j},\ x_{1j},\ \text{and}\ \sum_{k=1}^{2} x_{kj}.$$

For c_{kj}, x_{kj}, and λ_{kj}, $k = 0$ refers to the marginal cost, quantity which can be removed (0 tons/day), and applicable special variable $(0 \leqq \lambda_{0j} \leqq 1)$ at the origin.

It is then easily seen that the ELC constraint,

$$a^* \sum_j (x_{1j}\lambda_{1j} + \sum_k x_{kj}\lambda_{2j}) \geqq b^*,$$

embodies the rollback calculation and is therefore only valid when a given percentage reduction in mass emissions causes an equivalent percentage improvement in air quality. The transfer coefficient, a^*, is defined in terms of $(\mu g/m^3)/(\text{ton/day})$ as:

$$(B_{\max} - B_{\text{back}})/\text{RE},$$

where RE is regional emissions/day. The term b^* is the maximum required improvement in ambient air quality measured in $\mu g/m^3$ and defined as $B_{\max} - B_{\text{std}}$. Since

$$\sum_j (x_{1j}\lambda_{1j} + \sum_k x_{kj}\lambda_{2j})$$

is the amount of regional emissions which must be removed (RER) to satisfy the ELC constraint, it can be written as:

$$[(B_{\max} - B_{\text{back}})/\text{RE}](\text{RER}) = B_{\max} - B_{\text{std}},$$

or

$$\text{RER/RE} = (B_{\max} - B_{\text{std}})/(B_{\max} - B_{\text{back}}). \tag{3}$$

Thus, from Eq. (3), the desired result is obtained: the required percentage reduction in regional emissions equals the required improvement in regional air quality.

The ALC model minimizes the total cost of control for all sources subject to nine air quality constraints. This strategy utilizes a unique transfer coefficient to map the emissions from each source into air quality at each receptor, while ELC maps mass emissions into ambient air quality with a single coefficient. Thus, the ALC strategy requires one constraint equation for each receptor, while the ELC strategy employs only the constraint corresponding to the receptor with the worst air quality. The ALC formulation assumes that the contributions from all sources to the degradation of air quality are independent at each receptor and additive in effect. The ALC model is expressed as follows:

minimize

$$z = \sum_{j=1}^{27} \{c_{1j}x_{1j}\lambda_{1j} + (\sum_{k=1}^{2} c_{kj}x_{kj})\lambda_{2j}\}, \qquad (4)$$

subject to

$$\sum_{j=1}^{27} a_{ij}(x_{1j}\lambda_{1j} + \sum_{k=1}^{2} x_{kj}\lambda_{2j}) \geqq b_i, \quad i = 1, \ldots, 9,$$

$$\sum_{k=0}^{2} \lambda_{kj} = 1, \quad j = 1, \ldots, 27,$$

$$\lambda_{kj} \geqq 0, \quad \text{for each } k, j,$$

$$x_{kj} \geqq 0, \quad \text{for each } k, j,$$

where

$$x_{1j}\lambda_{1j} + \sum_{k=1}^{2} x_{kj}\lambda_{2j} = x_j \ (j = 1, \ldots, 27)$$

and for a given j, no more than two λ_{kj} can be positive, and this pair must be adjacent.

The variables are defined as:

- b_i the reduction in particulate concentration required to achieve the standard at the ith receptor ($i = 1, \ldots, 9$),
- c_{kj} the cost coefficients as defined in the ELC model,
- x_{kj} the number of tons which can be removed per day, as defined in the ELC model,
- a_{ij} the transfer coefficient which relates all emissions from the jth source to air quality at the ith receptor,
- λ_{kj} the special variables (weights) as defined in the ELC model,
- x_j the actual tonnage removed per day as defined in the ELC model.

The complete functional relationship between total regional costs and ambient air quality was also generated for the ALC and ELC strategies. Since the ALC strategy is based on transfer coefficients as well as marginal cost data for each source, output from the ALC strategy directly provides a point on the function relating actual or achieved air quality to regional control costs. Derivation of this function for the ELC strategy requires the additional step of mapping postcontrol ELC emissions by source into ambient air quality with the Gaussian diffusion model, and selecting the highest air quality reading. For the St. Louis model region, the achieved air quality is never better than the predicted, and generally is substantially worse. The predicted level is the maximum ambient level which would be achieved at any receptor by reducing mass regional emissions, and presumably particulate concentration, the greatest amount required at any receptor to achieve the ambient standard. The equality of achieved and predicted air quality at all levels of air quality requires that all transfer coefficients are equal.

III. DISCUSSION OF RESULTS

Figure 2, which contains the principal results of this study, presents total regional control costs for the SIP, ELC, and ALC control strategies as a function of air quality. The functions for the SIP and ALC strategies relate costs to achieved air quality as explained previously. Two ELC curves are presented—one for achieved, and one for predicted ambient quality.

The range of air quality 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, although there may be considerable variation from region to region. Assuming a moderate standard geometric deviation, the Federal standards become 85 and 65 $\mu g/m^3$ annual arithmetic average, primary and secondary, respectively.[8] The 60 and 40 $\mu g/m^3$ concentrations in Fig. 2 correspond roughly to these primary and secondary ambient particulate standards when the 25 $\mu g/m^3$ increment for omitted sources is added.

The control costs for the SIP strategy in Fig. 2 are seen to be as much as one order-of-magnitude larger than those for the ALC strategy. From the primary to the secondary standard, this ratio never drops below six, indicating a very substantial penalty for using the SIP strategy.

The difference between the cost functions for ALC and ELC strategies quantifies the importance of including individual dispersion characteristics, since the ALC includes this variable plus variations in marginal costs, while the ELC considers only marginal costs. Over the 60–40 $\mu g/m^3$ range, the ELC requires at least twice the expenditure required by the ALC to achieve 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 same (each varies by as much as a factor of 100), i.e., these two variables are of roughly equal importance. Because it uses the rollback calculation, the ELC achieves results short of predicted levels for air quality better than 50 $\mu g/m^3$.

Despite the considerable cost savings of the ALC strategy over the 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 6–1 at 60 $\mu g/m^3$, but drops to about 4–3 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 Fig. 3. Here the assimilative capacities

[8] Based on Larsen [12], 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.

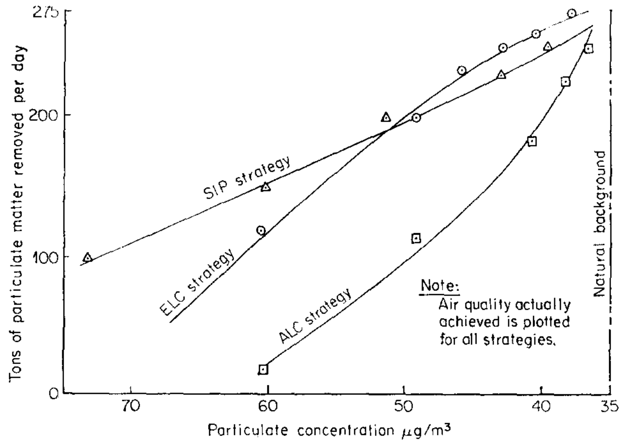

FIG. 3. Total regional tons removed per day as a function of air quality.

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 also minimizes the tons of particulate matter to be disposed of in landfill or on-site locations. This strategy, therefore, poses the fewest inter-media pollutant-transfer problems. From Fig. 3, the ALC strategy achieves an ambient air 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 overall. That is, the air quality under ELC not only meets the standard at the worst receptor but also 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-à-vis ELC and ALC. These relationships are illustrated in Fig. 4.

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 Fig. 4 (dotted line labeled ALC). The ELC strategy lies midway between the ALC and SIP (where 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. Area A shows the air quality improvement achieved by moving from ALC to ELC, and area B shows the gain from ELC to SIP. As shown above, each of these movements may increase costs by a factor of two or more.

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.

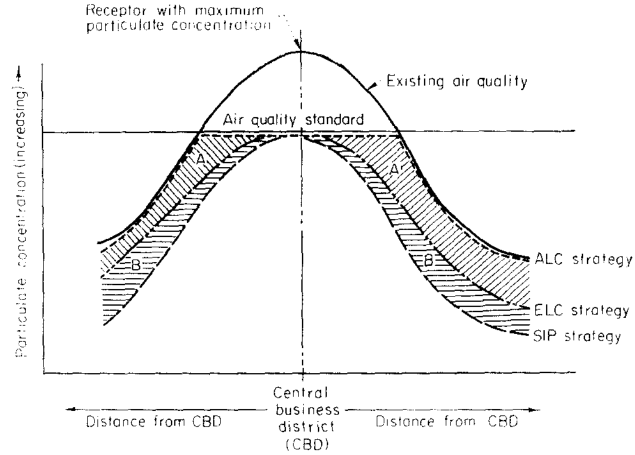

FIG. 4. Regional air quality as a function of location—cross-sectional view.

However, it is highly probable that the cost ratios among strategies will basically remain unaltered.

IV. CONCLUSION

Particulate air pollution control strategies of the type included in the SIP Guidelines [23] are 6–10 times as costly as the ALC strategy, and $1\frac{1}{3}$–6 times as costly as the ELC strategy. The ALC strategy allocates the control burden on the basis of both individual-source marginal control costs and transfer coefficients, derived from individual-source pollutant-dispersion characteristics. This strategy produces the minimum-cost solution to achieve ambient air quality standards.

The ELC strategy allocates the control burden only on the basis of marginal control costs without considering the impact of individual transfer coefficients. The cost of adopting the simplifying assumption that the improvement in regional ambient air quality is proportional to reductions in mass emissions is seen to be substantial. Thus, the ELC strategy produces the required reduction in regional emissions at minimum cost, but only in the trivial case yields the minimum cost to achieve ambient air quality standards. In general, the ELC strategy enjoys one-half of the cost savings of the ALC strategy over the currently-enforced SIP strategy.

By including the cost of controlling minor point sources and area sources, which comprise 20% of regional emissions, and costs of administration and strategy enforcement, the advantage of the least-cost strategies over the SIP may be somewhat reduced, but the effect should be negligible. Future research should consider synergistic multiple-pollutant effects of particulate removal and multi-media effects of particulate disposal.

REFERENCES

1. S. E. Atkinson and D. H. Lewis, "A Cost Evaluation of Alternative Air Quality Control Strategies," U. S. Environmental Protection Agency, Office of Research and Development Report EPA-600/5-74-003, January, 1974.
2. E. Burton and W. Sanjour, Multiple source analysis of air pollution abatement strategies, *Fed. Account.*, **18**, 48–69 (1969).
3. CONSAD Research Corporation, "The Direct Cost of Implementation Model," Vol. I, Prepared for the U. S. Environmental Protection Agency, Washington, July 1972.
4. G. Hadley, "Nonlinear and Dynamic Programming," Addison-Wesley, Reading (1964).

5. IBM, "Mathematical Programming System/360, Version 2, Linear and Separable Programming," (1968).
6. A. V. Kneese and B. T. Bower, Standards, charges, and equity, in "Economics of the Environment," (Dorfman and Dorfman, Eds.), pp. 159–70, W. W. Norton and Company, New York, (1972).
7. R. E. Kohn, Abatement strategy and air quality standards, in "Development of Air Quality Standards," (Atkisson and Gains, Eds.), pp. 103–22, Charles E. Merrill Publishing Co., Columbus (1970).
8. R. E. Kohn, Application of linear programming to a controversy on air pollution control, *Management Sci.*, **17**, 609–21 (1971).
9. R. E. Kohn, Optimal air quality standards, *Econometrica*, **39**, 983–95 (1971).
10. K. O. Kortanek, *et al.*, "On the Numerical Determination of Optimal Control Strategies for Air Quality Standards and Regulatory Policy," Carnegie-Mellon University, August, 1971.
11. K. O. Kortanek, *et al.*, "Optimal Control Strategies for Air Quality Standards and Regulatory Policy," Carnegie-Mellon University, August, 1971.
12. R. I. Larsen, "A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards," U. S. Environmental Protection Agency, Office of Air Programs Publication No. AP-89, 1971.
13. D. O. Martin and J. A. Tikvart, A general atmospheric diffusion model for estimating the effects on air quality of one or more sources, *JAPCA*, **18**, 68–148 (1968).
14. J. R. Norsworthy and A. Teller, "A Design of a Study to Estimate the Regional Economic Impact of Air Pollution Control Policy," Temple University.
15. S. E. Plotkin and D. H. Lewis, "Controlling Air Quality: St. Louis Case Study," TRW Systems Group, June 1971.
16. C. S. Russell and W. O. Spofford, Jr., A quantitative framework for residuals management decisions, in "Environmental Quality Analysis," (Kneese and Bower, Eds.), pp. 115–79, Johns Hopkins Press, Baltimore (1972).
17. J. H. Seinfeld and C. P. Kyan, Determination of optimal air pollution control strategies, *Socio-Economic Planning Science*, **5**, 173–90 (1971).
18. A. Teller, Air pollution abatement: Economic rationality and reality, *Daedalus*, **96**, 1082–98 (1967).
19. A. Teller, The use of linear programming to estimate the cost of some alternative air pollution abatement policies, *Proceedings of IBM Scientific Computing Symposium Water and Air Resource Management*, 345–53 (1968).
20. TRW Systems Group, "Air Quality Implementation Planning Program," Vol. 1, Operator's Manual, Washington, November, 1970.
21. R. Turvey, On divergences between social cost and private cost, *Economica*, **30**, 309–13 (1963).
22. U. S. Department of Health, Education, and Welfare, "Control Techniques for Particulate Air Pollutants," January 1969.
23. U. S. Environmental Protection Agency, Requirements for preparation, adoption, and submittal of implementation plans, Rules and Regulations, *Fed. Reg.*, **36**, No. 158.
24. T. Waddell, "The Economic Damages of Air Pollution," U. S. Environmental Protection Agency, 1973.
25. C. E. Zimmer and R. I. Larsen, Calculating air quality and its control, *JAPCA*, **15**, 565–72 (1965).