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COSTS INHERENT IN USE OF SUB-OPTIMAL MEASURES OF AIR QUALITY*

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ABSTRACT

Atmospheric aerosols are thought to produce many classes of effects, e.g., morbidity, mortality, property damage. It would be possible to specify a unique theoretically optimal metric for each class of effects. Alternatively a single surrogate metric could be used to represent the combined impact of all classes of effects. Here, the impacts of using surrogates in establishing ambient air pollution standards are explored. It is demonstrated that costs arise due to: (1) reduction in dimensionality of the set of exposure metrics, and (2) imprecision in the relationships between the surrogate and each of the theoretically optimal metrics. These costs must be balanced against the savings flowing from operation of simplified monitoring networks.

INTRODUCTION

Since 1970 national standards for exposure of the public to particulate matter in the ambient air have been expressed in terms of Total Suspended Particulate (TSP) levels. Currently there is interest in replacing, or augmenting, these standards with standards expressed in terms of Inhalable Particulate (IP) levels [1].

The impetus for the proposed change was the recently completed review of the Criteria Document for Sulfur Oxides and Particulate Matter [2], required by Section 108 of the Clean Air Act (CAA). It is natural that during such a periodic

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review new information will come forward. A critical issue for those responsible for air pollution policy is to determine the point at which changes in scientific understanding of air pollution and its effects on human well being are significant enough to justify changes in National Ambient Air Quality Standards (NAAQS). Changes in NAAQS can take many forms, e.g., numerical limits on allowable ambient concentrations may be changed, averaging times or areas to which standards apply may be modified, or the list of regulated pollutants may be altered.

In response to issues raised in the Criteria Document the EPA has issued a Staff Position Paper which advocates a change in the pollutants to be regulated [3]. Specifically, the position paper discusses four alternative pollutant indicator classes within which to frame a new standard:

(a) Indicators used in community epidemiological studies (TSP, British Smoke (BS), Coefficient of Haze (CoH));
(b) Chemically specific indicators (By class, e.g. sulfates, or by compound, e.g. sulfuric acid);
(c) Size specific indicators (e.g. Fine Particulate Matter (FP), Mass Respirable Particulate Matter (MRP), and/or IP); and
(d) Combined particle/SO_2 index.

While each indicator class offers advantages over the others in some respect, the position paper found that the third class, size specific indicators, possessed the most favorable attributes.

From the point of view of a public health professional the issue may seem clear-cut. It has been known since at least 1925 that particles larger than 10 μm do not penetrate to the deep lung [4]. It is widely accepted that the potentially more toxic particles (e.g., heavy metals, sulfates, polycyclic organic materials) tend to be concentrated in the fine mode [5-7]. And it would seem that much, if not most, of the damage to human welfare caused by airborne particles is due to degradation of human health (in contrast to visibility impairment or household soiling) [8]. Logically then, it would seem clear that the NAAQS for ambient particulate matter should be expressed in terms of an air quality measure, such as IP, which is closely related to the concentrations of fine particles in the air.

An economist might have a different point of view. Proceeding from the premise that air quality standards should be set to achieve maximum social welfare, he or she might ask what increase in social welfare could be expected to flow from the proposed change [9, 10]. Realizing that an increase in social welfare could occur only if the benefits (due to improved human health or reduced air pollution control costs) more than offset any cost differential (e.g., due to operation of more sophisticated monitoring equipment) associated with the change from TSP- and IP-based standards, the economist might ask for estimates of the benefits and costs expected to accompany the proposed change.

Although in the case under consideration it may be true that the benefits far exceed the costs, several intersting issues are involved. What is the source of public benefits in the redefinition of air quality standards from one measure of air quality to another? In what circumstances would these benefits be large? What circumstances would justify adding a new NAAQS (e.g., having both TSP and IP NAAQS) rather than simply redefining the existing NAAQS in terms of a new air quality measure? What is the source of costs in the implementation of changes such as these?

Here we explore the factors which govern the changes in social welfare expected to accompany redefinition of ambient air quality standards, paying particular attention to the social costs incurred as a result of adoption of standards based upon sub-optimal measures of air quality. The analysis is presented in two parts. The first concentrates upon the effect on total social costs of imprecision in the relationship between a surrogate, e.g., TSP, and a measure of primary interest, e.g., IP. The second is devoted to an investigation of the costs associated with reduction of the dimensionality of air quality standards—for example setting a single IP standard rather than setting separate standards for each of the components of IP, i.e., fine particles (FP) and coarse particles (CP).

Various authors have considered the influence of uncertainty and multiple objectives on environmental decision making. The treatment of the uncertainty problem has focused principally on imprecision in our knowledge of the marginal benefit and marginal control cost functions [11, 12]. Adar and Griffin evaluated opportunity losses due to uncertainty in the vertical position (i.e., intercept) of these functions for three emission control policies: emission taxes, emission standards, and auctionable pollution rights [11]. Opportunity losses were shown to be influenced by both the degree of uncertainty in the intercept and by the relative slopes of the two functions. Fishelson's analysis introduced the added complexity of stochastic slopes [12].

The problem of multiobjective decision making, and more specifically, the issues related to reduction of dimensionality of sets of evaluators have been discussed elsewhere, see for example Keeny and Raiffa [13]. In addition there has been quite a bit of research in the related areas of social and environmental indices [14–22]. However most of this work has not explicitly addressed the issue of choice of system parameters to be monitored. Rather it has dealt with how: (1) to make decisions once measurements or predictions of the values of many parameters are available, or (2) to condense the information given by the set of monitored parameters into a single index of social or environmental quality. For example, Davos argued that rather than collapsing environmental decisions into a two-dimensional analytical framework, that a priority-tradeoff scanning approach should be adopted [14]. In discussing environmental indices Ott pointed out the fundamental tension [15].

> One viewpoint prefers the data in the most complete form possible, but is willing to accept the resulting complexity, while the other viewpoint prefers the data in as simple a form as possible, but is willing to accept the distortion introduced in the simplification process.

Ott recognized that if valid physical or economic damage functions were available it would be a relatively simple matter to create meaningful environmental indices, and explored in some detail the relationships between damage functions and environmental indices. However, citing Hunt [16], he concluded that there was not adequate scientific understanding upon which to base damage functions. Winer noted the importance of problem definition and recognized the relationship between problem definition and choice of environmental (noise) metrics [17].

Our analysis introduces the concept of an optimal environmental metric, notes that a different optimal metric is likely to be appropriate for each class of pollution impact, points out that the use of sub-optimal measures of environmental quality is one source of uncertainty in benefit and cost functions, and identifies the costs which may arise from both this uncertainty and from attempts to represent environmental quality by a single measure rather than the full set of optimal metrics.

COSTS OF IMPRECISE SURROGATES

To illustrate the nature of the problem, a data set consisting of 1418 paired TSP, IP samples from the Harvard-NIEHS Six Cities Study is examined [23]. The TSP data are based upon gravimetric analysis of the mass collected on glass fiber filters by standard High-Volume samples. The IP data are based upon β-gauge analysis of the mass collected on Teflon filters by dichotomous samplers (virtual impactors). The distribution of data pairs by city and by season is shown in Table 1.

Table 1
Distribution of Illustrative Data by City and Season

	% Winter (Dec-Feb)	*% Spring (Mar-May)*	*% Summer (Jun-Aug)*	*% Autumn (Sept-Nov)*	*Total Number of Samples*
Kingston, TN	22	34	25	18	338
St. Louis, MO	22	34	18	25	162
Portage, WS	30	27	19	24	181
Steubenville, OH	18	32	33	17	280
Topeka, KS	20	24	25	27	225
Watertown, MA	28	19	26	27	232
All Cities	23	29	25	23	1418

Table 2
Classification of Data by TSP and by IP Levels (%)

	$\leqslant TSP^*$	$> TSP^*$	*Total*
$> IP^*$	0.5	8.1	8.6
$\leqslant IP^*$	82.3	9.1	91.4
Total	82.8	17.2	100.

Figure 1 demonstrates the correlation of IP and TSP values in the pooled data set from the six cities. Superimposed upon the plot are dashed lines indicating the levels of hypothetical IP and TSP standards. These dashed lines divide the set of observed IP, TSP pairs into four subsets. Points falling into the lower left or upper right quadrants are indicative of concordance of the hypothetical IP and TSP standards. Points in the other two quadrants are indicative of discordance. Table 2 gives the fractions of all points which fall into each of the quadrants. In our example most (90.4%) of the data are classified identically regardless of which air quality measure is used as the basis for classification. However, based upon TSP values 17.2 percent of all days are above the hypothetical standard. When classified according to IP value, only 8.6 percent of all days are above the hypothetical IP standard.

Does this imply that substitution of the hypothetical IP standard for the hypothetical TSP standard would result in a reduction in social welfare? Although some might believe so, careful analysis indicates otherwise. It is true that the hypothetical IP standard leads to only half as many violations as the hypothetical TSP standard. But this is not synonymous with a reduction in social welfare. To properly analyze the social welfare impact we must first identify those areas from which social costs originate in the redefinition of standards.

Some of the sources of social costs may be illustrated using an example in which we assume that all of the damage caused by particulate air pollution is due to inhalable particles. It would then seem reasonable for society to set an IP standard. Economic considerations would dictate that the standard be set at the level IP* which minimized the sum of air pollution control costs and air pollution-induced damage costs. The social cost associated with this optimal level of particulate air pollution may be designated TC*.

Consider the influence on total social costs of a strategy in which ambient air quality standards are based upon a second measure of air quality, e.g., TSP, which is related, though imprecisely, to the measure of primary interest, i.e., IP. Although it might at first seem that no additional social costs would be involved, further consideration reveals that additional social costs are a direct consequence of imprecision in the relationship between TSP and IP. This is clearly indicated in Figure 2. The minimum social costs are obtained at IP*. Intuitively it is clear

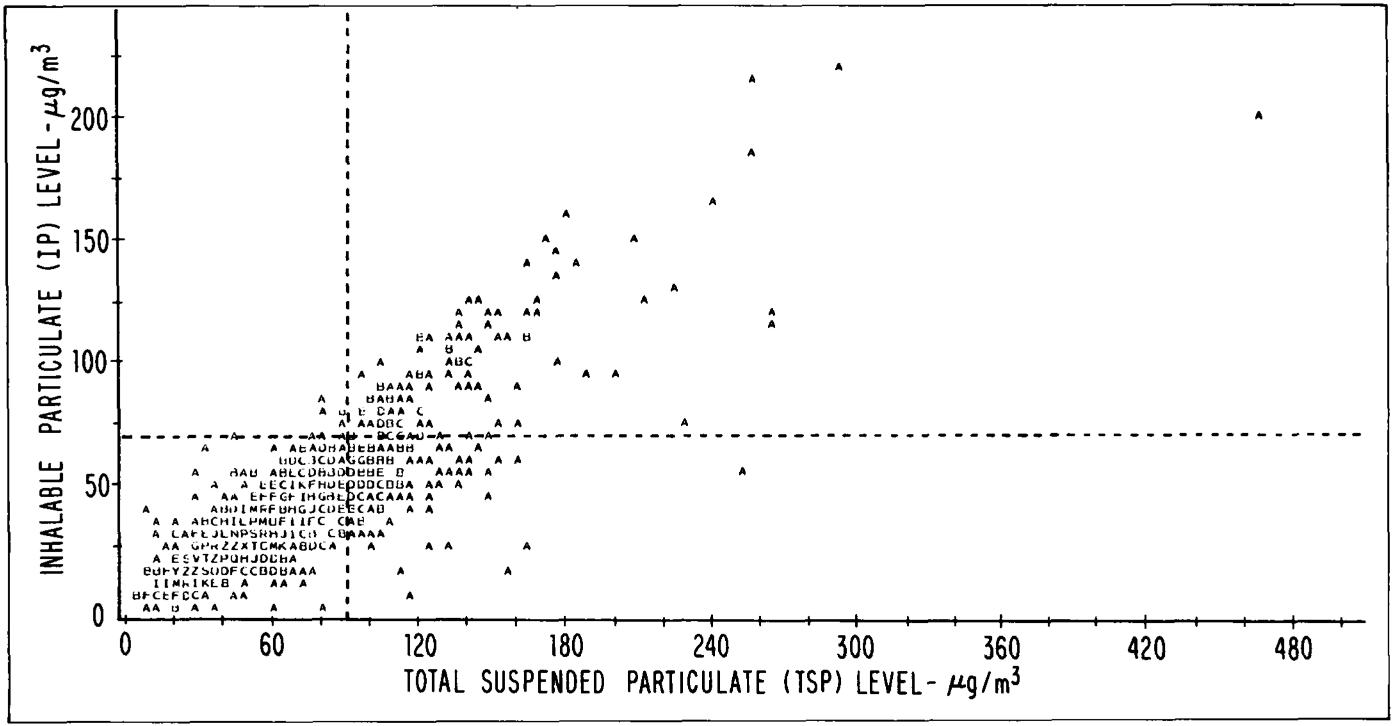

Figure 1. Level of Inhalable Particulate (IP) Matter as a function of Total Suspended Particulate (TSP) Matter . . .
Pooled data from the Six Cities Study [23].
Legend: A = 1 OBS, B = 2 OBS, ETC.
NOTE: 15 CBS HIDDEN

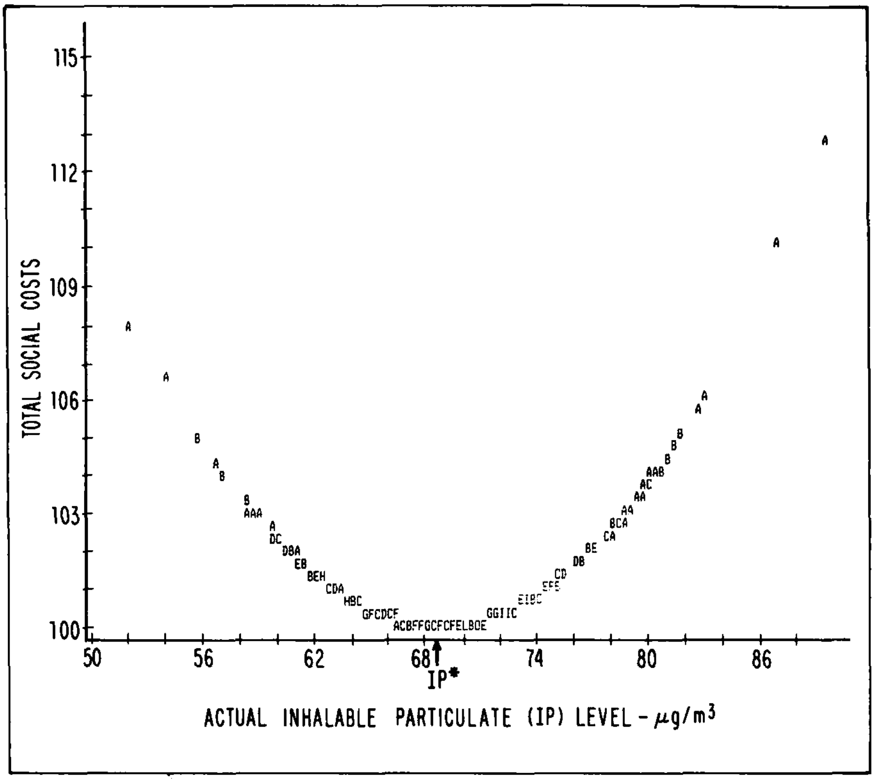

Figure 2. Variation in total social costs due to random fluctuations in inhalable particulate levels with TSP levels held at the optimal level, TSP*. n.b. – units are arbitrary on both axes.

that if ambient standards must be framed in terms of TSP levels, the TSP level which should be chosen is that corresponding to IP*. For example, if IP and TSP values were related to each other by the stochastic linear equation:

$$IP = a_0 + a_1 TSP + \epsilon \qquad (1a)$$

$$a_0, a_1 = \text{empirical constants} \qquad (1b)$$

$$\epsilon = \text{a random variable distributed normally with mean } 0 \qquad (1c)$$

then the TSP level associated with the lowest expected costs would satisfy the relationship, $TSP^* = (IP^* - a_0) / a_1$. Although at this level the expected social costs would be at a minimum, there would be no certainty that IP levels would be IP*. By definition, at any IP level other than IP* the total social costs would be above their minimum level, TC*.

The difference between the social costs achieved with a TSP standard set at TSP* and those which could have been achieved with an IP standard set at IP* represents an opportunity loss incurred due to the imperfect information provided by TSP monitors. Mathematically, the opportunity loss, (OL), may be expressed as:

$$\mathrm{OL(IP|TSP^*)} = \mathrm{TC(IP|TSP^*)} - \mathrm{TC^*} \tag{2a}$$

Using the first four terms of a Taylor series expansion, the opportunity loss may be approximated to be:

$$\mathrm{OL(IP|TSP^*)} \approx \frac{\mathrm{dTC}}{\mathrm{dIP}}\epsilon + \frac{1}{2}\frac{\mathrm{d^2TC}}{\mathrm{dIP^2}}\epsilon^2 + \frac{1}{6}\frac{\mathrm{d^3TC}}{\mathrm{dIP^3}}\epsilon^3 + \frac{1}{24}\frac{\mathrm{d^4TC}}{\mathrm{dIP^4}}\epsilon^4 \tag{2b}$$

Thus, the opportunity loss itself is a stochastic quantity. The magnitude of the expected opportunity loss is determined jointly by the degree of curvature of the total social cost curve in the vicinity of its minimum, and by the degree of imprecision in the relationship between the surrogate, TSP, and the measure of primary interest, IP.

The principle involved is illustrated by the data presented in Table 2. For the moment examine the table with the point of view that the correct classifications of data are based upon their IP values, but that regulatory actions must be based upon the evidence provided by TSP monitors. Over 90% of the data would be correctly classified. But 9.1 percent would be erroneously classified as above the optimal IP level, IP*, and 0.5 percent would be mistakenly interpreted as below IP*. In the cases erroneously thought to be above the optimal IP level, additional social costs would result from unnecessary control efforts. In the cases mistakenly thought to be below the optimal IP level, excess social costs would result from undesirably high levels of air pollution damage, e.g., ill health, visibility degradation, household soiling.

A second, more detailed, example of the imprecision inherent in IP predictions based upon TSP levels is found in the data from a single city, Kingston, Tennessee. Figure 3 is a plot of the daily values of IP monitored in Kingston between 14 August 1978 and 10 May 1981. During this period, twenty of the IP values were above the hypothetical IP* level of 68.75 $\mu g/m^3$. Analysis of the paired IP,TSP data indicated that the equation, IP = 4.93 + 0.556TSP ±9.96, R^2 = 0.708, allows IP levels to be predicted from TSP data. Figure 4 is a plot of the predicted IP levels developed by applying this equation to the daily TSP data. Note that only twelve of the predicted values are above the hypothetical IP*. Furthermore, in only nine of these twelve cases are the true IP levels above IP*. In addition, note that there were eleven days with true IP levels above IP* which were similarly misclassified. Imperfect information such as this would be the basis for incorrect classification of the compliance status of regions, which in turn could be expected to lead to imprecise regulatory and control actions—with the associated economic opportunity losses.

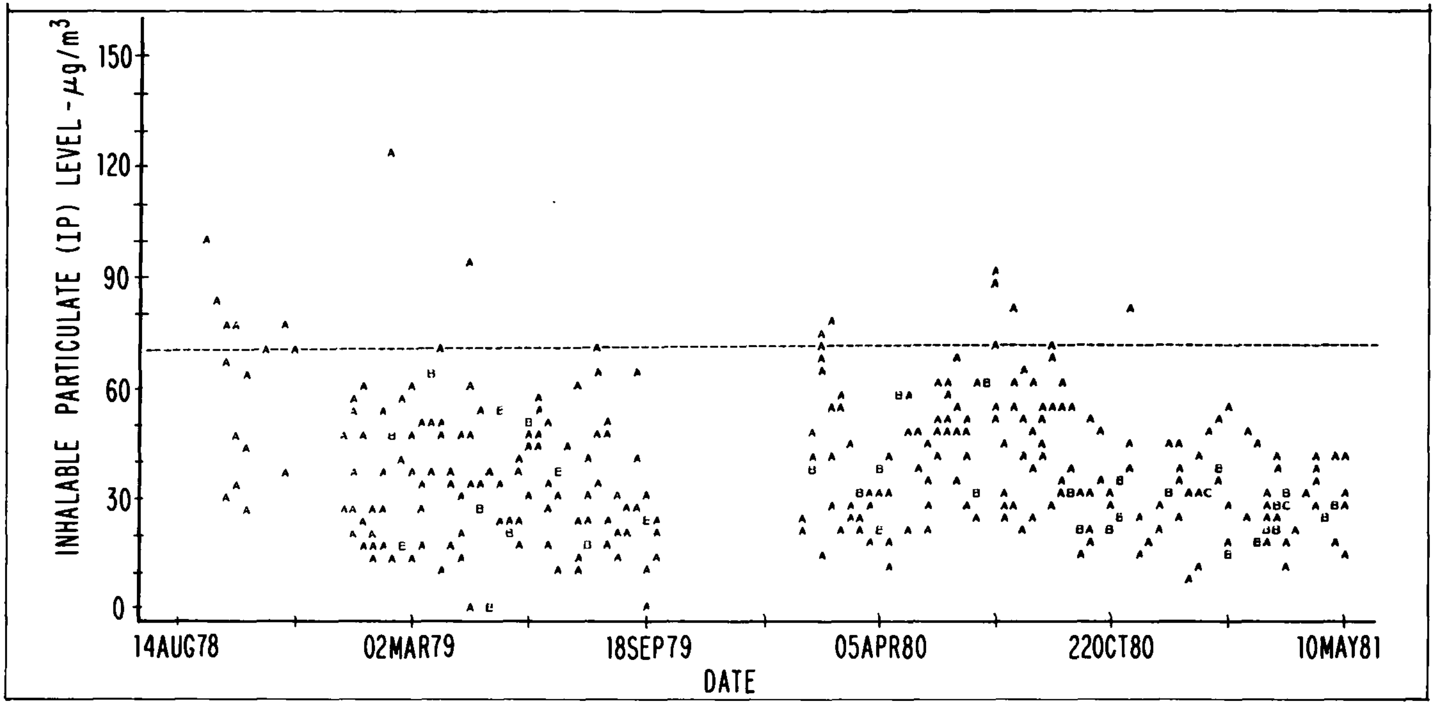

Figure 3. Actual Inhalable Particulate (IP) levels in Kingston, Tennessee during the interval between 14 August 1978 and 10 May 1981. The dashed horizontal line indicates the level of a hypothetical IP standard.
Legend: A = 1 OBS, B = 2 OBS, ETC.

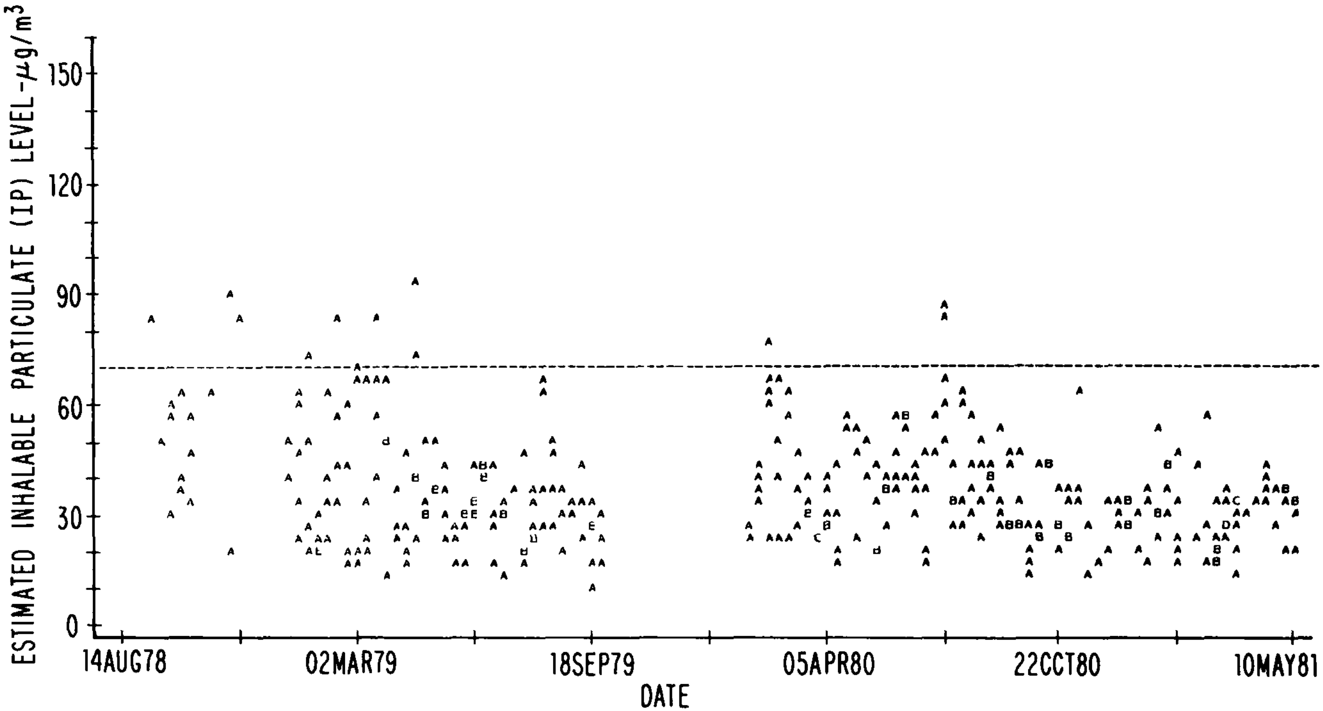

Figure 4. Estimated Inhalable Particulate (IP) levels in Kingston, Tennessee during the interval between 14 August 1978 and 10 May 1981. The dashed horizontal line indicates the level of a hypothetical IP standard.
LEGEND: A = 1 OBS, B = 2 OBS, ETC.

To more clearly illustrate the factors which influence the expected opportunity loss we performed several analyses. In these analyses we assumed that total social cost functions for particulate air pollution could be adequately approximated as parabolas. A parabola, after appropriate translation and rotation, is completely described by a single parameter, p—the distance from the directrix to the horizontal axis. In the first set of calculations we restricted attention to social cost functions which were symmetric about their minima.

The expected opportunity loss is found simply by integrating the product of the opportunity loss and the probability density function (pdf) for IP given TSP* (IP|TSP*) over the relevant range of IP values. For parabolic total social cost curves and normal probability density functions the expected opportunity loss may be found analytically:

$$\mathrm{EOL} = \int [\mathrm{OL}(\mathrm{IP} - \mathrm{IP}^*)]\ \mathrm{pdf}(\mathrm{IP}|\mathrm{TSP}^*)d\mathrm{IP} = \frac{\sigma^2}{4p} \qquad (3)$$

This result indicates that as the cost curve becomes steeper in the vicinity of its minimum, i.e., p becomes smaller, and as the imprecision in the relationship between the surrogate and the measure of primary interest becomes greater, i.e., σ^2 becomes larger, the expected opportunity loss increases. Empirical verification of this behavior is evident in the results from four Monte Carlo simulations presented in Table 3. Each simulation involved 1000 realizations. The total social cost curve and the stochastic linear equation relating IP and TSP values are given below:

$$\mathrm{TC}(\mathrm{IP}) = 100 + \frac{(\mathrm{IP} - 68.75)^2}{4p} \qquad (4a)$$

$$\mathrm{IP}(\mathrm{TSP}) = 1.63 + 0.572\mathrm{TSP} + \epsilon \qquad (4b)$$

$$\epsilon = N(0,\sigma) \qquad (4c)$$

As indicated by equation 4a, for all of the simulations the parabolic total social cost functions were constrained to have minima of TC* = 100 at the arbitrarily chosen optimal IP value, IP* = 68.75 $\mu g/m^3$. The four simulations which were

Table 3
Simulated and Analytical Expected Opportunity Losses for Symmetric Parabolic Cost Curves

		EOL (%)	
Uncertainty in Prediction	*Shape of Curve*	*Simulation*	*Analytical*
Small σ = 6.5	Flat p = 8.450	1.29	1.25
	Steep p = 2.817	3.88	3.75
Large σ = 13	Flat p = 8.450	5.06	5.00
	Steep p = 2.817	15.2	15.0

Table 4
Simulated Expected Opportunity Losses for Asymmetrical Parabolic Cost Curves

TSP	*E(IP | TSP)*	*Simulation Results*					
		Run #1		*Run #2*		*Run #3*	
		$\overline{IP}$	*EOL (%)*	$\overline{IP}$	*EOL (%)*	$\overline{IP}$	*EOL (%)*
117.3	68.75	68.47	10.46	68.10	10.27	69.44	9.71
124.2	72.75	72.47	8.72	72.10	8.36	73.44	8.49
126.0	73.75	73.47	8.56	73.10	8.17	74.44	8.44
127.8	74.75	74.47	8.51	74.10	8.08	75.44	8.49
129.5	75.75	75.47	8.55	75.10	8.09	76.44	8.63
131.2	76.75	76.47	8.70	76.10	8.20	77.44	8.88

conducted involved two levels of steepness of the social cost curve (relatively flat(p=8.450) and relatively steep(p=2.817)) and two levels of imprecision in prediction of IP from TSP (relatively precise(σ=6.5) and relatively imprecise(σ=13)). The anticipated behavior is evident–the expected opportunity losses for the steep social cost curves are about three times those for the flat curves, and the expected opportunity losses for the imprecise IP - TSP relationships are about four times as great as those for the more precise relationships.

While the principles illustrated above are of general relevance, the precise results are limited to social cost functions which are symmetrical about a vertical axis through their minima. For social cost functions which are asymmetrical the situation is more complicated. Since the opportunity losses are larger on one side of the minimum than on the other, the minimum expected opportunity loss is not achieved at the TSP value corresponding to IP*. This point is illustrated in the Monte Carlo simulations summarized in Table 4.

Included in the table are the results from eighteen simulations, three at each of six tentatively optimal TSP levels. Each of the eighteen sets of simulations involved 500 realizations. In all of these simulations the social cost curve increased more steeply to the left of its minimum than to the right. The social cost function used in these analyses was constructed by joining two parabolas at their minima. As in the previous simulations, the minimum social cost was 100 at the arbitrarily selected optimal IP value, IP* = 68.75. To the left of this minimum, the cost increase was determined by a parabolic curve with p_1=2.817. To the right, a parabolic curve with p_2=8.450 was used to generate the social costs. The six TSP values which were explored varied from 117.3 $\mu g/m^3$ to 131.2 $\mu g/m^3$, corresponding to IP values varying from 68.75 $\mu g/m^3$ to 76.75 $\mu g/m^3$. Again, IP values in the simulations were generated from TSP values according to equation 5b, with σ=13. As expected, the TSP value yielding the lowest expected opportunity loss (and therefore the lowest expected social cost) lies to the right of the TSP value corresponding to IP*. In the simulations a TSP value in the neighborhood of 127.5 $\mu g/m^3$ appears to yield the lowest expected opportunity loss, approximately 8.25 percent. This is appreciably lower than the expected opportunity loss, 10 percent, associated with a TSP value of 117.3 $\mu g/m^3$ – the TSP value corresponding directly to IP*.

For the special case considered here, i.e., an asymmetrical social cost curve created by joining two parabolas at their minima, the shift in IP required to minimize expected total social costs may be calculated directly using the relationship:

$$\text{IP-IP*} = \frac{\frac{\sqrt{2}\sigma}{\sqrt{\pi}}(a-b)}{a+b} \tag{5a}$$

$$\text{where } a = \frac{1}{4p_1},\ b = \frac{1}{4p_2} \tag{5b}$$

Applying this equation to the parameters of the parabolas used in the simulations yields an optimal shift in IP of +5.185 $\mu g/m^3$, corresponding to an optimal TSP level, TSP*, of 126.4 $\mu g/m^3$.

It is not expected that the total social cost function applicable to airborne particles is actually parabolic. However the use of a parabolic functions simplified analytical derivation of many useful results. Where actual cost functions can not adequately be approximated by parabolas, numerical methods may be used to find exact solutions.

In summary, the analyses presented in this section have demonstrated that use of a sub-optimal measure of air quality may be expected to lead to economic opportunity losses; that these losses increase as the social cost curve increases in steepness near its minimum and as the imprecision in the relationship between the surrogate and the measure of primary interest increases; and that if the social cost curve is asymmetrical additional costs may be incurred unless the optimal level of the surrogate, e.g., TSP, is shifted appropriately to reflect the impact of the asymmetry upon the expected opportunity losses.

Our analysis of uncertainty has concentrated on the influence of use of suboptimal measures of air-quality, e.g., TSP rather than IP or FP. However, the real optimization problem is more complex. Additional uncertainties in our knowledge of air quality levels are introduced due to: (1) limitations in the spatial and temporal density of monitoring, (2) both systematic and random errors in the behavior of monitoring devices, and (3) mistakes in the transcription, encoding and analysis of air quality data. Further, there are uncertainties in our knowledge of health effects and in valuation of health effects which are not related to the uncertainties in our knowledge of air quality levels. These additional sources of uncertainty could easily be introduced into the analysis and would not be expected to qualitatively influence the conclusions.

COSTS OF REDUCED DIMENSIONALITY OF STANDARDS

In this second section of analysis we consider the added complexity introduced by allowing for differential potencies and control costs of the various components of inhalable particulate matter. To simplify the analysis we consider IP to be composed of two components, fine particulate (FP) material and coarse particulate (CP) material, of potential regulatory interest. The problem faced by an official responsible for establishing ambient air quality standards would be to determine whether to issue a single standard for IP or to issue two standards—one applicable to FP and another applicable to CP.

Intuitively it is clear that the factors which govern the decision include: the degree of difference of potency of fine and coarse particles, the degree of difference of unit control costs applicable to fine and coarse particles, and the relative importances of both fine and coarse particles in determining total social costs. To illustrate qualitatively the importance of each of these factors, we consider an example in which it is assumed that fine particles are twice as potent as coarse particles, but are four times as expensive to control.

$$TC_{coarse} = D_{coarse} + C_{coarse} \tag{6a}$$

$$\text{for } 0 < CP,\ D_{coarse} = CP^2 \tag{6b}$$

$$\text{for } 0 < CP < CP_0,\ C_{coarse} = (CP\text{-}CP_0)^2 \tag{6c}$$

$$TC_{fine} = D_{fine} + C_{fine} \tag{6d}$$

$$\text{for } 0 < FP,\ D_{fine} = 2FP^2 \tag{6e}$$

$$\text{for } 0 < FP < FP_0,\ C_{fine} = 4(FP\text{-}FP_0)^2 \tag{6f}$$

where,

D_{coarse} = costs due to coarse particle damage, C_{coarse} = costs due to coarse particle control, D_{fine} = costs due to fine particle damage, C_{fine} = costs due to fine particle control, and $FP_0 = CP_0$.

These exemplary control cost functions exhibit increasing marginal control costs as the level of air pollution control is increased. The air quality damage functions exhibit increasing marginal damage costs as the levels of ambient air pollution are increased. However, the only feature of the chosen functions which is critical to our conclusions is that the marginal rate of substitution of fine particles for coarse particles is not constant.

If the air quality regulator were interested in achieving minimum total social costs using two separate standards, he or she would set the standards at the values CP* and FP* which minimized the total cost equations 6a and 6d. Solving for these values yields $CP^* = \frac{CP_0}{2}$ and $FP^* = \frac{2FP_0}{3}$. To give a numerical example, we set $CP_0 = FP_0 = 58.93$ yielding $CP^* = 29.46$ and $FP^* = 39.29$. The total social cost (TSC*) associated with these optimal values is 100, found by substitution of FP* and CP* into the equation:

$$TSC^* = (CP^{*2} + (CP^*-CP_0)^2 + 2FP^{*2} + 4(FP^*-FP_0)^2)\,k \tag{7}$$

where k is an arbitrary scaling constant, which we have set at the value 0.0157 to yield a total social cost of 100 at the optimum. Figure 5 gives the total social costs incurred at levels of FP and CP between 0 and 80 $\mu g/m^3$. Equation 7 is valid for values of FP and CP below FP_0 and CP_0, respectively. For FP and CP values falling in different regions, total social costs were computed using equations similarly defined on the basis of equations 6a through 6f. The point corresponding to FP*, CP* is shown on the figure.

Figure 5 illustrates how additional social costs would be incurred in any attempt to regulate on the basis of IP levels alone in circumstances similar to these. Since by definition IP = FP + CP it would seem clear that the optimal level

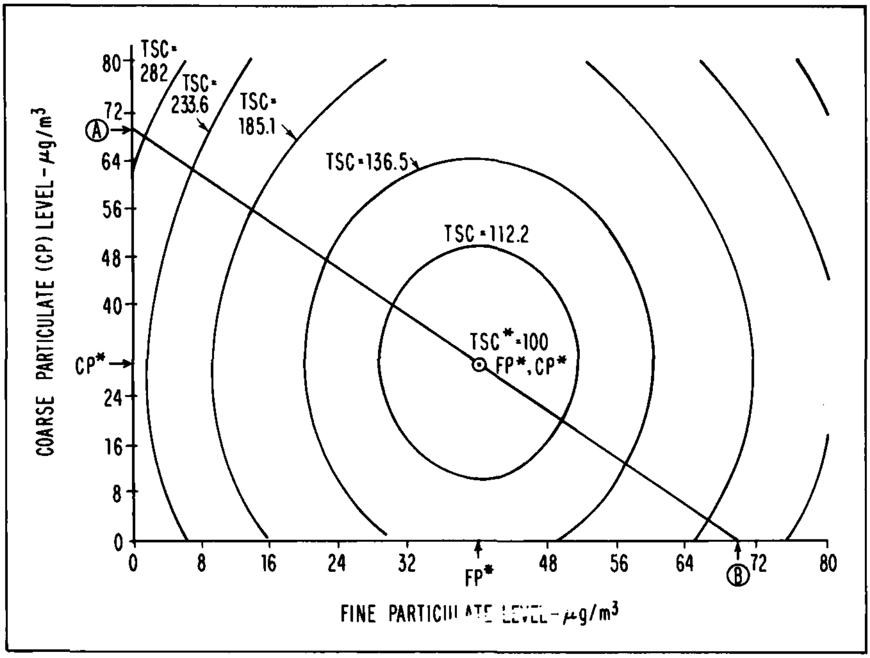

Figure 5. Hypothetical levels of Total Social Costs (TSC) as a function of levels of both fine (FP) and coarse (CP) particle levels. Minimum cost point at FP*=39.3 $\mu g/m^3$, CP*=29.5 $\mu g/m^3$. Also indicated by the line AB is a hypothetical IP standard of IP*=68.75 $\mu g/m^3$.

of IP would be IP* = FP* + CP* = 68.75. However, a direct consequence of the reduction in dimensionality is the potential for obtaining suboptimal levels of FP and CP. A standard defined simply in terms of IP could be met at any point on line AB of Figure 5, with social costs increasing in either direction away from the point FP*, CP*. Moves in the direction of point B would be favored by pollution producers since, in the region of the optimum, marginal control costs are less for CP than for FP. Groups concerned exclusively with costs due to air pollution damage would favor moves in the opposite direction, towards point A, because marginal damage costs are less for CP than for FP. Since polluters would be in a position to exercise control as best suited their self interest (i.e., internal cost minimization), we might expect actual FP and CP levels to fall on line AB at points somewhere between FP*, CP* and point B. Thus, added social costs arise through a combination of reduction in dimensionality and the internal cost minimization of those with the power to choose emission control options.

DISCUSSION

In summary, it has been demonstrated that the social costs of using a single imprecise surrogate, e.g., TSP, rather than the complete set of theoretically optimal metrics, e.g., FP, CP, arise in two ways. The first problem stems from the imprecision in the relationships between the surrogate and each of the theoretically optimal metrics. The second stems simply from reducing the dimensionality of the problem. The expected total cost to society associated with use of an imprecise surrogate is a function of both components. A third factor which must be considered is the set of social benefits associated with simplified monitoring networks. For example, benefits might accrue due to reduced costs of monitoring programs and administrative activities, e.g., modeling, record keeping, and inspections.

The analysis demonstrates that with complete knowledge of the social costs and control costs of air pollution, the theoretically optimal metrics, and the relationships between any proposed surrogate and each of these optimal metrics, it would be possible to estimate the additional social costs introduced by use of the surrogate as a basis for regulatory action. Theoretically, then, it should be possible to:

(a) rationally select the best of a group of proposed alternative surrogates; and
(b) determine whether the opportunity losses associated with use of a surrogate are commensurate with the benefits which flow from any simplification of monitoring networks and data collection-storage systems.

Actually, gaps in data and scientific knowledge prevent quantitative application of the approaches outlined above. Consider, for example, the situation with respect to airborne particles. A fundamental problem is the lack of consensus about the relationship(s) between exposure to airborne particles and various health outcomes. The few (highly controversial) studies which provide any basis for a quantitative relationship between particle exposure and community mortality rates are based upon measures of exposure such as TSP, CoH, and BS [24-26]. In most of these studies there was no concurrent measurement of exposures in terms of measures of current regulatory interest, e.g., IP, FP, or CP. Therefore, the necessary information about both the damage function (in terms of the optimal metric) and the relationship between the surrogate and the optimal metric is not available.

As a practical matter, the dynamics of scientific enquiry are such that this will most often be the case. The optimal metric will rarely, if ever, be identified in advance. Therefore it is extremely unlikely that there will be available information relating the exposure, defined in terms of the optimal metric, to effect.

Since crude measures (e.g., TSP) are likely to be developed before sophisticated measure (e.g., IP, FP, or CP) it is more likely to be the case that a regulator will be faced with the problem of deciding whether an existing measure should be replaced by an "improved" measure (or set of measures). Furthermore, even in the best circumstances, he or she is likely to have available quantitative information only on: the relationship between the existing measure and environmental effects, and the relationship between the proposed "improved" measure and the existing one.

Nonetheless, it seems clear that qualitative consideration of each of the major determinants of the costs associated with surrogates is useful. For example, in the discussions of whether or not TSP is an adequate regulatory measure of atmospheric aerosols, several points should be considered:

1. How precisely is TSP related to the optimal metrics for health, soiling, and visibility?
2. How much more precisely, if at all, are the alternative measures FP, CP, IP related to the optimal metrics?
3. Relatively how costly is each of these effects, i.e., health impairment, visibility degradation, and soiling damage?
4. How much more expensive is it to operate a monitoring network and data handling system for the alternative measure (or set of measures) than for TSP alone?
5. How steep is each of the social cost functions (health, soiling and visibility) thought to be in the neighborhood of the optimal level?
6. To what degree can ambient levels of each alternative measure (or set of measures) be altered independently of TSP using feasible control strategies?

Furthermore, the analysis indicates the potential value of simultaneous determination of ambient concentrations of particles in terms of both existing and proposed measures. Such simultaneous exposure estimation would be of particular value in epidemiological studies. When such concurrent measurements are not available, it may be useful to postpone decisions concerning the replacement of one measure by another.

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