Controlling Urban Air Pollution: A Benefit-Cost Assessment

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To help focus debate about the best use of society's resources, it is important to have estimates of the benefits and costs of further improvements in air quality. Such estimates are developed, with focus primarily on reductions in ground-level ozone resulting from the control of volatile organic compounds; to a lesser extent, particulate control also is considered. Proposed controls are evaluated for both the nation as a whole and for the Los Angeles metropolitan area, where violations of air quality standards are most frequent and severe. Subject to a number of uncertainties, the costs of proposed new controls are found to exceed the benefits, perhaps by a considerable margin.

ENVIRONMENTAL REGULATION IS IMPORTANT TO OUR health and well-being and also is quite expensive. For these reasons, we must look carefully at our environmental laws and regulations to see what they will accomplish and at what cost.

Recently, three major changes were made to the Clean Air Act. First, over the next decade electric power plants must make sharp reductions in emissions of sulfur dioxide (SO_2)—10 million tons per year measured from their 1980 level. Second, most major sources of what are called hazardous air pollutants (less ubiquitous but still potentially harmful substances such as benzene, acrylonitrile, beryllium, and coke oven emissions) must install state-of-the-art emissions control equipment and, eventually, further reduce any residual emissions that pose unacceptably high health risks. Third, a number of new measures have been enacted to improve air quality in areas where the national ambient air quality standards (NAAQS) are currently being violated (*1*).

This third problem, referred to as nonattainment with regard to the NAAQS, is by far the most difficult to solve. According to the Environmental Protection Agency (EPA), in 1989 more than 66 million people in the United States lived in counties where the ozone (O_3) standard was being exceeded at one or more monitors (*2*). Another 27.4 million lived in areas violating the particulate standard; the corresponding totals were 0.1 million for SO_2, 33.6 million for carbon monoxide (CO), and 8.5 million for nitrogen dioxide (NO_2).

Most of the inexpensive pollution control measures were implemented during the last 20 years, so that future reductions in emissions are likely to be more expensive than earlier ones. Furthermore, the measures required to address remaining pollution problems will fall increasingly on individuals rather than on the large industrial facilities (called point sources) and motor vehicles, which shouldered most of the burden of the initial clean-up (*3*). More and more, air pollution problems are those associated with wood stoves, small dry-cleaning and degreasing operations, painting shops, bakeries, and other decentralized sources. As a result, the burden of pollution control will become more obvious to the public.

To help focus debate about the best use of society's resources, it is important to have estimates of the benefits and costs of further improvements in air quality. In this article we develop such estimates, focusing primarily on reductions in ground-level O_3 resulting from the control of volatile organic compounds (VOCs) (*4*); we also consider particulate control. We evaluate proposed efforts both at the national level and in the Los Angeles metropolitan area, where violations of air quality standards are most frequent and severe. In both cases, we first present point estimates of benefits and costs and then discuss uncertainties in a subsequent section. A brief background precedes this analysis.

Benefit-Cost Analysis and Air Quality Regulation

Benefit-cost analysis. Benefit-cost analysis is used by economists to identify, quantify, and weigh the advantages and disadvantages of public policies designed to increase society's overall well-being. Originally used by the Army Corps of Engineers to judge alternative water resources projects, it has become an integral part of policy analysis at all levels and types of government.

The quantification of benefits and costs rests on the idea that an action has value if someone is willing to pay for it, and each individual is held to be the best judge of how a policy affects him or her (*5*). If an individual assigns a high or a low value to something about which others feel different, that value must be counted nonetheless. The overall value to society of a proposed policy change is measured by the sum of the individual valuations. Thus benefit-cost analysis is unabashedly anthropocentric in that things have value only to the extent that they provide well-being to individuals. These effects, however, are not restricted to purely financial gains and losses. They include the reduced well-being that results from aesthetic degradation, for instance, as well as that felt directly in the pocketbook.

The values that individuals would be willing to pay for the favorable impacts of a policy—whether increased agricultural output or intangibles such as cleaner air, purer drinking water, or the removal of hazardous wastes—often are difficult to ascertain, but economists have devoted much effort to developing valuation techniques consistent with the underlying principles of welfare economics (*6*). Costs are generally measured as the expenditures that

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private firms, governments, and individuals must make to comply with regulations. Analogous to benefits, however, costs should be measured by the amount of money required to compensate individuals for the unfavorable effects associated with a regulatory or other public policy; these might take the form of higher prices, reduced incomes, the inconvenience of forced car-pooling, or some other welfare-reducing policy (*7*). Because models frequently are not available to estimate costs in the preferred way, pollution control expenditures are usually used as proxies. That is the approach taken here.

In principle, benefit-cost analysis includes the value of even the most intangible effects of a policy. For instance, if everyone in the United States was willing to pay $4 per year to preserve a particular wetland area, annual benefits of its preservation would be about $1 billion; similarly, to the extent that people are willing to pay something for the preservation of species diversity, whether for commercial or philosophic reasons, it is counted as an economic benefit. It is important to understand that benefit-cost analysis is not restricted to goods bought and sold in private exchange.

Finally, although benefit-cost analysis is a technique for identifying efficient policies, economic efficiency is surely not the only basis on which policy decisions should be made. Distributional considerations, legal mandates, and ethical concerns are also of great importance, and benefit-cost analysis is generally (but not always) silent about such matters (*8*).

Air quality regulation. When the Clean Air Act was amended in 1970, Congress directed the administrator of the new EPA to establish air quality standards to protect human health with an adequate margin of safety. The first standard for O_3 was set in 1971, the basis of which was total photochemical oxidants: The daily high 1-hour reading was not to exceed 0.08 part per million (ppm) on more than 1 day per year. In 1979 the EPA changed the basis of the standard from total photochemical oxidants to O_3 and relaxed the 1-hour standard to 0.12 ppm, not to be exceeded on more than 3 days in any 3-year period (in other words, the reading on the fourth highest day, called the design value, determines attainment status). The O_3 standard remains the same today.

In spite of the 1979 relaxation, violations of the O_3 standard are frequent. For instance, 101 metropolitan areas failed to meet the standard in 1988; 31 of these had more than 10 violations, and 3 (Los Angeles, Fresno, and Bakersfield) had more than 20 violations. Of these 3, Los Angeles led the pack with 148 days on which the 0.12-ppm 1-hour standard was exceeded at least one monitor.

In many of the areas where violations occur, the standard is exceeded only slightly. This is not the case everywhere, however. In Houston, New York, Chicago, and Philadelphia, for instance, the 1988 design values were about 0.22 ppm. In Los Angeles, the design value for 1988 was 0.33 ppm, nearly three times the level of the standard (*9*). Thus both the frequency and the severity of violations of the O_3 standard are fueling concern about the nonattainment problem nationwide.

Reducing Ozone in Urban Areas

To evaluate the benefits and costs of reducing ambient O_3 concentrations, one must first estimate the VOC reductions expected in various areas and the O_3 improvements that they imply. Then the costs of the measures to be used to obtain the VOC reductions and the benefits associated with the O_3 improvements can be estimated.

In 1989, the Office of Technology Assessment (OTA) released a major study of air quality problems in the United States (*10*). The study estimated the changes in emissions of VOCs and, subsequently, reductions in O_3 design values that would result in the years 1994 and 2004 from the application of all currently available VOC control technologies in nonattainment areas and some added control in clean areas (*11*). No transportation control plans or additional controls on nitrogen oxides (NO_x) were included.

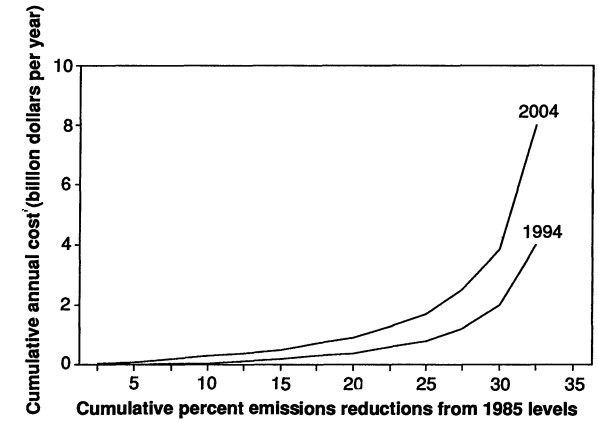

Fig. 1. Escalation of cumulative annual cost above a 30% reduction in VOC emissions, using control methods analyzed by OTA (nonattainment cities only). [Adapted from (*10*)]

As estimated by OTA, by the year 2004 these control measures would reduce total annual emissions of VOCs in nonattainment areas from about 11 million to about 7 million tons, representing a 35% reduction. Depending on the particular urban area in question, the annual VOC reduction would vary from 20 to 50% (*12*). Our benefit and cost estimates pertain to this predicted change in air quality.

These estimated emission reductions for each city were then passed through a set of EPA trajectory models, which predict peak ambient concentrations of O_3 (*13*). The VOC controls that OTA considered were projected to bring 31 of the 94 areas in mild violation of the O_3 standard in 1985 into attainment by 2004. Areas such as Los Angeles, however, with design values greater than 0.15 ppm, were predicted to remain in violation even after controls were implemented, although the predicted design values would be reduced somewhat. For instance, in Los Angeles the highest single reading was predicted to fall by about 20% by the year 2004 as a result of the controls that OTA considered.

Costs. According to OTA, the annualized cost associated with this ambitious set of measures would be $6.6 billion to $10.0 billion in the nonattainment areas alone, or about $1800 to $2700 per ton of VOC reduced there. Adding in the costs that would be borne in attainment areas raises the estimated total to $8.8 billion to $12.8 billion per year.

Of all the control measures examined, reducing the volatility of gasoline accounts for the greatest emission reduction (about 14%) and would also be the most cost-effective control technology because this reduction would cost between $120 and $740 annually per ton of VOC reduced. At the other extreme, OTA found that using methanol (an 85% blend) to power fleet vehicles would be an expensive measure: $8,700 to $51,000 per ton of VOC reduction (*14*). A ranking of individual approaches by cost effectiveness shows that marginal costs increase sharply for obtaining any more than a 30% reduction in VOC emissions (Fig. 1).

Benefits. How does one ascertain the amount individuals would be willing to pay for the air quality improvements that OTA projects? We concentrate on acute health benefits because protecting health is the primary justification for setting air quality standards under the Clean Air Act and because only acute health effects have been linked convincingly to O_3 concentrations. Other benefits could accrue in the form of reduced damage to exposed materials, crops, and other vegetation and possibly reductions in the prevalence of chronic illness.

To determine the acute health benefits associated with the estimated 35% reduction in VOC emissions in nonattainment areas, we used a county-level model developed for this purpose (*15*). The model predicts reduced baseline O_3 concentrations in each area for each day of the O_3 season on the basis of the percentage reductions in O_3 design values obtained from OTA (*16*). These air quality changes must then be mapped into improved human health. To do so, we combined area-specific data on air quality improvements and population with dose-response functions based on epidemiologic and clinical (controlled laboratory) studies relating ambient O_3 concentrations to various symptoms and other adverse human health effects (*17*). Thus, for example, the predicted air quality improvement in a particular urban area in the year 2004 can be translated into fewer asthma attacks, reduced incidence of coughing and chest discomfort, reduced number of days of restricted activity, and the like on the basis of predicted population of that area in that year. For example, the clinical dose-response function we used to predict the reduced incidence of coughs for an entire population at a given reduction in ambient O_3 concentrations is

$$\Delta C = \left\{\left[\frac{1}{1 + \exp(\gamma - \beta X_1)}\right] - \left[\frac{1}{1 + \exp(\gamma - \beta X_0)}\right]\right\} \theta(\text{pop}) \qquad (1)$$

where ΔC is the change in number of cough episodes for a 2-hour period; X_0 is the average concentration for a 2-hour period, baseline; X_1 is the average concentration for a 2-hour period, postcontrol; $\gamma = 1.742$; $\beta = 14.100$ per parts per million; and θ is the percentage of time that the population is engaged in exercise.

Because clinical and epidemiologic studies provide quite different types of information for use in estimating health effects, we computed two separate estimates of these physical improvements on health. Clinical studies are relatively precise in quantifying relationships between O_3 exposure in the laboratory and either respiratory symptoms or changes in lung function. The most useful clinical studies estimate dose-response functions by observing the presence or absence of specific symptoms in a small group (from 20 to 135 individuals) of heavily but intermittently exercising young adults (generally men) exposed to O_3 for 2 hours at various carefully controlled concentrations. Extrapolating from these clinical studies to determine health benefits to the general population from reduced exposures to ambient O_3 is difficult. Among other things, it requires adjusting for the exposures and the time that people spend indoors and outdoors as well as the time that they spend either at rest or exercising at low rates. Information about such behavior, particularly at alternative O_3 levels, is sparse.

Epidemiologic studies have the advantage of not requiring these extrapolations and adjustments. Nevertheless, they can show only statistical associations that may not have causal connections between pollution concentrations or exposure and adverse health effects (*18*). The studies that we used associate ambient O_3 concentrations, measured at fixed monitoring stations located close to a person's home, to daily or 2-week records of illness, symptoms, or days of restricted activity that the person experienced.

We estimated the reduced incidence of the quantifiable adverse health effects in the year 2004 accompanying a 35% reduction in emissions of VOCs for an estimated 129 million people living in the 94 metropolitan areas (322 counties) predicted to be in nonattainment in 2004 (*19, 20*). For each metropolitan area, we made separate calculations on the basis of the predicted change in air quality there and then aggregated these estimates to obtain the national estimates.

From the epidemiologic studies, we found that the average asthmatic will experience about 0.2 fewer days per year on which he or she has an asthma attack and that the average nonasthmatic will experience about 0.1 fewer minor restricted activity days per year because of reduced VOC emissions and subsequently improved air quality (*21*). In addition, nonasthmatics will experience other minor health benefits as well in the form of reduced number of symptom days.

To convert these predicted changes in physical health into economic benefits, it is necessary to ascertain individuals' willingness to pay for a reduced incidence of illness and adverse symptoms. To do so, we drew on a number of studies designed to uncover these values, primarily through questioning of both healthy and infirm respondents with supplemental data on the out-of-pocket medical costs and lost income that may be associated with illness or symptomatic effects (*22*). These studies have found an average value of $25 for each asthma attack prevented, $20 for a reduction of one restricted activity day (on which an individual is neither bedridden nor forced to miss work but must alter his or her usual pattern in some way), and $5 for one fewer day of occasional coughing. When reduced incidence is combined with these values, the predicted aggregate dollar benefits across the United States from these improvements in individuals' acute health status amount to $250 million per year.

By using clinical rather than epidemiologic studies to estimate health benefits, we arrive at a somewhat larger value for acute health benefits. For example, we predict that the number of coughing spells of 2 hours' duration would be reduced by as much as 2.5 episodes per person per year. Also, fewer episodes of shortness of breath and pain on deep inspiration are predicted to occur. Both are important consequences of air pollution control. We estimate that the annual monetary benefits associated with these improvements in health would be on the order of $800 million annually (*23*).

Comparison. To summarize, according to OTA, the costs associated with a 35% reduction in nationwide emissions of VOCs in nonattainment areas will be at least $8.8 billion annually by the year 2004 and could be as much as $12 billion. Yet the acute health improvements that we predict to result from these changes are valued at no more than $1 billion annually and could be as little as $250 million. The high estimate relies on the most generous of the four clinical studies that the EPA sanctioned in its staff paper on the health effects associated with O_3 and other photochemical oxidants (*24*). We also assumed that exercise rates would be high in the exposed population (which increases health benefits), and we included benefits even for those engaged in light or moderate exercise. Subject to the caveats discussed below, total health benefits are still relatively small.

In contrast to, say, the removal of lead from gasoline, for which estimated benefits are well in excess of costs (*25*), the benefit-cost comparison for national O_3 control is unfavorable. The reasons for this are, in part, the relatively small improvements in ambient O_3 levels that the controls effect (which in turn imply fairly small benefits) as well as the high costs of control.

The Los Angeles Plan

What about air pollution control efforts in Los Angeles, the nation's most notably polluted metropolis? In 1989, the supervisors of the South Coast Air Quality Management District (SCAQMD) approved an ambitious new plan designed to bring the four-county district into attainment with the NAAQS (*26*). The South Coast plan is designed to reduce ambient concentrations of particulates (such as sulfates), NO_x, SO_2, and CO in addition to O_3. To effect these reductions, the plan envisions three tiers of controls. Tier I consists mainly of the wider application of known pollution control technologies. The 120 measures identified in Tier I include such things as installing pollution control devices on equipment used in the manufacture of rubber products, substituting less polluting solvents in degreasing operations and in auto refinishing facilities, and adding new controls on electric power plants. Tier I also contains a number of less conventional pollution control measures, such as the banning of bias-ply tires (to improve mileage and to reduce particulate levels) and even restricting fuels used in backyard barbecues.

The 37 measures in Tier II of the South Coast's plan all require some advancement or extension of current pollution control techniques. They call for such measures as additional control of dust blown from roads and parking lots, incentives to reduce residential and industrial fuel consumption, and restrictions on automobile usage. The South Coast authorities envision implementing these measures over the next 10 to 15 years.

Tier III controls are more speculative still and are designed to bring about major technologic breakthroughs. The South Coast plan does not provide an explicit list of control measures for Tier III, but it does identify programs that together aim to eliminate almost all hydrocarbons from solvents, coatings, and motor vehicles and to convert all the region's vehicles to low-emitting vehicles. According to South Coast officials, enactment of all three sets of controls will, by the year 2010, bring the area into attainment with the NO_2 and CO standards and into virtual attainment for particulates and O_3.

Costs. The annual costs associated with 58 of the control measures in Tier I are estimated to be \$3.4 billion per year and will obtain about one-third of the total emissions reductions under the whole plan (*26*). These control measures include those designed to reduce O_3 concentrations as well as particulates and CO. By itself, this estimate provides some insight into the sweep of the South Coast plan: In 1988, total spending to comply with all federal air pollution control regulations across the entire United States was approximately \$30 billion (*27*).

The costs of the other elements of the plan to residents of the South Coast basin are difficult to assess because, among other things, they involve valuing time losses and inconvenience, such as those experienced in car-pools and those that require changes in driving, shopping, and even living habits. Although some of these measures involve relatively small out-of-pocket outlays, they will be costly in an economic sense if they increase inconvenience, waste time, or reduce well-being in other ways.

A recent study provides an indication of the potential costs of the entire Los Angeles air quality plan (*28*). The overall cost was estimated on the assumption that the per-ton costs of the control measures for which no cost data were provided were equal to the per-ton costs for the measures for which cost data were provided. The estimated annual cost of the entire plan is about \$13 billion per year, or about \$2700 per household in the Los Angeles basin.

Pollution control in the South Coast appears to be far more expensive on a per-ton basis than for the rest of the nation. For VOC control alone, the same study (*28*) estimated that the average cost is about \$11,000 per ton compared to OTA's estimate of \$1,800 to \$2,500 per ton nationally (or about \$9 billion to \$12 billion per year). These differences occur mainly because the South Coast has already implemented far more stringent control sources than other parts of the country (*29*).

Benefits. Are the benefits valued at more than \$10 billion to \$13 billion annually? The South Coast authorities have made two sets of estimates of the benefits of the plan. The first, which was based on a study sponsored by the California Air Resources Board in 1985 (*30*), covered various health benefits (mortality and morbidity from particulates and acute morbidity from O_3) as well as materials, agricultural, and visibility effects from meeting the air quality standards in the basin in 2010. It estimated annual health benefits of \$2.4 billion (a point estimate) with an upper bound of \$6.4 billion annually and total benefits of \$3.7 billion to \$7.7 billion annually. A more recent estimate, sponsored by the South Coast authorities in 1989 (*31*), only addressed the above health effects, finding a best conservative estimate of \$9.4 billion annually and health benefits as high as \$20 billion or as low as \$5 billion per year. Perhaps it is surprising, given the association of Los Angeles with O_3 problems, that \$6 billion of the \$9.4 billion in health benefits is for reduced mortality risks from meeting the particulate standards, whereas only \$2.4 billion is for O_3-related benefits.

Because of the availability of newer studies on the health effects of air pollution, a number of serious methodologic problems with the second study (*32*), and the wide disparity in estimates issued by the South Coast, we have reexamined the benefits. On the basis of dose-response functions drawn from a recent epidemiologic study (*33*) and the South Coast's estimate that annual average ambient concentrations of sulfate (a proxy for acid aerosols) would be reduced by more than 7 $\mu g/m^3$, we estimate that premature mortality in the region might be reduced by 2000 cases per year with full implementation of the South Coast plan. Using results from several studies designed to ascertain the values that individuals place on reduced risk of premature mortality, we assign a value of \$1000 to each reduction of 0.001 in annual mortality risk (*34, 35*). Combining the reduced mortality risk per individual, the expected population of the South Coast in the year 2010 (16 million), and the valuation of the risk reduction, we estimate possible mortality benefits of \$2 billion annually associated with the pollution control plan.

To estimate benefits in the South Coast in the form of reduced acute morbidity, we use a procedure similar to that described in the discussion of nationwide pollution control benefits. That is, we translate the predicted reductions in airborne concentrations of O_3 and particulates into reduced illness and reduced frequency of respiratory symptoms by using epidemiologic and clinical studies. These are valued by means of willingness-to-pay estimates drawn from sources described above.

On the basis of this approach, we estimate that reduced O_3 concentrations will effect an annual reduction of 22 million person-days on which adverse respiratory or other symptoms will be experienced by South Coast residents. In dollar terms, these benefits amount to about \$300 million annually. According to the South Coast officials, reduced ambient particulate concentrations will result in \$700 million annually in reduced morbidity; reduced particulate loadings will provide \$700 million annually in reduced materials damage, and another \$130 million in materials damage will be saved as a result of reductions in ambient SO_2. We take these at face value.

In all, annual benefits to human health are predicted to be \$3 billion (\$2 billion in premature mortality, \$0.3 billion in O_3-related morbidity, and \$0.7 billion for particulate-related morbidity). If one includes the South Coast's estimates of materials damage, total annual benefits rise to about \$4 billion. This is far short of the \$13 billion per year that the plan may cost.

Caveats and Uncertainties

To this point, we have presented benefits and costs as point estimates, but there are clearly great uncertainties in making such estimates. It is essential to understand them and to bear them in mind in interpreting the findings above.

With respect to our national comparison, OTA's estimate of control costs has a number of limitations. For instance, OTA did not estimate the cost of the mandatory introduction of alternative motor vehicle fuels (methanol, ethanol, or reformulated gasoline) such as is called for in the new Clean Air Act amendments. This will add approximately $3 billion to annual costs. Also, OTA did not anticipate the second round of vehicle emissions reductions that will almost surely be required under the amendments; this will add another $5 billion annually (*36*). Finally, no attempt was made to estimate nonpecuniary costs. For instance, OTA estimates that an enhanced motor vehicle inspection and maintenance program will cost about $50 per vehicle annually, including fees, administrative costs, and repair costs. The opportunity cost of people's time is ignored, however, even though the time spent can be significant. If this time were properly priced, it could add up to $7 per vehicle (*37*).

There is also great uncertainty about the costs of the South Coast plan. Marginal costs generally begin to rise sharply at higher levels of control, and VOCs have been controlled longer and more stringently in Southern California than in any other part of the country. For this reason, the controls envisioned in the South Coast plan could prove to be more expensive than anticipated. Also, we have little experience in the United States with stringent transportation control measures. If they are implemented and prove to be quite inconvenient to those affected, costs could be higher than those projected here. It is impossible to provide anything approaching statistical confidence intervals for either the national or the South Coast plan.

There are several respects in which costs could be much lower than those forecast here for both national and Los Angeles area air pollution control. For example, the cost of vehicle emissions controls are based on modest extensions of proven control technology (the catalytic converter). If, however, the electrically heated catalyst can be perfected and produced relatively inexpensively, control costs may be overstated here. Similarly, breakthroughs in reformulated gasoline or other alternative motor vehicle fuels could bring costs down considerably. Likewise, if the pace of technologic innovation accelerates sharply for VOC control from stationary sources, the same conclusion would apply. Finally (and particularly in Los Angeles), if driving restrictions eventually are imposed, and if commuters easily adapt to them, O_3 control costs may be lower than projected here.

Perhaps it is not surprising that uncertainties are greater concerning the benefit estimates presented here. These uncertainties arise from several sources, primarily the prediction of physical effects and the attribution of dollar values to them. For instance, if we had used the analysis of Whittemore and Korn (*38*) instead of that of Holguin *et al.* (*17*) to predict changes in asthma attacks, estimated benefits to asthmatics would be less than half those included above.

The largest such uncertainty concerns the link between particulate matter at current ambient concentrations and premature mortality. The statistical associations that epidemiologists and others have found between city mortality rates and annual particulate levels do not offer convincing evidence of the existence and magnitude of such effects; for instance, these effects become insignificant with minor changes in sample composition and model specification, and even the best of these studies uses a poor proxy (sulfates) for the particles now thought to be the causal agents (acid aerosols) (*39*). Because the total number of deaths from lung disease in the South Coast is 4000 annually, attributing a reduction of 2000 premature deaths to the South Coast's plan seems likely to be optimistic.

In monetizing the reduced frequency of respiratory symptoms or disease, a range of values could have been used. In the literature, the range cited for an asthma attack is $10 to $40; for a restricted-activity day, the corresponding range is $10 to $30; for a symptom day, it is $3 to $10.

The choice among epidemiologic and clinical studies, and among values to assign to physical effects, can have an important effect on estimated benefits. If we had used only upper bound estimates to predict each type of acute health effect from O_3 and, correspondingly, to attribute dollar values to reduced incidence of each, acute health benefits nationwide of a 35% VOC reduction would be $2 billion annually, and acute health benefits in the South Coast (of meeting only the O_3 standard) would be $2.4 billion per year. If we had used lower bound estimates, on the other hand, benefits would be 3% of our upper bound estimate.

There is another important caveat to be attached to the benefit estimates presented above, one that can only impart a downward bias to them. Specifically, we excluded certain types of benefits for which it was impossible to predict physical effects or to make reasonable dollar attributions. For instance, some animal toxicologic studies suggest that prolonged exposure to O_3 can permanently reduce the elasticity of the lung and, hence, initiate chronic respiratory illness (*40*). Although there is no convincing epidemiologic evidence for this potential effect in humans to date, such a finding would affect any benefit-cost analysis of efforts to control ground-level O_3 either nationally or locally (*41*). Similarly, we excluded in our estimates of national as well as South Coast benefits any improvements in forests or agricultural output in rural regions that might result from VOC control in urban areas because of the difficulty of translating emission reductions in urban areas into reduced ambient concentrations in agricultural regions. Also omitted are possible reductions in damage to rubber and other products exposed to O_3. Nevertheless, including such agricultural benefits would be unlikely to add more than $1 billion to the national total predicted here (*15*); South Coast benefits would increase minimally. Finally, the totals omit a dollar attribution for the improved visibility that should result from reduced ambient sulfate concentrations.

It is important to find ways to predict the physical likelihood of the exclusions identified here and to ascertain individuals' willingness to pay for any such improvements. These omitted categories would have to have large benefits associated with them, however, to tip the apparently unfavorable balance between benefits and costs for either the national or the regional air pollution control plans that we have examined.

Conclusions and Policy Implications

It is unpleasant to have to weigh in such a calculating manner the pros and cons of further air pollution control efforts. We would all prefer limitless resources so that every pollution control measure physically possible could be pursued. Because resources are scarce, however, the real cost of air pollution control is represented by the government programs or private expenditures that we forego by putting our resources into reducing VOC emissions. In the health area alone, $10 billion invested in smoking cessation programs, radon control, better prenatal and neonatal health care, or similar measures might contribute much more to public health and well-being (*42*).

Although we have discussed both national and regional air pollution control plans in all-or-nothing terms, neither plan is indivisible. Because the benefits and costs of air pollution control are sure to vary considerably among metropolitan areas, it may make economic sense to control a great deal in some places but little in others. Further controls will almost inevitably be justified in the Los Angeles area, where despite concerted efforts over the last 30 years air pollution is quite clearly unacceptable and adverse health effects are the most significant. On the basis of cost estimates made by the South Coast authorities in the Los Angeles area, particularly attractive VOC control possibilities include reformulating coatings used in the manufacture of wood furniture, modifying aircraft engines, and substituting less volatile cleaning solvents (*26*). By the same token, one must be especially careful in evaluating the benefits of mandatory van-pooling and other transportation control measures that have possibly large nonpecuniary costs. Even if such efforts temporarily relieve freeway congestion, new drivers may appear in the commuting brigade and wipe out apparent pollution reductions. The important point to emphasize is that all control measures must be viewed with an eye toward the good that they are likely to do and the costs that they are likely to impose.

Next, although smog is the pollution problem with which Los Angeles is most often associated, a substantial share of the benefits of further air pollution control there appears to arise from reduced particulate concentrations, according to the SCAQMD (*30, 31*). Controlling VOCs will have no direct effect on these particulates and will be quite expensive. It may make sense for authorities there to reorient their control plan toward particulate control to maximize health benefits per dollar of pollution control (*32*).

Finally, implicit in our discussion is discomfort with the premises on which our national air quality standards are now based. If, as seems likely, there are no pollution concentrations at which safety can be assured, the real question in ambient standard setting is the amount of risk that we are willing to accept. This decision must be informed by economics. Although such economic considerations should never be allowed to dominate air pollution control decisions, it is inappropriate and unwise to exclude them.

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9. *National Air Quality and Emissions Trends Report, 1988* (Document EPA-450/4-90-002, EPA, Washington, DC, March 1990).
10. *Catching Our Breath: Next Steps for Reducing Urban Ozone* (OTA, Washington, DC, 1989).
11. The controls that OTA considered include reasonably available technology on all existing stationary sources not up to current practice; more state-of-the-art controls on new sources not currently being regulated; emission controls on all facilities that transport, store, or dispose of hazardous wastes; controls on applicators of surface coatings; added refueling controls on autos and gas pumps; strengthened vehicle inspection and maintenance programs; more stringent tailpipe standards for vehicles; restrictions on gasoline volatility; and required methanol use in fleet vehicles in selected cities.
12. Because some of these controls would also affect attainment areas, OTA dealt with them separately. By 2004, reductions of VOCs in attainment areas were estimated to be 3.1 million tons from a baseline of 10.9 million tons, or a reduction of 28%.
13. See J. H. Seinfeld, *J. Air Pollut. Control Assoc.* **38**, 616 (1988), for a critical review of these and other, more sophisticated models.
14. A recent report by investigators at Resources for the Future basically supports the OTA conclusions. See A. J. Krupnick, M. Walls, M. Toman, *The Cost-Effectiveness and Energy Security Benefits of Methanol Vehicles* (final report to EPA, Resources for the Future, Washington, DC, September 1990).
15. A. J. Krupnick and R. Kopp, "The Health and Agricultural Benefits and Reductions in Ambient Ozone in the U.S.," report to OTA for *Catching Our Breath: Next Steps for Reducing Urban Ozone* (OTA, Washington, DC, 1989).
16. The O_3 season varies by state and generally includes the summer months and some portion of the spring and fall. States such as California feature a 12-month O_3 season, however.
17. The epidemiologic studies were chosen on the basis of criteria developed primarily by the EPA [see A. J. Krupnick, *An Analysis of Selected Health Benefits from Reductions in Photochemical Oxidants in the Northeastern United States*, report prepared for EPA, Ambient Standards Branch, Office of Air Quality Planning and Standards, Contract 68-02-4323 (Resources for the Future, Washington, DC, 1987)]. These studies include the following: A. H. Holguin *et al.*, in *Air Pollution Control Association Transactions on Ozone/Oxidants Standards* (Air Pollution Control Association, Houston, 1984), p. 262; A. J. Krupnick, W. Harrington, B. Ostro, *J. Environ. Econ. Manage.* **18**, 1 (1990); P. R. Portney and J. Mullahy, *J. Urban Econ.* **20**, 21 (1986); J. Schwartz, V. Hasselblad, H. Pitcher, *J. Air Pollut. Control Assoc.* **38**, 158 (1989). The clinical study used was that of W. F. McDonnell *et al.*, *J. Appl. Physiol.* **54**, 1345 (1983), one of four key clinical studies identified by the EPA for standard setting. The others are E. L. Avol, W. S. Linn, T. G. Venet, D. A. Shamoo, J. D. Hackney, *J. Air Pollut. Control Assoc.* **34**, 804 (1984); T. J. Kulle, L. R. Sauder, J. R. Hebel, M. D. Chatham, *Am. Rev. Respir. Dis.* **132**, 36 (1985); W. S. Linn *et al.*, *Toxicol. Ind. Health* **2**, 99 (1986). McDonnell *et al.* provide larger estimates of health benefits than the other clinical studies.
18. A. R. Feinstein, *Science* **242**, 1257 (1988).
19. There are few reliable studies linking O_3 to symptoms or restricted-activity days in children. Nevertheless, we assume that they respond like adults and include benefits to them in our calculations.
20. The 1985 urban population of 110.8 million was assumed to grow at 0.8% per year (Bureau of the Census projections). Only counties out of compliance in 1985 are included.
21. These are days that involve no work loss or time in bed but do involve some symptomatic distress.
22. E. T. Loehman *et al.*, *J. Environ. Econ. Manage.* **6**, 222 (1979); M. Dickie *et al.*, "Reconciling Averting Behavior and Contingent Valuation Benefit Estimates of Reducing Symptoms of Ozone Exposure" (draft), report to EPA, Washington, DC, 1987; G. S. Tolley *et al.*, *Valuation of Reductions in Human Health Symptoms and Risks* (University of Chicago, final report to the EPA, Office of Policy Analysis, Washington, DC, 1986); R. D. Rowe and L. G. Chestnut, *Oxidants and Asthmatics in Los Angeles: A Benefits Analysis* (Energy and Resource Consultants, Inc., report to the EPA, Office of Policy Analysis, EPA-230-07-85-010, Washington, DC, 1985).
23. These estimates of health effects and benefits also depend heavily on assumptions about exercise patterns in the population and the more uncertain effect of O_3 on individuals exposed while moderately exercising.
24. *Review of the National Ambient Air Quality Standards for Ozone: Assessment of Scientific and Technical Information* [draft staff paper, EPA, Office of Air Quality Planning and Standards (OAQPS), Research Triangle Park, NC, November 1987]. See also *EPA Report of the Clean Air Scientific Advisory Committee Review of the NAAQS for O_3: Closure on the OAQPS Staff Paper (1988) Criteria Document Supplement (1988)* (EPA, Washington, DC, May 1989).
25. J. Schwartz *et al.*, *Costs and Benefits of Reducing Lead in Gasoline* (Publication EPA-230-05-85-006, EPA, Washington, DC, 1985).
26. South Coast Air Quality Management District and Southern California Association of Governments, *Draft 1988 Air Quality Management Plan* (South Coast Air Quality Management District and Southern California Association of Governments, Los Angeles, 1989).
27. P. R. Portney, in *Public Policies for Environmental Protection*, P. R. Portney, Ed. (Resources for the Future, Washington, DC, 1990), p. 68.
28. D. Harrison, Jr., *Economic Impacts of the Draft Air Quality Management Plan Proposed by the South Coast Air Quality Management District* (National Economic Research Associates, Inc., Cambridge, 1988).
29. How can OTA peg the costs of a national O_3 control plan at $9 to $12 billion annually when the cost of air pollution control in the South Coast alone may be on the same order? There are two explanations for this apparent inconsistency. First, the OTA study considered only the control of VOCs; the South Coast plan is aimed at VOCs primarily but also controls other air pollutants as well, as discussed above. Second, the OTA cost estimate is not predicated on attainment of the O_3 standard in the South Coast area (or most other areas, for that matter). Rather, it assumes but a 23% reduction in ambient O_3 levels in the Los Angeles area (from a design value of 0.36 ppm to a value of 0.28 ppm in the year 2010), stopping far short of ensuring attainment with the NAAQS. The South Coast estimate, on the other hand, is predicated on a set of controls designed to meet (or nearly meet) the current standards for O_3 and particulate matter.
30. R. D. Rowe *et al.*, *The Benefits of Air Pollution Control in California* (report prepared for California Air Resources Board, Contract A2-118-32, Energy and Resources Consultants, Boulder, CO, 1986).
31. J. V. Hall *et al.*, *Economic Assessment of the Health Benefits from Improvements in Air Quality in the South Coast Air Basin* (final report prepared for South Coast Air Quality Management District, California State University Fullerton Foundation, Fullerton, CA, June 1989).
32. A. Nichols and D. Harrison, Jr., *Benefits of the 1989 Air Quality Management Plan for the South Coast Air Basin: A Reassessment* (National Economic Research Associates, Inc., Cambridge, 1990).
33. H. Ozkaynak and G. D. Thurston, *Risk Anal.* **7**, 449 (1987).
34. A. Fisher, L. Chestnut, D. Violette, *J. Policy Anal. Manage.* **8**, 88 (1989).
35. The studies published in the literature ascertain such values from wage premia paid to workers in risky jobs and from direct survey techniques. These studies generally find that a reduction in annual mortality risk of 0.001 is valued at between $800 and $8000. Wage studies usually infer such values from cohorts of workers

averaging 40 years of age, however. The premature mortality expected to result from ambient air pollution falls predominantly on the elderly. Thus fewer life years are likely to be saved per case of premature mortality avoided by air pollution control than through programs that reduce occupational risks, for instance. For this reason, we choose a value for reduced mortality risk that falls toward the lower end of the observed range.
36. These additional measures will produce added benefits as well. See P. Portney, Econ. Perspect. 4, 173 (1990).
37. V. D. McConnell, Environ. Manage. 30, 1 (1990).
38. A. S. Whittemore and E. L. Korn, *Am. J. Public Health* 70, 687 (1980).
39. F. W. Lipfert, S. C. Morris, R. E. Wyzga, *Environ. Sci. Technol.* 23, 11 (1989); *Envion. Health Perspect.* 79, 3 (1989).
40. D. Bartlett, Jr., C. S. Faulker II, K. Cook, Appl. Physiol. 37, 92 (1974); B. E. Barry, F. J. Miller, J. D. Crapo, *Lab. Invest.* 53, 682 (1985).
41. Several preliminary epidemiologic analyses have found statistically significant associations between ambient air quality and some chronic respiratory illnesses. See P. R. Portney and J. Mullahy, *Reg. Sci. Urban Econ.* 20, 407 (1990); D. Abbey *et al.*, paper presented at the annual meeting of the Air Pollution Control Association, Dallas, TX, 1988.
42. P. R. Portney, *Issues Sci. Technol.* 4, 74 (1988).
43. We thank P. Abelson, R. Frank, A. M. Freeman III, R. Friedman, B. Goldstein, D. Harrison, Jr., M. Lippman, G. McRae, and our colleagues at Resources for the Future. We alone are responsible for the conclusions, however.

Back-Action Evasion as an Alternative to Impedance Matching

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Back-action evasion is a measurement technique originally devised to overcome certain limits imposed by quantum mechanics on the sensitivity of gravitational radiation detectors. The technique is, however, more generally applicable and can be used to improve the sensitivity of instrumentation with noise floors much greater than the quantum noise floor. The principle of back-action evasion is described here by means of a simple example. A comparison of back-action evasion with impedance matching is made to clarify when back-action evasion may be useful. Back-action evasion allows one to achieve a sensitivity comparable to that achieved by impedance matching.

IT HAS BEEN A LONG-STANDING GOAL OF A NUMBER OF experimental groups (*1*) to detect the gravitational radiation that should be emitted during violent astrophysical events such as supernova explosions, as predicted by general relativity. One method of detection, pioneered by Weber (*2*), utilizes a massive cylindrical bar of aluminum (Weber bar), typically weighing about 1 ton, suspended so that it is isolated from ambient acoustic and seismic noise. Tidal forces exerted on the bar by passing gravitational radiation cause the length of the bar to oscillate. If the length of the bar could be monitored with sufficient sensitivity for detection of this vibration, one would have a gravitational wave detector. Because the tidal forces exerted on a Weber bar are very weak, there was considerable interest in determining the ultimate sensitivity of this type of detector (*3, 4*). Of particular concern was whether quantum mechanics, through the energy-time uncertainty principle or the position-momentum uncertainty principle, placed limitations on the sensitivity of Weber bar detectors. Quantum nondemolition detection schemes (*5*) were devised which showed that the "standard quantum limits" obtained by naive application of the uncertainty principles could be overcome by sufficient cleverness in instrumentation.

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Back-action evasion (*6–8*) is one type of quantum nondemolition measurement scheme. Although the scheme was originally devised with Weber bar detectors in mind, the technique can be applied more generally. The method is not limited to quantum noise. It can also be used to overcome classical noise and thermal noise and, thus, may be useful even in instrumentation in which noise is much larger than that of the standard quantum limit. So that the usefulness of back-action evasion can be evaluated, this technique should be compared to the standard technique for optimizing sensitivity, namely impedance matching. It will be shown here that with back-action evasion one can achieve a performance level comparable to the level one would achieve if the detector were impedance-matched to the source, provided one is content with looking at the information carried by only one phase of the signal (*9*). Back-action evasion thus provides an alternative to impedance matching. It may be particularly useful in cases where it is difficult or undesirable to match impedances. Voltage measurement provides an example where impedance matching is undesirable, because the volt meter should not significantly load the circuit on which the measurement is being made. It is also inconvenient to match impedances if the source impedance of a signal source changes with time.

To keep the discussion simple, I will consider back-action evasion methods applied to purely electrical systems rather than to the electromechanical systems that constitute Weber bar detectors. Also, for simplicity, I will only consider circuits in which all the impedances are real (resistive).

Equivalent Circuits for a Source

Consider a black box with one port, that is, two terminals, across which one can put a meter. With a volt meter one could measure the open circuit voltage V across the two terminals. I will take this voltage to consist of two parts: a voltage V_S, which is the signal of interest, and V_N, which is a fluctuating noise voltage uncorrelated