The Difficulty of Forecasting Ambient Air Quality—A Weak Link in Pollution Control

W. David Conn

This article examines one important component of the problem of implementing the federal government's Clean Air policy, namely, the difficulty of quantifying the relationship between emissions to the atmosphere and ambient air quality. Short-, middle-, and long-term control strategies are discussed with an emphasis on the information needed for their effective assessment and implementation. The requirement thus identified is compared with the information provided by air pollution models; it is shown that at their present stage of development, even the most sophisticated diffusion models are of limited usefulness in implementing current air pollution legislation. In view of the high cost of pollution control, further investment in model development is thought justifiable, though there are significant problems to be overcome. It is suggested that for the time being, panels of experts might be used to make air quality forecasts.

INTRODUCTION

Much of the continuing debate on the control of air pollution in the United States has been concerned with the setting of appropriate air quality standards and the preparation of plans to implement them. Reaction to the proposed control strategies has been particularly vocal in view of their supposed impact on lifestyles and (of more recent interest) on energy consumption. There has been a tendency to overlook the fact that neither the reduction in emissions which the controls will bring nor even the achievement of the standards are strictly an *end* in themselves; rather, they are a *means* to the ultimate goal, set by Congress, of protecting public health and welfare. Working from first principles toward this ultimate goal, it is necessary to know:

1. The effects of indirect control strategies on the activities that give rise to emissions;
2. The effects of changes in activities and/or of direct control measures on the nature and quantity of pollutants emitted;
3. The effects of changes in emissions on ambient air quality; and
4. The effects of changes in ambient air quality on the state of public health and welfare.

For example, in assessing the likely impact of a proposed regional shopping center, one needs to know how much auto travel would be generated by the development, how the increase in travel would affect the emission of pollutants, how the predicted changes in emissions would affect ambient air quality, and, finally, how the new levels of pollution would affect public health and welfare. A complete assessment of the proposal can be made only if all this information is available.

Under certain circumstances, however, one or more of the relationships can be counter-intuitive. For ex-

W. David Conn is Assistant Professor of Environmental Planning at the University of California, Los Angeles. He received his education at Oxford University, where he studied chemistry as an undergraduate and economics as a graduate. His research interests include not only air quality planning but also solid waste management; he is currently studying possible measures to reduce the waste stream at source.

ample, it is possible for an *increase* in the emission of one pollutant (for example, nitrogen oxide) to lead to a local *reduction* in the level of another pollutant (for example, oxidant) as the result of chemical reactions. Furthermore, due to both chemical and meteorological processes, significantly high levels of pollution can occur in areas where emissions of all kinds are very low.

In the 1970 Clean Air Act Amendments (P. L. 91-604), Congress called for the establishment of performance standards governing ambient air quality. The Environmental Protection Agency (EPA) was assigned the task of setting the *levels* of these standards, which meant in effect that the Agency was left to quantify the relationship between ambient air quality and the state of public health and welfare. The EPA proceeded to define (for certain pollutants) the concentrations at which "significant harm" might be expected and set National Ambient Air Quality Standards (NAAQS) to protect the public health (primary standards) and the public welfare (secondary standards). The states were instructed to prepare contingency plans to prevent pollutants from ever reaching the significant harm levels, and implementation plans to meet and maintain the national standards.

The establishment of the standards gave rise to considerable controversy, and the debate still continues. The fact that the primary standards have been based solely on health effects, without regard for the costs of attainment, has come under sharp criticism. It is now apparent that these costs may be very high, especially in an area like Los Angeles where the only means of achieving the mandated levels of air quality within the currently specified time-span seem to require no less than a change in lifestyles (McCahill, 1973). Furthermore, existing knowledge concerning the health effects of pollution is far from complete; consequently, the levels specified by the EPA as being necessary to protect the public health have come under challenge. However, recent studies (including one by the National Academy of Sciences)[1] have found no justification for relaxing the standards at the present time and Congress is thought unlikely to call for such a relaxation, though proposals to extend the deadlines for compliance are currently being considered.[2]

This article does not deal with the problems of setting standards but focuses instead on the problems of quantifying the relationship between emissions to the atmosphere and ambient air quality. It is this relationship that determines the changes in emissions necessary to meet the federal requirements, and that is currently one of the weakest links in the chain of policy formulation for air quality control.

The article will describe various approaches to quantifying the emissions/air quality relationship using mathematical models. As mentioned earlier, pollution levels can be affected by chemical as well as meteorological and other physical processes, and the modelers' most challenging task is to predict the concentrations not only of the "primary" pollutants that are emitted directly to the atmosphere, but also of the "secondary" pollutants that are formed subsequently in chemical reactions. The phenomenon known as photochemical smog is mainly caused by secondary pollutants (such as oxidants) and is a particularly severe problem in the Los Angeles area, to which reference will frequently be made in the discussion (though findings are not limited in relevance to that one metropolitan area). It happens that until recently,[3] more data has been available for Los Angeles than for anywhere else, and, as a result, the EPA chose it as the location for initial testing of the most sophisticated models yet developed.[4] However, other models have been developed and tested in such places as Nashville (Turner, 1964; Miller and Holzworth, 1967), Cincinnati (Clark, 1964), Jacksonville (Koogler et al., 1967), St. Louis (Koch and Thayer, 1972; Ludwig and Dabberdt, 1972; Dabberdt et al., 1973; Shir and Shieh, 1973), Connecticut (Hilst, 1967; Bowne, 1969), Chicago (Roberts et al., 1970), New York (Shieh et al., 1970), San Francisco (MacCracken et al., 1971; Ludwig and Kealoha, 1974), and the Hackensack (NJ) Meadowland (Wills, 1973).

Before the various modeling approaches are described, and in order to more easily understand their strengths and weaknesses from the planner's viewpoint, the types of air pollution control strategy needed to satisfy federal requirements will be categorized and, under each category, the kind of information necessary for assessment and implementation will be examined.

AIR POLLUTION CONTROL STRATEGIES

Control strategies can conveniently be categorized on the basis of time-scale: the control of "episodes" or emergency situations (in which significant harm levels might be reached) can be regarded as *short term;* the strategies adopted to bring existing pollution levels down to below the newly established ambient air quality standards within a specified time period can be regarded as *middle term;* and the strategies used to ensure that processes of growth and change do not interfere with the continued maintenance of standards can be regarded as *long term.* The formulation and implementation of the three different categories of control strategies require different inputs of information regarding the emissions/air quality relationship.

Short-term controls[5]

The law requires that steps be taken to prevent the significant harm levels from ever being reached. The agency responsible for controlling air pollution in an episode situation must decide (1) when to initiate control measures, and (2) which measures to use. There are two approaches to making the first decision. One involves the continuous monitoring of pollutant concentrations in the air, an "alert" being called whenever the measured concentrations (instantaneous or time-averaged) exceed certain prespecified levels; at this time, emission-reducing strategies are introduced in an attempt to prevent the concentrations from increasing further, and ultimately to restore them to acceptable levels. This is known as the *feedback* approach and it underlies the alert system currently operated by the Air Pollution Control District (APCD) in Los Angeles as well as in many other United States cities.

The alternative *feedforward* approach is based on predictions of changes in air quality; whenever it is anticipated that pollutant concentrations will reach significant harm levels, measures are immediately taken to reduce emissions, without waiting for a rise in observed concentrations (and in the hope of avoiding such a rise).

The feedforward approach has the advantage of providing time for the measures to take effect before the significant harm levels are reached; if the response is slow (as in the situation when photochemical reactions continue to generate oxidants some time after the emission of primary pollutants), the feedback approach is unlikely to prove effective in control. However, the feedforward approach, by its very nature, requires a predictive capability of high accuracy; considerable costs may be attached to the measures that are likely to be taken in an emergency situation (such as, for example, the wholesale closure of government offices) and it is doubtful if these measures will be acceptable to the policy-makers or their constituents unless there is a high degree of confidence in the predictions.[6]

No matter which approach is used to decide *when* measures should be initiated (and it is possible that a combination of both might be adopted), there remains the problem of deciding *which* measures to employ. Ideally, the least costly action should be taken that will prevent the significant harm levels from being reached. In this context it is important to recognize that, at any given time, a potentially harmful build-up of contaminents may be confined to a small part of an airshed as concentrations vary from place to place depending on the precise locations of sources, the meteorology, the topography, and so on. It is therefore technically possible on many occasions to moderate the pollution levels by reducing emissions "selectively" rather than universally, thereby reducing the cost of control. For this purpose, the controlling agency must be able to analyze the effects of selective emission controls on ambient pollution concentrations, to determine which controls will actually be effective in avoiding or ending the episode.

If the conditions that characterize an episode are frequently repeated, the results of a single analysis can be used to provide guidelines for future action to be taken whenever the same situation recurs. However, if conditions are constantly changing, a separate analysis is required for each episode and this may have to be carried out at short notice and with limited resources. In the latter case, an agency is unlikely to use a highly sophisticated model that requires a vast amount of nonreusable data, a huge computer, and a lengthy running-time; instead, it needs an analytical technique that can be applied simply and inexpensively.

Middle-term controls

Middle-term controls are those intended to reduce, within a specified time-period of a few years, currently excessive levels of pollution to below the National Ambient Air Quality Standards. Examples include measures to decrease the quantities of fuel that are burned (for example, by reducing vehicle miles traveled) and improvements to the control devices fitted to individual emitters.

To verify the effectiveness or ineffectiveness of the proposed measures, it is necessary to show that the reductions in emissions will be sufficient to ensure that the standards are exceeded no more than once a year for the appropriate averaging time, anywhere in the airshed. In principle, there is no need to predict ambient air quality at all times in the future, or even on any one specific day; rather, it is sufficient to show that the requirement is met under the worst possible conditions, whenever these might occur. To do this, it must be assumed that the meteorology which historically has characterized the days of highest pollution will continue to do so in the future, and that conditions worse than those monitored in the past will not arise; the validity of these assumptions cannot be guaranteed, and thus a confidence level of less than 100 percent is inevitable.

Long-term controls

Long-term controls are intended to ensure that processes of change and growth do not interfere with the attainment and subsequent maintenance of the standards. Even if reductions are made in the emissions generated by each individual source (if, for example, there are less pollutants emitted per car, less emitted per stationary source, and so on), the level of air pollution in an airshed may clearly continue to rise if growth is permitted (so that there are more cars, more stationary sources, and so on). Furthermore, the law requires that air quality should not be allowed to "significantly deteriorate" even in areas currently meeting or bettering the standards.[7]

Controls are necessary to ensure that any change or growth which does occur is constrained in such a way that absolute levels of pollution do not rise. In Los Angeles, for example, past patterns of development have promoted an ever-increasing reliance on motor vehicles which are currently the principal source of atmospheric pollutants;[8] air quality considerations would dictate that any further growth must be designed to encourage the use of a less polluting form of transportation.

To implement long-term controls, it must be possible to assess in advance the impact of both new construction and the modification of existing facilities on pollutant emissions and ambient air quality. Consideration must be given to the "impact not only of pollutants emitted directly from stationary sources, but also of pollution arising from mobile source activity associated with such buildings or facilities (termed indirect sources)" (*Federal Register* 38, 29894, 1973).

The analysis may, in principle, be done on one of two scales, either the "macro" scale (assessing the aggregate impact of a number of anticipated changes within a given area), or the "micro" scale (assessing each proposed change incrementally). The macro scale approach can be viewed as an attempt to establish the capacity of the air for receiving emissions within a given locality. Once this has been done, either construction or modification proposals, or both can thereafter be assessed directly by comparing the emissions that they would generate against the previously established "carrying capacity." The micro scale approach, on the other hand, requires a separate assessment of each new proposal for its likely impact on air quality. This might be called for automatically whenever a major departure from a previously assessed growth plan is proposed.

Whichever approach is used, it is necessary at some stage to relate changes in emission patterns to changes in air quality. As in the analysis of middle-term controls (and subject to the same provisos), there is no need to make predictions for specific days, but rather for "worst-case" conditions to determine whether or not the legal requirements for air quality are met. The micro scale approach, involving the assessment of individual projects, is the more demanding as it necessitates the use of an analytical tool capable of fine resolution, sensitive to the effects of making small changes in the pollution load.

PREDICTIVE CAPABILITY REQUIREMENTS

The requirements for formulating and implementing the three categories of control strategies can be summarized thus: for the short-term controls, assuming that the feedforward approach is preferred, it must be possible to accurately predict the peak level of pollution on a specified day with a given emission pattern, and also (when necessary) to analyze the effectiveness of selected emission reductions in bringing this peak level down to an acceptable value. For the middle-term controls, it must be possible to predict whether the Clean Air standards will be exceeded under anticipated worst-case conditions with given changes in emission patterns (which are unlikely to be uniform over space and time). Finally, for the long-term controls, it must be possible to predict whether the standards will be maintained under worst-case conditions when successive changes are made in the pattern of emissions.

PRESENT PREDICTIVE CAPABILITY

Several models have been developed to chart the relationship between emission levels and ambient air quality. Most of those in current use can be categorized as either *rollback* or *diffusion* models. On the whole, the rollback models are reasonably simple and inexpensive to apply, but they suffer from taking an oversimplified view of the subject relationship; also they are often formulated for a specified set of emissions and/or meteorological conditions and cannot therefore be extrapolated. The diffusion models, on the other hand, are more versatile and have a greater potential for accuracy, but they are generally more expensive (especially in terms of data needs) and more difficult to apply.

Rollback models

The simplest rollback model assumes a proportional relationship between emissions and air quality; in other words, a given reduction in emissions applied uniformly over space and time is assumed to give rise to a proportional reduction in the level of pollution. However, as pointed out by de Nevers and Morris

(1973), the model has a number of serious limitations.

To begin with, application of the model requires knowledge of the highest concentration of pollutant in the area; this will equal the highest *observed* concentration only if monitoring has taken place at precisely the time and location of maximum pollution. The second limitation stems from the implied assumption that the meteorological conditions which will exist when pollution reaches its highest level in the future will be the same as those that existed when the highest level was reached in the past.

Finally, the model's linear specification assumes away the occurrence of chemical reactions among pollutants. The formation of photochemical smog is known to involve chemical reactions that diminish the concentrations of some pollutants while others are generated, and the situation is further complicated by processes of accumulation and dispersion.

In a recent study (TRW, Inc., 1973), the assumption of a one-to-one proportionality was explicitly dropped in favor of a fractional proportionality based on a comparison of weekday and weekend emission patterns and pollution levels; in other words, based on empirical evidence, it was suggested that an X% reduction in primary emissions on a given day (assuming no reduction on the previous day) would lead to a reduction of less than X% in pollution levels. For example, an X% reduction in emissions of reactive hydrocarbons would lead to a reduction of about 1/2 X% in peak oxidant levels, while the same percentage reduction in emissions of carbon monoxide and nitrogen dioxide would lead to a 2/3 X% reduction in the maximum concentrations of those pollutants. However, the method is crude and may not be applicable in situations other than those in which the empirical observations were made.

Another approach for dealing with chemical reactions is to derive relationships between primary and secondary pollutant concentrations either from measurements at outdoor sites or from observations using physical simulation models (for example, smog chambers); then, by assuming some relationship (usually proportional) between primary pollutant emissions and their concentrations in the air prior to reaction, it is possible to relate changes in emissions to changes in the final product concentration.[9]

However, even if they can be modified to take account of chemical reactions, the rollback models have another limitation which may be their most crucial weakness from the planner's viewpoint; this is the assumption of "homogeneous emission reduction." Essentially, this means that the model can only be applied if every emission is reduced by the same percentage simultaneously *unless* emissions other than the one reduced can be considered negligible, *or* the emissions reduced are so distributed in time and space that their reduction has the same overall effect as a homogeneous reduction, *or* complete mixing within a fixed air-volume can be assumed. As de Nevers and Morris (1973) conclude, "if none of these three conditions can be shown or reasonably assumed to exist, then the application of simple rollback or proportional modeling to the question of the impact of changes in the emission of one class of emitters on ambient air quality is totally without theoretical or experimental foundation."

Recognizing this limitation of the simple model, the same authors have attempted to modify it in such a way that it will allow for considerations of emission type, height, and location, without sacrificing its simplicity and cheapness of application. This they have achieved by introducing some Gaussian diffusion concepts into the model. However, even in its improved state, it remains a crude tool for testing control strategies (Sklarew, 1973) and the authors acknowledge that in many situations "we have reason to believe that full diffusion models will give more reliable predictions of the consequences of changes in emission rates and patterns than any of the rollback models."

Diffusion models

Full diffusion models are the results of attempts to simulate mathematically the physical and chemical processes that affect primary pollutants on their release to the atmosphere. The intention is that once a model has been established, the emission patterns and meteorological conditions can be fed in, and predicted concentrations of selected pollutants at specified points in space and time will be given as output.

The simplest of the diffusion models are the Gaussian plume and puff versions which describe the concentration distribution of an inert pollutant downwind of a point, line, or area source. These models have already been widely applied in predicting the concentrations of pollutants such as sulphur dioxide, carbon monoxide, and particulates (especially emissions from large point sources);[10] however, they cannot account for chemical reactions other than simple decay processes and their accuracy is limited by the usually unrealistic assumption of constant and uniform meteorological conditions.

More complicated models are now being developed which attempt to overcome both these limitations, taking into account chemical reactions (notably photochemical processes) and variations in meteorology. In Southern California, three private firms have constructed models of this kind under contracts from the Environmental Protection Agency, and a team of faculty and graduate students in the Environmental Science and Engineering Program at the University of California, Los Angeles has been working on a fourth version, incorporating certain novel features.

The models are of two basic kinds. Those developed by Systems Applications, Inc. (SAI) (Reynolds et al., 1973) and the UCLA team (Liu and Perrine, 1975) employ a system of fixed coordinates, computing the hourly average concentrations of pollutants in a three-dimensional grid. Those developed by General Research Corporation (Eschenroeder et al., 1972) and Pacific Environmental Services (Wayne et al., 1973) utilize a moving cell or trajectory approach, in which concentration changes within a hypothetical parcel of air are computed as the parcel traverses the airshed.

The models are all complex, requiring very extensive input data and a moderately large computer to perform the calculations. The SAI model, which is the longest running of the three sponsored by the EPA, gives as output predictions for all grid points. In simulating a single day for the Los Angeles air basin, it absorbs about 40,000 words of input (of which some 25,000 words of meteorological data must be respecified for each day) and requires a computer with approximately 300K bytes of memory as well as a minimum of three disk or tape drives; the ten-hour simulation takes about seventy-three minutes on an IBM 370-155 or twenty-two minutes on an IBM 370-165 (Horowitz et al., 1973).

The moving cell models generally give more selective coverage, though by drawing enough trajectories it is possible to generate a contour map of pollution. In order to take account of emission sources throughout the Los Angeles basin, a computer with approximately 200K bytes of memory is necessary to run the GRC model, and the time ratio is 300:1 (that is, each ten-hour simulation takes two minutes).

The accuracy of each of the three EPA-sponsored models has been tested by validation runs in which predicted pollution concentrations in the Los Angeles airshed have been compared with observed data. A number of problems exist, some stemming from inaccuracies within the models themselves (due to an incomplete understanding and an inability to adequately represent the highly complex processes being simulated) and others from the nonavailability of adequate empirical data.

Difficulties in obtaining satisfactory input data seriously limit the accuracy and usefulness of the models at their present stage of development. Requirements include a complete inventory of emissions within the study area and a full description of the meteorological conditions, including wind speed and direction, inversion height, surface temperature, and air temperature. In addition, the initial mixing volume and initial pollutant concentrations must be defined.

The task of compiling an emissions inventory is difficult because even major emitters are rarely monitored on a continuous basis. Thus, emissions must be calculated indirectly, using factors that represent the average rate of emissions per unit of fuel consumed, distance traveled, and so on. Contributors to air pollution are generally classified into two broad categories, namely *stationary* sources (including single identifiable point sources such as power plants, as well as aggregations of smaller emitters, represented as area sources) and *mobile* sources (including highway vehicles, off-highway mobile equipment, and aircraft).

A major problem is that of adequately determining the temporal and spatial variations in emissions, to which air quality is known to be sensitive. For example, calculations of power plant emissions based on annual fuel consumption and average emission factors (specified according to the rated power capacity of the boiler) fail to reflect the temporal variations that occur as operating characteristics change diurnally and seasonally. A report recently prepared for the Senate Committee on Public Works (1974b) estimated that for one class of pollutants (nitrogen oxides), "emission estimates based on fuel use for individual facilities are subject to inaccuracies of up to 50 percent due to the influence of specific operating conditions at the facility. Emission estimates for entire regions containing more facilities are often more reliable, but a range of ± 25% may be the maximum degree of accuracy attainable."

The treatment of area sources presents in addition a spatial problem: distributing their emissions over all populated parts of a region (as was done in the SAI inventory for Los Angeles) can cause industrial-type emissions to be incorrectly attributed to a residential neighborhood (Roberts et al., 1973) whereas attempting to allocate the emissions according to zoned density for each use suffers from the fact that actual land use and zoning often fail to conform (Houser et al., 1974).

Emissions from motor vehicles (especially important in areas like Los Angeles) are particularly difficult to estimate with accuracy as they are known to depend on many factors, including the type, age, and condition of the vehicle; engine temperature; miles traveled; speeds; driving habits; and so on. The emissions are generally calculated using test cycle emission factors, deterioration factors (which account for aging of pollution control devices), weighted annual mileages (which reflect the average mileage traveled in a year by a car of a given age), and average speed adjustment factors (which account for variations in average speeds). As pointed out in the report for the Senate Committee on Public Works (1974b), great care must be exercised in applying emission factors that have been determined for a specific test cycle; for example, the EPA's factors are currently based on a cycle designed to reflect primarily the driving patterns in downtown metropolitan areas (incorporating hot and cold starts) and they are significantly different (by up to 30 percent) from the factors developed by the California Air Resources Board (using a different, seven-mode cycle) (Wada, 1975).

The problem is that there is no such thing as a single "typical" trip pattern, and thus the use of a single test cycle must represent a gross oversimplification. Revised emission factors based on individual modes of driving (cruise, idle, decelerate, accelerate, and so on) are being developed (Nordsieck, 1973; Calspan Corporation, 1974), and may presumably be used to "tailor" a test cycle more closely to observed conditions in a given situation. However, their usefulness must ultimately depend on the availability of adequate data describing individual trip patterns, and these data have always been difficult to obtain.

The availability of meteorological data is also very limited. The monitoring network in Los Angeles is relatively good, and yet no wind measurements are made on a regular basis at any height exceeding thirty feet (Liu and Perrine, 1975). Interpolation of the readings fom the twenty-nine monitoring stations is necessary to provide the appropriate spatial distribution of readings required by the models, and the "raw" data inevitably has to be modified to prevent erroneous divergences created by small errors in the measurements and computations. Measurements of other needed meteorological parameters are also inadequate. If it is difficult to obtain satisfactory historical data, as indicated here, it is virtually impossible to obtain reliable predictions of future meteorology.

Finally, there is the problem of defining the initial and the boundary conditions. For example, pollutants remaining from previous days can have an important effect (Martinez et al., 1973); however, the monitoring of pollutant concentrations (like the monitoring of meteorology) is wholly inadequate. The Los Angeles APCD maintains throughout the entire county only thirteen permanent monitoring stations plus one mobile facility, and one of the permanent stations was added only recently. Pollution levels can vary considerably within very short distances, depending on the local topography, and suchlike; the precise spatial location of a monitoring device is therefore critical in determining whether the levels recorded are truly representative of those found in the surrounding area and are not peculiar to the immediate vicinity of the device itself. Because many of the monitoring facilities in Los Angeles are located within 100 feet of roadways carrying traffic in excess of 15,000 vehicles daily (Reynolds et al., 1973), the recorded pollution levels are not likely to be representative of the full spectrum of concentrations found in the city. In the absence of adequate measurements of these and other parameters, there is inevitably a certain amount of inspired (and uninspired) guesswork in determining the inputs to the models.

Accuracy of the Diffusion Models

Notwithstanding all the difficulties, it is appropriate to examine the results of the validation runs to determine whether the models are sufficiently accurate to perform a useful function in air quality management. Unfortunately, the validation process itself has to be treated with some caution owing to the already mentioned problems of obtaining accurate observed readings on a scale commensurate with the models' predictions. Because many of the monitoring stations are located near busy roadways, the predicted *average* pollution levels within the two-mile square zones used in the grid models would often be expected a priori to be different from the observed levels at the stations.[11] Validating the moving-cell models is complicated because the cell trajectories rarely pass directly over a monitoring station; the observed readings therefore have to be obtained by spatial interpolation, a process known to produce large errors.[12]

A further problem with the validation process reported so far is that the runs have been limited to one-day time periods (ten hours maximum). There has been no attempt to make a real-time prediction of an extended "episode," using the computed results from one day to define the initial conditions for the next; indeed, this is currently thought to be impossible because of the problems of forecasting the meteorology and, for the moving-cell models, of handling the more complicated geometry of an expanded air volume. There is an additional difficulty in that the validation runs for the Los Angeles models have necessarily been conducted under present conditions only, which happen to be characterized by relatively high levels of emissions. It is by no means certain that the models would perform even as well as they do now if emissions were to be considerably reduced and pollutant concentrations were to approach background levels; under these circumstances one might expect that different atmospheric processes could become significant.

Disregarding these problems, and assuming the validation results can be accepted as meaningful, the appropriate question to consider is whether the models do accurately predict the hourly average peak concentrations of pollutants (with which current legislation is concerned). Not surprisingly, none of the models' authors claims anything approaching 100 percent accuracy in predicting pollutant concentrations. In reporting the results of the validation studies, the usual procedure has been to emphasize the correlation between predicted and observed values over each entire run; however, it is the accuracy with which peak values are predicted that is most relevant in determining the models' applicability. The published reports show that the *best* of the three established complex diffusion models at predicting peak ozone (a key pollutant) gave values within 2 parts per hundred million (pphm) of the observed values in about 70 percent of the runs, but it occasionally erred greatly, by 10 or more pphm. The existing federal standard for ozone is 8 pphm. More generally, according to Hameed (1974), "most current models of urban air pollution predict concentrations with errors, on the average, of the order of a factor of 2 . . . Most of the currently available data are such that a prediction better than with an error of a factor of 2 may be regarded as fortuitous."

In principle it might be more useful if the output of the models were given as probability distributions rather than single values. Then, in order to satisfy the Clean Air legislation, the probability that the peak hourly-averaged level of any given pollutant would exceed the federal standard on any particular day could not be greater than $(1/365 \times 100)\%$. If it could confidently be assumed (for example, because of predictable seasonable variations in meteorology) that the probability of exceeding the standard would be zero on a significant number of days, say 200 out of 365 (leaving 165 days "at risk"), then the requirement could be relaxed to permit up to a $(1/165 \times 100)\%$ probability of exceeding the standard on the other days. However, as the accuracy of the model is poor, the stringency of the controls necessary to guarantee compliance with the law would inevitably be overestimated. Furthermore, the existing models are not really suitable for generating probability distributions as a very large number of runs would be required.

The accuracy of the diffusion models can be, and is being, improved. Efforts are currently being made to improve the modelers' understanding of, and ability to simulate, the chemical and meteorological processes. The SAI team, for example, is studying the chemistry of reactions in the heterogeneous gas phase, and is developing kinetic mechanisms that will include sulfur compounds; in addition, at UCLA, attempts are being made to refine the numerical procedures used to perform the calculations.

Regardless of the work done on the models themselves, however, the nonavailability of adequate input data is a serious constraint on the potential accuracy of the output. As mentioned earlier, existing facilities for the monitoring of both pollution and meteorology are inadequate; data-gathering projects (such as the LARPP program in Los Angeles and the RAPS program in St. Louis)[13] provide useful additional information, but it is unrealistic to expect greatly improved monitoring on a permanent and widespread basis in the near future (if ever) because of the tremendous expense and practical difficulties involved. Many measurements are technically infeasible; for example, it is most unlikely that motor vehicles will ever be monitored individually, despite the critical dependence of their emissions on variations in engine performance, driving habits, and so on.

USEFULNESS OF THE MODELS

The information provided by the models will now be compared with the requirments, listed earlier, for assessing and implementing the short-, middle-, and long-term control strategies, to determine whether these requirements can be met.

Short-term strategies

Assuming the feedforward approach, these strategies pose a particularly difficult problem, in requiring predictions for specific days. Though the rollback models are of little use, the more sophisticated diffusion models have the *potential* for providing the necessary forecasts but their accuracy is sharply constrained by the accuracy of meteorological forecasts (which are notoriously poor). As mentioned earlier, if conditions do not change, a few runs of a model might be used to construct a table of results that could be used repeatedly thereafter; on the other hand, if conditions do change, it is significant that the models are so complex and costly to operate (especially in terms of their data-gathering needs) that no local agency would be likely to run them on a day-to-day basis.

Middle-term strategies

The EPA, in administering the Clean Air legislation, has used rollback models to assess State Implementation Plans, but at best these models provide a crude indicator of compliance. As discussed earlier, the models lack realism; in particular, the usual assumptions of a linear emission/air quality relationship and of uniform emissions reductions are conspicuously weak.

The diffusion models, on the other hand, have more to offer, especially as there is no need to forecast meteorology on specific days (as the computations are based on historically-established "worst-case" conditions). The high cost of operating the more sophisticated models is probably not too important a factor, as the plans are not expected to be constantly reassessed. Furthermore, the impact of a middle-term strategy is likely to be much greater than that of a short-term strategy (if only because it extends over a longer period of time), so that a greater initial expenditure on assessment can be justified more easily.

Long-term strategies

Only the diffusion models have the potential of being really useful. Assessing the aggregate impact of a number of anticipated changes presents less of a problem than attempting to assess the incremental impact of each individual change, especially for secondary pollutants. Existing emissions inventories are so crude that their sensitivity to small variations is very limited. Furthermore, the high cost of running the more sophisticated models is already likely to deter their use in making repeated assessments of individual projects. Any attempt to improve the resolution of the emissions inventory would inevitably raise the cost even higher.

The problem of cost

Cost is an important factor in determining the usefulness of the models, especially the photochemical diffusion models. Data collection is particularly expensive. However, it is worth mentioning that one way of reducing the cost is currently being explored, namely, the use of so-called repro-models. Essentially, these are "models of models," in other words, attempts to directly link the inputs and outputs of the larger models by statistical means. Research is still at an early stage, but a report by Horowitz, Meisel, and Collins (1973) claims to demonstrate the feasibility of the approach; it concedes that precision is inevitably reduced but points out that in tests of repro-models (using the SAI model as the subject), the "accuracy of approximation was close to the limiting accuracy with which the output was reported and certainly well within the accuracy with which the model corresponds to reality." Forty-thousand words of input into the larger model were reduced to five words of input into the repro-model, and computation time was reduced from twenty-two minutes to just milliseconds on a comparable computer (with a corresponding reduction in cost).

How accurate must the models be?

Diffusion models, in particular the photochemical and meteorological diffusion models (where photochemical smog is a problem), seem *potentially* capable of providing the appropriate *kind* of information needed to assess and implement air pollution control strategies, even if in practice (neglecting the possibility of repro-modeling) they may prove too expensive for some uses.

However, their currrent lack of precision (especially in predicting the levels of secondary pollutants) and the fact that they are never likely to even approach 100 percent accuracy pose a major problem, because the present law requires that *precise* standards be met. For example, in reviewing a proposal for the construction of an indirect source, a crucial question is whether the hourly averaged oxidant level will exceed 8 pphm (the federal standard); concluding that it might reach, say 8 ± 4 pphm does not help in making a decision. The wide range of error characterizing present models is such that frequent disagreement among experts is not only possible but likely. Indeed, according to de Nevers (1973), there have already been court cases in which the accuracy of modeling has been challenged (sometimes successfully) and other cases have been initiated in which the basic argument is whether the EPA can "force the expenditure of large amounts of money (for pollution control equipment) on the basis of calculations of what the effects will be, rather than proven effects." The latter issue has not yet been resolved but if the decision goes against the EPA, it would make enforcement of much of the Clean Air legislation (in its present form) virtually impossible; indeed, it would establish a precedent against planning ahead that could be far-reaching in its implications.

CONCLUSIONS

As mentioned in the Introduction, the establishment and enforcement of the Clean Air standards provide only one means to the end of protecting the public health and welfare. Alternative means are possible and have been discussed elsewhere,[14] but they are outside the scope of this article. Here it has been taken as given that the standards have been set, and that compliance is required by law. This means that the emissions/air quality relationship must be quantified, so that proposed control measures can be assessed and implemented. Various models have been developed for this purpose but, as has been shown, they currently do not provide sufficiently accurate information for the precise terms of the law to be met. The EPA is well aware of the problems: its latest assessment of available models is extremely cautious in its sanctioning of their use, stressing that they "are useful only if the user understands how to apply them and is aware of their vagaries" (U. S. Environmental Protection Agency, 1974b). In discussing indirect source regulations, the EPA Administrator has "on several occasions . . . expressed reservations concerning the adequacy of available analytical techniques to accurately analyze the impact of a specific indirect source on ambient air quality concentrations of photochemical oxidant and nitrogen dioxide" (*Federal Register* 39, 25295, 1974). Interim guidelines for indirect source review focused almost entirely on the prediction of localised carbon monoxide levels (which are the most readily modeled, since no chemistry is involved), while the review process for other, chemically reactive pollutants was left unspecified (U. S. Environmental Protection Agency, 1974a).

If the present standards-oriented approach to air quality management is to be maintained, there are several possible directions (that are not necessarily mutually exclusive) in which to move. One is to spend more money on improving both the models and their data base. Another is to amend the present law to explicitly permit the enforcement of decisions based on information from the "best available" models at any given time. Yet another possibility is to abandon the sole reliance on models and base decisions instead on the judgment of "experts."

Not surprisingly, the modelers generally favor continued development of the models, together with improved and more widespread monitoring to obtain the necessary input data. They have a strong case in arguing for increased expenditure in this field: according to the Council on Environmental Quality (1973), total expenditures on air pollution control in the United States are already measured in billions of dollars per year and are expected to grow substantially in the future; thus there is ample justification for spending sizable funds, if necessary, to investigate the fundamental relationship underlying many of the present control strategies.

However, model development takes time, and decisions must be made in the interim. As mentioned earlier, the authority of the EPA to enforce control measures on the basis of calculations that are inevitably less than perfectly accurate is currently being challenged. If this challenge is upheld by the courts, it might be sensible for the Clean Air legislation to be modified to explicitly permit the exercise of controls based on information derived from the "best available" models, as determined at any given time by the EPA Administrator. In effect, this would give legal backing to the procedure already adopted by the EPA, whereby the Agency announces in advance which models it will accept as providing a means of demonstrating compliance with the Clean Air Act provisions. In order to ensure that this procedure does not discourage further efforts at model improvement, the Agency's "sanction" of specified models might be reviewed and updated at regular intervals (say, every six months).

Although this approach might solve the legal problem caused by the present wording of the law, the problem would remain that the "best available" models at this time commonly provide information that is characterized by such a wide range of uncertainty that its usefulness in decision making is very limited. As Wada (1975) points out, if decisions are based on these models, "industries subject to controls could argue that severe economic hardships were being imposed when they may well be unnecessary. On the other hand, public interest groups could simultaneously claim that appropriate measures were not being taken to *ensure* attainment and maintenance of the air quality standards."

A suggestion made by Wada is to put aside the more sophisticated models and instead apply linear rollback in an *iterative* fashion; the simpler technique would be used to define a level of allowable emissions which would form the basis of an initial set of controls; then, as compliance with these controls was achieved, the resulting ambient air concentrations would be monitored and the process would be repeated, using the same rollback technique to define a new level of allowable emissions, *and so on*. The author argues that this "buys time . . . buys information . . . buys flexibility as a hedge"; however, he recognizes that it might also cause a considerable delay in the achievement of the Clean Air standards as each iteration could take several years to complete. Because the standards are set at a level thought necessary to protect the public health, such a delay could prove costly in human lives (a fact which is often overlooked when proposals to extend the period for compliance with the Clean Air

Act are debated). It might therefore be considered unacceptable.

It is possible to go one stage further than Wada and suggest that decisions on air pollution control measures should not be based solely on the information from *any* mathematical model, but instead should depend on the judgment of "experts" (that is, people who are familiar with the meteorological, chemical, and other processes involved, and have practical experience in dealing with air pollution).

A key difference between the two approaches is that experts do not make fully explicit the data base and predictive relationships that they employ (indeed, if they did so, their reasoning could, in principle, be reproduced in a model); unlike the models, therefore, they provide *no basis for validation.* Even if it could be shown that past predictions made by experts have proved no worse (and have sometimes been better) than those derived from models, this is insufficient justification for assuming that they will continue to do so in the future, especially if the models are to be further improved. On the other hand, due to the shortage of satisfactory data at the present time, it is also true to say that the models have not yet been adequately validated; thus it could be argued that there is no more reason to trust them in the short term than to trust the experts. Furthermore, experts have the ability to modify parameters that they consider in making their estimates more rapidly than a mathematical model can be changed. This ability, combined with their lower cost (at least in comparison with the more complex models) make the option of using experts worth considering.

Panels of experts could be appointed for each EPA region. It should be recognized that they would not be called upon to make *normative* judgments (that is, to say whether a proposed measure is "good" or "bad") but instead to make a *positive* prediction as to whether a measure would promote, or be consistent with, the aim of achieving and maintaining the Clean Air standards. The experts would be permitted, if they wish, to use models for guidance (thereby obtaining, perhaps, the maximum benefit from both approaches), but their ultimate judgments would be binding. Almost inevitably, there would occasionally be disagreements between different experts on a panel, but a technique such as Delphi could then be used in an attempt to reach consensus (Dalkey et al., 1972).

It is important to point out that the use of experts is not being suggested as a long-term solution to the problem of quantifying the emission/air quality relationship. By removing the *objective* (albeit currently unreliable) basis for decision making that models provide, the opportunities for judgments to be influenced by political considerations must inevitably increase. As mentioned earlier, a strong case can be made for investing considerable resources in the development of reliable models that might ultimately provide the sole basis for predictions. However, the current limitations of the models and the difficulties to be faced in improving them (especially in terms of data collection) should not be underestimated.

Author's Note

I wish to thank Robert E. Klein for his help with the research, and Don McAllister, Alan Eschenroeder, Phil Roth, Chris Foote, Walt Westman, Gene Leong, and Ron Wada for their thoughtful comments on earlier drafts of the article. The research was supported by NSF Grant No. GZ 2269.

NOTES

1 Senate Committee on Public Works (1974a).

2 Hearings on proposed amendments to the Clean Air Act were started by committees of both the Senate and the House in the early part of 1975.

3 A comprehensive data-gathering study known as the Regional Air Pollution Study (RAPS) is currently being sponsored by the EPA in St. Louis for the specific purpose of developing and validating improved air quality models (Ruff and Fox, 1974).

4 See Eschenroeder et al. (1972), Reynolds et al. (1973), Wayne et al. (1973). Other applications of models to Los Angeles are described in Frenkiel (1956), Lamb and Neiberger (1971), Sklarew et al. (1972), Trijonis (1972), Hamming et al. (1973), Liu and Perrine (1975).

5 For a more detailed discussion of short-term controls, see, for example, the report by TRW, Inc. (1973).

6 Ironically, the very success of emergency measures introduced in response to a predicted alert could cause a problem in public relations, for people might afterwards argue that the episode would not have occurred anyway (even without the measures), and it might be impossible to prove them wrong. Of course, an even greater problem arises if the measures prove ineffective!

7 EPA's current interpretation of this requirement is given in *Federal Register* 39, 42510-42517 (Dec. 5, 1974).

8 As emissions from motor vehicles are progressively reduced, those from stationary sources are likely to become relatively more important.

9 Barth (1970), Trijonis (1972), Hamming et al. (1973). See also, *Federal Register* 36, 15486-15506 (Aug. 14, 1971).

10 See, for example, Turner (1964), Clark (1964), Miller and Holzworth (1967), Koogler et al. (1967), Hilst (1967), Bowne (1969), Shieh et al. (1970), Roberts et al. (1970).

11 A similar problem arises when the models' predictions are used in the implementation of the Clean Air legislation, as this currently governs point levels of pollution. However, the problem may be solved by the development of subgrid models that deal with localized effects, on which the SAI team is working under a new EPA contract.

12 When the concentration of ozone at the West San Gabriel Valley station was determined by interpolation using observed data from three other locations and compared with an actual measurement at the station itself, the relative error (that is, true-computed/true) ranged from 6 percent to 63 percent

(average 35 percent) on one day, and from 0 percent to 33 percent (average 20 percent) on another. See Eschenroeder et al. (1972).

13 See Eschenroeder and Perkins (1974), Black (1974), Perkins (1974) with reference to LARPP; and Ruff and Fox (1974) with reference to the RAPS program.

14 See, for example: Mackintosh (1973), Kneese and Schultze (1975), Wolozin (1966), Thompson (1973), Freeman et al. (1973).

REFERENCES

Barth, D. S. (1970) "Federal Motor Vehicle Emission Goals for CO, HC, and NO_x Based on Desired Air Quality Levels," *Journal of the Air Pollution Control Association* 20 (August): 519-523.

Black, J. F. (1974) "Background on LARPP," Presented at LARPP Symposium, Santa Barbara, California (November).

Bowne, N. E. (1969) "A Simulation Model for Air Pollution over Connecticut," *Journal of the Air Pollution Control Association* 19 (August): 570-574.

Calspan Corporation (1974) *Automobile Exhaust Emission Modal Analysis Model,* Prepared for the EPA (NTIS PB 229 635).

Clark, J. F. (1964) "A Simple Diffusion Model for Calculating Point Concentrations from Multiple Sources," *Journal of the Air Pollution Control Association* 14 (September): 347-352.

Council on Environmental Quality (1973) *Environmental Quality 1973.* Washington D. C.: U. S. Government Printing Office.

Dabberdt, W. F., F. L. Ludwig and W. B. Johnson Jr. (1973) "Validation and Application of an Urban Diffusion Model for Vehicular Pollutants," *Atmospheric Environment* 7 (June): 603-618.

Dalkey, N. C. et al. (1972) *Studies in the Quality of Life: Delphi and Decision-Making.* Lexington, Mass.: Lexington Books.

de Nevers, Noel (1973) "Enforcing the Clean Air Act of 1970," *Scientific American* 228 (January): 14-21.

——— and J. R. Morris (1973) "Rollback Modeling—Basic and Modified," Paper No. 73-139, 66th Annual Meeting, Air Pollution Control Association.

Eschenroeder, A. Q., J. R. Martinez and R. A. Nordsieck (1972) *Evaluation of a Diffusion Model for Photochemical Smog Simulation,* Report EPA R4-73-012a, General Research Corporation.

Eschenroeder, A. Q. and W. A. Perkins Jr. (1974) "LARPP—A New Data Base for Atmospheric Modelers," *California Air Environment* 4 (Spring): 7-9.

Freeman, A. M., R. H. Haveman and A. V. Kneese (1973) *The Economics of Environmental Policy.* New York: John Wiley.

Frenkiel, F. N. (1956) "Atmospheric Pollution in Growing Cities," *Smithsonian Report for 1956*: 296-299.

Hameed, S. (1974) "Modeling Urban Air Pollution," *Atmospheric Environment* 8 (May): 555-561.

Hamming, W. J. et al. (1973) "Motor Vehicle Control and Air Quality: The Path to Clean Air in Los Angeles," Paper No. 73-73, 66th Annual Meeting, Air Pollution Control Association.

Hilst, G. R. (1967) "An Air Pollution Model of Connecticut," Proceedings of IBM Scientific Computing Symposium on "Water and Air Resource Management."

Horowitz, A., W. S. Meisel and D. C. Collins (1973) *The Application of Repro-Modeling to the Analysis of a Photochemical Air Pollution Model,* Report EPA 650/4-74-001, Technology Service Corporation.

Houser, G., R. Tan and R. L. Perrine (1974) "Problems in Data Collection and Utilization in the Development of an Urban Airshed Model," *California Air Environment* 4 (Spring): 5-7.

Kneese, A. V. and C. Schultze (1975) *Pollution, Prices and Public Policy.* Washington D. C.: Brookings Institution.

Koch, R. C. and S. D. Thayer (1972) "Validity of the Multiple-Source, Gaussian Plume Urban Diffusion Model Using Hourly Estimates of Input," Conference on Urban Environment and Second Conference on Biometeorology, American Meteorological Society.

Koogler, J. B. et al. (1967) "A Multivariable Model for Atmospheric Dispersion Estimates," *Journal of the Air Pollution Control Association* 17 (April): 211-214.

Lamb, R. G. and M. Neiberger (1971) "An Interim Version of a Generalized Urban Air Pollution Model," *Atmospheric Environment* 5 (April): 239-264.

Liu, C. Y. and R. L. Perrine, eds. (1975) *Modeling Los Angeles Photochemical Air Pollution,* Environmental Science and Engineering, University of California, Los Angeles.

Ludwig, F. L. and W. F. Dabberdt (1972) *Evaluation of the APRAC-1A Urban Diffusion Model for Carbon Monoxide,* Final Report to the EPA, Stanford Research Institute.

Ludwig, F. L. and J. H. S. Kealoha (1974) *Present and Prospective San Francisco Bay Area Air Quality,* Final Report, SRI Project 3274, Stanford Research Institute.

MacCracken, M. C. et al. (1971) *Development of a Multi-Box Air Pollution Model and Initial Verification for the San Francisco Bay Area,* Lawrence Radiation Laboratory, University of California.

Mackintosh, D. R. (1973) *The Economics of Airborne Emissions: The Case for an Air Rights Market.* New York: Praeger.

Martinez, J. R., R. A. Nordsieck and A. Q. Eschenroeder (1973) *Impacts of Transportation Control Strategies on Los Angeles Air Quality,* Report EPA-R4-73-012d, General Research Corporation.

McCahill, E. (1973) "They Don't Want Clean Air; They Want Pure Air," *ASPO Planning* 39 (March/April): 32-39.

Miller, M. E. and G. C. Holzworth (1967) "An Atmospheric Diffusion Model for Metropolitan Areas," *Journal of the Air Pollution Control Association* 17 (January): 46-50.

Nordsieck, R. A. (1973) *Estimates of Pollutant Emission Factors for California Motor Vehicles: 1967-2000,* Report RM-1849, General Research Corporation.

Perkins, W. A., Jr. (1974) "The Los Angeles Reactive Pollutant Program," Presented at LARPP Symposium, Santa Barbara, California (November).

Reynolds, S. D. et al. (1973) *Further Development and Evaluation of a Simulation Model for Estimating Ground Level Concentrations of Photochemical Pollutants,* Report R73-109, Systems Applications, Inc.

Roberts, J. J., E. S. Croke and A. S. Kennedy (1970) "An Urban Atmospheric Dispersion Model," Proceedings of Symposium on Multiple Source Urban Diffusion Models, AP-86, Environmental Protection Agency.

Roberts, P. J. W. et al. (1973) *Extensions and Modifications of a Contaminent Emissions Model and Inventory for Los Angeles* (Appendix A of Reynolds et al., *Further Development and Validation of a Simulation Model for Estimating Ground Level Concentrations of Photochemical Pollutants*), Report R73-15, Systems Applications, Inc.

Ruff, R. E. and D. G. Fox (1974) "Evolution of Air Quality Models through the Use of the RAPS Data Base," Paper No. 74-124, 67th Annual Meeting, Air Pollution Control Association.

Senate Committee on Public Works (1974a) *Health Effects of Air Pollution,* Senate Report No. 92-369 (August).

——— (1974b) "The Relationship of Emissions to Ambient Air Quality," *Air Quality and Automobile Emission Control,* Vol. 3, Senate Report No. 93-24 (September).

Shieh, L. J., B. Davidson and J. P. Friend (1970) "A Model of Diffusion in Urban Atmospheres: SO_2 in Greater New York," Proceedings of Symposium on Multiple Source Urban Diffusion Models, AP-86, Environmental Protection Agency.

Shir, C. C. and L. J. Shieh (1973) *A Generalized Urban Air*

Pollution Model and its Application to the Study of SO_2 Distributions in the St. Louis Metropolitan Area, IBM Research Report No. RJ71227, IBM San Jose Research Laboratory.

Sklarew, R. C., A. J. Fabrick and J. E. Prager (1972) "Mathematical Modeling of Photochemical Smog Using the PICK Method," *Journal of the Air Pollution Control Association* 22 (November): 865-869.

Sklarew, R. C. (1973) "Evaluation of Implementation Plans Using Photochemical Air Pollution Models," Paper No. 73-131, 66th Annual Meeting, Air Pollution Control Association.

Trijonis, J. C. (1972) "An Economic Air Pollution Control Model and Application to Photochemical Smog in Los Angeles in 1975," PhD. Thesis, California Institute of Technology.

TRW, Inc. (1973) *Episode Contingency Plan Development for the Metropolitan Los Angeles Air Quality Control Region*, Prepared for EPA Region IX.

Turner, D. B. (1964) "A Diffusion Model for an Urban Area," *Journal of Applied Meteorology* 3 (February): 85-91.

U. S. Environmental Protection Agency (1974a) *Interim Guidelines for the Review of the Impact of Indirect Sources on Ambient Air Quality*, Office of Air Quality Planning and Standards (July).

——— (1974b) "Applying Atmospheric Simulation Models to Air Quality Maintenance Areas, *Guidelines for Air Quality Maintenance Planning and Analysis*, Vol. 12, Office of Air Quality Planning and Standards (September).

Wada, R. Y. (1975) "A Critical Assessment of the Role of Computer Models in Air Quality Planning and Decision-Making," Doctoral Thesis, Environmental Science and Engineering, University of California, Los Angeles.

Wayne, L. G., A. Kokin and M. I. Weisburd (1973) *Controlled Evaluation of the Reactive Environmental Simulation Model (REM)*, Report EPA R4-73-013a, Pacific Environmental Services, Inc.

Willis, B. H. (1973) *Hackensack Meadowlands Air Pollution Study—Summary Report*, Report EPA 450/3-74-056a, Environmental Research and Technology, Inc.

Wolozin, H., ed. (1966) *The Economics of Air Pollution*. New York: Norton.