Effects of Transportation on Ozone in Cities

Appraisal of the Air Quality Planning Process

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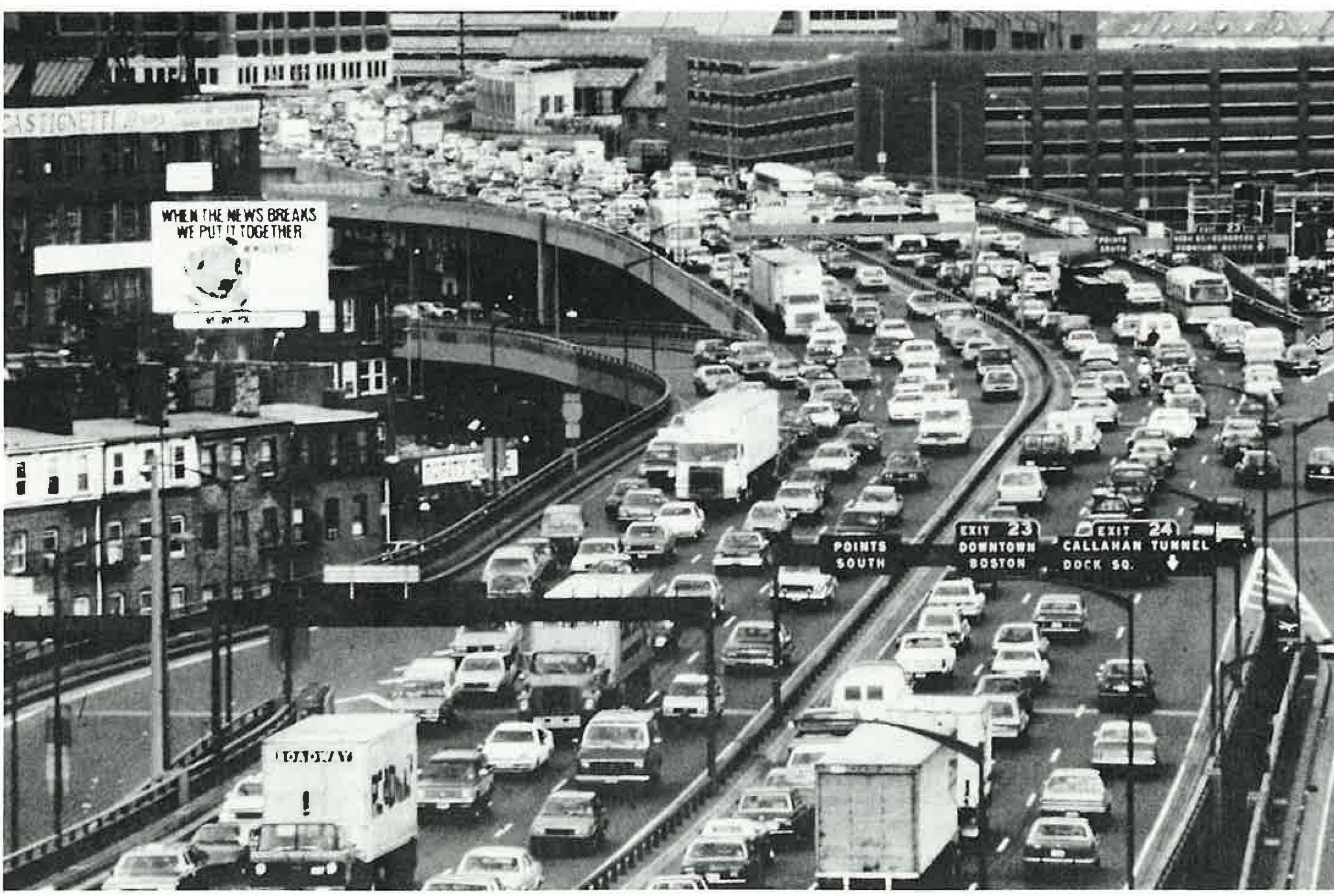
During the 1980s, ozone concentrations exceeded the National Ambient Air Quality Standards (NAAQS) in as many as 110 cities in the United States. To many observers, these lapses signaled the failure of two decades of emissions control efforts. Despite the substantial reduction in emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) from motor vehicles, the reformulation of solvents and surface coatings to reduce VOC emissions through evaporation, and the reduction of NO_x emissions from large stationary sources in some areas, peak ambient ozone concentrations have remained about constant or declined only slightly in many cities that had



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exceeded the standard. Progress in many urban areas is indicated primarily by a decrease in the number of days on which the ozone standard is exceeded *(1)*.

From the late 1970s through the mid-1980s, public agencies took part in two or three rounds of detailed and complex planning exercises: compilations of emissions inventories, development and testing of photochemical air quality models, and, through the use of these models, evaluation of alternative emissions control strategies. Typically, the plans that emerged suggested that attainment of the ozone standard could be achieved in a prescribed time frame.

The realities, however, were far different. During the last decade, peak ozone concentrations in most areas declined less than predicted. This apparent miscalculation has disturbed regulators so that they treat attainment of recommended ozone levels as a primary topic in the current debates on amending the Clean Air Act. Why have objectives not been met? The answer is neither simple nor clear: there are several possible reasons for the discrepancies between the predictions of the planning process and the observations of recent years, and many aspects of the problem still require investigation.

Motor Vehicle Emissions

Carbon monoxide (CO) exceedances occur during the winter in some 40 U.S. cities and thus are a current concern in Congress. Most CO emissions come from motor vehicles. In the short term, it is expected that CO concentrations will decrease almost in direct proportion to the reductions in CO emissions resulting from increased effectiveness of catalyst systems, fleet turnover, and, in some areas, addition to fuels of methyl tertiary butyl ether (MTBE), ethanol, and other oxygen-containing additives. In the longer term, however, the effect of increases in vehicle miles traveled is expected to slow and then reverse this beneficial trend.

With the removal of tetraethyl lead from fuels, lead concentrations have already declined dramatically. Reductions in sulfur dioxide emissions will be effected in the 1990s by the increasing use of low-sulfur fuels and the imposition of emissions standards for diesel-powered vehicles.

Although these emissions and others are of concern to many, the emissions product that most concerns Americans is ozone. Ozone levels are regularly exceeded in many locations across the United States. Because transportation sources play a major role in ozone concentrations, emission control strategies involving motor vehicles will be important in any solution proposed for the ozone problem.

Ozone and Vehicles: A Volatile Connection

Emitted VOCs and NO_x are precursors to ozone formation; these compounds provide some of the major building blocks for ozone production. In most cities, these compounds are emitted in similar amounts: from 100 to 1,000 tons per day, depending on population. Motor vehicles (automobiles, trucks, construction equipment, and off-road vehicles), evaporation of solvents and surface coatings, industrial plants and processes, dry cleaning operations, and other transportation sources (aircraft, ships, and trains) all produce VOCs. Fuel combustion is the primary means by which human beings produce NO_x emissions—through motor vehicles, electric power generation plants, industrial processes and facilities, other transportation sources, home heating, and other stationary combustion processes.

Transportation sources contribute about 31 percent of the VOC emissions produced by human activities and about 43 percent of NO_x emissions nationwide *(1)*. The overall influence of motor vehicles on ozone formation, however, may be greater than these percentages suggest. The automobile can be found almost everywhere in the United States and morning rush hours produce large quantities of VOCs that, under the energetic influence of the day's sunlight, react with other compounds in the atmosphere, producing ozone.

The abilities of the many different species of VOCs to react with atmospheric compounds vary greatly, as do their atmospheric concentrations. The contribution of any particular VOC to ozone formation is directly related to its reactivity and its ambient concentration.

A reduction in VOC emissions slows both the rate at which ozone is formed and the amount of ozone produced. A reduction in NO_x emissions increases ozone formation rates and may increase or decrease the amount of ozone formed, depending on the local ratio of VOC to NO_x concentrations at the time. Increases in ozone concentrations from decreases in NO_x emissions tend to occur near city centers, in areas where emissions sources are concentrated, and in areas immediately downwind of these areas. Farther downwind, in what are usually areas of higher ambient ozone concentrations, this adverse effect tends to lessen or disappear. Under complex weather conditions, these generalizations may not apply. Each situation must be analyzed separately.

The ratio of VOC to NO_x concentrations in the early morning (6 to 9 a.m.) has been used as an indication of which precursor pollutant would, if its emissions were reduced, be most effective in reducing ozone concentrations. In regions where VOC/NO_x is less than 10, a reduction in VOC emissions is believed to be the most effective way to reduce ambient ozone concentrations. If NO_x emissions are reduced in such areas, however, greater VOC emissions reductions may be needed to achieve the same reduction in peak ambient ozone concentration that would have been achieved in the absence of the NO_x emissions reduction. In regions where VOC/NO_x is greater than 10 and less than 20, either VOC reductions or combined VOC and NO_x reductions may be the preferred control strategies. For areas in which VOC/NO_x is greater than 20, NO_x emission reductions are believed to be the most effective strategy.

Regardless of the urban area of interest and its "characteristic ratio," it is important to recognize that VOC/NO_x varies across the area and during the day in any urban area, as well as varying with the weather. In addition, the actual reductions in emissions that a control strategy can produce may vary widely within the area. If the range of VOC/NO_x is not consistently low or high (making classification easy), a well-planned, spatially resolved analysis is needed to determine which control strategy will be most effective. Other factors, such as the amounts of fine particle matter, nitrates, or nitric acid in the air, can also be important in choosing a control strategy.

Modeling Urban Air

Source-receptor relationships link emissions levels or emissions changes with ambient ozone concentrations or concentration changes. These mathematical relationships, which are used in models to evaluate the effects of urban emissions control strategies, vary in complexity and detail. The Empirical Kinetics Modeling Approach (EKMA), which was used in various versions in the late 1970s and early 1980s, included a detailed treatment of atmospheric chemistry but simplified variations in key parameters within the modeled area. Urban planning agencies tailored EKMA-type models for the peculiarities of their own cities and then used the customized models to relate emissions to air quality. The modeling results were used to judge the acceptability of proposed emissions control strategies.

During this time, a few cities were using grid-based models in planning. By the late 1980s, the regulatory community decided that the EKMA-type models were not useful in most of the scenarios that needed to be modeled. The regulators advised that grid-based models, which were applicable to a wider variety of situations, should be used. This change in position is just now being reflected in practice.

Although many in the scientific and policy communities advocate the use of more sophisticated models, others argue that these models require data of such quality and quantity that they would be costly and sometimes quite difficult to acquire. Moreover, because the full round of modeling and related activities may take as long as five years or more, many feel that using more complex models would further delay the process. Although a more sophisticated model could provide additional insight, the decision to use such a technique must involve careful consideration of the possible benefits and delays.

Why Emissions Reduction Plans Fail

The underprediction of future ozone levels in urban areas is due to several factors. Incomplete implementation of emissions control strategies, inadequate understanding or representation of emissions, deficient modeling, and inadvertent selection of relatively ineffective strategies have individually or collectively contributed to this underestimation.

Shortfalls in Emissions Reductions

Evidence suggests that emissions reduction plans are often incomplete. Emissions control systems may be less effective than described or anticipated, they may deteriorate with use, or they may even be illegally altered. Actual automotive emissions reductions in California, as determined through official state testing, were less effective for VOCs, CO, and NO_x than researchers initially estimated *(2)*. An oversight review committee reported that improvements in practice—such as improved surveillance, mechanics training, and enforcement of emissions recalls—would double the emissions reductions of VOCs, reduce CO emissions by two-thirds, and nearly triple NO_x reductions.

In general, shortfalls are probably caused by overly optimistic descriptions of the effectiveness of control technology and enforcement, as well as by underestimates of the extent and effects of illegal alteration of control systems. In addition, controls may be implemented incompletely or delayed. Conflicts between neighboring or overlapping jurisdictions or reluctant enforcement on the part of a public agency can also cause problems.

As regulators gain more experience with emissions controls, data should be acquired, archived, and analyzed to help shed light on the extent to which emissions reduction plans are followed, the effectiveness of control equipment, and the rate of deterioration in equipment performance. The relevant findings can then be used in emissions projections to produce more realistic estimates of future emissions reductions for the planning endeavors of the early 1990s.

Inaccurate Emissions Reports

Evidence is now available to confirm the long-time belief that emissions reports may significantly underestimate or inaccurately represent actual emissions. Some of the inaccuracy is caused by omission or serious underestimation, such as the underestimation of running losses from motor vehicles *(1)*. Other sources of bias include flawed assumptions in the use of the emissions information and inadequate or neglected treatment of environmental influences *(3)*.

Estimates of emissions from area sources can also cause inaccuracy because the methods used are frequently coarse and thus very approximate. Smaller sources that may be omitted from these inventories can, when taken together, make up a significant part of the total emissions. Recent evidence, for example, suggests that emissions from motor vehicles are underestimated. In a study carried out during 1987–1988, investigators measured VOC, NO_x, and CO concentrations in a Los Angeles tunnel and used the results to determine if the net increases in ambient concentrations of ozone precursors were consistent with the estimated emissions from motor vehicles counted as they entered the tunnel *(4)*. The NO_x emissions and concentrations were consistent, but the CO and VOC "running" emissions, estimated by using the California mobile source emissions factor model, were not high enough to account for the ambient CO and VOC concentrations observed. These and other findings suggest that vehicle emissions factors need to be reexamined, and that the accuracy of emissions representations should be reappraised.

Ineffectiveness of Control Paths

Control paths are the paths followed on schematic NO_x-VOC diagrams from current to target air quality. The quality of these schematic paths can vary greatly, from highly effective to ineffective. A path is considered ineffective if ozone concentrations change slowly along it (that is, the path parallels or nearly parallels the contours of constant peak ozone concentration) or if the path intersects the constant peak ozone concentration contours at a sharply oblique angle. Ineffective control paths may be selected inadvertently. For example, such a path might be derived from analyses of "unrepresentative" ambient measurements of ozone precursor concentrations. Alternatively, in areas where the chemical situation in the air is complex, an ineffective path might be the result of an attempt to meet multiple objectives simultaneously. In such cases, attempts to reduce the effects of other kinds of emissions might prevent local regulators from adopting the strategy that would be most effective in reducing ozone.

In some urban areas, ambient ozone reductions are more sensitive to the overall design of a control strategy and thus to the control path. In these cases, regulatory researchers must use careful analysis and accurate representation of emissions levels if reduction plans are to be successful. If multiple objectives are to be met, the plan should reflect the complexity of the problem.

Inadequate Model Formulation and Use

The city-specific versions of EKMA have collectively been the models most frequently used in developing air quality plans for ozone attainment. As mentioned previously, most experts now believe that EKMA-type models are inadequate in the ways in which they model many of the physical characteristics of urban emissions situations. Some of the problems with EKMA-type models are caused by the way in which the models were used. Often, default values—values assumed for variables in the absence of data or other direct means of estimation—were used as inputs. These values may not be specific to the particular area or situation and may represent averages or some other approximation. Results from EKMA-type models used in this way are frequently deficient or flawed.

Results were expected to be better with the less-restrictive grid models that were first applied in the late 1970s. However, the earliest predictions from these models were typically still at variance with subsequent reality. For most urban areas (the San Francisco Bay Area being a notable exception), reductions in peak ozone concentrations were overestimated by grid models. Researchers do not yet know whether these failures are due to inadequacies in model formulation or to other causes.

It is true that grid models only approximate the dynamics of relevant atmospheric processes. For some of the phenomena involved, the adequacy of the models' approximations has been, and is still being, questioned. In addition, the supporting data base in most of the applications (the Los Angeles Basin being the primary exception) was deficient. Despite these real concerns, there is no evidence to suggest that the discrepancies between model estimates and reality are due primarily to flaws in model formulation. In fact, evaluations of grid model performance indicate that, when care is taken in modeling, the accuracy of prediction is generally acceptable. Other factors appear to weigh more heavily in explaining the failures.

Transport of Emissions

If transport of emissions from upwind areas makes a significant contribution of VOCs or ozone to an urban area, its omission or inadequate treatment will distort any analysis of current or future air quality. Most quantitative planning exercises carried out through the mid-1980s did not treat transport adequately. When the issue of how to account for emissions reductions in an upwind area with significant emissions is considered, the problem becomes clear.

Investigators now recognize that geographical regions need to be designated for air quality planning and analysis so that transport from upwind areas will have at most a very limited impact on the region *(5)*. Modeling and monitoring studies are in progress or being planned for several regions, including central California, the Southeast, the Lake Michigan area, and the Northeast, where the influence of transport is a key factor in defining the size and scope of the region.

Recent Changes in Emissions

The overall air quality planning process usually takes 1.5 to 3 years from start to completion. During that time, important changes can occur in key parameters. When lead was removed from gasoline, for example, the chemical speciation of the fuel changed because additional "aromatic" species were added. The photochemical reactivity of the fuel changed accordingly, and the intermediate and final reaction products formed during atmospheric reactions were altered. It is important that the reactions included in a model's chemical mechanism be able to reflect such modifications; however, given the nature of the planning process, obtaining adequate knowledge of changes in time to include the information in a model or analysis is often difficult.

The planning process necessarily includes projections of future events and circumstances. If projections are made early in planning, and if their bases change during the calculational phase of the work, appropriate modifications may not be made. This type of omission can cause inaccuracies in the estimates produced.

Biogenic Emissions

Emissions of VOCs from trees and other vegetation have been neglected in most ozone-related air quality planning analyses. Recently, William Chameides and his colleagues argued that in southeastern cities and other areas with abundant vegetation and warm climate, vegetation may contribute significantly to the overall mass of reactive VOCs emitted into the atmosphere *(6)*. Including these emissions in a photochemical simulation increases the VOC/NO_x ratio and creates a reactive atmospheric mixture that lessens the benefits of VOC emission reductions and increases the benefits of NO_x emissions reductions.

To properly include biogenic emissions in a model or analysis, emissions rates and biomass distribution for individual species must be known. Because emissions rates from vegetation vary greatly with weather conditions *(7)*, the conditions that influence biogenic emissions must be understood and incorporated into the analysis. The chemical mechanisms used in models must account for the reactions of the biogenic compounds. In general, the knowledge of biomass, emissions rates, and reaction mechanisms—and thus the ability to represent the influence of biogenics—is limited.

Modeling the Future

Researchers and regulators can take many actions to improve the basis for making plans for attaining ozone reduction standards.

Develop a Knowledge Base

Various information needs, determined by patterns of deficiency in earlier work, have been identified. Examples include documentation of the actual timing of implementation and of the observed (not estimated) effectiveness of emissions controls. Underestimation of VOC emissions rates must be explained and corrected. A commitment must be made to developing the needed information and understanding so that the scientific basis for planning will be firm. Major programs will be required, along with commensurate budgets.

Undertake Full Planning Analyses

Sound planning for improving air quality is a comprehensive technical and political undertaking. The technical endeavor includes clearly and carefully identifying the set of interlocking problems to be addressed, specifying suitable modes of analysis, developing a comprehensive plan for gathering needed data, planning for data archiving, setting forth a plan for modeling and analysis, and delineating an approach for integration of the varied information that results. This approach has been adopted in only a few areas. The cost of this strategy may appear to be high, but it is usually quite low in comparison with the control costs and the "opportunity costs" associated with inadequate plans that must be revised later.

Develop and Apply Integrated Approaches for Multiple Pollutants

Air quality planning for an urban area is frequently carried out for individual pollutants or pollutant groups, such as ozone or acidic deposition (acid rain and fog). This approach can lead to the development of emissions control plans for reducing one pollutant that conflict with plans to reduce another pollutant. An integrated planning process permits identification of strategic options and allows the choices to be evaluated in light of the attainment requirements for each pollutant involved. Integrated air quality planning should be considered vital to future planning endeavors.

Carry Out Corroborative Analyses

No analytical approach to air quality planning is without significant limitations or flaws. Some methodologies require overly restrictive assumptions, whereas others, perhaps more soundly based, require data that are difficult to obtain, costly, or, in some cases, unobtainable. The risk of error in technical findings is reduced if more than one analytical approach is used because the findings of one approach may be used to corroborate or contradict a second approach. The use of two distinct approaches—an "observational approach" that relies mainly on the analysis of atmospheric measurements, and a "modeling approach" that relies on the use of emissions data—is now being considered by the Environmental Protection Agency.

Practitioners may argue that the notion of planning for two comprehensive approaches instead of one does not adequately recognize limitations in data availability, budgets, and schedules. Corroborative analyses, however, will assuredly reduce the chances of producing another round of flawed and misleading control strategies. The merits and deficits of both arguments must be considered.

Treat Planning as a Continuing Endeavor

Air quality planning is often carried out in fits and starts. A major effort mounted to meet a short- or intermediate-term requirement may be scaled down or abandoned until the next round of requirements is pursued. A three- to five-year cycle is inefficient and ineffective. Planning should be a continuing endeavor: an initial start-up effort followed by an ongoing process that is planned for a defined length of time, subject to continuing review and modification, and, in effect, "sampled" to obtain information as needed. Information is generated continuously, so crisis conditions are avoided. A primary characteristic of the continuous planning process is the growth of understanding with time.

Retrospective analysis should be an integral component in overall planning and analysis. Looking back to earlier work, how accurate were the estimates and projections? If estimates were inaccurate, what were the probable causes? Revisitation of the past is an important element in the learning process, and thus in improving planning practice.

Commit the Needed Funding

Funding patterns often parallel air quality planning activities: typically, low-level, longer-term funding is supplied, with periodic injections of more substantial (but perhaps still insufficient) support. This latter infusion of funds may arrive so late that there is little time for properly planning its use or carrying out the work intended.

A more effective approach is to plan funding for the estimated duration of the overall activity. Although this kind of funding may be difficult to effect politically, decision makers should be clearly informed of the benefits of the longer planning horizon.

Recognize the Regional Nature of Air Pollution

The air quality of many urban areas is dependent, in part, on the emissions of cities upwind. Air quality planning for a city should be on a scale to incorporate all areas upwind that can significantly affect the city.

Provide Sound Projections of Future Emissions

Often, emissions-related activities focus on development of a "current" inventory and model that are used in air quality model evaluation and, when properly adjusted, in near-term impact assessment. Longer-term analyses require emissions projections for alternative futures, which are frequently made on an ad hoc basis. Long-term emissions projection techniques tend to be relatively primitive in comparison with air quality and meteorological modeling techniques.

Sound, comprehensive planning of the type recommended earlier requires the development, evaluation, and use of improved emissions projection procedures. Adoption and use of techniques for incorporating upper and lower bounds on the projections should be a part of the improved methodology.

Treat Uncertainties Explicitly

When inaccuracy exists, it is usually difficult to estimate its extent. Too often, the extent of the uncertainties associated with the findings of an analysis are not estimated. Yet this information may be as important to a policymaker as the "best estimates" that are typically reported. The explicit treatment of uncertainties should become common practice.

Improve the Flexibility of Chemical Mechanisms

The mixture of chemicals emitted into the urban atmosphere continually changes, and therefore the chemical mechanisms used in models must be updated regularly to reflect changing needs. Consequently, ongoing, substantive support for research and development is needed.

Develop and Implement Model Evaluation and Application Protocols

The use of sophisticated, grid-based photochemical models is now increasing rapidly. The practice has matured in the 1980s, and procedures are becoming more routine. Yet no protocols exist to provide clear guidance for evaluating and applying models. Clearly, there is need for protocols to help researchers decide on models for their particular applications.

A Commitment to Sound Practices

In the past, researchers and regulators have often been frustrated in their attempts to make accurate estimates of the results of emissions regulation programs. As models and data collection techniques improve, and as legislators become more willing to fund air pollution research, estimations should become more accurate, providing decision makers with a firm basis for regulatory action. A commitment to extending the relevant knowledge base, to sound planning practice, and to intelligent integration of scientific practice and findings into the policy-making framework will do much to improve transportation-related air quality planning.

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