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COMPUTER SIMULATION IN URBAN PLANNING AND AIR POLLUTION CONTROL

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ABSTRACT

The air pollution sequence which starts with urban activity patterns and ends with the degree of damage caused by degraded quality of air can be influenced by planning decisions. This causative chain is a complex process involving physical, technological, economic, social, health, and legal factors. The purpose of this paper is twofold: 1) to examine some of the complex cause and effect relationships which exist between planning decisions and air quality; and 2) to describe the resultant need for modern analytical methods to predict the long-term air quality implications of planning scenarios.

INTRODUCTION

Over the past twenty years the degraded quality of air over metropolitan regions resulting from intense land use and transportation activities, has become of major concern to urban and regional planners. In the U.S., the federal and state governments have assumed active roles in planning for air quality. A central feature of government involved in this area has been the establishment of air quality standards. To determine the attainment of improved air quality and long-term maintenance of these standards, planning agencies must be able to predict the air quality conditions associated with proposed interventions in transportation and land-use patterns.

The purpose of this paper is twofold; to examine some aspects of the complex cause and effect relationship which exists between planning decisions and air quality; and to describe the resultant need for modern analytical methods to predict the long-term air quality implications of planning scenarios.

The first part of this paper discusses the objectives of air quality planning

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and some of the means available for the attainment of those objectives; in particular, the value of transportation and land-use plans as instruments for air quality control. This is followed by a discussion of recent U.S. research on relations between air quality and transportation and land-use patterns. This research clearly demonstrates that the simulation of these relations requires the use of complex analytical tools. The paper concludes with an outline of a computer simulation system which recently has been shown to be the most promising tool for such analysis.

BASIS OF PUBLIC ACTION TO CONTROL AIR QUALITY

The air has two major economic attributes: it is a biological necessity, stuff of breath, medium of vision, sound and smell; and it is a dump for unwanted residual products of human activities. Each discharge of waste into the atmosphere changes the chemical composition and temperature of the air. These changes can have major impacts upon human health (through poisoning and induced disease); they frequently cause damage to buildings, clothes and other property (soiling and corrosion); and they are the cause of several kinds of nuisance, ranging from smoggy skies to unpleasant smells.

The magnitude and distribution of pollution damage costs are determined by a number of variables:

1. the spatial and temporal distribution of the emission sources;
2. the composition and rate of airborne emissions;
3. the manner in which the wastes are dispersed and degraded in the air;
4. the location of places where ambient pollutants are inhaled, smelt, seen, or otherwise impressed upon human affairs; and
5. schemata by which consequent damages are measured and evaluated.

The preceding discussion indicates that the capacity of the atmosphere to assimilate, degrade, and dispose of waste matter must be regarded as a scarce resource. This resource is used in the production and consumption of private goods. Although the costs resulting from its use provide a measure of its value, it is not exchanged directly in private market transactions. Therefore, the open market cannot ensure correspondence between the benefits and costs caused by use of the resource. A mismatch is likely, implying both inefficiency in the use of the resource, and inequity in the incidence of its cost.

For example, suppose a company has decided to equip its factory for the manufacture of a new product. There is a choice between two mechanical processes, A and B. The company's analysis shows that process A, which emits large quantities of soot and smoke, is slightly cheaper than the clean alternative, process B. In the absence of public regulation or political pressure, the company chooses A. But damage to the welfare of the community far exceeds the financial benefit accruing to the company from its choice of A; and that damage is borne by individuals residing and working in the neighborhood of the factory, not by the company.

In the above example there is a *prima facie* case for public intervention to prevent a decision which, from the whole community's point of view, would be both inefficient and inequitable. These are the primary motives behind all forms of air-quality regulation.

AIR QUALITY CONTROL STRATEGIES

Air quality is generally controlled by two types of strategies [1]. The first type focuses on the emission process through either the restriction of the type, volume, and timing of waste emissions or through the regulation of emission techniques (factory stack height ordinances, regulations requiring catalytic converters in motor vehicle exhaust systems, etc.). The second type directs the location and spatial distribution of emission sources. Land-use plans and transportation plans fall under this latter category. Whether by intentional design or unintended consequence, they influence air quality by controlling the location, type, and size of emission sources; hence, the spatial relations between emittors (polluters) and receptors ("pollutees").

These controls can be used deliberately to regulate air quality, often at far less cost than other methods would require. For example, consider the available alternatives in the following situation. A factory, located at G, is emitting particulate matter at the rate of g grams per second; and the people living in nearby neighborhoods consider the consequent levels of damage to be just tolerable. Another firm wishes to build a similar factory in the same city. The firm is considering two sites: Q, adjacent to the existing factors; and R, twenty miles away on the other side of town. Of the two sites, the firm considers site Q marginally superior. Faced with this situation, the city can maintain pollution damages at their present level simply by persuading the new firm to build at R. If the firm were permitted to build at Q, the city could maintain air quality by having the combined emissions from the two adjacent factories; but to do this it would be necessary to force both firms to spend vast sums on emission control equipment.

In the above example, the suggested *ad hoc* intervention in the company's locational decision would be unnecessary if the city had specified and applied air quality criteria when designing its land-use ordinance. Similarly, highway layouts can be designed to minimize pollutant concentrations caused by automobile exhaust fumes. In the preparation of these plans, air quality has been traditionally regarded as a rather minor issue, and so was easily neglected. The present situation, however, reveals air pollution to be an important factor in the development of comprehensive land-use plans. Therefore, it is desirable that explicit air quality objectives and procedures be formally incorporated in the process of metropolitan locational planning.

Emission Density Zoning is a form of supplementary land-use regulation which has been devised specifically for air quality control purposes. This method

> . . . assigns specific, maximum allowable areal emission rates to different classes of land use . . . For example, a regional emission density zoning might establish an upper limit of three tons per year of reactive hydrocarbon emissions per acre of land in areas designated for heavy industry [2].

Thus emission density zoning resembles an emission control strategy, but through its linkage with locational measures it can encompass the spatial dimensions of air quality issues. An extended form of emission density zoning involves the idea of transferable pollution rights: with this system, firms which use less than their maximum assigned emission rates can sell the balance to others located nearby.

An effective way of embedding air quality controls within the larger context of metropolitan transportation and land-use planning is provided by air quality standards. Once air quality standards, i.e., maximum desired ambient concentration levels have been established for each significant pollution type, they can be applied as criteria in the evaluation of transportation and land-use plans, along with more traditional socio-economic criteria. This method is probably more effective in controlling air quality than any single non-spatial technique. It reduces the long-range air quality planning task to the minimization of control costs, subject to satisfaction of air quality standards.

For example, damage due to emissions from mobile sources (motor vehicles) can be controlled by a combination of emission controls and locational controls: here (assuming that air quality standards have been established previously) the planner's task is to find the least-cost combination of measures which will attain the required air quality standards. To do this the planner must be able to predict the air quality outcomes of any proposed policy combination.

The problems of predicting the air quality consequences of various proposed policies will be addressed later in this paper. Before doing so, the relationships between air quality and urban land-use patterns will be discussed, illuminating the difficulties involved in accounting for the significant variables in an efficient manner.

URBAN FORM AND AIR QUALITY

Urban form may be defined as the spatial distribution of human activities in a metropolitan region. Two aspects of urban form—activities (land-use), and connections (transportation and communication)—are closely interrelated. For example, the construction of a radial highway or rapid transit line increases the accessibility of an outlying suburb to the central city area, thereby stimulating demand for a new housing in the suburb; conversely, the construction of a large retail store in a given area will tend to intensify travel between that area and other parts of the region.

These categories, transportation and land-use, also encompass virtually all the sources of airborne waste emission. Thus air quality may be considered an attribute of urban form, if the definition of the latter is extended to include local meteorological conditions.

The conclusion is obvious: land-use and transportation policies directly affect air quality. Nevertheless, very little research has been done on the relations between urban form and air quality. The following section will outline recent American work on this subject: first, three attempts to discern general relations between urban form and air quality; then a larger group of studies which focused upon these relations in individual cities; finally, the relative merits of the two approaches will be analyzed.

Optimization for Hypothetical Cities

Two studies sought a prior optimization of air quality in hypothetical urban forms. Rydell and Stevens assumed a mix of automobile trip lengths and trip distances, a directly proportional relationship between automobile travel distance and pollutants emitted, and an uncomplicated formulation of the dispersal process [3]. Representing these conditions as a system of simple linear equations, they determined the spatial form which minimized exposure to pollutants.

Alan M. Voorhees and Associates, and Ryckman, Edgerley, Tomlinson and Associates took a somewhat more sophisticated approach [4]. They investigated a variety of combinations of different land-use, highway, and transit systems. The basic elements were: eight types of land-use patterns (satellite cities, sprawl, etc.); four types of highway networks (e.g., arterial grid; freeways along major arterials), and three types of transit networks (e.g., bus network with express bus service). Using computer simulation techniques, vehicle miles traveled were used to predict six air pollutant concentrations. A satellite city configuration was found to have the shortest aggregate trip distance, while a decentralized corridor configuration generated the heaviest transit use. The best air quality conditions were associated with a radial corridor configuration.

An important empirical work on relations between urban form and environmental quality was carried out by Brian Berry and several of his colleagues at the University of Chicago [5]. Their analysis of data from seventy-six American metropolitan areas indicated that "high density, concentrated, core-oriented urban regions had superior air and water quality to sprawling, dispersed urban regions of similar size and economic functions." [6]

Planning Studies of Particular Urban Areas

A number of air quality studies carried out in the late 1960s and early 1970s concentrated on predicting the spatial distribution of emissions resulting from various land-use and transportation plans, but gave little attention to the actual dispersion processes and the resulting pollutant concentrations. Such studies were reported for the Hartford metropolitan area [7, 8]; for the Seattle area [9]; and for the Chicago area [10].

In the 1967 Chicago study, the emissions of oxides of nitrogen (NO_x) and particulates were compared for a finger (corridor) plan, a multi-towns plan and a satellite cities plan. The analysis indicated that the finger plan and satellite plan gave the lowest particulate concentrations, while the finger plan was the most effective in controlling NO_x. In a later study of the Chicago area, Tolley and Cohen [11] estimated emissions and the resulting air quality levels for two alternative land-use plans: a centralized layout with the city of Chicago as the economic hub; and a cluster of satellite cities. They found only slight differences in air quality between the two proposals.

Several similar studies have been carried out in areas at the fringes of metropolitan regions. Of these, the work of Voorhees and Associates [12] in Montgomery and Prince George's Counties in Maryland, and of Willis et al. [13] in the Hackensack Meadowlands in New Jersey highlighted the importance of air pollution problems due to airborne residuals spilled over from adjacent urban areas. In another peripheral region; Middlesex County in New Jersey [14], the researchers focused upon air quality problems due to urban growth within the study area. They compared two land-use plans: Controlled Growth concentrated around urban centers, and Dispersed Growth or Sprawl. Their analysis indicated that higher pollutant concentrations were created in and around the controlled growth plan's intensified urban centers. The periods of high pollutant concentrations were considerably lower in the sprawl alternative, but they spread over a wider area. Thus, for air quality the choice was between high pollutant concentrations confined to small areas, and low concentrations spread over large areas.

General Versus Particular Modes of Investigating Air Quality

Two cases will illustrate the difficulties inherent in attempting to construct a general theory of urban form and air quality. Of the two nucleated urban patterns shown in Figure 1 it seems clear, *ceteris paribus*, that type 1a would suffer less from air quality problems than type 1b. But under several circumstances the reverse may well occur. First, the attenuated layout of 1a will tend to induce longer travel paths, hence a larger volume of emissions from automobiles. Second, meteorological conditions particular to the case may negate the *a priori* advantages enjoyed by 1a. For example, the spine in 1a might run

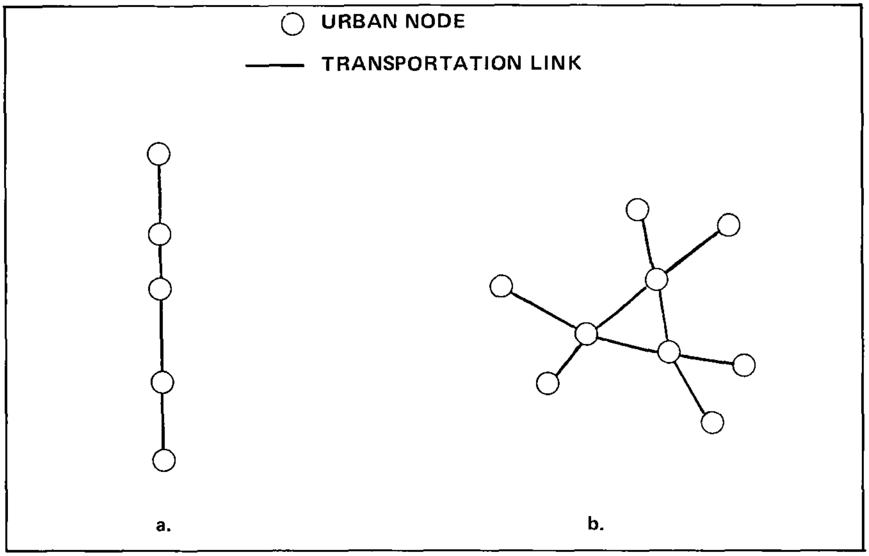

Figure 1. Nucleated urban patterns.

along a valley rarely swept by wind; whereas in 1b the satellite centers might be situated upon well-ventilated eminences.

In Figure 2 the transportation and meteorological conditions mentioned in the previous example are held constant. Now suppose that the aggregate building densities of 2a and 2b are equal; and that by some aggregate measure 2a and 2b have equally good air quality. Still, it is evident that the spatial distribution of air quality in 2a and 2b will differ. In 2a the ambient pollutant concentrations within each node will decline relatively sharply from center to periphery, while in 2b the gradient will be substantially flatter. Thus, 2b is a more equitable arrangement than 2a, but 2b is likely to offer few pollution-free sites for public parks. This is similar to the case of Middlesex County, New Jersey, discussed earlier.

To summarize: the first example shows that complexity of the problem and the importance of local physiographic-meteorologic conditions; while the second example emphasizes the normative basis of any optimizing approach. The conclusion of all this is that the number of significant variables, and the complexity of their interaction, probably are too great to be encompassed in simple general statements about relations between air quality and urban form. The main value of the generalized studies seems to be in alerting planners and the public to broad urbanistic issues as the negative impacts of urban sprawl.

Thus, the appropriate field of prediction in practical air quality planning situations is the specific context of the particular urban settings. The research

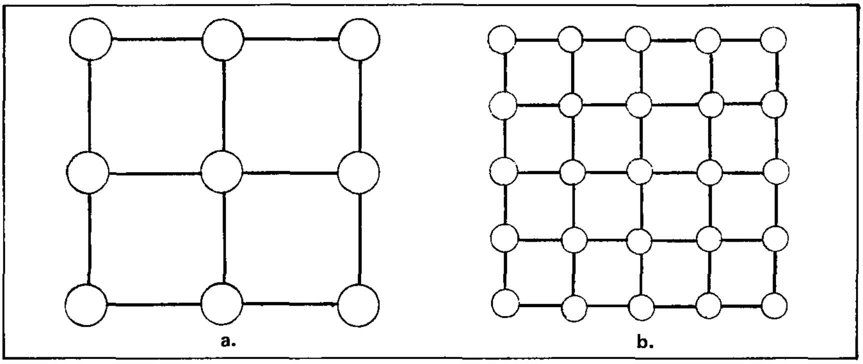

Figure 2. Urban density patterns.

discussed above brings out several important issues involved in this kind of approach.

First, few of the local studies arrived at strong conclusions. In some cases, the methods used were quite crude and the conclusions therefore were unconvincing; but from the discussion above, it is obvious that even a rigorous methodology may fail to find major air quality differences between widely different land-use transportation patterns. Under these circumstances, we may expect that the air quality attributes of a plan will have no critical bearing upon its adoption or rejection. But we cannot know whether air quality is a relevant issue unless we make air quality predictions.

Second, the level of detail at which the prediction is made must be suited to the type of evaluation required. For example, in Figure 2, too coarse a level of spatial detail would miss the distributional issues discussed above.

Third, because of the complexity of the processes under study, the assembly of a new predictive apparatus for each planning study would be quite inefficient. Serious effort needs to be given to the development of a predictive system suitable for application in many different local contexts. The main features of such a system will be discussed next.

AN AIR QUALITY SIMULATION SYSTEM

Any attempt to predict the impact of a transportation and land-use plan upon air quality must deal with three logically consecutive stages:

1. changes in the intensity and spatial distribution of land-use and transportation activities resulting from the plan;
2. changes in the intensity and spatial distribution of airborne emissions resulting from 1; and
3. changes in air quality at any point in the study region resulting from 2.

Each of these steps encompasses a number of complex processes. The first step (Location) should reflect the interdependence of social and spatial organization in human communities and the dynamic forces which determine the location of activities within a community. The second step (Emission) involves production and consumption technologies and emission control regulation. The last step (Diffusion) involves air pollution meteorology and aerochemistry, and regional physiography. Powerful analytical tools are needed to trace the effects of policy decisions through these social and environmental processes. One such tool is the computer simulation model.

The growth of computer technology, along with the mounting problems encountered by urban transportation and land-use planners, initiated the development of transportation models during the late 1950s and of urban activity models in the early 1960s. With increased public awareness of the degradation of the natural environment, the first environmental models (including air quality models) appeared shortly afterwards. Since the mid-1960s, models have been used successfully in scientific research to investigate and test social and environmental theories, and in planning to predict the outcomes of policy proposals. The role of these models in policy-making is now well established, and the craft of model development, testing, and application is documented in an extensive literature [15-17].

The most recent trend in modeling has been the integration of a group of models into a comprehensive system, simulating a number of social and environmental processes. With this approach it has been possible to model interactions between processes; resulting in a more realistic representation of the actual process involved. Such integrated systems have been designed for various purposes including analyzing the interactions among land-use patterns and transportation facilities [18], simulating the interchanges between economic and environmental systems [19-21], and tracing the effects of land-use and transportation policies on the quality of air [22, 23].

A system designed to analyze the long-range impacts of land-use and transportation policies on air quality typically consists of three major sections: transportation and land-use, emission and diffusion (Figure 3). These sections correspond with the three groups of processes indicated above. The transportation and land-use section consists of subsections which model transportation, employment and residential locations, and other land-use processes. These submodels are calibrated and operated as an integrated series, to capture the interdependence of the phenomena which they represent. The output from this section represents the spatial distribution of land-use and transportation activities over the region. This information is passed to the emission section where, based on their emission characteristics, the transportation and land-use activities are converted to pollutant emission rates. The output from this section represents the intensity and geographical distribution of emissions over the region. The emission information is passed to the third section, where

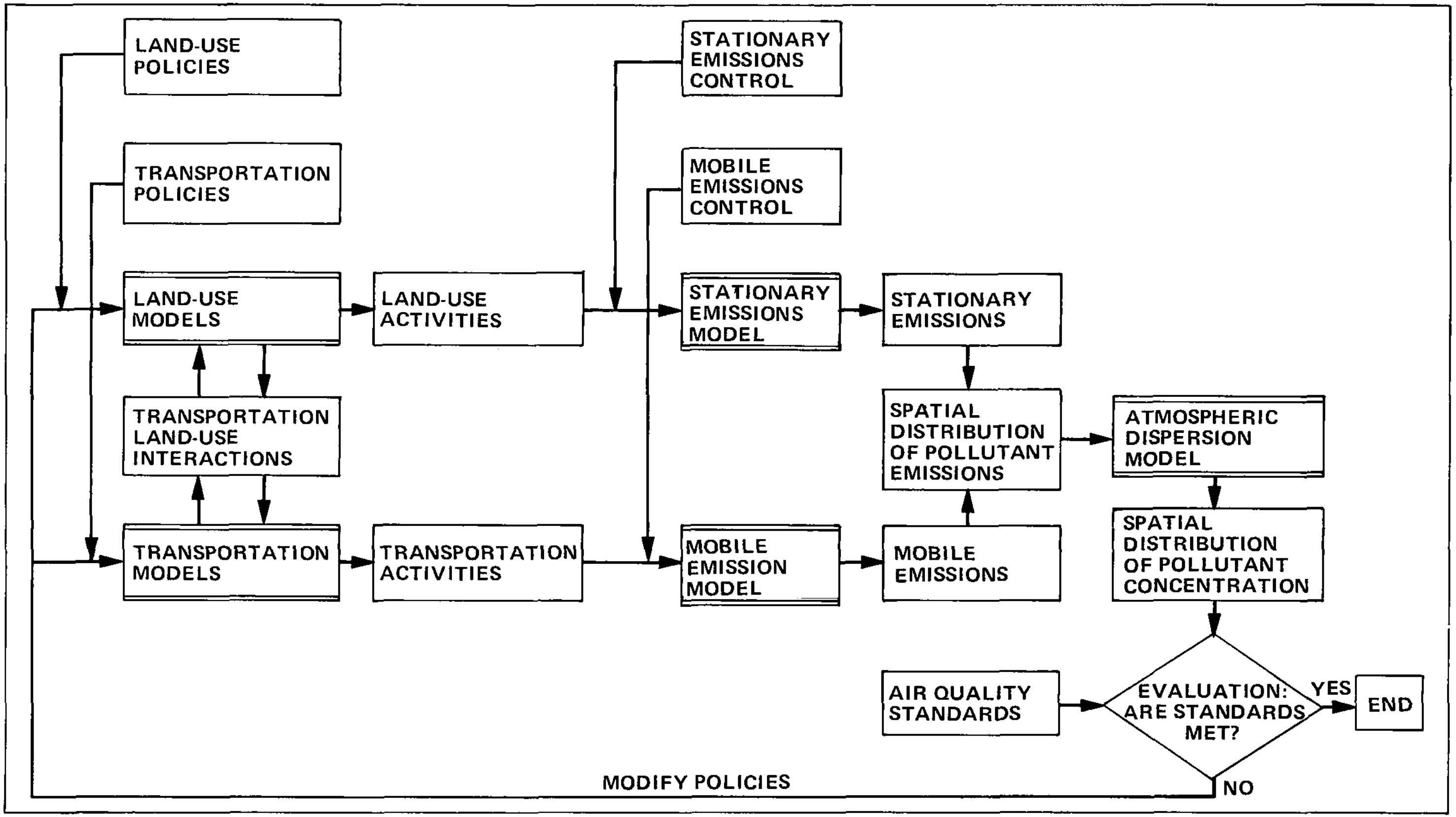

Figure 3. Air quality simulation system.

meteorological information and atmospheric dispersion models, are employed to forecast the spatial distribution of pollutant concentration over the metropolitan region. Generally, the criteria for the design of these systems include sensitivity to a wide range of policies, reasonable data requirement, and convenience and efficiency of operation.

Air quality systems, similar to the one just described, have been built and successfully tested with data from various locations including the Boston metropolitan region [22] and the San Francisco Bay area [23]. These computer simulation systems, although still limited in scope and needing additional developments and refinements, show the most promise of being capable of accurately predicting the air pollution consequences of land-use and transportation policies, and thus yielding substantial improvement in planning intelligence in general.

CONCLUSION

The air pollution sequence which starts with urban activity patterns and ends with the degree of damage caused by degraded quality of air can be influenced by planning decisions. The causative chain is a complex process involving physical, technological, economic, social, health, and legal factors.

To attain improved air quality, planners must be able to predict the air quality impacts of policies affecting the magnitude and spatial distribution of pollutant emissions. The task of predicting air quality requires an understanding of conditions which determine the spatial distribution of these activities, the composition of the wastes discharged from them, and the processes by which the wastes are dispersed and degraded in the atmosphere. Using mathematical models amenable to treatment with electronic computers, substantial progress has been made recently in representing the processes of locational behavior, pollutant emission and pollutant diffusion. A combination of the best of these models should yield substantial improvements in planning intelligence.

REFERENCES

1. R. R. Chirillo et al., *Air Quality Analysis Workshop, Volume I–Manual*, Office of Air Quality Planning and Standards, Research Triangle Park, N.C., U.S. Environmental Protection Agency, EPA-450/3-75-080a, 1975.
2. J. J. Roberts, J. Croke, and S. Booras, A Critical Review of the Effect of Air Pollution Control Regulations on Land Use Planning, *Journal of the Air Pollution Control Association, 25*:5, pp. 500–520, 1975.
3. P. C. Rydell and B. H. Steven, Air Pollution and the Shape of Urban Areas, *Journal of the American Institute of Planners, 34*:1, pp. 50–51, 1968.
4. U.S. Environmental Protection Agency, *A Guide for Reducing Air Pollution through Urban Planning*, Research Triangle Park, N.C., Alan M. Vorhees and Associates and Ryckman, Edgerley, Tomlinson & Associates, Report No. APTD-0937, 1973.

5. J. L. Berry et al., *Land Use, Urban Form, and Environmental Quality*, University of Chicago, Chicago, IL, 1974.
6. J. L. Berry, *Land Use Forms and the Environment: An Executive Summary*, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., Report No. EPA-600/5-75-003, p. 1, 1975.
7. A. M. Voorhees, C. F. Barnes, and F. E. Coleman, *Traffic Patterns and Land Use Alternatives*, Highway Research Board, Washington, D.C., 1962.
8. J. E. Yocum, D. A. Chisholm, G. F. Collins, J. A. Farrow, R. A. Gogosz, and J. C. Magyar, *Summary Report: Air Pollution Study of the Capital Region*, RRC Service Corp., Hartford, CT, 1967.
9. J. A. Kurtzweg and D. W. Weig, "Determining Air Pollutant Emissions from Transportation Systems," *Fourth Annual Symposium on the Application of Computers to the Problems of Urban Society*, Association for Computing Machinery, New York, 1969.
10. Northeastern Illinois Planning Commission, *Managing The Air Resource in Northern Illinois*, Technical Report No. 6, Northeastern Illinois Planning Commission, Chicago, IL, 1967.
11. G. S. Tolley and A. S. Cohen, Air Pollution and Urban Land Use Policy, *Journal of Environmental Economics and Management, 2*:3, pp. 247–254, 1976.
12. A. M. Voorhees and Associates, *A Transportation Study for Montgomery and Prince George's Counties, Maryland*, The Maryland National Capitol Park and Planning Commission, Baltimore, MD, 1970.
13. B. H. Willis, Jr., E. Mahoney, and J. C. Goodrich, *The Hackensack Meadowlands Air Pollution Study: Task 4 Report: Air Quality Impact of Land Use Planning*, U.S. EPA, Research Triangle Park, NC, 1973.
14. TRV, Inc., *Air Quality Management Plan and Program Recommendations, Middlesex County, New Jersey*, McLean, VA, 1974.
15. M. Batty, *Urban Modelling, Algorithms, Calibration, Predictions*, Cambridge University Press, Cambridge, MA, 1976.
16. S. R. Hanna, *Urban Diffusion Models*, Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Oak Ridge, TN, 1975.
17. S. H. Putman, *Urban Residential Location Models: Evolution and Development*, Martinus Nijhoff Publishers, The Hague, 1978.
18. S. H. Putman, "The Integrated Forecasting of Transportation and Land Use," paper prepared for presentation at *A Seminar on Emerging Transportation Planning Methods*, sponsored by U.S. Department of Transportation, Daytona Beach, FL, 1976.
19. J. H. Cumberland and R. J. Korback, "A Regional Inter-Industry Environmental Model, prepared for the Regional Science Association Philadelphia Meeting, University of Maryland, 1972.
20. J. Harrington, Jr., F. W. McElroy, and K. Paik, *An Integrated Multi-Media Pollution Simulation Model*, Georgetown University, Washington, D.C., 1973.

21. W. O. Spofford, Jr., *Integrated Residuals Management: A Regional Environmental Quality Management Model,* Resources for the Future, Reprint No. 130, Washington, D.C., 1976.
22. G. K. Ingram and G. R. Fauth, *TASSIM: A Transportation and Air Shed Simulation Model,* Final Report for the U.S. Department of Transportation, Harvard University, Report No. DOT-0S-30099-5, Cambridge, MA, 1974.
23. M. Gross, "The Impact of Transportation and Land Use Policies on Urban Air Quality," Ph.D. dissertation, University of Michigan, Ann Arbor, MI, 1979.

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