J. ENVIRON. SYS., Vol. 3(1), Spring, 1973

Relationship of Transportation and Land Use to Air Quality: A Systems Approach

HERSCHEL C. CONNER, JR.
EPA Fellow
ANDREW A. DZURIK
Assistant Professor
Department of Urban and Regional Planning
Florida State University

ABSTRACT

A systems framework for investigating the relationship of urban transportation and land use to air quality is set forth in this paper. The nature and interrelationships of the major components of the flow of airborne residuals are outlined, and the residuals management process is examined in terms of its components and their attributes. Part II consists of the analysis of the problem of mobile source emissions in the context of the general framework suggested in Part I. Possibilities for modeling the emissions–transportation system–land use interface are briefly explored and some alternative solutions are suggested.

It is becoming increasingly clear that the National Air Quality Standards will not be achieved by 1975 and 1976 as required by law with only emission control devices. Technology has failed to solve completely the emission control problem for mobile sources. Even if technology produces the perfect emissions control device by then, it will be at least 10 years, by the best estimate, before uncontrolled vehicles are eliminated from the nation's fleet [1]. The fact that transportation contributes more than half of our air pollution makes the problem even more serious. It appears that we will achieve acceptable air quality only in the long run.

Since the problem of air pollution will be solved only within a long range time frame, land use planning and transportation planning approaches to air quality management become more attractive solutions. The permanence of the

doi: 10.2190/1JHC-698E-684V-ERBJ
http://baywood.com

land use and transportation solutions, regardless of technological innovations, adds to their attractiveness. Furthermore, the secondary effects attributable to such approaches enhance their value. This paper provides a framework for investigating the efficacy of these types of solutions in the search for clean air.

Part I: General Framework

NATURE OF THE AIR POLLUTION PROBLEM

Before a clear statement of the problem is formulated, it might be helpful to discuss the problem area in general. The fact that air pollution is a problem in urban areas and even in some rural areas is recognized by most people. However, the magnitude and complexity of the problem is not so widely known.

Many environmental watchdogs regard air pollution as the most serious problem facing the Environmental Protection Agency [2]. The dimensions of the crisis in the air are incredibly large. Some 270 million tons of emissions were injected into the nation's atmosphere in 1970–100 million tons in excess of 1960 emissions [3]. Initial figures for 1971 seem to indicate that total emissions are still increasing [4].

The complexity of the socio-economic systems which generate and sustain such high levels of airborne residuals is surpassed only by the complexity of the necessary control strategies and their consequences. Furthermore, the way in which the problem is formulated predetermines the level and method of analysis and the nature of alternative solutions. A few examples will illustrate this point well.

If air pollution is considered as an emissions control problem, the solution set includes only strategies aimed at individual offenders and criteria for measuring the success of the control strategy do not include indicators of overall air quality. Conversely, if the problem is characterized as air quality maintenance, measures of success do not include emissions standards. Thus, EPA has established air quality standards in conjunction with emission standards. The implementation of an enforcement strategy for these dual standards, however, requires administrative, judicial, and planning mechanisms, thereby adding to the complexity of the problem.

As another example, airborne residuals may be regarded as a health problem [5]. By looking at air pollution strictly in this way, one could become locked in on personal prescription solutions, i.e., dispensing medicine, moving susceptable persons to less polluted areas, etc. Other responses to the health dilemma could be described as preventive medicine, under which title many different types of control strategies would lie, ranging from gas masks to land use planning.

Consequently, the way that the problem is perceived is quite important. It appears that the nature of the air pollution problem is highly complicated because both its source and its solution lie deeply embedded in the complex web of man's socio-economic and cultural systems. Let us now explain the viewpoint taken here.

If air pollution is defined as the existence of man-made particles and gasses in ambience, air pollution becomes a residuals management problem [6]. In general then, the problem arises from the recognition of a need for clean air and thus leads to an effort to reduce existing airborne residuals to an acceptable level.

COMPONENTS OF AIR POLLUTION ANALYSIS

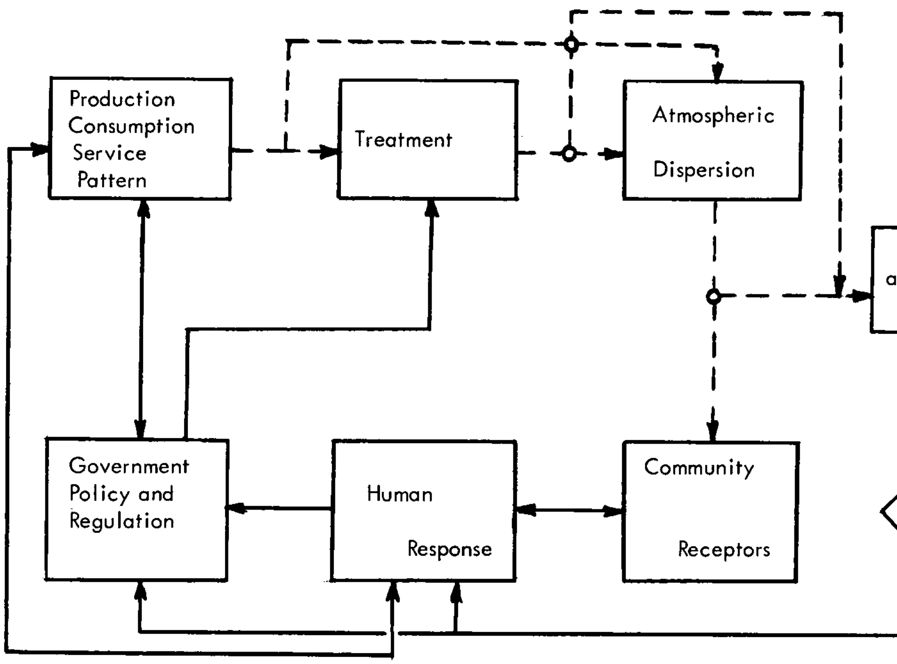
A major difficulty in studying the air pollution problem is finding the proper level of analysis. Detailed analysis of only one or two elements of the problem is susceptable to the risk of not including vital considerations in the analysis. If too many elements are included, the analysis becomes cumbersome and it is difficult to define the interrelationships of the components. In order to clarify the level of analysis proposed here, a description of the basic components of the problem in general (an airborne residuals flow management system) will be helpful.

Basically, the quality of the atmosphere at any given time and location is a function of the residuals it is receiving and its ability to disperse them via physical and chemical mechanisms. Residuals are the result of the production, consumption, and service patterns of the communities within the airshed [7].

This pattern is, of course, a result of the socio-economic and political forces as they control and are controlled by governmental structure, policy, and regulation. The flow of airborne residuals eventually has consequences for various community receptors (human, animal, plant, and inanimate). The socio-economic and political forces then respond to this reception of residuals and influence governmental policy so that the residuals are treated or filtered in some way before they are released into the atmosphere. (See Figure 1.) Treatment does not directly change the interindustry mix of the airshed or the production process itself. However, it may indirectly affect the allocation of resources within a given source or group of sources.

Treatment, as used here, refers to technological recovery of residuals, such as the use precipitators and scrubbers. It should be noted that treatment of residuals creates a problem of storage, collection, and transport or disposal. In other words, technological treatment results in the shifting of the residuals management problem from the air to the water or land (solid waste disposal).

The socio-economic and political forces also respond to the reception of residuals in such a way that the ensuing governmental action goes beyond treatment, e.g., temporary or permanent court ordered plant shut down,



---→ airborne residuals flow.

——→ information, influence, activity flows.

○ points at which the level of residuals are measured.

Figure 1. Air quality management system.

change in the region's industrial mix and land use over a period of time, and regulation of the consumption of coal and other fuels. Alternatively, the socio-economic and political forces may bypass the governmental subsystem and interact directly with the production-consumption-service pattern (e.g., demonstrations, boycotts, and strikes) in order to alter the pattern so that the level of residuals emitted will be reduced. This is indicated as the information-influence-activity feedback loop between the production-consumption-service pattern and the human response boxes in Figure 1.

The degree of success or failure of airborne residuals management strategies resulting from socio-economic and political pressures or governmental action can be measured at two different points in the flow, as also can be seen in Figure 1. If emission controls are being enforced, the level of residuals being emitted from sources, with or without treatment, is monitored at the source. The degree of achievement of air quality standards are measured after atmospheric dispersion. If standards are not met in either case, this information from the monitoring systems is fed back as input for new governmental policy.

The basic description of the flow of airborne residuals and the resulting residuals management system can be considered as an outline of the problem at a very high and broad level of analysis. This basic system's description can easily be broken down into component subsystems, each suggesting a somewhat lower and more detailed level of analysis. As can be seen in the diagram, these components of the general problem can be classified into two families of subsystems: one dealing with the flow of airborne residuals, the other dealing with the biological, human, and institutional responses to this flow. A slightly more detailed description of these component subsystems will help put the analytical framework in perspective.

RESIDUALS FLOW SUBSYSTEMS

1. *The Production-Consumption-Service Pattern.* As indicated above, this subsystem receives inputs and feedback from the governmental policy and socio-cultural systems. It is the initiator of the flow of residuals and can initially be viewed at a very general level of description [8]. Obviously, the production-consumption-service sector is the most complex subsystem in our general description of the problem and can be broken down much further and in many different ways. One way of doing this would be to consider the production, the consumption, and the service sectors individually in terms of their respective pollutants. Another scheme of analysis would entail classifying sources as stationary or mobile and examining factors relating to each. The outputs of this subsystem include sulfur oxides (SO_x), hydorcarbons, carbon monoxide (CO), nitrogen oxides (NO_x), particulates, and photochemical oxidants.

2. *Treatment.* The residuals flow generated by a given production-consumption-service pattern is taken as input, along with science and technology. This subsystem includes elements of research and design of emission control devices, their installation, the recovery and storage of some or all of the airborne residuals entering the subsystem, and the transportation and disposal of the recovered residuals. The major output of concern in this subsystem is a reduced flow of airborne residuals which are discharged into the atmosphere. Although the water pollution and solid waste disposal problems arising from treatment are secondary in the present frame of reference, they should not be considered minor difficulties. In fact, they are areas of investigation which are just as complex as the one at hand. At any rate, analysis of the problem of reducing the flow of airborne residuals at this level is the purview of the engineering sciences.

3. *Atmospheric Dispersion.* The weather has a tremendous bearing on the level of residuals in the atmosphere at any given time. Topography, wind speed and direction, lapse rate, and humidity are just a few of the elements that must be included in a complete model of the atmospheric dispersion of residuals. This level of analysis is clearly the domain of meteorologists. If atmospheric dispersion forces are functioning at a very low level of efficiency, as in the case of temperature inversions, the intensity of the residuals flow may be actually increased rather than reduced by this subsystem.

4. *Community Receptors.* Depending upon the meteorological variables operating, a certain amount of airborne residuals eventually settle out of the atmosphere. When this happens the flow of airborne residuals is terminated, but the problem is not terminated. The effects of the reception of residuals from the air is another area of investigation in itself. The generalized components of this subsystem include the specific receptors in the community: humans, fauna, flora, and inanimate objects. The chemical, biological, genetic, and ecological reactions that occur in and among these receptors suggest several different sets of lower order systems. Analyzing the air pollution problem at this point in the flow of residuals involves such components as medical and biological research; and the development of damage function models which will quantify the consequences of air pollution for human health, plant and animal life, and inanimate objects, and translate these consequences into monetary terms.

RESIDUALS MANAGEMENT PROCESSES

1. *Human Response.* The informal human response to air pollution is usually activated by a disaster such as the 4,000 deaths that resulted from London's 1952 episode [9]. However, the response may be the result of an increased public awareness brought about by the establishment of a monitoring system. For example, with a few exceptions, in the United States we have

avoided disasters of the magnitude of those in England, but the information about air and water pollution had become so distressing by the late sixties that environmental action groups began to proliferate. This response contains elements of socio-cultural, socio-economic, and political forces. Needless to say, each of these forces is a complex system in itself, and suggests various ways to analyze the problem at hand. The output of this complex subsystem of the informal human response is that intangible called influence. This influence is directed at the formal, institutional sector, i.e., the government. It is interesting to note the existence of a feedback loop between the human response and the production-consumption-service pattern. In other words, the production process in a given location may be creating airborne residuals, but the human response to this pollution may be stymied by the lure of jobs and increased tax revenues. Normally, these informal human responses are translated into formal action within the various levels of government.

2. *Governmental Policy and Regulation.* In a democratic society the government is sensitive to the needs of the people, but it is also sensitive to the needs of the production sector. Therefore, the prodings of environmental consumer groups and economic interests are inputs to that part of the governmental policy subsystem concerned with the management of airborne residuals. The outputs of the governmental process of concern here are the policies, laws, and court rulings that result in the treatment of residuals, or that result in a change in the pattern of production, consumption, and service so that the flow of residuals entering the atmosphere from a given pattern is reduced. The three main levels of government (Federal, state, and local) as well as a fourth level of semi-government, namely, the regional council of governments and the three powers of government suggest twelve different approaches to reducing the level of airborne residuals.

The best level at which to implement air quality plans is at the regional level, where, unfortunately, governmental power is weak or non-existent. Thus, intergovernmental relations are essential for the success of any regional airborne residuals control strategy.

3. *Monitoring the Flow.* The flow of residuals can be monitored at the emissions point or source, and after atmospheric dispersion has effected the flow. The emissions and air quality monitoring subsystem suggests still another level of analysis of the problem. Accurate and standardized data about the residuals flow is difficult to obtain but is a necessary input for proper human and institutional responses. The monitoring subsystem for attaining such accurate and standardized data about the problem of air pollution should be part of a regional environmental information system. This, of course, is another area of investigation. A monitoring system can be the cause or effect of human and institutional responses to air pollution. But once established, the monitoring system functions as a feedback mechanism for measuring the success or failure of various control strategies.

Although the framework described in this paper deals with only one facet of one of the component subsystems, each of the seven major components of the air pollution problem discussed above are necessary considerations for a total solution.

Part II: Land Use, Transportation Analysis of Mobile Source Emissions

In terms of the weight of airborne residuals produced, mobile sources constitute more than half of the nation's air pollution [10]. Therefore, one industry in the service sector, namely, transportation, creates the majority of the nation's airborne residuals. In light of this fact, knowledge about ways to reduce residuals originating from the transportation sector would be a valuable information input for a major part of the total solution set. Therefore, the generalized formulation of the problem relating to reduction of airborne residuals to an acceptable level can be addressed to a more specific question: how can the level of airborne residuals from mobile sources be reduced to an acceptable level?

Although mobile sources include airplanes, trains, and automotive vehicles, the term will be used here to denote only the latter. Elimination of planes and trains from consideration is justified on the grounds that they contribute a small percentage of the total amount of air pollution arising from mobile sources. The specific residuals resulting from automotive travel that will be of interest here are carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons. This is not to say that these are the only residuals resulting from transportation, or that transportation accounts for all these pollutants in the atmosphere, but transportation does produce two-thirds of the CO, over half of the hydorcarbons, and two-fifths of the NO_x [11]. Therefore, the "acceptable levels" can be quantified by using the National Air Quality Standards (NAQS) as a base. For example, the NAQS for carbon monoxide is 35 parts per million maximum concentration for a one hour period. The "acceptable level" in terms of transportation residuals would be $2/3 \times 35 = 23.3$ ppm.

As is the case with any industry in the service sector, transportation is a derived demand. It would seem logical to conclude, then, that part of the problem of air pollution resulting from transportation lies at the source of this demand. The demand for transportation is created by the separation of different uses of the land into homogeneous zones. This generates a spatial barrier to interaction between dissimilar activities. The more that human activities of differing types are physically isolated into separate adapted spaces, the greater will be the demand for transportation to cross this spatial barrier. Therefore, the land use configuration of a given human settlement influences the amount of travel and hence the level of residuals arising from mobile sources.

The land use configuration itself is a function of the population size; the economic character of the area; governmental policies relating to land controls such as the zoning, density and building height controls, and capital improvements; and the supply and demand pressures in the real estate market, which is also related to the population and economy of the area. In addition, there is a certain feedback effect between the transportation system and the land use configuration. In other words, the transportation system not only responds to land use, but also helps determine the shape of the land use configuration [12]. Figure 2 provides a schematic diagram of the interrelationship of these factors, with special emphasis on land use, transportation, and air quality.

Governmental policy and regulations in regard to emission control devices and

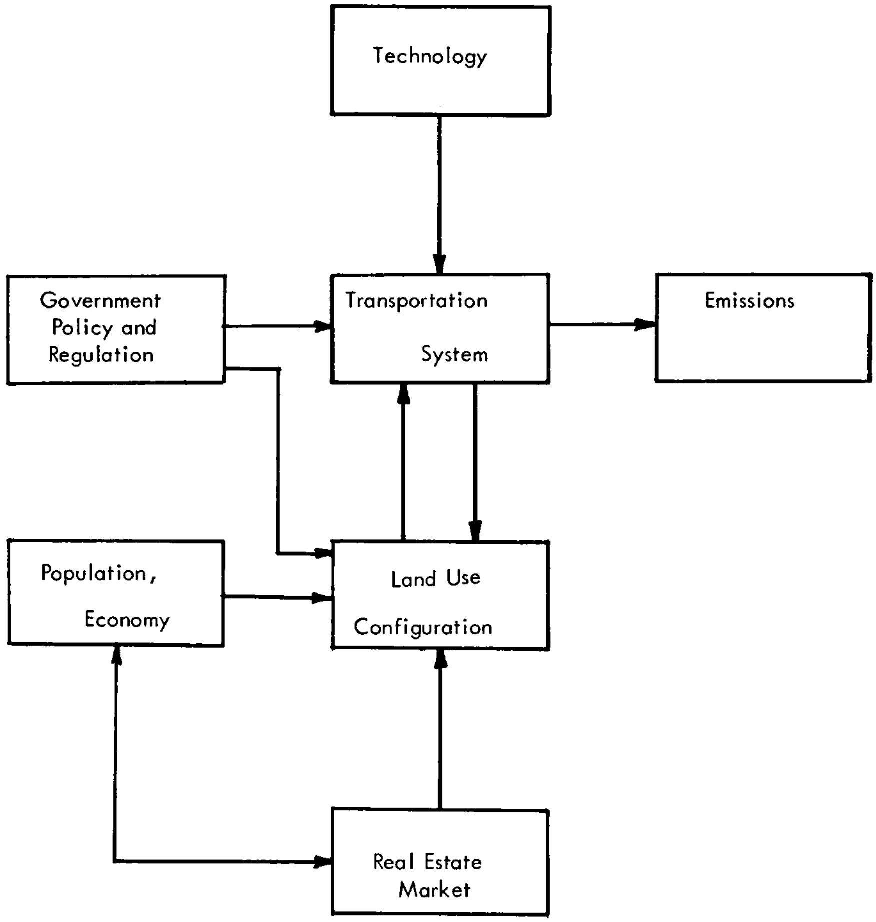


Figure 2. Factors in mobile source emissions.

transportation planning will also affect the flow of residuals from mobile sources. For example, California required emission control devices on autos long before the Clean Air Act of 1970. Government policies and investments, such as mass transit, or an expressway system which creates or alleviates congestion, will influence the level of residuals from mobile sources. Los Angeles had a governmental policy which fostered expressways. Consequently, although the California emission control laws resulted in a decrease in emissions per vehicle, the proliferation of automobiles on the expressway system offset this gain and the overall air quality remained the same at best.

Technology clearly has a role to play in determining mobile emissions. Emission control devices on internal combustion engines, the development of external combustion engines, and innovations in mass transit equipment are all examples of the role of technology. As mentioned previously, however, the failure of technology to solve the emissions control problem, the country's economic fixation on petroleum as an energy source, and the dominance of the steel industry dictate that other types of solutions should be considered.

GOALS AND OBJECTIVES

Starting with the premise that a major goal is to find ways to reduce airborne residuals from mobile sources, this goal can be translated into three specific objectives: minimize CO emissions, minimize NO_x emissions, and minimize hydorcarbon emissions. These objectives reflect the viewpoint of the Federal Environmental Protection Agency and state air quality implementation plans. The criteria to be used in measuring the degree of achievement of these objectives are based upon the National Air Quality Standards: CO, maximum 8-hour concentration = 9 ppm.; NO_x, annual arithmetic mean = .05 ppm.; and hydrocarbons, maximum 3-hour concentration = .24 ppm.

An additional goal related to the first is to find ways to reduce air pollution from mobile sources, with the most feasible abatement program(s) in regard to its probability of being implemented. The objective set attached to this goal of feasibility includes some quantifiable objectives and some that require non-numeric criteria. Abatement programs should be feasible in terms of the objective of an acceptable time frame for implementation. The criterion for measuring attainment of this objective would consist of the target date to be set by the appropriate planning body. Of course the alternative abatement program capable of being implemented at the earliest date would appear to be desirable, but quick implementation may conflict with other objectives stemming from this goal. The objective of the shortest acceptable time frame represents the viewpoint of the environmental activist.

Feasibility can also be translated into costs: capital improvement outlays and consumer costs. The objective function associated with these costs is one of minimization. Consumer costs are measured in terms of travel costs, and additional taxes and facility user fees which may be incurred through the abatement strategy. The cost of capital improvements are eventually borne by the consumer. Therefore, minimization of either capital or consumer costs implies minimization of the other. This objective is measured by a simple least cost standard and reflects the viewpoint of government officials and that segment of the region's population that is concerned with keeping government expenditures down. The cost minimization objective may conflict with the least time objective since properly focused massive expenditures over a short period of time should tend to alleviate the problem sooner than token appropriations over a long period of time.

A most important, but illusive, objective relating to the feasibility goal is that of avoiding socio-economic disruption of a serious nature. Measuring this objective is difficult. A survey of consumers, producers, and government officials would give an indication of expected disruption resulting from a given alternative. By stating this objective, an intuitive guide is established. For example, it is obvious that immediate banning of automobile traffic from large areas would create considerable disruption since alternative means of travel could not be provided immediately.

The feasibility of any alternative abatement program hinges on consumer support. The objective of consumer support is a prerequisite for any plan but especially one that will alter such basic elements in the city as land use configurations and transportation systems. The objective can be measured with a survey containing a somewhat different set of questions than the minimal socio-economic disruption objective survey, part of which is also aimed at consumers. This survey would probe only potential user response rather than the views of the entire spectrum of political and monetary power. Figure 3 indicates the interrelationships of goals and objectives relating to emission reductions and implementation feasibility.

MODELING THE TRANSPORTATION–LAND USE INTERFACE

Several modeling techniques are appropriate for analysis of urban land use and transportation patterns. Regression analysis can be used to explore the interrelationship of transportation and land use configurations and air quality, based on a sample of metropolitan regions. By controlling for demographic, economic, and meteorological variables, so that the variation in air quality due to city size, industrial mix, and weather will be minimized, variation in air quality due to land use configuration and transportation system characteristics can be more readily measured. Statistical analysis will indicate which land use variables and which transportation system variables tend to optimize air quality.

Statistically determined parameters can be used as inputs to a simulation model of the study region which can depict feedback effects resulting from changes in the urban system [13]. Modeling the land use and transportation

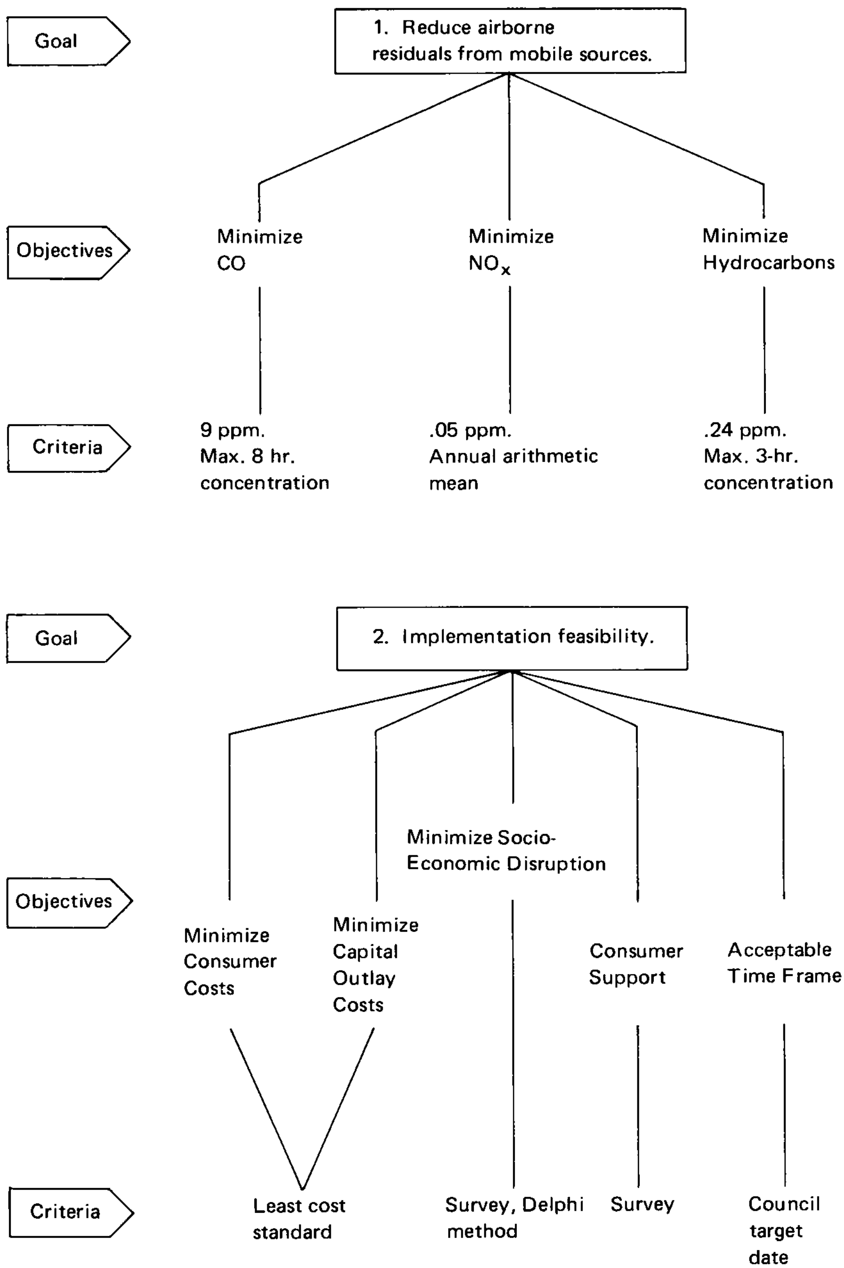


Figure 3. Interrelation of goals, objectives, criteria.

system characteristics, which according to the regression model optimize air quality, against the backdrop of this particular region's dynamics will permit the time frame, capital outlay, and consumer costs associated with evolving these states (of land use and transportation) in this region. This modeling process will help generate alternative solutions and part of the information needed to evaluate them.

SOME ALTERNATIVES AND EXTENSIONS

Alternative abatement strategies discussed here would fall into two general classes: altering land use configurations or changing the transportation system. Of course, a hybrid solution is in the realm of possibility. Because of the interrelationship of the land use pattern and the transportation system, it is impossible to tell at this point which class of alternatives will more quickly generate corresponding changes in the other without going through the modeling process. This would be one of the more interesting pieces of secondary information produced by this framework for analysis.

It is interesting to note that both extremely low and extremely high density development tend to reduce travel and hence air pollution from transportation. But in the area between the nadir and zenith of possible densities lies much variation. Heavy corridors of employment and population and satellite cities are just two of the possibilities which would tend to reduce vehicle miles of travel and therefore air pollution. Regional open space programs create natural buffer zones which shield transportation residuals from other land uses and help disperse and oxidize them. Fostering planned unit developments tends to integrate land uses and reduce travel by eliminating the spatial barrier to human interaction. Careful location and design of new towns (both in-town and out-of-town) obviously affects the volume and origin destination patterns in the region.

Alternative solutions aimed at the transportation system itself range from holding the existing system constant, to drastically changing the modal split in favor of transit. For example, traffic flow on the existing system could be improved by reverse land operations, ramp control, and interchange design on freeways. Parking restrictions, widening intersections, and reversible one way streets on the arterials will improve flow and thus reduce pollution by allowing the auto engine to operate more efficiently. This appears to be valid only up to a certain threshold volume where the increased number of cars offset the per vehicle reduction in emissions. Other traffic control measures such as staggered work hours, and auto-free zones do not seem to appreciably reduce air pollution levels. The institution of mass transit, even if this means bus lanes on freeways and arterials, will probably prove to be the transportation variable which has the greatest impact on air quality. Of course the success of mass transit system in a low density-sprawl urban pattern is questionable. Perhaps, establishment of this mode in such an area will generate a compatable land use configuration and eventually capture a majority of total person trips. This question can be answered most economically through the modeling process.

These are only a few of the possible alternative abatement programs, rooted in land use and transportation considerations, which can be evaluated by this study framework.

EVALUATION OF ALTERNATIVES

The level of residuals produced by the alternative land use and transportation based abatement programs should be estimated to allow for the evaluation of alternative solutions relative to the objectives set forth for emissions. The best alternatives, in terms of these objectives.

The cost/benefit analyses that have been attempted in the environmental area tend to overstate the costs of clean up and understate the value of the benefits to be derived. Therefore, this evaluative process should not rely too heavily on economic analysis. In other words, the consumer and capital outlay costs should not be equally weighted against the benefits of pollution abatement, which cannot be adequately quantified. A weighted hierarchy of the various implementation feasibility objectives (time, cost, avoidance of socio-economic disturbance, etc.) should be established for the purpose of determining an alternative's utility in terms of community values.

After the various consequences of alternative solutions are evaluated, the alternatives that meet the criteria specified at the outset should be presented to the appropriate planning council for their consideration. If the planning council opts to reject all of the proposals that are offered, a reexamination of the goals and objectives of the study will be in order. (See Figure 4 for a diagram of the entire process outlined here.)

The value of the analysis discussed here as it relates to the air pollution abatement goals and objectives has been established, but there are certain secondary reverberations to be gained from this research framework. The externalities of knowledge include an insight into the temporal sequence of the land use transportation causal relationship. In other words, the question of whether the urban transportation system determines land use patterns, or whether the land use pattern dictates the type and size of the transportation system may be better understood.

Secondly, if any of the proposals that come out of this approach are implemented, a powerful precedent will have been established for the planner. Future urban growth may be directed not only from political, economic, and social considerations, but also from environmental considerations. Air pollution abatement may be a powerful lever for moving the urban system toward a more orderly and coherent growth.

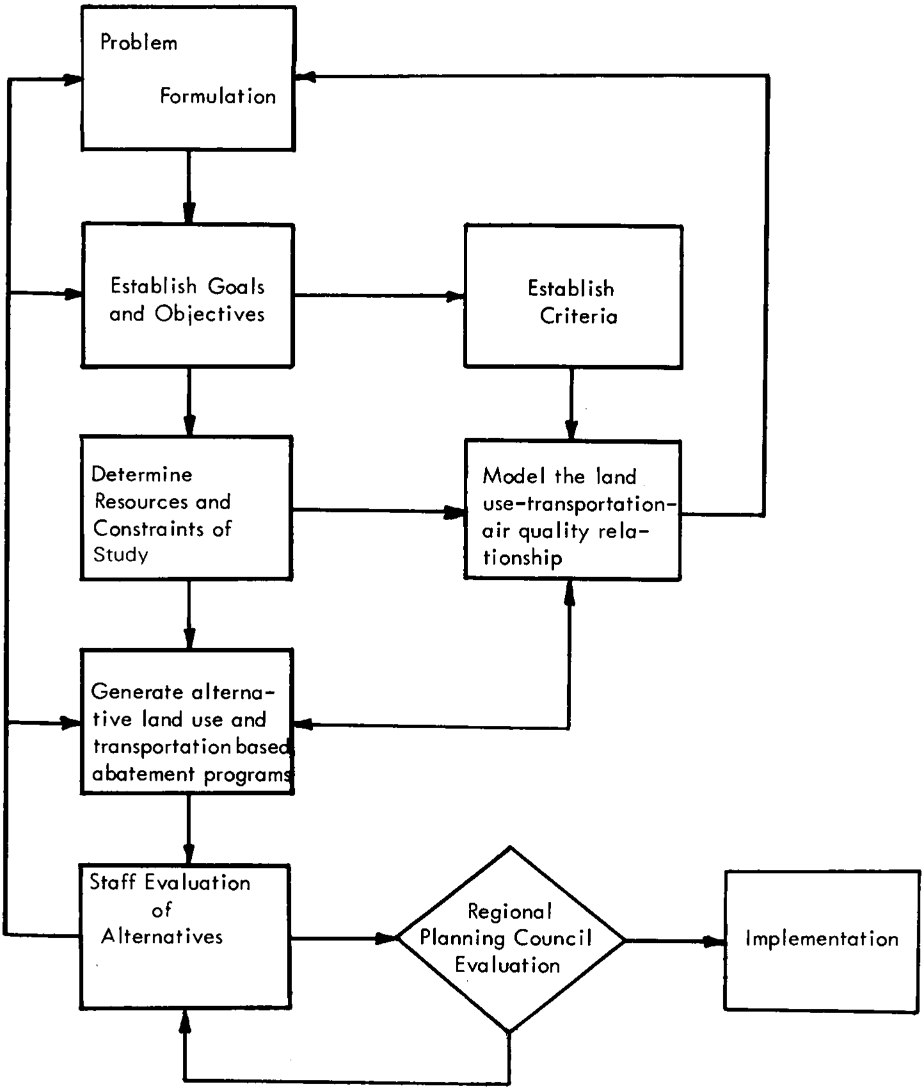


Figure 4. Framework for analysis of transportation-land use aspects of air quality.

Finally, analysis of a problem which obviously supercedes political boundaries will tend to foster improved intergovernmental relations and cooperation.

The framework set forth in this paper is not a cure for the air pollution problem, nor for the land use-transportation dilemma. It does provide, however, a systematic approach for dealing with these problems and a recognition of the interrelations existing in the urban setting.

REFERENCES

1. Kenneth E. Noll, "Transportation and Air Pollution," *Traffic Engineering*, 42(9):56, 1972.
2. National Wildlife Federation, *1971 EQ Index*, p.6.
3. The Conference Board, October 15, 1972, No. 1700.
4. National Wildlife Federation, *loc. cit.*
5. Lester Lave, "Air Pollution Damage: Some Difficulties in Estimating the Value of Abatement," in *Environmental Quality Analysis*, ed. by Allen V. Kneese and Blair T. Bower, pp. 213-243, Johns Hopkins Press, Baltimore: 1972.
6. Russell and Spofford, in a project for Resources for the Future, have ascertained that any environmental problem lends itself to analysis as a residuals flow problem. See Clifford S. Russell and Walter O. Spofford, "A Quantitative Framework for Residuals Management Decisions," *Ibid.*, pp. 115-179.
7. Only man-made residuals are being discussed here. Natural air pollutants such as volcanic ash, pollen, etc., are not considered and, in fact, are viewed as normal and acceptable conditions.
8. For an explanation of a systems interpretation see George Chadwick, *A Systems View of Planning: Towards a Theory of the Urban and Regional Planning Process*, pp. 43-46, Pergamon Press, Oxford, 1971.
9. Paul R. Ehrlich and Anne H. Ehrlich, *Population, Resources, Environment: Issues in Human Ecology*, p. 148, W. H. Freeman and Company, San Francisco, 1972.
10. *The Conference Board*, op. cit.
11. Sterling Burbaker, *To Live on Earth: Man and His Environment in Perspective*, pp. 22-23, The Johns Hopkins Press, Baltimore, 1972.
12. Roger L. Creighton, *Urban Transportation Planning*, pp. 239-243, University of Illinois Press, Urbana, 1970.
13. Jay Forrester, *Urban Dynamics*, for an extensive urban simulation model. MIT Press, Cambridge, 1969.
14. Kneese and Bower, *op. cit.*, pp. 213-278.