

AN ECONOMIC AIR POLLUTION CONTROL MODEL-
APPLICATION: PHOTOCHEMICAL SMOG IN LOS
ANGELES COUNTY IN 1975

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AN ECONOMIC AIR POLLUTION CONTROL MODEL-
APPLICATION: PHOTOCHEMICAL SMOG IN LOS
ANGELES COUNTY IN 1975

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December, 1970 found the author in a dilemma. I was a graduate student in aeronautics, but I had a greater interest in doing economics. At that time, my friend, Roger Noll, (then a Caltech Economics Professor and now at the Brookings Institution), provided the impetus for me to investigate switching options to Environmental Engineering Science, where I could do research involving economics. After consultations with Professors Noll, Norman Brooks (EES), Lester Lees (Environmental Quality Laboratory), Lance Davis (Economics), Burton Klein (Economics), and Wolfgang Knauss (Aeronautics), I made the change in departments. This decision I have never regretted, and I thank all those involved in making the change possible.

Once having transferred to Environmental Science, I began formulating the research project that has resulted in this thesis. Professors Noll, Lees, Michael Dohan (Economics), and John Seinfeld (Chemical Engineering) were my initial research advisors. Professors Noll and Dohan subsequently left Caltech, and John List (EES), Lance Davis (Economics), Charles Plott (Economics), and Shell Friedlander (EES), joined my advisory committee. All of my advisers have been ideal in the sense that they have been always willing to answer questions and offer insights but have allowed me the liberty to pursue the parts of my research project that interested me the most. In this respect, I am particularly grateful to John List, my principal adviser. I also thank him for being a friend and for offering the encouragement that is needed in completing a Ph. D. research project.

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ABSTRACT

An economic air pollution control model, which determines the least cost of reaching various air quality levels, is formulated. The model takes the form of a general, nonlinear, mathematical programming problem. Primary contaminant emission levels are the independent variables. The objective function is the cost of attaining various emission levels and is to be minimized subject to constraints that given air quality levels be attained.

The model is applied to a simplified statement of the photochemical smog problem in Los Angeles County in 1975 with emissions specified by a two-dimensional vector, total reactive hydrocarbon, (RHC), and nitrogen oxide, (NO_x), emissions. Air quality, also two-dimensional, is measured by the expected number of days per year that nitrogen dioxide, (NO_2), and mid-day ozone, (O_3), exceed standards in Central Los Angeles.

The minimum cost of reaching various emission levels is found by a linear programming model. The base or "uncontrolled" emission levels are those that will exist in 1975 with the present new car control program and with the degree of stationary source control existing in 1971. Controls, basically "add-on devices", are considered here for used cars, aircraft, and existing stationary sources. It is found that with these added controls, Los Angeles County emission levels [(1300 tons/day RHC, 1000 tons/day NO_x) in 1969] and [(670 tons/day RHC, 790 tons/day NO_x) at the base 1975 level], can be reduced to

260 tons/day RHC (minimum RHC program) and 460 tons/day NO_x (minimum NO_x program).

"Phenomenological" or statistical air quality models provide the relationship between air quality and emissions. These models estimate the relationship by using atmospheric monitoring data taken at one (yearly) emission level and by using certain simple physical assumptions, (e. g., that emissions are reduced proportionately at all points in space and time). For NO_2 , (concentrations assumed proportional to NO_x emissions), it is found that standard violations in Central Los Angeles, (55 in 1969), can be reduced to 25, 5, and 0 days per year by controlling emissions to 800, 550, and 300 tons/day, respectively. A probabilistic model reveals that RHC control is much more effective than NO_x control in reducing Central Los Angeles ozone. The 150 days per year ozone violations in 1969 can be reduced to 75, 30, 10, and 0 days per year by abating RHC emissions to 700, 450, 300, and 150 tons/day, respectively, (at the 1969 NO_x emission level).

The control cost-emission level and air quality-emission level relationships are combined in a graphical solution of the complete model to find the cost of various air quality levels. Best possible air quality levels with the controls considered here are 8 O_3 and 10 NO_2 violations per year (minimum ozone program) or 25 O_3 and 3 NO_2 violations per year (minimum NO_2 program) with an annualized cost of \$230,000,000 (above the estimated \$150,000,000 per year for the new car control program for Los Angeles County motor vehicles in 1975).

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CHAPTER 1

AN ECONOMIC MODEL FOR AIR POLLUTION CONTROL

§1.1 ORIGINS OF AIR POLLUTION

The earth's atmosphere is a two phase system, a mixture of gases and aerosols. Its composition, specified by gaseous concentrations and by particulate size and chemical distributions, varies with time and location. These changes in air constituency result from natural processes as well as from human activities. We are all very familiar with man-made perturbations in urban atmospheres. Natural variations are also common: the aerosol above the ocean contains more sodium than the aerosol above land, higher concentrations of organic gases occur in more densely vegetated areas, and humidity changes continually in time and space.

When certain atmospheric components reach high enough concentrations to cause measurable damage to plants, animals, materials, or humans, the atmosphere is termed "polluted" (Faith, 1959; Leithe, 1970). Air pollution may occur naturally; examples are volcanic eruptions, forest fires, sandstorms, and heavy fogs. At the present time, however, the sporadic episodes of natural air pollution are dwarfed by the persistent air quality problems resulting from human activities.

Man affects air quality in two ways, by altering meteorological and topographical conditions, and by emitting contaminants into the

atmosphere. Few significant examples exist of the first type of interference; one is the destruction of vegetation in certain areas leading to higher dust levels and changes in organic gas concentrations. The overwhelming part of anthropogenic air pollution results from contaminant emission into the atmosphere as by-products from technological processes, most notably, combustion.

The effect that emissions have on air quality of course depends on the intensity of the dispersive and self-cleansing processes of the local atmosphere; that is, on local meteorology. Automobile emissions in Los Angeles produce an order of magnitude more oxidant pollution on a tranquil, sunny, summer day than on a stormy winter day. With these considerations in mind, the basic conceptual model for almost all air pollution problems is as illustrated in Figure 1.1. The accumulation of emissions from human activities, governed by meteorology, leads to air pollution and to receptor damage.

§1.2 AIR POLLUTION CONTROL

The objective of air pollution control policy is to lessen the damage experienced by receptors. As illustrated in Figure 1.2, there are three general control methods: emission control, meteorological control and receptor control. Strictly speaking, air quality planning is only concerned with the first two types of measures. A general control strategy with the goal of reduced receptor damage would consider all three. Temporarily, all three types of control will be considered in this study. Below, it will be contended that one type of control,

Figure 1.1

BASIC CONCEPTUAL MODEL FOR
AIR POLLUTION PROBLEMS

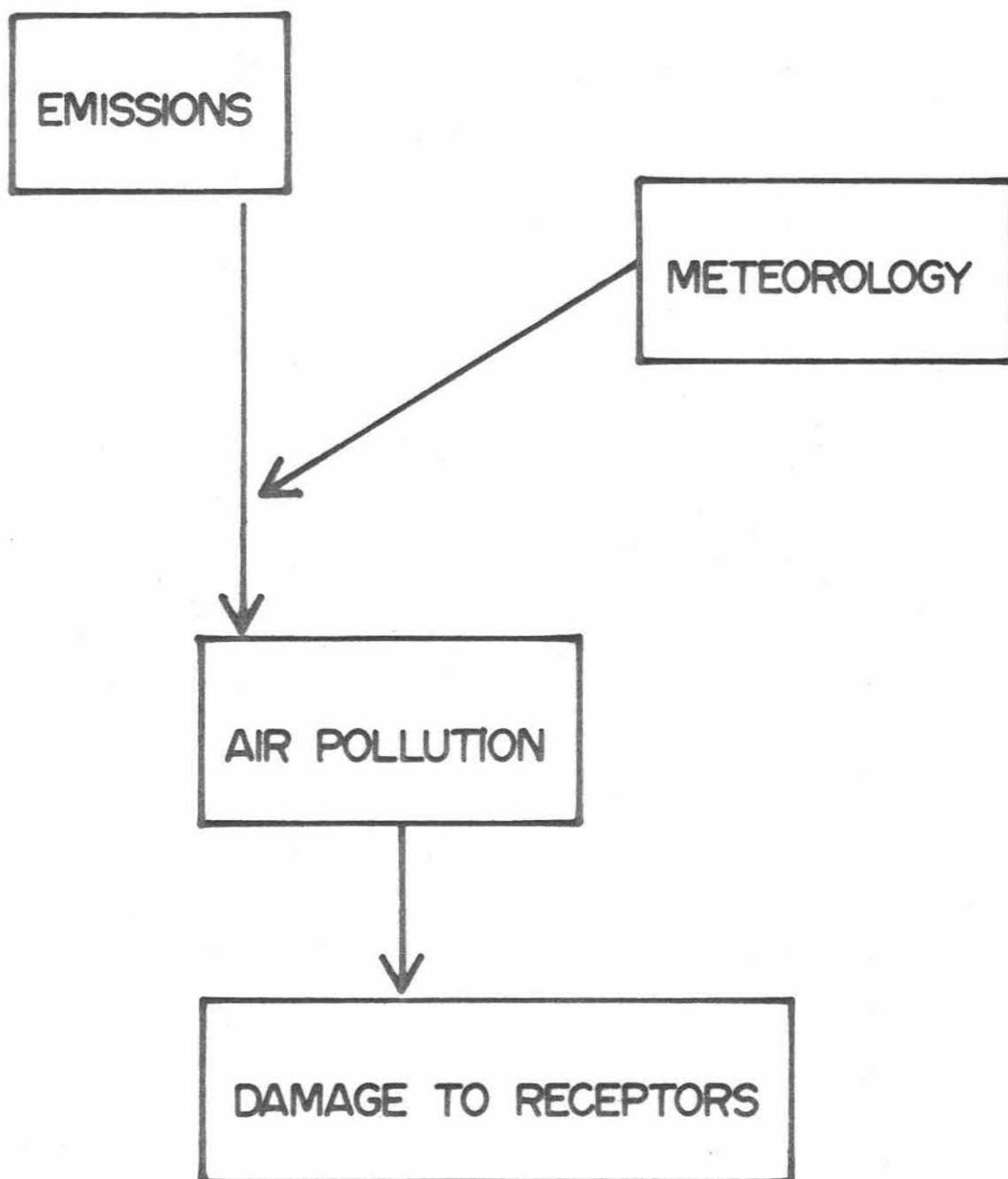
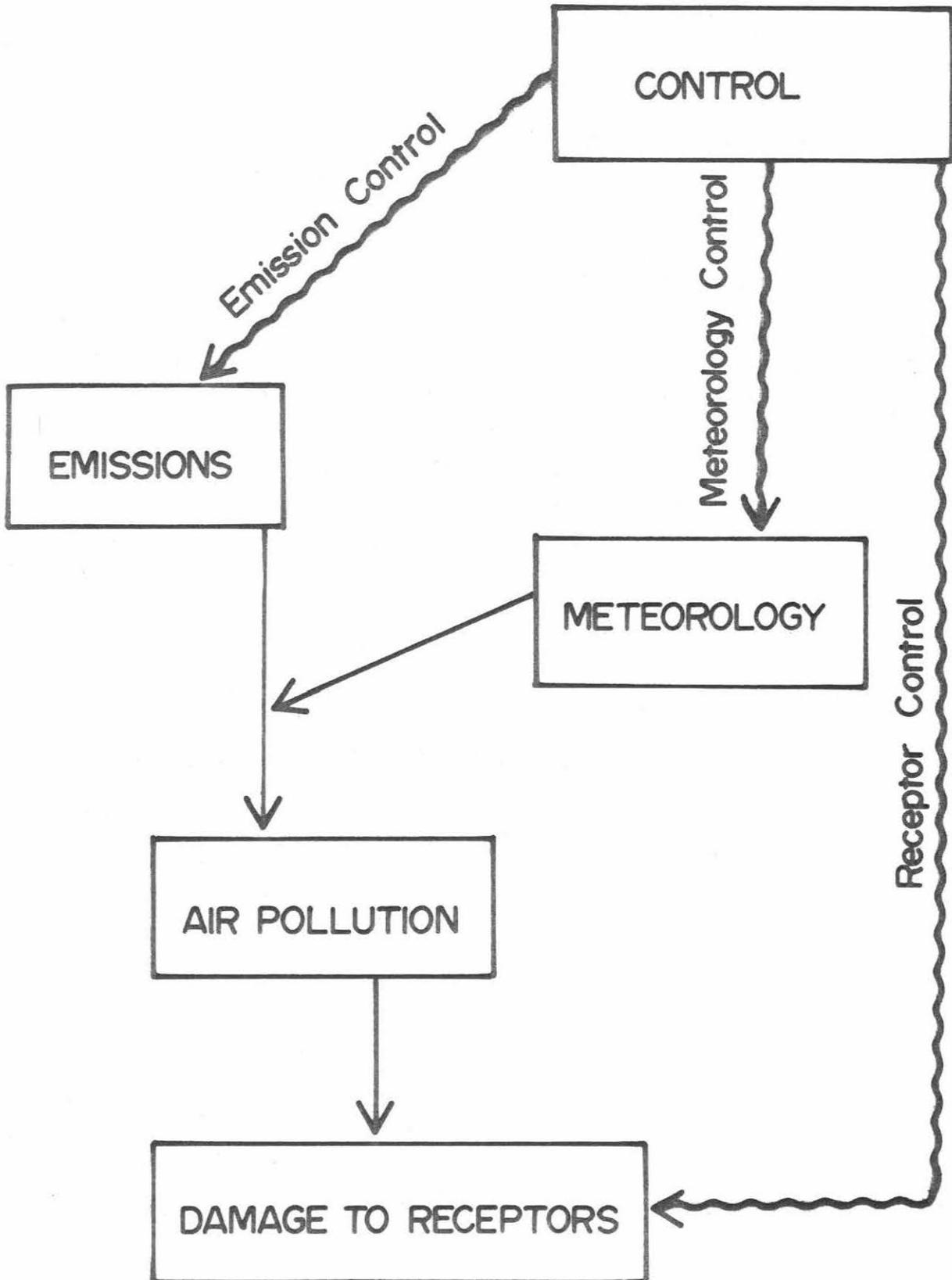


Figure 1.2
TYPES OF AIR POLLUTION CONTROL



emission regulation, dominates for air pollution problems.

Emission control refers to altered level, time, or position of emissions. Air quality can be improved by reducing total emissions, by regulating the time of emission, or by changing the place of emission. Absolute emission levels can be reduced by either process modification to decrease the amount of contaminant generated or by treatment of effluent gases. Emissions can be stored, or the processes producing them postponed, until the assimilative capacity of the atmosphere is increased by high winds, a break in a temperature inversion, or a storm. Air quality can be improved at ground level by emitting from tall stacks and in a basin by emitting in downwind areas.

Meteorological control refers to deliberate alteration of air flow or other weather conditions so as to improve the assimilative capacity of the atmosphere. Although impractical for air pollution control, cloud seeding to produce rain lies within man's technological capabilities. Schemes such as putting fans in manholes to suck street and freeway air into the sewers (or even more fantastic and impractical schemes of "putting tunnels with fans in the mountains") are examples of this type of control. The technology to move around the great quantities of air occupying a whole air basin does not exist. Thus, although meteorological control is a theoretical possibility, it appears to be of little practical use in most air pollution problems.

Receptor control limits the damage of air pollution by altering the properties of the receptor. Examples of such control would be developing air pollution resistant vegetation, having more frequent

lung check-ups, changing place of residence, staying in air-filtered buildings, or wearing gas masks. It is theoretically possible to let the ambient air be an open sewer and to control the pollution problem only with receptor control. However, aesthetic considerations appear to make such a solution unacceptable (Friedlander, 1970). In fact, since one of the greatest (if not the greatest) component of air pollution damage is aesthetic costs to human beings, receptor control is, in general, of limited usefulness.

It is interesting to note that these same three basic control alternatives occur in water quality planning. For instance, a water management plan for a river might include any of the following (Kneese and Bower, 1968):

- A. Controlling Effluent Discharge
 - 1. Decrease in total effluent
 - 2. Time regulation of discharge according to flow conditions
 - 3. Transportation of effluent to regions of high assimilative capacity (usually to the ocean outlet)
- B. Increasing river assimilative capacity (by flow regulation dams, re-aeration, mixing reservoirs, etc.)
- C. Cleaning the water before use (by municipalities and industries)

All three types of control are frequently useful in solutions to water planning problems. As noted above, however, the last two types appear impractical for air pollution problems. In this work, only the

first type, emission control, will be considered. The fundamental air pollution control problem to be examined is as illustrated in Figure 1.3. Air pollution, resulting from the interaction of emissions and meteorology, is controlled by emission regulation.

§1.3 A LEAST-COST AIR POLLUTION CONTROL MODEL

The purpose of this thesis is to formulate a mathematical model that determines the cost of achieving various air quality levels and to apply this model, in an approximate way, to an actual air quality problem, Los Angeles photochemical smog. A detailed description of the model will be given later. Here, only the conceptual structure will be outlined.

The elements of the model to be developed are shown in Figure 1.4. They exactly correspond to Figure 1.3, except that the cost of emission control has been added as a basic strategy parameter. This cost is minimized in the solution to the problem. That is, of the many alternative emission control programs which can be used to attain a given air quality (e.g., controlling different combinations of auto exhaust, refinery heaters, power plants, etc.) the model selects that program which achieves the air quality goal at least cost.

From Figure 1.4, it can be seen that the model naturally divides into two sub-problems. These are the determination of the control cost-emission relation and the emission-air quality relation. This division will also appear later when the problem is formulated in mathematical notation. Once these two relationships are found, the model is completed by their synthesis.

Figure 1.3
AIR POLLUTION CONTROL
EXAMINED HERE

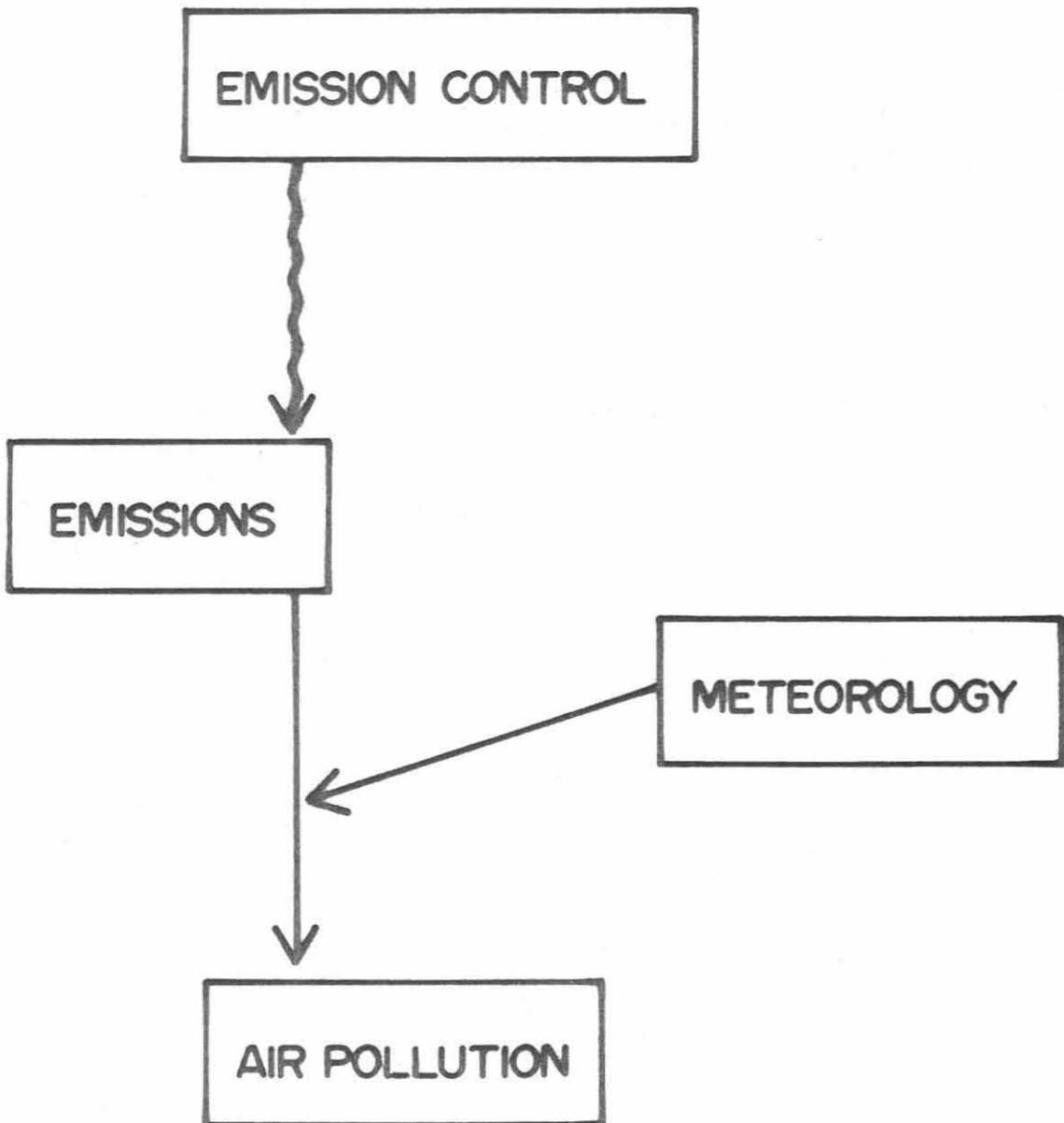
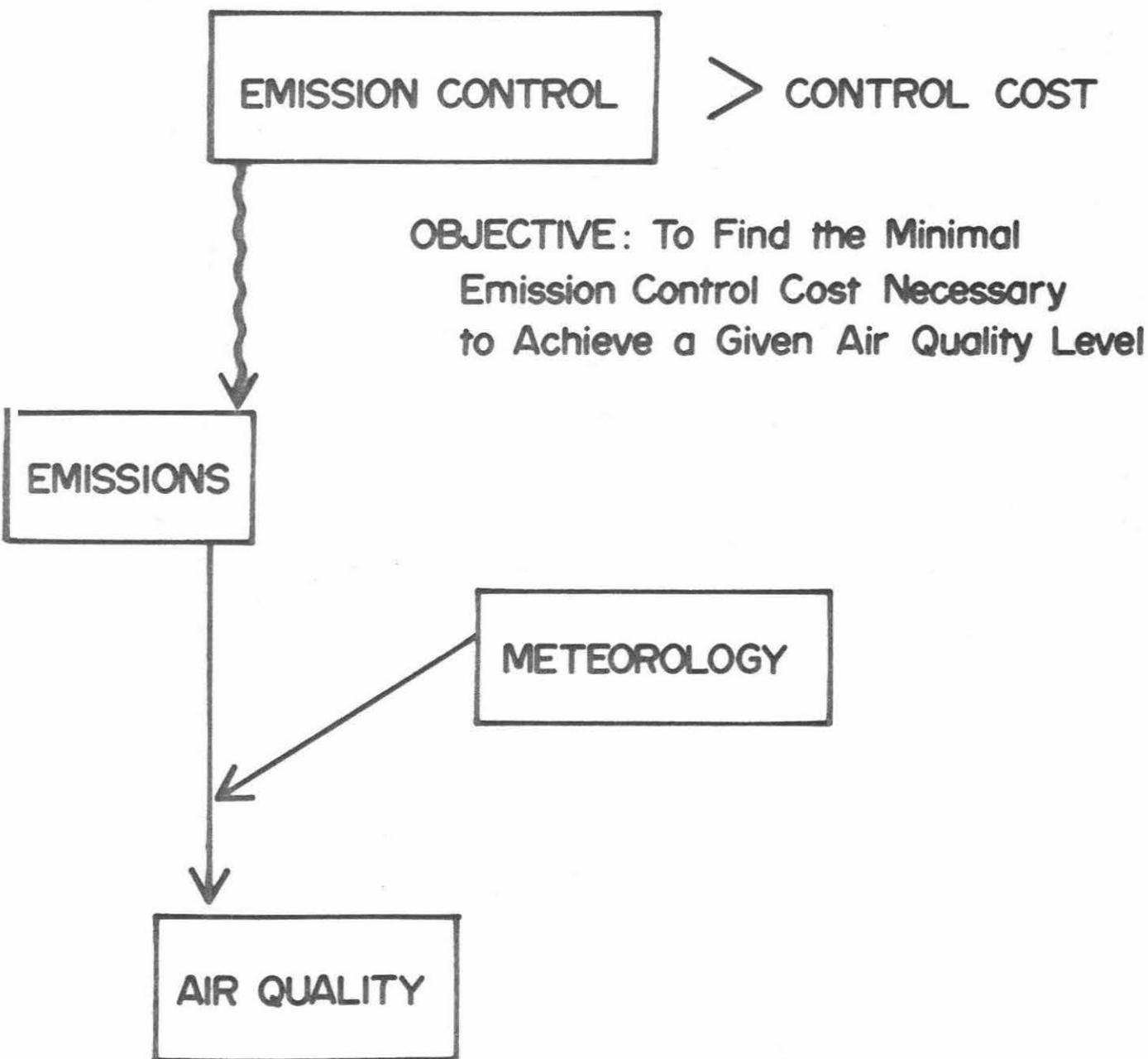


Figure 1.4

THE LEAST COST AIR QUALITY MODEL



Some type of time specification must be made for the model. One alternative is to examine a given fixed time period. Such a static model can be either a short term or long term model, e. g. , it could find the cost of achieving various air quality levels during either an expected two-day smog episode or some entire year in the future. A second alternative is to formulate a more complex, dynamic model that examines the costs of various "air quality paths" for "n" successive time periods. Seinfeld and Kyan (1971), have formulated such a dynamic model. Here, a long term, static model is constructed. This model calculates the cost of reaching various air quality levels for some given year.

§1.4 ECONOMICS AND AIR POLLUTION CONTROL

The fact that an air pollution problem exists does not, a priori, imply that an economic inefficiency exists in the sense that it is possible to reallocate resources so that some members of society are made better off while none are made worse off.* True, decreasing air pollution would increase human satisfaction if it were achieved without cost. But, controlling pollution uses resources that could otherwise be employed to further human satisfaction. It is theoretically possible that for a given air pollution problem, the loss in allocating resources for pollution control is greater than the benefits from control (the decrease in physical and psychological damage from pollution). In such

*The criterion that it be impossible to reallocate resources so as to make someone better off without making anyone worse off is the "Paretian" standard of economic efficiency.

a case, the persons injured by air pollution would still say that there was an "air pollution problem"; they might feel that their property rights (the right to clean air) were violated. But this would be a legal problem and not an economic problem. The judiciary system would have to decide whether the polluter has the right to benefit by emitting or whether the receptor has the right to clean air.

However, it is the consensus of most economists that in almost all cases air pollution involves economic inefficiency in addition to presenting a legal problem. Much of the pollution supposedly results from a "market failure", and there exists "gains from trade" to be realized in reducing the pollution. The receptors would gain more than the polluters would lose by controlling pollution, but the two parties (which often contain the same people) are unable to bargain or trade because of institutional reasons (non-excludability, "prisoner's dilemma", or other similar effects) (Plott, 1968). In such cases, a reduction in pollution, if carried out with appropriate compensations for income distribution changes, could realize these gains from trade and make everyone better off. The extraction of these gains is an economic problem; it is the work of economists to formulate proposals as to how this might be done.

Many economists have advocated "cost-benefit" solutions to air quality problems (Wolozin, 1968; Teller, 1967; Ridker, 1967). According to the cost-benefit approach, the air pollution control agency determines (1) the sets of controls that achieve given air quality levels at least cost, and (2) the damage costs at the same given levels and

then picks that air quality level (and corresponding control strategy) that minimizes the sum of pollution control and damage costs. Of course control costs should include all costs, indirect (induced unemployment, enforcement cost, etc.) as well as direct (capital, maintenance, etc.) costs, and damages should include intangibles (aesthetics, pain, etc.) as well as tangibles (crop losses, material damage, hospital bills, etc.). The elements of such a cost-benefit analysis are shown in Figure 1.5.

It has proved extremely difficult to carry out the cost-benefit analysis in large scale, real life, air pollution problems. Some progress has been made with methods to determine the control cost-air quality function. Kohn (1970), has developed a linear programming model that determines minimum cost strategies for achieving various emission levels (and air quality levels, if the pollutants are inert). However, the damage cost-air quality relationship remains totally obscured. It has proved difficult to estimate total damage cost at a given, existing air quality level (Ridker, 1967). To determine total damage as a function of any hypothetical air quality level is completely out of the question with existing knowledge.

The fact that cost-benefit analysis has had little actual application to air pollution problems is perhaps not that discouraging. Welfare economists have attacked the cost-benefit approach on theoretical grounds (Krutilla, 1961). A cost-benefit solution to an air quality problem does not really guarantee that everyone in society has gained. One can conclude that there has been an increase in economic

Figure 1.5

COST BENEFIT AIR POLLUTION CONTROL MODEL



CONTROL COST



OBJECTIVE: To Find that Control Program that Minimizes the Sum of Control and Damage Costs



DAMAGE COST

efficiency only if those who benefit in a control program actually compensate those who lose. In fact, if this compensation is not made, the distortion of the income distribution* by the cost-benefit solution may lead to what would be considered a decrease in "social well-being" in the value system of most policy makers.**

It is not within the scope of this work to become involved in the details of the cost-benefit controversy. Suffice it here to note that although the output of this work provides one of the two basic functions for a cost-benefit analysis (the control cost-air quality relationship), it is not meant exclusively for that purpose. This work is being done basically with the hope that it will provide useful information, in the form of technical relationships, to air quality policy makers. The model should be of use to air quality planners in at least two ways. First, as a method for determining the least cost emission control strategy that achieves a given air quality, the model would be useful in guiding an air quality control agency with fixed pollution standards to meet. Second, since the model, solved for all air quality levels, provides the control cost-air quality function, it should be useful in setting air pollution standards. Whether or not the policy maker using this

* It can be argued that pollution control tends to favor the affluent (who have all the necessities and to whom aesthetic considerations are more important) at the expense of the poor (who are more concerned with other needs).

** The following is an example: Assume that the elimination of smog is worth \$1000 each to 100,000 Beverly Hills drivers and \$50 each to 1,000,000 Watts drivers. Assume further that smog is eliminated by a \$100 per car control device. Cost-benefit analysis calls for installation of the device (benefits = \$150 million, costs = \$110 million). Such a solution, with no compensation of the poor by the rich, is very questionable on grounds of equity.

information follows a strict cost-benefit approach is of no great concern to this work.

§1.5 A GENERAL MATHEMATICAL REPRESENTATION OF THE LEAST-COST CONTROL MODEL

As discussed in section 1.3, the problem at hand is to determine the (minimum) cost of achieving various air quality levels for some year through emission control. In order to formulate the problem mathematically, the first step is to put the two basic sets of variables, "emissions" and "air quality" (or "air pollution") in mathematical notation.

In the most general case, emissions and pollution are each vector valued functions of space and time. Emissions for N primary* contaminants in an air basin are completely specified by N source functions,

$$e_i(\underline{\xi}, \tau); \quad i = 1, 2, \dots, N, \quad (1-1)$$

giving the rate of emission of the i^{th} contaminant per unit volume at all positions, $\underline{\xi}$, in the air basin and for each time, τ , within a year.**

Pollution can be completely specified by the levels of M final (primary and secondary) pollutants,

* A primary contaminant is one which is emitted directly. A secondary contaminant is one formed in the atmosphere by reactions stemming from primary contaminants.

** Because laws are passed on a yearly basis and because expected meteorology and certain human activity patterns are yearly periodic, a year is the basic time period for air pollution problems.

$$P_j(\underline{x}, t), \quad j = 1, 2, \dots, M, \quad (1-2)$$

giving the concentration of the j^{th} pollutant at position \underline{x} and time t . Final pollution, P_j , results from the interaction of emissions and meteorology according to physical and chemical laws. Because of the meteorological input, which is uncertain,* pollution is a stochastic variable when discussed as a function of hypothetical emission levels. The $P_j(\underline{x}, t)$, which in principle can be calculated from $E_i(\underline{x}, \tau)$ and from probability distributions describing the frequency of occurrence of various meteorological conditions, are given in the form of probability distributions. That is, pollution, as a function of hypothetical $E_i(\underline{x}, \tau)$, is actually specified by the probability at any \underline{x} and t of various pollution levels, $P_j(\underline{x}, t)$.

For a specification of "air quality", it is too cumbersome to use the complete mathematical description of the probability distributions of $P_j(\underline{x}, t)$. In practice, and in this work, a weighted integration over space, time, and the probability distribution is made for each $P_j(\underline{x}, t)$ distribution to obtain a single number, P_j , specifying "air quality" for the j^{th} pollutant. To clarify this concept examples are given in a footnote below.** Actually, it may be desirable to have more than

* Actually, since human activities are not completely deterministic, the emission levels, as well as the meteorology, are stochastic. However, for certain specified conditions (e. g., a weekday with certain industrial activity levels) emissions are fairly predictable. The uncertainty in emissions is much less than the uncertainty in the weather. It is assumed here that emissions can be described deterministically and that the meteorology is the source of the stochastic nature of the problem.

** 1. P_j may be the expected number of days per year that P_j at a given monitoring station exceeds some standard, P_j^s , for one hour. In this case, the weighting function of the integration is such that it

one number, P_j , specifying air quality for a single pollutant, P_j . For example, one may want to express air quality for a pollutant as both an expected yearly average and an expected yearly maximum. To include such cases, one need only expand M , the dimension of P_j . For example,

$$\begin{aligned} P_1(\underline{x}, t) &\rightarrow P_1, P_2, P_3 \\ P_2(\underline{x}, t) &\rightarrow P_4, P_5 \\ &\vdots \\ P_m(\underline{x}, t) &\rightarrow \dots, P_{m'} \geq m \end{aligned}$$

It is assumed here that this has been done and that air quality is specified by a M (m') dimensional vector \underline{P} . Each P_j is a function, F_j , of $\mathcal{E}_i(\underline{\xi}, \tau)$.*

$$P_j = F_j(\mathcal{E}_i(\underline{\xi}, \tau)) = F_j(\mathcal{E}_1(\underline{\xi}, \tau), \dots, \mathcal{E}_N(\underline{\xi}, \tau)) \quad (1-3)$$

The exact form of this function is of course determined by the meteorology.

(a) examines one point in space, (b) counts the number of days with violations for at least one hour, and (c) takes the expected value over the probability distribution.

2. P_j may be the probability that the yearly average for P_j at some station exceeds a given standard. In this case the weighting function (a) examines one point in space, (b) averages over the year, and (c) integrates the distributions to find the probability that the standard is exceeded.

3. P_j may be the expected average over ten monitoring stations of the yearly average P_j . In this case, the weighting function (a) averages over ten fixed points in space, (b) averages over the year, and (c) takes the expected value of the probability distribution.

* Actually, the function $P_j = F_j(\mathcal{E}_i(\underline{\xi}, \tau))$, which for each j maps a function, $\mathcal{E}_i(\underline{\xi}, \tau)$, into a scalar, is called a "functional".

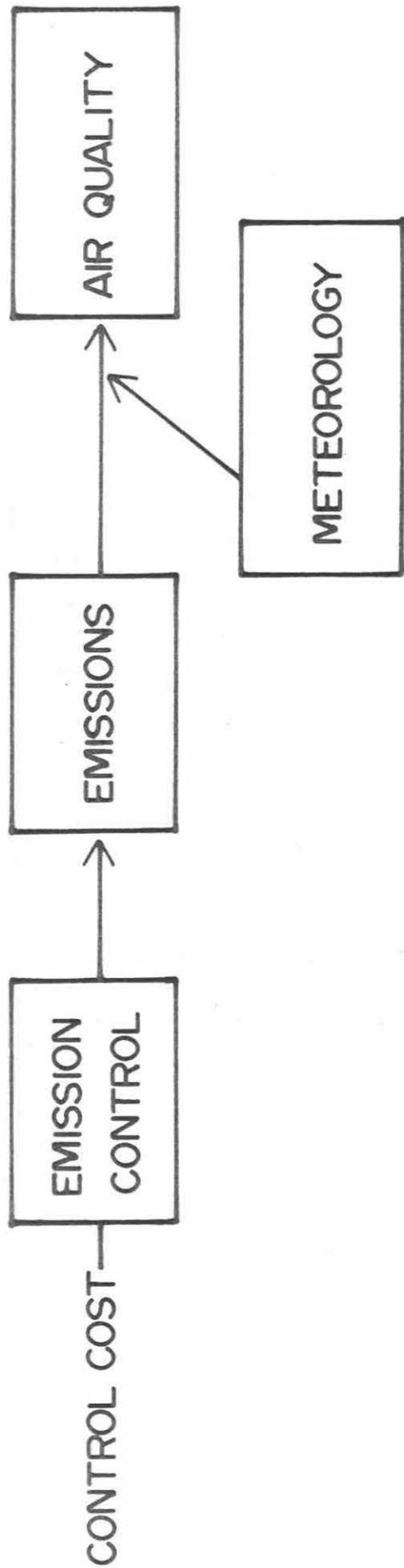
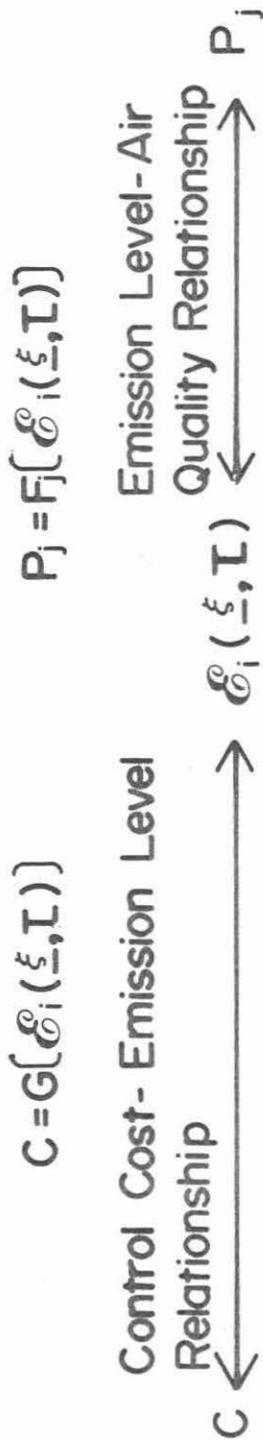
In this new notation, the model is to present a method of calculating the least cost of attaining any given air quality level, specified by \underline{P} . It is convenient to allow as solutions of reaching a given \underline{P} those cases in which some air quality specifications are more than met. That is, the problem will be stated not as finding the least cost of exactly attaining \underline{P} , but as finding the least cost of getting \underline{P} or better. The air quality levels are thus expressed as inequality constraints.

The problem, with some of the mathematical notation so far introduced, is illustrated in Figure 1.6. It can be seen from Figure 1.6 that the problem readily divides into two sub-parts. The first of these is the determination of the control cost-emission level relation. This is a techno-economic relationship that gives the minimum cost of achieving any emission level, specified by $\mathcal{E}_i(\underline{\xi}, \tau)$, $i = 1, 2, \dots, N$. It is found by taking each emission level, $\mathcal{E}_i(\underline{\xi}, \tau)$, technically determining that subset of controls that exactly achieves that emission level, and choosing the specific control plan with minimum cost, C . In such a way a mapping, called a functional, is generated from $\mathcal{E}_i(\underline{\xi}, \tau)$ space into a scalar, cost. It will be denoted below by G ,

$$C = G(\mathcal{E}_i(\underline{\xi}, \tau)) \quad (1-4)$$

With a fixed available technology, many regions in "emission space", $\mathcal{E}_i(\underline{\xi}, \tau)$, will be unattainable. For instance, it might be impossible to stop all emissions in an air basin. Also, it might be impossible (and certainly not desirable!) to generate huge quantities of emissions. Such unattainable regions are characterized by an unbounded or infinite control cost.

Figure 1.6
FORMULATION OF THE LEAST COST
AIR QUALITY MODEL IN
MATHEMATICAL NOTATION



The second problem is to determine the emission level-air quality relationship. This is done, in principle, by (1) finding the frequency distribution of all meteorological conditions, (2) using the $\mathcal{E}_i(\underline{\xi}, \tau)$, meteorology, and topography as inputs into appropriate physical and chemical equations to solve for the frequency distributions of $\rho_j(\underline{x}, t)$ and (3) integrating the ρ_j distributions to obtain the P_j that have been selected as the indicators of air quality. The result is a mapping from $\mathcal{E}_i(\underline{\xi}, \tau)$ space into vectors, \underline{P} . For each j , this is a functional which will be denoted by F_j ,

$$P_j = F_j(\mathcal{E}_i(\underline{\xi}, \tau)) . \quad (1-3)$$

The inverse of this mapping gives the emission levels that exactly achieve a given P_j . This inverse, denoted by F_j^{-1} , of course need not be 1-1, i. e., it need not be a function. Regions in $\mathcal{E}_i(\underline{\xi}, \tau)$ space can correspond to a single P_j .

Knowing the mapping $\mathcal{E}_i(\underline{\xi}, \tau) \rightarrow C$ (min. cost), G , and the mapping $P_j \rightarrow \mathcal{E}_i(\underline{\xi}, \tau)$, F_j^{-1} , the problem of determining the minimum cost emission control program that (at least) achieves a given air quality level is solved by the following algorithm:

For any P_j , $j = 1, 2, \dots, M$, by F_j^{-1} find that subset of $\mathcal{E}_i(\underline{\xi}, \tau)$ that achieves all of the levels $F_j(\mathcal{E}_i(\underline{\xi}, \tau)) \leq P_j$. Then, using G , pick that element of the subset of \mathcal{E}_i which has the lowest $C = G(\mathcal{E}_i(\underline{\xi}, \tau))$. The result is the minimum cost of attaining the air quality level specified by P_j .

Stated symbolically, the problem is (once G and F are found) to

$$\text{minimize} \quad C = G(\mathcal{E}_i(\underline{x}, \tau)) \quad \text{over} \quad \{\mathcal{E}_i(\underline{x}, \tau)\}, \quad (1-5a)$$

$$\text{subject to} \quad F_j(\mathcal{E}_i(\underline{x}, \tau)) \leq P_j, \quad j = 1, 2, \dots, M. \quad (1-5b)$$

§1.6 THE NECESSITY OF SIMPLIFICATIONS IN THE MODEL

The problem stated at the end of the last section is of course impossible to solve in complete generality for an air basin. In fact, each subpart of the problem presents overwhelming difficulties in practice. To consider all possible distributions of emissions, $\mathcal{E}_i(\underline{x}, \tau)$, for all contaminants and find all possible means of attaining these distributions is an insurmountable informational problem. To find the cost of all alternative means of attaining a given emission pattern and then select the alternative with least cost adds further difficulty. In finding the emission-air quality relation, one of the necessary tasks is to measure all relevant meteorological variables at all points in an air basin for long enough time to establish their frequency distribution. Then, complicated non-linear chemical and physical equations must be used to determine the probability distributions of the pollutants $P_j(\underline{x}, t)$ for all emission patterns, $\mathcal{E}_i(\underline{x}, \tau)$. The first task is formidable from a measurement standpoint, the second from a computational standpoint.

In the next section the problem will be considerably simplified by neglecting the space and time dependence of emissions. In later chapters, well-defined bounds will be put on the number of control alternatives, emitted contaminants, final pollutants, and air quality indicators considered. Also, approximate methods of determining

the air quality-emission level relationship will be used which bypass the necessity of measuring meteorology directly and using physico-chemical equations. The basic mathematical structure of the model used here will be still as given in (1-5), but the information required for a solution will be considerably reduced.

§1.7 ELIMINATION OF EMISSION SPACE AND TIME DEPENDENCE

Emissions, $\mathcal{E}_i(\underline{x}, \tau)$, and pollution, $P_j(\underline{x}, t)$, are multi-dimensional in two ways. They are vector valued, and they are functions of space and time. To simplify air quality specification, pollution was integrated over space and time to give a vector, P_j , as an air quality index. In this section, the space and time dependence of emissions is eliminated in both the control cost-emission relation and the emission-air quality relation. Emissions for the whole basin will here be simply described by a vector, $\underline{E} = (E_1, \dots, E_N)$, giving the yearly, basinwide emission level for each of N contaminants.*

In the emission-control cost relationship, no distinction will be made as to place or time of emissions. $C = G(E_1, \dots, E_n)$ will simply specify the least cost method of achieving any annual, basin-wide emission level for the N contaminants.

In the methods used here to determine the emission-air quality relationship (see Chapter 4) it is necessary to assume that emission changes occur homogeneously in space and time from some base emission level, $\mathcal{E}_i^0(\underline{x}, \tau)$. That is, it is assumed that all emission levels

* This simple approach could be refined by subdividing the basin and/or year into parts with an emission vector for each.

are such that they can be expressed as

$$\mathcal{E}_i(\underline{\xi}, \tau) = \alpha_i \mathcal{E}_i^0(\underline{\xi}, \tau) \quad (1-6)$$

for some α_i assumed constant in both space and time. The fact that the emission pattern is preserved in all changes fixes the space and time dependence, and emissions can then be specified by the vector \underline{E} , giving the total yearly emission level.

A difficulty arises here since the control cost model neglects emission patterns and the air quality model insists that emissions retain a given fixed pattern. If the control cost model calls for a program in which all sources are reduced proportionately in space and time, then the control cost relationship and air quality relationship can be used together with impunity. However, in almost all cases, the least cost method of achieving a given total emission reduction will call for some sources to be reduced more than others. Since different sources have different emission distributions, such control programs do not meet the homogeneity assumption and the air quality-emission relation can be used, at best, approximately. The accuracy of the approximation will depend on how much some sources are controlled more than others and on how different their respective emission patterns are. This problem will be discussed again in Chapters 4 and 5. Suffice it here to note that non-homogeneous changes in emission levels is one source of error in the complete model.

With the new space and time independent emission specification, \underline{E} , the mathematical statement of the problem, (1-5), becomes:

$$\text{minimize} \quad C = G(E_1, \dots, E_n), \quad (1-7a)$$

$$\text{subject to} \quad F_j(E_1, \dots, E_N) \leq P_j, \quad j = 1, 2, \dots, M, \quad (1-7b)$$

$$\text{and with} \quad E_i \geq 0, \quad i = 1, 2, \dots, N. \quad (1-7c)$$

(1-7c) is a physically obvious condition that is included in (1-7) because it puts the problem in the form of a general nonlinear mathematical programming problem.

The solution to the complete model proceeds in three steps: (i) find G , (ii) find F_j , and (iii) solve (1-7). The next three sections discuss the method that will be used in this work to accomplish each of these steps.

§1.8 THE CONTROL-COST/EMISSION-LEVEL RELATIONSHIP

Robert Kohn (1970), published a mathematical linear programming model for determining the minimum cost of achieving a given emission level (for several pollutants) in an air basin. This model, in a modified form, will be used here to determine the function, $C = G(E_1, \dots, E_N)$, the minimum cost of attaining (E_1, \dots, E_N) . The modification relates to the fact that Kohn's model expresses the emission level constraints as inequalities. That is, Kohn's model finds the set of controls that minimizes the cost of at least achieving (E_1, \dots, E_N) . In the present work, the function $C = G(E_1, \dots, E_N)$, is the cost of exactly achieving (E_1, \dots, E_N) .* Thus, some of the inequality

* It is not necessarily true that reducing emissions of a primary contaminant will reduce pollution levels (e.g., under certain conditions, control of ozone, a secondary pollutant, may call for increasing nitrogen oxide or hydrocarbon emissions). Thus, oversatisfying the (E_1, \dots, E_N) emission level constraint will not always improve air quality.

constraints in Kohn's model become equalities. The result is a slightly special type of linear programming model.

The linear programming model in this study uses the following definitions:

- S_i , $i = 1, \dots, s$ The i^{th} component of a vector specifying the magnitude of all emission sources (e.g., the number of large power plant boilers, or the number of refinery heaters).
- L_m , $m = 1, \dots, \ell^*$ The i^{th} component of a vector specifying the supply limits of fixed supply inputs into control activities, (e.g., the total available natural gas. Natural gas is a clean burning fuel that can be used to reduce emissions from automobiles as well as power plant boilers).
- x_j , $j = 1, \dots, r$ The j^{th} component of a vector specifying the levels of control activities, X_j (e.g., the number of a certain control device added to 1970 vehicles).
- c_j , $j = 1, \dots, r$ The j^{th} component of a vector specifying the costs of one unit of each control activity (e.g., the cost of adding a certain control device to one 1970 vehicle).

* Kohn in his thesis includes the L vector in the S vector since the two enter the problem in the same mathematical form (specifying upper limits to control activity levels). However, confusion results because he consistently calls the S vector "source magnitudes", a misnomer if L is included. To avoid this confusion, they will be kept separate here.

- E_k^0 , $k = 1, \dots, N$ The k^{th} component of a vector specifying the yearly emission levels of the N contaminants under consideration with "no control" ($x_j = 0$) (e.g., with no controls installed, the average NO_x emission level, say in tons/day).
- E_k , $k = 1, \dots, N$ The k^{th} component of a vector specifying the yearly emission levels of the N contaminants to be obtained by the control activities X_j .
- A_{ij} , $i = 1, \dots, s$
 $j = 1, \dots, r$ The number of units of source i controlled by one unit of activity j (e.g., one 1970 vehicle is controlled by adding one unit of a certain control device to 1970 vehicles).
- D_{mj} , $m = 1, \dots, \ell$
 $j = 1, \dots, r$ The amount of the m^{th} limited supply input used by one unit of the j^{th} control activity (e.g., the amount of natural gas used by a unit of a given control activity).
- B_{kj} , $k = 1, \dots, M$
 $j = 1, \dots, r$ The emission reduction of the k^{th} contaminant resulting from one unit of the j^{th} control activity (e.g., the reduction in NO_x emissions resulting from addition of one control device to a 1970 vehicle).

The mathematical statement of the cost minimization problem, once the constants S_i , L_m , c_j , E_k^0 , E_k , A_{ij} , D_{mj} , and B_{kj} are given is:

Find x_j that minimizes

$$C_T = \sum_{j=1}^r c_j x_j \quad (a)$$

subject to the constraints:

$$\sum_{j=1}^r B_{kj} x_j = E_k^0 - E_k, \quad k = 1, \dots, N, \quad (b)$$

(emissions are reduced to E_k)

$$\sum_{j=1}^r A_{ij} x_j \leq S_i, \quad i = 1, \dots, s, \quad (c) \text{ (1-8)}$$

(no more of source i than S_i
can be controlled)

$$\sum_{j=1}^r D_{mj} x_j \leq L_m, \quad m = 1, \dots, \ell, \quad (d)$$

(supply limits of fixed inputs,
 L_m , are not exceeded)

$$x_j \geq 0, \quad j = 1, \dots, r \quad (e)$$

(non-negativity of
control activities)

If we let C denote the minimum of C_T , then the solution to this problem (for fixed S_i , L_m , c_j , A_{ij} , D_{mj} , and B_{kj}) for various values of E_i gives the minimum emission control cost function, $C = G(E_i)$.

There are many assumptions implicit in the linear emission control model, (1-8). Kohn, in his thesis, discussed these and gives examples. Here a list of remarks and assumptions will be made with

explicit reference to their mathematical form in the model. For examples and further comments, pages in Kohn's thesis are referenced.

Remarks and Assumptions:

1. The mathematical model computes the minimum emission control cost only for the given set of control alternatives, x_j . This set does not necessarily include all the possible control alternatives open to society. In an actual problem, some control alternatives may be considered politically unacceptable; insufficient information may be available for others. These will not be included in x_j . Thus, $C = G(E_i)$ is not necessarily the minimum emission control cost for society but is rather the minimum cost given the fixed set, x_j , of control alternatives (Kohn, 1971, pp. 5-6).
2. It is assumed that all control activities are infinitely divisible since x_j , in the mathematical solution, can take on any positive values satisfying the constraints (Kohn, 1971, p. 6).
3. It is assumed that the control activities are homogeneous in their effect on emissions (B_{kj} constant), in their consumption of limited inputs ($D_{mj} = \text{constant}$), in the number of source units controlled ($A_{ij} = \text{constant}$), and in cost ($c_j = \text{constant}$). (Actually by subdividing a control activity, a control method that has a rising unit cost or some other nonlinearity can be included if it can be approximated by a piecewise linear function (Kohn, 1971, pp. 4, 12, 13).)
4. Since sources, limited inputs, and emissions are added in equations (1-8a, b, c, d), it is assumed that they are all homogeneous (Kohn, 1971, pp. 4, 7).

5. Constant coefficients rules out all interactions and secondary effects. Constant A_{ij} , B_{kj} , D_{mj} , and C_j rule out interactions between different control activities. Since S_i and L_m are constant, it is assumed that the establishment of controls does not affect the source numbers nor the supply of limited factors (Kohn, 1971, pp. 4, 14).

Because of the equality constraints, (1-8b), (1-8) is not in the usual form for a linear programming problem. However, the usual computational techniques of linear programming can be applied to this problem with very slight modification. Thus, the determination of the control-cost/emission-level relationship has been reduced to solving an elementary linear programming problem. Solution methods for such problems are well developed.

For the specific example examined in this work, photochemical smog in Los Angeles, emissions are specified by a two-dimensional vector, reactive hydrocarbons (RHC) and nitrogen oxides (NO_x). In Chapter 3, the linear programming model (solved with the IBM 360D-15, 2,006 routine) is used to find the cost of reaching various RHC and NO_x emission levels in Los Angeles County by 1975. The inputs to the model and the results are presented in that chapter.

§1.9 THE EMISSION LEVEL-AIR QUALITY RELATIONSHIP

Determination of the relationship between air quality and emissions, $P_j = F_j(E_i)$, is a problem in atmospheric physics and chemistry. As noted earlier, to determine this relationship exactly from basic physical laws is impossible because of the enormous information and

computation problems involved. Approximate solutions are therefore necessary.

Two basic approaches toward obtaining an approximate solution exist. The first is to use an atmospheric simulation model. In principle, such a model can be physical or mathematical. However, physical models, because of the extreme change in scale involved, appear impractical for quantitative prediction of air quality-emission level relationships.* Thus, only mathematical simulation, which solves the appropriate physical and chemical equations with simplified boundary conditions and simplified specification of meteorology and emissions, will be discussed. The second approach, here called the phenomenological approach, assumes certain simple physical conditions are met and determines the relationship from atmospheric monitoring data.

Which of the two approaches is chosen in a given situation depends on several factors: How soon does one want an answer? How accurate should the answer be? Will the simple physical assumptions of the phenomenological approach, e. g., homogeneous emission reductions, be met? What type of air quality index is used? Should meteorological fluctuations be emphasized? Generally, the phenomenological approach is useful for quick, approximate answers and for situations where the necessary simplifying physical assumptions are likely to be met. Since it works with atmospheric monitoring data containing meteorological

*The smog chamber, a type of atmospheric simulator, can provide quantitative information on the chemical processes. But a complete model requires simulation of air flow conditions as well as the chemistry, and therein lies the difficulty with physical models.

fluctuations, the phenomenological approach is most useful for air quality indices that emphasize these fluctuations, e. g., air quality measured by the number of days per year that a standard is exceeded.

Simulation models are more appropriate for long-term, detailed studies. If the simple physical assumptions of the phenomenological approach will be seriously violated, simulation models must be used. (The simulation approach can handle any type of emission level change, homogeneous or not.) Since simulation models tend to be difficult to complete again and again for various meteorological conditions, they are more appropriate for air quality indices with fixed meteorological specifications, e. g., air quality measured by the pollution level on a given type of day.

The complete least-cost control model, as summarized by the equations in (1-5) or (1-7), just requires the input of some air quality-emission level relation, $P_j = F_j(E_i)$, and its form is independent of which approach is used to obtain that relationship. For the specific example to be studied in this thesis, photochemical smog in Los Angeles, the air quality-emission level relation was determined by the phenomenological approach. There were four reasons for choosing this approach:

1. An air quality-emission level relationship was needed in short time to fit into the whole least-cost model. Simulation models were not far enough advanced to provide such a relationship. The phenomenological approach could provide results rather quickly.

2. Since the whole least-cost model was to be applied very approximately, an approximate air quality-emission level relation, such as that yielded by a phenomenological model, appeared satisfactory.
3. As will be discussed in detail in Chapter 4, the assumption of homogeneous emission reductions would appear to hold fairly well for the emission controls considered here. This assumption was the basic simplifying physical condition for the phenomenological models.
4. The air quality index chosen here was the number of days per year various pollutant standards were exceeded. This index emphasizes meteorological fluctuations and was thus well suited for the phenomenological approach.

Two phenomenological models were formulated for determining air quality-emission level relations. Each depended on certain simple physical assumptions and each arrived at the air quality-emission level relation by using air monitoring data taken at a given, fixed emission level. They are presented in detail in Chapter 4. Here, these models will just be summarized.

Model I

The first model, applicable to inert pollutants, determines the expected number of days per year that an "n-hour standard"* for the pollutant, P, is exceeded as a function of emission level from air

* An "n-hour standard" is one specifying that the pollutant not exceed some level, P_s , for more than n hours.

monitoring data taken at a given yearly emission level, E^0 . There are two physical assumptions underlying the model: (1) that the pollutant is an inert, primary contaminant, and (2) that emission level changes are homogeneous (that they occur proportionate in space and time to the emission pattern existing at E^0).

The calculations proceed as follows:

At some base yearly emission level, E^0 , one determines from atmospheric monitoring data the distribution function, $N^0(P)$, where

$$N^0(P)dP = \text{the expected number of days per year that the maximum n-hour pollutant concentration is in the range } P \rightarrow P + dP \text{ at emission level } E^0. \quad (1-9)$$

Then, by (1), (2), and the linearity of the equation of advective diffusion describing the dispersion of an inert pollutant, pollution levels on any day are strictly proportional to the yearly emission level, $E = \alpha E^0$. Thus, at any emission level, E , the corresponding distribution function, $N(P)$, is

$$\begin{aligned} N(P)dP &= N^0(P/\alpha)d(P/\alpha) \\ &= \text{the expected number of days per year that the maximum n-hour pollutant concentration is in the range } P \rightarrow P + dP \text{ at emission level } E = \alpha E^0. \end{aligned} \quad (1-10)$$

But, knowing $N(P)$, the air quality at any emission level is simply calculated by

the expected number of days
per year that the n-hour
standard, P_s , is exceeded
at any emission level,
 $E = \alpha E_o$

$$\begin{aligned} &\equiv \int_{P_s}^{\infty} N(P) dP \quad , \\ &= \int_{P_s}^{\infty} N^o(P/\alpha) d(P/\alpha) \quad , \quad (1-11) \\ &= \int_{P_s/\alpha}^{\infty} N^o(\xi) d\xi \quad , \end{aligned}$$

$$= \text{function of } \begin{cases} P_s, \dots & \text{the standard} \\ \alpha, \dots & \text{the emission level} \\ N^o, \dots & \text{the distribution function measured} \\ & \text{at one emission level.} \end{cases}$$

In Chapter 4 and Appendix B this model is applied to the one and twelve-hour state carbon monoxide standards and to the one-hour state nitrogen dioxide standard.* Since the least-cost model is only concerned with photochemical smog, only the NO_2 air quality results are later used.

Model II:

The second model is applicable to mid-day air quality levels of a secondary, photochemical pollutant, Z, produced by reactions stemming from two primary contaminants, X and Y. The expected number of days per year that a given standard for the pollutant, Z, is exceeded as a function of emission levels of the two primary contaminants is

* NO_2 is not an inert pollutant. The assumption is made that NO_2 levels are strictly proportional to NO_x emissions.

determined from air monitoring data taken at a given yearly emission level, (E_1^0, E_2^0) . There are four physical assumptions underlying the model:

(1) Emission reductions of X and Y occur homogeneously.

(2) In the air mass that will lead to the pollution of any day, emissions of X and Y accumulate without reacting to produce final (morning) concentrations x and y , respectively.

(3) Accumulation stops and then certain weather variables act on the primary contaminant concentrations, x and y , to produce a (mid-day) level z of the secondary contaminant, Z.

(4) The weather factors that determine the level of Z produced from given x and y are statistically independent of the distribution of x and y .

The calculations proceed as follows:

At some base yearly emission level of the primary contaminants, (E_1^0, E_2^0) , one determines from atmospheric monitoring data the following two distribution functions:

$$N^0(x, y) dx dy = \text{the expected number of days per year that the morning concentrations of the primary contaminants are in the ranges } x \rightarrow x + dx \text{ and } y \rightarrow y + dy, \text{ respectively at emission level } (E_1^0, E_2^0), \quad (1-12)$$

$$P_s^0(x, y) = \text{the probability that } z \text{ exceeds some standard, } z_s, \text{ on a day with morning concentrations } x \text{ and } y \text{ of the primary contaminants at emission level } (E_1^0, E_2^0). \quad (1-13)$$

Then, as discussed in Chapter 4, (1), (2), (3), and (4) imply that at any emission level, $(E_1, E_2) = (\alpha E_1^0, \beta E_2^0)$, the corresponding

distribution functions are

$$N(x, y)dx dy = N^0(x/\alpha, y/\beta)d(x/\alpha)d(y/\beta) , \quad (1-14)$$

$$P_s(x, y) = P_s^0(x, y) . \quad (1-15)$$

But, knowing $N(x, y)$ and $P_s(x, y)$, the air quality at any emission level is simply calculated by

$$\begin{aligned} \text{the expected number of days per} \\ \text{year that } z \text{ exceeds the stan-} \\ \text{dard, } z_s, \text{ at emission level} \\ (E_1, E_2) = (\alpha E_1^0, \beta E_2^0) \end{aligned} &= \int_0^\infty \int_0^\infty N(x, y)P_s(x, y)dx dy , \\ &= \int_0^\infty \int_0^\infty N^0(x/\alpha, y/\beta) \\ &\quad P_s^0(x, y)d(x/\alpha)d(y/\beta) , \\ &= \int_0^\infty \int_0^\infty N^0(\xi, \eta)P_s^0(\alpha\xi, \beta\eta)d\xi d\eta , \end{aligned}$$

$$= \text{function of } \begin{cases} \alpha, \beta \dots \text{ emission levels} \\ N^0, P_s^0 \dots \text{ distribution functions measured} \\ \text{at a base emission level for a} \\ \text{given standard, } z_s. \end{cases}$$

In Chapter 4 and Appendix C, this model is applied to the problems of eye irritation in downtown Los Angeles and of mid-day ozone in central Los Angeles (Downtown, Pasadena, Burbank area). The relevance of the model in regard to assumptions (1)-(4) is discussed in detail in that chapter. Since the ozone and eye irritation results turn out to be qualitatively similar and since eye irritation is such a subjective measure of pollution, only the ozone results are used in the complete least-cost air quality model for Los Angeles photochemical smog.

§1.10 SOLUTION OF THE COMPLETE MODEL

Once the control cost-emission level relationship, $C = G(E_i)$, and air quality-emission level relationship, $P_j = F_j(E_i)$, have been determined by the methods outlined in sections 1.8 and 1.9, the cost of achieving various air quality levels is found by solving the nonlinear mathematical programming problem, (1-7). This problem is

$$\text{to minimize} \quad C = G(E_1, \dots, E_N) , \quad (1-7a)$$

$$\text{over} \quad \{E_i\} ,$$

$$\text{subject to} \quad F_j(E_1, \dots, E_N) \leq P_j , \quad j = 1, \dots, M , \quad (1-7b)$$

$$\text{and} \quad E_i \geq 0 , \quad i = 1, \dots, N . \quad (1-7c)$$

The development of techniques for solving nonlinear programming problems has been a rapidly advancing field of applied mathematics during the past ten years (Abadie, 1970). Many different numerical solution methods have been developed. For a specific problem, the choice of solution method depends on N , M , and the form of the functions G and F_j . If G is determined by the linear programming model of (1-8), it is necessarily a convex function, and this should aid in the solution of (1-7) (Baumol, 1965). However, it is not the purpose of this work to become involved in an extended discussion of nonlinear programming; suffice it to note that techniques for the solution of (1-7) have been developed (Abadie, 1970).

For the photochemical smog example studied here, (1-7) is considerably simplified since the emission vector is only two dimensional,

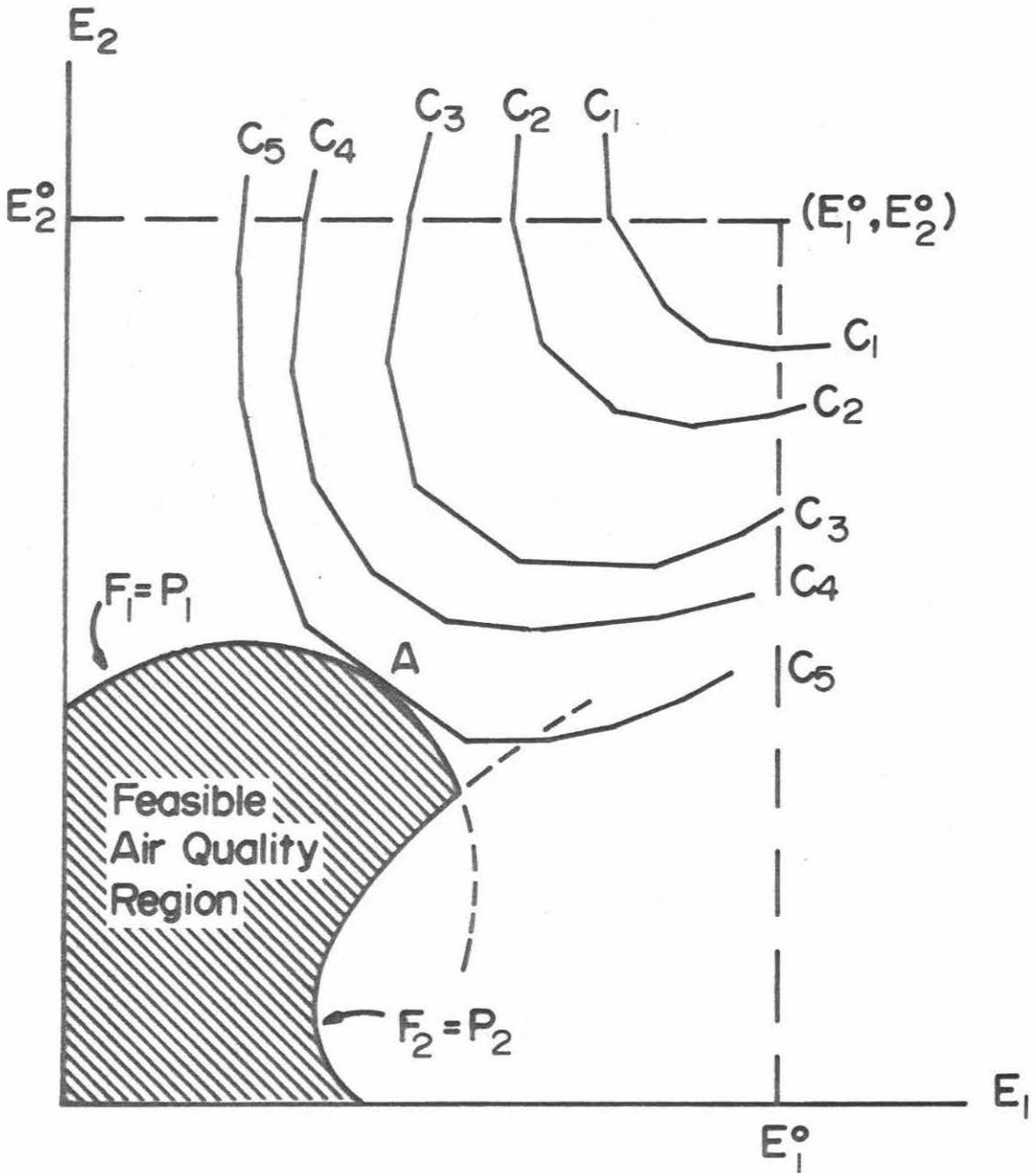
($N = 2$). This allows the problem to be represented graphically. Figure 1.7 depicts the situation with two air quality constraints, ($M = 2$).

The curves labelled C_1, C_2 , etc., are iso-cost curves, i. e., $G(E_1, E_2) = C_1, G(E_1, E_2) = C_2, \dots$. The theory of linear programming indicates that these curves are piecewise linear as well as convex. As illustrated in Figure 1.7, the iso-cost curves may extend into the region $E_1 \geq E_1^0$ and/or $E_2 \geq E_2^0$. These extensions result if some of the control activities considered in the linear programming model actually increase emissions. The curves, $F_1(E_1, E_2) = P_1$ and $F_2(E_1, E_2) = P_2$, are the two air quality constraints. The feasible air quality region, $E_1 \geq 0$ and $F_j \leq P_j$, is cross-hatched. For the two given air quality constraints, the solution to the nonlinear programming problem occurs at point A.

Chapter 5 solves the nonlinear programming problem for the Los Angeles photochemical smog example and presents the costs of reaching various air quality levels in Los Angeles County by 1975. Simple graphical analysis is used for the solution.

Figure 1.7

TWO DIMENSIONAL ILLUSTRATION
OF THE SOLUTION TO THE LEAST
COST AIR QUALITY MODEL



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CHAPTER 2
LOS ANGELES PHOTOCHEMICAL SMOG IN 1975--
DELINEATION OF THE PROBLEM

In order to reduce a real-life air pollution problem to a well-posed mathematical model, bounds which define the parameters of the model must be established. This chapter delineates such bounds for the problem of determining the least cost of attaining various photochemical smog levels in Los Angeles County by 1975 so that it can be formulated according to the mathematical least-cost air quality model of Chapter 1.

Section 2.1 outlines the general scope of the problem, photochemical smog in Los Angeles County in 1975. Section 2.2 selects well defined emission and air quality vectors and restates the mathematical model in terms of these parameters. Section 2.3 discusses some of the assumptions inherent in this formulation of the problem.

§2.1 GENERAL SCOPE OF THE PROBLEM

Already, three general specifications of the problem to be examined here have been made; we are dealing with photochemical smog in Los Angeles County in 1975. This section elaborates on these specifications and discusses the reasons for selecting them.

Area of Study: Los Angeles County

Los Angeles has a notorious, long-standing air pollution problem.

Los Angeles "smog"* has existed for more than thirty years, and the Los Angeles County Air Pollution Control District has been attempting to alleviate it for twenty-five years (Carlin and Kocher, 1971). During this time, a great deal of data have been generated on Los Angeles air pollution, and the efforts to control it have served as examples for many other metropolitan areas. Because of the availability of data and the exemplary role of Los Angeles, it is chosen as the area for application of the control model.

Having chosen the general Los Angeles area, the problem of selecting explicit boundaries for the study region remains. Two candidates for the study area readily appear, the state designated South Coast Air Basin (equivalent to the federal Metropolitan Los Angeles Air Quality Control Region) and Los Angeles County. These regions are shown in Figure 2.1 (Feely and Russo, 1970).

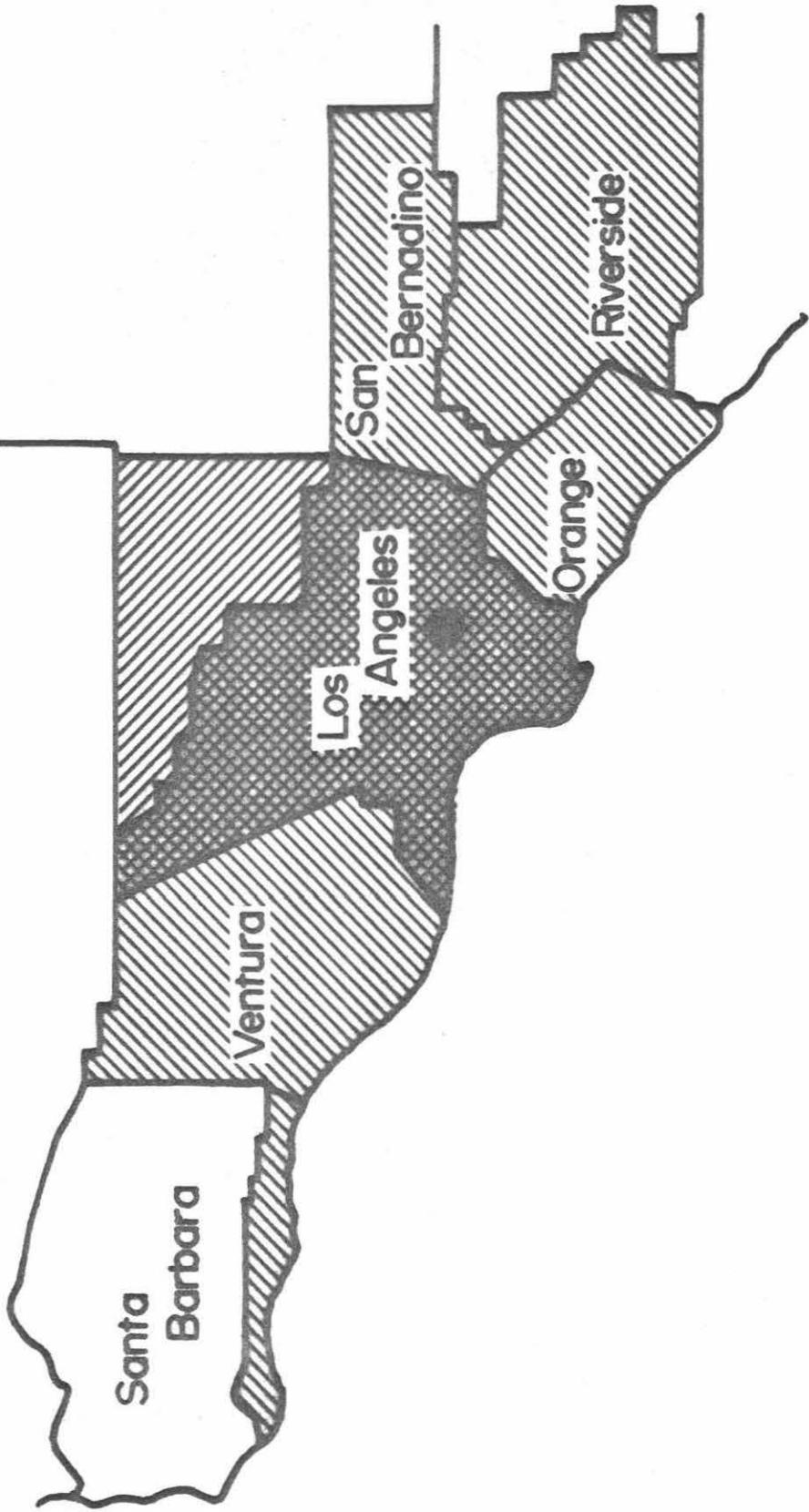
At first consideration, the South Coast Air Basin might appear to be the most appropriate region for study, as this area was selected as an integral air quality region by both federal and state investigators (HEW, 1968; California ARB, 1969). However, a much better emission source inventory is available for Los Angeles County, and principally for this reason this study will focus on the County rather than the Air Basin. For two decades, the Los Angeles County APCD has inventoried pollution sources, and detailed surveys have been completed for many

*"Smog", a synthesis of the words "smoke" and "fog", is appropriate for the type of air pollution in London but is actually a misnomer for Los Angeles air pollution. Most of Los Angeles' smog results from chemical reaction of gaseous pollutants (not smoke) on sunny (not foggy) days.

Figure 2.1

SOUTHERN CALIFORNIA: SOUTH COAST AIR BASIN:

L.A. COUNTY:



source categories. Considerable information gaps exist in some of these surveys (some are out of date), but these gaps can be rather easily filled since many other agencies and industries keep records on a County basis. For the South Coast Air Basin as a whole, no detailed source inventory is available (Lemke, 1971).

A second reason for choosing the County is that the air quality index used is more representative of the County than the Basin. The air quality-emission level model of this work and the available air monitoring data are such that the air quality index can only be calculated for Central Los Angeles (denoted by ● in Figure 2.1). Air quality in Central Los Angeles is not really representative of air quality throughout the County, but it is much more appropriate for the County than for the complete Basin.

One objection that might be raised against choosing Los Angeles County over the South Coast Air Basin is that almost all of the air pollution in the latter results from sources internal to it while the County is affected to a higher degree by sources external to it. By examining only County emission reductions, we cannot be sure that we will get a corresponding improvement in County air quality. This objection is countered by an examination of Southern California meteorology which reveals that the usual air flow pattern is a strong daytime sea breeze and a weak nocturnal land breeze (Neiburger and Edinger, 1954). The usual air flow is thus from the southwest to the northeast. As seen in Figure 2.1, since the ocean is southwest of the County, the air flow is usually such that Los Angeles County air is affected mainly by Los Angeles County sources. A study of the trajectories of polluted air

parcels passing through Central Los Angeles (where air quality for the County is measured in this work) has revealed that 62% of the time the air has arrived from the southwest coastline, 31% of the time it comes from the mountains in the northeast portion of the County, and only 7% of the time does it arrive from the direction of Ventura County or San Bernardino County (Neiburger et al., 1956). This, coupled with the fact that sources are more intense in Los Angeles County than in surrounding areas, implies that Central Los Angeles air pollution does result almost exclusively from Los Angeles County emissions.

Type of Pollution: Photochemical Smog

Los Angeles County air contains significant quantities of several pollutants. At one time or another, the LAAPCD has monitored carbon monoxide (CO), sulfur dioxide (SO₂), nitric oxide (NO), nitrogen dioxide (NO₂), ozone (O₃), various "eye irritants" (such as aldehydes and PAN), a variety of organic gases, total particulates, certain chemical species in the particulate phase (such as asbestos, lead, beryllium, and fluoride), and level of radioactivity. At present, the six major pollutants for which the APCD reports frequency of standard violation are CO, SO₂, NO₂, O₃, "eye irritants", and "visibility reducing particulates". In 1970, the number of days that the state standard was violated anywhere in the County for each of these pollutants is given in Table 2-I (APCD Profile, 1971).

"Photochemical smog" refers to the air pollution syndrome that results when certain gaseous pollutants are exposed to sunlight. The main symptoms of photochemical smog are eye irritation, visibility

TABLE 2-I
Los Angeles Air Quality in 1970

Pollutant	Standard	Days of Violation in 1970
1. Visibility Reducing Particulates	10 miles at relative humidity \leq 70%	335
2. Ozone	0.10 ppm for 1 hr	241
3. Carbon Monoxide	10 ppm for 12 hrs	203
4. Eye Irritation*	as determined by a meteorologist	128
5. Nitrogen Dioxide	0.25 ppm for 1 hr	115
6. Sulfur Dioxide	0.04 ppm for 1 day	95

*Eye irritation is a very subjective measure of pollution levels and must therefore be used with care.

loss, plant damage, and the presence of oxidizing gases, particularly O_3 and NO_2 . Starting with the work of Haagen-Smit in the early 1950's, twenty years of research on photochemical smog has established that it is the result of hydrocarbon (HC) (organic gases)* and nitrogen oxide ($NO_x = NO + NO_2$)** emissions (Haagen-Smit, 1952; Leighton, 1961; Altshuller and Bufalini, 1971). Other pollutants, e. g., SO_2 and CO, may take part in the photochemical reactions, but HC and NO_x are definitely the main precursors of photochemical smog.

*Hydrocarbon emissions result principally from the use of organic fuels and solvents.

**Nitrogen oxide emissions result almost exclusively from combustion processes. NO_x is emitted primarily as NO, which is oxidized to NO_2 in the atmosphere.

Unlike the pollution in cities such as New York, London, and St. Louis, where high concentrations of particulates and SO_2 are the main problems, photochemical smog is considered to be the major air pollution problem in Los Angeles. Four of the six pollutants listed in Table 2-I (1., 2., 4., and 5.) are associated with photochemical smog. The fact that photochemical smog is the most important part of the Los Angeles air pollution problem is one reason for choosing it for application of the control model. A second reason is that the model was formulated in enough generality to be able to include nonlinear interaction effects among emissions in producing final pollution. Photochemical air pollution, the result of a highly nonlinear interaction of HC and NO_x emissions, serves as an excellent example since it takes advantage of this generality in the model.

Control Date: 1975

The control model was formulated to calculate the cost of achieving various expected air quality levels for a given year. The choice of a reference time enters the complete model by fixing the technological parameters in the emission level-control cost model. That is, specifying the time fixes X, the set of control methods available; c, the control method costs; A, B, and D, the effects of the control methods; S, the source magnitudes; L, the supply of limited inputs; and E⁰, the uncontrolled emission level. Examples of these effects are given in Table 2-II.

In choosing a control date for this study, the criterion was to select the earliest possible date subject to the constraint that there be

TABLE 2-II

Example of the Effects of Control Date on the Emission Level-Control Cost Model

Control Date	X_{27} (natural gas conversion of fleet vehicles)	C_{27} annual cost of conversion (\$)	B_{27} reduction in NO_x emissions from one unit of X_{27} (tons/day)	S_{20} fleet vehicles	L_1 natural gas supply left from residential and industrial use (equiv. bbls./year)	$E_{NO_x}^0$ uncontrolled NO_x emission level (tons/day)
1969	not available	-	-	270,000	42,000,000	1000
1972	available	\$40	2×10^{-4}	310,000	31,000,000	1100
1975	available	\$30	1.5×10^{-4}	350,000	21,000,000	800

sufficient time for implementing the proposed control strategy. Two or three years appears to be a reasonable period for implementation of a control program.* A date around 1974 or 1975 thus seems appropriate. The first target date of the Federal Clean Air Act is 1975. With this consideration in mind, January 1, 1975, is selected here as the control date.

§2.2 SPECIFIC DELINEATION OF THE PROBLEM

The previous section outlined the general scope of the Los Angeles photochemical smog example. However, a more specific definition of the problem is required in order to fit the structure of the least-cost air quality model as given by equations (1-7). This section selects explicit emission and air quality vectors for the Los Angeles photochemical smog problem and restates the mathematical model in terms of these parameters.

The Emission Vector: \underline{E}

As noted in the previous section, hydrocarbons (HC) and nitrogen oxides (NO_x) are the basic precursors of photochemical smog. In the model developed here, only HC and NO_x emissions will be considered, the effect of other contaminants on photochemical air pollution being neglected.**

* In a recent study, the California ARB used a two-year period. Two years, however, would appear to be a lower bound for the time necessary to complete an air pollution control program (Brattain, 1971).

** A more general formulation would include SO_2 , CO, particulate, and other emissions which do take some part in the photochemical reactions.

NO_x emissions will be simply described by one parameter, E_2 = the average (tons/day) emission of NO_x in Los Angeles County in 1975. Almost all NO_x emissions result from combustion sources, and more than 95% is emitted as NO (HEW-AP-67, 1970; Seinfeld, Jan. 1972). The NO is generally oxidized to NO_2 in the atmosphere.

The emission category, hydrocarbons, is extremely complex. It consists of a great variety of organic gases with different degrees of photochemical reactivity,* ranging from photochemically inert methane, and nearly inert ethane, to the highly reactive olefins and aromatics. Reactivity can be measured according to several scales; HC consumption rate, NO_2 formation rate, ozone production, and eye irritation production are the principal ones (Altshuller and Bufalini, 1971). The rankings according to the different scales are often inconsistent with one another (Altshuller, 1966), which adds to the complexity.

Some allowance should be made for hydrocarbon reactivity. It makes a significant difference to air quality whether a given reduction in HC emissions is obtained by controlling olefins or methane. In the most general case, HC emissions could be described by scores of vector components, E_1, E_2, \dots, E_N , giving the emissions of each specific compound. However, this would present a great informational problem. Here, the very simple approach of classifying emissions as either reactive or not, based on the Los Angeles County APCD

*Photochemical reactivity refers to the potential of a given HC to produce various photochemical smog symptoms when irradiated in the presence of NO_x .

reactivity index,* will be used. It will be assumed that only reactive hydrocarbons (RHC) produce photochemical air pollution, and the emission vector component for hydrocarbons will be simply given by E_1 = the average (tons/day) emission of RHC in Los Angeles County in 1975.

The Air Quality Vector: P

As noted in §2.1, the four principal photochemical smog symptoms that are monitored by the APCD are visibility reduction, eye irritation, ozone, and NO_2 . A relevant measure of photochemical air quality is the number of days per year that these pollutants exceed state standards. This type of air quality index is used here.

In Chapter 4, air quality-emission level models are developed which determine the frequency of standard violation by NO_2 , ozone, and eye irritation as a function of RHC and NO_x emission levels. Visibility reduction is not included in this work since it depends significantly on particulate and SO_2 emissions as well as RHC and NO_x emissions. This dependence is extremely complex, making visibility reduction one of the least understood aspects of photochemical smog (Altshuller and Bufalini, 1971).

Because of the type of air quality model used here and because of limitations in the available air monitoring data, the ozone and eye irritation results could only be obtained for mid-day in the Central

* The reactivity index is the result of two decades of smog chamber experiments, chromatographic analyses, and other tests performed by the APCD (Dickinson, Jan. 1972). Many of these are referenced in Brunelle, et al., (1966).

Los Angeles area (see Figure 2. 1). To correspond with these results, the NO_2 air quality index is also developed for Central Los Angeles. Since the eye irritation results appear to be very similar to those for ozone and since eye irritation is such a subjective measure of air pollution, it is not included in the final air quality index.

Thus, the air quality vector used here is the following:

P_1 = the number of days per year that NO_2 exceeds the state standard (0.25 ppm for one hour) in Central Los Angeles

P_2 = the number of days per year that mid-day (11 AM - 1 PM) ozone exceeds the state standard (0.10 ppm for one hour) in Central Los Angeles

The least-cost air quality model, as applied to photochemical smog in Los Angeles in 1975, can now be stated as follows:

To determine the (minimum) cost of achieving any given air quality level, specified by P_1 and P_2 , find (E_1, E_2) that minimizes

$$\begin{aligned}
 & C = G(E_1, E_2) , \\
 \text{subject to} & \quad F_1(E_1, E_2) \leq P_1 , \\
 & \quad F_2(E_1, E_2) \leq P_2 , \\
 \text{and} & \quad E_1 \geq 0 , \quad E_2 \geq 0 .
 \end{aligned}
 \tag{2-1}$$

Here, $G(E_1, E_2)$ (determined in Chapter 3), is the minimum cost of attaining emission levels E_1 and E_2 of RHC and NO_x in Los Angeles County by 1975, and $F_1(E_1, E_2)$ and $F_2(E_1, E_2)$ (determined in Chapter 4), give the number of days per year that NO_2 and O_3 standards are violated as a function of the emission levels.

§2.3 AN APPROXIMATE SOLUTION

The problem to be solved here, as given by (2-1), is already a highly simplified model of the real-life problem of finding the (minimum) cost of reaching various photochemical smog levels in Los Angeles County by 1975. Only RHC and NO_x emissions have been included in the model, and changes in the spatial and time distribution of emissions have not been considered. Air quality is specified only in terms of violation of one hour NO_2 and ozone standards and only for Central Los Angeles.

To solve even this simplified model, one must first determine $G(E_1, E_2)$, $F_1(E_1, E_2)$, and $F_2(E_1, E_2)$. Finding these functions involves even further approximations. For instance, in finding the control cost-emission level relation (Chapter 3), only major sources and control methods are considered, estimates are used for the costs and effects of controls, and the structure of the problem is approximated by a linear programming model with the inherent assumptions listed in section 1.8. In finding the air quality-emission level relation (Chapter 4), it is assumed that emission changes occur homogeneously and that the other simple physical assumptions of the phenomenological model are met.

Even with these simplifications, the model should provide realistic, though very approximate, answers to basic questions such as, "What air quality levels can be achieved in Los Angeles County by 1975?", "About how much would achieving these levels cost?",

"Should control efforts be concentrated on RHC or NO_x emissions?", and "Which sources should be controlled according to a cost-effectiveness criterion?" Even approximate answers to such questions should be very useful to formulating an air pollution control strategy.

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CHAPTER 3

THE CONTROL COST-EMISSION LEVEL RELATION

Before one can determine the cost of reaching various air quality levels, one must know the cost of attaining various emission levels. This chapter uses the linear programming model of §1.8 to develop the control cost-emission level relation for the Los Angeles photochemical smog example. §3.1 restates the linear programming model particular to the smog example. The data for the program are developed in Appendix A and summarized in §3.2. §3.3 presents and discusses the control cost-emission level results. §3.4 examines the assumptions and approximations inherent in the programming model.

§3.1 THE LINEAR PROGRAMMING MODEL

§2.2 selected a two dimensional emission vector, reactive hydrocarbons and nitrogen oxides, for the Los Angeles photochemical smog study. This chapter uses the linear programming model presented in §1.8 to determine $G(E_1, E_2)$, the minimum cost of reaching various emission levels in L. A. County by 1975. The model, specific to the photochemical smog example, is as follows:

To determine $C = G(E_1, E_2)$, find the x_j which minimize

$$\begin{array}{l}
 C = G(E_1, E_2) = \sum_{j=1}^r c_j x_j , \\
 \text{subject to} \\
 \sum_{j=1}^r B_{kj} x_j = E_k^0 - E_k , \quad k = 1, 2 , \\
 \sum_{j=1}^r A_{ij} x_j \leq S_i , \quad i = 1, \dots, s , \\
 \sum_{j=1}^r D_{mj} x_j \leq L_m , \quad m = 1, \dots, l , \\
 \text{and} \quad x_j \geq 0 , \quad j = 1, \dots, r .
 \end{array} \quad (3-1)$$

Table 3-I defines the parameters in equations (3-1). The actual values that will be used for these parameters are presented in the next section.

§3.2 DATA FOR THE LINEAR PROGRAMMING MODEL

The inputs to the linear program are possible control activities (X), their costs (c), emission levels (E), source magnitudes (S), limited supply factors (L), and matrices (B, A, and D) which describe the interaction between the control activities and E, S, and L. The data for computing the minimum cost of reaching various RHC and NO_x emission levels in Los Angeles County by 1975 are developed in Appendix A and summarized in Table 3-II.

An examination of Table 3-II reveals that sources of RHC and NO_x in Los Angeles County are grouped in 35 categories, 14 stationary sources of NO_x, 9 stationary sources of RHC, and 12 mobile sources of RHC and NO_x. In Appendix A, more than 60 possible control

TABLE 3-I

Definition of Parameters for the Linear Programming Model

Parameter	Unit	Description
$x_j, j=1, \dots, r$	control unit	The level of the j^{th} control activity.
$E_k, k=1, 2$	(tons/day)	The emission levels of RHC and NO_x to be attained in L. A. County by 1975.
$E_k^0, k=1, 2$	(tons/day)	The "uncontrolled"* emission levels of RHC and NO_x in L. A. County in 1975.
$S_i, i=1, \dots, s$	source unit	The magnitude of the i^{th} emission source in L. A. County in 1975.
$L_m, m=1, \dots, \ell$	factor unit	The amount of the m^{th} limited supply factor available in L. A. County in 1975.
$C_j, j=1, \dots, r$	$\frac{\text{dollars}}{\text{control unit}}$	The annualized cost of one unit of the j^{th} control activity.
$B_{kj}, k=1, 2, j=1, \dots, r$	$\frac{(\text{tons/day})}{\text{control unit}}$	The emission reduction of the k^{th} contaminant resulting from one unit of the j^{th} control activity.
$A_{ij}, i=1, \dots, s, j=1, \dots, r$	$\frac{\text{source unit}}{\text{control unit}}$	The number of units of source i controlled by one unit of the j^{th} control activity.
$D_{mj}, m=1, \dots, \ell, j=1, \dots, r$	$\frac{\text{factor unit}}{\text{control unit}}$	The amount of n^{th} limited supply factor consumed by one unit of the j^{th} control activity.

*The "uncontrolled" emission level is defined to be the level resulting from the existing new car control program and from the degree of stationary control present at 1-1-71.

Table 3-II. Data for the Linear Programming Model

Source i Description	S _i : Source Magnitude in 1975 -Unit	S _k : Emissions per Source Unit (tons/day) e ₁ , RHC; e ₂ , NO _x	Total Source Emissions (tons/day) RHC; NO _x	References for Source i and Associated Control Methods				C _j : Annual Flue Gas per Control Unit	Total Annual Cost, All Source Units Controlled	Cost per Ton Controlled RHC; NO _x	A _{1j}	D _{1j}
				% Emission Reduction RHC; NO _x	B _{kj} : Emission Reduction per (C _j × Unit) RHC; NO _x	All Source Units Controlled (tons/day) RHC; NO _x	D _{1j}					
I. STATIONARY SOURCES OF NO_x												
1. Large, Non-Power Plant, Boilers (≥ 30 MBTU/hr.) --one boiler	140	-- .20	-- 28	References: (APCD Profile, 1971), (Bay Area APCD, 1969), (ES&O, 1969), (HEW-AP-67, 1970), (Mills et al., 1961a), (Walden, 1971)				\$1,000	\$140,000	--	A ₁₁ = 1 A ₁₂ = 0, 1, 4	D ₁₁ = 0
1. Low Excess Air Firing (LEA)-- (LEA) to one large boiler				-- 40	-- .08	--	11	\$1,000	\$140,000	--	A ₁₁ = 1 A ₁₂ = 0, 1, 4	D ₁₁ = 0
2. Low Excess Air (LEA) and Flue Gas Recirculation (FGR)--(LEA) and (FGR) to One Large Boiler				-- 70	-- .14	--	20	\$10,500	\$1,470,000	--	A ₁₂ = 1 A ₁₃ = 0, 1, 4	D ₁₂ = 0
Other Control Methods Discussed: Flue Gas Recirculation, Steam or Water Injection, Two-Stage Combustion, Flue Gas Treatment												
2. Medium Size Boilers (2-30 MBTU/hr.)-- one boiler	6,000	-- 6.8 × 10 ⁻³	-- 41	References: (Bay Area APCD, 1969), (ES&O, 1969), (George and Chas., 1967), (HEW-AP-67, 1970), (Mills et al., 1961b), (Walden, 1971)				\$1,270	\$7,610,000	--	A ₂₃ = 1 A ₂₄ = 0, 1, 4, 2	D ₁₃ = 0
3. Low Excess Air Firing (LEA)-- (LEA) to one medium boiler				-- 40	-- 2.7 × 10 ⁻³	--	16	\$1,270	\$7,610,000	--	A ₂₃ = 1 A ₂₄ = 0, 1, 4, 2	D ₁₃ = 0
4. Low Excess Air and Flue Gas Recirculation--(LEA) and (FGR) to one medium boiler				-- 70	-- 4.7 × 10 ⁻³	--	28	\$2,700	\$16,200,000	--	A ₂₄ = 1 A ₂₅ = 0, 1, 4, 2	D ₁₄ = 0
Other Control Methods Discussed: Flue Gas Recirculation, Steam or Water Injection, Two-Stage Combustion, Flue Gas Treatment												
3. Large Refinery Heaters (≥ 90 MBTU/hr.)-- one large heater	60	-- .24	-- 14	References: (APCD Profile, 1971), (ES&O, 1969), (George and Chas., 1967), (HEW-AP-67, 1970), (Mills et al., 1961a), (Walden, 1971)				\$950	\$57,000	--	A ₃₅ = 1 A ₃₆ = 0, 1, 4	D ₁₅ = 0
5. Low Excess Air Firing (LEA)-- (LEA) to one large heater				-- 40	-- .096	--	6	\$950	\$57,000	--	A ₃₅ = 1 A ₃₆ = 0, 1, 4	D ₁₅ = 0
Other Control Methods Discussed: Flue Gas Recirculation, Two-Stage Combustion, Flue Gas Treatment												
4. Small Refinery Heaters (< 90 MBTU/hr.)-- one small heater	160	-- .06	-- 10	References: (APCD Profile, 1971), (ES&O, 1969), (George and Chas., 1967), (HEW-AP-67, 1970), (Mills et al., 1961b), (Walden, 1971)				\$1,900	\$304,000	--	A ₄₆ = 1 A ₄₇ = 0, 1, 4	D ₁₆ = 0
6. Low Excess Air Firing (LEA)-- (LEA) to one small heater				-- 40	-- .024	--	4	\$1,900	\$304,000	--	A ₄₆ = 1 A ₄₇ = 0, 1, 4	D ₁₆ = 0
Other Control Methods Discussed: Flue Gas Recirculation, Two-Stage Combustion, Flue Gas Treatment												

Personal Conversations: Anderson, Hunt, Marshall, Myler, Sommerlad, Tauer, Wendt

Personal Conversations: Anderson, Gonzal, Hunt, Marshall, Sommerlad, Tauer

Personal Conversations: Crawford, Fletcher, Glauser, Lanche, Ray, Thomas, Towell, Wendt

Personal Conversations: Glauser, Lanche, Ray, Thomas, Towell, Wendt

TABLE 3-II (continued)

Source i Description	S _i : Source Magnitude in 1975	E _i : Emissions per Source Unit (tons/day)	Total Source Emissions (tons/day)	References for Source i and Associated Control Methods			C _j : Annual Cost per Control Unit	Total Annual Cost, All Source Units Controlled	Cost per Ton Controlled	A _{1j}	D _{1j}
				% Emission Reduction	B _{kj} : Emission Reduction per Control Unit (tons/day)	Total Reduction, All Source Units Controlled (tons/day)					
				RHC	NO _x	RHC	NO _x	RHC	NO _x		
5. Rule 68-Complying Large Power Plant Boilers Burning Fuel Oil--one boiler	8	--	3.8	--	--	1.3	--	0	--	A _{5,7} =1 A _{1,7} =0.1#5	D _{1,7} =2.8x10 ⁶
7. Substitution of Natural Gas Fuel Oil--Substituting 2.6 M equiv. bbls./Yr. of gas for fuel oil	7										
Other Control Methods Discussed: Further Combustion Modification; Flue Gas Treatment											
6. Non-Rule 68-Complying Large Power Plant Boilers Burning Fuel Oil--one boiler	8	--	9.5	--	--	--	76				
8. Substitution of Natural Gas for Fuel Oil--Substituting 3.7 M equiv. bbls./Yr. of gas for fuel oil	8					3.2	--	25	--	A _{6,8} =1 A _{1,8} =0.1#6	D _{1,8} =3.9x10 ⁶
9. Addition of Advanced Combustion Modification Control to Comply with Rule 68--to one boiler	9					3.8	--	30	\$220,000	A _{6,9} =1 A _{1,9} =0.1#6	D _{1,9} =0
10. Addition of Advanced Combustion Modification Control and Substitution of Natural Gas for Fuel Oil--Substituting 3.9 M equiv. bbls./Yr. of gas for fuel oil to adding adv. comb. contr. to one boiler	10					5.7	--	46	\$220,000	A _{6,10} =1 A _{1,10} =0.1#6	D _{1,10} =3.9x10 ⁶
7. Small Power Plant Boilers--one boiler	37	--	.62	--	--	--	23				
References (APCD Profile, 1971), (Chass et al., 1971), (ESSO, 1969), (HEW-AP-67, 1970), (Walden, 1971)											
11. Low-Excess Air Firing--Adding LEA to one boiler	11					.19	--	7	\$14,000	A _{7,11} =1 A _{1,11} =0.1#7	D _{1,11} =0
12. LEA and flue gas recirculation--FGR to LEA on one boiler	12					.31	--	11	\$51,000	A _{7,12} =1 A _{1,12} =0.1#7	D _{1,12} =0
Other Control Methods Discussed: Two-Stage Combustion; Flue Gas Recirculation; Flue Gas Treatment											
Personal Conversations: Felgar, Nevitt, Sanderling											
Personal Conversations: Anderson, Felgar, Nevitt, Sanderling											
Personal Conversations: Bagwell, Felgar, Hall, Sanderling											

TABLE 1-II (continued)

Source i Description	S _i : Source Magnitude in 1975 - Unit	k _i : Emissions per Source Unit (tons/day)			Total Source Emissions (tons/day)			References for Source i and Associated Control Methods									
		e _{1,i} -RHC	e _{2,i} -NO _x	- Unit	RHC	NO _x	% Emission Reduction RHC NO _x	B _{1,j} -RHC (tons/day)	B _{2,j} -NO _x (tons/day)	Total Reduction, All Source Units Controlled (tons/day)	C _j : Annual Cost per Control Unit	Total Annual Cost, All Source Units Controlled	Cost per Ton Controlled RHC NO _x	A _{i,j}	D _{1,j}		
8. Large Stationary Internal Combustion Engines--one large engine	140	-	.18	-	-	25	-	-	-	19	\$680	\$95,000	-	A _{8,13} =1 A _{1,13} =0,148	D _{1,13} =0		
13. Water Injection (WI) or Exhaust Gas Recirculation (EGR)--WI or EGR to one small engine	360	-	.019	-	-	7	.75	.14	-	5	\$190	\$68,000	-	A _{9,14} =1 A _{1,14} =0,149	D _{1,14} =0		
9. Small Compressor Engines--one small engine	360	-	.019	-	-	7	-	-	-	-	-	-	-	-	-		
Other Control Methods: Increasing Air/Fuel Ratio, Exhaust Gas Treatment																	
References: (Downing and Stoddard, 1970), (ESSO, 1969), (HEW-AP-67, 1970), (Mills et al., 1961b), (Walden, 1971)																	
Other Control Methods: Increasing Air/Fuel Ratio, Exhaust Gas Treatment																	
References: (APCD Profile, 1971), (HEW-AP-67, 1970), (Mills et al., 1961b)																	
i. Residential Fuel Combustion						28											
ii. Metallurgical and Mineral Industry Furnaces						8											
iii. Catalytic Regenerators in Refineries						10											
iv. Small Commercial and Industrial Boilers						9											
v. Oil-Fuel Pump Engines						2											
vi. Miscellaneous						3											
OTHER STATIONARY SOURCES OF NO _x																	
References: (APCD Profile, 1971), (Burlin and Fudurich, 1962), (A. D. Little Report, 1967)																	
ii. STATIONARY SOURCES OF RHC	34,000	5,840-4	-	-	20	-	99	.052	-	20	\$3,900	\$1,470,000	\$205	A _{10,15} =90 A _{1,15} =0,1410	D _{1,15} =0		
10. Underground Service Station Tanks--one tank																	
References: (APCD Profile, 1971), (Burlin and Fudurich, 1962), (A. D. Little Report, 1967)																	
15. Vapor Recycle Systems for Underground Tanks--Vapor recovery system for one tank truck and 30 tanks																	
Personal Conversations: Lanche, Thomas, Wendt, Glauser																	
Personal Conversations: Wendt																	
Personal Conversations: Lanche, Wendt																	
Personal Conversations: McCutcheon																	
Personal Conversations: Thomas																	

TABLE 3-II (continued)

Source i Description	S _i : Source Magnitude in 1975	E _k : Emissions (tons/day)			Total Source Emissions (tons/day)			References for Source i and Associated Control Methods															
		e ₁	RHC	NO _x	e ₂	NO _x	RHC	NO _x	% Emission Reduction RHC	NO _x	B ₁ : RHC	B ₂ : NO _x	B _k : Emission Reduction per Control Unit (tons/day)	Total Reduction, All Source Units Controlled (tons/day)	C _i : Annual Cost per Control Unit	Total Annual Cost, All Source Units Controlled	Cost per Ton Controlled RHC	NO _x	A ₁ : J	D ₁ : J			
11. Service Stations, Automobile Tank Filling--one service station	11,300	3.6x10 ⁻³	--	40	--	--	--	--	--	--	--	76	--	2.7x10 ⁻³	--	31	--	\$330	\$3,730,000	\$333	--	A ₁₁ 16 = 1 A ₁ 16 = 0, 1, #11	D ₁ 16 = 0
16. Vapor Recirculation Systems for Service Station Nozzles--addition of a vapor recirculation system to one service station																							
12. Surface Coating--one ton per day of emitted reactive organic solvent	51	1	--	51	--	--	--	--	--	--	--	75	--	38	--	38	--	\$4,500,000	\$4,500,000	\$330	--	A ₁₂ 17 = 51 A ₁ 17 = 0, 1, #12	D ₁ 17 = 0
17. Further Restrictions on Reactive Organic Solvents in Surface Coating																							
13. Degreasers--one ton per day of reactive organic solvent used for degreasing	26	.9	--	23	--	--	--	--	--	--	--	100	--	.9	--	23	--	-\$3,280	-\$95,000	-\$10	--	A ₁₃ 18 = 1 A ₁ 18 = 0, 1, #13	D ₁ 18 = 0
18. Substitution of 1,1,1-trichloroethane for trichloroethylene--Sub. of .75 tons/day of 1,1,1-T for one ton/day of TCE																							
Other Control Methods Discussed: Substitution of Perchloroethane (PCE) for TCE, Addition of Condensers or Absorbers to Degreasers																							
14. Dry Cleaners Using Petroleum-based Solvents--one day cleaning plant	25	.20	--	5	--	--	--	--	--	--	--	95	--	.19	--	5	--	\$3,300	\$82,000	\$48	--	A ₁₄ 19 = 1 A ₁ 19 = 0, 1, #14	D ₁ 19 = 0
19. Activated Carbon Adsorption Systems--one absorption system to one plant																							
Other Control Methods Discussed: Switching to Non-reactive Synthetic Solvents																							

Personal Conversations: Hunter, Thomas, Vergamini

Personal Conversations: Ellis, Finnigan, Hecht, Weiss

Personal Conversations: Bitwell, Krenz, Weiss

References: (APCD Profile, 1971), (HEW-AP-68, 1970)

Personal Conversations: Classon, Pierce, Weiss

TABLE 3-II (continued)

Source i Description	S _i : Source Magnitude in 1975	e _{k,j} : Emissions per Source Unit (tons/day) e _{1,j} :RHC e _{2,j} :NO _x	Total Source Emissions (tons/day) RHC NO _x	References for Source i and Associated Control Methods										
				Control Method j	% Emission Reduction RHC NO _x	B _{k,j} : Emission Reduction per Control Unit (tons/day) B _{1,j} :RHC B _{2,j} :NO _x	Total Reduction, All Source Units Controlled (tons/day) RHC NO _x	C _j : Annual Cost per Control Unit	Total Annual Cost per Source Unit Controlled	Cost per Ton Controlled RHC NO _x	A _{i,j}	D _{i,j}		
24. Vacuum Spark Advance Disconnect and Tuning Adjustment ("GM Smog Package") --one "smog package" device for one vehicle			- Unit		30	40	1.4x10 ⁻⁵	4.2x10 ⁻⁵	19	57	\$6	\$8,280,000	\$1,170	A _{1,24} =0.1#17 D _{1,24} =0
Other Control Methods Discussed: Exhaust Gas Recirculation (EGR) and Controlled Spark Retard (CSR), Thermal Reactors.														
18. 1966-1969 Model Motor Vehicles, Evaporative Emissions--one vehicle	1.38x10 ⁶	7.0x10 ⁻⁵	97	--	85	--	6.0x10 ⁻⁵	--	82	--	\$50	\$69,000,000	\$2,300	A _{1,25} =0.1#18 D _{1,25} =0
25. Evaporative Control Device Retrofit--one device to one vehicle														
19. 1970 Model Motor Vehicles--one vehicle	390,000	5.0x10 ⁻⁵	20	58	--	--	8.7x10 ⁻⁵	--	32	--	\$0	\$0	\$0	A _{1,26} =0.1#19 D _{1,26} =0
26. Capacitor Discharge-Ignition Optimization System--one CDIOS to one 1970 vehicle														
Other Control Methods Discussed: Vacuum Spark Advance Disconnect, Exhaust, Gas Recirculation and Controlled Spark Retard (Dana Corp. Device), Thermal Reactors, Catalytic Reactors														
20. 1971-1974 Model Year Fleet Vehicles Suitable for Conversion to Gaseous Fuel--one vehicle	345,000	9.8x10 ⁻⁵	34	65	--	--	8.7x10 ⁻⁵	--	32	--	\$0	\$0	\$0	A _{1,27} =0.1#20 D _{1,27} =0
27. Conversion of Fleet Vehicles to Operate on Natural Gas--conversion of one fleet vehicle														
28. Conversion of Fleet Vehicles to Operate on Liquid Petroleum Gas (LPG)--conversion of one fleet vehicle					94	79	9.2x10 ⁻⁵	1.5x10 ⁻⁴	32	52	\$30	\$10,300,000	\$880	A _{1,28} =0.1#20 D _{1,28} =0
28. Conversion of Fleet Vehicles to Operate on Liquid Petroleum Gas (LPG)--conversion of one fleet vehicle														
					82	70	6.0x10 ⁻⁵	1.3x10 ⁻⁴	28	45	\$130	\$44,900,000	\$4,500	A _{1,28} =0.1#20 D _{1,28} =0

References: (APCD Profile, 1969), (ARB Implementation Plan, 1971), (Downing and Stoddard, 1970), (HEW-AP-66, 1970)

References: (APCD Profile, 1969), (ARB Implementation Plan, 1971), (Downing and Stoddard, 1970), (HEW-AP-66, 1970)

References: (APCD Profile, 1971), (ARB Implementation Plan, 1971), (Czech Clean Air Car Project, 1971), (Downing and Stoddard, 1970), (McJones and Corwell, 1970)

Personal Conversations: Bantz, Bonanasa, Dickinson, Helmer, Nevitt

TABLE 1-11 (continued)

Source i Description	S _i : Source Magnitude in 1975	e _{1,1} - RHC e _{2,1} - NO _x	e _{k,1} : Emissions per Source Unit (tons/day)	Control Method j	Total Source Emissions (tons/day)		References for Source i and Associated Control Methods										
					RHC	NO _x	% Emission Reduction RHC	NO _x	B _{k,j} : Emission Reduction per Control Unit (tons/day)	B _{1,j} : RHC B _{2,j} : NO _x	Total Reduction, All Source Units Controlled (tons/day)	C _j : Annual Cost per Control Unit	Total Annual Cost, All Source Units Controlled	Cost per Ton Controlled RHC	NO _x	A _{1,j}	D _{1,j}
21. Jet Aircraft-JTRD Engines--one JTRD engine	2,500	5.6 × 10 ⁻³	1.2 × 10 ⁻³	14	3	95	-20	5.3 × 10 ⁻³	-2.4 × 10 ⁻⁴	13	-1	\$4,000	\$10,000,000	\$2,100	-\$45,000	A _{1,29} = 0, i#21	D _{1,29} = 0
22. Jet Aircraft-Other Engines--one non-JTRD jet engine	2,900	1.4 × 10 ⁻³	1.7 × 10 ⁻³	4	5	95	-20	1.3 × 10 ⁻³	-3.4 × 10 ⁻⁴	4	-1	\$4,000	\$11,600,000	\$8,000	-\$33,000	A _{2,30} = 0, i#22	D _{1,30} = 0
23. Piston Aircraft Engines--one engine	7,000	1.7 × 10 ⁻³	6.0 × 10 ⁻⁴	12	4	75	--	1.3 × 10 ⁻³	--	9	--	\$350	\$1,220,000	\$130	--	A _{2,31} = 1	D _{1,31} = 0
OTHER MOBILE SOURCES OF RHC AND NO _x																	
i. 1971-1974 Model Year Motor Vehicles (non-fleet)	69	--	--	--	124	--	--	--	--	--	--	--	--	--	--	--	--
ii. Diesel Powered Motor Vehicles	--	--	--	--	18	--	--	--	--	--	--	--	--	--	--	--	--
iii. Piston Aircraft not Registered in L.A. County	5	--	--	--	2	--	--	--	--	--	--	--	--	--	--	--	--
References: (APCD Profile, 1971)																	

TABLE 3-II (continued)

IV. LIMITED SUPPLY INPUTS:

1. Natural Gas Available to Power Plants (Control Methods 7, 8, and 10) or to Fleet Vehicles (Control Method Z7):	$L_1 = 21,000$ equiv. bbls./year	References: (APCD Profile, 1971), (Ralph and Walker, 1971)
---	----------------------------------	--

methods for these resources are considered. Not all of these possible controls are included in the linear programming model. Those control activities which appear technically infeasible for 1975 or which lack sufficient documentation for estimating cost and effectiveness or which are strictly inferior to an alternate control method for the same source (in the sense that the other control method produces a greater emission reduction at less cost) are not entered in the program. This elimination leaves 31 control methods ($r = 31$) for 23 of the major sources ($s = 23$) as inputs to the program. These sources and control activities are assigned numerical indices in Table 3-II and Appendix A.

Three of the units that are used to measure source and control method parameters deserve special comment. Magnitudes of nearly all the sources are measured in units describing numbers of equipment (e.g., the number of 1970 motor vehicles, or the number of dry cleaners) rather than in units describing the amount of fuel or solvent used (e.g., the amount of gasoline consumed by 1970 motor vehicles, or the amount of dry cleaning solvent used). Control costs relate more directly to the equipment unit, but emission rates relate more directly to the rate of fuel or solvent use. The choice of which unit to use is arbitrary. One unit can be converted to another by a simple usage factor (e.g., the gasoline used per day by one 1970 motor vehicle). Emission rates are measured in terms of the average tons/day emissions. This does not mean to imply that emissions are constant each day for each source. The essential assumption was that the time and space distribution of emissions remained fixed in the control program so that emission changes could be represented by just changes in average emission level. Control costs are measured in terms of annualized dollar cost. The cost of each control activity was written off as an annual cost over the life of that control. This method

allowed systematic comparison of initial and operating costs.*

The "uncontrolled" or base emission levels, (E_1^0, E_2^0) of reactive hydrocarbons and nitrogen oxides are defined as those levels that would result in 1975 from the existing new car control program and from the degree of stationary source control in effect on January 1, 1971. These emission levels are found by summing all of the entries in columns 4 and 5 of Table 3-II. The results are $E_1^0 = 666$ tons/day RHC and $E_2^0 = 786$ tons/day NO_x .

As indicated in the final section of Table 3-II, only one limited supply input ($\ell = 1$), natural gas, is included in the program. L_1 is not the total natural gas available to L.A. County in 1975 but rather the gas available for controlling power plants and fleet cars. This consists of the total gas supply minus the amount consumed by residential, commercial, and industrial combustion sources. At the uncontrolled level, it is assumed that automobiles burn only gasoline, power plants use fuel oil, and residential, commercial, and industrial boilers and heaters burn natural gas.

Appendix A and Table 3-II are not intended to be definitive statements of sources, control methods, and limited supply inputs. Considerable uncertainty exists in the information used to compile the data, and many of the parameters used are essentially estimates. The assumptions implicit in these estimates are carefully outlined in

* For sources with long expected lifetimes, (e.g., large boilers), the annual control cost will be incurred for 25 or more years. For sources which have short expected life and which will not be replaced by equivalent emission sources, (e.g., pre-1969 motor vehicles), the annual control cost must be paid for only 3 to 5 years. Fortunately, the most expensive controls considered here fall in the latter category.

To obtain approximate estimates of initial or capital costs, the annualized costs presented here should be multiplied by about 5 or 6.

Appendix A. The basic assumption used to predict source magnitudes to 1975 was a 4% growth rate for most stationary sources and the APCD projection of about 2.5% growth in automobile emissions. The sensitivity of the results to the assumptions on growth rates and control method costs is examined in §3.4.

§3.3 RESULTS--THE COST OF ATTAINING VARIOUS RHC AND NO_x EMISSION LEVELS IN LOS ANGELES COUNTY BY 1975

With the data presented in the previous section, (\underline{X} , \underline{E}^0 , \underline{S} , L_1 , \underline{c} , \underline{B} , \underline{A} , and \underline{D}), the linear programming problem, (3-1), is solved for various values of (E_1, E_2) to yield the control levels, \underline{x} , and the minimum annualized cost, C , associated with various emission levels of RHC and NO_x. Figure 3.1 illustrates the resulting minimum cost function, $G(E_1, E_2)$, and Table 3-III presents the control activities, \underline{x} , for several selected emission levels. Figures 3.2 and 3.3 give the costs for RHC and NO_x reductions alone.

In Figure 3.1, the 1969 emission level is marked at (1300 tons/day RHC, 1000 tons/day NO_x). The California new car control program, the stationary source control level of 1-1-71, along with growth and attrition of various sources results in a base emission level of ($E_1^0 = 666$ tons/day RHC, $E_2^0 = 786$ tons/day NO_x) in 1975. The minimum annual cost of achieving further emission reductions with the set of control alternatives considered here is illustrated by iso-cost curves, $G(E_1, E_2) = C_1 = \$2$ million, ..., $G(E_1, E_2) = C_7 = \$200$ million.

The control cost function is convex because it is a solution of a linear programming problem. It is also piecewise linear; however,

FIGURE 3.1

THE MINIMAL COST OF ATTAINING VARIOUS NO_x & RHC EMISSION LEVELS IN L.A. COUNTY BY 1975

1969 EMISSION LEVEL •

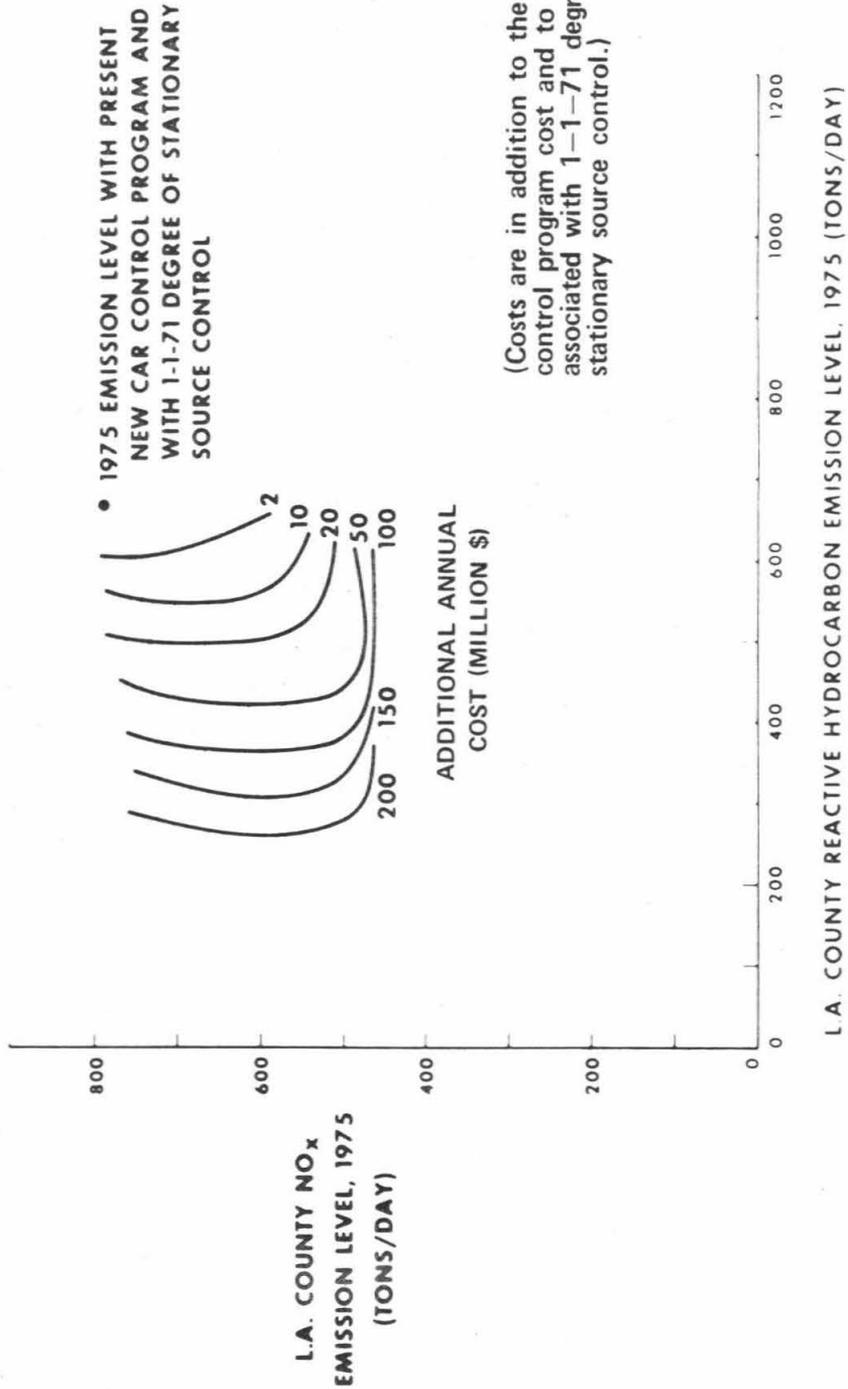


TABLE 3-III

The Least Cost Control Methods Associated with Various Emission Levels

List of Controls:

Stationary NO_x Sources

1. Low Excess Air Firing (LEA) on Large Commercial and Industrial Boilers
2. LEA and Flue Gas Recirculation (FGR) on Large Commercial and Industrial Boilers
3. LEA on Medium Size Commercial and Industrial Boilers
4. LEA and FGR on Medium Size Commercial and Industrial Boilers
5. LEA on Large Refinery Heaters
6. LEA on Small Refinery Heaters
7. Natural Gas in Rule 68 Complying Large Power Plant Boilers
8. Natural Gas in Non-Rule 68 Complying Large Power Plant Boilers
9. Advanced Combustion Control on Non-Rule 68 Complying Large Power Plant Boilers
10. Advanced Combustion Control and Natural Gas in Non-Rule 68 Complying Large Power Plant Boilers
11. LEA on Small Power Plant Boilers
12. LEA and FGR on Small Power Plant Boilers
13. Water Injection (WI) or Exhaust Gas Recirculation (EGR) on Large Stationary Internal Combustion Engines (ICE)
14. WI or EGR on Small Stationary ICE

Stationary RHC Sources

15. Vapor Recycle Systems for Underground Service Station Tanks
16. Vapor Recycle Systems for Service Station Nozzles
17. Further Restrictions on Reactive Organic Solvents in Surface Coating

TABLE 3-III (continued)

List of Controls (continued):

18. Substitution of 1, 1, 1-Trichloroethane for Trichloroethylene in Degreasers
19. Activated Carbon Absorption Systems on Dry Cleaners Using Petroleum Based Solvents

Mobile Sources

20. Capacitor Discharge-Ignition Optimization Systems (CDIOS) on Pre-1966 Used Motor Vehicles
21. EGR and Controlled Spark Retard Systems on Pre-1966 Used Motor Vehicles
22. Evaporative Control Retrofit on Pre-1966 Used Motor Vehicles
23. CDIOS on 1966-1969 Used Motor Vehicles
24. GM Smog Package on 1966-1969 Used Motor Vehicles
25. Evaporative Control Retrofit on 1966-1969 Used Motor Vehicles
26. CDIOS on 1970 Used Motor Vehicles
27. Conversion of 1971-1974 Fleet Vehicles to Natural Gas
28. Conversion of 1971-1974 Fleet Vehicles to Liquid Petroleum Gas
29. Combustion Chamber Redesign of JT8D Jet Engines
30. Combustion Chamber Redesign of Non-JT8D Jet Engines
31. Afterburners on Piston-Aircraft Engines

RHC Control Alone

Emission Levels (tons/day)	Controls
666	Uncontrolled
540 (point A in Figure 3.2)	Stationary RHC Sources: 15, 16, 17, 18, 19

TABLE 3-III (continued)

<u>RHC Control Alone (continued)</u>		
Emission Levels (tons/day)		Controls
420 (point B in Figure 3.2)		Stationary RHC Sources: 15, 16, 17, 18, 19 Mobile Sources: 20, 23, 27, 29, 31
260 (point C in Figure 3.2)		Stationary RHC Sources: 15, 16, 17, 18, 19 Mobile Sources: 20, 22, 24, 25, 27, 29, 30, 31
<u>NO_x Control Alone</u>		
Emission Levels (tons/day)		Controls
786		Uncontrolled
640		Stationary NO _x Sources: 1, 5, 8, 13, 14 Mobile Sources: 23, 26
540		Stationary NO _x Sources: 1, 5, 6, 9, 10, 11, 13, 14 Mobile Sources: 23, 26, 27
460		Stationary NO _x Sources: 2, 4, 5, 6, 9, 10, 12, 13, 14 Mobile Sources: 21, 23, 26, 27
<u>Both RHC and NO_x Control</u>		
Emission Levels (tons/day)		Controls
RHC	NO _x	
666	786	Uncontrolled
560	780	Stationary RHC Sources: 15, 16, 17, 18, 19 Stationary NO _x Sources: 8 Mobile Sources: 23, 26
560	530	Stationary RHC Sources: 15, 17, 18, 19 Stationary NO _x Sources: 1, 5, 6, 9, 10, 11, 13, 14 Mobile Sources: 23, 26, 27

TABLE 3-III (continued)

Emission Levels (tons/day)		Controls
RHC	NO _x	
410	780	Stationary RHC Sources: 15, 16, 17, 18, 19 Mobile Sources: 20, 24, 25, 27, 29, 31
410	530	Stationary RHC Sources: 15, 16, 17, 18, 19 Stationary NO _x Sources: 1, 5, 6, 9, 10, 11, 13, 14 Mobile Sources: 20, 24, 25, 26, 27, 29, 31
270	580	Stationary RHC Sources: 15, 16, 17, 18, 19 Stationary NO _x Sources: 1, 5, 8, 13 Mobile Sources: 20, 22, 24, 25, 26, 27, 29, 30, 31
360	460	Stationary RHC Sources: 15, 16, 17, 18, 19 Stationary NO _x Sources: 2, 4, 5, 6, 9, 10, 12, 13, 14 Mobile Sources: 21, 22, 23, 25, 26, 27, 29, 31
260	530	Stationary RHC Sources: 15, 16, 17, 18, 19 Stationary NO _x Sources: 1, 5, 6, 9, 10, 11, 13, 14 Mobile Sources: 20, 22, 24, 25, 26, 27, 29, 30, 31

rather than draw the actual piecewise linear curves, smooth curves were drawn through 70 solutions to obtain the graph in Figure 3.1.

As can be seen in Figure 3.1, even with all of the control activities considered here in effect, (with an annualized cost of around \$220,000,000), RHC emissions can only be reduced to around 260 tons/day and NO_x emissions to around 460 tons/day. List (1971), has found that a technological lower limit for emissions exists at around 100-150 tons/day RHC and 150-200 tons/day NO_x . These are the emission levels that would be achieved if all motor vehicles in L. A. County met the 1975 standards, stationary sources of RHC were reduced 90% from uncontrolled levels, and all stationary combustion sources emitted NO_x at the lowest existing emission factor, that of a gas range. The main reason that the present study has emission lower bounds about twice those of List's study is the impossibility of all used cars meeting the 1975 standards with just the add-on control devices considered here. Also, most stationary sources of RHC and NO_x cannot be controlled to List's specifications with the control methods now available.

An interesting feature of the control cost function is that, for a given level of RHC control, NO_x control is almost free for considerable reductions, and then it becomes very costly. For instance, for a RHC emission level of 500 tons/day, emission reductions of (0, 50, 100, 150, 200, 250, 300, and 320) ton/day NO_x cost around (\$20 M, \$20 M, \$20 M, \$20 M, \$21 M, \$25 M, \$40 M, \$85 M), respectively. For a RHC emission level of 365 tons/day, emission reductions of (50, 100, 150, 200, 250, 300, and 320) tons/day NO_x cost around (\$110 M, \$99 M,

\$96 M, \$96 M, \$99 M, \$113 M, \$192 M), respectively.* This phenomenon results from two properties of the control methods. First, exhaust controls for RHC in used motor vehicles also reduce NO_x . In buying RHC control for used cars, one gets some NO_x control free. Second, NO_x intensive control methods tend to divide into two categories, very inexpensive controls and very expensive controls. Considering only controls that concentrate on NO_x reduction, a reduction of 95 tons/day can be achieved at around \$20/ton, 35 more tons/day can be bought at \$175/ton, and 50 more tons/day can be gained at around \$2000/ton. Once the inexpensive NO_x control methods are exhausted, one is forced to go to very costly control alternatives. This high non-linearity in the NO_x control cost function is also illustrated in Figure 3.3 by the strong curvature at around 500 tons/day NO_x .

For given NO_x control, RHC control costs rise nonlinearly but more gradually. For instance, for a NO_x emission level of 600 tons/day, RHC emission reductions of (50, 100, 150, 200, 300, and 390 tons/day) respectively cost (\$3 M, \$8 M, \$16 M, \$28 M, \$55 M, \$96 M, \$148 M, and \$192 M). The more gradual curvature (see Figure 3.2) results because, unlike NO_x controls, most RHC intensive controls are rather evenly distributed in cost from around \$200/ton to \$2000/ton.

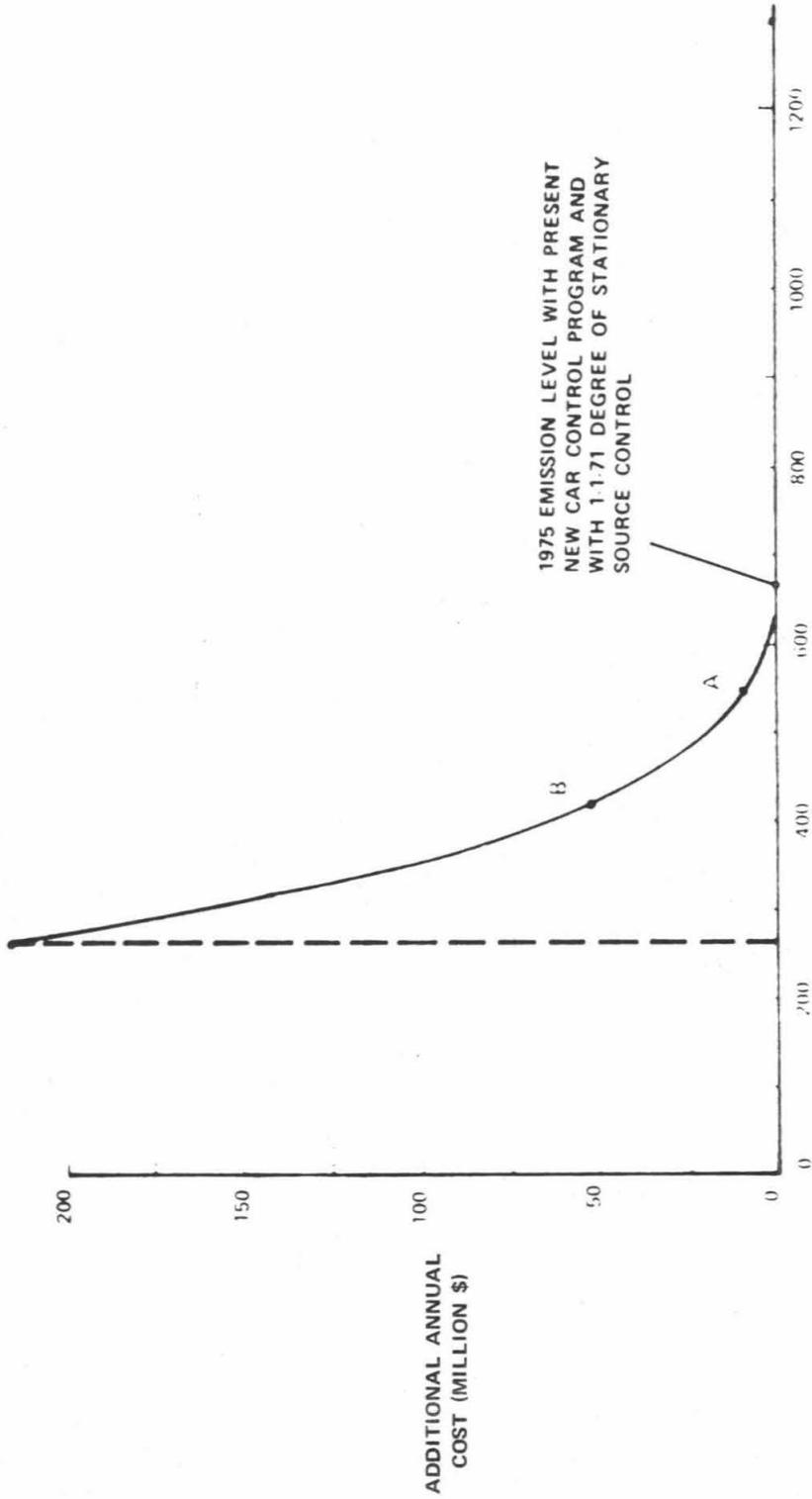
Figure 3.2 presents the cost of RHC control alone, irrespective of NO_x control. The base 1975 emission level is

* Costs here initially decrease with NO_x reductions! This results because extensive RHC control with little NO_x control precludes the use of some inexpensive RHC controls that also reduce NO_x considerably.

Figure 3.2

THE MINIMAL COST OF RHC CONTROL ALONE

THE COST OF ATTAINING VARIOUS REACTIVE HYDROCARBON EMISSION LEVELS IN L.A. COUNTY BY 1971



L.A. COUNTY REACTIVE HYDROCARBON EMISSION LEVEL 1975 (Tons/Day)

666 tons/day. Additional control costs rise according to the curve up to around \$215 M per year at an emission level of 260 tons/day. As indicated in Table 3-III, reaching point A (550 tons/day at a cost of \$10 M per year) involves control of stationary RHC sources, gas stations and various users of organic solvents. The average cost-effectiveness of this control is around \$240/ton RHC. To attain point B (420 tons/day at \$50 M per year), one adds exhaust control to pre-1969 used cars, converts fleet cars to natural gas, and controls aircraft emissions. The average cost-effectiveness ratio for this added set of controls is \$840/ton RHC. Reaching point C (260 tons/day at \$215 M per year) basically requires evaporative control to pre-1969 used cars. The cost effectiveness of evaporative control retrofit is \$2,810 per ton RHC.

For comparison, the cost-effectiveness of some parts of the new car control program are as follows:

<u>Control</u>	<u>Cost-Effectiveness</u>
Exhaust Control, 1966-1969 cars	\$100/ton RHC*
Evaporative Control, 1970 [†] cars	\$600/ton RHC**
Exhaust Control, 1975 [†] cars	\$1750/ton RHC***

* Assuming an initial cost of \$25 per car (HEW AP-66, 1970), no operating costs, $i = 10\%$, emission reduction of 4.5 gm/mile RHC (ARB Implementation Plan, 1971), (APCD Profile, 1969), an average lifetime of 10 years (California ARB), and average use of 22 miles/day (California ARB). (This control system consists basically of "leaning out" the cars and making minor engine design changes.)

** Assuming an initial cost of \$45 (HEW AP-66, 1970), maintenance cost of \$9 per year (Downing and Stoddard, 1970), fuel savings of \$3 per year, $i = 10\%$, an emission reduction of .12 lbs./day RHC (ARB Implementation Plan, 1971), (APCD Profile, 1969), and an average life of 10 years. (This is the carbon adsorption evaporative control system.)

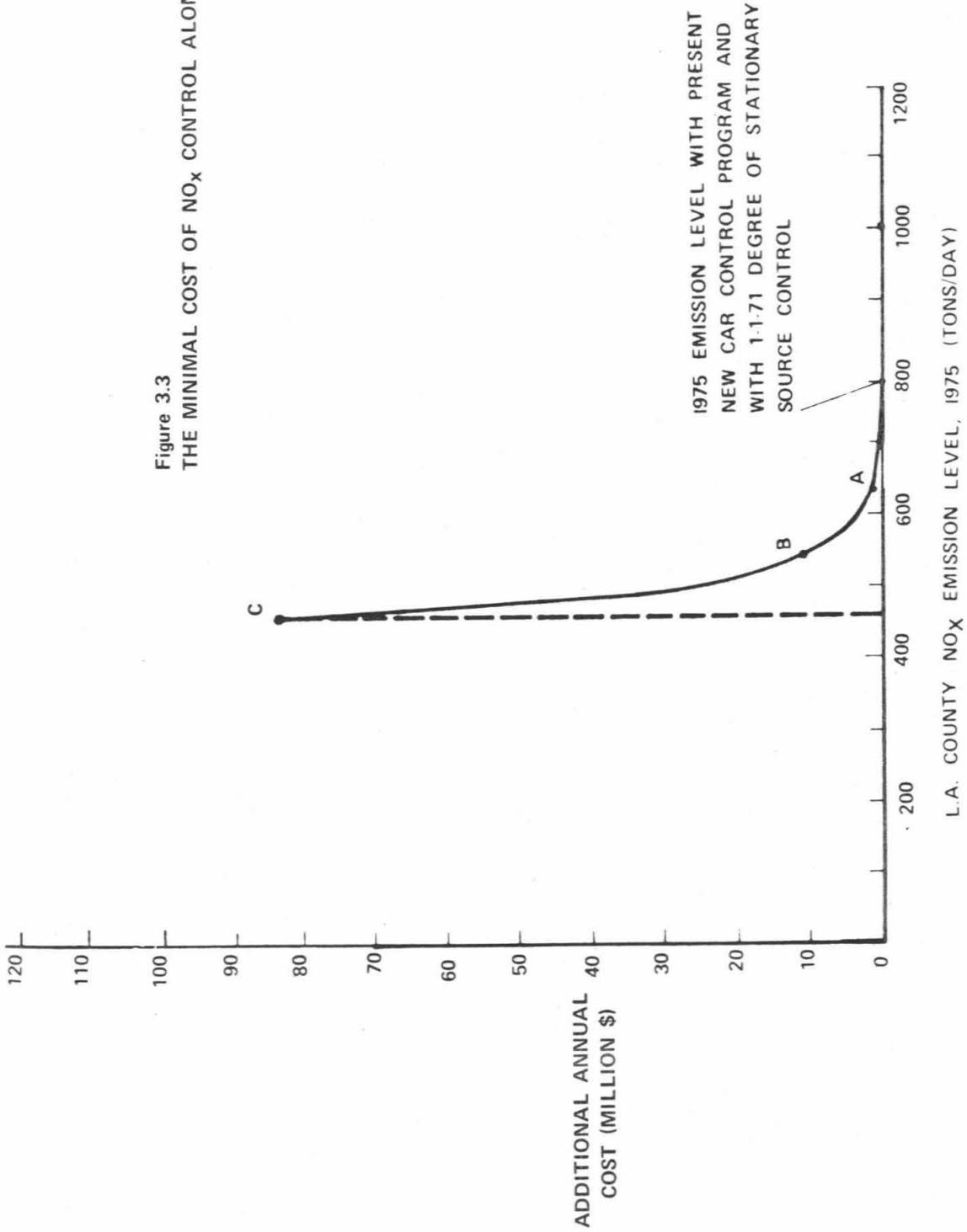
*** Assuming an additional initial cost of \$150 for RHC control (National Academy of Sciences, 1972), (Postma, March, 1972), an

The original new car RHC controls are inexpensive compared to the controls considered here. However, meeting the 1975 standards, will apparently involve control costs almost as high as the most expensive controls considered in this study.

Figure 3.3 presents the cost of NO_x control alone. The 1975 level is 786 tons/day. The costs of further reductions are indicated by the curve up to \$83 M per year at 460 tons/day. As indicated in Table 3-III, reaching point A (640 tons/day NO_x at \$1 M per year) involves low excess air control on large industrial boilers and large refinery heaters, exhaust retrofit to 1966-1970 used cars, control of large and small stationary engines, and burning available natural gas in power plants. The average cost-effectiveness of these controls is only \$19 per ton NO_x . To reach point B (540 tons/day NO_x at \$11 M per year), one adds low excess air control to small refinery heaters and small power plant boilers, converts fleet cars to natural gas, and adds the most advanced type of combustion control to large power plant boilers. The average cost-effectiveness of these extra controls is \$280 per ton NO_x . Finally, to attain point C (460 tons/day NO_x at \$83 M per year), one adds flue gas recirculation to large industrial boilers and small power plant boilers, controls medium size boilers, and puts exhaust control on pre-1966 cars. The average cost-effectiveness of these controls is \$2500 per ton NO_x .

operating cost of \$10 per year, $i = 10\%$, an additional reduction over the 1969 level of 2.2 gm/mile RHC, (ARB Implementation Plan, 1971), (APCD Profile 1969), an average life of 10 years, and average use of 22 miles/day. (This control system consists of further engine design modifications and an oxidizing catalytic afterburner.)

Figure 3.3
THE MINIMAL COST OF NO_x CONTROL ALONE



For comparison, the cost-effectiveness of new car NO_x control is estimated as follows:

<u>Control</u>	<u>Cost-Effectiveness</u>
Exhaust Control, 1972 cars	\$ 60 per ton NO_x *
Exhaust Control, 1974 cars	\$1700 per ton NO_x **

Again, the initial new car control is inexpensive compared to the controls studied here. However, advanced new car control becomes very expensive. The extreme jump from \$60 per ton to \$1700 per ton in new car NO_x control costs is similar to the high nonlinearity in costs for the NO_x controls of this study. NO_x emissions from combustion sources can initially be reduced rather easily, but once they are cut about in half, further control becomes very costly.

All the controls considered in this study can be established at an annual cost of \$220 M, or \$28 per Los Angeles County resident. To give more insight into the magnitude of this cost, the following comparisons can be made. In 1975, the new car control program for Los Angeles County vehicles alone will cost around \$150 M per year.*** Total highway construction costs in L. A. County are around \$300 M per year

* Assuming an initial cost of \$10 (National Academy of Sciences, 1972), no operating cost, $i = 10\%$, an emission reduction of 3.0 gm/mile (from 6.0 to 3.0 gm/mile), an average life of 10 years, and average use of 22 miles/day. (This is basically the spark retard system.)

** Assuming an extra initial cost of \$100 (National Academy of Sciences, 1972), (Postma, March 1972), an operating cost of \$10 per year, $i = 10\%$, an additional emission reduction of 1.7 gm/mile (from 3.0 gm/mile to 1.3 gm/mile), an average life of 10 years, and average use of 22 miles/day. (This control package will probably consist of flue gas recirculation and other engine design changes.)

*** Assuming each car costs \$320 for control (National Academy of Sciences, 1972).

(California Statistical Abstract, 1969). In 1975, total gasoline taxes in the County will be around \$420 M per year (APCD Profile, 1971).

§3.4 ASSUMPTIONS AND APPROXIMATIONS

§1.8 listed five assumptions implicit in using a linear programming model to determine the control cost-emission level relation. These assumptions are discussed below with specific reference to the model as applied to RHC and NO_x emissions in Los Angeles County.

1. The linear programming model computes the minimum emission control cost only for the given control activity input, the set X_j . All possible control alternatives are not included in this set. Some are not entered in the program because insufficient information for estimating cost and effectiveness is available. For instance, reduced driving is not included since the cost of such control is not readily determined. Some controls are not included because they interact in a nonlinear way with other controls, violating assumption 5 (see below). For example, reducing gasoline volatility is not considered because of nonlinear interaction with vapor control systems for gas stations.* Other control possibilities (e. g., thermal or catalytic reactors for used cars) were eliminated on the basis that they were technically infeasible for the 1975 program. In other studies, certain control alternatives might be ruled out on grounds of political or administrative infeasibility.

* If one unit of "reducing gasoline volatility", X_1 , reduces RHC emissions by $(1 - y_1)\%$, and if one unit of "vapor recycle system", X_2 , reduces RHC emissions by $(1 - y_2)\%$, then x_1 units of X_1 and x_2 units of X_2 reduce emissions by $(1 - y_1 y_2)^{x_1 x_2}\%$.

The effect of including more possible control methods would be to increase the set of controls over which the minimum cost solution is sought. The minimum cost over this larger set will be less than or equal to the cost for the original set. Thus, entering more controls would shift the cost curves in Figures 3.1, 3.2, and 3.3 downward and to the left. This effect is, in fact, the purpose of advances in control technology, to make greater emission reductions available at less cost.

2. The second assumption is that all control activities are infinitely divisible, since x_j , the levels of the controls can take any positive real values. Almost all the controls considered here do not exactly meet this requirement, but the violations of the assumption are not consequential in practice. All the solutions from the linear programming model have the form in which each control method is either fully used or is not used at all except for at most two controls. For each solution, the divisibility assumption is relevant only for these two controls. If, for a particular program, the solution calls for controlling 6.4 of the 8 large power plant boilers and 5,323.2 of the 11,300 service stations, one can just round off to the nearest integer values (6 and 5,323) to take care of the divisibility problem. This problem is actually very insignificant in view of the purpose of this work. We are really interested in whether or not we should control service stations at all and not whether we should control 5,000 or 6,000 of them.

3. It is assumed that control activities have a uniform effect on emissions, the number of sources controlled, and the amount of

limited supply factors used and that they have a fixed unit cost. In actuality, this is not true. For instance, controlling some large boilers with low excess air costs more than others and emission reductions will not be strictly uniform. However, as noted in 2. above, this study is concerned with comparing the average cost-effectiveness of controlling different sources and the non-uniformities within a given control category do not significantly affect these overall results. For the purpose of this work, it is sufficient to regard control activities as homogeneous, with appropriate average values.

4. As with control method effects, it is assumed that sources, emissions, and limited supply inputs themselves are homogeneous. Again, this is not strictly true. For instance, the source category, "large industrial boilers," consists of many different sizes, ranging from 30 MBTU/hr to around 200 MBTU/hr capacity. However, for the purpose of this study, using uniform average values should be sufficient. (See 3 above.)

5. Finally, constant coefficients rules out interactions between different control methods and secondary effects between control methods and source magnitudes or availability of limited supply inputs. As noted in 1. above, control methods which interacted significantly with other control activities were not included in the program. The availability of natural gas, the only limited supply factor, should not depend on the control method levels. However, there may be some secondary effects between control activities and source magnitudes. For instance, if refineries are forced to control stationary internal combustion

engines, they may switch to electric motors (Glauser, July 1971). Instead of fitting their used car with an expensive control device, some drivers may buy new cars. The addition of air pollution control expenses may decrease the growth in gas stations or the use of paints. The effect of all of these secondary effects is similar to the existence of a control method not included in the study, e. g. , replacing engines with electric pumps or decreased use of paints. As noted in 1. above, neglecting some control alternatives leads to an overstatement of the cost of reaching various emission levels.

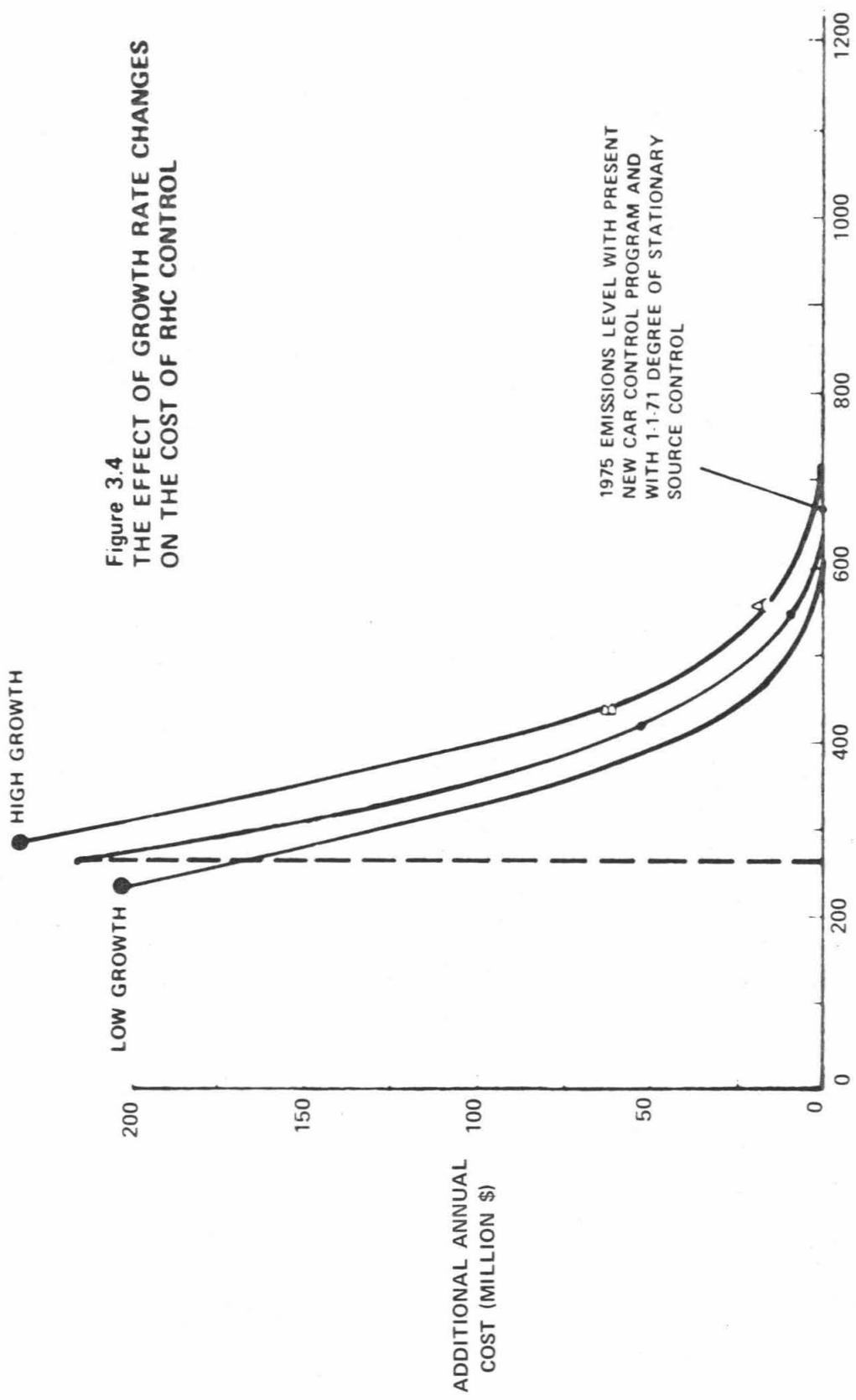
A secondary effect that leads to an underestimate of the cost of reaching various emission levels is the possibility that pollution control will lead to increased growth in Los Angeles. Increased growth means more sources and, thus, higher control costs. The effect of higher growth rates on the results is examined below.

In addition to the above five approximations which are inherent in the use of a linear programming model, the control cost-emission level results contain the approximation of using estimates as the data for the program. The data on natural gas supply and most of the data on source magnitudes and emissions and control method effects should contain less than 20% error. The data on control costs are less reliable; most relative errors are probably in the 20-50% range. In order to investigate the sensitivity of the control cost-emission level results to the approximations made in compiling the data, two studies were performed. First, the assumed growth rate (4% for most stationary sources and 2.5% for motor vehicles) was varied. Results were obtained for

low growth (2% for stationary sources and 1% for motor vehicles) and for high growth (6% and 4%). The effect of growth rate changes on the RHC and NO_x cost curves is shown in Figures 3.4 and 3.5. As expected, higher growth shifts the curves upward and to the right; a given emission level costs more. Lower growth has the opposite effect. The curves do not shift greatly. The overall effect of growth rate change is not large because the growth is compounded only for four years (1971-1975) and because even though higher growth increases emissions, it also increases the amount of emissions that can be controlled. The shift of the curves is very significant in one sense, however. Where the curves are steep, the cost of reaching a given emission level undergoes rather large changes even with small shifts in the curve. For instance, to reach 400 tons/day RHC costs \$50 M for low growth, \$70 M for moderate growth, and \$100 M for high growth. To reach 500 tons/day NO_x costs \$20 M for low growth, \$30 M for moderate growth, and \$150 M for high growth. Thus, the control cost-emission level results are very sensitive to growth rate changes at emission levels where control costs are rapidly rising.

Second, in order to investigate the sensitivity to assumptions on control costs, the program was rerun with high and low cost estimates for each control. The high and low cost curves for RHC and NO_x control are shown in Figures 3.6 and 3.7. As can be seen in these figures, there is considerable possible error in the cost estimates. Reaching 450 tons/day RHC is expected to cost around \$40 M, but could cost as high as \$75 M or as low as \$15 M. 260 tons/day RHC should cost

Figure 3.4
THE EFFECT OF GROWTH RATE CHANGES
ON THE COST OF RHC CONTROL



L.A. COUNTY REACTIVE HYDROCARBON EMISSION LEVEL 1975 (Tons/Day)

1975 EMISSIONS LEVEL WITH PRESENT
NEW CAR CONTROL PROGRAM AND
WITH 1-1.71 DEGREE OF STATIONARY
SOURCE CONTROL

Figure 3.5
THE EFFECT OF GROWTH RATE CHANGES
ON THE COST OF NO_x CONTROL

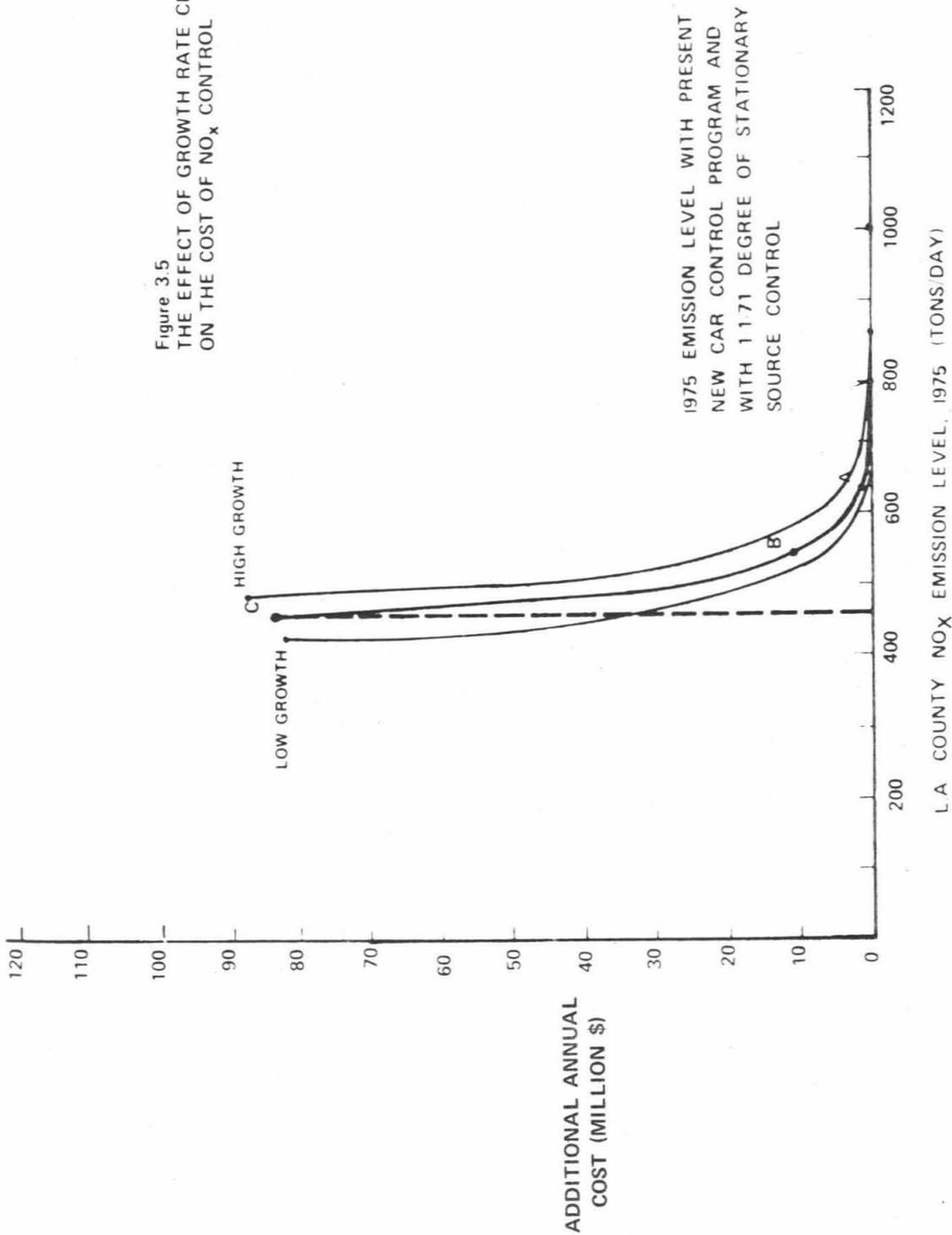
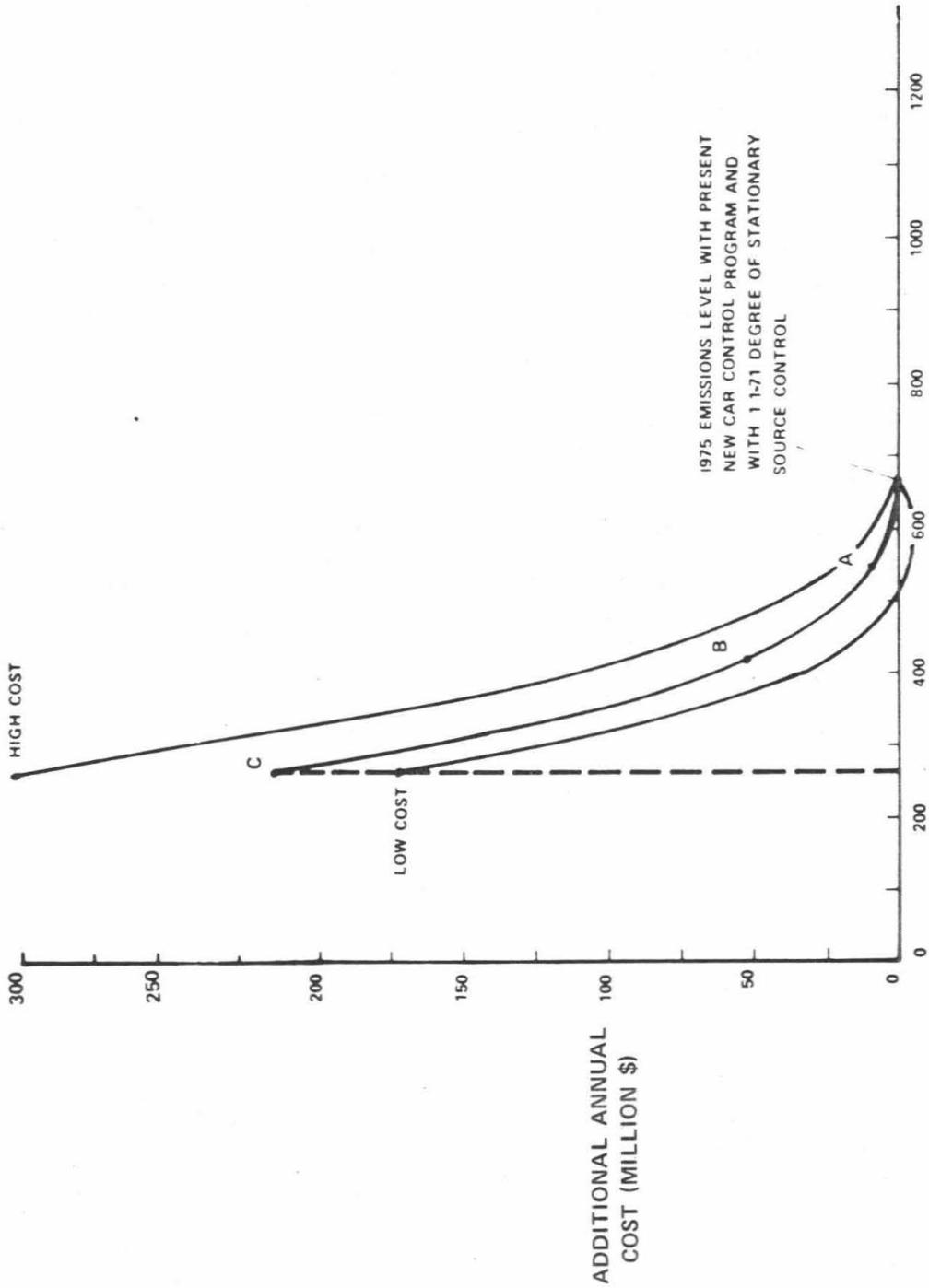


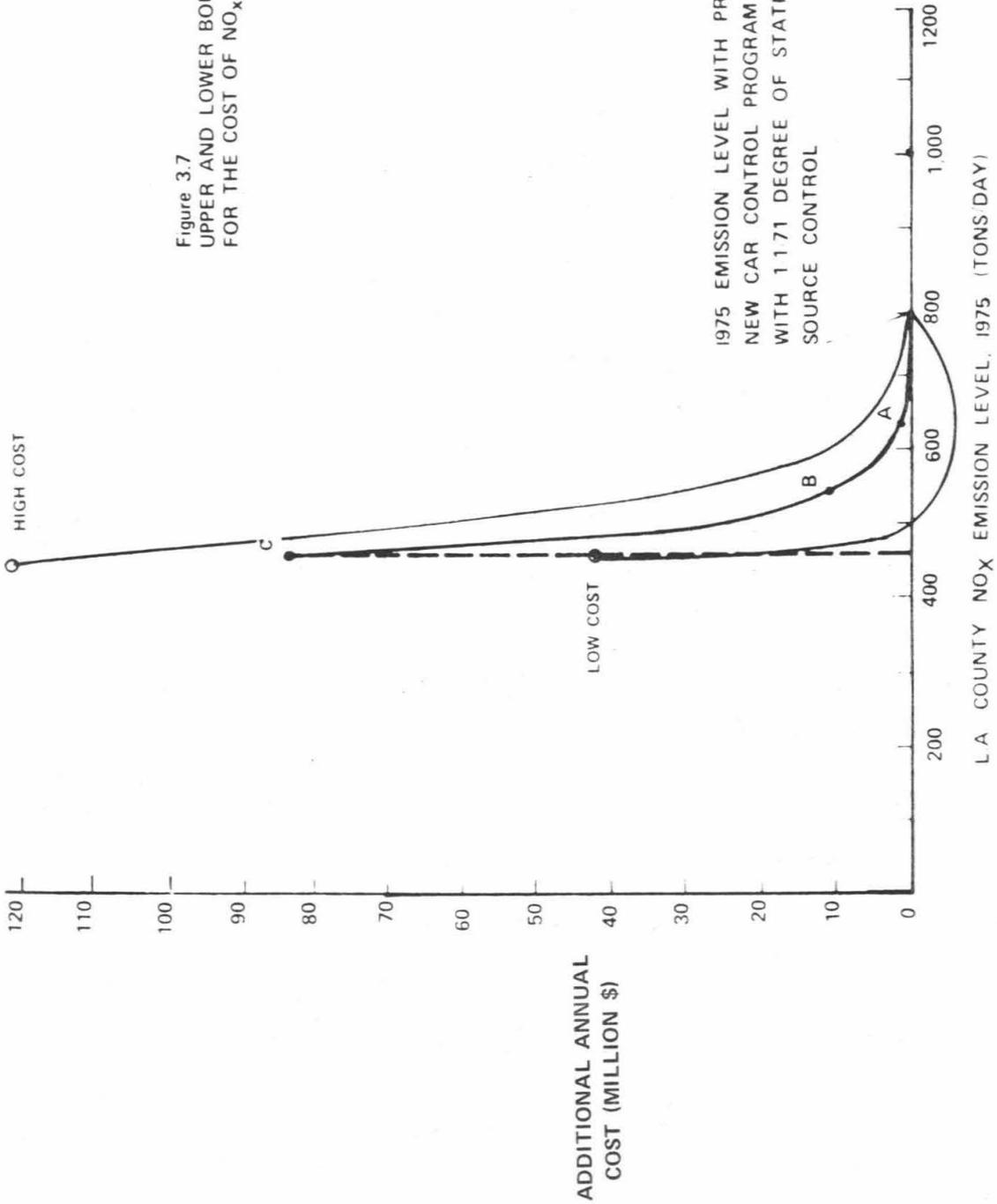
Figure 3.6

UPPER AND LOWER BOUNDS FOR THE COST OF RHC CONTROL



L.A. COUNTY REACTIVE HYDROCARBON EMISSION LEVEL 1975 (TONS/DAY)

Figure 3.7
UPPER AND LOWER BOUNDS
FOR THE COST OF NO_x CONTROL



around \$220 M, but could cost as high as \$300 M or as low as \$170 M. The price of 600 tons/day NO_x should be about \$3 M, but could be as high as \$9 M or as low as an \$8 M savings. 460 tons/day NO_x , with an expected cost of \$83 M, could be as expensive as \$120 M or as inexpensive as \$41 M. The maximum error at full control is thus around $\pm 50\%$. The actual error in the expected costs curves should not be as great as the upper and lower bounds, however. These bounds were obtained by taking maximum and minimum costs for each control. There is no reason to expect that the cost estimates that are actually used are either consistently low or consistently high. The cost estimates are probably low for some controls but high for others. These errors should thus cancel to some degree, and the actual error in the cost curves at full control should be somewhere within, say, the 20% range.

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CHAPTER 4

THE AIR QUALITY-EMISSION LEVEL RELATIONSHIP

§4.1 INTRODUCTION

The previous chapter dealt with the problem of finding the function, $C = G(E_i)$, the minimum cost of reaching various emission levels. The next step in obtaining the minimum cost of various air quality levels is to relate emissions to air quality, i. e., to find the functions, $P_j = F_j(E_i)$, in the least cost air quality model. As noted in §1.9, two general methods for determining the air quality-emission level relation exist, the physico-chemical approach and the phenomenological approach. For reasons discussed in that section, the latter method is used here.

As defined in this work, "phenomenological" or "statistical" models are those which determine expected air quality as a function of emissions by using atmospheric monitoring data taken at one emission level and by making certain simple physical assumptions. §4.2 serves as an introduction to phenomenological models. It examines the case of a strictly proportional air quality-emission level relation. Some of the physical assumptions for this case carry over to the non-proportional models developed in the later sections which are used to find the air quality functions for the Los Angeles photochemical smog example.

§4.3 develops a statistical model for an inert primary pollutant where air quality is measured in terms of the frequency that standards

for the contaminant are exceeded. This model is used to determine $F_2(E_1, E_2)$ for the L. A. smog example, the number of days per year that NO_2 standards are exceeded in Central Los Angeles as a function of emission levels.* An application to carbon monoxide is found in Appendix B.

§4.4 presents a simple stochastic model for determining the frequency of standard violation by a secondary photochemical contaminant formed from two primary contaminants. This model is used to find $F_1(E_1, E_2)$, the number of days per year that mid-day ozone in Central Los Angeles exceeds the state standard as a function of RHC and NO_x emission levels. Appendix C contains an application of this model to eye irritation.

§4.5 develops a more sophisticated stochastic model for the problem examined in §4.4. This model should provide a better estimate of $F_1(E_1, E_2)$, the ozone air quality function. However, the model requires extensive meteorological data as an input and is not applicable with available data.

§4.2 STATISTICAL AIR QUALITY MODELS

4.2.1 The Case of Strict Proportionality

This work takes the statistical approach to air quality-emission level relations and examines cases where air monitoring at one

* NO_2 is, of course, not an inert primary pollutant. This problem is dealt with in §4.3.

emission level allows prediction of air quality at any emission level. For this extrapolation to be possible, certain physical conditions must be met. For an example of the type of conditions involved, the physical assumptions leading to a strictly proportional relationship between air quality and emissions will first be discussed. Of course, when it is known, a priori, that strict proportionality holds, measurement of expected air quality at one emission level allows prediction of air quality at any emission level without difficulty.

A proportional relationship between expected air quality and emissions holds when three conditions are met:

I. Inert Pollutant

Air quality is measured in terms of the concentrations of a single inert pollutant. In this case, the emission and pollution vectors become scalars, E and P. The final pollutant, P, is the same chemical substance as the emitted contaminant, E, and none of the contaminant is lost in chemical reactions. (If such reactions did occur, the amount lost might depend nonlinearly on the concentration and thus destroy proportionality.)

For any given yearly meteorological conditions, the concentration of an inert pollutant at any point in space and time produced by an emission source at some other point in space and time is proportional to the emission level of that source. Also, the total pollution at any point is an algebraic sum of the contributions from all sources. These conditions result from the linearity of the equation of advective diffusion which describes the dispersion of an inert pollutant. Expressed mathematically, these linearity conditions become:

$$P(\underline{x}, t) = \int_0^t \int_V M(\underline{x}, t, \underline{\xi}, \tau) E(\underline{\xi}, \tau) dV(\underline{\xi}) d\tau \quad (4.1)$$

Here, $P(\underline{x}, t)$ is the concentration of the pollutant at any point \underline{x} in V , the air basin, and time t in T , the year. * $M(\underline{x}, t, \underline{\xi}, \tau)$ is the pollutant concentration at (\underline{x}, t) produced by a unit emission at $(\underline{\xi}, \tau)$ for the given yearly meteorology. $E(\underline{\xi}, \tau)$ is the emission source function.

Actually, as noted in §1.5, the meteorology is uncertain. In general, the function M will be specified in the form of a probability distribution. This will lead to a probability distribution for the pollution function, $P(\underline{x}, t)$. ** The stochastic mathematical formulation is cumbersome, and this discussion will proceed in the notation for given meteorology. It should be kept in mind, however, that final pollution is actually specified by probability distributions.

II. Homogeneous Emission Reductions

Emission reductions are carried out homogeneously in space and time in the sense that all sources are reduced in proportion and the reductions occur uniformly throughout the year. In mathematical

* As noted in §1.5, air quality is being considered on a yearly time basis in this work.

** The probabilistic formulation would be as follows: Meteorology would be specified by

$$PR_m(M, \underline{x}, t, \underline{\xi}, t) dM = \text{the probability that the pollution concentration at } (\underline{x}, t) \text{ produced by a unit source at } (\underline{\xi}, \tau) \text{ is in the range } M \rightarrow M + dM.$$

Final pollution would be specified by

$$PR_p(P, \underline{x}, t) dP = \text{the probability that the pollution concentration at } (\underline{x}, t) \text{ is in the range } P \rightarrow P + dP.$$

notation, this condition states that in an emission level change to $E(\underline{\xi}, \tau)$ from a base level of $E^0(\underline{\xi}, \tau)$, reductions occur so that

$$E(\underline{\xi}, \tau) = \alpha E^0(\underline{\xi}, \tau), \quad \text{for all } \begin{cases} \underline{\xi} \in V \\ \tau \in (0, T) \end{cases}, \quad (4-2)$$

where α , independent of $\underline{\xi}$ and τ , is a measure of total emissions.

This assumption rules out the possibility of control measures that improve air quality with no total emission change by emitting contaminants at either favorable places or times, i. e., places or times of high dispersive conditions. Such control measures which alter the emission pattern destroy the proportionality between air quality and total emissions, as measured by α .

It should be emphasized that no assumption is made about the specific emission pattern, $E^0(\underline{\xi}, \tau)$; it can be any function of space and time. The assumption is that whatever the original spatial and temporal pattern is, it is preserved in the emission level changes.

III. Weighted Average Air Quality Index

Air quality is the expected value of a weighted time and spatial average of the pollutant. If V is the air basin volume and T is one year, this condition is expressed mathematically as

Air Quality Loss = AQL

$$= EV^* \left(\frac{1}{T} \int_0^T \int_V K(\underline{x}, t) P(\underline{x}, t) dV(\underline{x}) dt \right). \quad (4-3)$$

*EV \equiv Expected Value.

Here, $K(\underline{x}, t)$ is a weighting function that specifies how pollution at various points in space and time, is counted in the air quality index. It is an arbitrary function. In an actual case, it might be taken to be the population distribution or some other pattern of receptors.*

Combining equations (4-1), (4-2), and (4-3), for given meteorology, one has

$$AQL = \alpha \left\{ \frac{1}{T} \int_0^T \int_V K(\underline{x}, t) \int_0^t \int_V M(\underline{x}, t, \underline{\xi}, \tau) E^0(\underline{\xi}, \tau) dV(\underline{\xi}) d\tau dV(\underline{x}) dt \right\} \therefore (4-4)$$

$E^0(\underline{x}, \tau)$ represents the fixed emission pattern. $M(\underline{x}, t, \underline{\xi}, \tau)$ is the response function, fixed by meteorology. $K(\underline{x}, t)$ is the pollution weighting function.

The quantity contained in the brackets is constant as the emission level, α , changes. Thus,

$$AQL = \alpha \cdot \text{constant} ,$$

which is a proportional relationship.

For stochastic meteorology and final pollution, the proportionality still holds by taking the expected value for air quality. Thus, conditions

* In many applications, air quality is measured by the annual average pollution level at a given monitoring station. If such a station were located at \underline{x}^0 , it would correspond to the weighting function

$$K(\underline{x}, t) = \delta(\underline{x} - \underline{x}^0) \quad (\text{three dimensional Dirac delta function, constant in time})$$

In this case

$$AQL = EV \frac{1}{T} \int_0^T P(\underline{x}^0, t) dt = \text{expected yearly average of } P \text{ at } \underline{x}^0.$$

I, II, and III do lead to a proportional relationship between air quality and total emissions.

4.2.2 Non-Proportional Statistical Models

If a proportional relationship between air quality and total emissions is known to hold a priori, measurement of expected air quality at any given emission level allows prediction of air quality at all emission levels. This chapter will formulate three statistical models for cases in which proportionality does not hold but yet air quality can still be determined as a function of emission levels by air monitoring data taken at one emission level. In the first case, condition III will be relaxed, but conditions I and II will be retained. Air quality will not be measured by a weighted average of pollution levels but rather by the frequency of violation of standards which are stated in terms of pollution not exceeding certain levels for certain periods of time. An example of such an air quality index would be the expected number of days per year that carbon monoxide exceeds 40 ppm for one hour. For such an index, the relation between air quality and total emissions will be, in general, nonlinear. In fact, for constant daily weather conditions, it would be a step function.

§4.3 presents a very simple statistical model for predicting air quality as a function of total emissions in this first case. The model is extremely simple because conditions I and II still insure that pollution at any point in space and time still is proportional to total emissions. This model is applied to the problem of determining the number of days

per year that NO_2 standards are exceeded in Central Los Angeles as a function of L. A. County NO_x emissions, the function $F_2(E_1, E_2)$ in the photochemical smog example. An application to carbon monoxide in Los Angeles is found in Appendix B.

In the second case, examined in §4.4, conditions I and III will both be relaxed. Air quality will be specified in terms of the frequency of standard violation by a secondary photochemical pollutant that forms in chemical reactions stemming from two primary pollutants. A statistical model, similar to one presented by Shuck et al. (1966), will be developed to relate air quality to emissions. For this model to be rigorously applicable, it is necessary to assume that four conditions are met. First, condition II (homogeneous emission reductions) is assumed for the primary pollutants. Second, three assumptions about the daily pollution process are made: that the primary contaminants first accumulate without reacting, that this accumulation stops and then certain weather factors trigger the photochemical pollution reaction, and that the weather factors governing the reaction are statistically independent of the primary contaminant concentrations resulting from the accumulation process. These assumptions are discussed in detail in §4.4. This model is used to determine $F_1(E_1, E_2)$ for the L. A. smog example, the number of days per year that mid-day ozone in Central Los Angeles exceeds the state standard as a function of RHC and NO_x emission levels in L. A. County. Appendix C applies this model to eye irritation in Los Angeles.

The third model, presented in §4.5, is the same as the second except that more refined statistical methods, which take the reaction governing weather factors into account, are used. The final assumption of the second model is dropped, and possible correlations between the weather factors and the primary contaminant concentrations are explicitly accounted for. This last model depends only on condition II and on the two assumptions about the way primary contaminants accumulate. It should provide a better estimate of the ozone air quality index. However, attempts at completing the model for the ozone problem failed because of insufficient meteorological data.

§4.3 A STATISTICAL MODEL FOR AIR QUALITY MEASURED BY FREQUENCY OF STANDARD VIOLATIONS, APPLICATION: NO₂ AIR QUALITY IN CENTRAL LOS ANGELES

4.3.1 Analytical Framework

As mentioned in §4.2, a proportional relationship between air quality and emission levels is no longer assured if air quality is gaged by the frequency of violation of certain standards. An example of such an air quality scale, and the one to be considered here, occurs when air quality loss is taken to be the number of days per year that certain standards (stated in terms of pollution not exceeding some level for n hours) are exceeded. For such an air quality scale, however, air quality at any emission level can still be determined from air monitoring data at one emission level provided conditions I and II of §4.2 hold, i. e., provided the pollutant is inert and emissions are reduced homogeneously. This determination of the air quality-emission relationship is accomplished as follows:

At a given emission level, call it E^0 , of the pollutant, P , one measures the following distribution function of pollutant levels:

$N^0(P) dP$ = the number of days per year that the maximum n hour concentration* of the pollutant is in the range $P \rightarrow P + dP$.

Now, if conditions I and II hold, then pollution at any point in space and time is proportional to emissions. Thus, in an emission change to $E = \alpha E^0$, days with maxima in the range $Q \rightarrow Q + dQ$ at emission level E^0 go to days with maxima in the range $\alpha Q \rightarrow \alpha Q + \alpha dQ$. The distribution function $N(P)$ at emission level $E = \alpha E^0$ will therefore satisfy:

$$N(P)dp = N^0(P/\alpha) d(P/\alpha) . \quad (4-5)$$

Thus, if P^s is the n hour standard for pollutant, P ,

$$\left. \begin{aligned} \text{the number of days per year} \\ \text{that } P^s \text{ is exceeded for } n \text{ hours} \\ \text{at emission level } E = \alpha E^0 \end{aligned} \right\} &= \int_{P^s}^{\infty} N(P) dP = \int_{P^s}^{\infty} N^0(P/\alpha) \frac{dP}{\alpha}, \\ &= \int_{P^s/\alpha}^{\infty} N^0(P) dP, \quad (4-6) \\ &= \text{function of } \left\{ \begin{array}{ll} P^s & \dots \text{ the standard ,} \\ \alpha & \dots \text{ emission level ,} \\ N^0(P) & \dots \text{ distribution function} \\ & \text{measured at one emis-} \\ & \text{ sion level .} \end{array} \right. \end{aligned}$$

*The maximum can be measured either at a fixed monitoring point or taken as the maximum over several monitoring points. The choice depends on whether one is interested in violations at a fixed point or at any of several points in a region. This paper, which examines violations in Central Los Angeles, takes the case of a fixed point.

Thus, if conditions I and II of §4.2 are met, one can calculate air quality at any emission level by measuring the distribution function, $N^0(P)$, at one emission level and by using equation (4-5).

4.3.2 NO₂ Standard Violations in Downtown Los Angeles As A Function of L. A. County NO_x Emission Levels, $F_2(E_1, E_2)$

4.3.2.1 Applicability of the model.

This section applies the statistical model of 4.3.1 to determine the number of days per year that the state NO₂ standard (0.25 ppm for 1 hour) is exceeded in Downtown L. A. as a function of the L. A. County NO_x emissions. The analysis is predicated on conditions I and II of section 4.2. Some discussion of the validity of these assumptions for the problem at hand is in order.

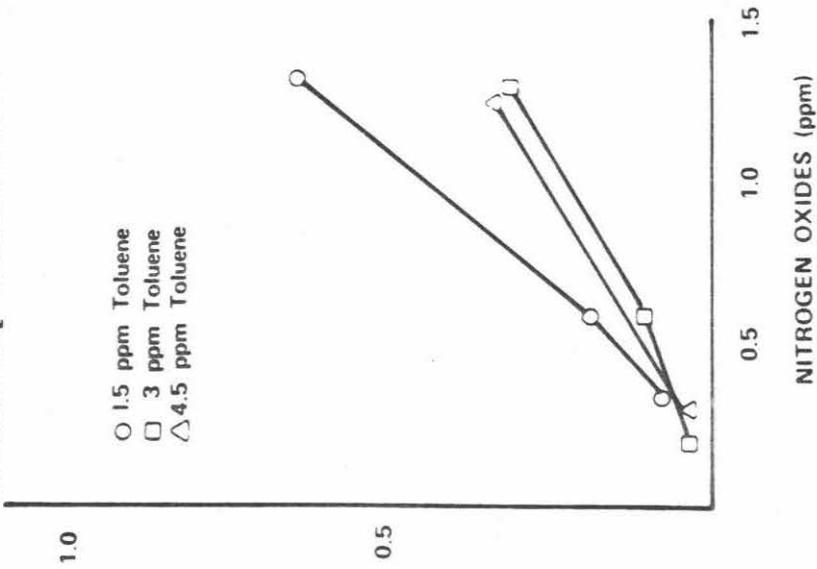
For this example, some difficulty obviously exists with condition I, the inert pollutant assumption. NO₂ pollution is being examined as a function of NO_x emissions. NO_x, the sum of NO and NO₂, is emitted primarily as NO, (HEW, AP-67, 1970). Once in the atmosphere, the NO is oxidized to NO₂. This oxidation process is greatly enhanced by the presence of reactive hydrocarbons and sunlight. Thus, NO₂, rather than being an inert primary pollutant, is in reality more of a secondary pollutant.

With this in mind, it might seem best to relate NO₂ levels to both NO_x and RHC emissions. However, here it is simply assumed that NO₂ atmospheric concentrations are proportional to NO_x emissions. Experimental results, presented in Figures 4.1 and 4.2,

Figure 4.1 EXPERIMENTAL NO₂ · NO_x RESULTS

Figure 4.1a

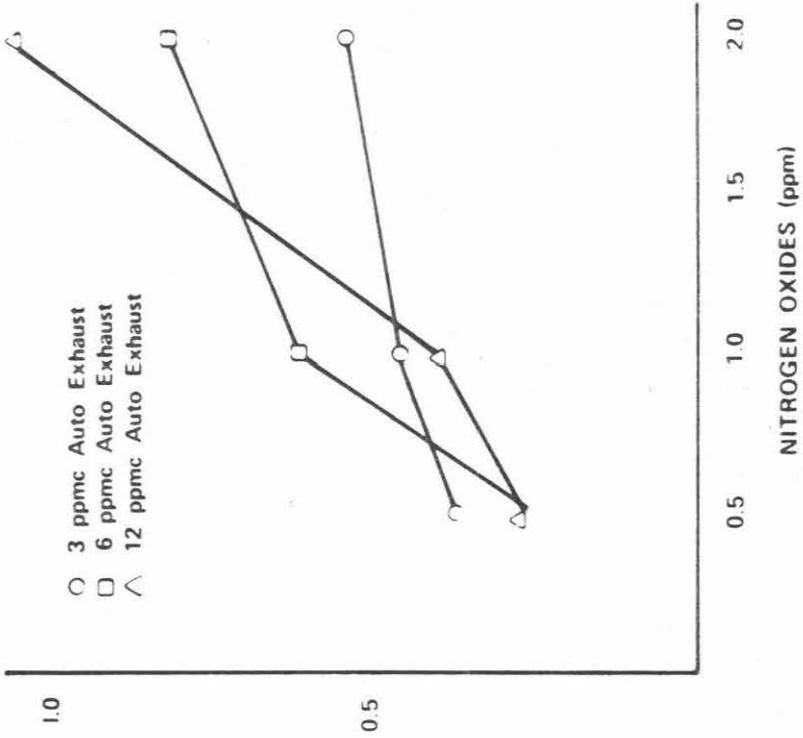
AVERAGE NO₂ CONCENTRATION (0.6 hrs.)



AVERAGE NO₂ CONCENTRATION AS A FUNCTION OF INITIAL NO_x (80-95% NO) CONCENTRATION AT THREE TOLUENE LEVELS DURING 6 HR. IRRADIATION (ALTSHULLER, KOPCZYNSKI, et al. 1970)

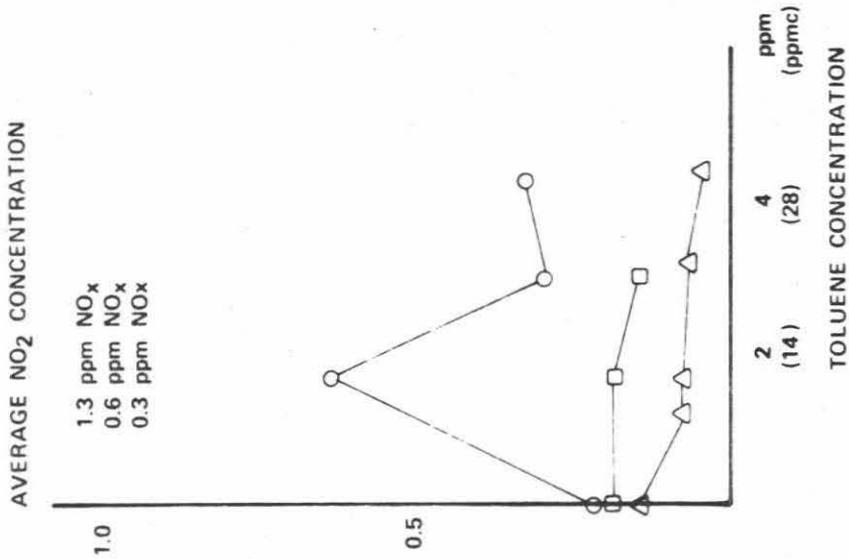
Figure 4.1b

AVERAGE NO₂ CONCENTRATION (0.4 hrs.)

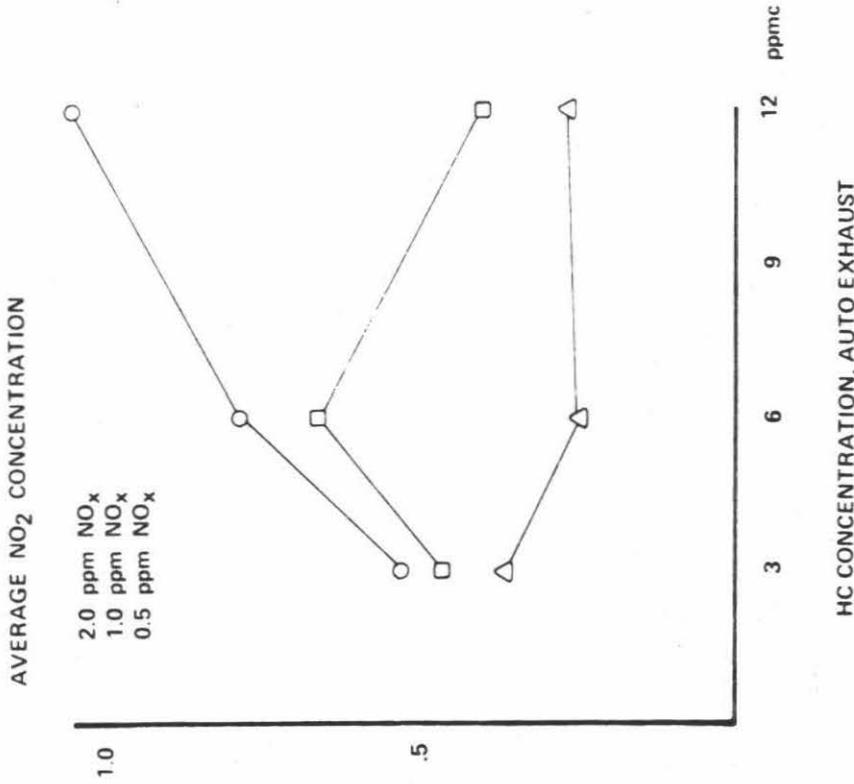


AVERAGE NO₂ CONCENTRATION AS A FUNCTION OF INITIAL NO_x CONCENTRATION AT THREE HC LEVELS DURING 4 HOUR IRRADIATION. (KORTH, ROSE, STAHPMAN, 1964)

Figure 4.2 EXPERIMENTAL NO₂ · HC RESULTS
 FIGURE 4.2a



AVERAGE NO₂ CONCENTRATION AS A FUNCTION OF TOLUENE CONCENTRATION AT THREE NO_x (80-90% NO) LEVELS DURING 6 HOUR IRRADIATION. DATA FROM (ALTSHULLER, KOPCZYNSKI, et al., 1970)



AVERAGE CONCENTRATION, AUTO EXHAUST OF HC CONCENTRATION AT THREE NO_x LEVELS DURING 4 HOUR IRRADIATION. DATA FROM (KORTH, ROSE, STAHPMAN, 1964)

(Altshuller et al., 1970, Korth et al., 1964), attest to this being a good first approximation. Figures 4.1 and 4.2 give average* NO_2 concentrations produced by irradiating various NO_x and HC mixtures. Figures 4.1a and 4.1b give average NO_2 concentration as a function of initial NO_x concentration for given HC levels. Figures 4.2a and 4.2b give NO_2 yield vs initial HC concentration for fixed NO_x levels. Figure 4.1 reveals that NO_2 concentrations consistently rise with the initial NO_x level. In the Altshuller experiment, the rise appears slightly more than proportional, in the Korth experiment less than proportional. Figure 4.2 apparently shows that NO_2 levels follow no consistent trend with HC concentrations. In the Altshuller experiment, considerable NO_2 is produced even at zero HC input due to "trace organic contaminants in the dilution air or desorbed from the walls." It appears that even trace amounts of HC lead to considerable NO_2 production and that once the critical amount of HC is present, NO_2 concentrations do not follow a consistent trend with further HC addition. Since NO_2 levels do consistently rise with increasing NO_x , a rough first approximation would be to simply assume NO_2 concentrations are proportional to NO_x input. This assumption is made here.

The second assumption, homogeneity of NO_x emission reductions, also does not hold exactly. In Los Angeles County, there are two principal sources of NO_x , automobiles (68%), and stationary source fuel combustion (26%), (APCD Profile, 1971). Fifty-five percent of

*Actually, data on maximum NO_2 concentrations would be more appropriate, but no such experimental results were found in the literature.

the latter results from power plants. As seen in Figure 4.3, the spatial distribution of power plants differs considerably from that of automobile use (APCD Profile, 1969; Roberts et al., 1971). Motor vehicle mileage centers around Downtown Los Angeles, while power plants are concentrated in the southwest coastal area and just to the north of Downtown. The temporal distributions of vehicular and power plant emissions also differ. Since automobile emissions affect Downtown Los Angeles more than power plant emissions, a control program that preferentially controlled motor vehicles would benefit Downtown more than by the total emission reduction factor. Conversely, controlling power plants more strictly would leave Downtown with an NO_x emission reduction less than proportional to the total emission change. This limitations must be kept in mind in using the results of the model. It may not be very significant since both power plants and motor vehicles will be included in most control programs. Fortunately, the other 45% of stationary source NO_x emissions does not differ radically in spatial distribution from automobile mileage. This is illustrated in Figure 4.4 showing vehicular mileage and the location of large non-power plant boilers and heaters (APCD Profile, 1969; Roberts et al., 1971). Both distributions center near Downtown Los Angeles.

4.3.2.2 Data

Hourly concentration data from the APCD Downtown station were used to determine $\text{N}^0(\text{P})$, the distribution of daily one hour NO_2 maxima. Data were obtained for the years 1966, 67, 68, and 69, with L. A. County NO_x emission levels of 920, 940, 970, and 1000 tons per

Figure 4.3

COMPARISON OF MOTOR VEHICLE MILEAGE AND POWER PLANT SPATIAL DISTRIBUTIONS

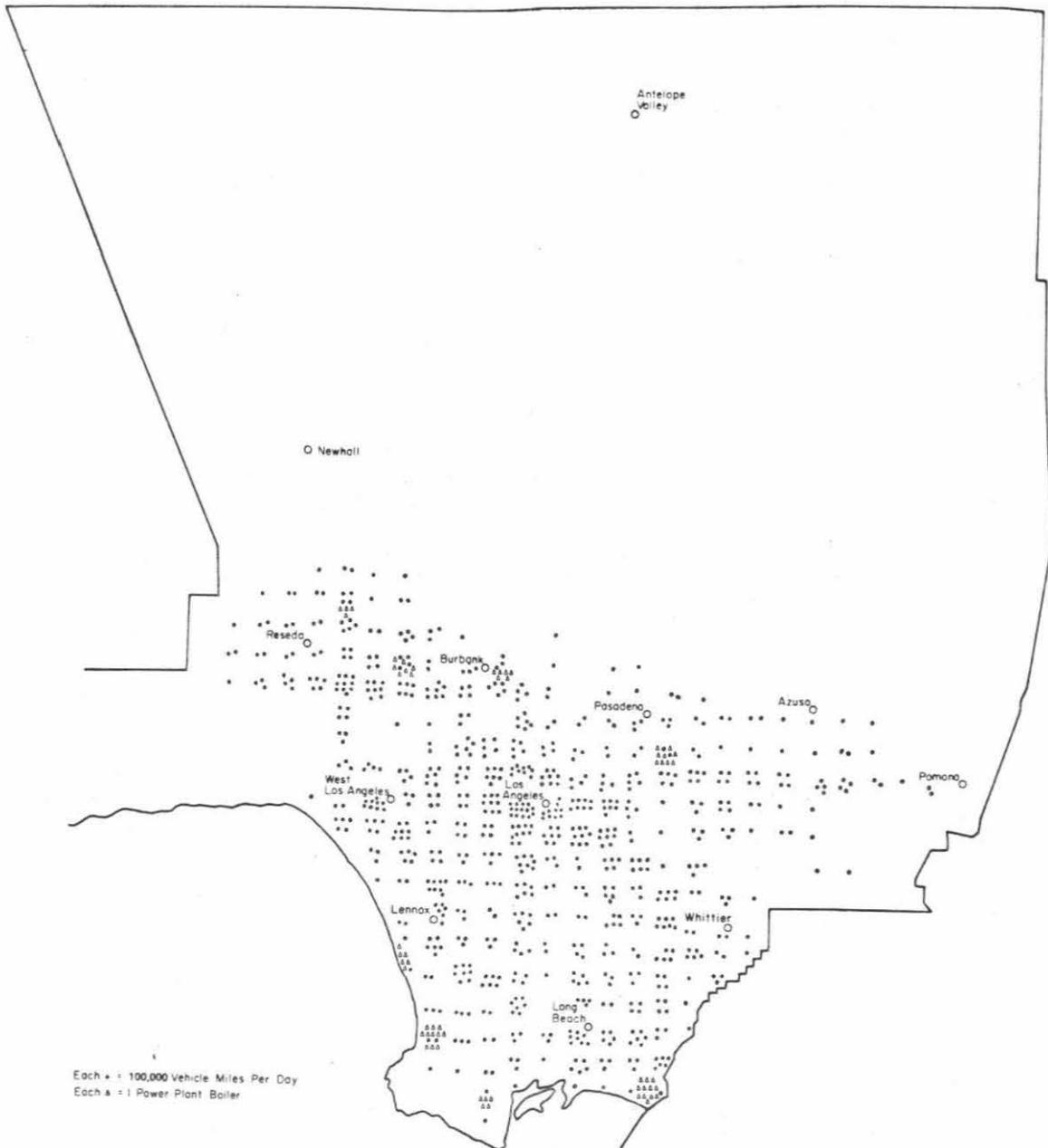
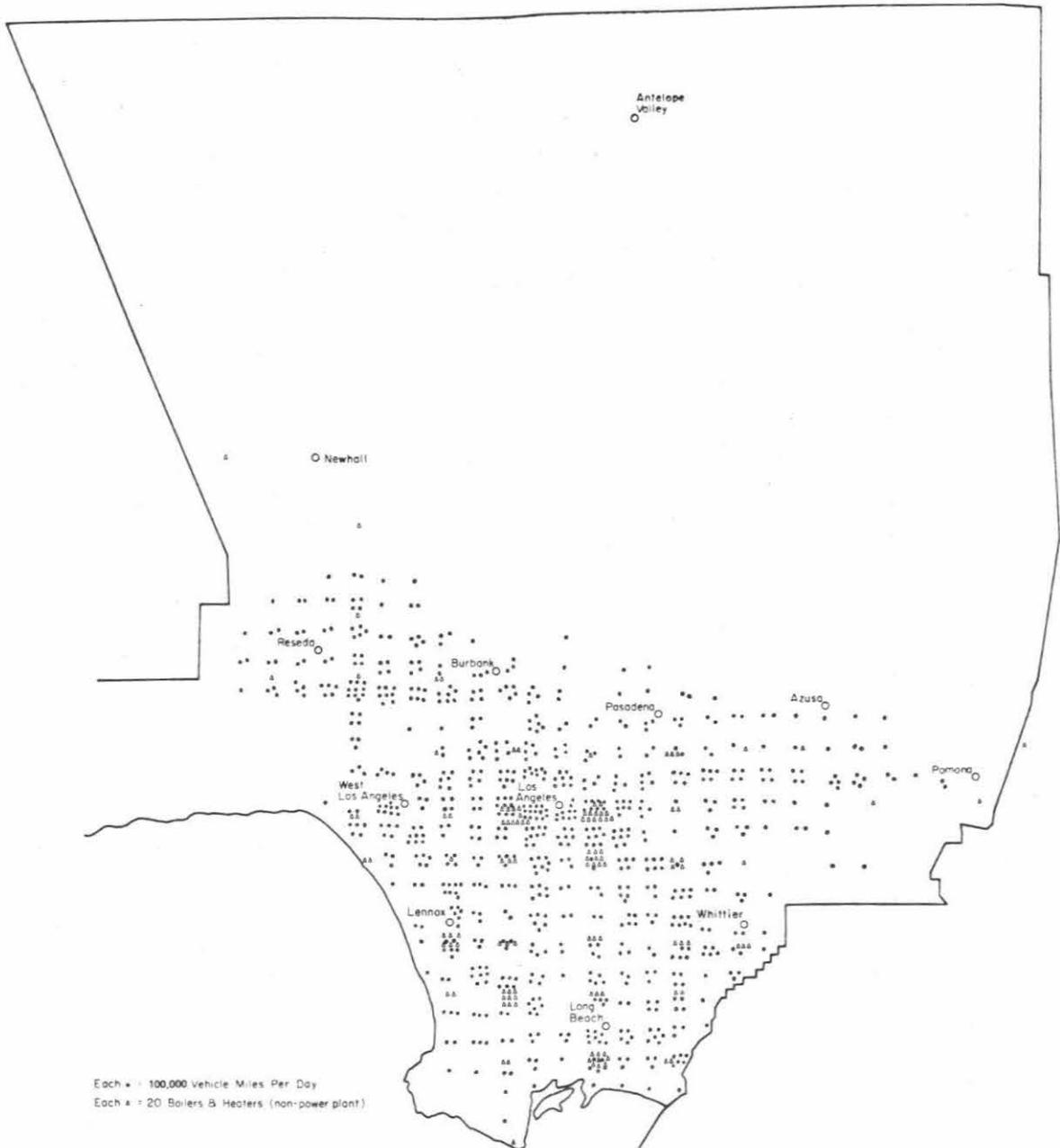


Figure 4.4

COMPARISON OF MOTOR VEHICLE MILEAGE AND NON-POWER PLANT COMBUSTION SOURCE SPATIAL DISTRIBUTIONS



day, respectively (APCD Profile, 1971). Each year was reduced to a base emission level of $E^0 = 1000$ tons/day by multiplying the concentrations of that year by E^0 and dividing by the emission level of that year. This was a small correction.

Figure 4.5 gives the measured distribution function, $N^0(P)\Delta P$, for $\Delta P = 0.01$ ppm. Figure 4.6 presents a smooth curve of the $N^0(P)$ distribution.

4.3.2.3 Results and conclusions.

Equation 4-5 was used to calculate the expected number of days per year that NO_2 exceeds the state standard in Downtown L. A. as a function of the L. A. County NO_x emissions. Figure 4.7 presents the results, the function $F_2(E_1, E_2)$ (independent of E_1), in the photochemical smog example. Emission levels for the 1960's are marked off on the abscissa. It can be seen that at the 1969 emission level, NO_2 standard violations occurred around 55 days per year. A 50% reduction in NO_x emissions (500 tons/day) reduces violations to around 3 days per year. Bringing emissions to less than 300 tons/day virtually eliminates days exceeding the standard. For the first 500 ton/day reduction, one less violation per year is brought by each 10 tons/day less emissions. For the next 200 tons/day reduction, one less violation required 60 tons/day less emissions. Since a given emission reduction is more costly at lower emission levels, this change in the slope of the function at about 500-600 tons/day NO_x may be very significant to control policy decisions.

As illustrated in Figure 4.8, the present control policy calls

Figure 4.5 MEASURED DISTRIBUTION FUNCTION, $N^0(P)$

$N^0(P)/\Delta P$ = NUMBER OF DAYS PER YEAR WITH
 MAXIMUM ONE HOUR NO_2 CONCENTRATION IN THE RANGE $P \rightarrow P+\Delta P$
 here, $\Delta P = 1\text{pphm}$

for: Downtown Los Angeles
 at: Emission level of 1000
 tons per day of NO_x

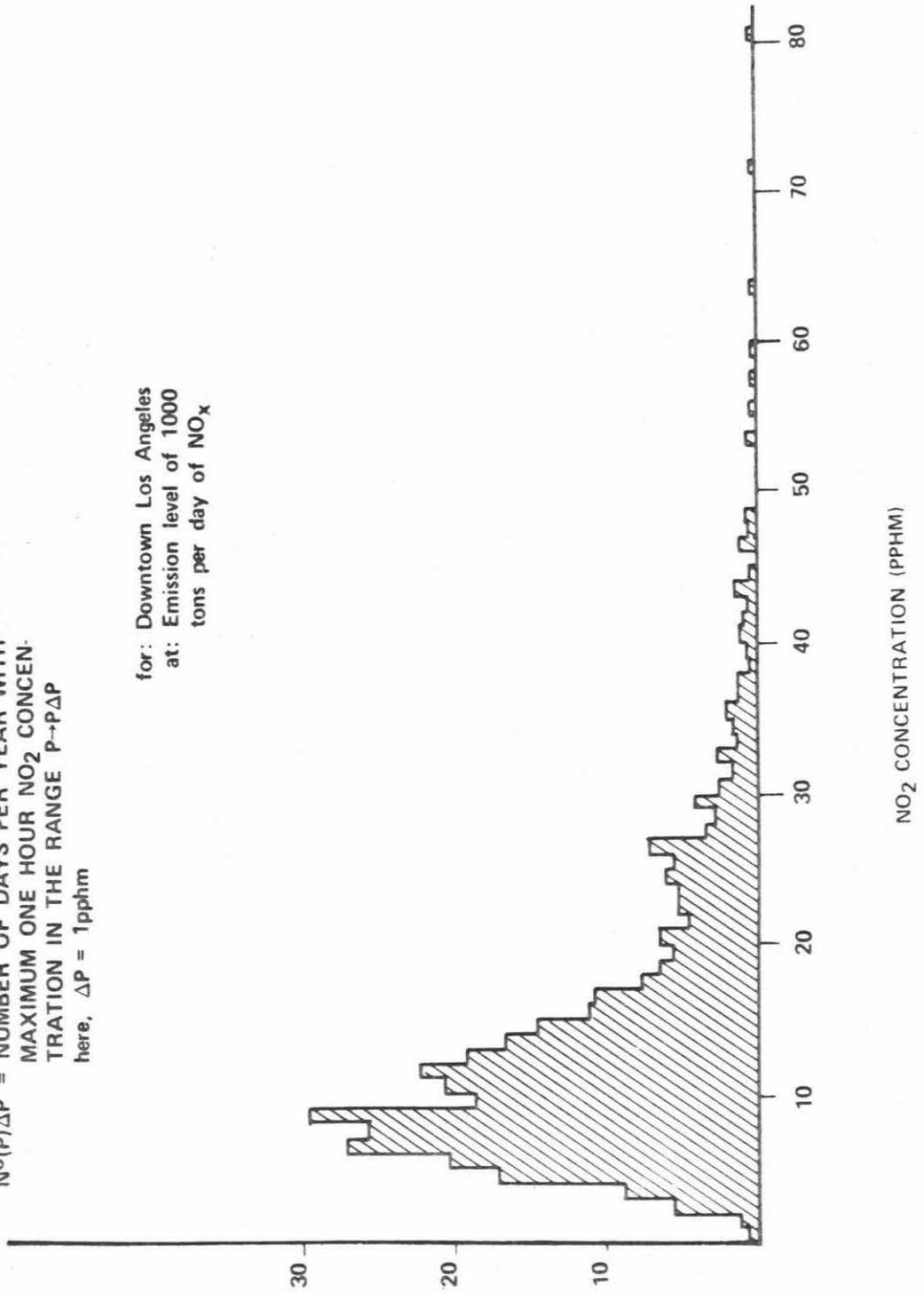
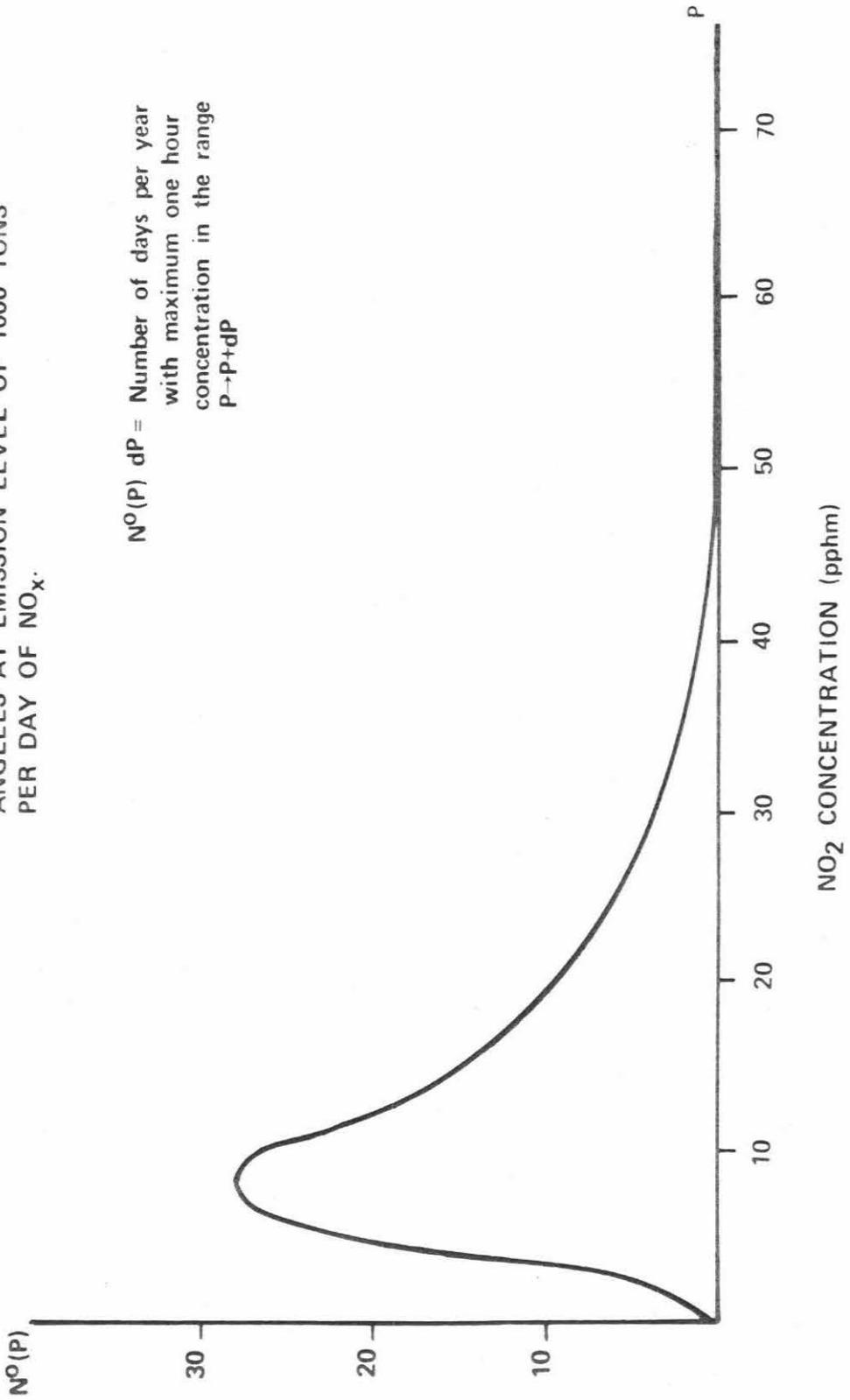


Figure 4.6
 DISTRIBUTION OF DAILY ONE HOUR MAXIMAL
 NO₂ CONCENTRATIONS FOR DOWNTOWN LOS
 ANGELES AT EMISSION LEVEL OF 1000 TONS
 PER DAY OF NO_x.



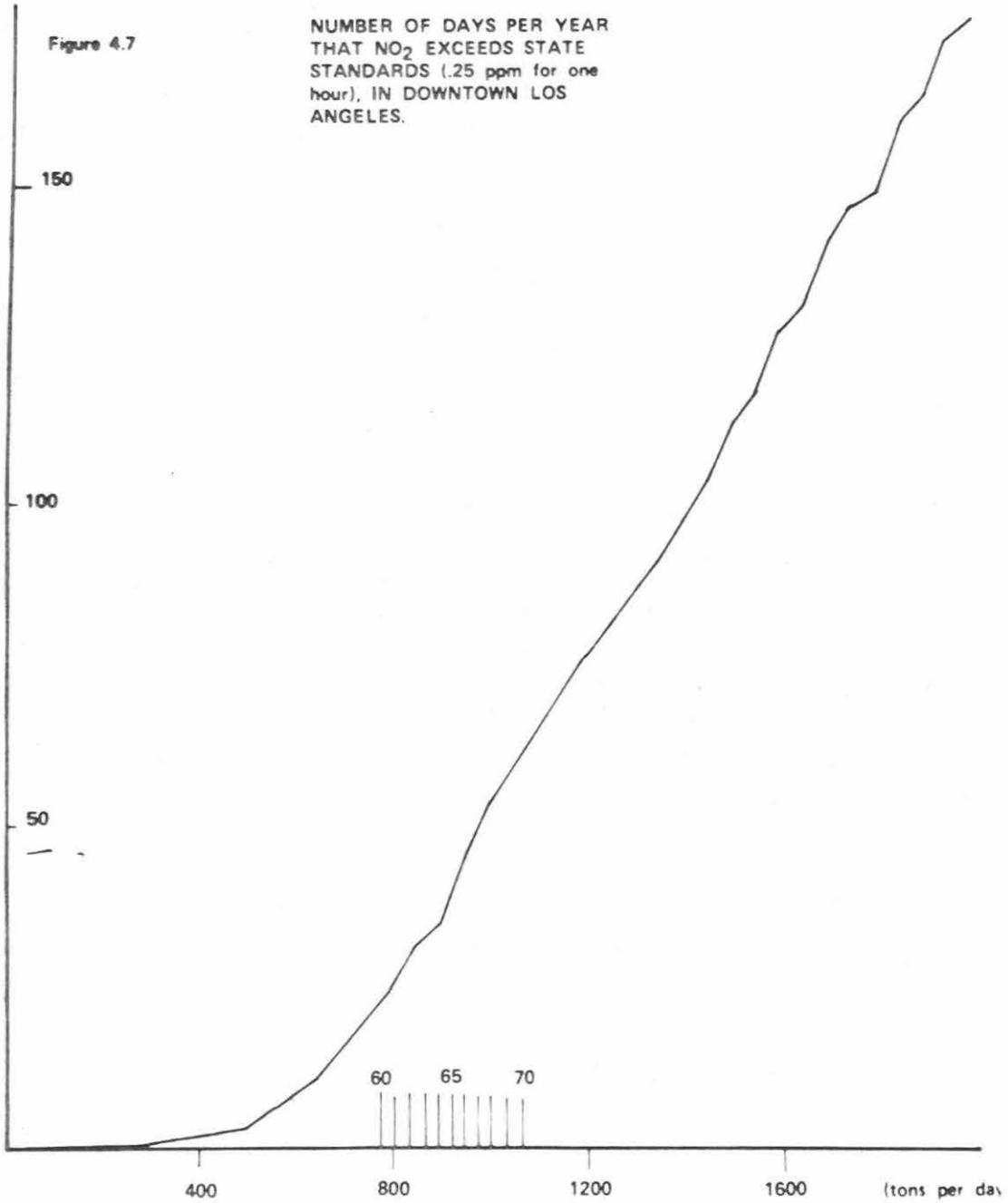
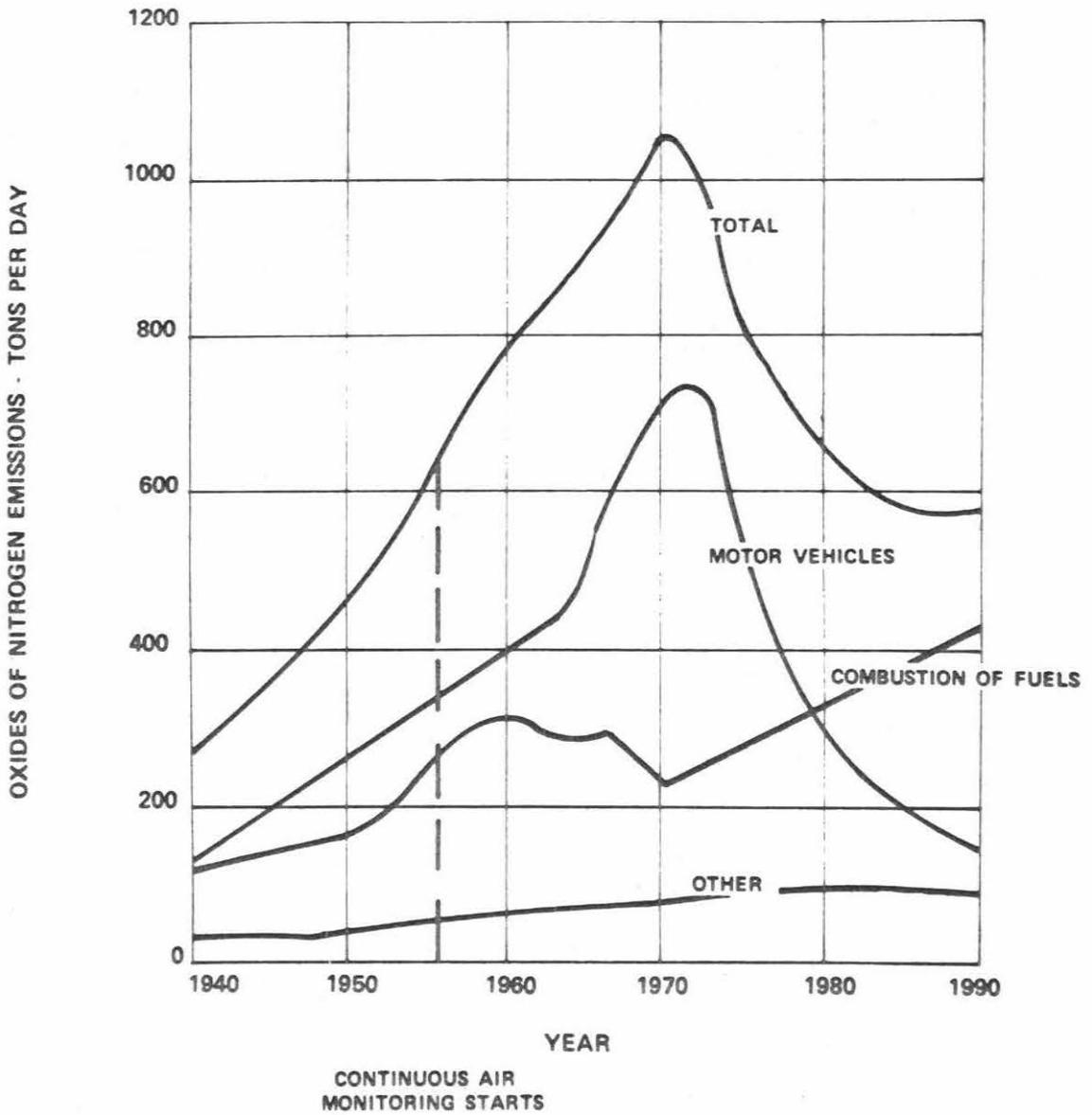


Figure 4.8
 HISTORY OF OXIDES OF NITROGEN IN L.A. COUNTY



for NO_x emissions to be reduced to 800 tons/day by 1975 and to around 600 tons/day by 1980. With this policy, the 55 days per year violations in 1969 will be reduced to 25 days per year in 1975 and 8 days per year in 1980.

Since there has been significant NO_x emission level changes since air monitoring began in 1956 (see Figure 4.7), it appears possible to check the results of the model by comparing them with the actual emission level-standard violation history. Table 4-I presents data for this check gathered from APCD pollution log books. The data reveal

TABLE 4-I

History of NO_2 Air Quality in Downtown Los Angeles

Year	Number of Days/Year $\text{NO}_2 \geq 0.25$ ppm in Downtown Los Angeles
1957	28
1958	46
1959	47
1960	38
1961	41
1962	46
1963	30
1964	23
1965	53
1966	59
1967	46
1968	37
1969	16
1970	42

that NO_2 standard violations in Downtown Los Angeles have changed very little since 1956. From the results of the statistical model, one would expect about 15-20 days per year violations in the late 50's and about

50 days per year in the late sixties. The model does not check with the historical data. However, a discussion with Walter Hamming, (July 1971), of the APCD revealed that the model cannot be expected to fit past data. The homogeneity of emission reduction assumption was definitely not met in the emission level changes that occurred since the 1950's. Much of the NO_x emission increase in L. A. County has been the result of growth in motor vehicle use. This growth took place in a distinctly unhomogeneous fashion; the Downtown area received little growth compared to outlying areas of the County. This growth pattern, which does not submit Downtown L. A. to much increase in NO_x emissions, is illustrated by the fact that yearly average NO_x concentration increased only from 15.6 pphm (1959-1964) to 16.7 pphm (1965-1970) in Downtown L. A. This nonhomogeneous emission level increase explains the failure of the model in fitting historical data. Future emission reductions will occur by addition of controls on each source with little redistribution of emissions. The model should work much better for this case.

A partial check of the model can be made from air monitoring history by comparing maximal NO_2 concentrations to average NO_x concentrations at stations that have experienced growth in NO_x . This comparison would serve as a check on the assumption that maximal NO_2 concentrations are proportional to NO_x emissions. In Table 4-II, 3 year averages of NO_x concentration are compared with average maximal NO_2 concentrations for the 50 highest days in those three years for Burbank and Azusa. For Burbank, the relationship is very

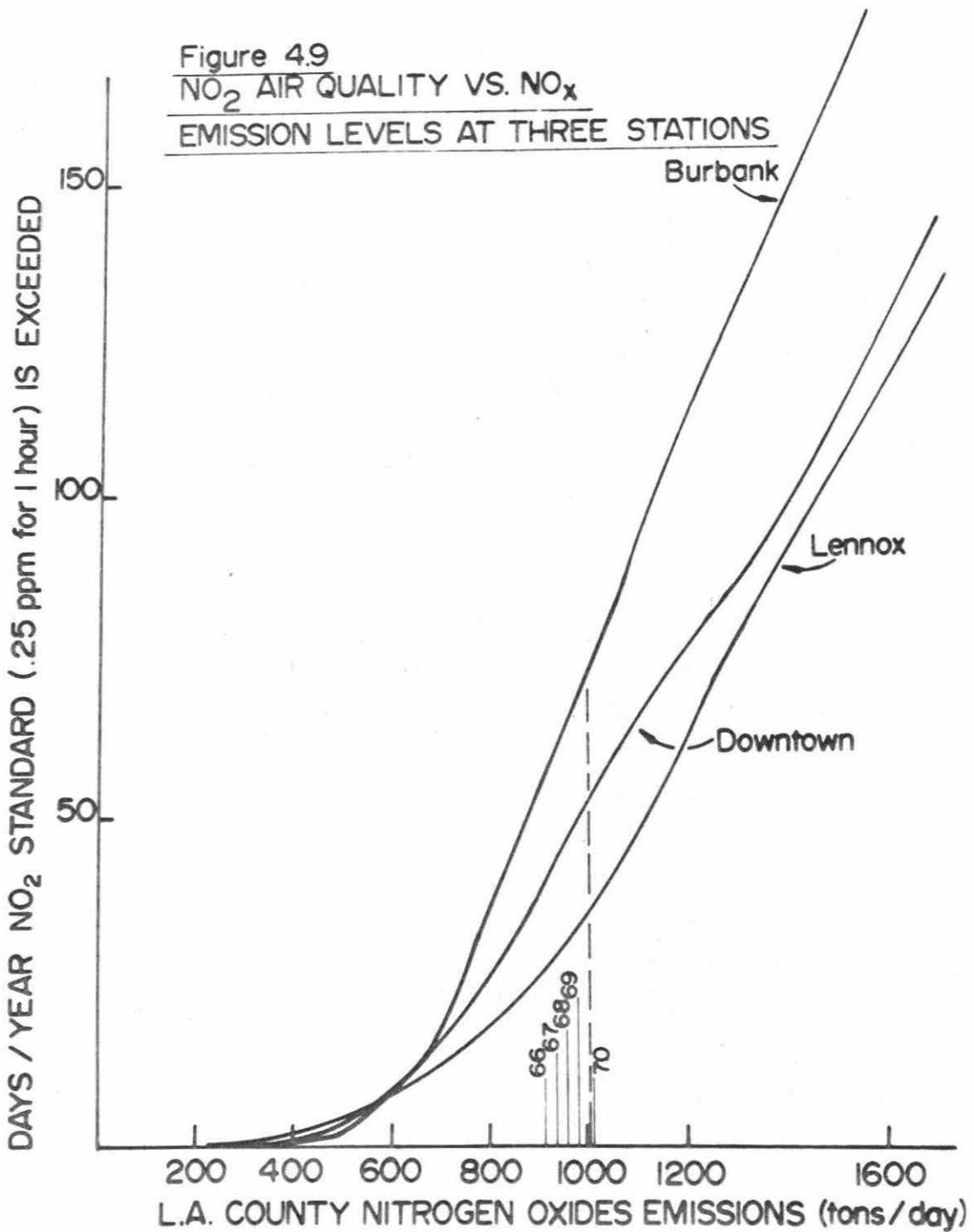
close to proportional; an average NO_x increase of 1.50 corresponds to a maximal NO_2 increase of 1.48. For Azusa, the relationship is less than proportional, average NO_x increasing by 1.42 while maximal NO_2 increases only by 1.22. In both cases, however, maximal NO_2 concentrations increase with NO_x concentrations, and the first approximation that NO_2 concentrations are proportional to NO_x emissions is probably not grossly in error.

TABLE 4-II
Comparison of Maximal NO_2 Concentrations to Average
 NO_x Concentrations at Burbank and Azusa

	Average Yearly NO_x Concentration		1 hr. Average NO_2 Concentration on 50 Worst Days in 3 Years	
	62, 63, 64	68, 69, 70	62, 63, 64	68, 69, 70
Burbank	15.5 ppm	23.2 ppm	28.0 ppm	41.4 ppm
	ratio 1.50		ratio 1.48	
Azusa	5.7 ppm	8.1 ppm	22.4 ppm	27.4 ppm
	ratio 1.42		ratio 1.22	

4.3.2.4 Comparison to other stations.

For comparison, the model was also applied to NO_2 standard violations in Burbank and Lennox. Downtown, Burbank, and Lennox are the three L.A. County stations with the highest NO_2 levels (APCD Profile, 1971). The results are shown in Figure 4.9. The air quality emission curves for all three stations are very similar. A reduction



of NO_x emissions to 500 tons/day leaves just 3-7 violations per year at each station. It is interesting that above 600 tons/day, NO_x violations are highest at Burbank, and below 600 tons/day, they are highest at Lennox. Burbank has many "moderately bad" days but few "very bad days." Lennox has less "moderately bad" days but more "very bad days."

§4.4 A SIMPLE PROBABALISTIC MODEL FOR DETERMINING THE FREQUENCY OF STANDARD VIOLATION BY A SECONDARY CONTAMINANT FORMED FROM TWO PRIMARY CONTAMINANTS

4.4.1 Analytical Framework

This section develops a simple stochastic model for predicting air quality levels of a secondary pollutant, Z, produced by reactions stemming from two primary contaminants, X and Y.* The model will be applied to the problems of determining the number of days per year that mid-day (11 A.M. - 1 P.M.) ozone and eye irritation, ($Z = \text{O}_3$) and ($Z = \text{EI}$), violate standards in Central Los Angeles as functions of reactive hydrocarbon ($X = \text{RHC}$) and nitrogen oxide ($Y = \text{NO}_x$) emissions in Los Angeles County. As will become apparent below, the assumptions underlying the model tailor it specifically to mid-day levels of a secondary photochemical pollutant.

Four assumptions form the basis for the model: condition II of §4.2 (homogeneous emission reductions) and three assumptions about

*The reaction leading to the formation of Z need not be a binary reaction, $X + Y \rightarrow Z$; natural atmospheric components may participate and there may be intermediate reaction steps.

the daily temporal pattern of X and Y formation and Z production. These assumptions are discussed below. To aid comprehension, the conditions about the daily pollution pattern are briefly illustrated with the ozone example. Complete discussions of the validity of the assumptions as they apply to the ozone and eye irritation problems are found in section 4.4.2.2 and Appendix C.

Assumptions for the Model:

(i) Emission reductions of the primary contaminants, X and Y, occur homogeneously. This is condition II of §4.2 which states that emission reductions are carried out proportionately among all sources in space and time for each pollutant.

Daily pollution pattern assumptions:

(ii) In the air mass that will lead to the pollution on any day, emissions of X and Y accumulate without reacting. The accumulation process produces final concentrations x and y of X and Y in the air mass. [For the ozone problem, this refers to overnight and early morning accumulation of RHC and NO_x emissions. It is assumed that these emissions are made into previously uncontaminated air and that they do not react during the night and early morning.]

(iii) At some point in time, t_1 , emissions stop, and at some later time, $t_2 \geq t_1$, certain meteorological factors trigger the reaction of X and Y to produce Z. The only effect of emissions on Z production is through the concentrations x and y . "z", the level of Z formed on any day, is a function of x , y , and the meteorological factors that

govern the reaction. These weather factors will be symbolically represented by a vector \underline{W} . Thus,

$$z = z(x, y, \underline{W}) \quad (4.7)$$

[In the ozone problem, solar radiation is the principal weather factor that starts the reaction of RHC and NO_x . Temperature, vertical mixing, and horizontal mixing also govern the reaction. The assumption that emissions of RHC and NO_x stop before the reaction starts is of course not really valid. This is discussed in section 4.4.2.2.]

(iv) The weather factors, \underline{W} , that determine the level of Z produced from x and y are statistically independent of x and y . That is, the daily probability distribution of \underline{W} is independent of the daily probability distribution of x and y . [For the ozone problem, this means that days of various morning concentrations all have the same distribution of ozone producing weather factors.]

Based on these four assumptions, a statistical model, similar to one employed by Shuck et al. (1966), is developed for determining the number of days per year that the secondary pollutant, Z , exceeds standards as a function of emission levels for X and Y . The input of the model consists of monitoring data taken at one (yearly) emission level. The analysis is as follows:

At one emission level of X and Y , call it $\underline{E}^0 = (E_1^0, E_2^0) = \underline{E}^0(\underline{x}, t)$, one measures the following two functions

$N^0(x, y) dx dy \equiv N(E^0, x, y) dx dy$ is the number of days per year (4-8)
that concentrations of X and Y are in the ranges
 $x \rightarrow x + dx$ and $y \rightarrow y + dy$, respectively.

$P_{z_s}^0(x, y) dx dy \equiv P_{z_s}(E^0, x, y)$ is the probability that the Z (4-9)
standard, z_s , will be violated on any day
in the air mass containing x and y .

Then for any emission level, $\underline{E} = (\alpha E_1^0, \beta E_2^0) = (\alpha, \beta) \cdot \underline{E}^0(x, t)$,
assumptions (i) \rightarrow (iv) imply that the new functions $N(x, y)$ and $P(x, y)$
satisfy

$$N(x, y) dx dy = N^0(x/\alpha, y/\beta) d(x/\alpha) d(y/\beta) , \quad (4-10)$$

and

$$P_{z_s}(x, y) = P_{z_s}^0(x, y) . \quad (4-11)$$

Equation (4-10) just states that concentrations x and y are
proportional to emission levels for X and Y, respectively. This pro-
portionality follows from (i) and assumption (ii), that no reactions
occur while the concentrations x and y are forming. (As dis-
cussed in §4.2, the concentrations of an inert pollutant undergoing
homogeneous emissions changes are proportional to total emissions
because of the linearity of the equation of advective diffusion.)

Equation (4-11) results from assumptions (iii) and (iv).
Since the probability of a violation depends on (x, y) and the \underline{W} dis-
tribution, and since the \underline{W} distribution is independent of (x, y) , days

of concentration (x, y) after an emission change will have the same probability of a violation as those of concentration (x, y) before the change. A mathematical proof of (4-11) is presented in the footnote below.*

From (4-10) and (4-11), the expected number of days per year of standard violation for the secondary pollutant is calculated as follows:

*Proof of (4-11)

By assumption (iii), on any day

$$z = z(x, y, \underline{W}) \quad . \quad (a)$$

Consider the distribution function, η , defined as follows:

$$\begin{aligned} \eta(\underline{E}, x, y, \underline{W}) dx dy d\underline{W} \\ = \eta(\underline{E}, x, y, \underline{W}) dx dy d\underline{W}, \dots, d\underline{W}_N = \text{the number of days per} \\ \text{year with concentrations in the ranges} \\ (x \rightarrow x+dx), (y \rightarrow y+dy) \text{ and weather in the} \\ \text{range } \underline{W} \rightarrow \underline{W}+d\underline{W} \text{ at emission level } \underline{E}. \end{aligned}$$

By (iii), the only effect of \underline{E} is on (x, y) . By (iv), the \underline{W} distribution is independent of the (x, y) distribution. This implies η has the special form

$$\eta(\underline{E}, x, y, \underline{W}) = \psi(\underline{E}, x, y) \phi(\underline{W}) \quad (b)$$

Now,

$$P_{z_s}(x, y) \equiv P_{z_s}(\underline{E}, x, y) = \frac{\int_{\text{all } \underline{W}} \eta(\underline{E}, x, y, \underline{W}) H[z(x, y, \underline{W}) - z_s] d\underline{W}}{\int_{\text{all } \underline{W}} \eta(\underline{E}, x, y, \underline{W}) d\underline{W}} \quad (c)$$

Expected number of days per year that z exceeds the standard, z_s , as a function of emission levels, α and β } = $\int_0^\infty \int_0^\infty P_{z_s}(x, y) N(x, y) dx dy$,

which by (4-10) and (4-11)

$$\begin{aligned}
 &= \int_0^\infty \int_0^\infty P_{z_s}^0(x, y) N^0(x/\alpha, y/\beta) \frac{dx}{\alpha} \frac{dy}{\beta} , \\
 &= \int_0^\infty \int_0^\infty P_{z_s}^0(\alpha x, \beta y) N^0(x, y) dx dy \\
 &= \text{function of } \begin{cases} z_s & \dots \text{ the standard} \\ \alpha, \beta & \dots \text{ primary contaminant emission levels} \\ P^0, N^0 & \dots \text{ distribution functions measured at one emission level.} \end{cases} \quad (4-12)
 \end{aligned}$$

where $H(z) \equiv \begin{cases} 0, & z < 0, \\ 1, & z > 0, \end{cases}$ and $z_s =$ the Z standard.

But, (b) and (c) imply

$$\begin{aligned}
 P_{z_s}(x, y) &= \frac{\psi(\underline{E}, x, y)}{\psi(\underline{E}^0, x, y)} \frac{\int_{\text{all } \underline{W}} \phi(\underline{W}) H[z(x, y, \underline{W}) - z_s] d\underline{W}}{\int_{\text{all } \underline{W}} \phi(\underline{W}) d\underline{W}} \\
 &= \frac{\psi(\underline{E}^0, x, y)}{\psi(\underline{E}^0, x, y)} \frac{\int_{\text{all } \underline{W}} \phi(\underline{W}) H[z(x, y, \underline{W}) - z_s] d\underline{W}}{\int_{\text{all } \underline{W}} \phi(\underline{W}) d\underline{W}} \\
 &= \frac{\int_{\text{all } \underline{W}} \eta(\underline{E}^0, x, y) H[z(x, y, \underline{W}) - z_s] d\underline{W}}{\int_{\text{all } \underline{W}} \eta(\underline{E}^0, x, y) d\underline{W}} \\
 &= P_{z_s}(\underline{E}^0, x, y) = P_{z_s}^0(x, y)
 \end{aligned}$$

One further aspect of this model deserves comment. Assumptions (i) → (iv) include all the theoretical requirements necessary for (4-12) to be valid. However, to apply the model, one must be able to measure $P_{Z_s}^O(x, y)$ for all x and y . In order to determine $P_{Z_s}^O(x, y)$, some mechanism must exist that produces substantial variations in (x, y) for a given emission level, $\underline{E}^O(x, t)$. Such variations could be produced by either daily fluctuations in emissions* or daily fluctuations in the meteorological factors that produce (x, y) from emissions. In the ozone problem, both types of fluctuations occur to provide data over wide ranges of (x, y) . These are discussed in detail in section 4.4.2.2. Suffice it here to note that putting the model into practice requires that fluctuations in (x, y) occur so that $P_{Z_s}^O(x, y)$ will be measurable.

4.4.2 Mid-day Ozone Standard Violations in Central Los Angeles as a Function of RHC and NO_x Emission Levels in L. A. County, $F_1(E_1, E_2)$

4.4.2.1 Description of the problem.

This section applies the stochastic model of section 4.4.1 to the problem of one hour ozone standard violations in Central Los Angeles. Ozone pollution basically results from photochemical reactions stemming from reactive hydrocarbon (RHC) and nitrogen oxide (NO_x) emissions (Haagen-Smit, 1952; Leighton, 1961; Altshuller and Bufalini, 1971). For this example, primary contaminant concentrations, (x, y) ,

*As noted in §4.2, $\underline{E}^O = \underline{E}^O(x, t)$ refers to a yearly emission level. Day-to-day emission changes within the year are not ruled out. Condition II just asserts that emission level changes preserve these daily fluctuations.

are taken as 7:30-9:30 A.M. civil time averages of total HC* (minus 1 ppm for natural background methane) and NO_x concentrations in Downtown Los Angeles. In order to best correspond to the same air mass as the primary contaminants, maximum one-hour ozone, z , is taken as a weighted average (according to wind speed and direction) of maximum one hour concentrations between 11 A.M. and 1 P.M. at Downtown, Burbank and Pasadena.** The model is applied for three one-hour ozone standards, $z_s = 10$ pphm, 15 pphm, and 20 pphm. The results for the 10 ppm state standard represent the ozone air quality function, $F_1(E_1, E_2)$, in the least cost air quality study for photochemical smog.

4.4.2.2 Applicability of the model.

The stochastic model can only be applied rigorously to situations that meet the four assumptions listed in section 4.4.1. The

* Actually, we are concerned with reactive hydrocarbons, not total hydrocarbons. Unfortunately, because reactivity is such a complex problem, (there are many types of hydrocarbons and several reactivity scales), it is practically ignored in air monitoring procedures. The Los Angeles APCD measures only total HC and the photochemically inert methane, CH_4 . It might first appear best to subtract methane from total HC and work with "non-methane" hydrocarbons. However, the data are such that this cannot be done advantageously. Total HC averages about 3-4 ppm, and CH_4 averages around 2-3 ppm. Since data are recorded only to the nearest ppm, subtracting CH_4 from total HC leaves rather meaningless numbers. The procedure used here is to subtract 1 ppm for natural background methane, (Altshuller et al., 1964; Ehhalt, 1967), and to assume that the remainder is proportional to the reactive hydrocarbons present.

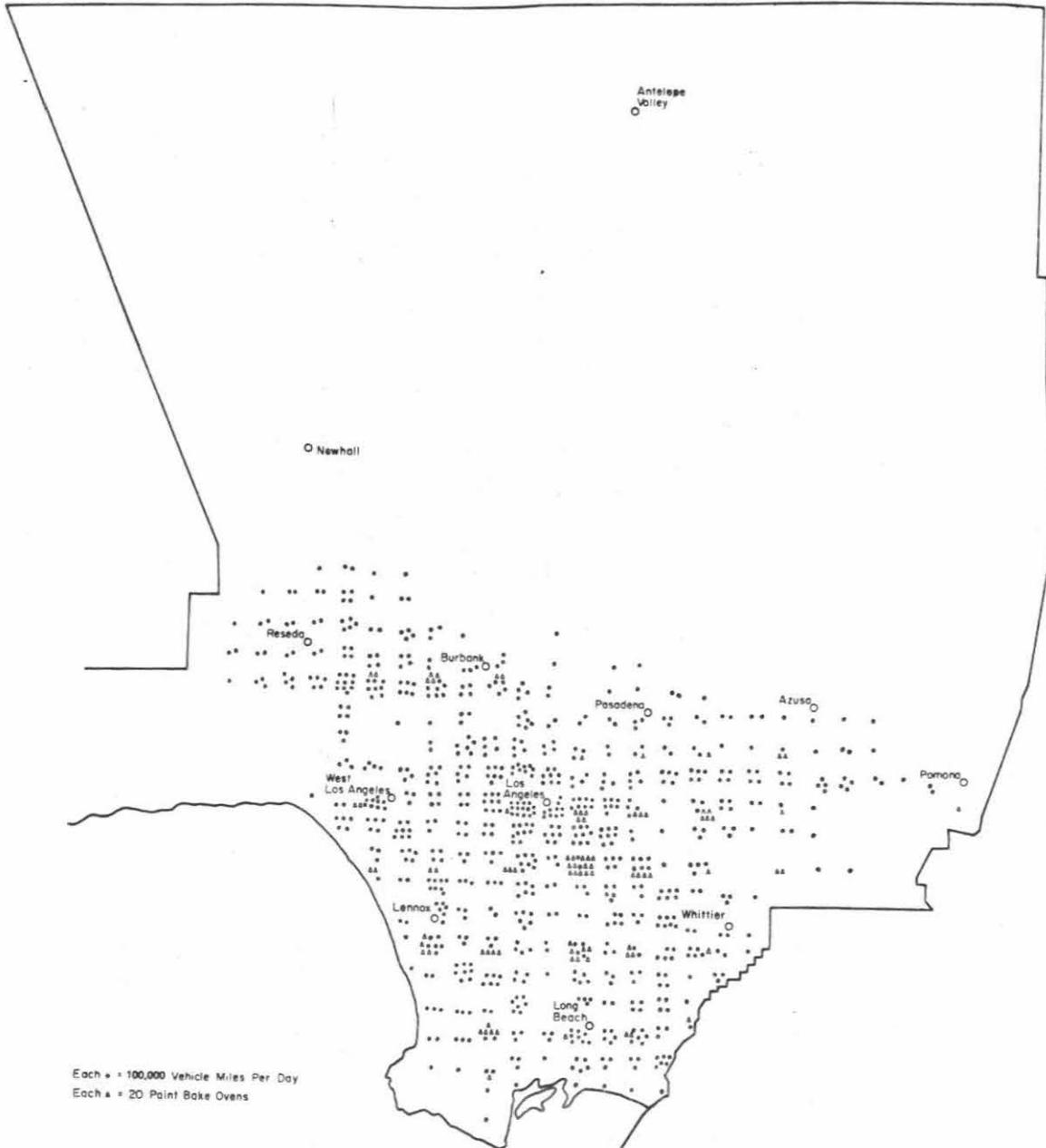
** Daily maximum ozone values for the County usually occur slightly later than mid-day, at about 2-3 P.M., at downwind stations such as Pasadena and Azusa. However, these ozone levels cannot be readily related to morning concentrations of RHC and NO_x because of the difficulty of following the air mass for longer times and because post-9:30 emissions play a greater role in the ozone formation.

ozone problem is analyzed below to determine how well it corresponds to these assumptions.

Homogeneity of RHC and NO_x emission reductions constitutes the first assumption, (i). This condition for NO_x emissions was discussed in section 4.3.3.1. That section noted that because of differences in power plant and vehicular emission patterns, the condition might not be met in practice, but that the error should not be very large. Homogeneous emission reductions should be better approximated in the case of RHC. Motor vehicles account for approximately 86% of the RHC emitted in L. A. County, (APCD Profile, 1971). Among stationary sources, the two largest emitters are gas stations, 5%, and organic solvent users, 7%. The large scale spatial distribution of gas stations is probably very similar to that of automobile mileage. As concerns organic solvent users, data on paint bake oven location are shown in Figure 4.10 (Roberts et al., 1971; APCD Profile, 1969). Although centered in the industrial region to the southeast of Downtown Los Angeles, the distribution of paint bake ovens is not radically different from automobile mileage. Thus, even if stationary sources and motor vehicles undergo different degrees of control, the total RHC emission level change will still be nearly homogeneous.

The second assumption, (ii), is that the primary contaminant concentrations, (x, y) , accumulate without reacting before leading to the daily pollution episode. In the ozone problem, x and y are 7:30-9:30 A.M. averages of HC and NO_x in Downtown Los Angeles. In order to investigate the extent to which these concentrations have reacted,

Figure 4.10 COMPARISON OF THE SPATIAL DISTRIBUTIONS OF AUTOMOBILE MILEAGE AND PAINT BAKE OVENS



it is necessary to consider the meteorological history of the air mass containing them.

The usual wind pattern in Los Angeles is a sea breeze during the day and early evening and a nocturnal land breeze. In the late spring, summer, and fall, there is a relatively strong sea breeze from approximately 11 A.M. -9 P.M. PDT and a weak land breeze from 1 A.M. -9 A.M. PDT. In the winter, the sea and land breezes usually have about the same magnitude, the former existing from approximately 1 P.M. -8 P.M. PST and the latter existing from approximately 11 P.M. -10 A.M. PST. Figure 4.11 illustrates these patterns, (Neiburger and Edinger, 1954).

During late spring, summer, and fall, the most frequent trajectory of the air mass in Downtown Los Angeles at 8 A.M. PDT is the type illustrated in Figure 4.12, (Neiburger and Edinger, 1954; Neiburger et al., 1956). The air first crosses the coast late in the afternoon of the previous day. It mills around the Central Los Angeles area during the night and early morning. Then, it blows across the basin with the sea breeze of the next day.* For such trajectories, the primary contaminants start to accumulate in the early evening when the air crosses the coast. Accumulation continues through the night with a large pulse of traffic emissions being added in the morning.

The absence of sunlight during the night prevents significant reaction between the primary contaminants, RHC and NO_x . However, the morning concentrations are measured from 7:30-9:30 PDT, and

* Other types of trajectories do occur. Sometimes the Downtown L. A. air mass originates from the northern mountains or from the southern coast. Rarely, it arrives from the populated northwestern or eastern valleys, (Neiburger et al., 1956).

Figure 4.11
 AVERAGE HOURLY WIND PATTERNS IN CENTRAL
 LOS ANGELES (Neigurger and Edinger, 1954)

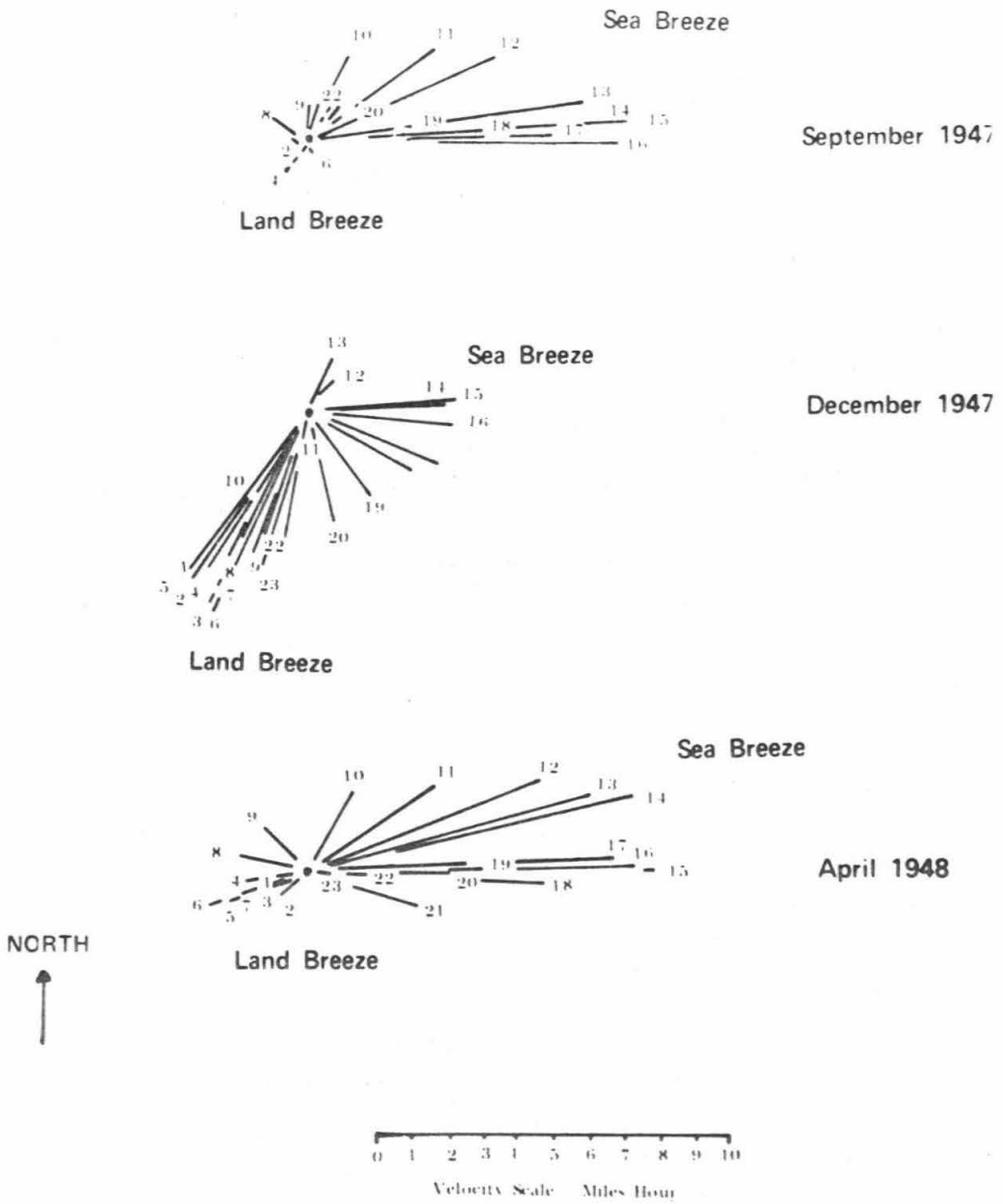
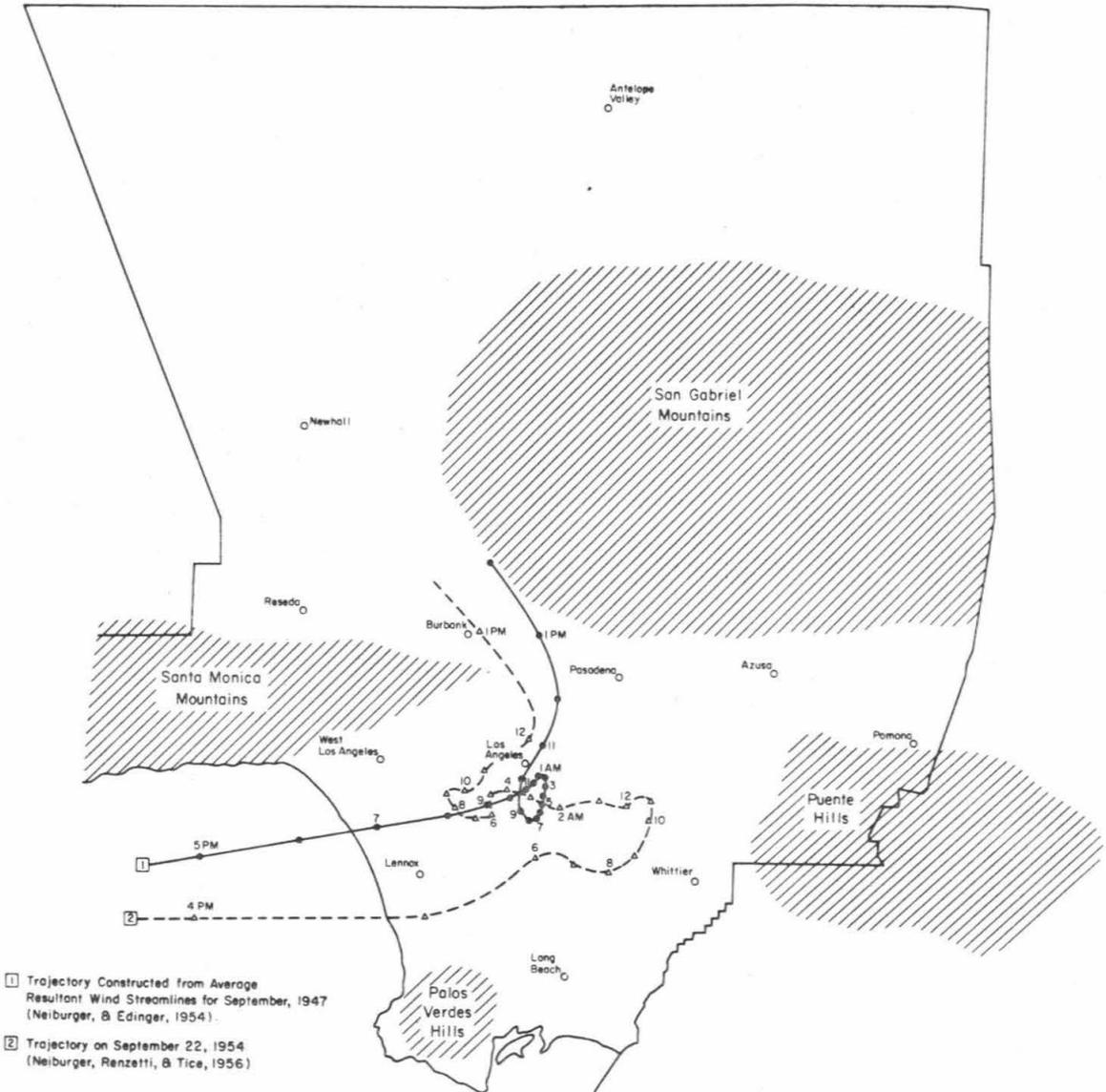


Figure 4.12
September Air Trajectories



the reaction has actually started by this time. Figure 4. 13 shows that RHC and NO_x concentrations start decreasing and ozone starts increasing at about 8:30 A. M. , (Dickinson, 1961).^{*} Thus, some reaction has occurred by 9:30, and assumption (ii) is not totally satisfied. However, it should be recalled that the purpose of the assumption was to insure that HC and NO_x concentrations were proportional to their respective emission levels. (If reaction occurs, the amount of primary contaminants consumed might depend nonlinearly on the concentrations and destroy proportionality.) Since, as evidenced by Figure 4. 13, most of the HC and NO_x has not been consumed by 9:30, it is still a good first approximation that these concentrations are proportional to emission levels even if the amount reacted depends nonlinearly on the concentrations.

During the winter, there is a different problem with assumption (ii). Because of the near balance between the land and sea breezes, air masses may remain in the basin for as long as two or three days, (Holmes et al. , 1956). Trajectories of the type shown in Figure 4. 14 are common, (Neiburger and Edinger, 1954; Holmes et al. , 1956). For such cases, the hydrocarbons and nitrogen oxides that were emitted into the air mass that is found in Downtown L. A. in the morning have undergone reaction during the previous day or two as well as during that morning. These reactions may destroy the proportionality between

^{*}Actually, the initial phases of the reaction start about an hour earlier as evidenced by conversion of NO to NO_2 (Leighton, 1961).

Figure 4.13
TEMPORAL PHOTOCHEMICAL POLLUTION DISTRIBUTION

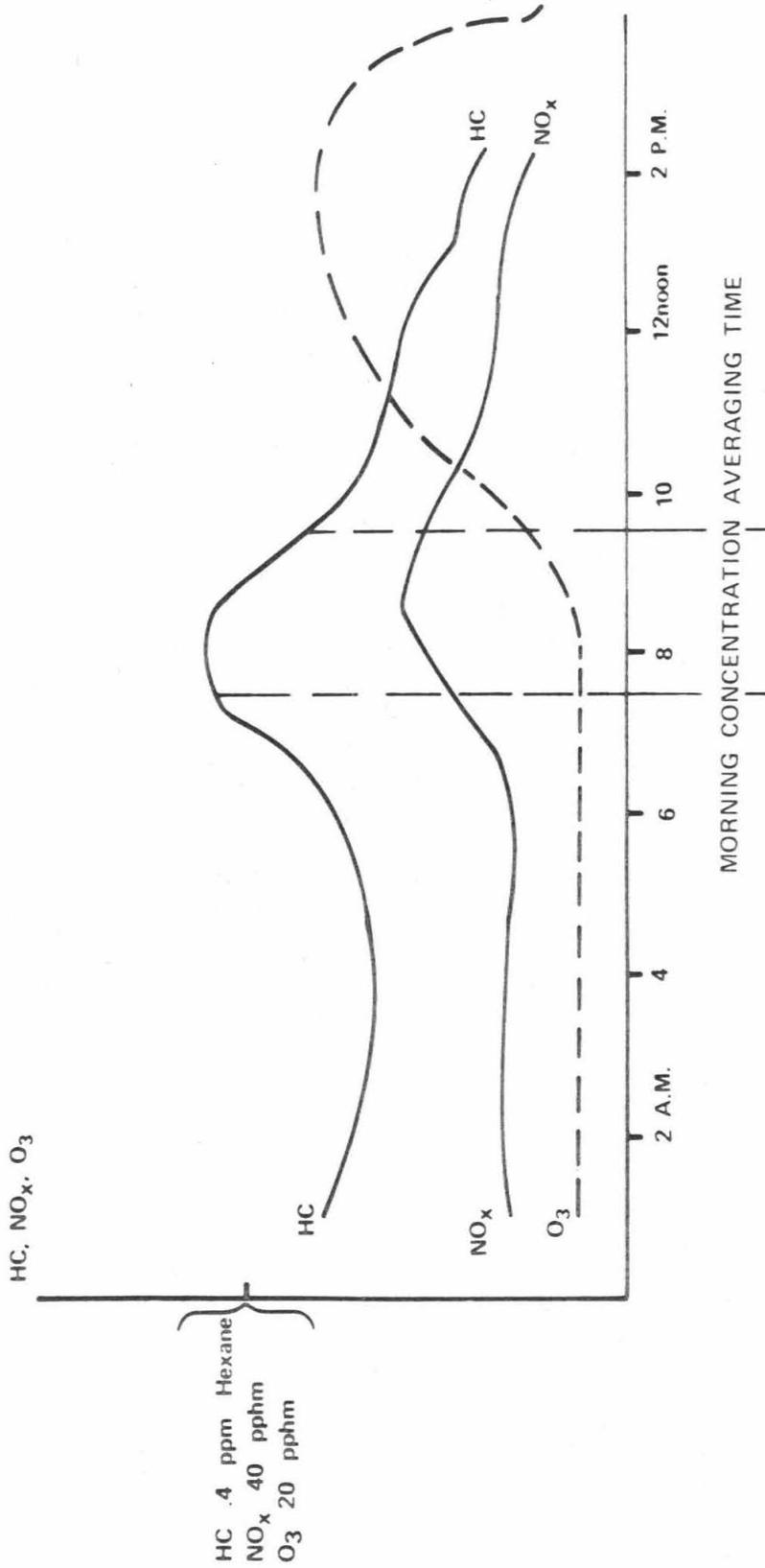
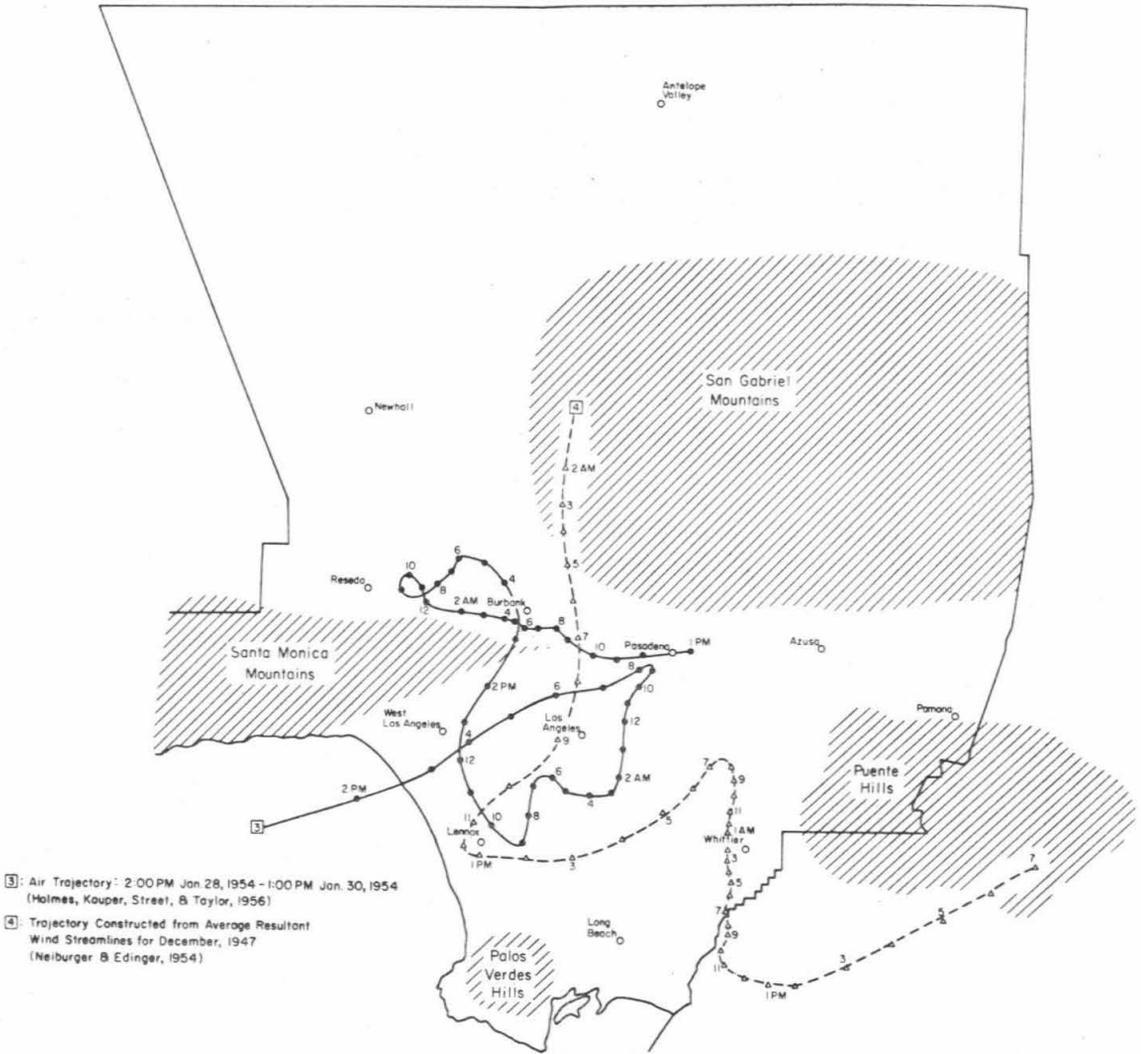


Figure 4.14
December Air Trajectories



morning concentrations and emission levels.* However, the validity of making the proportionality assumption is somewhat saved since during the winter, because of low temperature and solar radiation, little reaction occurs. Also, even if the morning concentrations are not exactly proportional to emissions, it is not obvious in which direction the deviation would be. It is still probably an acceptable approximation to assume that morning concentrations are proportional to emission levels for the primary contaminants.

Of course, assumption (ii) would be better satisfied by using earlier averages, say 6:00-8:00 A.M. averages. But then the morning traffic emissions might not be adequately represented. Some sacrifice in meeting condition (ii) has to be made in order to better satisfy condition (iii).

Assumption (iii) states that emissions stop after x and y have accumulated and then the reactions start. The effect of an earlier start for the reactions has been dealt with in the previous three paragraphs. The assumption that emissions stop, which in reality is, of course, not true, will be considered here. Emissions do continue after 9:30, and contaminants added after this time do participate in the ozone forming reactions. However, the concentrations (x, y) , contain emissions from the previous evening, the night hours, and the morning traffic rush, and the maximum ozone is measured at about noon. The extra emissions

*The reader should remember that it is not assumed that the concentrations of a given day are proportional to the emissions of that day. It is assumed that they are proportional to the general (yearly) emission level.

between 9:30 and noon are probably small compared to those that have accumulated by 9:30. Figure 4.15, showing the temporal distribution of automobile traffic (Roberts et al., 1971), illustrates this effect for vehicular emissions. Though the assumption that no further emissions take place after (x, y) has accumulated is by no means exactly satisfied, the violation for mid-day ozone should not be very serious.*

The final assumption, (iv), is that the weather factors that govern the ozone formation from the primary contaminants are statistically independent of the morning concentrations. In §4.5, four weather factors will be identified as being highly correlated with the ozone levels formed from given morning concentrations. These are solar radiation intensity (SR), maximum daily temperature (TM), maximum mixing height (HM), and Los Angeles-Palmdale temperature gradient (TLP).** A regression model in §4.5 indicates that changes in these weather factors can account for around 60-70% of the variance in the ozone values for given morning concentrations. A test of assumption (iv) would be the absence of correlation between the morning concentrations, (x, y) , and these four meteorological factors. Such a test was performed with multiple linear regressions between x (and then y) and the weather factors.*** Table 3-III gives the results.

* The probability of a mid-day ozone violation does show a distinct dependence on morning concentration levels. This fact attests to these concentrations being the main precursors of mid-day ozone.

** See §4.5 for explicit definitions of these parameters.

*** A linear regression picks $(a, b, c, d, \text{ and } e)$ for a least squares fit of $(a + bSR + cTM + dHM + eTLP)$ to the data for x (or y). The square of the total correlation coefficient, R^2 , is the fraction of the variance in x (or y) explained by the multiple linear regression. The partial correlation coefficient for each variable is the square root of the variance in the dependent variable which is not explained by the other independent variables but which is explained by the addition of that variable.

Figure 4.15

TEMPORAL DISTRIBUTION OF TRAFFIC IN L.A. COUNTY

(Ref., Roberts et al., 1971)

Fraction of Daily Traffic
Assignable to Each Hour

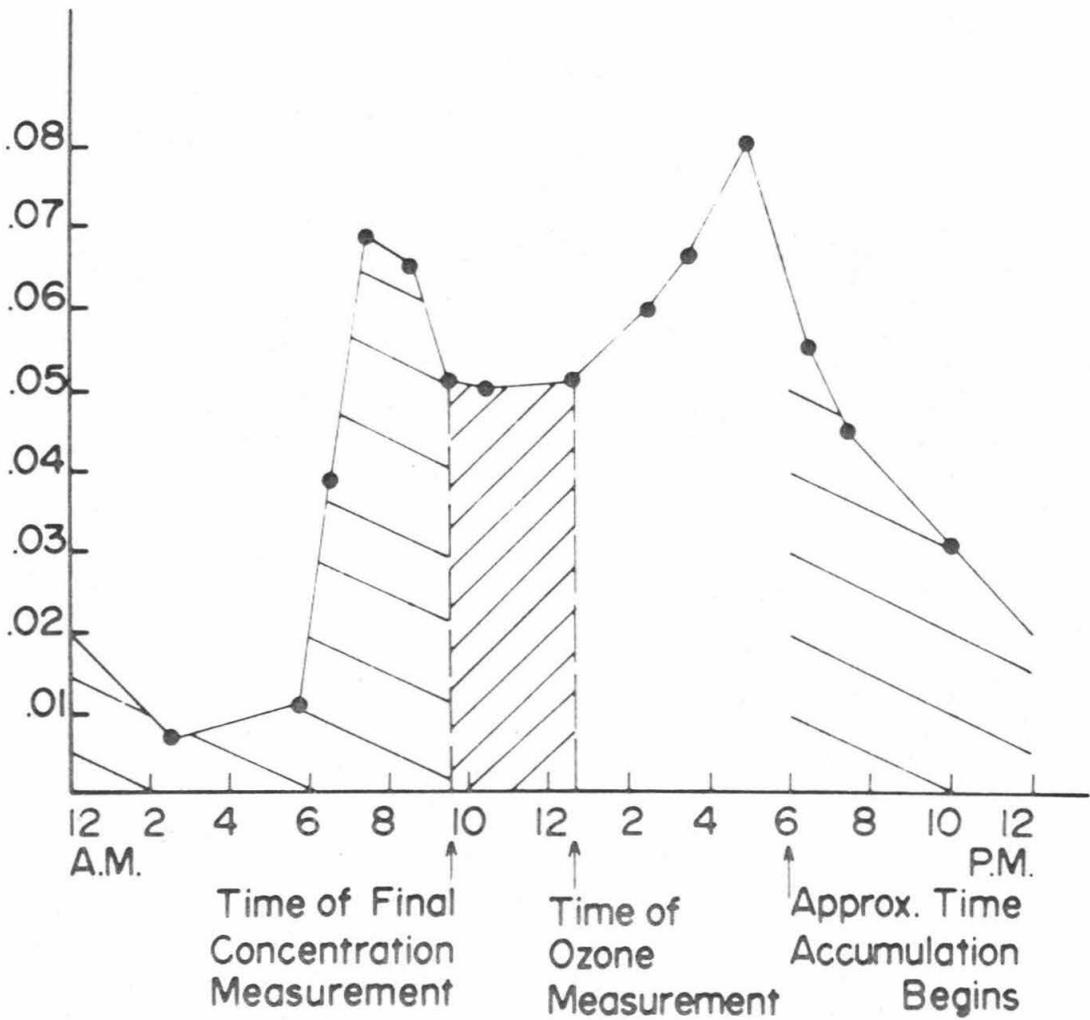


TABLE 4-III
The Correlation Between Morning RHC and NO_x Concentrations
and Ozone Producing Weather Factors

	Partial Correlation Coefficient				Total Correlation Coefficient, R
	SR	TM	HM	TLP	
Morning HC, x	0.06	0.33	-0.28	0.08	0.48
Morning NO _x , y	-0.01	0.17	-0.01	0.35	0.47

Table 3-III reveals that both morning HC and NO_x concentrations correlate significantly with maximum temperature and temperature gradient. Morning HC also correlates significantly with mixing height. A footnote below discussed the reasons for these correlations.*

Since temperature correlates positively with ozone and mixing height and temperature gradient negatively, morning HC would appear

* Max. Temperature: Both morning HC and NO_x correlate positively with TM because when the air is more stagnant (leading to higher concentrations) the temperature tends to be higher. Evaporative HC emissions increase with the temperature, making the correlation even stronger for x. More NO_x is emitted in winter by fuel burning, and since TM is less in winter, the correlation is less for y.

L. A. -Palmdale Temperature Gradient: TLP is a measure of horizontal mixing, correlating negatively with average wind speed. This accounts for the + correlation to both HC and NO_x. TLP is also a strong summer-winter indicator (- in summer, + in winter). Since NO_x emissions are high in winter, there is a stronger y correlation. Since evaporative HC are higher in summer, the correlation is less for x.

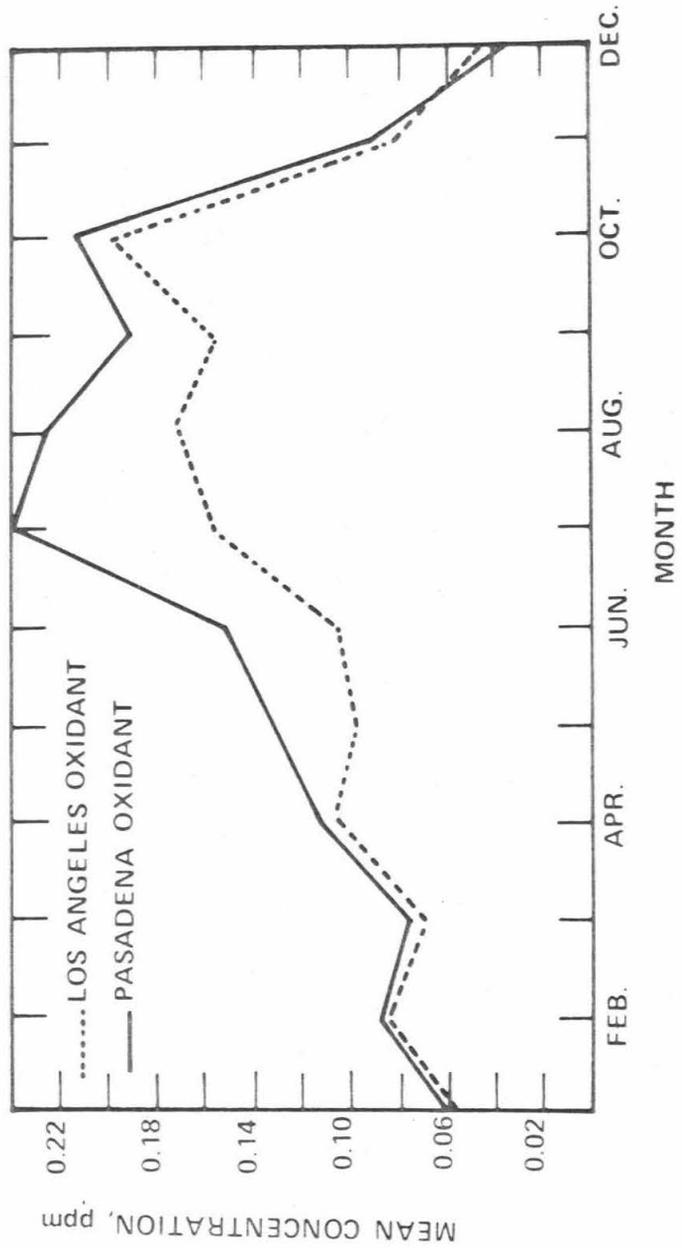
Mixing Height: The correlation of HC to HM is just the natural correlation between the early morning vertical mixing that influences x and the vertical mixing later in the day.

to correlate positively with high ozone producing weather and morning NO_x probably negatively. This correlation would tend to overstate the role of HC concentrations and understate the role of NO_x concentrations in ozone formation.

R^2 for morning HC and NO_x versus the weather factors is 0.23. This implies that 23% of the variance in x and y can be accounted for by these weather factors in a linear regression. It is not obvious if this correlation is large enough to affect seriously the independence assumption, (iv). In order to minimize the effect of the intercorrelation that does exist, the data for the model are divided into winter and summer. As noted earlier, wind patterns tend to be different in winter and summer. This is just one aspect of a general winter-summer meteorological dichotomy that exists in Southern California. Summer is characterized by high temperature, intense solar radiation, and a persistent marine layer inversion that restricts vertical mixing. Winter has lower temperature and solar radiation and a low, but weak nocturnal inversion (Frank, 1970). As illustrated by Figure 4.16, (HEW-AP-63, 1970), these weather patterns make photochemical smog "in season" in the summer and "out of season" in the winter. The largest changes in ozone producing weather factors occur when one compares summer days to winter days. These changes do have some correlation to the morning concentrations since NO_x emissions tend to be higher in winter, HC emissions tend to be higher in summer, and morning concentrations for given emissions tend to be higher in winter. Splitting the data into winter and summer and performing separate analyses should minimize the effects of these intercorrelations.

Figure 4.16

MONTHLY VARIATION IN MEAN DAILY MAXIMUM
1-HOUR OXIDANT CONCENTRATIONS IN LOS ANGELES
AND PASADENA, 1964-1965. (HEW-AP-63, 1970)



This completes the discussion of the theoretical assumptions for the model as they relate to the ozone example. However, as noted at the end of section 4.3.1, one further condition must be satisfied before the model may be put into practice. There must be some mechanism which produces large variations in (x, y) for a given yearly emission level so that the function $P_{z_s}^O(x, y)$ can be measured over a large domain. In the ozone problem, such variations do occur. Part of the variation results from daily changes in source levels, e.g., weekend-weekday traffic and changes in residential, commercial, and industrial activity. Further variation results from the stochastic nature of the overnight and early morning weather conditions that govern the accumulation of (x, y) . Changes in inversion height and wind speed produce changes in the general level of x and y . The erratic nocturnal wind trajectories (see Figures 4.12 and 4.13) produce relative changes in x and y according to whether they stagnate near stationary sources of HC or stationary sources of NO_x . The resulting distribution of (x, y) provides data over a large domain. Figures 4.17 and 4.18 in the next section give the summer and winter distributions. Since automobiles are the dominant source affecting Downtown L.A., most of the data lie along a ray of fixed x - y ratio. However, a great deal of variance away from that ratio exists. For fixed HC level, the maximum NO_x level is anywhere from 5 to 20 times the minimum NO_x level.

4.4.2.3 Data

The morning concentrations (x, y) are 7:30-9:30 PDT averages of total HC and NO_x at the APCD Downtown Los Angeles station. A correction for natural background methane is made by subtracting 1 pphm from the HC measurements. Data are used for the years 1966, 1967, 1968, 1969 and 1970 in L.A. County RHC and NO_x emission levels of (1600, 920)

(1500, 940, (1400, 970), (1300, 1000) and (1200, 1050) tons per day, respectively (APCD Profile, 1971; EQL, 1972). All five years are reduced to a base emission level, $\underline{E}^0 = (1300, 1000)$ tons/day by multiplying the concentrations for each year by \underline{E}^0 and dividing by that year's emissions. These are small corrections. These data provide the distribution functions $N^{o(w)}(x, y)$ and $N^{o(s)}(x, y)$ giving the number of winter and summer days with various morning concentrations. Table 4-IV and Figures 4.17 and 4.18 summarize these distributions.

Maximum one hour ozone is taken as a weighted average (according to windspeed and direction) of the maximum concentrations between 11 A.M. and 1 P.M. at Downtown, Burbank, and Pasadena.* From these ozone values and the corresponding morning concentrations, the probability that ozone exceeds the standard, z_s , $P_{z_s}^{o(w)}(x, y)$ and $P_{z_s}^{o(s)}(x, y)$, is calculated for winter and summer. Calculations are performed for three standards, $z_s = 10, 15, \text{ and } 20$ pphm for 1 hour. Figures 4.19-4.24 give the resulting probability functions. The dashed portions of the curves in these figures are extrapolations of the data. Extrapolation is necessary only at very high HC or NO_x levels. Since practically no days would have such concentrations in an emission reduction program, the final results of the model should be very insensitive to the extrapolations.

* If the magnitude of the average, Downtown Los Angeles wind resultant vector from 9:00-12:00 A.M. was less than 4 mph, Downtown ozone values alone were used. For average resultant wind magnitudes greater than 4 mph the following weightings were employed: (i) for average 9:00-12:00 A.M. wind direction to the northeast, Pasadena and Burbank ozone values were used weighted according to angle from east (Pasadena) to north (Burbank), (ii) for average wind direction to the northwest, Burbank and Downtown ozone values were used weighted according to angle from north (Burbank) to west (Downtown), (iii) for average wind direction to the southwest, Downtown ozone was used, and (iv) for average wind direction to the southeast, Downtown and Pasadena ozone values were used weighted according to angle from south (Downtown) to east (Pasadena).

Figure 4.17
DISTRIBUTION OF SUMMER
MORNING CONCENTRATIONS,
(7:30 - 9:30 average)

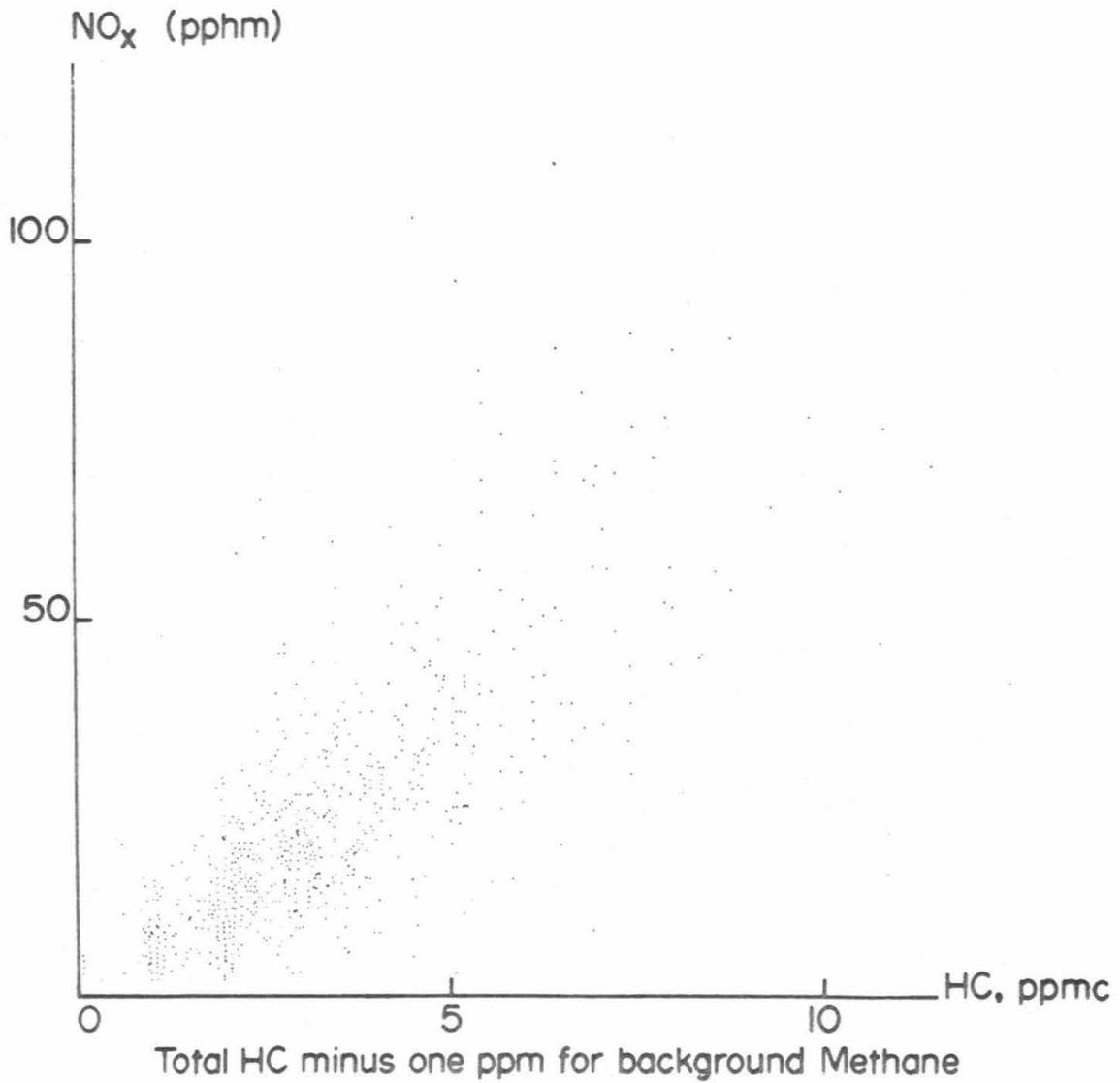


Figure 4.18
DISTRIBUTION OF WINTER
MORNING CONCENTRATIONS,
(7:30 - 9:30 average)

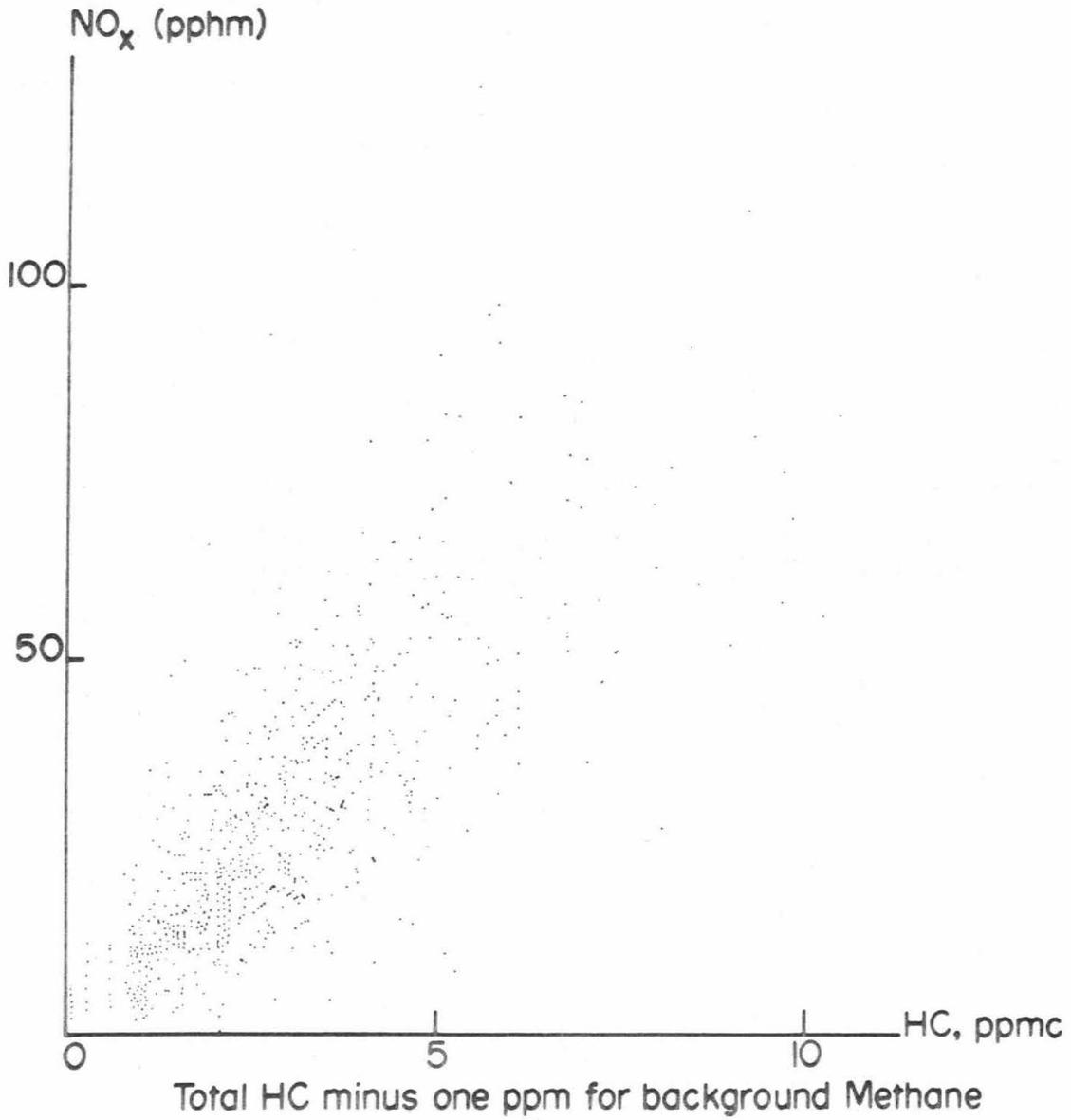
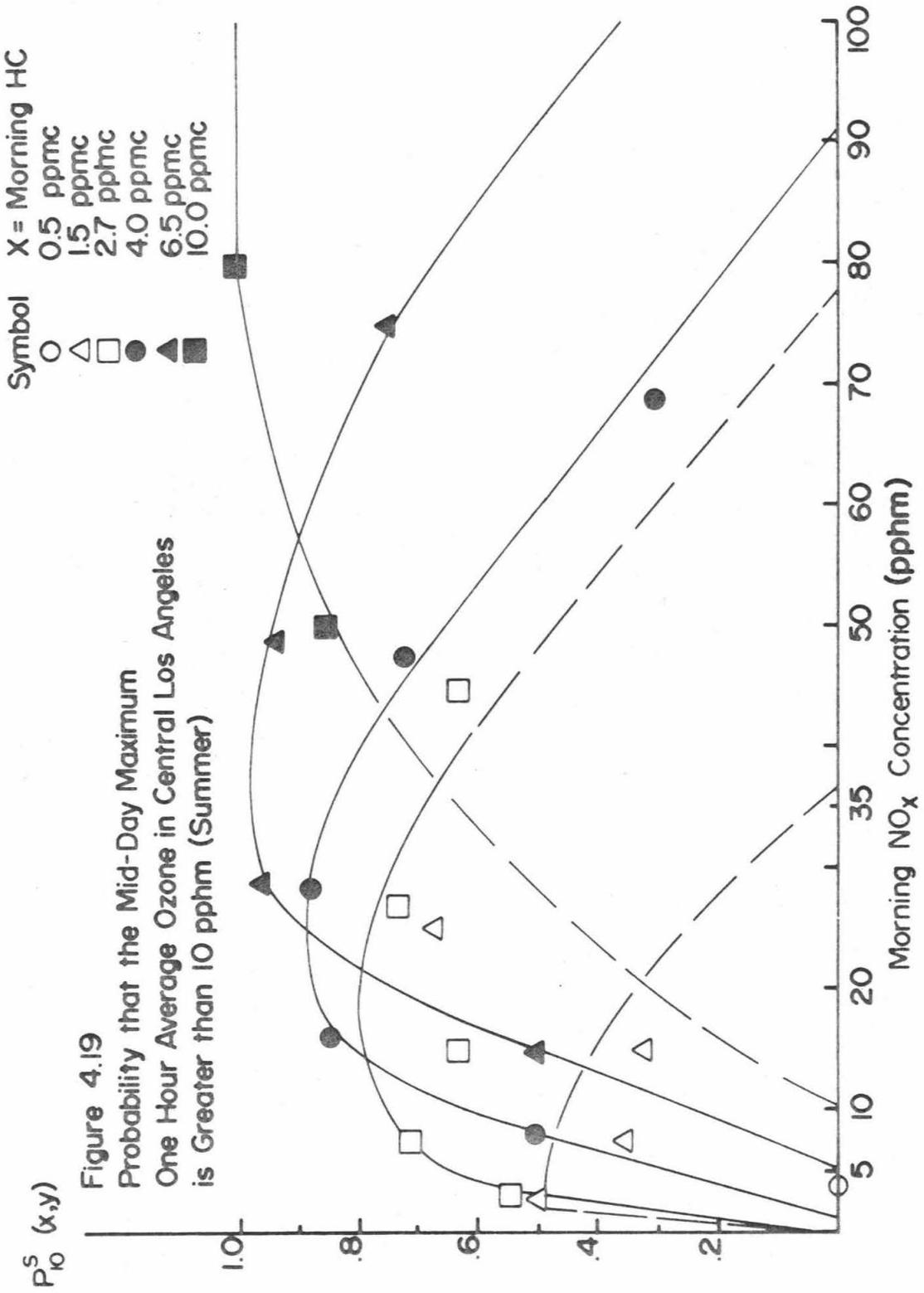


TABLE 4-IV

Winter and Summer Distributions of Morning RHC and NO_x Concentrations in Downtown Los Angeles

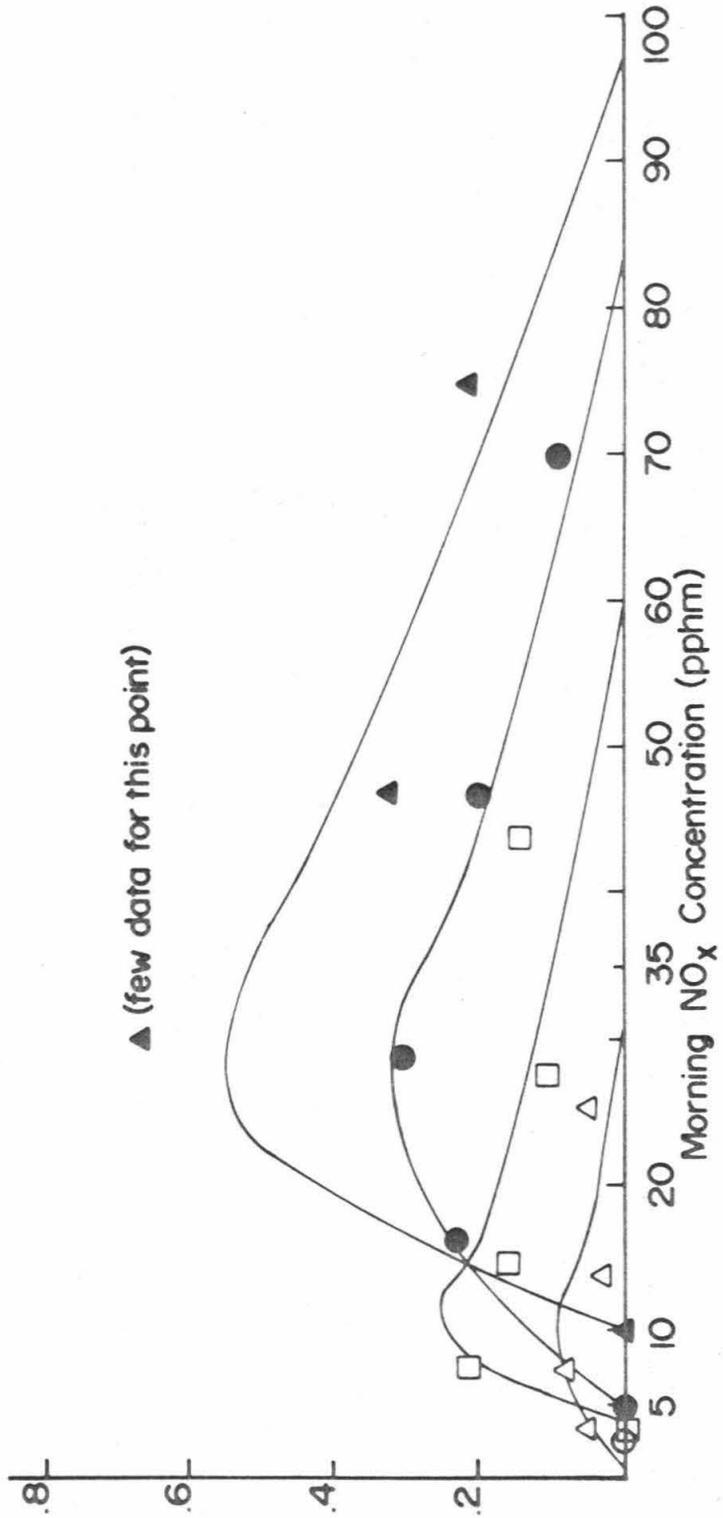
Winter Distribution: N _(w) ^o (x, y)		Summer Distribution: N _(s) ^o (x, y)	
Fraction of winter days with morning hydrocarbons, x, and morning nitrogen oxides, y in specified concentration ranges. (RHC ^o = 1300 tons/day, NO _x ^o = 1000 tons/day)		Fraction of summer days with morning hydrocarbons, x, and morning nitrogen oxides, y in specified concentration ranges. (RHC ^o = 1300 tons/day, NO _x ^o = 1000 tons/day)	
↓ HC conc., x ppm		↓ HC conc., x ppm	
0	0	0	0
.8	.8	.8	.8
1.8	1.8	1.8	1.8
3.1	3.1	3.1	3.1
5.1	5.1	5.1	5.1
7.8	7.8	7.8	7.8
12.1	12.1	12.1	12.1
— NO _x conc., y, pphm —→		— NO _x conc., y, pphm —→	
0	0	0	0
5	5	5	5
10	10	10	10
20	20	20	20
35	35	35	35
60	60	60	60
100	100	100	100



Symbol X = Morning HC
 ○ 0.5 ppmc
 △ 1.5 ppmc
 □ 2.7 ppmc
 ● 4.0 ppmc
 ▲ 8.0 ppmc

Figure 4.20
 Probability that the Mid-Day Maximum
 One Hour Average Ozone in Central Los Angeles
 is Greater than 10 pphm (Winter)

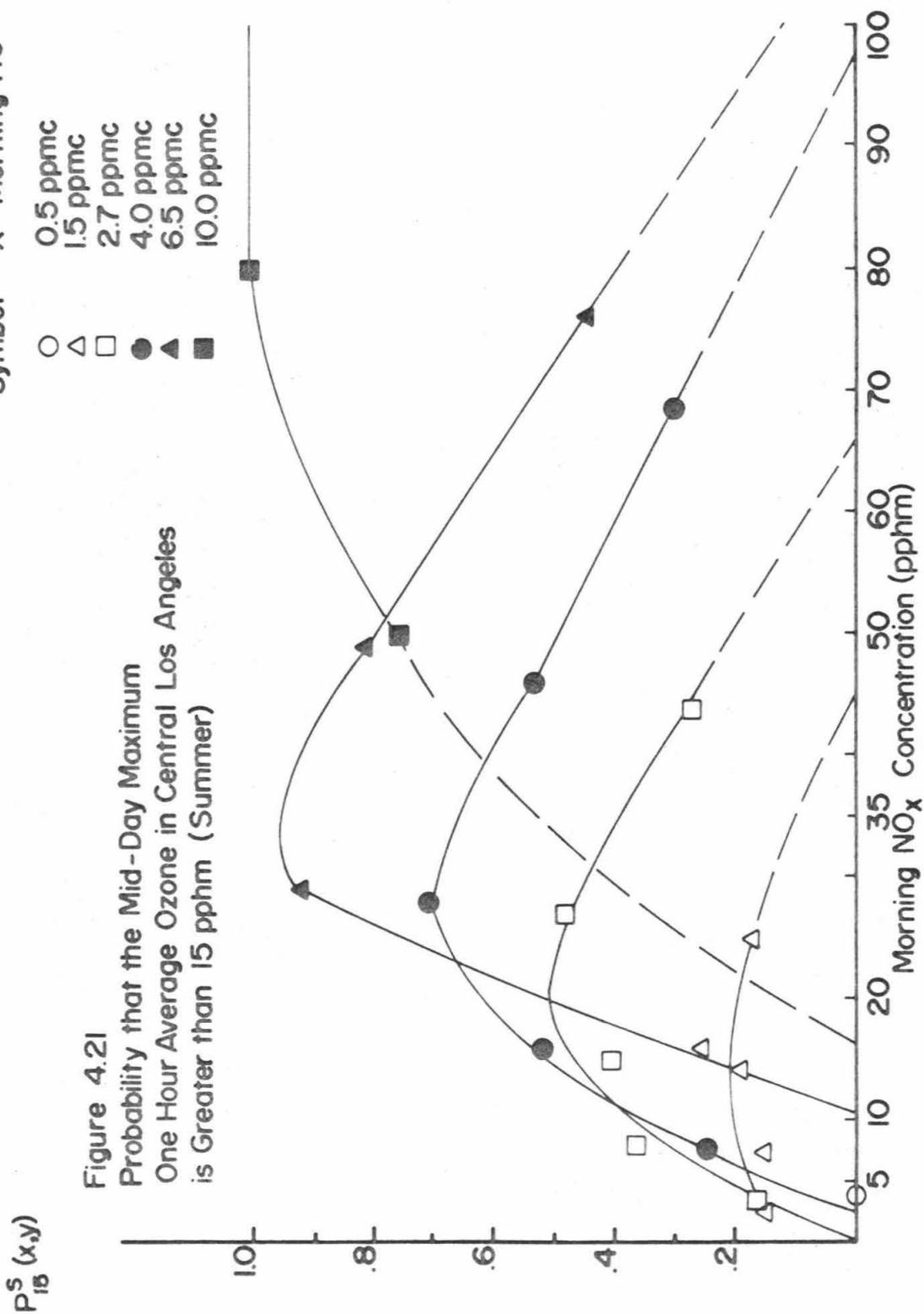
$P_{10}^W(x,y)$

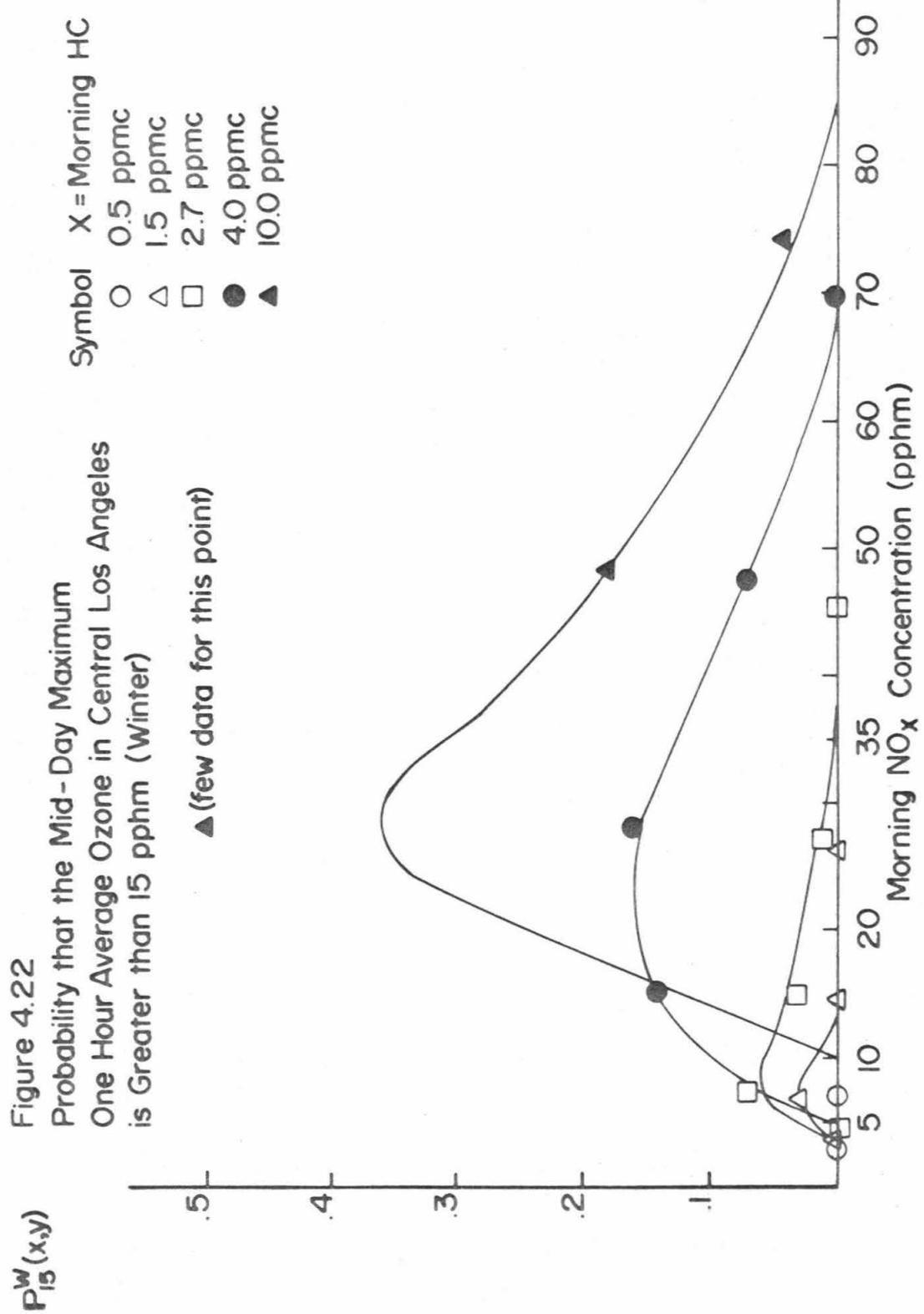


Symbol X = Morning HC

- 0.5 ppmC
- △ 1.5 ppmC
- 2.7 ppmC
- 4.0 ppmC
- ▲ 6.5 ppmC
- 10.0 ppmC

Figure 4.21
 Probability that the Mid-Day Maximum
 One Hour Average Ozone in Central Los Angeles
 is Greater than 15 pp hm (Summer)

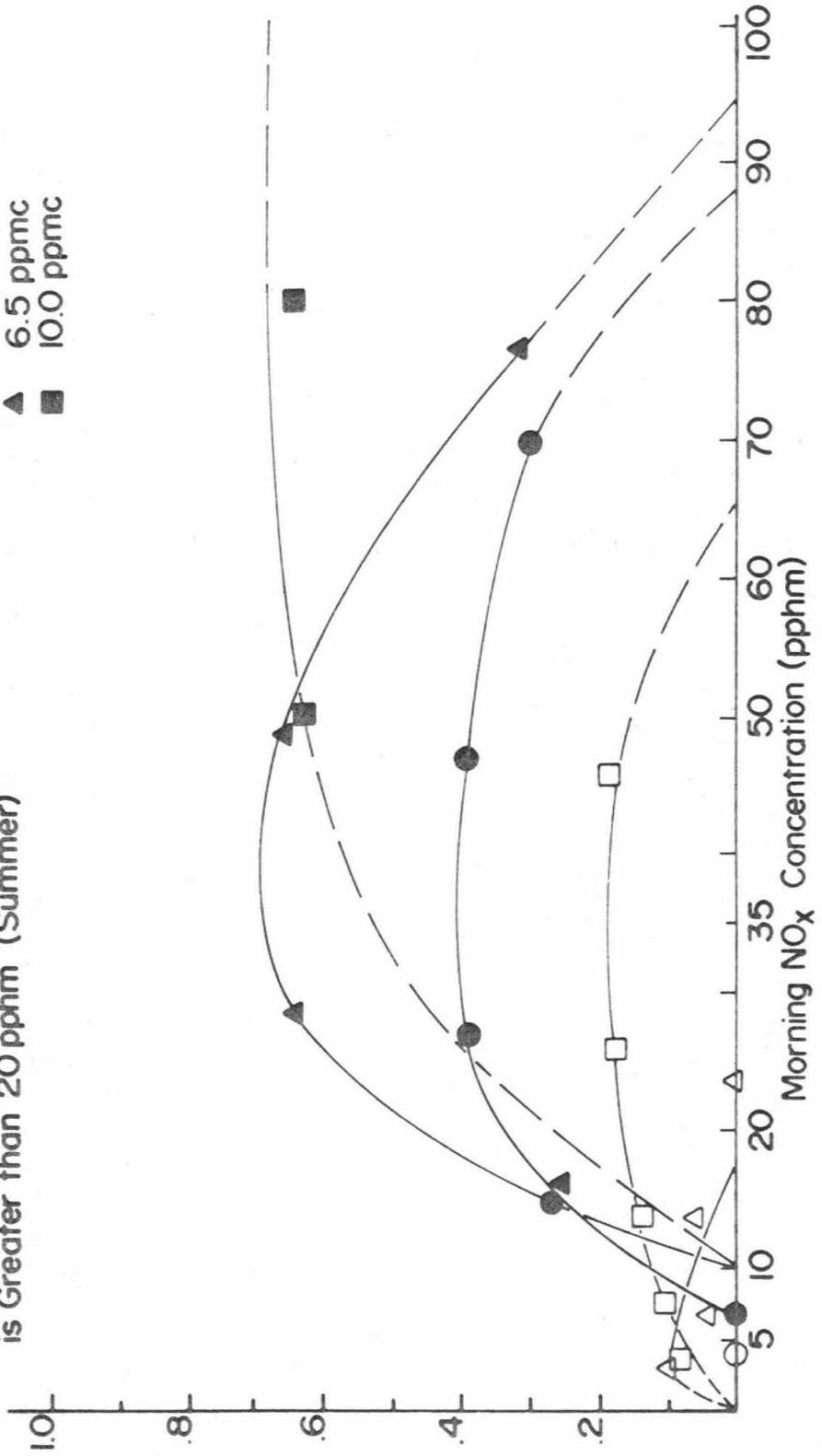




Symbol X = Morning HC

- 0.5 ppmc
- △ 1.5 ppmc
- 2.7 ppmc
- 4.0 ppmc
- ▲ 6.5 ppmc
- 10.0 ppmc

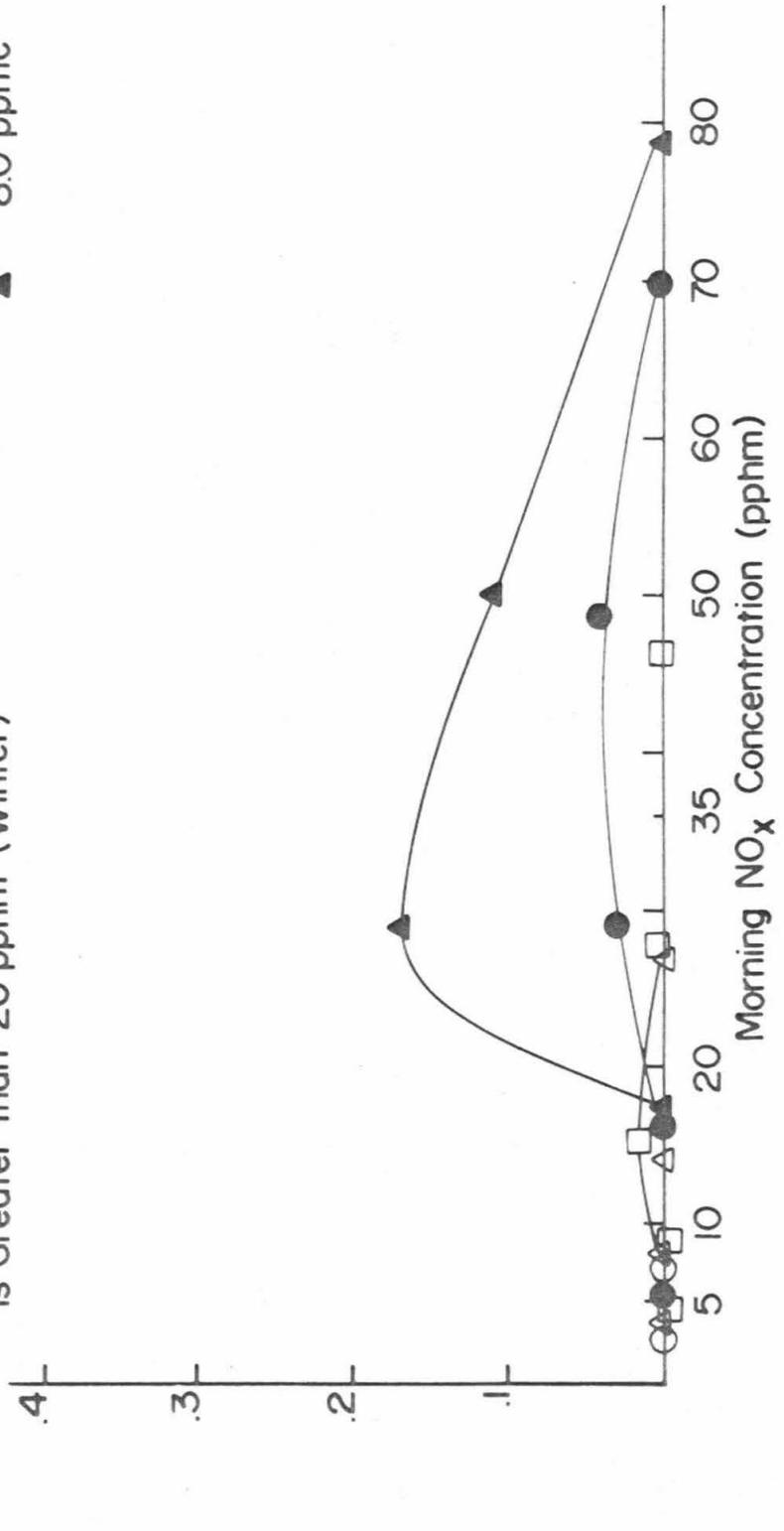
$P_{20}^S(x,y)$ Figure 4.23
 Probability that the Mid-Day Maximum
 One Hour Average Ozone in Central Los Angeles
 is Greater than 20 pphm (Summer)



Symbol X = Morning HC

- 0.5 ppmc
- 1.5 ppmc
- △ 2.7 ppmc
- 4.0 ppmc
- ▲ 8.0 ppmc

Figure 4.24
 Probability that the Mid-Day Maximum
 One Hour Average Ozone in Central Los Angeles
 is Greater than 20 pphm (Winter)



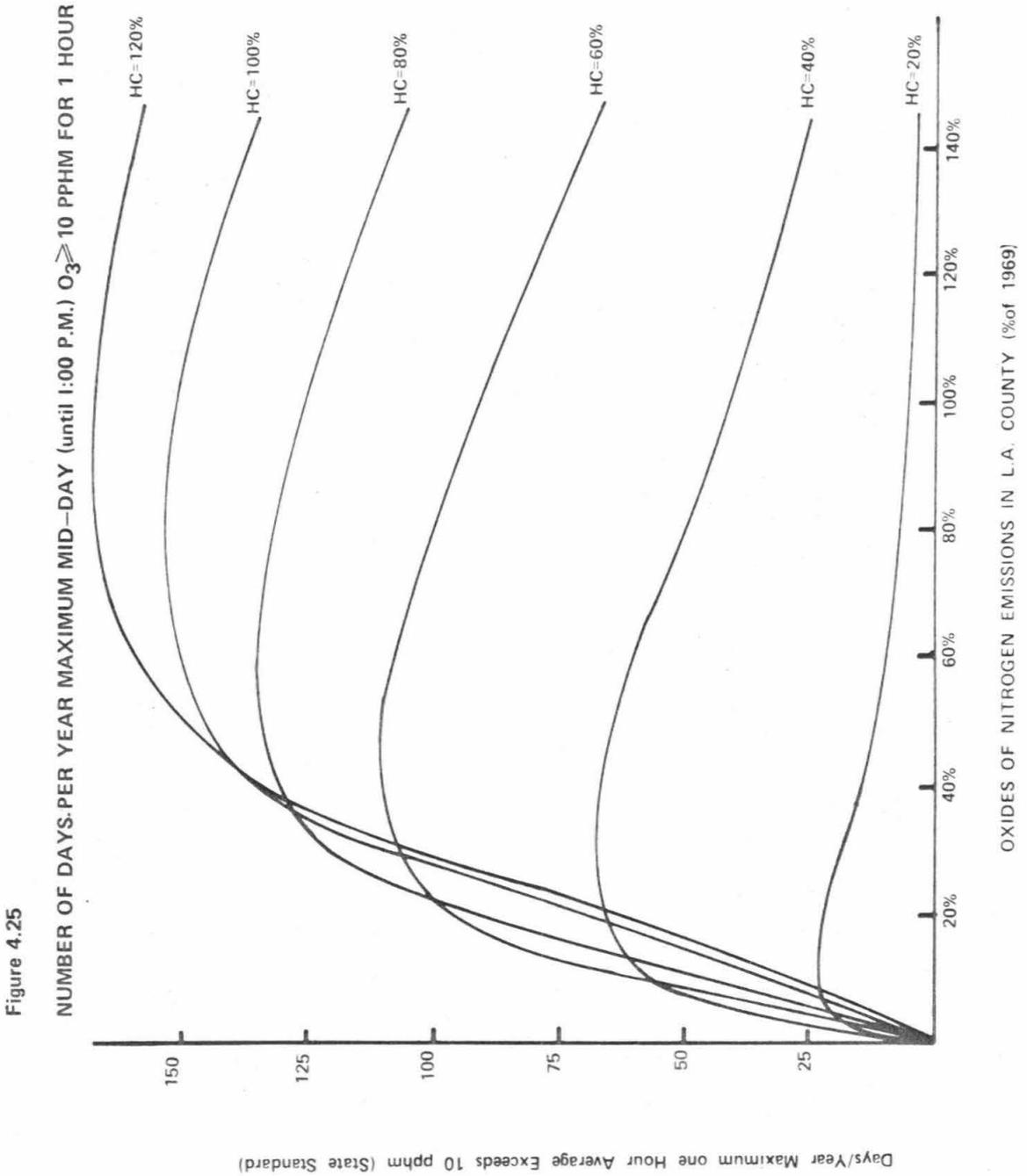
4.4.2.4 Results and conclusions.

From the measured functions, $N^{o(w)}(x, y)$, $P_{z_s}^{o(w)}(x, y)$, $N^{o(s)}(x, y)$, and $P_{z_s}^{o(s)}(x, y)$, the expected number of winter and summer days that mid-day ozone in Central Los Angeles exceeds z_s is calculated as a function of RHC and NO_x emission levels for L. A. County by equation (4.12). Figures 4.25, 4.26, and 4.27 give the results for the three ozone standards, ($z_s = 10, 15,$ and 20 pphm for one hour), in the form of the total expected number of days exceeding the standard vs NO_x emission level for various RHC emission levels. The ozone air quality function to be used in the least cost air quality model corresponds to the 10 pphm standard. This function, $F_1(E_1, E_2)$, is represented in terms of iso-air quality curves in Figure 4.28.

Figures 4.25-4.28 indicate that for a given percentage emission reduction, ozone is better controlled by RHC reductions than by NO_x reductions. Figure 4.29 shows the effect of RHC and NO_x control alone. For each standard, RHC control is much more efficient. Of course, a decision as to which primary contaminant should be controlled must wait for a comparison of the cost of reducing each. The cost factor is added in Chapter 5.

The 1966-1970 and the presently planned 1975 and 1980 emission levels are marked off in Figure 4.28 (APCD Profile, 1971; EQL, 1972). Figure 4.27 reveals that in 1966, Los Angeles was near the peak of the "ozone hill." The control policies of the late sixties, dominated by "leaning out" of automobiles, decreased RHC emissions at the expense of increasing NO_x . For ozone in Central Los Angeles, this

HYDROCARBON EMISSIONS IN L.A. COUNTY (% of 1969 Level)



HC=HYDROCARBON REACTIVE EMISISON LEVEL AS % OF 1300 TONS/DAY (~1969 LEVEL)

Figure 4.26

NUMBER OF DAYS PER YEAR MAXIMUM MID-DAY (until 1:00 P.M.)
 $O_3 \geq 15$ PPHM FOR 1 HOUR

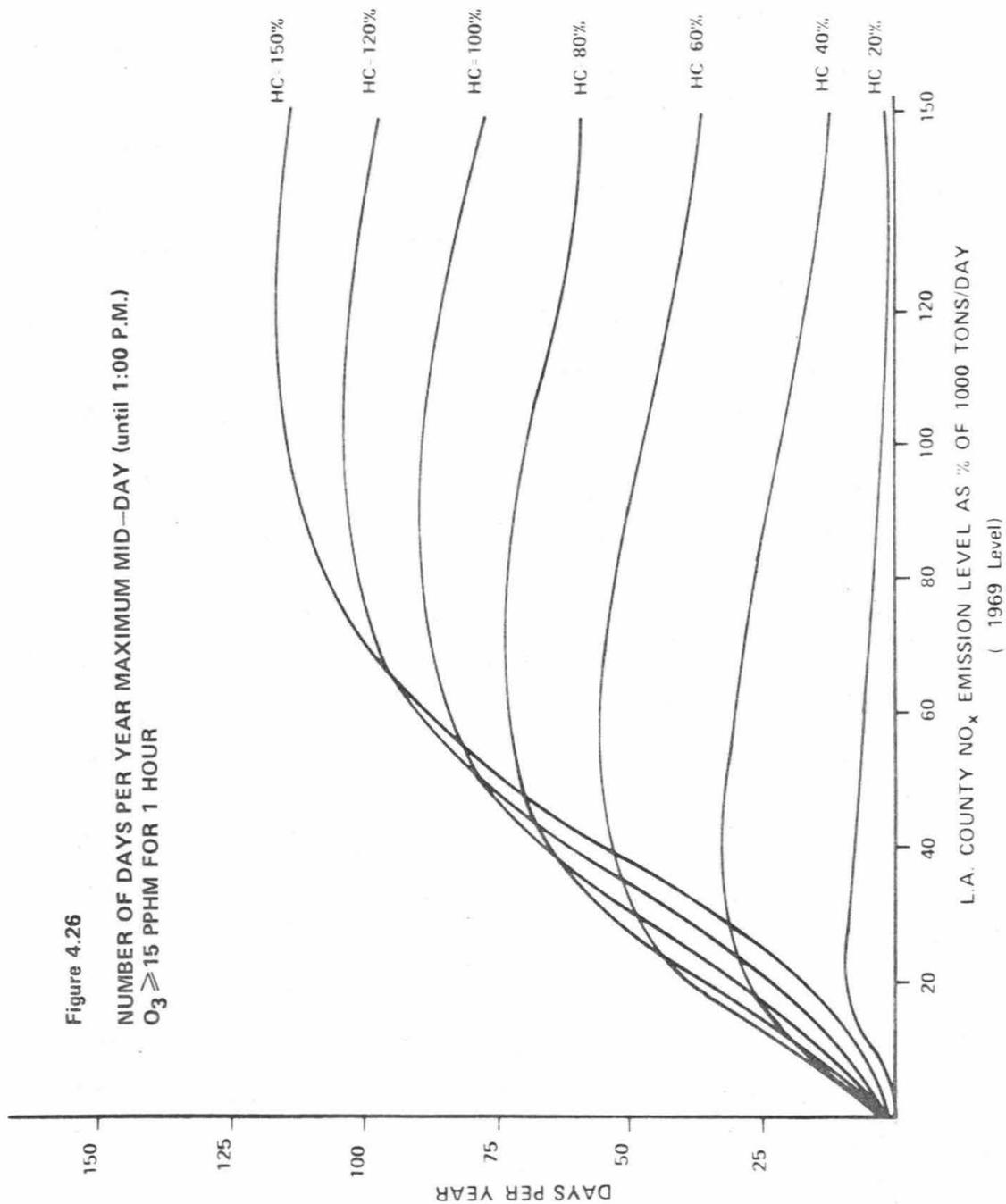
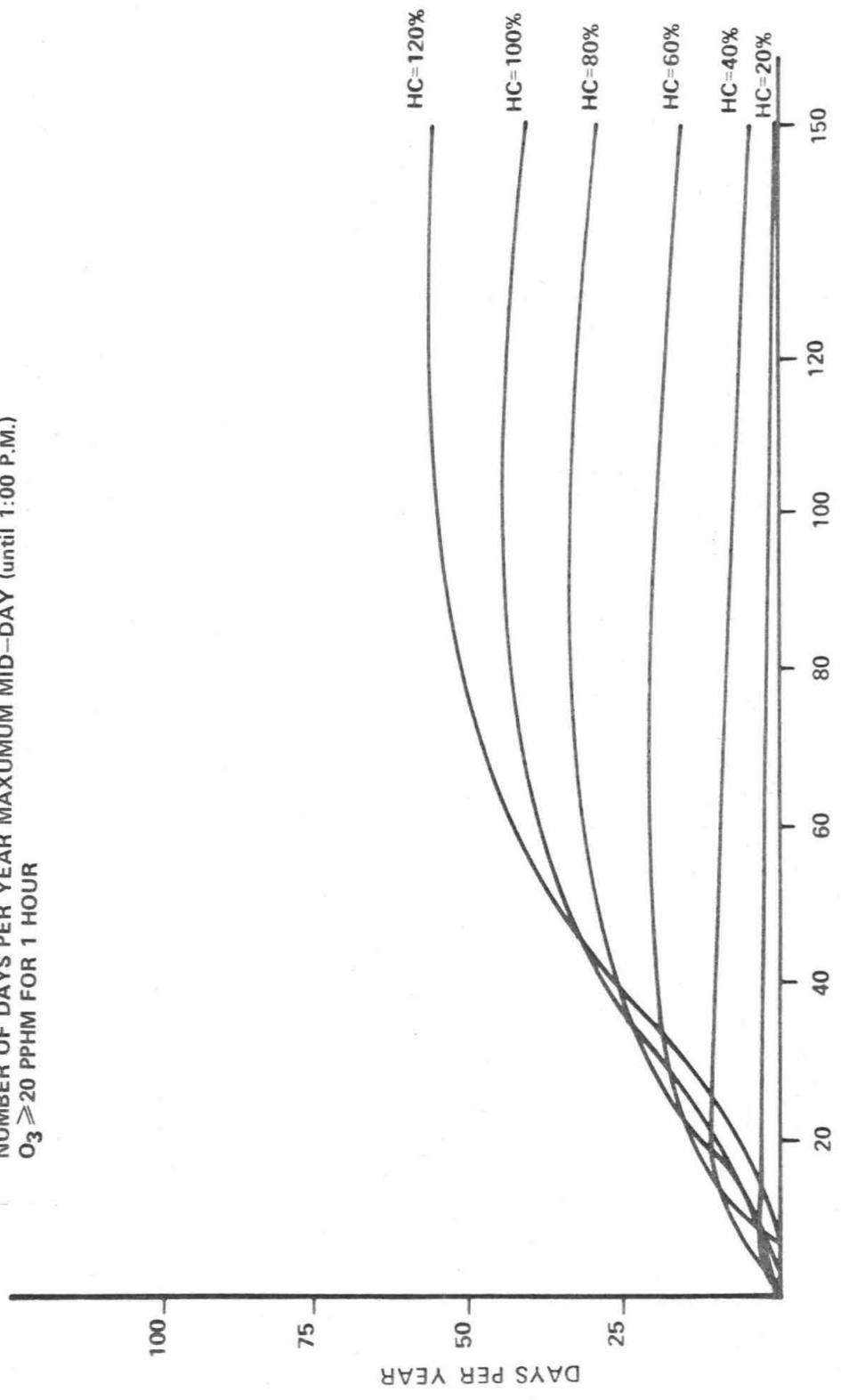


Figure 4.27

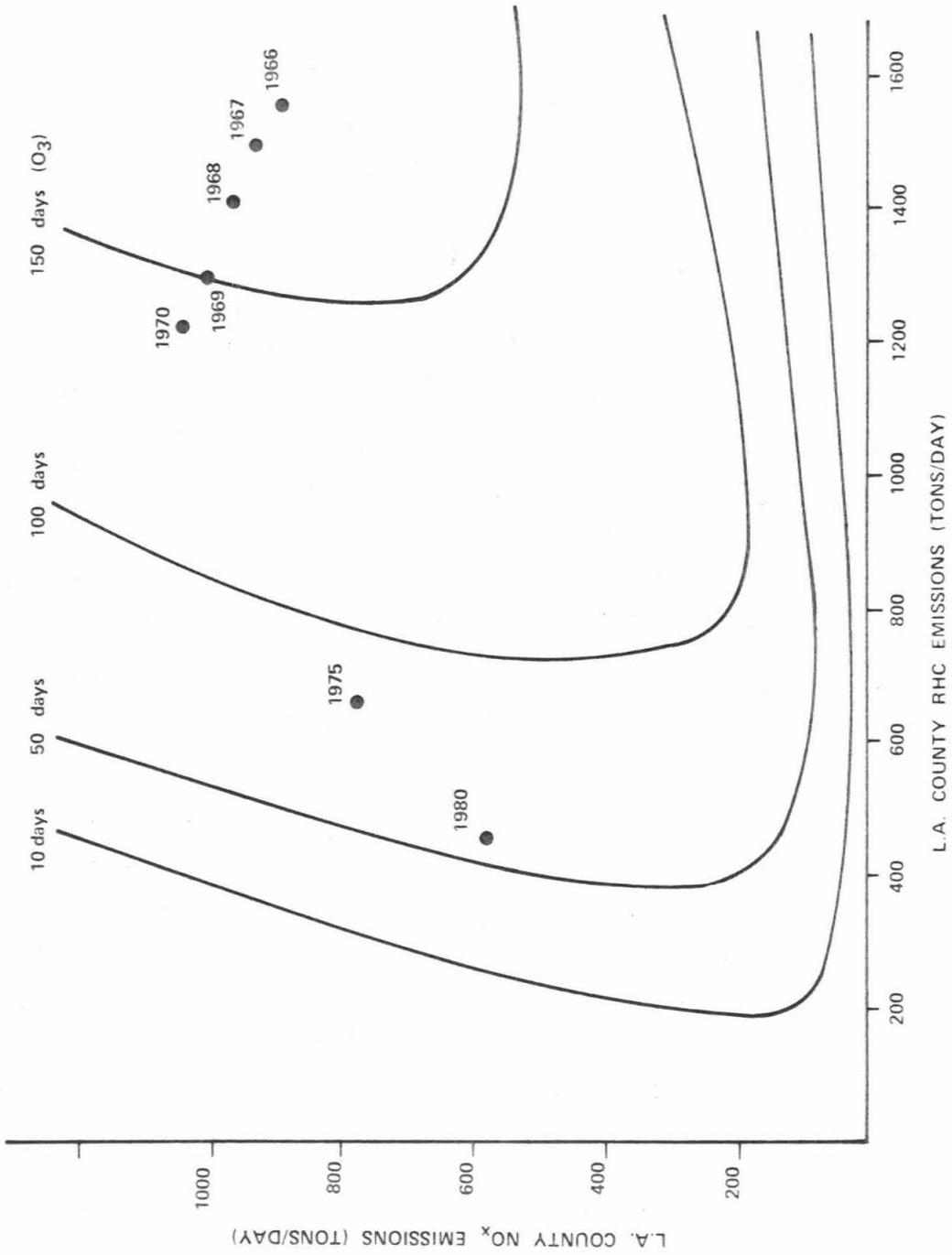
NUMBER OF DAYS PER YEAR MAXIMUM MID-DAY (until 1:00 P.M.)
 $O_3 \geq 20$ PPHM FOR 1 HOUR



L.A. COUNTY NO_x EMISSION LEVEL AS % OF 1000 TONS/DAY (~1969 LEVEL)

Figure 4.28

OXIDANT AIR QUALITY VS. EMISSIONS FOR CENTRAL LOS ANGELES



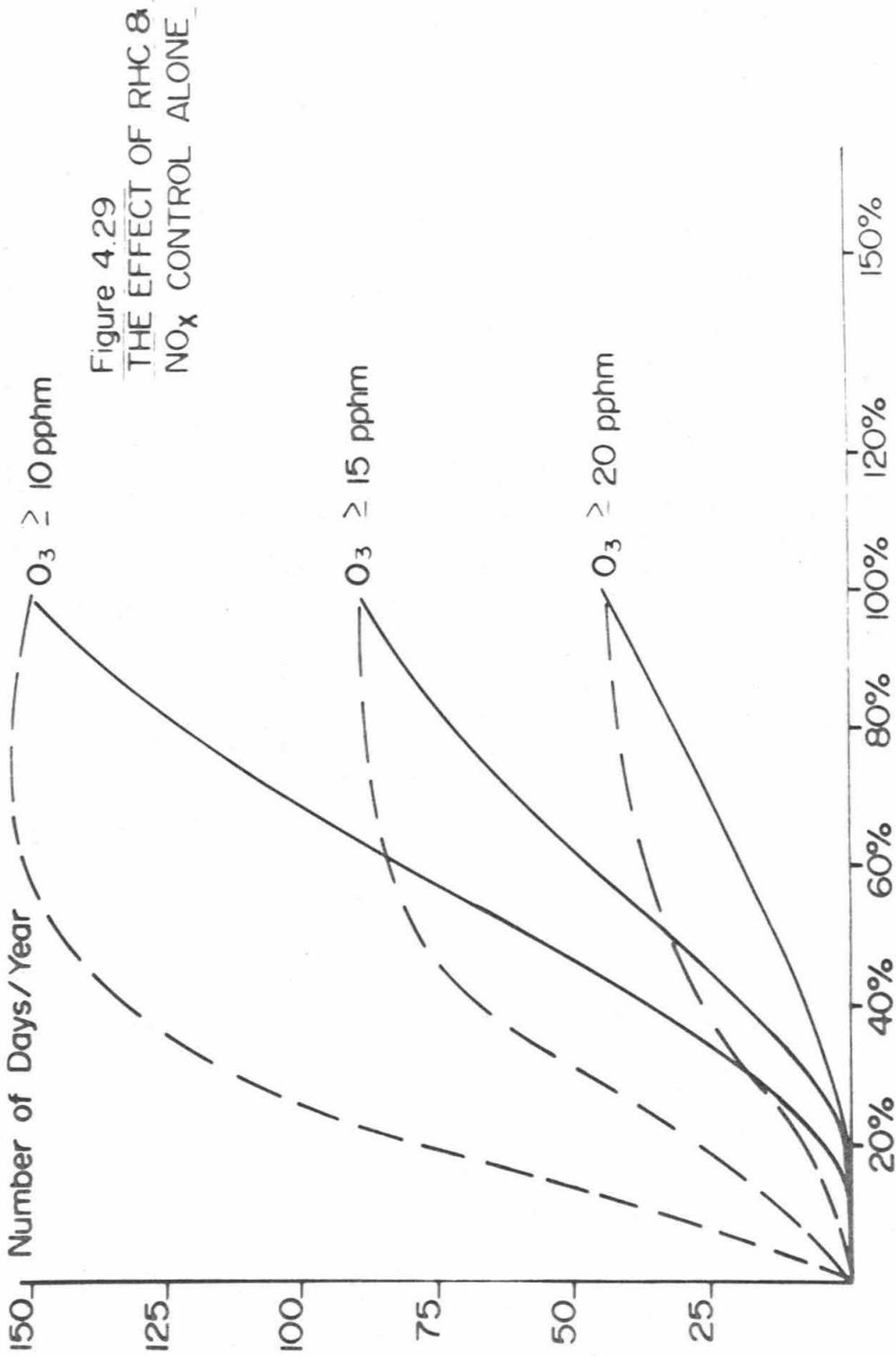


Figure 4.29
 THE EFFECT OF RHC &
 NO_x CONTROL ALONE

Emissions as % of 1300 tons/day RHC, _____ = RHC Control only
 or % of 1000 tons/day NO_x, - - - - = NO_x Control only

was evidently not a bad strategy. The present control strategy is taking Los Angeles down the low RHC ride of the ozone hill.

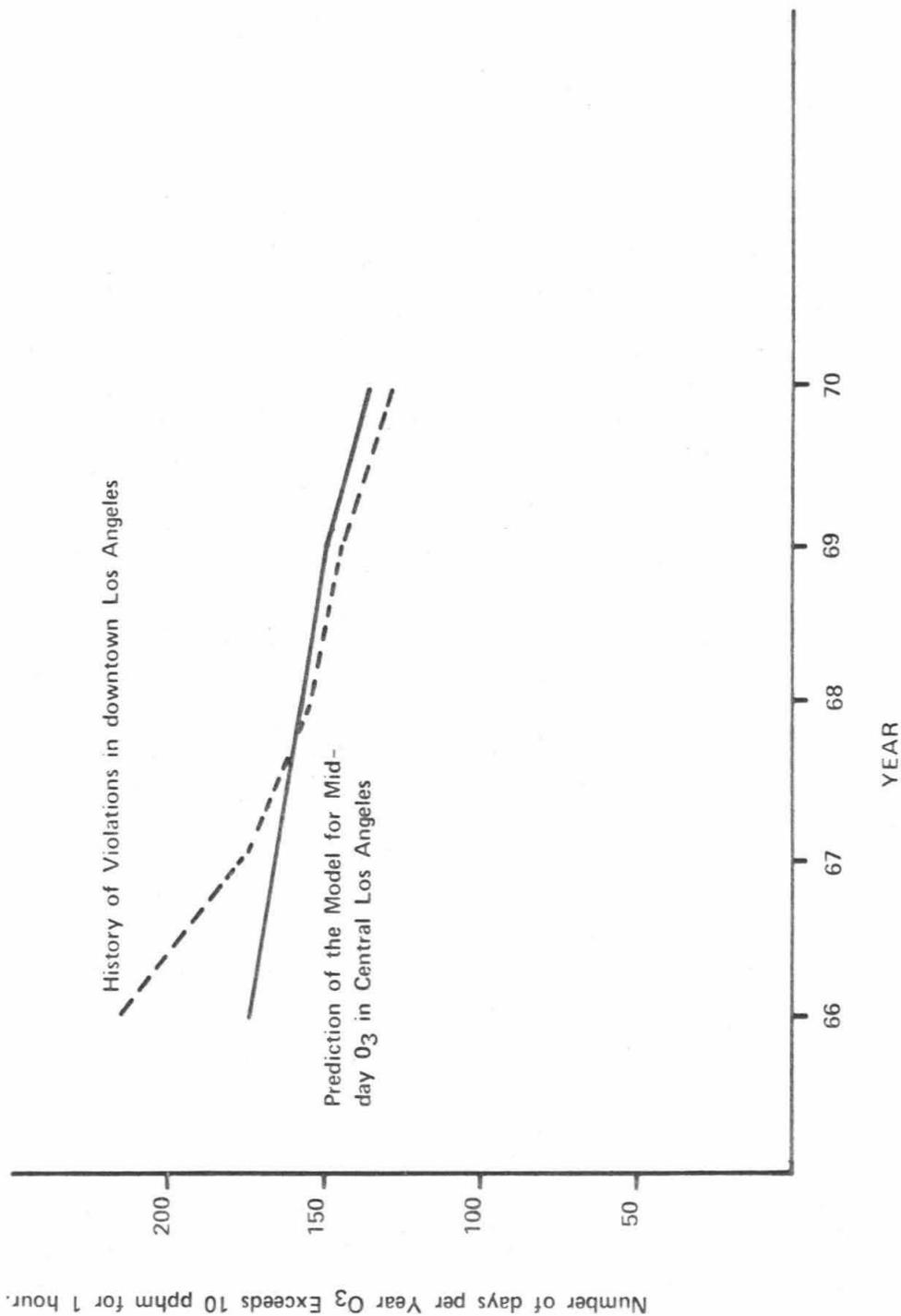
A qualitative check of the self-consistency of the model can be made by comparing the results to historical data on ozone air quality. Figure 4.30 plots the predictions of the model for state standard violations by mid-day ozone in Central Los Angeles from 1966 through 1970. The actual standard violation history in Downtown Los Angeles is given for comparison. The two curves in Figure 4.30 cannot be expected to agree exactly for two reasons. First, the model gives the expected number of violations per year, while the historical data contain yearly meteorological fluctuations. Second, the model gives results for mid-day ozone in the Central Los Angeles area (a weighted average of Burbank, Pasadena, and Downtown from 11:00-1:00), and the historical data are for Downtown at any time of the day. Considering these qualifications, the agreement between the curves in Figure 4.30 is very good. Both curves show about the same trend in the improvement in ozone air quality in the late sixties. The model does appear to be self-consistent with the ozone air quality history for the years that were used as data for the model.

§4.5 A SECOND STATISTICAL MODEL FOR DETERMINING THE FREQUENCY OF STANDARD VIOLATION BY A SECONDARY CONTAMINANT PRODUCED FROM TWO PRIMARY CONTAMINANTS

4.5.1 Analytical Framework

This section addresses the same problem as §4.4, determining air quality levels of a secondary, photochemical pollutant, Z, produced by reactions stemming from two primary contaminants, X and Y. The

Figure 4.30
COMPARISON OF THE RESULTS OF THE
MODEL TO HISTORICAL OZONE AIR QUALITY



model developed here will again be directed toward finding the expected number of days per year that mid-day ozone in Central Los Angeles exceeds standards as a function of L. A. County RHC and NO_x emission levels. The assumptions underlying this model are exactly the same as those in §4.4, except the fourth condition is dropped. Instead of assuming that ozone producing weather factors are statistically independent of primary contaminant concentrations, the present analysis includes the weather factors in the model so that any interdependence is explicitly accounted for.

The three assumptions that form the basis for this model are repeated below from §4.4:

(i) Emission reductions of the primary contaminants, X and Y, occur homogeneously.

Daily pollution pattern assumptions:

(ii) In the air mass that will lead to the pollution on any day, emissions of X and Y accumulate without reacting. This accumulation process produces final concentrations, (x, y) , of X and Y in the air mass.

(iii) At some point in time, t_1 , emissions stop, and at some later time, $t_2 \geq t_1$, certain meteorological factors trigger the reaction of X and Y to produce Z. The only effect of emissions on Z production is through the concentrations x and y . "z", the level of Z formed on any day, is a function of x , y , and the meteorological factors that govern the reaction. It is assumed that these weather factors are

known and measurable and can be represented by an n dimensional vector, \underline{W} , so that

$$z = z(x, y, \underline{W}) = z(x, y, W_1, \dots, W_n) . \quad (4-13)$$

Based on these three assumptions, a statistical model, the input to which atmospheric monitoring data are taken at one (yearly) emission level, is developed below to determine the number of days per year that the secondary pollutant, Z , exceeds standards as a function of emission levels for X and Y . The analysis follows.

At one emission level of X and Y , call it $\underline{E}^0 = (E_1^0, E_2^0) = \underline{E}^0(\underline{x}, t)$, one measures the following two functions:

$$\begin{aligned} \text{(i) } N^0(x, y, \underline{W}) dx dy d\underline{W} \\ &= N^0(x, y, W_1, \dots, W_n) dx dy dW_1, \dots, dW_n^* , \\ &= \text{the number of days per year with primary con-} \quad (4-14) \\ &\quad \text{taminant concentrations in the range } x \rightarrow x + dx, \\ &\quad y \rightarrow y + dy \text{ and with weather factors in the range} \\ &\quad W_1 \rightarrow W_1 + dW_1, \dots, W_n \rightarrow W_n + dW_n , \end{aligned}$$

$$\begin{aligned} \text{(ii) } z^0(x, y, \underline{W}) &= z^0(x, y, W_1, \dots, W_n) , \\ &= \text{the level of } Z \text{ produced as a function} \quad (4-15) \\ &\quad \text{of } x, y, \text{ and } \underline{W} . \end{aligned}$$

Then, for any emission level, $\underline{E} = (\alpha E_1^0, \beta E_2^0) = (\alpha, \beta) \cdot \underline{E}^0(\underline{x}, t)$, assumptions (i) \rightarrow (iii) imply that the new functions, $N(x, y, \underline{W})$ and $z(x, y, \underline{W})$ satisfy

* In §4.4, it was assumed that N^0 took the special form, $N^0(x, y, \underline{W}) = \psi^0(x, y)\varphi(\underline{W})$. This allowed the weather factors to be eliminated from the analysis.

$$N(x, y, \underline{W}) dx dy d\underline{W} = N^0(x/\alpha, y/\beta, \underline{W}) \frac{dx}{\alpha} \frac{dy}{\beta} d\underline{W} , \quad (4-16)$$

and

$$z(x, y, \underline{W}) = z^0(x, y, \underline{W}) . \quad (4-17)$$

Equation (4-16) just states that concentrations x and y are proportional to emissions of X and Y , respectively. As described in §4.4, this results from (i), (ii), and the linearity of the equation of advective diffusion for inert contaminants.

Equation (4-17) is really just an identity by the way the problem has been physically defined. The change in emissions only affects the distribution of concentrations, (x, y) , and z is the same function of the concentrations and the weather parameters that produce Z from the concentrations.

From (4-16) and (4-17), the expected number of days per year that the secondary pollutant exceeds a standard, z_s , is calculated as follows:

Expected number of days per year that z exceeds z_s as a function of emission levels, α and β

$$\begin{aligned} &= \int_0^{\infty} \int_0^{\infty} \int_{\text{all } \underline{W}} N(x, y, \underline{W}) H(z(x, y, \underline{W}) - z_s) dx dy d\underline{W} , \\ &= \int_0^{\infty} \int_0^{\infty} \int_{\text{all } \underline{W}} N^0\left(\frac{x}{\alpha}, \frac{y}{\beta}, \underline{W}\right) H(z^0(x, y, \underline{W}) - z_s) \frac{dx}{\alpha} \frac{dy}{\beta} d\underline{W} , \end{aligned} \quad (4-18)$$

$$= \int_0^{\infty} \int_0^{\infty} \int_{\text{all } \underline{W}} N^O(x, y, \underline{W}) H(z^O(\alpha x, \beta y, \underline{W}) - z_s) dx dy d\underline{W} ,$$

$$= \text{function of } \left\{ \begin{array}{ll} z_s & \dots \text{ the standard ,} \\ \alpha, \beta & \dots \text{ primary contaminant} \\ & \text{emission levels ,} \\ N^O, z^O & \dots \text{ functions measured at} \\ & \text{one emission level ,} \end{array} \right.$$

where

$$H = \text{Heaviside step function} \equiv H(z) = \begin{cases} 0, & z < 0, \\ 1, & z > 0. \end{cases}$$

4.5.2 Mid-day Ozone Standard Violations in Central Los Angeles As A Function of L. A. County RHC and NO_x Emission Levels, $F_1(E_1, E_2)$

4.5.2.1 Description of the problem.

This section describes an attempt at applying the model of section 4.5.1 to obtain a second, more reliable estimate of $F_1(E_1, E_2)$, the number of ozone standard violations in Central Los Angeles as a function of RHC and NO_x emissions. As in §4.4, primary contaminant concentrations, (x, y) , are 7:30-9:30 A.M. civil time averages of total HC (minus 1 ppm for natural background methane) and NO_x concentrations in Downtown Los Angeles. Also, maximum one hour ozone, z , is again a weighted average (according to wind speed and direction) of maximum one hour ozone between 11 A.M. and 1 P.M. at Downtown, Burbank, and Pasadena. \underline{W} , the weather vector, consists of those smog related meteorological factors that the L. A. County APCD records each day.

4.5.2.2 Applicability of the model.

The discussion of the applicability of the model with respect to the assumptions about homogeneous emission reductions and about the daily temporal pollution pattern is exactly the same as in §4.4, (see section 4.4.2.2). The only new assumption in the present model is that the weather factors that govern Z production are known and measurable and can be represented by a vector, \underline{W} . In an attempt to apply the model, (discussed in the following paragraphs), violation of this assumption leads to failure; it did not prove possible to find the function $z = z(x, y, \underline{W})$, with the set of weather factors that has been recorded.

The data (morning concentrations, (x, y) , mid-day ozone, z , and weather factors, \underline{W}), for finding the function, $z(x, y, \underline{W})$, were taken from APCD records for the years 1966-1970 with a total of 1270 "usable" days.* The first and second columns of Table 4-V describe the weather factors that had been recorded. In order to determine the function, $z(x, y, \underline{W})$, the data were first divided into groups of "constant" x and y .** Then, for fixed (x, y) , regressions were run between z and \underline{W} in an attempt to find $z(x, y, W_1, \dots, W_n)$ for various given (x, y) . A log-log regression form,

*The APCD data contained many missing points. About two-thirds of the days had at least one measurement absent. More than half of these days were salvaged by interpolating data for hours surrounding the missing measurement. The other 30% of the days had no data at all for one of the concentrations or weather parameters and were eliminated.

**Actually, there were groups of small ranges in x and y . The data were divided into thirty such groups.

TABLE 4-V

Ozone Related Weather Factors

Weather Parameter	Description	Form Used In Regressions	Typical Partial Correlation Coefficient	Typical Partial Regression Coefficient
SR	Average solar radiation intensity in Downtown L. A. from 9:00 A. M. to 1:00 P. M. Civil Time, (Langleys per hour)	$W_1 = SR$	0.7	0.5
TM	Maximum daily temperature in Downtown L. A., ($^{\circ}F$)	$W_2 = TM - 50$	0.7	0.6
HM	Maximum mixing height in L. A. as calculated by the APCD from temperature readings, (feet)	$W_3 = HM$	0.6	-0.5
TLP	7:00 PST temperature gradient between L. A. International Airport and Palmdale, ($^{\circ}F$)	$W_4 = TLP + 30$ $W_5 = TLP $	0.5 0.1	-0.3 0.0
WS	Average 9:00-12:00 PST wind speed (miles per hour)	$W_6 = WS$	0.2	-0.2
RH	Minimum hourly relative humidity in Downtown L. A., (per cent)	$W_7 = RH$ $W_8 = RH - 40 $	0.2 0.1	0.1 0.0
IS	Inversion strength, difference in temperature at base and top of inversion at 7:00 PST, ($^{\circ}F$)	$W_9 = IS$	0.4	0.1

TABLE 4-V (Continued)

Weather Parameter	Description	Form Used In Regressions	Typical Partial Correlation Coefficient	Typical Partial Regression Coefficient
PLP	7:00 PST pressure gradient between L.A. International Airport and Palmdale, (millibars)	$W_{10} = \text{PLP} + 100$ $W_{11} = \text{PLP} $	0.1 0.2	0.0 0.0
DPLP	Daily <u>change</u> in PLP, (millibars)	$W_{12} = \text{DPLP} + 30$	0.1	0.0
HO	7:00 PST inversion base height, (feet)	$W_{13} = \text{HO}$	0.1	-0.1

$$\log z = a + b_1 \log W_1 + \dots + b_n \log W_n$$

or

(4-19)

$$z = AW_1^{b_1} W_2^{b_2} \dots W_n^{b_n}$$

was used.* Column 3 of Table 4-V gives the explicit forms of the weather variables used in the regressions, and columns 4 and 5 present typical values that resulted for partial correlation and regression coefficients.

Only four of the weather factors consistently had high correlation and significant regression coefficients. In order to simplify the analysis (it is easier to find the functional form with 6 independent variables rather than 15), all the other weather parameters were eliminated from the study. The problem then became to determine $z(x, y, W_1, W_2, W_3, W_4)$.

Again the data were divided into thirty groups of fixed x and y and log-log regressions were run for each group from z to W in an attempt to find the function in the form

*A multiple regression, $v = a + b_1 u_1 + \dots + b_n u_n$, picks (a, b_1, \dots, b_n) for a least squares fit of the data for (u_1, \dots, u_n) to the data for v . The partial correlation coefficient, ρ_i , for the i th independent variable, u_i , is the square root of the variance in the dependent variable, v , that is explained by the multiple regression but which is not explained if u_i is not included. The partial regression coefficient, b_i , is the net relation of u_i to v , the change in v from a unit change in u_i with the other variables held constant.

A log-log regression rather than a linear regression was performed because many weather parameters, (e.g., SR, TM, and HM), completely squelch z formation when they reach extreme values (e.g., SR = 0, TM-50 = 0, or HM = ∞). The log-log form fits this behavior.

$$z = A(x, y)W_1^{b_1(x, y)} W_2^{b_2(x, y)} W_3^{b_3(x, y)} W_4^{b_4(x, y)} \quad (4-20)$$

Total correlation coefficients resulting from the regressions for each group ranged from 0.70 to 0.95, with most between 0.78 and 0.90. This meant that around 60-70% of the variance in z , for fixed (x, y) , was explained by the log-log regression equation.

Although the results for total correlation coefficients appeared rather promising, the above analysis did not provide a satisfactory form of the function, z . First, the coefficients, b_i , depended erratically on x and y . This occurred because many of the data groups contained few points (10-25) while others contained numerous points (100-200).^{*} Those data groups with few points had regression coefficients with large errors, and a great deal more total data would be required to obtain better estimates of the b_i associated with these groups. Second, even for those data groups with high correlation and very accurately estimated b_i , the regression analysis was unsatisfactory for the purpose of this work in the sense that it tended to fit days of low ozone well but days of high ozone rather poorly. The log-log regression form minimized relative errors in z , so that for low ozone days the estimate was, say, $z = 2.5 \text{ pphm} \pm 1 \text{ pphm}$ while for high ozone days it was, say $z = 25 \text{ pphm} \pm 10 \text{ pphm}$. This work is most interested in the high ozone days that exceed the standards, and the results were not satisfactory for these days.

^{*}As noted in section 4.4.2.3, most x and y fall along a fixed HC-NO_x ratio. Away from this ratio, the data are scarce.

A great deal of effort was devoted to improve the analysis. Larger data groups and "moving"* groups were used in an attempt to overcome the lack of data for some (x, y) regions. Eliminating very low ozone days, adding further nonlinearity to the regression form, and using some of the other weather factors that had been dropped, were tried in an attempt to improve the prediction on high ozone days. These additions to the analysis lead to improvements in the results, but only marginal improvements. None of the procedures provided an estimate of the function, z, that was deemed satisfactory. Rather than devote a great deal more time to obtain further marginal improvements, this analysis was finally abandoned and the results for $F_1(E_1, E_2)$ from §4.4 were used.

*For example, x ranges such as 1-1.5 ppm, 1.2-1.8 ppm, 1.6-2.2 ppm, etc. were chosen.

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CHAPTER 5
THE LEAST COST OF REACHING VARIOUS
AIR QUALITY LEVELS

Chapter 3 determined the minimum cost of reaching various RHC and NO_x emission levels in Los Angeles County by 1975. Chapter 4 related ozone and nitrogen dioxide air quality in Central Los Angeles to emissions. The present chapter combines these two results to find the least cost of reaching various air quality levels for the Los Angeles photochemical smog example.

§5.1 restates the least cost air quality model and employs it to find the cost of various combinations of ozone and nitrogen dioxide air quality levels in Central Los Angeles. §5.2 examines the ozone and nitrogen dioxide problems separately. §5.3 discusses the conclusions, and §5.4 suggests possible extensions of this study.

§5.1 SOLUTION OF THE LEAST COST AIR QUALITY MODEL

The mathematical least cost air quality model, (developed in Chapter 1), in a form appropriate to the L. A. photochemical smog problem (Chapter 2), is as follows:

To find the least cost of attaining air quality levels, (P_1, P_2) , one chooses (E_1, E_2) that minimizes

$$C = G(E_1, E_2) ,$$

subject to the constraints

$$P_1 \geq F_1(E_1, E_2) ,$$

$$P_2 \geq F_2(E_1, E_2) ,$$

$$E_1 \geq 0, E_2 \geq 0 ,$$

where

E_1 = Average (tons/day) RHC emission level in L. A. County in 1975,

E_2 = Average (tons/day) NO_x emission level in L. A. County in 1975,

P_1 = Expected number of days per year that mid-day ozone in Central Los Angeles exceeds the State standard (10 pphm for 1 hr.),

P_2 = Expected number of days per year that nitrogen dioxide in Central Los Angeles exceeds the State standard (25 pphm for 1 hr.),

$G(E_1, E_2)$ = The minimum cost of reaching emission levels, (E_1, E_2) ,

$F_1(E_1, E_2), F_2(E_1, E_2)$ = Expected air quality as a function of emission levels.

(5. 1)

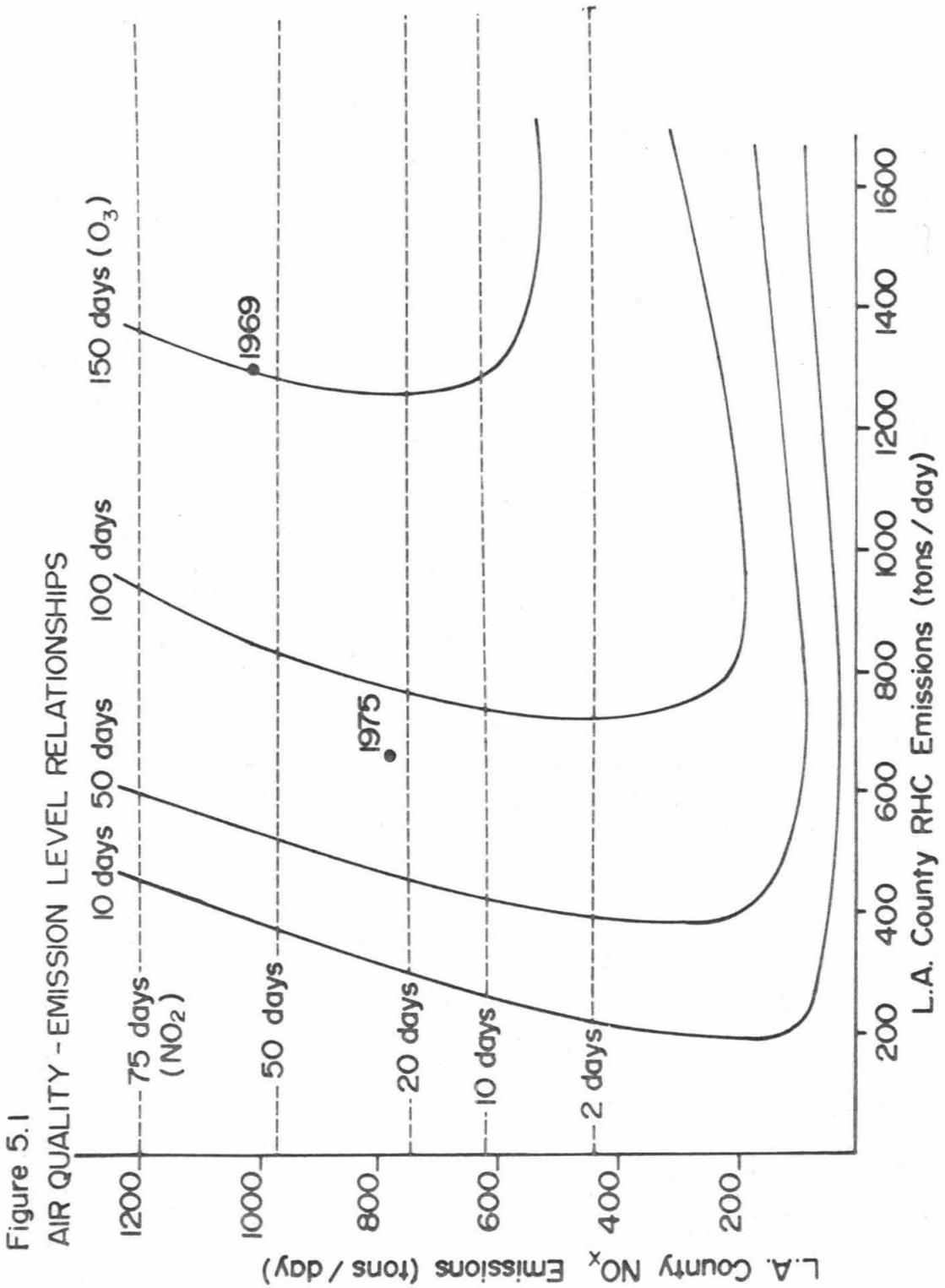
Chapter 3 showed how a linear programming model could be used to find the least cost of reaching various RHC and NO_x emission levels. Figure 3. 1, page 72, presented the results. The function, $G(E_1, E_2)$, is represented by iso-cost curves giving the minimum annualized cost (in \$ millions) associated with various emission levels.

Chapter 4 employed phenomenological air quality models to determine ozone and nitrogen dioxide levels as functions of RHC and NO_x emission levels. Figure 5.1 (taken from Figures 4.7 and 4.28) presents these results. The functions $F_1(E_1, E_2)$ and $F_2(E_1, E_2)$, O_3 and NO_2 , respectively, are represented by iso-air quality curves giving the expected number of standard violations per year for each pollutant associated with various emission levels.

By combining Figures 3.1 and 5.1, the least cost air quality model, (5-1), can be solved by simple graphical analysis. Figure 5.2 illustrates such an analysis for the case P_1 equal to 50 ozone violations per year and P_2 equal to 10 nitrogen dioxide violations per year. The points in the emission space that satisfy both air quality constraints lie in the shaded region. The minimum cost of at least attaining P_1 and P_2 is found by taking that point in the shaded region that has the least emission control cost. For this example, the optimal point occurs at A, ($E_1 = 430$, $E_2 = 620$), and the cost is \$50 million per year.

By using the curves in Figure 5.2, the minimum cost of attaining any air quality levels, (P_1, P_2) , can be found by a similar graphical analysis. The results for several selected air quality levels are presented in Table 5-I. For the specific control methods associated with each emission control level, the reader is referred to Table 3-III of Chapter 3.

Since it was assumed that maximal NO_2 concentrations were proportional to NO_x emissions and were independent of RHC emissions



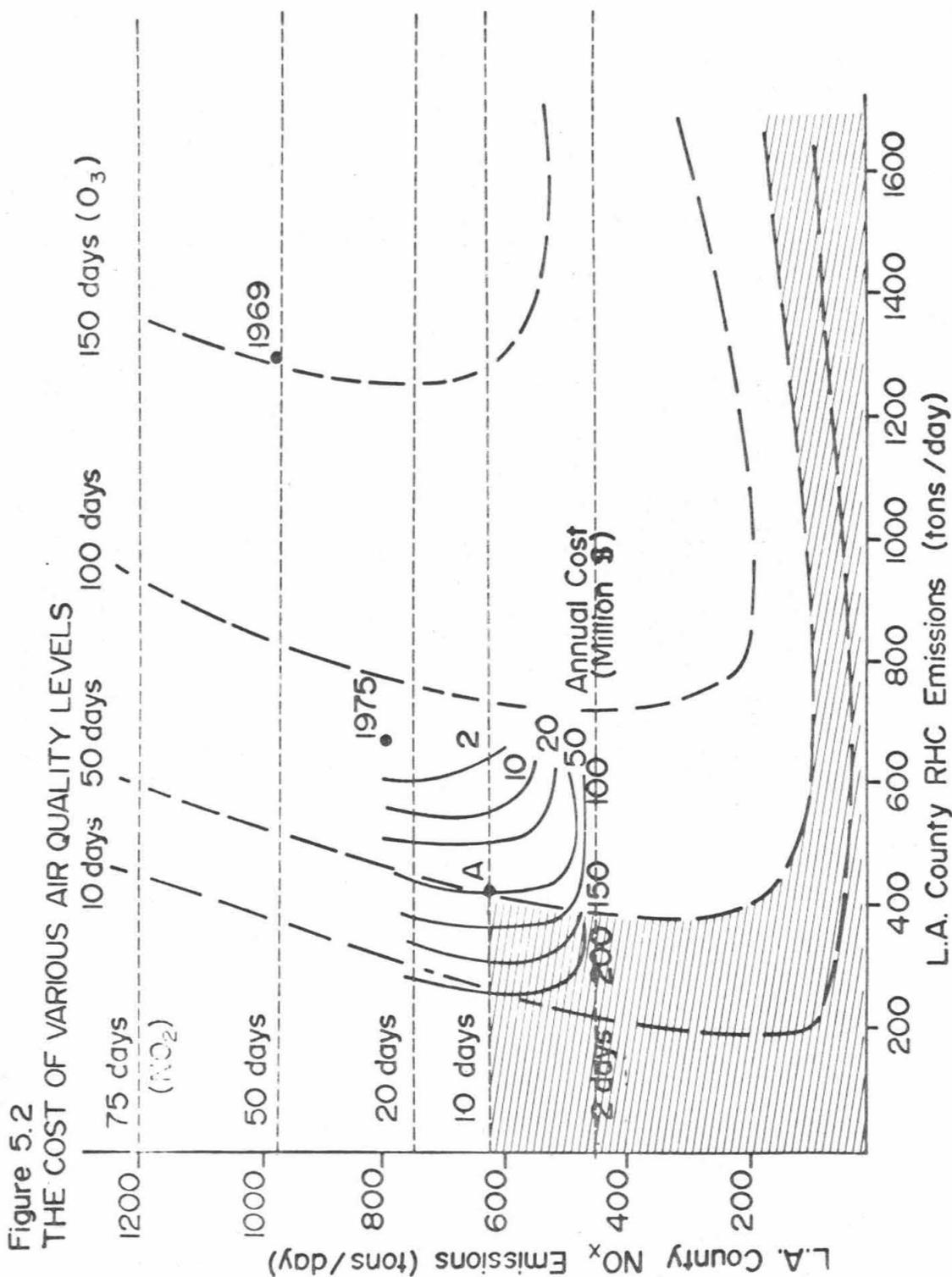


TABLE 5-1

The Minimum Cost of Reaching Various Air Quality Levels

Air Quality		Minimum Cost	Associated Emission Levels	
P ₁	P ₂		E ₁	E ₂
Expected number of O ₃ violations per year	Expected number of NO ₂ violations per year	Millions of dollars	E ₁ (RHC)	E ₂ (NO _x)
1975 level → 80	25	- -	670	790
80	15	1	670	690
80	10	2	650	620
80	5	12	630	550
80	3 (lowest feasible)	80	590	460
-----	-----	-----	-----	-----
50	25	45	430	700
50	15	50	420	690
50	8	60	400	600
50	3 (lowest feasible)	150	380	460
-----	-----	-----	-----	-----
25	25	120	370	760
25	15	125	350	690
25	8	140	320	600
25	3 (lowest feasible)	200	290	460
-----	-----	-----	-----	-----
10 (lowest feasible)	25	180	300	750
10	15	185	280	690
10	8 (lowest feasible)	220	260	600

(see §4.3.2.2), NO_2 air quality depends only on NO_x emissions; improving NO_2 air quality, P_2 , requires reductions in NO_x , E_2 . Ozone air quality depends on both RHC and NO_x emissions and can be improved by reducing either E_1 or E_2 . However, Figure 5.2 reveals that RHC control is much more cost-effective in reducing ozone in Central Los Angeles than is NO_x control. From the 1975 starting point, RHC reductions take Central Los Angeles directly down the "ozone hill", while moderate NO_x reductions just slide along the contours of the "ozone hill". Fifty million dollars spent on RHC control reduces ozone violations from 80 to 50 days per year. Fifty million dollars spent on NO_x control slightly increases violations to 85 days per year. The two-dimensional photochemical air quality problem thus contains two one-dimensional subproblems: (1) the cost of O_3 control by RHC emission reductions and (2) the cost of NO_2 control by NO_x emission reductions. The next section will examine these two problems separately. This section will continue to discuss their interrelationship in the two dimensional problem.

From Figure 5.2 and Table 5-I, it is apparent that neither NO_2 nor O_3 violations can be completely eliminated with the control methods considered in this study. NO_2 violations can only be reduced to about 3 days per year at a cost of \$80 M. O_3 violations can only be reduced to around 8 days per year at a cost of \$210 M. A trade-off effect exists between maximal O_3 and NO_2 reductions. Best possible NO_2 air quality, 3 violations per year, limits ozone to above 25 violations per year at a cost of \$230 M. Best possible O_3 air quality,

8 days per year, limits NO_2 violations to above 10 days per year at a cost of \$230 M. Basically, this trade-off results because used cars can either be intensively NO_x controlled (improving NO_2 air quality) or intensively RHC controlled (improving O_3 air quality). Choosing high NO_x (NO_2) control for used cars limits possible RHC (O_3) control and vice versa.

In §3.3, it was noted that for given RHC control, NO_x control is inexpensive for initial, rather large reductions but then becomes very expensive for further, slight reductions. This property of the cost function is illustrated by the vertical character of the cost curves over rather large regions in Figures 3.1 and 5.2. This effect carries over to air quality costs, so that for given O_3 control, NO_2 control is fairly inexpensive for initial reductions and then becomes very expensive. For instance, at 80 days per year O_3 violations, NO_2 violations of (25, 15, 8, and 3) days per year, respectively, cost (0, 1, 3, and 80) million dollars. For 25 days per year O_3 violations, with a cost of \$120 M, NO_2 violations of (25, 15, 8, and 3) days per year have total costs of (120, 125, 140, and 200) million dollars, respectively. For given NO_2 air quality, ozone control costs rise more consistently. For instance, at 15 days per year NO_2 violations, (80, 50, 25, and 10) days per year O_3 violations respectively cost (1, 50, 125, and 185) million dollars.

Out of all the possible air quality levels and associated control costs in Figure 5.2 and Table 5-I, the air pollution policy maker must choose one. This choice depends on how ozone and nitrogen dioxide

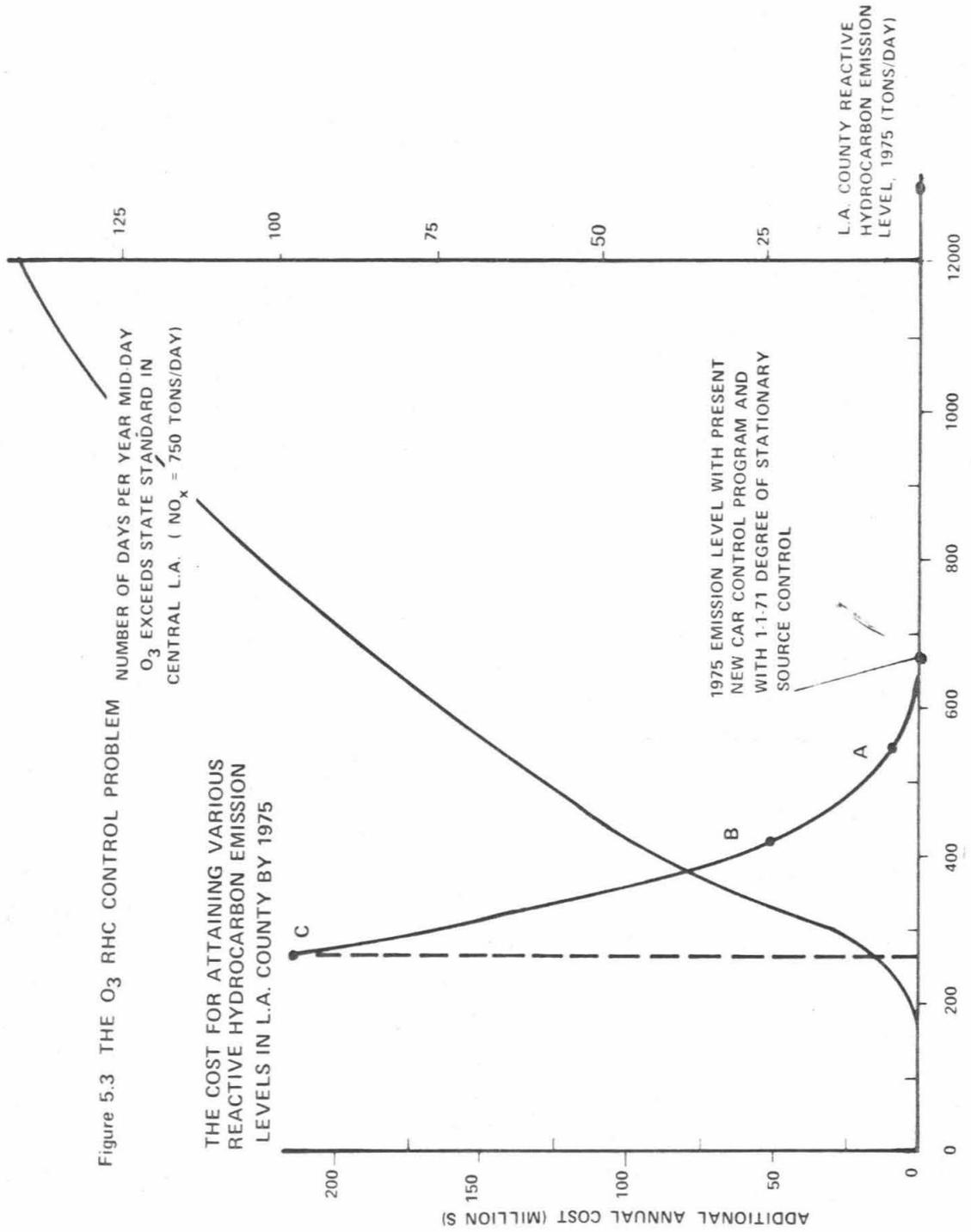
standard violations are evaluated in comparison to control dollars. Even if reducing violations has utmost priority, so that control dollars do not count, some value must be attached to the relative importance of O_3 and NO_2 violations. It is not the purpose of this work to make such evaluations. The objective here is only to delineate the basic technical relationships between costs and air quality so that some of the trade-offs in the total air pollution control problem become more apparent. The air pollution policy maker can use these results for a more systematic evaluation of the problem and arrive at decisions by making the appropriate evaluations.

§5.2 THE OZONE AND NITROGEN DIOXIDE PROBLEMS EXAMINED SEPARATELY

The previous section determined the costs of various combinations of ozone and nitrogen dioxide air quality levels and examined some of the trade-off effects existing in that two-dimensional problem. This section discusses two one-dimensional problems, the cost of ozone air quality levels by RHC emission control and the cost of nitrogen dioxide air quality levels by NO_x emission control.

Figure 5.3 presents the control cost-emission level and air quality-emission level functions for the O_3 -RHC problem. The lower axis measures L. A. County RHC emissions. The vertical axis on the left measures emission control dollars. The curve rising to the left relates control costs to emissions. The specific control programs associated with points A, B, and C are given in Table 3-III. The

Figure 5.3 THE O₃ RHC CONTROL PROBLEM



relationship between mid-day ozone violations in Central Los Angeles (measured on the axis to the right) and RHC emissions is given by the curve rising to the right. By using these two curves to relate both control costs and air quality to emissions, one can find the cost of various air quality levels. Figure 5.4 gives the resulting ozone violation-control cost curve. Starting at zero cost for 80 violations per year, (the base level for this study), control costs rise nonlinearly to \$210M for 8 days per year. Although this curve is nonlinear, (increasing slope or marginal cost), it does not have very great curvature. This results because even though marginal emission control costs rise as emissions fall, marginal improvements in ozone air quality also rise slightly (see Figure 5.3). The marginal cost of reduced ozone violations thus increases less than the marginal cost of emission reductions.

Figure 5.5 presents the appropriate functions for the NO_2 - NO_x problem. The curve rising to the left gives the cost of NO_x emission control, measured on the left axis. The curve rising to the right gives the relationship between NO_2 standard violations and emissions. Again, by combining these two curves, one finds the cost of various air quality levels. Figure 5.6 presents this function. The curve in Figure 5.6 is strikingly nonlinear. Above ten violations per year, the marginal cost of air quality improvement is \$100,000 per day of violation reduction (dollars/year - days violation/year). Below 6 violations per year, marginal costs rise to around \$35,000,000 per day reduction. This effect results because, as shown in Figure 5.5, marginal

Figure 5.4
THE COST OF ATTAINING
VARIOUS OZONE AIR QUALITY
IN L.A. COUNTY BY 1975

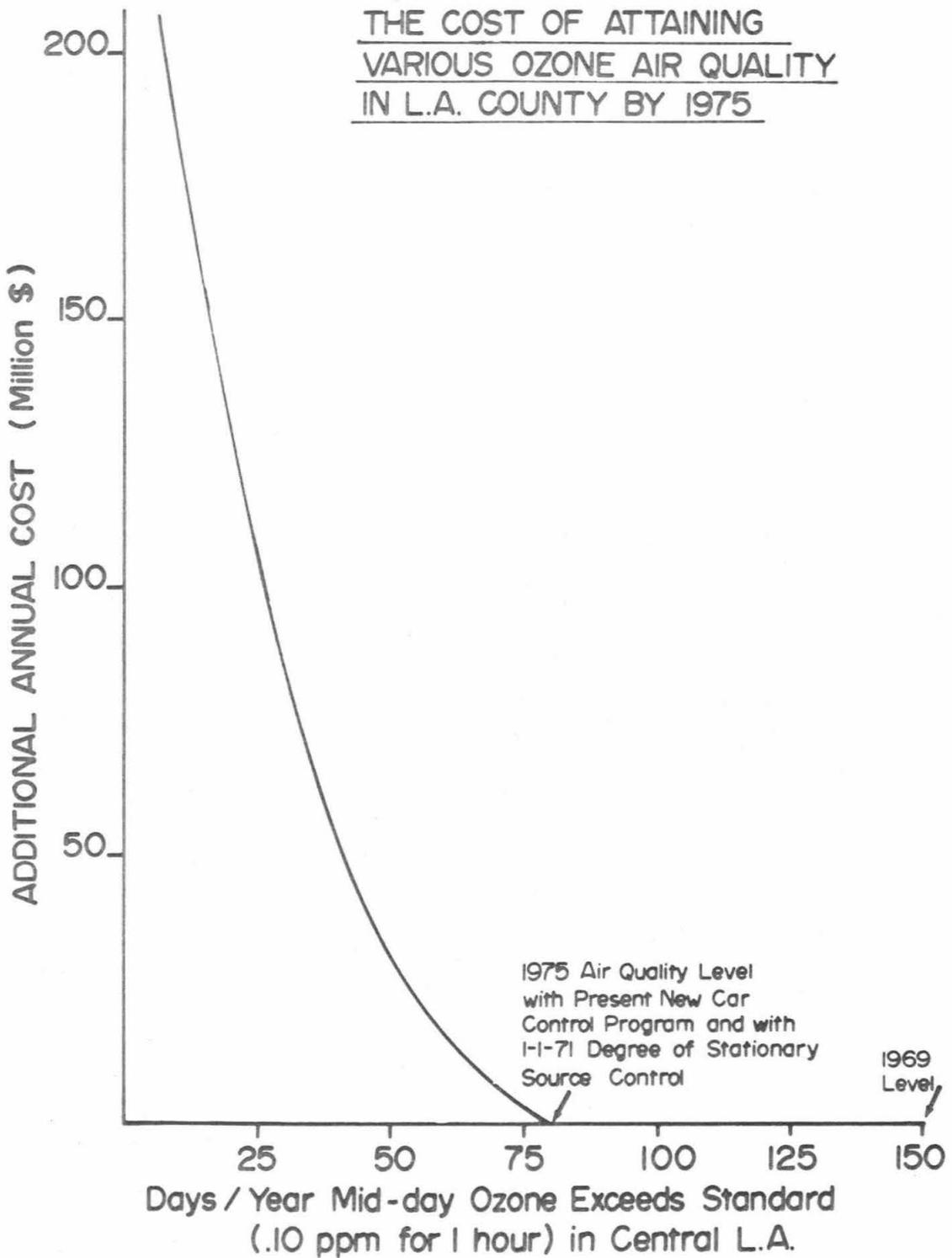
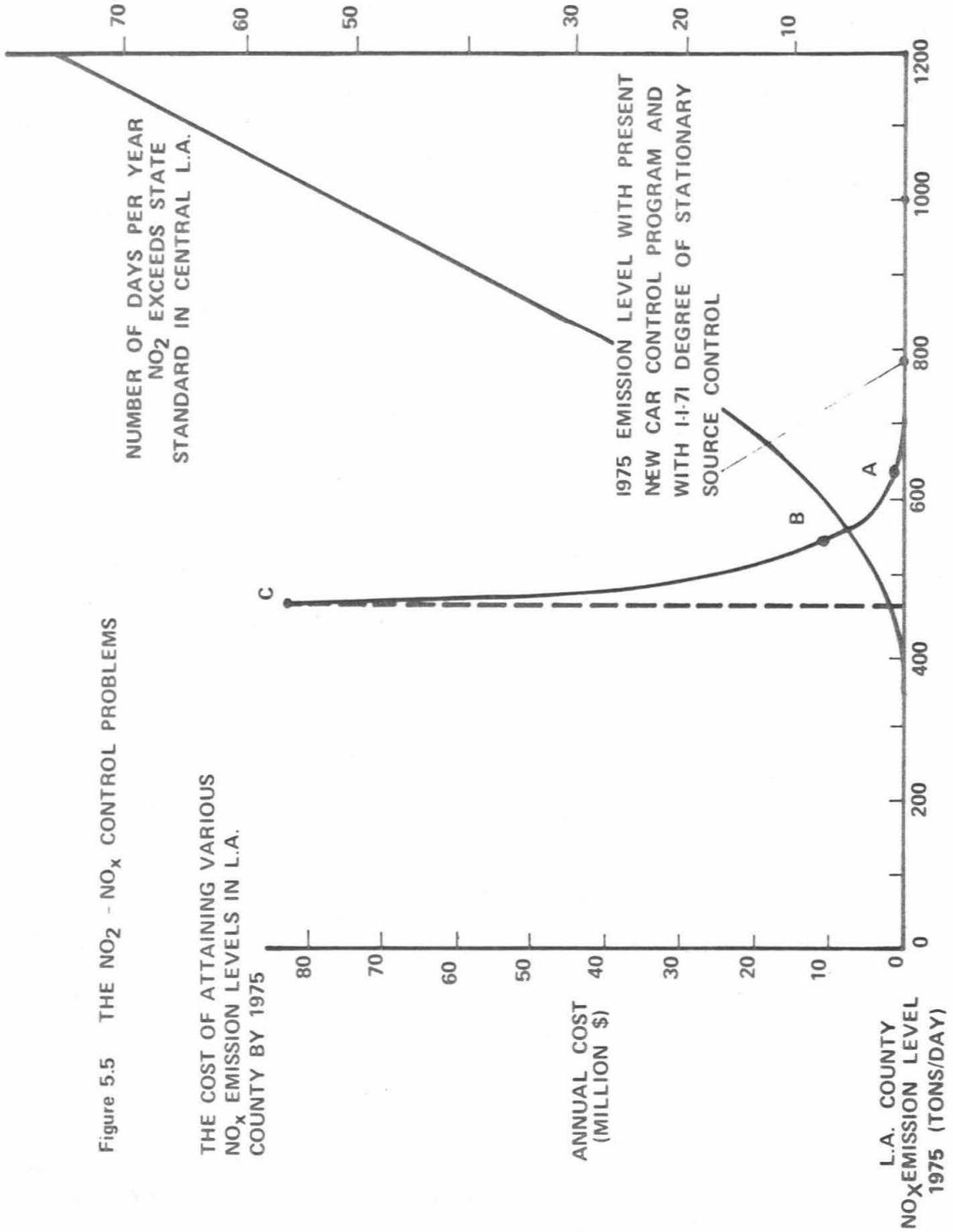
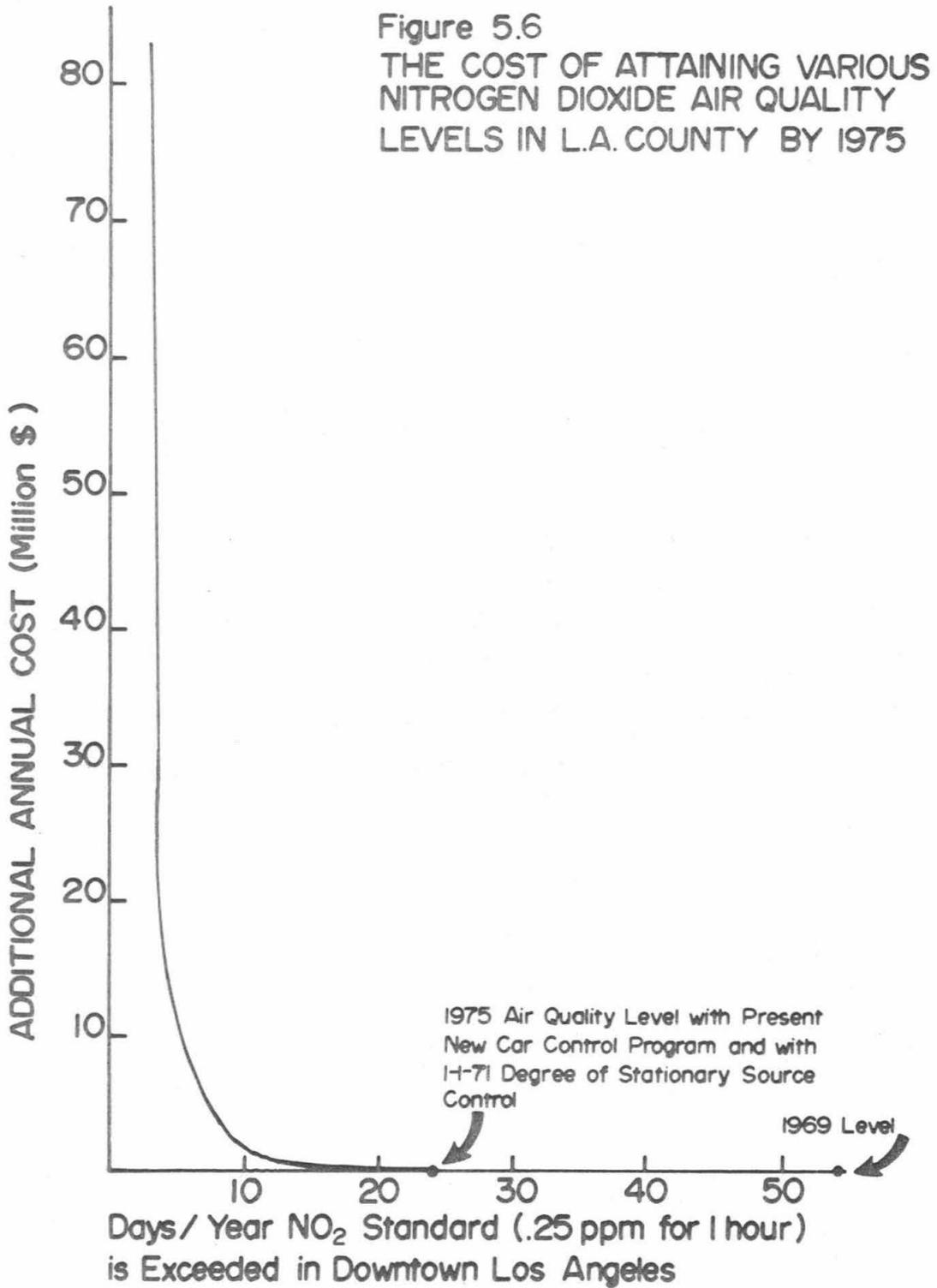


Figure 5.5 THE NO₂ - NO_x CONTROL PROBLEMS





improvement in air quality from a given emission reduction falls as marginal emission control costs rise. Thus, marginal costs of air quality improvements increase even more than marginal emission control costs.

In certain situations, air quality cost functions with high non-linearity, such as that in Figure 5.6, may make air pollution control decisions much easier. For a totally hypothetical example, let us first assume that days per year standard violation is a relevant measure* of NO_2 air pollution damage. Let us further assume that total damage costs (tangibles and intangibles) are estimated to be somewhere between \$200,000 and \$20,000,000 for each day of standard violation. Then, according to the results of Figure 5.6, the cost-benefit solution to this hypothetical NO_2 air pollution problem lies somewhere between 6 and 10 violations per year. (Above 10 violations per year, each day less violation costs less than \$100,000, and below 6 days per year, each day less violation costs \$35,000,000.) Somewhere between \$2 M and \$10 M per year should be spent on NO_x control. Thus, for this case, even gross estimates of marginal damage costs, (two orders of magnitude here), provide rather small bounds on the cost-benefit solution to the air quality problems. This is a result of the highly nonlinear form of the air quality cost curve in Figure 5.6.

*By a "relevant measure," it is meant that total damage is, say, roughly proportional to the number of days per year that exceed the standard. This assumption is not obviously true and may be grossly wrong.

§5.3 CONCLUSIONS

§2.3 noted that the least cost air quality model, as applied to the photochemical smog example, could provide approximate, but realistic answers to questions such as:

1. What air quality levels can be achieved in Los Angeles County by 1975?
2. About how much would these levels cost?
3. Should control efforts be concentrated on RHC or NO_x emissions?
4. Which sources should be controlled first according to a cost-effectiveness criterion?

The last three chapters have provided the following answers:

1. Possible Air Quality Levels (see Figure 5.2)

In 1969, expected air quality in Central Los Angeles was 150 standard violations per year by mid-day ozone and 55 standard violations per year by NO_2 . The present new car control program and the degree of stationary source control existing in 1971, (the base or zero control level for this study), should reduce pollution levels to 80 expected O_3 violations and 25 expected NO_2 violations per year in 1975. Even with all the control methods of this study, (basically add-on control devices), in effect, neither O_3 nor NO_2 violations can be eliminated. Best possible pollution levels in 1975 are 3 NO_2 violations and 25 O_3 violations per year for maximal NO_2 reduction and 10 NO_2 violations and 8 O_3 violations per year for maximal O_3 reduction. With the

maximal O₃ reduction program, eye irritation in Downtown Los Angeles should be reduced to below 2 days per year (see Appendix C).

Further reductions in O₃ and NO₂ would require further controls than those considered here, such as reduced driving (by a mass transit system or by decreased driving incentives), control of NO_x from residential sources, stricter new car control, etc.

2. Cost of Air Quality Levels (see Figure 5.2)

In 1969, with 150 O₃ and 55 NO₂ expected violations per year in Central Los Angeles, total annual air pollution control costs in L.A. County were about \$25 million.* In 1975, with 80 O₃ and 25 NO₂ violations per year, total annual costs will be about \$175 million.** For \$230 million more per year, violations can be reduced to 3 NO₂ and 25 O₃ days or 10 NO₂ and 8 O₃ days per year. Most of this \$230 M, about \$160 M, is for evaporative control retrofits to pre-1970 used cars. Without evaporative control retrofits, violations can be reduced to around 3 NO₂ and 60 O₃ days or 10 NO₂ and 40 O₃ days per year at an annual cost of \$70 M.

* In 1969, the new car control program cost around \$10 million for Los Angeles County motor vehicles, assuming a cost of \$25 per car (HEW AP-66, 1970). Approximately \$15 million was spent annually on non-vehicular sources (Ulbrich, 1968).

** In 1975, assuming a new car control cost of \$320 (National Academy of Sciences, 1972), about \$150 million is the cost of the new car control program for L.A. County motor vehicles. It is assumed that \$25 million will be spent on non-vehicular source control.

3. RHC Control vs. NO_x Control (see Figure 5.2)

Controlling NO_2 pollution requires reductions in NO_x emissions. Ozone, on the other hand, can be controlled by reducing either RHC or NO_x emissions. However, the results of this study indicate that for Central Los Angeles,* RHC control is much more effective than NO_x control for abating ozone in 1975. RHC control is also much more effective for reducing eye irritation in Downtown Los Angeles, (see Appendix C). Thus, the question of whether control efforts should be concentrated on RHC or NO_x emissions reduces to a consideration of whether ozone (and eye irritation) or nitrogen dioxide is the worst pollutant. It is not in the purpose of this study to make an evaluation of the damage of ozone compared to that of nitrogen dioxide. If air pollution policy makers consider ozone (and eye irritation) more important, they should concentrate on reducing RHC emissions. If they hold NO_2 to be more damaging, they should concentrate efforts on NO_x .

*The importance of RHC emissions relative to NO_x emissions in ozone formation may not hold for stations downwind of Central Los Angeles, e.g., Azusa, Pomona, and Riverside. Increasing the RHC/ NO_x reactant ratio tends to delay or retard the photochemical reactions (Glasson and Tuesday, 1970). This delay effect makes RHC control particularly effective for mid-day ozone in Central Los Angeles. However, retarding the reaction may not reduce ozone levels later in the day at downwind stations.

During the late sixties, RHC emissions decreased and NO_x emissions increased in L. A. County (APCD Profile, 1971). Ozone levels decreased in Downtown Los Angeles but increased in Riverside (ARB Implementation Plan, 1971). It may be that RHC emission control is not effective for later-day ozone at stations such as Riverside. But, it may also be that the growth in Riverside ozone was due to growth in the number of pollution sources between Downtown and Riverside. To the knowledge of this author, this question has not been resolved. An obvious and very important extension of this work would be to add an ozone air quality index for downwind stations. To relate later-day ozone to emissions, a physico-chemical air quality model would probably be required.

4. Source Control and Cost-Effectiveness (see Tables 3-II and 3-III)

Table 3-II, in §3.2, contains the detailed data on cost-effectiveness of control for various sources. Table 3-III, in §3.3, gives the least cost controls associated with various emission levels. Here, to summarize, sources of RHC and NO_x are each grouped into three categories of control cost-effectiveness.

Average Cost Per Ton Controlled

RHC Sources

(i) Stationary sources (gas stations and organic solvent users)	\$240
(ii) Pre-1969 used car exhaust, 1971-1974 fleet cars, and aircraft	\$840
(iii) Pre-1969 used car evaporative emissions	\$2,810

NO_x Sources

(i) Large industrial boilers and heaters (primary control), 1966-1970 used car exhaust, and stationary internal combustion engines	\$20
(ii) Small refinery heaters, small power plant boilers (primary control), 1971-1974 fleet cars, and large power plant boilers (advanced control)	\$280
(iii) Large industrial and small power plant boilers (advanced control), medium size industrial boilers, pre-1966 used cars	\$2,500

It is notable that even though stationary sources of RHC have been controlled by several L. A. County APCD regulations in the 50's

and 60's, further control for these sources is the least expensive form of RHC control. Evaporative control retrofits for used cars is by far the most expensive of the RHC controls considered here. Many NO_x sources are very inexpensive to control. But, once these sources are controlled, further NO_x reductions become very costly. Both mobile and stationary sources of NO_x are found in both the inexpensive and expensive control categories.

§5.4 EXTENSIONS OF THIS STUDY

This study has dealt with a rather limited model of Los Angeles air pollution. The least cost of reaching various photochemical smog levels in Los Angeles County by 1975 was calculated for a rather special case. Air quality was specified by the frequency of standard violations in Central Los Angeles by mid-day ozone and nitrogen dioxide. Emissions were specified by total reactive hydrocarbon and nitrogen oxide emissions in Los Angeles County.

The scope of this study can be expanded in several ways. A list of possible extensions follows. These considerations for future research are grouped into three categories: A. Extensions of the Complete Model; B. Extensions of the Control Cost-Emission Level Model, and C. Extensions of the Air Quality-Emission Level Model.

Future Research Possibilities:

A. Extensions of the Complete Model

1. Additional Pollutants. The model was applied only to RHC and

NO_x emissions and only to ozone and nitrogen dioxide pollution. Other emissions and final pollutants could be included in an extended study. The major candidates for additional emissions are CO, SO₂, and particulates. Final pollution could then be expanded to include CO, SO₂, and visibility levels.

2. Pollution Damage Costs. This study dealt with the minimum control costs associated with various air quality levels. An important extension would be to add pollution damage as a function of air quality. If it were possible to put such a damage function in monetary units, a complete cost-benefit analysis of the air pollution problem could be made. However, §1.4 noted that estimating damage costs monetarily is extremely difficult. But, quantitative damage functions not based on monetary units may be attainable. Such damage functions would expose the essentials of the basic air pollution trade-off, control costs vs. pollution damage.
3. Further Control Dates. The model in this work was solved only for one control date, 1975. An extended study could consider other control dates, e.g., 1973, 1978, etc. Seinfeld and Kyan (1971), have formulated a dynamic model that can be used to calculate the costs of various pollution time paths, e.g., pollution levels specified for each year of a decade. Unfortunately, Seinfeld's model requires extreme quantities of computing time. For a problem that is always large in scope, his model may not be practically applicable.

4. Expanded Study Area. This work considered emissions in Los Angeles County and air quality in Central Los Angeles. An extended study might be done for the South Coast Air Basin, (see Figure 2.1), which has been designated as an integral air basin by both State and Federal authorities. Air quality could be represented by pollution levels at several selected points in this region. Since, as noted in §2.2, phenomenological air quality models for ozone may not be possible with available data for areas other than Central Los Angeles, such an extended study region would probably require the use of physico-chemical air quality models.
5. Addition of Emission Space and Time Dependence. This study neglected emission space and time dependence and examined only total emissions for each contaminant. It was assumed that the space and time pattern of emissions remained fixed, (homogeneity of emission level changes). An extended study might explicitly account for changes in emission patterns. Control methods that just alter the emission pattern could then be included. One way of making this extension would be to subdivide the basin into several sections and time into discrete intervals. A second way would be to represent emission sources by time dependent point, line, and surface sources. Since the phenomenological air quality models used here rest on the assumption of homogeneity of emission changes, this extension could also require the use of physico-chemical air quality models.

B. Extensions of the Control Cost-Emission Level Model

6. Additional Controls. As noted in §3.2 and §3.4, this study considered a rather limited set of emission control activities. Control activities were eliminated which lacked sufficient documentation for estimating cost and effectiveness, (e.g., reduced driving), or which were deemed technically infeasible for 1975, (e.g., catalytic reactors for used cars), or which interacted in a nonlinear way with other controls (e.g., reduced gasoline volatility). An extended study might devote more effort to generating the appropriate information for control methods lacking in documentation. Or, instead of ruling out technically infeasible alternatives, the role of technological change might be explicitly examined. Finally, the linear programming might be modified to include interaction effects between control methods. Of course, by adding further possible controls, lower emissions and better air quality would be attainable.
7. Examination of Secondary Effects. Implicit in the linear programming model of Chapter 3 was the assumption that no secondary effects existed between control methods and other variables. As noted in §3.4, some secondary effects certainly exist between the control activity levels and source magnitudes. The extra cost of air pollution control for some sources (e.g., stationary internal combustion engines) may lead to attrition of those sources, (e.g., replacement of

stationary ICE's by electric pumps). Another type of secondary effect is the possibility that pollution control will lead to increased growth in Los Angeles. An extended study could include the first type of secondary effect simply by adding a control method to represent it, (e.g., replacing stationary ICE's by electric pumps). To handle the possibility of increased growth, a modification of the linear programming model itself would be required.

8. Distribution of Control Cost Expenditures. This study totally neglected the question, "Who will pay?", in finding the least cost of reaching various air quality levels. It might be very interesting for an economist to examine each control method in order to determine how the cost of that control will be distributed. It is quite possible that air pollution control expenditures will have significant income distribution effects. In certain cases, low income groups might be injured (see §1.4). Knowledge of these income distribution effects would allow compensation where appropriate.

C. Extensions of the Air Quality-Emission Level Model

9. Additional Air Quality Indices. This study considered air quality only in Central Los Angeles. The results of section 4.3.2.4 indicated that the NO_2 - NO_x air quality function was very similar at other stations. However, as noted in §5.3, page 191, the ozone-(RHC, NO_x) air quality function may be

quite different at other locations. Reducing RHC emissions is very effective in controlling mid-day ozone in Central Los Angeles, but it may not be effective in controlling later day ozone at stations downwind of Central Los Angeles. One of the most important extensions of this work would be to obtain the ozone air quality function for stations such as Azusa, Pomona, and Riverside. As noted on page 191, a physico-chemical air quality model would probably be needed for such a study. Seinfeld, (March, 1972), intends to use a physico-chemical model to obtain results for Azusa.

Only air quality indices that are based on frequency of standard violation have been considered. It would be useful to examine other air quality indices, for instance, yearly average concentrations. For inert pollutants, the proportional phenomenological model of §4.2 might be used. For ozone, other air quality indices apparently require physico-chemical models.

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APPENDIX A

This appendix develops an inventory of reactive hydrocarbon and nitrogen oxide emission sources for Los Angeles County in 1975 and of control methods for these sources. The inventory, a result of examining reports and interviewing representatives of the Los Angeles County APCD, the California ARB, the Department of Health, Education, and Welfare, and many industrial firms, is not intended to be a definitive statement of the sources and control methods. As evidenced by conflicting information from various reports and officials, considerable uncertainty exists in the material presented here, particularly as concerns the data on control methods. Estimates had to be made for many of the parameters necessary for the linear programming model. If any readers have objections to the figures presented here, the author would be very receptive to incorporating more accurate information.

The list of sources, based mostly on APCD data, should be nearly complete. The list of control methods is certainly not exhaustive of all possible. Those control methods which were deemed technically infeasible for 1975 or for which insufficient information was available to estimate cost and effectiveness are not included. However, some of the possible control methods in this category are briefly discussed.

The information on the sources and control methods is presented in the format given on page A-2. Pages A-3 and A-7 give a table of contents for the appendix. The material contained in this appendix is summarized in Table 3-II of the text.

SOURCE AND CONTROL METHOD FORMAT

i. Source # i:DescriptionSource Magnitudetotal number of source units, 1975 S_i Emissionstons/day of emission k per source unit i e_{ki} total emissions for source i $S_i e_{ki}$ Control Methods for Source iControl Method j X_j DescriptionEmission Reductionreduction in emission k by one unit of X_j
(tons/day per control unit) B_{kj} Costsannual cost, \$, for one unit of X_j C_j cost-effectiveness for emission k
(cost per ton of k prevented) $C_j/365 \times B_{kj}$ Other Control Parametersnumber of units of source i controlled
by one unit of X_j A_{ij} amount of limited supply input m consumed
by one unit of X_j D_{mj} Control Method j + 1 X_{j+1} Control Method j + N X_{j+N} Other Control Methods Considered for Source i

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§A-I. STATIONARY SOURCES OF NO_x

1. Source # 1: Large Boilers (Non-Power Plant)

Description

This source category, to be called simply "large boilers", consists of non-power plant commercial and industrial boilers of size greater than 30 MBTU/hr. \cong 30,000 lb/ steam/hr. \cong 800 H.P. The source unit is one boiler. * Large boilers range in size up to around 400 MBTU/hr. and have an average size of approximately 80 MBTU/hr. ** It is assumed here that all large boilers are fired by gas, natural gas or refinery make gas. *** Except for the use of gas rather than fuel oil (emissions on oil are approximately twice those on gas, Mills, et al., 1961a), large boilers have no existing control for NO_x.

* Control costs relate directly to this source unit. Emission rates relate more directly to a source unit describing the rate of fuel use. The conversion factor between these units is the boiler usage factor, e.g., amt. fuel per day/boiler. In making projections, it is assumed here that the average usage factor is constant.

** Calculations based on data from (Mills et al., 1961a) indicate an average size of 42 MBTU/hr. for boilers larger than 19 MBTU/hr. in 1961. Since 1961, however, the boiler size distribution has shifted. There are now more of the larger sizes (Wendt, Sept. 1971), (Myler, Nov. 1971). From a very approximate size distribution of boilers, obtained from Babcock and Wilcox (Hunt, Nov. 1971), the average size of boilers above 19 MBTU/hr. now appears to be around 50-60 MBTU/hr. For boilers above 30 MBTU/hr., of course, the average size is greater. Tanner, (Nov. 1971), estimates around 70-80 MBTU/hr. Since the average size is likely to continue to increase, 80 MBTU/hr., the upper bound for this estimate is used for the 1975 average size.

*** In 1971 more than 98% of the fuel consumed by commerce and industry in Los Angeles County was gas (APCD Profile, 1971).

Source Magnitude, 1975

The Southern California Gas Company Marketing Division estimates 100-120 large boilers in 1971 (Tanner, Nov. 1971). In 1961 there were 117 boilers over 500 H.P. (Mills, et al., 1961a). Assuming approximately 60% of the boilers over 500 H.P. are over 800 H.P. (Hunt, Nov. 1971), around 70 large boilers existed in 1961. Assuming a 5-6% growth rate in the '60's gives 115-125 boilers in 1971, the upper range of the Gas Company's estimate. Using 120 boilers in 1971 and assuming 4% growth to 1975 yields 140 boilers in 1975. Thus,

$$S_1 = 140$$

Emissions

Published NO_x emission factors, .28 lb/MBTU (Mills, et al., 1961a) and .23 lb/MBTU (Bay Area APCD, 1969) are for boilers greater than 500 H.P. The average emission factor increases with boiler size, so the larger of these figures, .28 lb/MBTU, is used for boilers greater than 800 H.P. With this emission factor, with the average size (80 MBTU/hr.), and with usage data (18 hrs./day) from (Mills et al., 1961a), the average NO_x emissions per boiler are .20 tons/day. The total emissions from all 140 boilers burning 32,000 eq. bbls. (190 MM cu. ft.) of gas per day is 28 tons/day. Thus,

RHC	NO_x
$e_{11} = 0$	$e_{21} = .20 \text{ tons/day}$
$S_1 e_{11} = 0$	$S_1 e_{21} = 28 \text{ tons/day}$

Control Methods for Source # 1

Control Method # 1: Low Excess Air Firing (LEA) on Large BoilersDescription

Control X_1 consists of adding combustion control to large boilers in order to effect a decrease in the excess air present during firing from present levels of 15-30% to levels of 2-6% (ESSO, 1969), (Walden, 1971). The control unit is adding LEA to one boiler. Detailed descriptions of LEA and its effects on NO_x emissions can be found in ESSO, (1969), HEW-AP-67 (1970), and Walden (1971).

Emission Reduction

The most extensive study of control methods for NO_x , ESSO, (1969), concludes that LEA results, on the average, in a 40% reduction in NO_x for commercial and industrial boilers. Subsequent studies indicate 30-50% reductions (HEW-AP-67, 1970), (Walden, 1971). Using the 40% figure and the unit emission of .20 tons/day per boiler, one unit of control method X_1 reduces NO_x emissions by .08 tons/day. Thus,

$B_{11} = 0$	$B_{21} = .08 \text{ tons/day}$
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Cost

For an 80 MBTU/hr. boiler interpolation of the results of the ESSO report gives an initial cost ("instrumentation and start up") of around \$6,000 for LEA. ESSO (1969), assumes that no equipment investment other than instrumentation is necessary. Walden (1971), gives an even lower \$3,500 initial cost for LEA. However, a burner manufacturer (Marshall, Nov. 1971) indicates that LEA requires a more

sophisticated control system with orifice plates to regulate air and fuel flow. The initial cost of such a system would be \$10-\$20,000. This estimate is close to the \$10-\$15,000 estimate of boiler and refinery industry representatives (Wendt, Oct. 1971), (Sommerlad, Oct. 1971). To reach very low excess air levels, high pressure burners and a new blower are required. The initial cost of a system including these modifications would be around \$40-\$45,000 (Marshall, Nov. 1971).

Thus, depending on the sophistication of the system to be installed, the initial costs for LEA range from around \$5,000 to \$45,000 on an 80 MBTU/hr. boiler. To attain a 40% reduction in NO_x while maintaining boiler performance, different boilers will require different control sophistication and will thus have different costs. Here it is assumed that the average initial cost per boiler is \$20,000.

The procedures of ESSO (1969), are used to calculate maintenance, supply, and other operating costs. These then total to \$1,100 per year.

LEA control results in fuel savings. The amount saved will depend, however, on the degree of control sophistication. For instance, for the simplest type of control, costing around \$5,000-\$10,000, the annual fuel savings would be around \$1,200 a year (ESSO, 1969). For the \$45,000 system, fuel savings would be around \$5,000 a year* (Marshall, Nov. 1971). Here it is assumed that the average fuel savings will \$2,500 per year.

* Actually because fuel savings rise with degree of LEA control, the annual cost of various degrees of control does not change much.

The total cost structure is thus

	Annual Cost
Initial Cost: \$20,000	
20 yr. lifetime at $i = 10\%$	\$2,400
Operating Cost	1,100
Fuel Savings	- 2,500
Total Annual Cost per Control Unit	$C_1 = \$1,000$

Since each control unit removes .080 tons/day or 29.2 tons/year of NO_x , the cost per ton of NO_x removed is \$34.2 per ton.

Other Control Parameters

One unit of control method X_1 , LEA to one large boiler, applies to one unit of source # 1, large boilers, and to no other sources. Thus,

$$\begin{aligned} A_{11} &= 1 \\ A_{i1} &= 0 \quad i \neq 1 \end{aligned}$$

Control X_1 uses none of the limited supply inputs. Thus,

$$D_{11} = 0$$

Control Method #2: Low Excess Air (LEA) and Flue Gas Recirculation (FGR) on Large Boilers.

Description

Control X_2 consists of adding equipment for recycling a portion of the flue gas back into the combustion chamber as well as adding low excess air instrumentation on large boilers. The control unit is adding LEA and FGR to one boiler. FGR and LEA are described in detail in ESSO (1969), HEW-AP-67 (1970), and Walden (1971).

Emission Reduction

70% is chosen as an average NO_x emission reduction on the basis of the ESSO (1969), estimate of 75% and the HEW-AP-67 (1970), estimate of 60-70%. Since each boiler emits .20 tons/day of NO_x , one unit of control method X_2 reduces NO_x emissions by .14 tons/day. Thus,

$B_{12} = 0 \quad B_{22} = .14 \text{ tons/day}$
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Cost

For an 80 MBTU/hr. boiler, interpolation of ESSO (1969), results gives an investment cost of around \$60,000 for FGR alone. Boiler manufacturers state that depending on the characteristics of the particular boiler, the cost of FGR will vary from 10-120% of the initial boiler cost and that the average cost should be 30-50% of the boiler cost (Andreason and Hunt, Aug. 1971), (Sommerlad, Oct. 1971). Assuming an average boiler cost of \$120,000, this amounts to \$36-60,000. Walden (1971), estimates only \$20,000 for FGR. Boiler manufacturers emphasize the difficulties in retrofitting many boilers and recommend

using the more conservative estimates. Here, for combined FGR and LEA (add \$20,000 to above figures), an average initial cost of \$75,000 is assumed. The ESSO (1969), results, factored by boiler size, are used for operating costs. Fuel savings arise from LEA as discussed in control method #1.

	Annual Cost
Initial Cost: \$75,000	
20 yr. lifetime at $i = 10\%$	\$8,900
Operating Cost	4,100
Fuel Savings	- 2,500
Total Annual Cost per Control Unit:	$C_2 = \$10,500$

Since each unit of X_2 removes .14 tons/day or 51 tons/year of NO_x , the cost per ton of NO_x controlled is \$195 per ton.

Other Control Parameters

Each unit of control X_2 applies to one unit of source #1 and to no other sources. Thus,

$$\begin{aligned} A_{12} &= 1 \\ A_{i2} &= 0 \quad i \neq 1 \end{aligned}$$

Control X_2 uses none of the limited supply inputs. Thus,

$$D_{12} = 0$$

Other Control Methods Considered for Source # 1(i) Flue Gas Recirculation (FGR):

FGR without low excess air is a possible control method. FGR yields a 30-60% reduction in NO_x emissions, (ESSO, 1969), (Walden, 1971), (Andreason, Aug. 1971), approximately the same as LEA. However, the cost of FGR is several times the cost of LEA (ESSO, 1969), (Walden, 1971). FGR is thus automatically eliminated from the least cost program because an equally effective, less expensive, control method is available.

(ii) Steam or Water Injection (SI):

Injection of steam or water into the combustion chamber of the boiler is another possible control method for NO_x . SI costs about the same as LEA, but only produces a 10% reduction in NO_x emissions (ESSO, 1969). SI is thus eliminated because an equally expensive, but more effective, control method is available.

(iii) Two Stage Combustion (TSC):

TSC is another control mechanism that has been proposed for large boilers. TSC has proved effective for utility boilers (George and Chass, 1967), (ESSO, 1969). However, the compact size and few-burner design of all boilers and heaters other than the large utility boilers preclude its use as a control method (ESSO, 1969), (HEW-AP-67, 1970), (Walden, 1971). It is thus eliminated as a general control method for other than large utility boilers on a technical feasibility basis.

(iv) Flue Gas Treatment (FGT):

There are several methods of removing NO_x by treatment of flue gases. However, these methods are at best at an early developmental stage. For the next few years, no FGT method for NO_x control of emissions resulting from combustion processes is considered feasible (ESSO, 1969), (Walden, 1971).

2. Source # 2: Medium Size Boilers

Description

The source category of medium boilers consists of commercial and industrial boilers in the size range 2-30 MBTU/hr. or 55-800 H.P. The source unit is one boiler. * On a capacity basis the average size of these boilers is approximately 9 MBTU/hr. ** As with other non-power plant stationary combustion sources, it is assumed here that only gas is burned in medium boilers. Except for the use of gas rather than fuel oil (emissions on oil are 3 to 4 times those on gas, Mills, et al., 1961b), these boilers have no existing control for NO_x.

Source Magnitude, 1975

Obtaining an estimate of the number of medium boilers is difficult. Mills, et al., (1961b) gave a census of 5,700 in 1961, but no lower bound on boiler size was indicated. Since there are a great many boilers in the size range, 1-2 MBTU/hr., (Gonzal, Nov. 1971), much of this number may be boilers less than 2 MBTU/hr. The Southern California Gas Company (Tanner, Nov. 1971) and a boiler manufacturer (Gonzal, Nov. 1971) "guess" around 5,000 in 1971. With published emission and usage

* This source unit relates directly to control costs. Emission rates relate directly to a source unit based on fuel consumption rate. The conversion factor between these source units is the usage factor of the boilers, e.g., the average (lbs. fuel/day) per boiler. It is assumed in making projections that the average usage factor is constant.

** The Southern Gas Company estimates an average size of 8-10 MBTU/hr. for boilers in this size range (Tanner, Nov. 1971). For a slightly smaller size range, 500 H.P. down to an unspecified limit in the 1-2 MBTU/hr. range, calculations with APCD 1961 data yield an average size of 8.5 MBTU/hr. (Mills, et al., 1961b). Thus, 9 MBTU/hr. appears to be a fairly reliable estimate for the average size.

factors (Mills, et al., 1961b) this number of boilers gives a total NO_x emission rate that accounts for most of the commercial and industrial emissions not accounted for by large boilers and refinery heaters. Thus, 5,000 appears to be a reasonable estimate, and it is used here. A 4% growth rate until 1975 gives around 6,000 boilers then. Thus,

$$S_2 = 6,000$$

Emissions

Using an average emission factor of .15 lb/MBTU (Mills, et al., 1961b), (Bay Area APCD, 1969), an average usage factor of 10 hrs./day (Mills, et al., 1961b) and the average size of 9 MBTU/hr., the average NO_x emissions per unit is .0068 tons/day per boiler. The total 1975 emissions coming from the 6,000 boilers, using 90,000 equiv. bbls. of gas/day (540 MM ft^3 of gas per day), is 41 tons/day. Thus,

RHC	NO_x
$e_{12} = 0$	$e_{22} = .0068 \text{ tons/day}$
$S_2 e_{12} = 0$	$S_2 e_{22} = 41 \text{ tons/day}$

Control Methods for Source # 2

Control Method # 3: Low Excess Air Firing (LEA) on Medium Boilers.

Description

Control method X_3 consists of adding combustion control to medium boilers in order to decrease the excess air present during firing from present levels of 15-50% to levels of 2-6% (ESSO, 1969), (Walden, 1971). The control unit is addition of LEA to one boiler. LEA and its effects on NO_x emissions are discussed in detail in ESSO, (1969), HEW-AP-67 (1970), and Walden (1971).

Emission Reduction

ESSO (1969) concludes LEA will result in a 40% reduction of NO_x emissions in commercial and industrial boilers. HEW-AP-67 (1970), and Walden (1971), indicate 30-50% reductions. Using the 40% figure and unit emission of .0068 tons/day per boiler, one unit of control method X_3 effects an NO_x emission reduction of .0027 tons/day. Thus,

$B_{13} = 0$	$B_{23} = .0027 \text{ tons/day}$
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Cost

According to ESSO (1969), and Walden (1971), the initial investment for LEA on medium-size boilers should be around \$3,500. This is the cost for a simple instrumentation system. A burner manufacturer (Marshall, Nov. 1971) indicates that a more sophisticated control system is necessary which costs around \$10,000. To attain very low excess air levels, burner and blower replacement are required and costs rise to around \$20,000 (Marshall, Nov. 1971).

Here it is assumed that the average cost per boiler is around \$8,000. Operating costs are computed according to ESSO, 1969 procedures. An average fuel savings of \$250 per year is assumed.

	Annual Cost
Initial Cost: \$8,000	
20 yr. lifetime at $i = 10\%$	\$940
Operating Cost	580
Fuel Savings	- 250
Total Annual Cost per Control Unit	$C_3 = \$1,270$

Since each control unit removes .0027 tons/day or 1.0 tons/year of NO_x , the cost per ton of NO_x removed is \$1,270 per ton.

Other Control Parameters

One unit of control X_3 , LEA to one medium-size boiler, applies to one unit of source # 2, medium boilers, and to no other sources. Thus,

$$\begin{aligned} A_{23} &= 1 \\ A_{i3} &= 0 \quad i \neq 2 \end{aligned}$$

Control X_3 uses none of the limited supply inputs. Thus,

$$D_{13} = 0$$

Control Method #4: Low Excess Air (LEA) and Flue Gas Recirculation (FGR) on Medium Boilers

Description

Control method X_4 consists of adding equipment to recycle a portion of the flue gas back into the combustion chamber of the boiler as well as operating on low excess air. The control unit is addition of LEA and FGR to one boiler. ESSO (1969), HEW-AP-67 (1970), and Walden, (1971) contain detailed descriptions of LEA and FGR.

Emission Reduction

On the basis of ESSO (1969) and HEW-AP-67 (1970) estimates, 70% is chosen as the average NO_x emission reduction from combined LEA and FGR on medium boilers. Since each boiler emits .0068 tons/day of NO_x , one unit of control method X_4 reduces NO_x emissions by .0047 tons/day. Thus,

$B_{14} = 0$	$B_{24} = .0047 \text{ tons/day}$
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Cost

From the results of ESSO (1969) and Walden (1971) reports, the initial cost for FGR on a medium-size boiler appear to be around \$6,000-\$8,000. Boiler manufacturers emphasize, however, that difficult problems can be encountered on many units and recommend taking conservative estimates (Andreason and Hunt, Aug. 1971), (Sommerlad, Oct. 1971). The figure of \$10,000 is chosen here for the initial cost of FGR. For LEA and FGR the initial cost is then \$18,000.

ESSO, 1969, procedures are used to calculate operating costs.

	Annual Cost
Initial Cost: \$18,000	
20 yr. lifetime at $i = 10\%$	\$2,100
Operating Cost	850
Fuel Savings	- 250
Total Annual Cost per Control Unit:	$C_4 = \$2,700$

Since each unit removes .0047 tons/day or 1.7 tons/year of NO_x , the cost per ton NO_x removed is \$1,590.

Other Control Parameters

One unit of control X_4 applies to one unit of source #2 and to no other sources. Thus,

$$\begin{aligned} A_{24} &= 1 \\ A_{i4} &= 0 \quad i \neq 2 \end{aligned}$$

Control X_4 uses none of the limited supply inputs. Thus,

$$D_{14} = 0$$

Other Control Methods for Source # 2(i) Flue Gas Recirculation (FGR):

FGR without low excess air is a possible control method. It yields approximately the same emission reduction as LEA, but costs more (ESSO, 1969), (Walden, 1971). FGR is thus eliminated as being inferior to LEA.

(ii) Steam or Water Injection (SI):

Steam injection into the combustion chamber is another possible control method. SI costs about the same as LEA, but only produces a 10% reduction in emissions (ESSO, 1969). SI thus is also inferior to LEA.

(iii) Two Stage Combustion (TSC):

See Source # 1

(iv) Flue Gas Treatment (FGT):

See Source # 1

3. Source # 3: Large Refinery Heaters

Description

This source category consists of refinery process heaters larger than 90 MBTU/hr. The source unit is one large heater. These heaters range in size up to around 290 MBTU/hr., but most are smaller than 130 MBTU/hr. They have an average size of around 120 MBTU/hr. (Wendt, Nov. 1971), (Glauser, Nov. 1971), (Ray, Dec. 1971). It is assumed here that all of these heaters are fired with gas, natural gas or refinery make gas. Except for the use of gas rather than fuel oil, (emissions on oil are about twice those on gas, Mills, et al., 1961a) large process heaters have no existing control for NO_x emissions.

Source Magnitude, 1975

Mills, et al., (1961a) reported 68 large refinery heaters. Although refinery throughput has increased 25% in the last decade, (APCD Profile, 1971), (Thomas, Nov. 1971), the number of large heaters has decreased due to process changes (Ray, Dec. 1971). By polling various size refineries and projecting the results to all Los Angeles County refineries, an estimate of 60-65 large heaters is obtained for 1971 (Wendt, Nov. 1971), (Glauser, Nov. 1971), (Fletcher, Nov. 1971), (Ray, Dec. 1971). Little refinery growth is expected by 1975 (Lunche, Nov. 1971). In accordance with the slight decrease in the number of heaters with process changes, 60 heaters is chosen here as the estimated census for 1975. Thus,

$S_3 = 60$

Emissions

Mills, et al., (1961a) gives an emission factor of .25 lb/MBTU for large refinery heaters (120 MBTU/hr.) and .06 lb/MBTU for small refinery heaters (45 MBTU/hr.). The average emission factor used for all refinery heaters by the APCD in 1971 is around .15 lb/MBTU. Refinery researchers have recently found a .14 lb/MBTU average emission factor for heaters (Wendt, Oct. 1971). This agrees well with the average APCD emission factor. However, the difference in emission factors for small and large heaters from the 1961 APCD report appears to be unreasonable. (The .06 lb/MBTU is as clean as a home range!). There are self contradictions in Mills, et al., (1961a) on refinery heater emissions, and the cause could be a misstatement of the large and small emission factors. Here, it is assumed that the emission factors for large and small heaters are .18 lb/MBTU and .12 lb/MBTU, respectively.

With the average size of 120 MBTU/hr. and average usage of 22 hrs./day (Mills, et al., 1961a) the emissions per large heater are .24 tons/day. Total emissions from all 60 heaters are then 14 tons/day. Thus,

RHC	NO _x
$e_{13} = 0$	$e_{23} = .24 \text{ tons/day}$
$S_3 e_{13} = 0$	$S_3 e_{23} = 14 \text{ tons/day}$

Control Methods for Source # 3

Control Method #5: Low Excess Air Firing (LEA), on Large Heaters

Description

Control X_5 consists of adding combustion control to large heaters in order to decrease the excess air present during firing. The control unit is adding LEA to one large heater. Detailed descriptions of LEA as a control method for NO_x can be found in ESSO, (1969), HEW-AP-67, (1970), and Walden, (1971).

Emission Reduction

There is a wide discrepancy in professional opinions on the effectiveness of LEA in reducing NO_x emissions from heaters. The ESSO report indicated that LEA was less applicable to heaters than to boilers. In fact, it did not even consider LEA control for heaters. However, Shell Development found that on the average about a 50% reduction in NO_x could be obtained by LEA on heaters (Wendt, Nov. 1971). Here, it is assumed that, as with boilers, a 40% reduction in NO_x can be obtained from LEA addition to heaters. Since each large heater emits .24 tons/day of NO_x one unit of control X_5 reduces NO_x emissions by .096 tons/day. Thus,

$B_{15} = 0 \quad B_{25} = .096 \text{ tons/day}$

Cost

Refinery heaters are usually built in a more flexible way than boilers so that they can handle wider variations in fuel composition. They operate at higher excess air levels than large boilers and have

less of a control system (Crawford, Oct. 1971), (Wendt, Oct. 1971). Because they have less of an existing control system, heaters require more additional controls for LEA than boilers. LEA control is thus more expensive for heaters than for boilers.

It is assumed here that the initial and operating cost of LEA on large heaters is 50% more than on large boilers. Using the results of control method X_1 , this implies a \$30,000 initial cost* and \$1,600 per year operating cost. Factoring the boiler fuel savings by size (110 MBTU/hr.)/(80 MBTU/hr.) and by usage (22 hr./day)/(18 hr./day), the fuel savings for the large heaters on LEA is \$4,200 per year. Total annual cost is thus calculated as follows:

	Annual Cost
Initial Cost: \$30,000	
20 yr. lifetime at $i = 10\%$	\$3,500
Operating Cost:	1,650
Fuel Savings:	- 4,200
Total Annual Cost per Control Unit:	$C_5 = \$ 950$

Since each control unit removes .096 tons/day or 35.1 tons/yr. of NO_x , the cost per ton NO_x is \$27.0 per ton.

Other Control Parameters

Each unit of Control X_5 applies to one unit of source # 3 and to no

*(Wendt, Oct. 1971) estimates \$10-\$30,000 initial cost for LEA on refinery heaters. Since the larger heaters would tend to cost the most, \$30,000 initial cost for large heaters agrees well with Wendt's estimate.

other sources. Thus,

$$A_{35} = 1$$

$$A_{i5} = 0 \quad i \neq 3$$

Control X_5 uses none of the limited supply inputs. Thus,

$$D_{15} = 0$$

Other Control Methods for Source # 3(i) Flue Gas Recirculation (FGR):

The only control method for refinery heaters that the ESSO report considered feasible enough to calculate costs for was flue gas recirculation. The report only considered control on new units, and the initial cost per unit was \$20,000 - \$200,000 per heater depending on heater size. The ESSO report noted that FGR was also feasible as a retrofit control. This is supported by some industry representatives (Towell, Nov. 1971). However, other refinery researchers and heater makers (Wendt, Aug. 1971; Sommerlad, Aug. 1971) say that FGR is not a possible retrofit control and that a whole new heater would have to be built to include it. In any case, even if FGR were a possible control method, it would cost much more than LEA on an annual basis. (LEA has negative operating costs while FGR has positive operating costs.) Since it produces about the same NO_x reduction as LEA, FGR is an inferior control method according to the minimum cost criteria.

(ii) Two-Stage Combustion:

See Source # 1.

(iii) Flue Gas Treatment:

See Source # 1.

4. Source #4. Small Refinery Heaters

Description

This source category consists of refinery process heaters smaller than 90 MBTU/hr. The source unit is one small heater. These heaters have a size range of 5 - 90 MBTU/hr. and have an average size of 45 MBTU/hr. (Mills, et al., 1961b), (Wendt, Nov. 1971), (Glauser, Nov. 1971), (Ray, Nov. 1971). It is assumed here that all small heaters are fired with gas. Except for the use of gas rather than fuel oil (emissions on oil are about three times those on gas, (Mills, et al., 1961b), small process heaters have no existing control for NO_x emissions.

Source Magnitude, 1975

In 1961, the APCD reported 283 small process heaters. Refinery throughput in Los Angeles County has increased 25% in the last ten years (APCD Profile, 1971), (Thomas, Nov. 1971), but the number of heaters has decreased due to process changes (Ray, Dec. 1971). By polling various size refineries and projecting the results to all Los Angeles County refineries, an estimate of 160-170 small heaters was obtained in 1971. Little refinery growth is expected by 1975 (Lunche, Nov. 1971). In accordance with the decreasing trend in number of heaters, 160 heaters is chosen here for the 1975 census. Thus,

$S_4 = 160$

Emissions

As noted under emissions for large heaters, a .12 lb/MBTU emission factor is assumed for small heaters. With the average size of 45 MBTU/hr. and average usage of 22 hrs./day (Mills, et al., 1961b), the emissions per small heater are .06 tons/day. Total emissions from all 160 heaters are then 10 tons/day. Thus,

RHC	NO _x
$e_{14} = 0$	$e_{24} = .06 \text{ tons/day}$
$S_4 e_{14} = 0$	$S_4 e_{24} = 10 \text{ tons/day}$

Control Methods for Source # 4

Control Method # 6: Low Excess Air Firing (LEA), on Small Heaters

Description

Control X_6 consists of adding combustion control to small heaters in order to decrease the excess air present during firing. The control unit is adding LEA to one small heater. Detailed descriptions of LEA as a control method for combustion sources of NO_x can be found in ESSO, (1969), HEW-AP-67, (1970), and Walden, (1971).

Emission Reduction

As with large refinery heaters, a 40% reduction in NO_x is assumed for LEA control. Since each heater emits .06 tons/day of NO_x , one unit of control X_6 reduces NO_x emissions by .024 tons/day. Thus,

$B_{16} = 0 \quad B_{26} = .024 \text{ tons/day}$

Cost

Small refinery heaters average slightly more than 1/3 the mean size of large heaters. Costs, although less for smaller heaters, do not decrease in proportion with size (Wendt, Sept. 1971). It is assumed here that initial and operating costs are 2/3 those of large heater. Fuel savings are factored according to size. Thus,

	Annual Cost
Initial Cost: \$20,000	
20 yr. lifetime at $i = 10\%$	\$2,400
Operating Cost:	1,100
Fuel Savings:	- 1,600
Total Annual Cost per Control Unit:	$C_6 = \$1,900$

Since each control unit removes .024 tons/day or 8.4 tons/year of NO_x , the cost per ton of NO_x removed is \$226 per ton.

Other Control Parameters

Each unit of control X_6 applies to one unit of source # 4 and to no other sources. Thus,

$$\begin{aligned} A_{46} &= 1 \\ A_{i6} &= 0 \quad i \neq 4 \end{aligned}$$

Control X_6 uses no limited supply inputs. Thus,

$$D_{16} = 0$$

Other Control Methods for Source # 4:(i) Flue Gas Recirculation:

See Source # 3.

(ii) Two-Stage Combustion:

See Source # 1.

(iii) Flue Gas Treatment:

See Source # 1.

5. Source # 5: Rule 68 Complying Large Power Plant Boilers Burning Fuel Oil

Description

This source category consists of power plant boilers larger than 175 MW which by Jan. 1, 1971, were controlled sufficiently well to meet the APCD's Rule 68.* The source unit is one boiler. These units range in size from 180 to 350 MW and have an average size of 260 MW.**

The existing state of control of these boilers is what might be called "advanced combustion modification control". In order to attain the Rule 68 levels, NO_x emissions in these boilers have been reduced by a factor of around 3-5 by various combinations of controls depending on the boiler. These controls include low excess air firing, two-stage combustion, flue gas recirculation, modified burner configuration and design, and modified operating procedures (Sanderling, Oct. 1971), (Felgar, Nov. 1971). The present NO_x emission concentrations from these boilers at full load are around 120 ppm on gas and 180 ppm on oil (Sanderling, Oct. 1971), (Felgar, Nov. 1971). In 1970-1971 these units were operating on about 80% gas. But as noted in Chapter 3, because of gas supply problems, the "uncontrolled state" for these boilers in 1975 is assumed to be 100% operation on low sulfur oil.

* Here, "Rule 68" refers to the specification that NO_x emissions in boilers over 175 MW not exceed 125 ppm NO_x on gas and 225 ppm NO_x on oil. The deadline on the rule is Dec. 31, 1974, with an intermediate stage deadline on Dec. 31, 1971 (Chass, et al., 1971).

** The actual size distribution of these eight boilers is two 180 MW's, two 220's, and four 320's, (Sanderling, Oct. 1971), (Felgar, Nov. 1971).

Substitution of gas for oil will be considered as a possible control mechanism. Since these boilers have such advanced combustion control, no further combustion modifications will be considered as control possibilities.

Source Magnitude, 1975

There are eight Rule 68 controlled large power plant boilers in Los Angeles County, four owned by Southern California Edison and four owned by Los Angeles Department of Water and Power. Thus,

$$S_5 = 8$$

Emissions

In 1970-1971 these 8 boilers emitted a total of around 20 tons/day NO_x (Sanderling, Nov. 1971), (Felgar, Nov. 1971). However, they were operating on about 80% natural gas (APCD Profile, 1971), (Chass, et al., 1971). Assuming a 3-2 ratio of emissions on oil to gas and assuming a 10% increase in load factor by 1975, these boilers would emit 30 tons/day in 1975 burning only fuel oil. This amounts to 3.8 tons/day per boiler. Thus, at the level defined as "zero control", all oil burned in these boilers, the emission rates are,

RHC	NO_x
$e_{15} = 0$	$e_{25} = 3.8 \text{ tons/day}$
$S_5 e_{15} = 0$	$S_5 e_{25} = 30 \text{ tons/day}$

Control Method for Source # 5Control Method # 7: Substitution of Natural Gas for Fuel Oil in Rule 68 Controlled Large Power Plant BoilersDescription

Control method X₇ consists of substituting natural gas for low sulfur fuel oil in source # 5, Rule 68 complying large power plant boilers. The control unit is taken to be substituting 2,800,000 equiv. bbls. per year of gas for fuel oil. This is the average amount of fuel per year consumed by one of the boilers in source # 5. *

Emission Reduction

As noted earlier in the description of source # 5, these boilers emit 3/2 as much NO_x on oil as on gas. Thus, one control unit, by converting one boiler completely from oil to gas, reduces the emissions from that boiler by 1/3. Since the average boiler emits 3.8 tons/day, the emission reduction from one control unit is 1.3 tons/day. Thus,

$B_{17} = 0$	$B_{27} = 1.3 \text{ tons/day}$
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Cost

For prices as of Nov. 1, 1971, control method # 7 has a large negative cost. Natural gas, with wellhead held regulated by the

* This is calculated as follows: The total fuel burned in power plants in Los Angeles County in 1975 is expected to be 66 M equiv. bbls. (APCD Profile, 1971). 80% of this, or 53 M equiv. bbls., is burned in boilers larger than 175 MW, sources # 5 and # 6 (Nevitt, Nov. 1971). Source # 5 accounts for approximately 41% of this and source # 6, 59% (Sanderling, Oct. 1971), (Felgar, Nov. 1971). Thus, the eight boilers of source # 5 burn 22.2 M eq. bbls./yr. This gives an average of 2.8 M eq. bbls. for each boiler.

FPC, sells for around 36¢ per MBTU. The price of low sulfur fuel oil in 1970 to 1971 rose from 40¢ per MBTU to 75¢ per MBTU (Nevitt, Nov. 1971). However, the price of natural gas, the more desirable of the two fuels for most applications, is expected to rise. With no FPC restrictions, it might more than double (Nevitt, Nov. 1971).

Here no costs will be assigned to the process of replacing fuel oil by natural gas. This control method will, of course, be very attractive to the least cost program, but it will be limited by the supply constraint on natural gas. Thus,

$$C_7 = 0$$

Other Control Parameters

One unit of control X_7 applies exactly to one unit of source #5, and to no other sources. Thus,

$$\begin{aligned} A_{57} &= 1 \\ A_{i7} &= 0 \quad i \neq 5 \end{aligned}$$

Each unit of control X_7 uses up 2,800,000 equiv. bbls. per year of natural gas, limited supply input #1. Thus,

$$D_{17} = 2,800,000 \text{ eq. bbls./yr.}$$

Other Control Methods for Source # 5:(i) Further Combustion Modification:

From combustion modification controls, NO_x emissions from this class of large power plant boilers have been reduced to 1/5 to 1/3 of uncontrolled levels. Present emissions, 120 ppm on gas and 180 ppm on oil, are very low. Tightening up on emissions through even further combustion control does not appear to be technically feasible.

(ii) Flue Gas Treatment:

See Source # 1.

6. Source # 6: Non-Rule 68 Complying Large Power Plant Boilers Burning Fuel Oil

Description

This source category consists of power plant boilers large than 175 MW which by January 1, 1971, were not sufficiently controlled to meet APCD Rule 68. The source unit is one boiler. These units range in size from 220 MW to 480 MW and have an average size of 375 MW.*

The existing state of control for these boilers is what might be called "first stage combustion modification control". Depending on the boiler, they have controls such as low excess air, two-stage combustion, modified burner design, and modified operating procedure. These controls have succeeded in cutting emissions to about 1/2-1/3 of the uncontrolled levels, so that they now operate at around 160-220 ppm on gas and 200-300 ppm on oil (Sanderling, Oct. 1971), (Felgar, Nov. 1971). In 1971 these boilers operated on about 80% gas and 20% low sulfur fuel oil. However, as noted in Chapter 3, the "zero control level" for power plants in 1975 is here defined as running on 100% oil. It will be assumed that, both before and after being controlled to Rule 68 standards, these boilers have an emission level on oil of 3/2 that on gas.

Source Magnitude, 1975

There are eight large power plant boilers in Los Angeles County that were not sufficiently well controlled to meet Rule 68 as of January

* Actually, there are 8 such boilers, two 220's, two 350's, and four 480 MW's (Sanderling, Oct. 1971), (Felgar, Nov. 1971).

1, 1971, 4 belonging to Southern California Edison and 4 to the Los Angeles Department of Water and Power. Thus,

$$S_6 = 8$$

Emissions

In 1970 these boilers emitted a total of around 50 tons/day of NO_x (Sanderling, Nov. 1971), (Felgar, Nov. 1971). However, they operated on 80% natural gas (APCD Profile, 1971), (Chass, et al., 1971). Assuming a 10% increase in load factor by 1975 and a 3-2 ratio of emissions on oil to gas, these boilers would emit 76 tons/day in 1975 burning only fuel oil. This amounts to 9.5 tons/day per boiler. Thus, at the "zero control level", all oil burned in these boilers, the emission rates are

RHC	NO_x
$e_{16} = 0$	$e_{26} = 9.5 \text{ tons/day}$
$S_6 e_{16} = 0$	$S_6 e_{26} = 76 \text{ tons/day}$

Control Methods for Source # 6

Control Method # 8: Substitution of Natural Gas for Fuel Oil in Non-Rule 68-Controlled Large Power Plant Boilers.

Description

Control method X_8 consists of substituting natural gas for low sulfur fuel oil in source # 6. The control unit is taken to be substituting 3.9 M equiv. bbls. per year of gas for fuel oil. This is the average amount of fuel per year burned in one of the boilers of source # 6.*

Emission Reduction

Since the large boilers emit only $2/3$ as much NO_x on gas as on oil, one control unit, by converting one boiler completely to gas, reduces emissions by $1/3$ that of a single boiler. The emission reduction per control unit is thus $1/3 \times 9.5$ tons/day, or 3.2 tons/day. Thus,

$$B_{1_8} = 0 \quad B_{2_8} = 3.2 \text{ tons/day}$$

Cost

As noted on page 237, under control #7, no costs are assigned to fuel switching. Control method # 8 is thus only limited by the supply constraints on natural gas. Thus,

$$C_8 = 0$$

* This is calculated as follows: Of the 66 M equiv. bbls. of fuel burned in power plants in Los Angeles County in 1975 (APCD Profile, 1971), 80% or 53 M equiv. bbls., is burned in large boilers, sources # 5 and # 6 (Nevitt, Nov. 1971). Source # 6 accounts for around 59% of this (Sanderling, Oct. 1971), (Felgar, Nov. 1971). The 8 boilers of source # 6 thus burn a total of 31.2 M equiv. bbls. per year for an average of 3.9 M equiv. bbls. per year per boiler.

Other Control Parameters

One unit of control X_6 applies to exactly one unit of source # 6 and to no other sources. Thus,

$$A_{68} = 1$$

$$A_{i8} = 0 \quad i \neq 6$$

Each unit of control X_6 uses 3,900,000 equiv. bbls of natural gas per year (limited supply #1). Thus,

$$D_{18} = 3,900,000 \text{ eq. bbls. /yr.}$$

Control Method # 9: Addition of Advanced Combustion Modification Control to the Boilers to Comply with Rule 68.

Description

Control method X₉ consists of making further combustion modifications on the boilers of source # 6 so that they comply with Rule 68. The control unit is taken to be addition of advanced combustion control to one boiler. The particular form of the combustion control, e. g. , modified burner design or flue gas recirculation or modified operating procedure, etc. , is left up to the discretion of the power plant operator. However, it presently appears that this control will probably be flue gas recirculation (Sanderling, Nov. 1971), (Felgar, Nov. 1971).

Emission Reduction

It is estimated by power plant engineers (Sanderling, Nov. 1971), (Felgar, Nov. 1971) that the average reduction in NO_x per boiler in meeting Rule 68 will be 40%. Since each boiler emits 9.5 tons/day, one control unit reduces NO_x emissions by 3.8 tons/day. Thus,

$B_{19} = 0 \quad B_{29} = 3.8 \text{ tons/day}$
--

Cost

APCD officials estimate that the total initial cost (development and investment) of meeting Rule 68 in the 16 large power plant boilers of Los Angeles County is \$ 20 M (Chass, et al. , 1971). After having complied on the first eight by 1971, power plant officials estimate around \$12 M will be required for the last eight (Sanderling, Nov. 1971),

(Felgar, Nov. 1971). Flue gas recirculation is the expected control method to be used on these boilers. Estimates for the initial cost of retrofitting FGR on large power plant boilers are \$1.0-1.5 M (Andreason, Aug. 1971) and \$1.5 M (Felgar, Aug. 1971). Using \$1.5 M per boiler gives a \$12 M cost for all eight boilers and agrees with the previous estimate. \$1.5 M is taken as the initial cost for FGR here. The operating costs are taken from the ESSO report factored for boiler size.

	Annual Cost
Initial Cost: \$1.5 M	
20 yr. lifetime at $i = 10\%$	\$170,000
Operating Cost	50,000
Total Annual Cost per Control Unit	$C_9 = \$220,000$

Since each control unit reduces emissions by 3.8 tons/day or 1,390 tons/yr., the cost per ton of NO_x removed is \$158 per ton NO_x .

Other Control Parameters

Each unit of control X_9 applies to one unit of source # 6 and to no other source. Thus,

$$\begin{aligned} A_{69} &= 1 \\ A_{i9} &= 0 \quad i \neq 6 \end{aligned}$$

None of the limited supply inputs is used by control X_9 . Thus,

$$D_{19} = 0$$

Control Method # 10: Addition of Advanced Combustion Modification Control and Substitution of Natural Gas for Fuel Oil in Large Power Plant Boilers not Complying with Rule 68.

Description

Control X_{10} consists of simultaneously applying control methods X_8 and X_9 . The control unit is taken to be substituting 3.9 M equiv. bbls. per year of gas for fuel oil and adding advanced combustion control to one boiler. These controls are discussed in the control # 8 and # 9 sections. One unit of X_{10} consists of one unit of X_8 and X_9 and applies to one boiler.

Emission Reduction

It is assumed here that emissions on gas are $2/3$ those on oil both before and after "advanced combustion control". Emissions per boiler with both control X_8 and X_9 are then $(2/3) \times (.60) \times (9.5)$ tons/day or 3.8 tons/day. Each unit of control X_{10} results in a 5.7 tons/day decrease in NO_x emissions. Thus,

$$B_{1\ 10} = 0 \quad B_{2\ 10} = 5.7 \text{ tons/day}$$

Cost

The cost per unit of control method X_{10} is the sum of the costs for controls X_8 and X_9 . Since $C_8 = 0$ and $C_9 = \$220,000$, the cost per control unit for X_{10} is

$$C_{10} = \$220,000$$

Each control unit removes 2,080 tons/year NO_x for a cost of \$105 per ton of NO_x removed.

Other Control Parameters

One unit of control X_{10} applies to one unit of source # 6 and to no other sources. Thus,

$$A_{6\ 10} = 1$$

$$A_{i\ 10} = 0 \quad i \neq 6$$

Each unit of control X_{10} uses 3.9 M equiv. bbls. of natural gas per year (limited supply input #1). Thus,

$$D_{1\ 10} = 3,900,000 \text{ eq. bbls/yr}$$

7. Source #7: Small Power Plant Boilers

Description

This source category consists of power plant boilers less than 175 MW in capacity. The source unit is one boiler. In Los Angeles County these units range in size from 10 MW to 175 MW (Hall, Nov. 1971), (Felgar, Nov. 1971) and have an average size of 65 MW (APCD Profile, 1971).

Except for the use of natural gas and low sulfur fuel oil, small power plant boilers have no existing control for NO_x (Sanderling, Nov. 1971). The APCD did not include them in Rule 68 because they were older, more difficult to control, and used less intensively than the larger boilers and because many were scheduled to be phased out during the '70's (Chass, et. al., 1971).

On the average these units emit about the same NO_x on oil as on gas.* Since all other combustion sources here emit less NO_x on gas than on oil, it is assumed here that fuel oil only is used in small boilers, leaving the gas for other sources.

Source Magnitude, 1975

In 1971 there were 44 small power plant boilers in Los Angeles County (APCD Profile, 1971). Seven of these were essentially inoperative (Felgar, Nov. 1971). It is assumed here that the rest will remain

* Almost all emit around 2/3 as much on gas than on oil. However, the six largest (175 MW's), which account for around half the emissions, emit 2/3 as much on oil than on gas. Thus, on the average they emit about the same on oil and gas (Sanderling, Nov. 1971), (Felgar, Nov. 1971).

in service until 1975 and that no new boilers will be added. Thus,

$$S_7 = 37$$

Emissions

In 1970 the 37 small power plant boilers emitted a total of around 21 tons/day of NO_x (Nevitt, Nov. 1971), (Sanderling, Nov. 1971), (Felgar, Nov. 1971). Assuming a 10% increase in load factor by 1975, total emissions will be 23 tons/day in 1975. This amounts to .62 tons/day per boiler. Thus,

RHC	NO_x
$e_{17} = 0$	$e_{27} = .62 \text{ tons/day}$
$S_7 e_{17} = 0$	$S_7 e_{27} = 23 \text{ tons/day}$

Control Methods for Source # 7

Control Method # 11: Low-Excess Air on Small Power Plant Boilers.

Description

Control method X_{11} consists of adding combustion control to small power plant boilers in order to decrease excess air present during firing from present levels of 8-15% (Hall, Nov. 1971), (Bagwell, Nov. 1971) to levels of 2-6%. The control unit is adding LEA to one boiler. Detailed descriptions of LEA and its effects on NO_x emissions can be found in (ESSO, 1969) and (HEW-AP-67, 1970).

Emission Reduction

Following the ESSO report a 30% reduction in NO_x is assumed here for LEA control. Since each boiler emits .62 tons/day of NO_x , each control unit reduces NO_x emissions by .19 tons/day. Thus,

$B_{111} = 0 \quad B_{211} = .19 \text{ tons/day}$
--

Cost

For retrofitting LEA on a small power plant boiler, the initial cost is approximately \$100,000 (ESSO, 1969). Using ESSO report procedures for calculating operating costs and fuel savings, the total annual cost is calculated as follows:

	Annual Cost
Initial Cost \$100,000	
10 yr. * lifetime at $i = 10\%$	\$16,000
Operating cost	8,000
Fuel savings	- 10,000
Annual Cost per Control Unit	$C_{11} = \$14,000$

Each control unit reduces NO_x emissions by .19 tons/day or 70 tons/year. The cost per ton of NO_x removed is thus \$200/ton.

Other Control Parameters

Each unit of control X_{11} applies to one unit of source # 7 and to no other sources. Thus,

$$\begin{aligned} A_{711} &= 1 \\ A_{i11} &= 0 \quad i \neq 7 \end{aligned}$$

Control X_{11} uses none of the limited supply inputs. Thus,

$$D_{111} = 0$$

* It is assumed that the older, small power plant boilers have half the life of the large power plant boilers which was taken as 20 years.

Control Method # 12: Low-Excess Air and Flue Gas Recirculation on Small Power Plant Boilers.

Description

Control method X_{12} consists of adding flue gas recirculation to the small power plant boilers as well as operating on low excess air. FGR and LEA and their effects on utility boilers are discussed in ESSO, 1969 and HEW-AP-67, 1970. The control unit is taken to be FGR and LEA on one boiler.

Emission Reduction

Following the ESSO report a 50% reduction in NO_x is assumed here for LEA and FGR control. Since each boiler emits .62 tons/day of NO_x , each control unit reduces NO_x emissions by .31 tons/day. Thus,

$B_{112} = 0 \quad B_{212} = .31 \text{ tons/day}$
--

Cost

To retrofit FGR on a small power plant boiler, the ESSO report estimates around \$120,000 initial cost. An estimate by a power plant representative is \$200,000 (Sanderling, Nov. 1971). The figure of \$150,000 is chosen here as the initial cost of FGR. When added to the cost of LEA, the total initial cost for control X_{12} becomes \$250,000. The ESSO report procedures are used to calculate operating costs.

	Annual Cost
Initial Cost: \$250,000	
10 yr. lifetime at $i = 10\%$	\$40,000
Operating Cost	21,000
Fuel Savings	- 10,000
Annual Cost per Control Unit	$C_{12} = \$51,000$

Each control unit reduces NO_x emissions by .31 tons/day or 113 tons/year. The cost per ton of NO_x controlled is thus \$450/ton.

Other Control Parameters

Each unit of control X_{12} applies to one unit of source #7. Thus,

$$\begin{aligned} A_{7,12} &= 1 \\ A_{i,12} &= 0 \quad i \neq 7 \end{aligned}$$

Control X_{12} uses none of the limited supply inputs. Thus,

$$D_{1,12} = 0$$

Other Control Methods for Source # 7(i) Two-Stage Combustion (TSC)

Two-stage combustion has been applied effectively to large utility boilers and is technically feasible for most small power plant boilers. However, it is very costly for small boilers. According to the ESSO report, it costs considerably more than combined LEA and FGR and produces less of an NO_x reduction. TSC is thus eliminated from this study as strictly inferior to control method # 12.

(ii) Flue Gas Recirculation (FGR)

FGR alone is a possible control mechanism but is eliminated from consideration in the least cost program since it produces about the same reduction as LEA but at higher cost. It is thus strictly inferior to control method # 11.

(iii) Flue Gas Treatment

See source # 1.

8. Source # 8: Large Stationary Internal Combustion Engines

Description

This source category, to be called "large engines", consists of stationary internal combustion engines larger than 300 H.P. The source unit is one large engine. These engines are found almost exclusively in the gas and oil industries where they are mostly used for gas compression (Mills, et al., 1961a). The average size of these engines is approximately 700 H.P. * Large engines have no existing controls for NO_x emissions.

Source Magnitude, 1975

Mills, et al., (1961a), gives a census figure of 140 large engines. As mentioned above, these engines are almost all from the gas and oil industries. From 1961 to 1971, refinery crude throughput has increased from 650,000 bbls./day to 820,000 bbls./day (Thomas, Nov. 1971), (APCD Profile, 1971). One would expect a corresponding increase in the number of large engines. However, some compression engines have been replaced by electric motors (Glauser, July, 1971). The change in engine population is thus not obvious. From 1961 and 1971 APCD emission inventories, calculations reveal that the total emissions from all stationary engines have remained nearly constant. It is assumed here that the engine population has not changed since 1961. Since little growth in the refinery industry is expected by 1975 (Lunche, Nov. 1971), the 1961 data will also be used for 1975. Thus, using the

* Calculated from data taken from Mills, et al., (1961a).

1961 census,

$$S_8 = 140$$

Emissions

According to Mills, et al., (1961a), the average emission per engine is .18 tons/day of NO_x . All the engines combined emit 25 tons/day. Thus,

RHC	NO_x
$e_{18} = 0$	$e_{28} = .18 \text{ tons/day}$
$S_8 e_{18} = 0$	$S_8 e_{28} = 25 \text{ tons/day}$

Control Methods for Source # 8

Control Method # 13: Water Injection (WI) or Exhaust Gas Recirculation (EGR) on Large Engines

Description

Control method # 13 consists of adding equipment to the engines to either inject water or recycle a portion of the flue gas into the intake manifold. WI and EGR are grouped together this way because within the accuracy of the cost and effectiveness estimates they have the same cost and produce equivalent reductions in NO_x emissions. The control unit is WI or EGR to one engine. Water injection and exhaust gas recirculation are discussed in more detail in ESSO, (1969) and HEW-AP-67, (1970).

Emission Reduction

The ESSO report estimates a 75% NO_x reduction from WI. For automobile engines, EGR produces around a 50%-80% reduction (Downing and Stoddard, 1970). EGR should also be effective for stationary gas engines; an industrial researcher (Wendt, Oct. 1971) estimates reductions as high as 80-90%. Here it is assumed that either water injection or exhaust gas recirculation produces a 75% NO_x emission reduction. Since each engine emits .18 tons/day, one unit of control X_{12} , WI or EGR on one engine, reduces NO_x emissions by .14 tons/day. Thus,

$B_{113} = 0 \quad B_{213} = .14 \text{ tons/day}$
--

Cost

Water Injection: The costs for water injection are taken from the ESSO report. The initial capital cost was estimated at \$2,000 per engine. There is no expected loss in power or fuel economy, but an operating cost of \$350/year for the water consumed exists. Thus,

	Annual Cost
Initial Cost: \$2,000	
10 yr. lifetime at $i = 10\%$	\$330
Operating cost	350
	\$680

Exhaust Gas Recirculation: EGR should also have an initial cost of around \$2,000 (Wendt, Oct. 1971). For automobile engines Downing and Stoddard, (1970), give a maintenance cost of 12% of the capital cost, or \$240 dollars per year. EGR reduces the maximum power of the engine and thus has an added cost that WI lacks. A slight allowance for this cost makes the cost of EGR equivalent to that of WI. It is assumed here that they are the same. Thus,

Annual Cost per Control Unit

$C_{13} = \$680$

Since each control unit removes .14 tons/day or 51 tons/ year of NO_x , the cost per ton of NO_x removed is \$13 per ton.

Other Control Parameters

Each unit of control X_{12} applies to one unit of source # 8 and to no other sources. Thus,

$$A_{813} = 1$$

$$A_{i13} = 0 \quad i \neq 8$$

Control X_{13} uses none of the limited supply inputs. Thus,

$$D_{113} = 0$$

Other Control Methods for Source # 8(i) Increasing the Air/Fuel Ratio

As much as a 70% reduction in NO_x emissions can be obtained by leaning out gas engines to around 70% stoichiometric fuel (ESSO, 1969). However, there is a loss in fuel economy and a 30% loss in power. For new engines the power loss can be made up for by using larger engines for the same tasks. Although increasing air/fuel ratio may be applicable to some existing engines, it is not considered here to be a viable retrofit control alternative for all engines because of the power loss.

(ii) Exhaust Gas Treatment

See source # 1.

9. Source # 9: Small Compressor Engines

Description

This source category, to be called "small engines", consists of stationary internal combustion engines less than 300 H.P. in size, exclusive of 30 H.P. oil well pump engines.* The source unit is one small engine. These small engines are found almost exclusively in the oil and gas industries (Mills, et al., 1961b). Their average size is approximately 200 H.P.** Small engines have no existing control for NO_x emissions.

Source Magnitude, 1975

As discussed for source # 7, it is assumed here that the stationary internal combustion engine population has remained approximately constant since 1961 and will continue constant until 1975. Using the 1961 census (Mills, et al., 1961b), the number of small engines is 360. Thus,

$$S_9 = 360$$

* The oil well pump engines have lb./hr. emissions factors that are 30 times lower (Mills et al., 1961b).

** Calculated from data in Mills, et al., 1961b.

Emissions

According to Mills, et al. , (1961b), the average emission per engine is .019 tons/day of NO_x . All engines combine to emit 7 tons/day.

Thus,

RHC	NO_x
$e_{19} = 0$	$e_{29} = .019 \text{ tons/day}$
$S_9 e_{19} = 0$	$S_9 e_{29} = 7 \text{ tons/day}$

Control Methods for Source # 9Control Method # 14: Water Injection (WI) or Exhaust Gas Recirculation (EGR) on Small EnginesDescription

Control method # 14 consists of adding either a water injection or exhaust gas recirculation system to small engines. It is entirely analogous to control method # 13 for large engines. The control unit is adding WI or EGR to one engine. Water injection and exhaust gas recirculation are discussed in ESSO, 1969 and HEW-AP-67, (1970).

Emission Reduction

As with control method # 13, a 75% reduction in NO_x emissions is assumed based on estimates from (ESSO, 1969), (Downing, and Stoddard, 1970), and (Wendt, Oct. 1971). Since each engine emits .019 tons/day, one unit of control X_{14} , WI or EGR on one engine, reduces NO_x emissions by .014 tons/day. Thus,

$$B_{114} = 0 \quad B_{214} = .014 \text{ tons/day}$$

Cost

The costs for WI or EGR on small engines are obtained by factoring the results for large engines according to size. Thus, it is assumed that the costs are 200 H.P./700 H.P. or 2/7 of the costs for large engines. Thus,

	Annual Cost
Initial Cost: \$570	
10 yr. lifetime at $i = 10\%$	\$90
Operating cost	100
Annual Cost per Control Unit	$C_{14} = \$190$

Since each control unit decreases NO_x emissions by .014 tons/day or 5.1 tons/year, the cost per ton of NO_x removed is \$37/ton.

Other Control Parameters

Each unit of control X_{14} applies to one unit of source #9 and to no other sources. Thus,

$$\begin{aligned} A_{9,14} &= 1 \\ A_{i,14} &= 0 \quad i \neq 9 \end{aligned}$$

Control X_{14} uses none of the limited supply inputs. Thus,

$$D_{1,14} = 0$$

Other Control Methods for Source # 9(i) Increasing Air/Fuel Ratio

See source # 8.

(ii) Exhaust Gas Treatment

See source # 1.

Other Stationary Sources of NO_x

(i) Residential fuel combustion: 28 tons/day

In 1971, there was an average of 24 tons/day of NO_x resulting from residential fuel combustion (APCD Profile, 1971). Assuming 4% growth to 1975 gives 28 tons/day NO_x: 12.5 tons/day, space heaters; 12.5 tons/day, water heaters; 3 tons/day, ranges (Mills, et al., 1961b).

Residential sources can be controlled by either combustion modification (e. g., low excess air, modified burner design, etc.) or by switching to electric power. However, the technology for combustion modification is only now being developed for small sources and would only be applicable to new units (HEW-AP-67, 1970). Retrofitting old units is not now technically feasible, and even if it were possible, such control would be so expensive that it might be politically unacceptable. Thus, no controls are considered here for residential emissions of NO_x.

(ii) Metallurgical and mineral industry furnaces: 8 tons/day

In 1971, emissions from metallurgical and mineral furnaces were around 8 tons/day (APCD Profile, 1971). The same amount was emitted in 1961 (Mills, et al., 1961b) and it is assumed here that the source magnitude will remain constant until 1975. Most of these emissions come from open hearth steel furnaces (4 emitting 2.6 tons/day in 1961) and glass furnaces (16 emitting 4.6 tons/day in 1961) (Mills, et al., 1961b).

Several possible control methods have been proposed for metallurgical and mineral furnaces in the ESSO report. However, no data exist for control costs or effectiveness. Because of the lack of such

information, and because these furnaces are a rather minor source, no control methods for them are considered here.

(iii) Catalytic regenerators in refineries: 10 tons/day

There were 10 tons/day of NO_x emissions from catalytic regenerators in refineries (mostly from CO boilers) in Los Angeles County in 1971 (APCD Profile, 1971), (Mills, et al., 1961a). This source should remain constant until 1975 (Lunche, Nov. 1971).

The ESSO report does not even discuss possible control methods for this source. A refinery representative (Wendt, Oct. 1971) indicates that they would be very difficult to control. Because of the lack of information, no controls are considered here for catalytic regenerators.

(iv) Small commercial and industrial boilers: 9 tons/day

In 1971, there were 94 tons/day of NO_x coming from commercial and industrial fuel combustion. About 26 tons/day was from refinery heaters, leaving 68 tons/day from commercial and industrial boilers. Assuming a 4% growth rate to 1975 gives 78 tons/day in 1975. Medium and large boilers, those over 2 MBTU/hr., account for 69 tons/day in 1975. This leaves 9 tons/day resulting from fuel combustion in small commercial and industrial boilers, those smaller than 2 MBTU/hr.

Small commercial and industrial boilers are about the size of residential units. No controls are considered for them here for the same reason that they are not considered for residential sources.

(v) Oil-well pump engines: 2 tons/day

In 1961, there were around 8,800 oil-well pump engines,

averaging 30 H.P., in Los Angeles County. They emitted around 8 tons/day of NO_x (Mills, et al., 1961b). These engines have been undergoing replacement by electrical pump engines so that by 1975 there should only be around 2,000 such engines in the County emitting around 2 tons/day (McCutcheon, Dec. 1971). By 1980 this source should be virtually eliminated.

(vi) Miscellaneous: 3 tons/day

This category consists of source groups such as asphalt paving, incineration, and general types of industrial equipment all of which emit less than 1 ton/day of NO_x .

§A-II. STATIONARY SOURCES OF RHC

10. Source # 10: Underground Service Station Tanks

Description

This source consists of underground gasoline tanks at service stations. The source unit is one tank. These tanks are a source of reactive HC when, during filling, the gasoline vapor contained in the tanks is displaced into the atmosphere. The existing degree of control for these tanks is the LACAPCD required submerged fill procedure. Submerged fill has produced around a 37% reduction in HC emissions from the tanks (Burlin and Fudurich, 1961).

Source Magnitude, 1975

In July 1971 there were around 32,200 permits for underground gasoline storage tanks in Los Angeles County (Thomas, July 1971). This number is only an upper bound for the number of tanks since permits are not cancelled when tanks are removed or destroyed. Assuming 31,000 tanks in actual use in 1971 and assuming 2.2% growth until 1975 (projected growth in gasoline use, APCD, 1971), 34,000 tanks will exist in 1975. Thus,

$$S_{10} = 34,000$$

Emissions

The total gasoline throughput in 1975 is 9.5 M gal/day. * Losses from underground tanks with submerged fill are approximately 7.5 lb/1000 gal (Thomas, July 1971), (A.D. Little Report, 1967). The total hydrocarbon loss from underground tanks in 1975 is thus 35.6 tons HC per day. Evaporated gasoline is 55% reactive according to the APCD reactivity index (APCD Profile, 1969). Thus, total emissions from underground tanks in 1975 are 19.6 tons RHC/day. Emissions per source unit are 5.8×10^{-4} tons/day per tank. Thus.

RHC	NO _x
$e_{110} = 5.8 \times 10^{-4}$ tons/day	$e_{210} = 0$
$S_{10}e_{110} = 20$ tons/day	$S_{10}e_{210} = 0$

* This estimate is obtained by applying LACAPCD projected auto use growth figures for 1971 to 1975 to the 8.7 M gal/day throughput of 1971 (APCD Profile, 1971).

Control Methods for Source # 10Control Method # 15: Vapor Recycle Systems for Underground TanksDescription

This control method consists of installing equipment to pipe the displaced vapors from the underground tank into the emptying tank truck. Modifications are required both on the trucks and at the service station. The tank trucks need special piping and a special valve or hose attachment. The storage tanks require a matching hose attachment and a pressure-vacuum valve for the vent. The control unit is a vapor recovery system for one tank truck and 90 tanks.* More detailed descriptions of vapor recycle systems for underground tanks can be found in (Burlin and Fudurich, 1962) and the **1967 A. D. Little Report**.

Emission Reduction

The proposed vapor return system should allow only negligible HC emissions from underground tank filling. Thus, 5.8×10^{-4} tons/day of RHC will be controlled from each tank. Since the control unit is for 90 tanks, each control unit decreases RHC emissions by .052 tons/day of RHC. Thus,

$B_{1\ 15} = .052 \text{ tons/day} \quad B_{2\ 15} = 0$

Cost

The 1962 APCD Report (Burlin and Fudurich, 1962) estimated an

* On the average, one tank truck is sufficient to serve 30 stations (A. D. Little Report, 1967) and each station has 3 tanks (Thomas, July, 1971).

initial investment cost of \$750 per tank and \$1200 per truck for a vapor recycle system using a Nishkian value. However, it noted the possibility of a simpler hose attachment system which could reduce the cost to as low as \$200 per tank and \$1200 per truck. The A.D. Little Report of 1967 estimated \$250 per tank and \$600 per truck. The A.D. Little Report is the more recent and more detailed study. Weighting the estimates in its favor, \$300 per tank and \$750 per truck appear to be reasonable answers for 1967. 1971 prices are used here, and an adjustment for inflation gives, finally, \$350 per tank and \$850 per truck. Since each control unit is one truck and 90 tanks, the initial capital cost is \$32,350 per control unit. The only operating cost considered here is the negative cost of the gasoline saved. Each control unit recovers .095 tons/day total HC. This amounts to 11,300 gal/year. The cost results, then, are for one control unit (90 tanks, 1 truck).

	Annual Cost
Investment Cost: \$32,350	
10 lifetime*, i = 10%	\$5,260
Gas Savings at 12¢/gal	- 1,360
Annual Cost per Control Unit	$C_{15} = \$3,900$

Since each control unit reduces RHC emissions by .052 tons/day or 19 tons/year, the cost per ton of RHC removed is \$205 per ton RHC.

* A.D. Little Report, 1967.

Other Control Parameters

One unit of control method X_{15} applies to 90 units of source # 10, underground tanks, and to no other sources. Thus,

$$\begin{aligned} A_{10 \ 15} &= 90 \\ A_{i \ 15} &= 0 \quad i \neq 10 \end{aligned}$$

Control X_{15} uses no limited supply inputs. Thus,

$$D_{1 \ 15} = 0$$

11. Source # 11: Service Stations, Automobile Tank Filling

Description:

During automobile tank filling, hydrocarbon emissions occur because the gasoline vapor from the car tank is displaced into the atmosphere and because of spillage. The source unit is chosen to be one service station. There are no existing controls for this source of RHC emissions.

Source Magnitude, 1975:

Assuming an average of 3 tanks per station (Thomas, July 1971) and using the projected figure of 34,000 tanks in Los Angeles County in 1975 (source # 10), the projected number of service stations in 1975 is 11,300. Thus,

$S_{11} = 11,300$

Emissions:

As calculated for source # 10, the total gasoline throughput in Los Angeles County in 1975 is 9.5 M gal./day. Losses from automobile filling amount to 15.5 lb./1000 gal., 12.5 lb. displaced vapors and 3 lb. spillage (Thomas, July 1971). The total HC loss from auto filling in 1975 is thus 73.6 tons/day. Using the APCD reactivity index, 55% for evaporated gasoline, the reactive emissions are 40 tons/day. Emissions per source unit are, then, 3.6×10^{-3} tons/day per station. Thus

RHC	NO_x
$e_{111} = 3.6 \times 10^{-3}$ tons/day	$e_{211} = 0$
$S_{11}e_{111} = 40$ tons/day	$S_{11}e_{211} = 0$

Control Methods for Source # 11Control Method #16: Vapor Recirculation Systems for Service Station NozzlesDescription

Control X_{16} consists of adding a vapor collection system of the type developed by Gilbarco, Inc., Greensboro, North Carolina, to service stations. The main features of such a system are a special nozzle that tight fits over the auto fill pipe and a piping system for recycling the displaced vapors back to the underground tank. The control unit is addition of a vapor recirculation system to one service station.

Emission Reduction

The proposed system would probably eliminate some of the 3 lb/1000 gal. spillage as well as almost all of the 12.5 lb/1000 gal. displaced vapor (Vergamini, Nov. 1971). It is assumed here that the system is 85% effective for the motor vehicles that it fits. However, not all filler pipes are of standard size. A spring-loaded, flexible, tight seal would probably fit around 90% of the cars, however (Hunter, Nov. 1971), (Vergamini, Nov. 1971). Thus, the overall efficiency of the system would be $.85 \times .90 = 76\%$. Since each source unit emits 3.6×10^{-3} tons/day of RHC and since each control unit applies to one source unit, the emission reduction per control unit is 2.7×10^{-3} tons/day. Thus,

$B_{1,16} = 2.7 \times 10^{-3} \text{ tons/day} \quad B_{2,16} = 0$

Cost

It is assumed that the average service station has 3 tanks and 9 pumps (Thomas, July 1971), (A.D. Little Report, 1967). Costs are then computed according to procedures of the A.D. Little Report on the Gilbarco System. According to that report, the initial cost per tank for a piping system is \$300 and the initial cost per pump for a special nozzle and piping system is \$190. Thus, the initial cost per station is $3 \times \$300 + 9 \times \190 , or \$3180. Thus,

	Annual Cost
Initial Cost: \$30,000	
10 yr. lifetime at $i = 10\%$	\$420
Fuel Saved at 12¢/gal	- 90
Total Annual Cost per Control Unit:	$C_{16} = \$330$

Since each control unit reduces RHC by 2.7×10^{-3} tons/day or .99 tons/year, the cost per ton of RHC controlled \$333/ton.

Other Control Parameters

Each unit of control X_{16} applies to one unit of source # 11 and to no other sources. Thus,

$$\begin{aligned} A_{11\ 16} &= 1 \\ A_{i\ 16} &= 0 \quad i \neq 11 \end{aligned}$$

Control X_{16} uses no limited supply factors.

$$D_{1\ 16} = 0$$

12. Source # 12: Surface Coating

Description

This source category consists of reactive hydrocarbons emitted from the application of protective and decorative surface coatings. The source unit is one ton per day of emitted reactive organic solvent.

There are two main categories of surface coating emissions: A. solvent evaporation with no change in chemical form, and B. solvent evaporation with a change in chemical form resulting from heat or flame contact (Krenz, et al., 1968). The main sources in these two categories are architectural coating and paint baking, respectively.

Reactive hydrocarbon emissions from surface coating are already strictly controlled by the Los Angeles APCD Rule 66.* RHC emissions from this source were around 44 tons/day in 1971, down 80% from around 250 tons/day (APCD Profile, 1971). This 80% control level is taken as the zero or base control level for 1975.

Source Magnitude, 1975

Assuming 4% growth in surface coating until 1975, reactive organic solvent emissions then will be 51 tons/day. Thus,

$$S_{12} = 51 \text{ tons/day}$$

Emissions

For source # 12, by definition emissions correspond to the source unit. Thus,

*Actually, Rule 66 applies to other organic solvent use as well as surface coating.

RHC	NO _x
$e_{112} = 1$	$e_{212} = 0$
$S_{12}e_{112} = 51 \text{ tons/day}$	$S_{12}e_{212} = 0$

Control Methods for Source # 12

Control Method # 17: Further Restrictions on Reactive Organic Solvents in Surface Coating.

Description

Control X₁₇ consists of tightening Rule 66 to further eliminate reactive hydrocarbon emissions from surface coating. The control method will be only vaguely specified here as "enough control to eliminate a further 75% of reactive solvent emissions". The actual control techniques used to achieve this reduction would be some combination of the following (Finnegan, Nov. 1971), (Ellis, Nov. 1971):

- A. Type A Coatings (evaporation with no change in chemical form):
 - a. Further substitution of nonreactive for reactive solvents
 - b. Substitution of water-based for organic-based coatings
- B. Type B Coatings (evaporation with change in chemical form due to contact with flame or to baking):
 - a. Substitution of water-based for organic-based coatings
 - b. Use of powdered coatings
 - c. Use of high solids content coatings

Rule 66 is already one of the most complex air pollution control regulations in existence. To tighten the rule 75% more, by promoting the use of some or all of the above mentioned control techniques, will require further sophistication and presents a difficult administrative task. To promote the use of non-reactive surface coatings except where they are very difficult to replace, perhaps a high tax on reactive

solvents is in order. The administrative problem will not be dealt with here, however. Suffice it to note that achieving the 75% reduction in practice may require new and more complex regulatory procedures.

Emission Reduction

By definition of the control method, a 75% reduction in RHC emissions from surface coating is to be achieved. Since the total emissions from source # 12 are 51 tons/day, the reduction is 38 tons/day. Thus,

$B_{117} = 38 \text{ tons/day}$	$B_{217} = 0$
---------------------------------	---------------

Cost

Since control method # 17 is so vaguely specified, a systematic appraisal of its cost is not possible. Here, a "ballpark" estimate of the costs will be made by: (i) estimating the cost of some of the means taken to meet Rule 66, and (ii) comparing these measures to the process of implementing control X_{17} .

(i) Some costs of meeting Rule 66 for surface coating:

For surface coating, Rule 66 was met by substitution of non-reactive solvents for reactive solvents for type A emissions and by installation of air pollution control equipment for type B emissions (Krenz, et al., 1968). It is assumed here that control X_{17} will be met by the process changes listed in the description section above. To get an idea of the cost of such process changes, the cost of the non-reactive solvent substitution in surface coatings for Rule 66 is estimated in the table below:

	Annual Cost
Equipment cost to manufacture non-reactive solvents: \$2 M [*] 10 year lifetime at i = 10%	\$330,000
Cost of reformulating coatings with non-reactive solvents: \$2 M ^{**} 10 year payoff at i = 10%	330,000
Yearly additional cost of more expensive, non-reactive solvents for industrial coatings ^{***}	3,000,000
Cost of reformulating alkyn resins ^{****}	negl.
<hr/>	
Total Annual Cost of Non-Reactive Solvent Substitution for Surface Coatings to Meet Rule 66:	\$3,660,000

(ii) Cost of control X₁₇

The proposed 75% reduction in reactive organic solvent emissions is to be attained with some combination of control techniques A (a) & (b), and B (a), (b), & (c) presented in the "description section". Cost estimates for control of type A and type B emissions will be developed separately.

* This is the cost of Rule 66 to refineries (Ellis, Nov. 1971).

** This estimate was arrived at by assuming 50% of the R & D expenditures of Los Angeles County paint companies for one year were devoted to reformulating for Rule 66 (Finnegan, Dec. 1971).

*** Assuming the 110 tons/day of industrial coatings increased \$.30/gal in price (Ellis, Nov. 1971).

**** Hecht, Dec. 1971.

Control of Type A Emissions

If it were possible to achieve a 75% reduction in type A emissions by control technique A (a), further substitution of non-reactive organics for reactive organics, alone, the costs would be approximately as follows:

	Annual Cost
Equipment cost to manufacture non-reactive solvents:	negl. *
Cost of reformulating coatings with non-reactive solvents: \$2 M ^{**} 10 year payoff at i = 10%	\$330,000 ^{**}
Yearly additional cost of more expensive, non-reactive solvents for industrial coatings:	500,000*
Cost of reformulating alkyn resins:	negl.
Total Annual Cost:	<hr/> \$830,000

However, it is probably not possible to achieve the 75% reduction in type A emissions by further reformulation with non-reactive organics alone. The performance of many coatings deteriorates with substitution of non-reactive organics (Ellis, Dec. 1971). For satisfactory performance, many coatings cannot take much further substitution. In these cases, reduction in RHC emissions will require control technique A (b), substitution of water-based coatings. Water-based coatings are

*(Ellis, Nov. 1971)

**The reformulation cost is assumed the same as for Rule 66 compliance.

gradually being substituted for oil-based finishes anyway, and they do not cost much, if any, more (Finnegan, Dec. 1971). For some types of coatings, however, water-based finishes still have to be developed. The arbitrary assumption is made here that substitution of water-based coatings costs the same as further substitution of non-reactive organics. Thus, the total cost of achieving 75% control of reactive emissions from type A coatings will be that estimated for further substitution of non-reactives alone. This is, as shown above, \$830,000 per year.

Control of Type B Emissions

For type B emissions, some combination of control techniques (2)(a), (b), and (c) will have to be used. The costs of these process changes is as yet unknown. They will need further development and may or may not prove expensive. As a guess of the cost of such a development project, the arbitrary assumption is made here that this cost will be the same as the total cost of developing and reformulating non-reactive coatings for Rule 66.* This, as calculated above, was \$3,660,000 per year.

Adding the cost for type A and B emissions, the ballpark estimate for the cost of control X_{17} is, (rounding off to the nearest \$100,000)

$$C_{17} = \$4,500,000$$

* This is somewhat justified by an estimate of Mr. Weiss of the APCD, (Dec. 1971). He indicated that the net operating cost of a process change such as powdered coatings would be around twice the existing cost. The largest element in the Rule 66 substitution cost was a doubling of industrial coating prices (Ellis, Nov. 1971).

Since the control unit removes 31 tons/day or 11,250 tons/year of RHC emissions, the cost per ton of RHC prevented is \$330 per ton.

Other Control Parameters

One unit of control X_{17} applies to 51 units of source # 12 and to no other sources. Thus,

$$A_{12\ 17} = 51$$

$$A_{i\ 17} = 0 \quad i \neq 12$$

Control X_{17} uses no limited supply inputs. Thus,

$$D_{1\ 17} = 0$$

13. Source # 13: Degreasers

Description

This source category consists of reactive hydrocarbons emitted from degreasing operations. The source unit is one ton per day of reactive organic solvent used for degreasing.

Almost all hydrocarbon emissions from degreasing come from three solvents: trichloroethylene (TCE), 1,1,1-trichloroethane (1,1,1-T), and perchloroethylene (PCE) (Krenz, Dec. 1971). According to the APCD reactivity index TCE is considered reactive and 1,1,1-T and PCE are considered non-reactive (Weiss, Nov. 1971). Thus, reactive hydrocarbon emissions from degreasing are almost all TCE.

The present state of control for reactive HC from degreasers is of two types. First, as a means of saving solvent, many degreasers have condensers or absorbers. This equipment, by preventing some of the solvent loss, also acts as air pollution control equipment (Weiss, Nov. 1971). Second, because of the Rule 66 limitations on reactive solvent use, non-reactive solvents have been substituted for reactive solvents. Thus, in 1971, of the 95 tons/day of total HC emissions from degreasing operations, only 20 tons/day was reactive (basically TCE), (APCD Profile, 1971). This present state of control is taken as the base or zero control level for this study.

Source Magnitude, 1975

In 1971 there were 20 tons/day of RHC emitted from degreasing (APCD Profile, 1971). Not all solvent used is emitted; some is disposed of as sludge. Assuming 90% of the used solvent is emitted

(Krenz, Dec. 1971), around 22 tons/day of solvent was used in 1971. Assuming a 4% growth in degreasing operations in 1975, around 26 tons/day of reactive solvent will be used in 1975 with the present degree of control (i. e., the present per cent use of reactive solvent). Thus,

$$S_{13} = 26 \text{ tons/day}$$

Emissions

For each ton/day of solvent used, .9 tons/day of solvent is emitted. Thus,

RHC	NO _x
$e_{113} = .9$	$e_{213} = 0$
$S_{13}e_{113} = 23 \text{ tons/day}$	$S_{13}e_{213} = 0$

Control Methods for Source # 13

Control Method # 18: Substitution of 1, 1, 1-Trichloroethane for Trichloroethylene in Degreasing Operations.

Description

Control X_{18} consists of substituting 1, 1, 1-trichloroethane for trichloroethylene in degreasers using the latter. The control unit is substitution of .75 tons/day of 1, 1, 1-T for 1 ton/day of TCE.*

Emission Reduction

Of each 1 ton/day of TCE used, .9 tons/day are emitted. Switching to the non-reactive 1, 1, 1-T thus eliminates .9 tons/day of RHC emissions. Thus,

$$B_{118} = .9 \text{ tons/day} \quad B_{218} = 0$$

Cost

Little or no process or equipment change is necessary in switching from TCE to 1, 1, 1-T (Krenz, Dec. 1971). In fact, 1, 1, 1-T may save on operating costs (Dow, 1968). The only costs considered here for control X_{18} are the extra cost of 1, 1, 1-T per pound and the savings resulting from less solvent consumption. TCE costs \$.0875/lb. and 1, 1, 1-T costs \$.111/lb. (tank truck prices) (Bidwell, Dec. 1971). One ton of TCE thus costs \$175. 0.75 tons of 1, 1, 1-T cost \$166. Thus,

* Because of its density and boiling point properties, less of 1, 1, 1-T is consumed in degreasing operations than TCE. In tests conducted by Dow Chemical, the reduction in solvent loss on a volume basis ranged from 5% to 41% with an average of around 25-30% (Dow, 1968). A 25% solvent consumption savings is assumed here.

each unit of control X_{18} results in a savings of \$9/day or \$3,280/year.

Annual Cost of One Unit of Control X_{18}

$$C_{18} = -\$3,280$$

Each control unit eliminates .9 tons/day or 320 tons/year of RHC emissions. The cost (actually a savings) per ton of RHC controlled is thus -\$10/ton.

Other Control Parameters

Each unit of control X_{18} applies to one unit of source # 13 and to no other sources. Thus,

$$A_{1318} = 1$$

$$A_{i18} = 0 \quad i \neq 13$$

No limited supply inputs are used by control X_{18} . Thus,

$$D_{i18} = 0$$

Other Control Methods for Source # 13(i) Substitution of Perchloroethylene (PCE) for TCE

RHC emissions from degreasers can also be eliminated by substituting PCE for TCE. PCE costs slightly more than TCE, and the solvent consumption is considerably more (Dow, 1968). Also, equipment changes are required for PCE and operating costs are greater (Dow, 1968), (Krenz, Dec. 1971). Substitution of PCE would have a positive cost, and it is thus ruled out as a control method on the basis that it is inferior to 1,1,1-T substitution.

(ii) Addition of Condensers or Absorbers to Degreasers

This is another possible control technique. However, many degreasers already have such equipment to save on solvent consumption. Much of the emissions from degreasers result from "dragging out" solvent, and these emissions are not controlled by condensers or absorbers. This control method is thus limited in its ability to reduce emissions. In any case, it would have a positive cost and would thus be inferior to control method X_{18} .

14. Source # 14: Dry Cleaners Using Petroleum Based Solvents

Description

Most dry cleaning in Los Angeles County is done with synthetic solvents, rated non-reactive on the APCD reactivity scale (Weiss, Nov. 1971). There are, however, a few large dry cleaning plants that use petroleum solvents. These solvents are reactive. This source category consists of such dry cleaners.

The source unit is one dry cleaning plant using petroleum solvent. There is no existing control on these installations.

Source Magnitude, 1975

In 1971, there were about 25 dry cleaning plants using petroleum based solvents (Weiss, Nov. 1971), (Pierce, Dec. 1971). No growth in such dry cleaning operations is expected by 1975; in fact, use of petroleum solvents is apparently on the decrease (Weiss, Nov. 1971). To be conservative, it is assumed that these 25 plants will still be in operation by 1975. Thus,

$S_{14} = 25$

Emissions

In 1971, emissions from dry cleaning with petroleum solvents were 5 tons/day of RHC (APCD Profile, 1971). The average plant thus emitted .20 tons/day = 400 lbs/day of reactive solvent. Thus,

RHC	NO _x
$e_{1\ 14} = .20 \text{ tons/day}$	$e_{2\ 14} = 0$
$S_{14}e_{1\ 14} = 5 \text{ tons/day}$	$S_{14}e_{2\ 14} = 0$

Control Methods for Source # 14

Control Method # 19: Activated Carbon Adsorption Systems for Dry Cleaning Plants Using Petroleum Solvents

Description

Control method X_{19} consists of adding activated carbon adsorption systems to the petroleum solvent dry cleaning plants in order to collect the solvent vapors. The control unit is addition of one adsorption system to one dry cleaning plant. Activated carbon adsorption systems and their application to dry cleaning units are discussed in detail in HEW-AP-68 (1970). Such systems have been used extensively in synthetic solvent plants where the recovery of high cost synthetic solvent (\$2.00/gal. vs. \$.30/gal. for petroleum solvent) justifies their use on economic grounds alone (Pierce, Dec. 1971), (HEW-AP-68, 1970).

Emission Reduction

Assuming a 95% collection efficiency (HEW-AP-68, 1970), the emission reduction from an average plant (.20 tons/day RHC emissions) is .19 tons/day. Since one control unit applies to one plant, the emission reduction for each control unit is,

$B_{119} = .19 \text{ tons/day} \quad B_{219} = 0$
--

Cost

For a dry cleaning plant emitting about .40 tons/day of RHC, the initial cost of an activated carbon adsorption system would be around \$60,000-\$80,000 (Classon, Dec. 1971). For the .20 tons/day size

plants considered here, initial cost should be only slightly less (Classon, Dec. 1971). From a cost curve for activated carbon adsorb-ers in the HEW-AP-68 report, cutting plant size in half cuts costs by only about 1/4-1/3. A \$50,000 initial cost is assumed here for the .20 tons/day size plants.

There is an operating savings from the recovery of the petroleum solvent. Saving .19 tons/day at \$.30/gal* (Pierce, Dec. 1971) gives a daily saving of \$17.5. The yearly saving is thus \$6,400.

Operating costs should be around 1/4 of the solvent savings (Classon, Dec. 1971). Thus, operating costs are \$1,600 per year.

These costs are summarized in the table below:

	Annual Cost
Initial Cost: \$50,000	
10 yr. lifetime at $i = 10\%$	\$8,100
Solvent Savings	- 6,400
Operating Cost	1,600
Total Annual Cost per Control Unit:	$C_{19} = \$3,300$

Since each control unit reduces RHC emissions by .19 tons/day, or 69 tons/year, the cost per ton of RHC controlled is \$48/ton.

* 1 gal. = 6.5 lb. (Classon, Dec. 1971).

Other Control Parameters

Each unit of control X_{19} applies to one unit of source # 14 and to no other sources. Thus,

$$A_{14\ 19} = 1$$

$$A_{i\ 19} = 0 \quad i \neq 14$$

No limited supply inputs are used by control X_{19} . Thus,

$$D_{i\ 19} = 0$$

Other Control Method for Source # 14Switching to Non-reactive Synthetic Solvents

This is ruled out here on the grounds that it costs much more and achieves only very slightly more control of RHC than adsorption control. Not counting the costs of equipment changes, which may be considerable, the extra solvent cost alone amounts to \$38,000 per year per plant as compared to \$3,300 per year per plant for adsorption control. (See pp. A-92, A-93).

Other Stationary Sources of Reactive Hydrocarbons

(i) Petroleum refining and marketing other than at service stations: 7 tons/day

In 1971 about 5.7 tons/day RHC emissions resulted from petroleum refining operations and about 1.3 tons/day from petroleum marketing other than at service stations. It is assumed here that these emissions will remain constant until 1975.

RHC emissions from these sources have been reduced well over 90% by APCD Rules 10, 56, 57, 58, 59, 61, 65 (APCD Profile, 1971). Further reductions would come from "putting controls on the controls" and would tend to be very expensive (Weiss, Dec. 1971). In any case, there is no readily available information on additional control techniques for these sources, and control for them is not considered here.

(ii) Miscellaneous manufacturing processes: 15 tons/day

In 1971 there were about 15 tons/day of RHC emissions from various manufacturing processes. The main sources were in the rubber, pharmaceutical, and chemical industries (APCD Profile, 1971). It is assumed that these emissions will remain constant until 1975.

These sources already are controlled by APCD Rule 66 (Weiss, Dec. 1971). In a tightening of Rule 66, as was considered for source # 12, emissions from these sources might be further reduced. No specific controls for these sources are considered here because a detailed source inventory for these manufacturing processes is not available (Weiss, Dec. 1971).

(iii) Other organic solvent use: 14 tons/day

In 1971 12 tons/day of RHC emissions resulted from miscellaneous users of organic solvents (APCD Profile, 1971). It is assumed these emissions will grow 4% per year by 1975.

These sources are already controlled by APCD Rule 66, and a tightening of Rule 66 might further restrict emissions. However, no specific controls are considered here because a detailed inventory of these sources is not available (Weiss, Dec. 1971).

§A-III. MOBILE SOURCES OF NO_x AND RHC

This section presents source magnitude and emissions along with control method effectiveness and cost for mobile sources of NO_x and RHC in Los Angeles County. Gasoline powered motor vehicles are the main source in this category. For easy reference later in this section, the basic assumptions made here about the automobile population are listed below.

1. The total number of gasoline powered motor vehicles in Los Angeles County in 1975 is 4,600,000 (APCD Profile, 1971).
2. 20% of the 1971-1974 model year vehicles (7.5% of the total motor vehicle population) are contained in fleets suitable for conversion to gaseous fuels.
3. The motor vehicle population has the age, mileage, expected lifetime, and emission distributions given in Table A-I on the following page.

TABLE A-I. Distribution of Motor Vehicle Age, Mileage, Expected Life, and Emissions*

Model Year	Age (years)	Age Distribution (a) (% per year)	Mileage (b) (miles/day)	Expected Life (b) (years)
1974	0-1	10	41	10.3
1973	1-2	9.5	36	9.3
1972	2-3	9	31	8.3
1971	3-4	9	26	7.3
1970	4-5	8.5	23	6.3
1969	5-6	8	21	5.5
1968	6-7	8	15	5.0
1967	7-8	7.5	14	4.5
1966	8-9	6.5	12	3.7
1965	9-10	5.5	11	3.2
1964	10-11	4.5	10	2.7
1963	11-12	3.5	10	2.5
1962	12-13	2.5	10	2.1
1961	13 ⁺	8	10	2.0

* For emissions see next page.

(a) Rounded off California age distribution (Downing and Stoddard, 1970).

(b) California ARB

TABLE A-1. (cont'd.)

Model Year	Emissions (c)		
	NO _x (d) Exhaust (gm./mile)	RHC Exhaust (e) (gm./mile)	Evaporation (f) (lb./day)
1975			
1974	1.3	1.1	.02
1973	3	1.1	.02
1972	3	1.1	.02
1971	4	1.6	.02
1970	6	1.6	.02
1969	6	2.7	.14
1968	6	2.7	.14
1967	6	2.7	.14
1966	6	2.7	.14
1965	4	7.5	.14
1964	4	7.5	.14
1963	4	7.5	.14
1962	4	7.5	.14
1961	4	7.5	.14

(c) It is assumed that crankcase emissions have been eliminated in all vehicles.

(d) (HEW-AP-66, 1970), (ARB Implementation Plan, 1971) It is assumed that 1971-1974 vehicles meet California state standards for NO_x.

(e) (HEW-AP-66, 1970), (ARB Implementation Plan, 1971), (APCD Profile, 1969) It is assumed that 1966-1969 vehicles are 10% over the state standard, that 1970-1974 vehicles meet the state standard, and that HC exhaust is 75% reactive.

(f) (HEW-AP-66, 1970), (ARB Implementation Plan, 1971), (APCD Profile, 1969) It is assumed that evaporative control devices are 85% effective and that evaporative emissions are 65% reactive.

15. Source # 15: Pre-1966 Motor Vehicles, Exhaust Emissions

Description

This source category consists of motor vehicles of model year less than or equal to 1965. The source unit is one pre-1966 vehicle. The number, usage, expected life, and emission rate of these vehicles are summarized in Table A-I. It is assumed here that pre-1966 vehicles are completely controlled for crankcase emissions and have only exhaust and evaporative emissions remaining. Exhaust emissions are considered in this section; evaporative emissions are source # 16.

Source Magnitude, 1975

Twenty-four per cent of the motor vehicle population of 4,600,000 vehicles in 1975 is made up of pre-1966 vehicles (Table A-I, page A-99).

Thus,

$$S_{15} = 1,100,000$$

Emissions

From Table A-I the average usage of pre-1966 vehicles is 10.2 miles/day, and exhaust emissions rates are 7.5 gm./mile RHC and 4 gm./mile NO_x . Thus, the emissions per source unit are .17 lb/day = 8.5×10^{-5} tons/day RHC and .09 lb/day = 4.5×10^{-5} tons/day NO_x .

Thus,

RHC	NO_x
$e_{1\ 15} = 8.5 \times 10^{-5}$ tons/day	$e_{2\ 15} = 4.5 \times 10^{-5}$ tons/day
$S_{15}e_{1\ 15} = 94$ tons/day	$S_{15}e_{2\ 15} = 50$ tons/day

Control Methods for Source # 15

Control Method # 20: Capacitor Discharge, Ignition Optimization System (CDIOS) for Pre-1966 Vehicles

Description

Control X_{20} consists of a capacitor discharge, ignition optimization system of the type developed by Air Quality Products Inc., Orange, California. There are three elements to the device. First, there is a capacitor discharge system to allow operation at lean fuel mixtures and to improve driveability. Second, the vacuum advance is controlled by inhibiting the vacuum to the distributor during certain operating modes. Third, the spark advance is retarded electronically (Upton, Dec. 1971). The control unit is one CDIOS device to one pre-1966 vehicle.

Emission Reduction

The CDIOS control reduces HC emissions by around 60% and NO_x emissions by around 35% in pre-1966 vehicles (Upton, Dec. 1971). It is assumed RHC emissions are controlled in proportion to HC emissions. Since each vehicle emits 8.5×10^{-5} tons/day RHC and 4.5×10^{-5} tons/day NO_x , the emission reductions per control unit are as follows:

$B_{1\ 20} = 5.1 \times 10^{-5} \text{ tons/day} \quad B_{2\ 20} = 1.6 \times 10^{-5} \text{ tons/day}$

Cost

The installed initial cost for one CDIOS unit is \$40. (Upton, Dec. 1971). There is no maintenance cost or fuel loss and driveability actually improves. Fewer tuneups are needed, and when they are done, only the spark plugs need

replacing. The tune-up savings amounts to around 1/2 a tune-up per year (Upton, Dec. 1971). A \$10 per year operating savings is assumed here. Thus,

	Annual Cost
Initial Cost: \$40	
$i = 10\%$, lifetime = 2.5 yrs. (Table A-I)	\$19
Operating Cost	- 10
Total Annual Cost per Control Unit	$C_{20} = \$ 9$

Since each control unit reduces RHC emissions by .018 tons/year and NO_x emissions by .0058 tons/year the cost per ton controlled is \$500 per ton of RHC and \$1550 per ton of NO_x .

Other Control Parameters

Each unit of control X_{20} applies to one unit of source # 15 and to no other sources. Thus,

$$\begin{aligned} A_{15\ 20} &= 1 \\ A_{i\ 20} &= 0 \quad i \neq 15 \end{aligned}$$

Control X_{20} uses no limited supply inputs. Thus,

$$D_{1\ 20} = 0$$

Control Method # 21: Exhaust Gas Recirculation (EGR) and Controlled Spark Retardation (CSR) on Pre-1966 Vehicles

Description

Control X_{21} consists of a combined EGR and CSR system of the type developed by the Perfect Circle Division of the Dana Corporation, Hagerstown, Indiana. A complete description of the system can be obtained from the brochure "RETRONOX, Clean-Air System" by the Dana Corporation. The control unit is addition of one EGR and CSR device to one pre-1966 vehicle.

Emission Reduction

The EGR and CSR control reduces HC emissions by around 15% and NO_x emissions by about 55% in pre-1966 vehicles (Vance, Dec. 1971). It is assumed RHC emissions are reduced in proportion to HC emissions. Since each vehicle emits 8.5×10^{-5} tons/day RHC and 4.5×10^{-5} tons/day NO_x , the emission reductions per control unit are

$$B_{1\ 21} = 1.3 \times 10^{-5} \text{ tons/day} \quad B_{2\ 21} = 2.5 \times 10^{-5} \text{ tons/day}$$

Cost

The installed cost of one EGR and CSR device is around \$80. (Vance, Dec. 1971). Maintenance costs amount to \$5 per year. Fuel economy loss is about 3.5% per year or \$2 per year. There is also a slight loss in performance (Vance, Dec. 1971). Thus,

	Annual Cost
Initial Cost: \$80	
$i = 10\%$ lifetime = 2.5 yrs. (Table A-I)	\$38
Maintenance Cost	5
Fuel Economy Loss	2
Total Annual Cost per Control Unit	$C_{21} = \$45$

Since each control unit reduces RHC emissions by 4.7×10^{-3} tons/year and NO_x emissions by 9.1×10^{-3} tons/year, the cost per ton controlled is \$9,600 per ton RHC and \$4,900 per ton NO_x .

Other Control Parameters

Each unit of control X_{21} applies to one unit of source # 15 and to no other sources. Thus,

$$\begin{aligned} A_{15\ 21} &= 1 \\ A_{i\ 21} &= 0 \quad i \neq 15 \end{aligned}$$

No limited supply inputs are used. Thus,

$$D_{1\ 21} = 0$$

Other Control Methods for Source # 15

(i) Vacuum Spark Advance Disconnect and Tuning Adjustment (GM "Smog Package")

The "smog package" is a possible control method for pre-1966 vehicles. This device consists of a vacuum spark advance disconnect and timing and carburetor adjustments (Postma, Dec. 1971). The "smog package" produces about a 50% reduction in RHC and a 30% reduction in NO_x in pre-1966 vehicles. It has an initial cost of around \$20 and no operating or maintenance cost. The cost annualizes to around \$9 per year.

For this study, the "smog package" is inferior to the CDIOS device for pre-1966 vehicles since it has the same annual cost as the CDIOS but produces slightly less reduction in both RHC and NO_x emissions. It is a fairly close substitute for the CDIOS, however, and might be used as a control measure especially if the control authority is concerned more with initial cost (the CDIOS has a \$40 initial cost).

(ii) Thermal Reactors

Thermal reactors can produce very high reductions in RHC exhaust emissions (Downing and Stoddard, 1970). This control method is not included in this study, however, since thermal reactors need further technical development and are not considered technically feasible as retrofit devices by 1975. (In order to be retrofitted by 1975 they would have to be in production by 1973.) (Brattain, 1971), (Hass, Dec. 1971).

(iii) Catalytic Reactors

Catalytic reactors also are a very effective control possibility for RHC (Downing and Stoddard, 1970). However, they suffer from the same technical feasibility problem as do thermal reactors (Brattain, 1971), (Hass, Dec. 1971). For this reason, they are not considered here as viable control devices.

16. Source # 16: Pre-1966 Motor Vehicles, Evaporative Emissions

Description

(See source # 15.) The source unit is one pre-1966 vehicle.

Source Magnitude, 1975

(See source # 15.)

$S_{16} = 1,100,000$

Emissions

From Table A-I, the average evaporative emissions of RHC per vehicle are .14 lb/day or 7.0×10^{-5} tons/day. Thus,

RHC	NO _x
$e_{116} = 7.0 \times 10^{-5}$ tons/day	$e_{216} = 0$
$S_{16}e_{116} = 77$ tons/day	$S_{16}e_{216} = 0$

Control Methods for Source # 16Control Method # 22: Evaporative Control Device Retrofit on Pre-1966 VehiclesDescription

Control X_{22} consists of retrofitting the evaporative control device developed for 1970 and later new vehicles to pre-1966 vehicles. Such a system would require fuel tank modification or replacement, a charcoal storage canister, special valves and piping, and some modifications on the carburetor (Downing and Stoddard, 1970), (Agnew, 1969). The control unit is addition of one evaporative control device to one pre-1966 vehicle.

Emission Reduction

Assuming these devices are 85% effective, the .14 lb/day RHC emissions per vehicle are reduced .12 lb/day or 6.0×10^{-5} tons/day.

Thus,

$B_{1\ 22} = 6.0 \times 10^{-5}$ tons/day	$B_{2\ 22} = 0$
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Cost

Estimates for initial and maintenance costs of an evaporative control retrofit device have been developed by Downing and Stoddard, (1970). Initial cost is around \$150 and maintenance cost is around \$10 per year. The device prevents loss of .19 lb/day of gasoline (total HC). Using a \$.15/gallon price, the fuel savings amount to less than \$2 per year. Total cost terms are

	Annual Cost
Initial Cost: \$150	
$i = 10\%$, lifetime = 2.5 yrs. (Table A-I)	\$70
Maintenance Cost	10
Fuel Savings	- 2
Total Annual Cost per Control Unit	$C_{22} = \$78$

Since each control unit reduces RHC emissions by 6×10^{-5} tons/day or 2.2×10^{-2} tons/year, the cost per ton of RHC controlled is \$3,500 per ton.

Other Control Parameters

Each unit of control X_{22} applies to one unit of source # 16 and to no other sources. Thus,

$$\begin{aligned} A_{16\ 22} &= 1 \\ A_{i\ 22} &= 0 \quad i \neq 16 \end{aligned}$$

No limited supply inputs are used by control X_{22} . Thus,

$$D_{1\ 22} = 0$$

17. Source # 17: 1966-1969 Model Motor Vehicles, Exhaust Emissions

Description

This source category consists of gasoline-powered motor vehicles of model years 1966-1969. The source unit is one 1966-1969 vehicle. The number, usage, expected life, and emission rate of these vehicles are summarized in Table A-I. It is assumed that 1966-1969 vehicles are completely controlled for crankcase emissions and 10% over the state standard for exhaust HC emissions. Exhaust emissions are considered in this section; evaporative emissions are source # 18.

Source Magnitude, 1975

From Table A-I, 30% of the total motor vehicle population of 4,600,000 vehicles in 1975 is made up of model years 1966-1969. Thus,

$$S_{17} = 1,380,000$$

Emissions

From Table A-I, the average usage of 1966-1969 vehicles is 15.7 miles/day, and exhaust emissions rates are 2.7 gm/mile RHC and 6 gm/mile NO_x . Thus, emissions per source unit are .094 lb/day = 4.7×10^{-5} tons/day RHC and .208 lb/day = 10.4×10^{-5} tons/day NO_x . Thus,

RHC	NO_x
$e_{17} = 4.7 \times 10^{-5}$ tons/day	$e_{27} = 10.4 \times 10^{-5}$ tons/day
$S_{17}e_{17} = 65$ tons/day	$S_{17}e_{27} = 143$ tons/day

Control Methods for Source # 17

Control Method # 23: Capacitor Discharge, Ignition Optimization System (CDIOS) for 1966-1969 Vehicles

Description

Control X_{23} is the same system as control X_{20} for pre-1966 vehicles (see control method # 20). The control unit is one CDIOS device to one 1966-1969 vehicle.

Emission Reduction

In 1966-1969 vehicles, the CDIOS control reduces HC emissions by around 10% and NO_x by around 55% (Upton, Dec. 1971). It is assumed that RHC emissions are controlled in proportion to HC emissions. Since each vehicle emits 4.7×10^{-5} tons/day RHC and 10.4×10^{-5} tons/day NO_x , the emission reductions are as follows:

$$B_{1\ 23} = 4.7 \times 10^{-6} \text{ tons/day} \quad B_{2\ 23} = 5.7 \times 10^{-5} \text{ tons/day}$$

Cost

As noted with control method # 20, the initial cost of one CDIOS unit is \$40; there are no maintenance, fuel economy, or performance costs, and a \$10 per year operating savings is realized from less frequent tune-ups. Thus,

	Annual Cost
Initial Cost: \$40	
$i = 10\%$, lifetime = 4.7 years (Table A-I)	\$11
Operating Cost	- 10
Total Annual Cost Per Control Unit	$C_{23} = \$1$

Since each unit reduces RHC emissions by .0017 tons/year and NO_x emissions by .021 tons/year, the cost per ton controlled is \$590 per ton RHC and \$48 per ton NO_x .

Other Control Parameters

Each unit of control X_{23} applies to one unit of source # 17. Thus,

$$A_{17 \ 23} = 1$$

$$A_{i \ 23} = 0 \quad i \neq 17$$

No limited supply inputs are considered by control X_{23} . Thus,

$$D_{1 \ 23} = 0$$

Control Method # 24: Vacuum Spark Advance Disconnect and Tuning Adjustment ("GM Smog Package") for 1966-1969 Vehicles

Description

Control X_{24} consists of disconnecting the vacuum spark advance and adjusting the engine timing and carburetion on 1966-1969 vehicles. Such a control system has been developed by General Motors, Detroit, Michigan, and has been called the "smog package". The control unit is one "smog package" device for one 1966-1969 vehicle.

Emission Reduction

In 1966-1969 vehicles, the smog package reduces HC and NO_x emissions by around 30% and 40%, respectively (Hass, Nov. 1971), (Heitner, Dec. 1971), (Postma, Dec. 1971). Since each vehicle emits around 4.7×10^{-5} tons/day RHC and 10.4×10^{-5} tons/day NO_x , the emission reductions per control unit are

$$B_{1\ 24} = 1.4 \times 10^{-5} \text{ tons/day} \quad B_{2\ 24} = 4.2 \times 10^{-5} \text{ tons/day}$$

Cost

The initial installed cost of the "smog package" is around \$20. There are no significant maintenance or operating costs (Postma, Dec. 1971). Thus,

Initial Cost: \$20

$i = 10\%$, lifetime = 4.7 yrs. (Table A-I)

Total Annual Cost Per Control Unit

Annual Cost

\$6

$C_{24} = \$6$

Since each control unit reduces RHC emissions by 5.1×10^{-3} tons/year and NO_x emissions by 1.53×10^{-2} tons/year, the cost per ton controlled is \$1,170 per ton RHC and \$390 per ton NO_x .

Other Control Parameters

Each unit of control X_{24} applies to one unit of source # 17. Thus,

$$A_{17\ 24} = 1$$

$$A_{i\ 24} = 0 \quad i \neq 17$$

No limited supply inputs are consumed. Thus,

$$D_{1\ 24} = 0$$

Other Control Methods for Source # 17(i) Exhaust Gas Recirculation (EGR) and Controlled Spark Retard (CSR)

The Dana Corporation EGR and CSR device is a possible control method for 1966-1969 vehicles. This device is described in control method # 21 for source # 15. It is ruled out here because it produces about the same emission reductions as the CDIOS device but costs considerably more (\$30 per year compared to \$1 per year for the CDIOS).

(ii) Thermal Reactors

See source # 15.

(iii) Catalytic Reactors

See source # 15.

18. Source # 18: 1966-1969 Model Motor Vehicles, Evaporative Emissions

Description

(See source # 17.) The source unit is one 1966-1969 vehicle.

Source Magnitude, 1975

(See source # 17.)

$S_{18} = 1,380,000$

Emissions

From Table A-I, the average evaporative emissions of RHC per 1966-1969 vehicle are .14 lb/day or 7.0×10^{-5} tons/day. Thus,

RHC	NO _x
$e_{1\ 18} = 7.0 \times 10^{-5}$ tons/day	$e_{2\ 18} = 0$
$S_{18}e_{1\ 18} = 97$ tons/day	$S_{18}e_{2\ 18} = 0$

Control Methods for Source # 18Control Method # 25: Evaporative Control Device Retrofit on 1966-1969 Motor VehiclesDescription

Control X_{25} is the same system as control X_{22} for pre-1966 vehicles (see control method # 22). The control unit is addition of one evaporative control device to one 1966-1969 vehicle.

Emission Reduction

Assuming the evaporative control device is 85% effective, the .14 lb/day RHC emissions per vehicle are reduced .12 lb/day or 6.0×10^{-5} tons/day. Thus,

$$B_{125} = 6.0 \times 10^{-5} \text{ tons/day} \quad B_{225} = 0$$

Cost

As calculated by Downing and Stoddard, (1970), the initial cost of an evaporative control retrofit is around \$150, and maintenance cost amounts to around \$10 per year. Fuel savings are around \$2 per year. Thus,

	Annual Cost
Initial Cost: \$150	
$i = 10\%$, lifetime = 4.7 yrs (see Table A-I)	\$42
Maintenance Cost	10
Fuel Savings	- 2
Total Annual Cost per Control Unit	$C_{25} = \$50$

Since each control unit reduces RHC emissions by 6.0×10^{-5} tons/day or 2.2×10^{-2} tons/year, the cost per ton of RHC controlled is \$2,300 per ton.

Other Control Parameters

Each unit of control X_{25} applies to one unit of source # 18. Thus,

$$\begin{array}{l} A_{18\ 25} = 1 \\ A_{i\ 25} = 0 \quad i \neq 18 \end{array}$$

Control X_{25} consumes no limited supply inputs. Thus,

$$D_{i\ 25} = 0$$

19. Source # 19: 1970 Model Motor Vehicles

Description

This source category consists of 1970 model year motor vehicles. The number, mileage, expected life and emission rate of these cars is given in Table A-I, page A-99 . 1970 vehicles are well controlled for hydrocarbons, both exhaust HC and evaporative HC. Most, however, have no NO_x control and have rather high NO_x emission rates. The source unit is one 1970 motor vehicle.

Source Magnitude, 1975

From Table A-I, 8.5% of the 4,600,000 gasoline powered motor vehicles in Los Angeles County in 1975 will be of model year 1970. Thus,

$S_{19} = 390,000$

Emissions

1970 vehicles emit .02 lb/day RHC from evaporation and 1.6 gm/mile RHC and 6 gm/mile NO_x in the exhaust. Since they are driven, on the average, about 23 miles/day in 1975 (Table A-I), total emissions are .10 lb/day = 5.0×10^{-5} tons/day RHC and .30 lb/day = 1.5×10^{-4} tons/day NO_x . Thus,

RHC	NO_x
$e_{119} = 5.0 \times 10^{-5}$ tons/day	$e_{219} = 1.5 \times 10^{-4}$ tons/day
$S_{19}e_{119} = 20$ tons/day	$S_{19}e_{219} = 58$ tons/day

Control Methods for Source # 19Control Method # 26: Capacitor Discharge, Ignition Optimization System on 1970 Motor VehiclesDescription

This is the same system that is applied to pre-1966 and 1966-1969 vehicles as control methods # 21 and # 23 (see control method # 21). The control unit is one CDIOS to one 1970 year vehicle.

Emission Reduction

In 1970 vehicles the CDIOS device reduces NO_x by about 55% and has little effect on RHC (Upton, Dec. 1971). Since each car emits 1.5×10^{-4} tons/day NO_x , the emission reduction per control unit is

$B_{1\ 26} = 0$	$B_{2\ 26} = 8.7 \times 10^{-5}$ tons/day
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Cost

As discussed under control method # 21, the initial cost of one CDIOS device is \$40 and there is an annual maintenance savings of around \$10. Thus,

	Annual Cost
Initial Cost: \$40	
$i = 10\%$, lifetime = 6.3 yrs. (Table A-I)	\$9
Maintenance	- 10
Total Annual Cost per Control Unit	$C_{26} = \text{Negl.}$

Other Control Parameters

Each unit of control X_{26} applies to one unit of source # 19. Thus,

$$\begin{array}{l} A_{19\ 26} = 1 \\ A_{i\ 26} = 0 \quad i \neq 19 \end{array}$$

No limit supply inputs are assumed. Thus,

$$D_{1\ 26} = 0$$

Other Control Methods for Source # 19(i) Vacuum Spark Advance Disconnect

A simple vacuum spark advance disconnect device (part of the GM "smog package") is a possible form of NO_x control for 1970 vehicles. However, it cost more than the CDIOS unit (\$5 per year vs negligible cost for the CDIOS) and produces slightly less emission reduction. It is, thus, ruled out as inferior to the CDIOS device.

(ii) Exhaust Gas Recirculation and Controlled Spark Retard (Dana Corporation Device)

See source # 17.

(iii) Thermal Reactors

See source # 15.

(iv) Catalytic Reactors

See source # 15.

20. Source # 20: 1971-1974 Model Year Fleet Vehicles Suitable for Conversion to Gaseous Fuels

Description

This source category consists of fleet vehicles suitable for conversion to gaseous fuels (natural gas, NG, or liquid petroleum gas, LPG).^{*} In 1975, nearly all fleet vehicles will be of model years 1971 to 1974 (Bonamasa, Dec. 1971), (Bintz, Dec. 1971). To simplify the analysis, it is assumed here that all the fleet vehicles are of these model years.^{**}

The source unit is one fleet vehicle. The existing degree of control for this source is as required by the California standards for new vehicles given in Table A-I. This includes blowby and evaporative control for HC and exhaust control for HC and NO_x. Actually, about half of these fleet vehicles are heavier trucks with slightly less restrictive emission standards than listed in Table A-I (Bintz, Dec. 1971). This will be accounted for in estimating average emissions from this source.

Source Magnitude, 1975

The Automobile Club of Southern California estimates that 7-8% of the total vehicle population (4,600,000 in 1975) is contained in fleets suitable for gaseous fuel conversion (Bintz, Dec. 1971). Bonamasa,

* The suitability requirement is that the fleet refuels at a central filling station as opposed to a "credit card fleet".

** Since 1971-1974 vehicles are the best controlled of pre-1975 vehicles, this assumption yields a conservative estimate of the emissions from these vehicles and of the emission reduction from their control.

(Dec. 1971),(California ARB) estimates 5-10%. Here it is assumed that 7.5% of the vehicle population (345,000) is contained in source # 20.

Thus,

$S_{20} = 345,000$

Emissions

From Table A-I the average vehicle is driven 22 miles/day and the average 1971-1974 vehicle is driven 34 miles/day. Fleet vehicles tend to be, on the average, more intensively used than non-fleet vehicles.* It is assumed here that they have an average usage of 50 miles per day.

Evaporative emissions from the fleet vehicles are assumed to be the same as the average for all 1971-1974 vehicles, .02 lbs/day RHC (Table A-I). Average exhaust emission calculations for fleet vehicles are complicated by the different standards for heavy-duty trucks ($\geq 6,000$ lb. gross weight) vs. light duty vehicles. These state standards are given in Table A-II below.

Assuming the fleet vehicle population is about half heavy duty and half light duty vehicles (Bintz, Dec. 1971), the average exhaust emission rates for fleet vehicles in 1975 is 1.6 gm./mile RHC and 3.4 gm./mile NO_x (Table A-II). With the assumed average usage of 50 miles/day, exhaust emissions are .176 lb./day RHC and .374 lb./day NO_x . Adding evaporative RHC emissions, the total emissions for each fleet vehicle are .196 lb/day = 9.8×10^{-5} tons/day RHC and 1.9×10^{-4} tons/day

* Bintz, (Dec. 1971), estimates that the upper 10% of most driven vehicles, mostly fleets, consumes 30% of the total gasoline.

NO_x. Thus,

RHC	NO _x
$e_{120} = 9.8 \times 10^{-5}$ tons/day	$e_{220} = 1.9 \times 10^{-4}$ tons/day
$S_{20}e_{120} = 34$ tons/day	$S_{20}e_{220} = 65$ tons/day

Table A-II Exhaust Emissions from Heavy-Duty Trucks

Model Year	State Standards*				Assumed Emission Rates**			
	light-duty		heavy-duty		light-duty		heavy-duty	
	THC (gm/mile)	NO _x (gm/mile)	THC (ppm)	NO _x (gm/mile)	RHC (gm/mile)	NO _x (gm/mile)	RHC (gm/mile)	NO _x (gm/mile)
1974	1.5	1.3	180	-	1.1	1.3	1.7	4
1973	1.5	3	180	-	1.1	3	1.7	4
1972	1.5	3	180	-	1.1	3	1.7	4
1971	2.2	4	275	-	1.6	4	2.6	4

* ARB Implementation Plan, (1971).

** Assuming standard are met, exhaust emissions are 75% reactive, 80 ppm HC = 1.0 gm/mile, and NO_x emissions are 4 gm/mile for heavy-duty vehicles (ARB Implementation Plan, 1971), (APCD Profile, 1971), (Downing and Stoddard, 1970).

Control Methods for Source # 20Control Method # 27: Conversion of Fleet Vehicles to Operate on Natural GasDescription

Control X₂₇ consists of converting the 1971-1974 fleet vehicles to operate on natural gas* and tuning for low emissions. The main components of the conversion system for the vehicles are an air-fuel mixer mounted on the carburetor, a series of regulators and valves to control fuel delivery, hoses and fittings, and a tanking system. A refueling station is also needed. Tuning for low emission consists essentially of operating at very high excess air levels (~ 25% excess air). These are described in more detail in reports by (McJones and Corbell, 1970) and (Caltech Clean Air Project, 1971). The control unit is conversion of one fleet vehicle to operate on natural gas.

Emission Reduction

Evaporative RHC emissions are almost completely eliminated by conversion to natural gas. Natural gas is nearly all methane, photochemically non-reactive, and thus even the slight amounts of gas that do escape are non-reactive. The .02 lb/day evaporative RHC emission is assumed completely eliminated.

By conversion to natural gas and tuning for low emissions, exhaust emissions for the average fleet vehicle (average of light and heavy-duty

* For more convenient operation the vehicles may also be converted to a dual-fuel (gasoline and natural gas) system.

vehicles) are reduced to about .65 gm/mile THC and .55 gm/mile NO_x . Without tuning for low emissions, emissions can average as high as 1.2 gm/mile THC and 2.0 gm/mile NO_x (Caltech Clean Air Project, 1971). Tuning for low emissions is assumed to be part of control method X_{27} . However, to be slightly conservative, it is assumed here that control method X_{27} reduces exhaust emissions to .8 gm/mile THC and .8 gm/mile NO_x . Natural gas exhaust emissions are less than 10-15% reactive (Heitner, Dec. 1971), (Dickinson, Dec. 1971). Thus, exhaust emission rates on natural gas are assumed to be .1 gm/mile RHC and .8 gm/mile NO_x .

Since there are no evaporative RHC emissions and since the vehicles are assumed to average 50 miles/day, total vehicle emissions with control X_{27} are .011 lb/day = 5.5×10^{-5} tons/day RHC and .077 lb/day = 3.9×10^{-5} tons/day NO_x . The reduction in emissions per vehicle is, thus, 9.2×10^{-5} tons/day RHC and 1.5×10^{-4} tons/day NO_x . This is a 94% reduction in RHC emissions and a 79% reduction in NO_x emissions. Thus,

$B_{1\ 27} = 9.2 \times 10^{-5}$ tons/day $B_{2\ 27} = 1.5 \times 10^{-4}$ tons/day

Cost

The initial cost for the conversion equipment, tankage, and installation for one fleet vehicle is about \$400-\$550 (Caltech Clean Air Project, 1971). A \$500 cost is used here. For the average size fleet (around 100 vehicles), the initial investment in a fueling station is around \$20,000 or \$200 per vehicle. Total initial cost for one unit of control X_{27} is thus around \$700.

To the user of the vehicle there is a considerable savings on fuel cost. Gasoline costs about 23¢ per gallon to fleet operator with his own refueling station. Natural gas costs about 6¢ per gallon equivalent (90 cu. ft.), (Clean Air Car Project, 1971). However, most of the 17¢ per gallon savings to the operator results from the tax exempt status of natural gas. Gasoline in 1971 has an 11¢/gal. tax (4¢ - Federal, 7¢ - State). Since this study is concerned with the total resource cost to society, the relevant prices for natural gas and gasoline are 6¢/gal. equivalent and 12¢/gal., respectively. This is still a considerable savings. However, the price of natural gas is held artificially low by the Federal Power Commission (F.P.C.) regulations on the well-head price. As a result, demand exceeds supply, and natural gas must be rationed (Liverstidge, 1969), (Nevitt, Nov. 1971). Some observers think that the base price for natural gas in large quantities (about 3.5¢/equiv. gal.) may more than double if the F.P.C. price restrictions were lifted (Nevitt, Nov. 1971). Here, to account for the artificially low price of natural gas, it is arbitrarily assumed that 9¢/gal. rather than 6¢/gal. is the cost of natural gas burned in fleet vehicles. With this price the fuel savings of burning natural gas in fleet vehicles is 3¢/gal. (9¢/gal. equiv. - NG, 12¢/gal.-gasoline). Assuming the average fleet vehicle drives 50 miles/day at 12 miles/gal. this amounts to a savings of \$43 per year.

There is some performance loss in converting to natural gas as a fuel. About a 10-15% loss in power occurs (McJones and Corbell, 1970). It is assumed that this power loss will not be highly objectionable

to the fleet operators, and no monetary cost allowance is made for performance loss.

Because natural gas is a clean-burning fuel, its use in internal combustion engines leads to considerable maintenance savings. The life of motor oil, spark plugs, and the engine itself are increased considerably. The maintenance savings on the average fleet vehicle is around \$40 per year (Caltech Clean Air Car Project, 1971).

The cost are summarized in the table below:

	Annual Cost
Initial Cost: \$700	
10 yr. lifetime, $i = 10\%$	\$113
Fuel Savings	- 43
Performance Loss	neglected
Maintenance Costs	- 40
Annual Cost per Control Unit	$C_{27} = \$30$

Since each control unit removes .034 tons/year RHC and .055 tons/year NO_x , the cost per ton controlled is \$880 per ton RHC and \$550 per ton NO_x .

Other Control Parameters

Each unit of control X_{27} applies to one unit of source # 20. Thus,

$$\begin{aligned} A_{20\ 27} &= 1 \\ A_{i\ 27} &= 0, \quad i \neq 20 \end{aligned}$$

Each unit of control X_{27} consumes 360 cu. ft. of gas per day (4 eq. gal./day \times 90 cu. ft./eq. gal.) or 135,000 cu. ft. per year. Since 6,000

cu. ft. = 1 equiv. barrel, one unit of control X_{27} uses 22.5 equiv. barrels per year. Thus,

$$D_{1\ 27} = 22.5 \text{ eq. bbls./year}$$

$$D_{2\ 27} = 0$$

Control Method # 28: Conversion of Fleet Vehicles to Operate on Liquid Petroleum Gas (LPG)

Description

Control X₂₈ consists of converting the 1971-1974 fleet vehicles to operate on liquid petroleum gas (mostly propane)* and tuning them for low emissions. The components of the conversion system are similar to those for natural gas conversion: an air-fuel mixer, regulators and valves, hoses and fittings, a tanking system, and a refueling station. Tuning for low emissions again is essentially high excess air operation (~25% excess air). A more detailed description of the system can be found in the Caltech Clean Air Car Project Gaseous Fuels Manual, (1971). The control unit is conversion of one fleet vehicle to operate on LPG.

Emission Reduction

Evaporative emissions (.021 lb/day RHC) are assumed here to be completely eliminated by conversion to LPG. Exhaust emissions, by conversion to LPG and tuning for low emissions, are reduced for the average fleet vehicle to about .6 gm/mile total HC and .65 gm/mile NO_x. Without low emission tuning, emissions can average as high as 1.3 gm/mile THC and 2.5 gm/mile NO_x (Caltech Clean Air Car Project, 1971). Tuning for low emissions is assumed in control X₂₈, but to be slightly conservative, emissions on LPG are here assumed to be .8 gm/mile THC and 1.0 gm/mile NO_x. LPG exhaust emissions are approximately 40% reactive (Heitner, Dec. 1971), (Dickinson, Dec. 1971). Thus

* As with natural gas conversion, the vehicles may be fitted with a dual-fuel (LPG-gasoline) system for more convenient operation.

emission rates with control X_{28} are .32 gm/mile RHC and 1.0 gm/mile NO_x .

Since it has been assumed that there are no evaporative RHC emissions and since the vehicles average 50 miles/day, total emissions with control X_{28} are .035 lb/day = 1.8×10^{-5} tons/day RHC and .011 lb/day = 5.5×10^{-5} tons/day NO_x . The reduction in emissions per vehicle is thus 8.0×10^{-5} tons/day RHC and 1.3×10^{-4} tons/day NO_x . This amounts to an 82% reduction in RHC emissions and 70% reduction in NO_x emissions. Thus,

$$B_{1\ 28} = 8.0 \times 10^{-5} \text{ tons/day} \quad B_{2\ 28} = 1.3 \times 10^{-4} \text{ tons/day}$$

Cost

As with natural gas conversion, the equipment on each fleet vehicle costs around \$500 installed. The cost of the fueling station is less than for natural gas, about \$10,000 (Heitner, Dec. 1971). Assuming an average fleet size of 100 vehicles, the fueling station costs around \$100 per vehicle. Total initial cost for one unit of control X_{28} is thus \$600.

To the fleet operator, there is some savings in fuel cost. Gasoline costs around 23¢/gal. and LPG costs about 18¢/gal. However, gasoline has an 11¢ tax (state and federal), while LPG has only a 4¢ tax (federal) (Caltech Clean Air Car Project, 1971). Since this study is concerned with resource cost, the tax must be subtracted. This leaves the prices at 12¢/gal. for gasoline and 14¢/gal. for LPG. Also, 1 gal. of gasoline is equivalent to 1.2 gal. of LPG. Thus on an equivalent

gallon of gasoline basis, the fuel costs are 12¢/gal. for gasoline and 17¢/eq. gal. for LPG. Thus, there is a fuel savings loss of 5¢/gal. using LPG, which for the average fleet vehicle driving 50 miles/day at 12 miles/gal. is \$73 per year.

There is a slight performance loss in using LPG; power is slightly less than on gasoline. No monetary cost allowance is made for this loss, however.

As with natural gas, there is a maintenance savings due to increased motor oil, spark plug, and engine life. This averages around \$40 per year (Caltech Clean Air Car Project, 1971).

The costs are summarized in the table below:

	Annual Cost
Initial Cost: \$600	
$i = 10\%$, lifetime = 10 yrs.	\$ 97
Extra Fuel Cost	73
Performance Loss	neglected
Maintenance Cost	- 40
Annual Cost per Control Unit	$C_{28} = \$130$

Since each control unit removes .029 tons/year RHC and .048 tons/year NO_x , the cost per ton controlled is \$4,500 per ton RHC and \$2,700 per ton NO_x .

Other Control Parameters

Each unit of control X_{28} applies to one unit of source # 20. Thus,

$A_{20\ 28} = 1$
$A_{i\ 28} = 0 \quad i \neq 20$

None of the limited supply input, natural gas, is used by control X_{28} . Thus,

$$D_{1 \ 28} = 0$$

21. Source # 21: Jet Aircraft - JT8D Engines

Description

This source category consists of flights (landings and takeoffs) of jet aircraft with JT8D engines. These engines are used on Boeing 727, Boeing 737, and Douglas DC-9 aircraft and account for 36% of the jet engine flights at Los Angeles International Airport (LAX), (George and Nevitt, 1971), (George, et al., 1971). The source unit is one JT8D engine used in Los Angeles County.

Jet engines are a source of both RHC and NO_x . Control of JT8D has already been initiated in 1971 because of federal regulations on aircraft emissions (APCD Profile, 1971). However, it is assumed here that JT8D engines have no control initially, so that the cost/effectiveness of this control can be examined.

Source Magnitude, 1975

From the results of an APCD survey (George and Nevitt, 1971) there were around 2,500 JT8D engines being used on aircraft flying in Los Angeles County in 1971. It is assumed that this number will remain constant until 1975. Thus,

$S_{21} = 2,500$

Emissions

An APCD study of the number of engine flights and of emission rates for jet engines determined that around 38 tons/day total HC and 2.4 tons/day NO_x are emitted by JT8D engines at L.A.X. (George, et al., 1971). Since L.A.X. accounts for about 80% of the jet engine

flights in Los Angeles County (APCD Profile, 1971), approximately 48 tons/day total HC and 3 tons/day NO_x are emitted from JT8D engines in all of Los Angeles County. Total HC from jet engines are about 30% RHC.* Thus, total Los Angeles County emissions from JT8D engines are 14 tons/day RHC and 3 tons/day NO_x . This amounts to 5.6×10^{-3} tons/day RHC and 1.2×10^{-3} tons/day NO_x per engine. Thus,

RHC	NO_x
$e_{1\ 21} = 5.6 \times 10^{-3}$ tons/day	$e_{2\ 21} = 1.2 \times 10^{-3}$ tons/day
$S_{21}e_{1\ 21} = 14$ tons/day	$S_{21}e_{2\ 21} = 3$ tons/day

* This was calculated with data from the 1971 APCD Profile on total aircraft THC and RHC, and jet and piston engine THC by assuming piston THC was 70% reactive, i. e., similar to automobiles.

Control Methods for Source # 21Control Method # 29: Combustion Chamber Redesign for JT8D EnginesDescription

This control method consists of modifying the combustion chamber on JT8D engines to reroute the air flow within the engine so as to promote better mixing and longer retention of the combusting gases and thus attain more complete burning (Pittman, July 1971), (Bastress et al., 1971). This method controls HC and particulates very effectively but at best holds NO_x constant (George, et al., 1969). The control unit is redesign of the combustion chamber on one JT8D engine.

Emission Reduction

George, et al., (1969) found that modified combustion chamber control on JT8D engines reduced total HC by 99% and increased NO_x by 40%. Other investigators indicate slightly less HC control and no NO_x emission increase (Nevitt, Aug. 1971). Here it is assumed that combustion chamber redesign is 95% effective for RHC and results in a 20% increase in NO_x emissions. Since each engine emits 5.6×10^{-3} tons/day RHC and 1.2×10^{-3} tons/day NO_x , the emission reductions per control unit are

$B_{1\ 29} = 5.3 \times 10^{-3} \text{ tons/day}$	$B_{2\ 29} = -2.4 \times 10^{-4} \text{ tons/day}$
---	--

Cost

Bastress, et al., 1971 estimated a total annual cost of around \$4000 per engine for modified combustion chamber control on JT8D engines. This included development (engineering, testing, design, and

procurement) and implementation (capital, installation, and lost service life) costs. This cost result is used here. Thus,

$$C_{29} = \$4,000$$

Since each control unit reduces RHC by 1.9 tons/year and NO_x by -.088 tons/year (actually an increase), the cost per ton controlled is \$2,100 per ton RHC and -\$45,000 per ton NO_x .

Other Control Parameters

Each unit of control X_{29} applies to one unit of source # 21. Thus,

$$\begin{aligned} A_{21\ 29} &= 1 \\ A_{i\ 29} &= 0 \quad i \neq 21 \end{aligned}$$

No limited supply inputs are consumed. Thus,

$$D_{i\ 29} = 0$$

22. Source # 22: Jet Aircraft - Other Engines

Description

This source category consists of flights (landings and takeoffs) of jet aircraft with other than JT8D engines. These engines consist mostly of JT3D engines (Boeing 707, Boeing 720, and Douglas DC-8 planes) and include JT4A, JT9D, JT3C-6, JT3C-7, CJ805, 501-D, and Conway engines (George and Nevitt, 1971). The source unit is one non-JT8D jet engine.

Source Magnitude, 1975

An APCD survey indicates that there were around 2,900 non-JT8D engines used on jet aircraft making flights in Los Angeles County in 1971. It is assumed this number will remain constant until 1975. Thus,

$$S_{22} = 2,900$$

Emissions

An APCD study of the number of engine flights and of emission rates for jet engines determined that around 10.5 tons/day total HC and 4 tons/day NO_x are emitted by non-JT8D jet engines at L.A.X. (George, et al., 1971). Since L.A.X. accounts for around 80% of the jet engine flights in Los Angeles County (APCD Profile, 1971), approximately 13 tons/day total HC and 5 tons/day NO_x are emitted by non-JT8D jet engines in all Los Angeles County. Total HC from jet engines are about 30% reactive HC.* Thus, total Los Angeles County emissions from non-

*See source # 21.

JT8D jet engines are 4 tons/day RHC and 5 tons/day NO_x . This amounts to 1.4×10^{-3} tons/day RHC and 1.7×10^{-3} tons/day NO_x per engine.

Thus,

RHC	NO_x
$e_{122} = 1.4 \times 10^{-3}$ tons/day	$e_{222} = 1.7 \times 10^{-3}$ tons/day
$S_{22}e_{122} = 4$ tons/day	$S_{22}e_{222} = 5$ tons/day

Control Methods for Source # 22

Control Method # 30: Combustion Chamber Redesign for Non-JT8D Jet Engines

Description

This control method is the same as control X_{28} for JT8D engines. The control unit is redesign of the combustion chamber on one non-JT8D engine.

Emission Reduction

As with JT8D engines it is assumed that the combustion chamber modifications control RHC by 95% and increase NO_x by 20%. Since each engine emits 1.4×10^{-3} tons/day RHC and 1.7×10^{-3} tons/day NO_x , the emission reductions per control unit are

$$B_{130} = 1.3 \times 10^{-3} \text{ tons/day} \quad B_{230} = -3.4 \times 10^{-4} \text{ tons/day}$$

Cost

It is assumed that the Bastress, et al., (1971) estimate of \$4,000 annual cost for JT8D engines also holds for non-JT8D engines. Thus,

$$C_{30} = \$4,000$$

Since each control unit reduces RHC by .50 tons/year and increases NO_x by .12 tons/year, the cost per ton controlled is \$8,000 per ton RHC and -\$33,000 per ton NO_x .

Other Control Parameters

Each unit of control X_{30} applies to one unit of source # 22. Thus,

$$\begin{aligned} A_{22\ 30} &= 1 \\ A_{i\ 30} &= 0 \quad i \neq 22 \end{aligned}$$

No limited supply inputs are used. Thus,

$$D_{i\ 30} = 0$$

23. Source # 23: Piston Aircraft Engines

Description

This source category consists of all piston aircraft engines registered in Los Angeles County. Engines for both rotorcraft and fixed winged aircraft and for both large commercial aircraft and light planes are included. These engines are a source of both RHC and NO_x . The source unit is one piston aircraft engine. There is no existing RHC or NO_x control for these engines.

Source Magnitude, 1975

The Federal Aviation Authority (F.A.A.) Western Region Air Traffic Division data supplied for Los Angeles County in February, 1971 indicated that 4,710 aircraft were registered in Los Angeles County at that time (Hubert, Dec. 1971). From data in the 1970 F.A.A. Statistical Handbook, it appears that around 4,400 of these aircraft were piston driven (Hubert, Dec. 1971). Assuming a 5% growth rate in piston aircraft until 1975, around 5,400 piston airplanes will be registered in Los Angeles County then. F.A.A. 1970 Statistical Handbook data reveals that piston aircraft average around 1.3 engines per plane. Thus, about 7,000 piston aircraft engines will be registered in Los Angeles County in 1975. Thus,

$S_{23} = 7,000$

Emissions

In 1971 piston aircraft emitted 19 tons/day total HC and 5 tons/day NO_x . Assuming total HC from piston aircraft is 75% reactive (equivalent

to motor vehicle emissions), 14 tons/day RHC and 5 tons/day NO_x were emitted. Assuming 5% growth until 1975, 17 tons/day RHC and 6 tons/day NO_x will be emitted in 1975. However, not all emissions from piston aircraft in Los Angeles County result from those actually registered in Los Angeles County. It is arbitrarily assumed here that 70% of piston aircraft emissions result from piston aircraft registered in Los Angeles County. Thus, the piston aircraft registered in Los Angeles County will emit around 12 tons/day RHC and 4.2 tons/day NO_x in 1975. This amounts to 1.7×10^{-3} tons/day RHC and 6.0×10^{-4} tons/day NO_x per engine. Thus,

RHC	NO_x
$e_{1\ 23} = 1.7 \times 10^{-3}$ tons/day	$e_{2\ 23} = 6.0 \times 10^{-4}$ tons/day
$S_{23}e_{1\ 23} = 12$ tons/day	$S_{23}e_{2\ 23} = 4$ tons/day

Control Methods for Source # 23

Control Method # 31: Afterburners (Thermal, Catalytic, or Direct-Flame) on Piston Aircraft Engines

Description

Control method X_{31} consists of adding afterburners to the piston aircraft engines to control hydrocarbon emissions. These afterburners can be either thermal reactors, catalytic reactors, or direct-flame afterburners. They are described in detail in Bastress, et al., 1971. The control unit is one afterburner on one piston aircraft engine.

All three types of afterburners are included in one control method because estimates of cost and effectiveness are approximately the same for all. They all will require further development. This would take from $2\frac{1}{2}$ -6 years (Bastress, et al., 1971). Since aircraft engines have rather long lives and since there are relatively few engines so that implementation will not take a long time after development is completed, afterburner control is considered here for 1975. (Afterburner control was not considered for used vehicles because of their shorter expected life and because of a greater implementation period.)

Emission Reduction

Although direct flame afterburners are probably slightly more effective than catalytic or thermal reactors, it is assumed here that all three types of afterburners reduce RHC emissions by 75% (Bastress, et al., 1971). There is no effect on NO_x emissions. Since the average engine emits 1.7×10^{-3} tons/day RHC, the emission reduction per

control unit is 1.3×10^{-3} tons/day. Thus,

$$B_{1\ 31} = 1.3 \times 10^{-3} \text{ tons/day} \quad B_{2\ 31} = 0$$

Cost

Bastress, et al., (1971), have calculated that the total annual cost (development, implementation, and operating costs) for all three types of afterburners is around \$350 per year, per engine. Thus,

$$C_{31} = \$350$$

Since each control unit reduces RHC emissions by .48 tons/year, the cost per ton controlled is \$730 per ton RHC.

Other Control Parameters

Each unit of control X_{31} applies to one unit of source # 23. Thus,

$$\begin{aligned} A_{23\ 31} &= 1 \\ A_{i\ 31} &= 0 \quad i \neq 23 \end{aligned}$$

No limited supply inputs are consumed. Thus,

$$D_{1\ 31} = 0$$

Other Mobile Sources of RHC and NO_x

(i) 1971-1974 model year (non-fleet) motor vehicles: RHC, 69 tons/day;
NO_x, 124 tons/day

In 1975, total emissions from non-fleet 1971-1974 motor vehicles will be 69 tons/day RHC and 124 tons/day NO_x.^{*} Fairly strict RHC and NO_x control will already exist on these vehicles. It is assumed here that further control on these vehicles will not be technically or politically feasible by 1975.^{**}

(ii) Diesel powered motor vehicles: RHC, none; NO_x, 18 tons/day

In 1971, diesel powered motor vehicles emitted 15 tons/day of NO_x in Los Angeles County (APCD Profile, 1971). Assuming 4% growth until 1975, emissions will then be 18 tons/day. Possible control techniques for diesel engines are engine redesign, fuel additives, catalytic converters, and steam or exhaust gas induction. However, all of these would require further technical development and costs are unknown (HEW-AP-67, 1970). No control for diesel engines is considered here.

* Average exhaust emissions from non-fleet 1971-1974 vehicles are 1.2 gm/mile RHC and 2.8 gm/mile NO_x (Table A-I). All 1971-1974 vehicles average 34 mi/day (Table A-I),^x but fleet vehicles, 20% of all 1971-1974 vehicles, average 50 mi/day (see source # 20). Non-fleet vehicles thus average 30 mi/day. Adding evaporative emissions, total emissions per non-fleet 1971-1974 vehicle are .10 lb/day RHC and .18 lb/day NO_x. All 1,380,000 such vehicles thus emit 69 tons/day RHC and 124 tons/day NO_x.

** More stringent new vehicle control has been legislated for 1975 and 1976. Auto makers have contested the technical feasibility of this control for 1975 and 1976 vehicles. To have such control on 1971-1974 vehicles would be even more difficult.

(iii) Piston aircraft not registered in Los Angeles County: RHC, 5 tons/day; NO_x , 2 tons/day

In 1975, 5 tons/day RHC and 2 tons/day NO_x will be emitted in Los Angeles County by piston aircraft not registered in the County (see source # 23). Because of difficulty in estimating the number of such aircraft, no controls are considered here for this minor source of RHC and NO_x .

§A-IV. LIMITED SUPPLY INPUTS

Natural Gas: $L_1 = 21,000,000$ eq. bbls./year

The only fixed supply input constraint on the control methods considered here is the natural gas supply constraint. It has been assumed above that residential and (non-power plant) industrial stationary combustion sources will use natural gas exclusively. The remaining natural gas available to Los Angeles County is insufficient to be used in all power plants (control methods # 7, 8, and 10) and in all fleet vehicles (control method # 27). This imposes a fixed supply input constraint on these control methods.

In 1975 around 110,000,000 equiv. bbls./year of natural gas will be available to Los Angeles County.* Residential and (non-power plant) industrial users will consume 89,000,000 equiv. bbls./year.** This leaves 21,000,000 equiv. bbls./year to be used in power plants and in fleet vehicles.

* In 1971 122,000,000 equiv. bbls. of natural gas were burned in Los Angeles County. The PACE Report on gaseous fuel supply (Ralph and Walker, 1971) estimates that the supply should decrease about 10% by 1975.

** In 1971 residential and industrial sources consumed 76,000,000 equiv. bbls. of natural gas. Assuming 4% growth until 1975, these sources will then use 89,000,000 equiv. bbls./year.

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APPENDIX B

VIOLATION OF CARBON MONOXIDE STANDARDS
IN DOWNTOWN LOS ANGELES

This appendix applies the statistical model of section 4.3.1 to determine the expected number of days per year that state standards for CO are violated in Downtown Los Angeles as a function of L. A. County CO emissions. The analysis is carried out for two CO standards, the 40 ppm-one hour standard and the 10 ppm-twelve hour standard.

B-I. Applicability of the Model

The statistical model is predicated on the assumption that conditions I and II of §4.2 are met. Some discussion of the validity of these assumptions for the carbon monoxide example is in order.

Condition I, that the pollutant is inert, is very well satisfied by carbon monoxide. Although evidence exists that CO takes some part in the photochemical reactions (Bufalini et al., 1971; Dimitriades and Whisman, 1971), the rate of CO consumption in these reactions is very small, and its half life is of the order of a couple months. Since Los Angeles air pollution usually consists of contaminants emitted during the past day and, even in unusual weather conditions, during at most the past three days, (Holmes et al., 1956), CO may be considered inert during its residence time in Los Angeles.

Condition II states that emission reductions occur homogeneously in time and space. Over 97% of CO emissions in L. A. County come from one major source, motor vehicles, (APCD Profile, 1971). It is expected that the control policy of the 1970's will involve considerable reductions in total motor vehicle CO emissions with comparatively minor changes in the spatial and temporal distribution of these emissions. Such a control policy would satisfy condition II very well.

B-II. Data

The distribution of the daily maximum one and twelve hour average concentrations, $N_1^0(P)$ and $N_{12}^0(P)$, is determined with data obtained from the L. A. County APCD monitoring station in Downtown Los Angeles. Data from 1964, 1965, and 1966 are used for the one hour distribution. Data from 1968, 1969, and 1970 provide the twelve hour distribution. The concentrations for each year are reduced to a base emission level, $E^0 = 10,000$ tons/day, by multiplying by E^0 and dividing by that year's emission level. These corrections are small. Figures B. 1 and B. 2 present the resulting distribution functions.

B-III. Results and Conclusions

The expected number of days per year that the 40 ppm-one hour and 10 ppm-twelve hour CO standards are exceeded in Downtown Los Angeles as a function of L. A. County CO emissions is calculated by equation (4-6). Figure B. 3 presents the results.

Figure B.1
DISTRIBUTION OF DAILY ONE HOUR MAXIMAL
CARBON MONOXIDE CONCENTRATIONS FOR
DOWNTOWN L.A. AT A CO EMISSION LEVEL OF
10,000 TONS / DAY

No (P) dP = Days / year with maximum
 one hour concentration in the range: P + dP

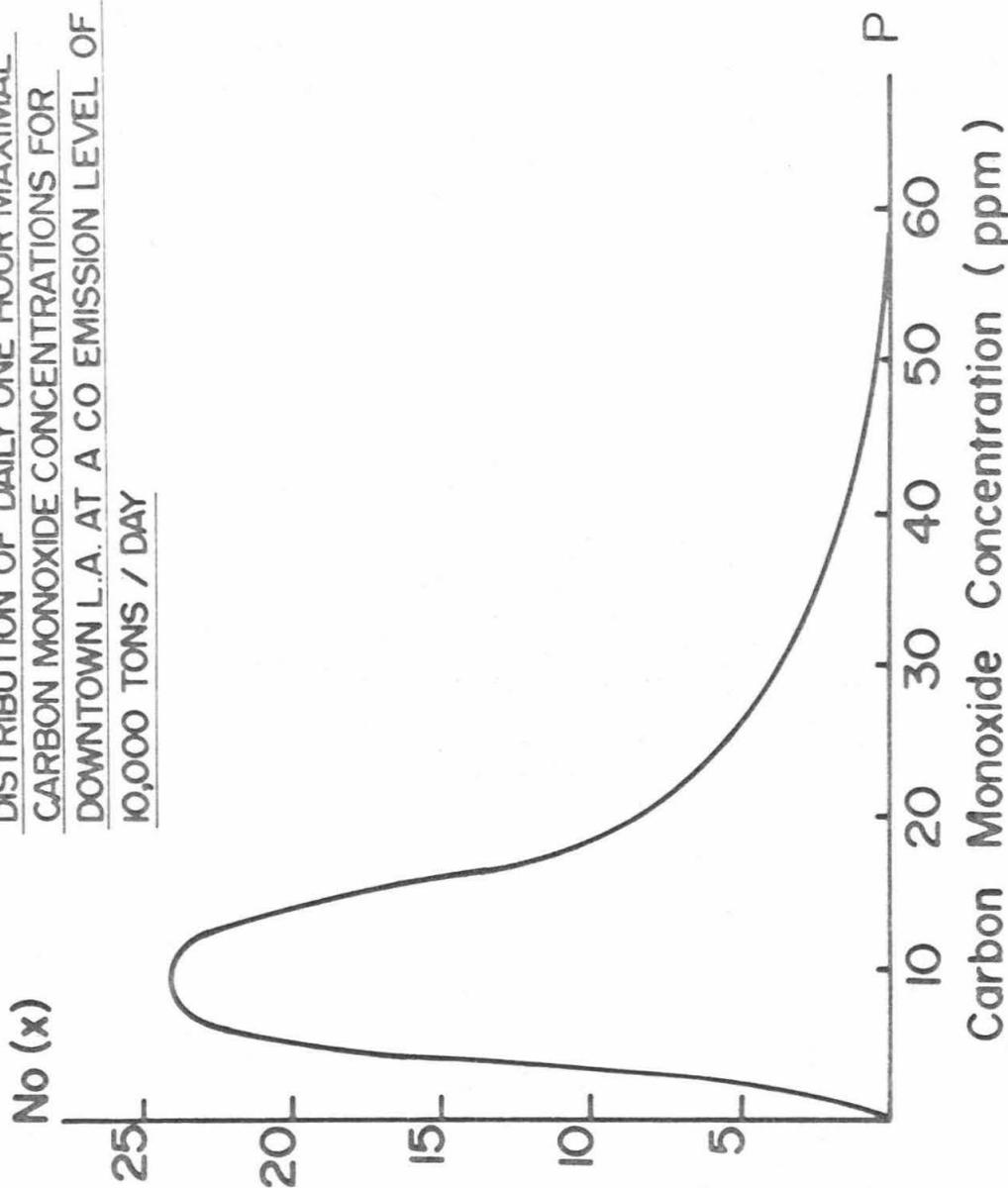


Figure B.2

DISTRIBUTION OF DAILY TWELVE HOUR AVERAGE
MAXIMAL CO CONCENTRATIONS FOR DOWNTOWN
LOS ANGELES AT EMISSION LEVEL OF 10,000
TONS/DAY CO.

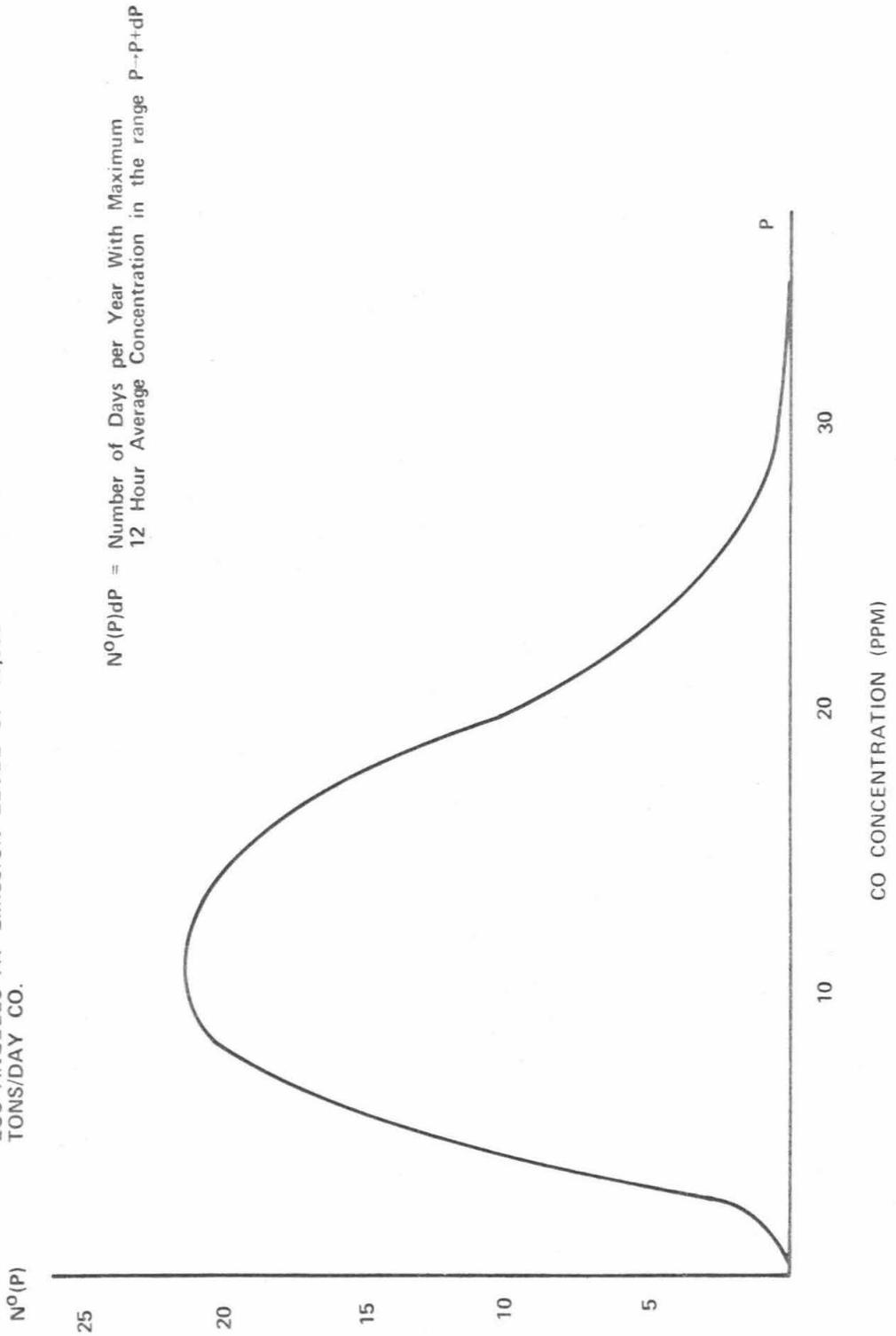
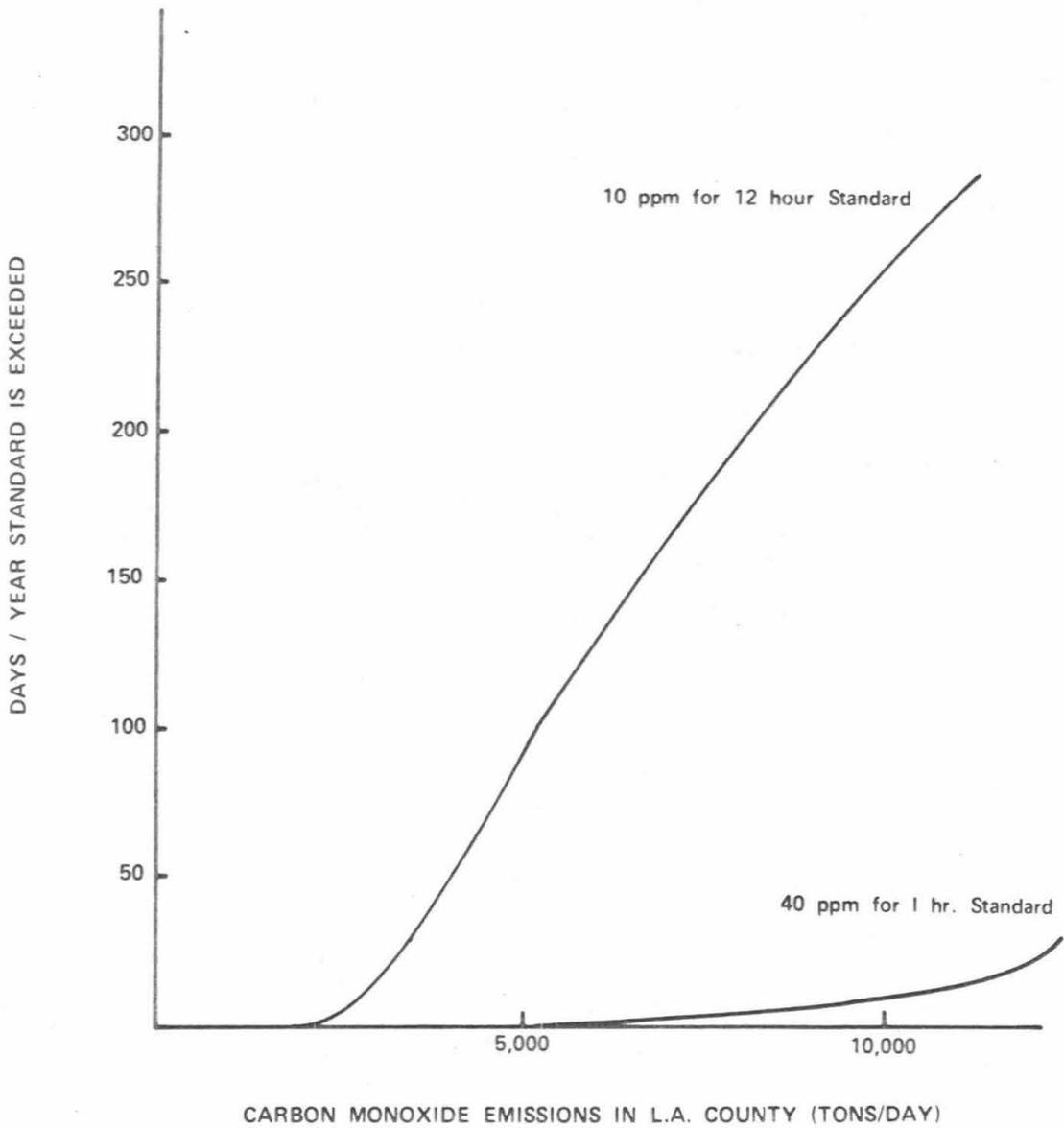


Figure B.3

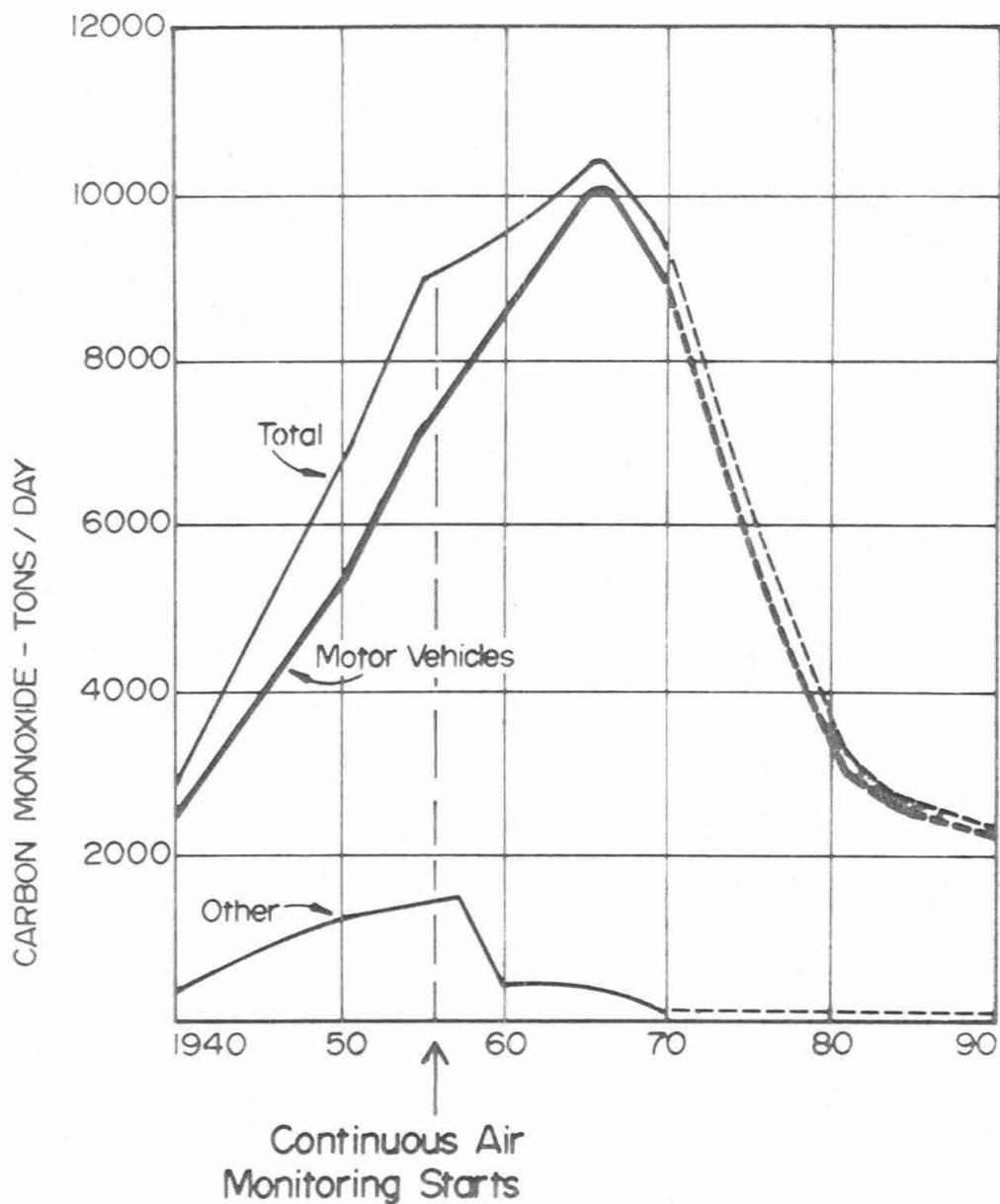
CARBON MONOXIDE AIR QUALITY
VS. EMISSIONS FOR L.A. COUNTY



Apparently, violations of the one hour standard are not a great problem in Los Angeles. At the emission levels of the late 60's (around 10,000 tons/day), violations occur only around 5 days per year. A 40% emission reduction would eliminate the violations. The twelve hour standard is exceeded almost 300 days per year in the late 60's. Fortunately, the number of violations is very sensitive to emission levels. A 75% emission reduction would eliminate these violations.

Present control strategy for CO in Los Angeles County, (Figure B.4, APCD Profile, 1971), calls for a 40% reduction in CO emissions by 1975 and a 60% reduction by 1980. According to Figure B.3, this strategy will reduce twelve-hour standard violations to around 125 days/year in 1975 and to around 35 days per year in 1980.

Figure B.4
CARBON MONOXIDE EMISSIONS
ALL SOURCES



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APPENDIX C

EYE IRRITATION IN DOWNTOWN LOS ANGELES
AS A FUNCTION OF L. A. COUNTY RHC AND
NO_x EMISSION LEVELS

C-I. Description of the Problem

This appendix applies the stochastic model of §4.4 to the problem of eye irritation in Downtown Los Angeles. Photochemical smog research has established that eye irritation, like ozone, results basically from the photolysis of RHC and NO_x emissions (Haagen-Smit, 1952; Wayne, 1962; HEW-AP-63, 1970). As in the ozone example, (section 4.4.2), primary contaminant concentrations, (x, y) , are taken as 7:30-9:30 Civil Time averages of total HC* (minus 1 ppm for natural background methane) and NO_x concentrations in Downtown Los Angeles. A Z standard violation is taken to be the recording by meteorologists of eye irritation in Downtown Los Angeles.

In order for the model to be applicable, data for the concentrations, (x, y) , and for eye irritation (EI) must correspond to the same air mass. Maximum eye irritation in Downtown Los Angeles is very suitable in this respect. Smog chamber experiments have established that eye irritation reaches a peak twice during photolysis of RHC and NO_x, once at about $1\frac{1}{2}$ hours after irradiation begins and then again

*See section 4.4.2.1 for a discussion of how this relates to RHC emissions.

after about $4\frac{1}{2}$ hours, (Hamming and Dickinson, 1966; Hamming and MacPhee, 1967). Downtown Los Angeles experiences the first type. (It is usually swept clean by the sea breeze in the afternoon.) Peak eye irritation in Downtown L. A. occurs at about 10:30-11:00 Civil Time. Since x and y are measured from 7:30-9:30 and since the sea breeze does not develop until about 11:00, one is somewhat assured of having the same air mass for the eye irritation and morning concentration measurements.

C-II. Applicability of the Model

The model is exactly applicable only to situations that meet the four assumptions given in section 4.4.1. The discussion of the eye irritation example as it relates to these assumptions is almost exactly the same as the discussion for the ozone example, (see section 4.4.2.2). The only major difference occurs with assumption (iii), that emissions after 9:30 have no effect. In this case, the assumption is better met by the eye irritation example. Since the eye irritation measurement is taken at about 10:30 and the ozone measurement at about 12:00, post 9:30 emissions should play less of a role in the eye irritation example. The reader is referred to section 4.4.2.2 for a complete discussion of the other assumptions of the model as they relate to both the ozone and eye irritation examples.

C-III. Data

The morning concentrations, (x, y) , are 7:30-9:30 PDT averages of total HC and NO_x at the APCD Downtown Los Angeles station. A

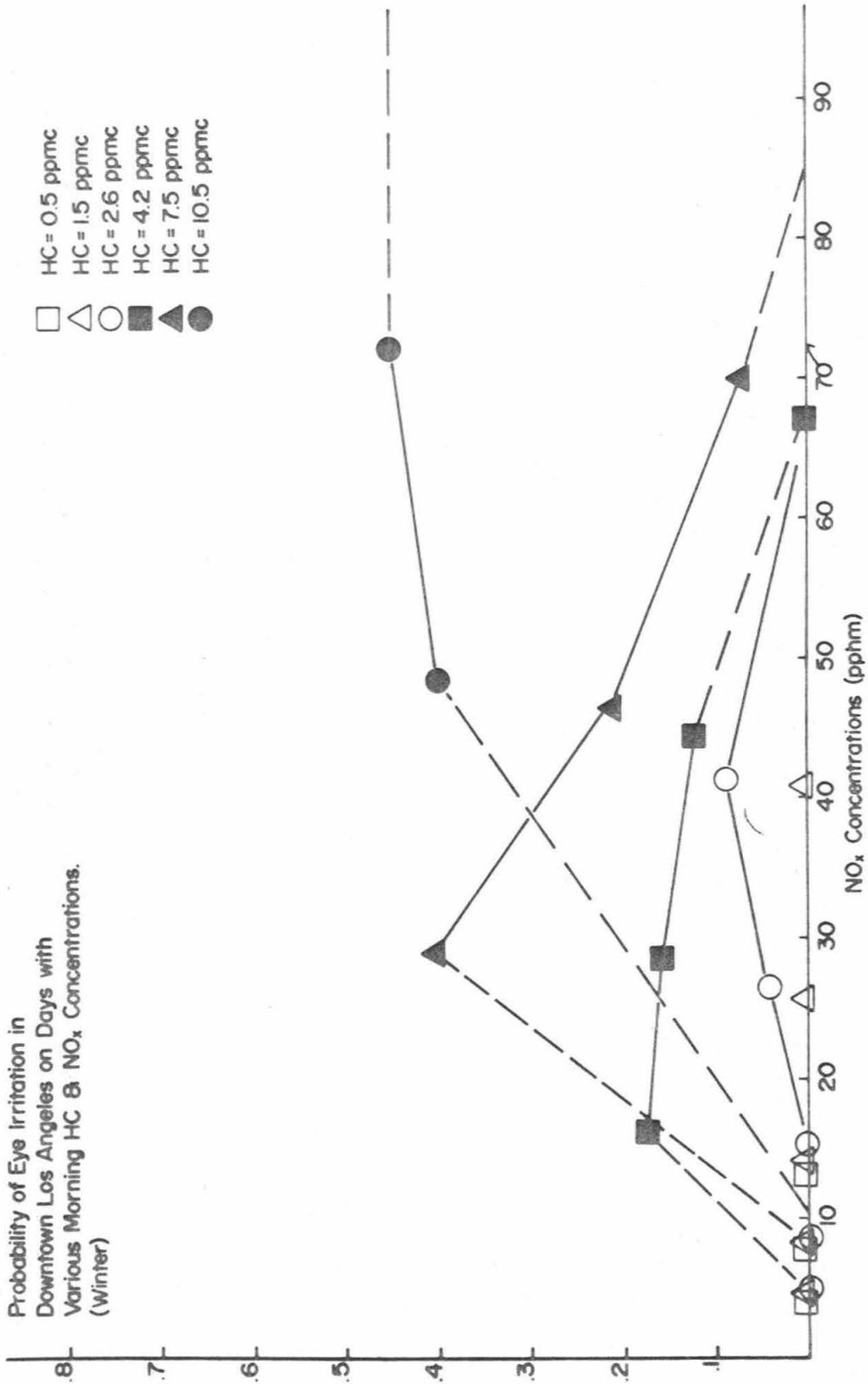
correction for natural background methane is made by subtracting 1 ppm from the HC measurements. Data are used for the years 1966, 1967, 1968, 1969, and 1970, with L. A. County RHC and NO_x emission levels of (1600, 920), (1500, 940), (1400, 970), (1300, 1000), and (1200, 1050) tons per day, respectively (APCD Profile, 1971; EQL, 1972). The concentrations for each year are reduced to a base emission level, $E^0 = (1300, 1000)$ tons/day as in the ozone example. These data provide the distribution functions $N^{o(w)}(x, y)$ and $N^{o(s)}(x, y)$ giving the number of winter and summer days with various morning concentrations. Table 4-IV and Figures 4.17 and 4.18 (of section 4.4.2.3) summarize these distributions.

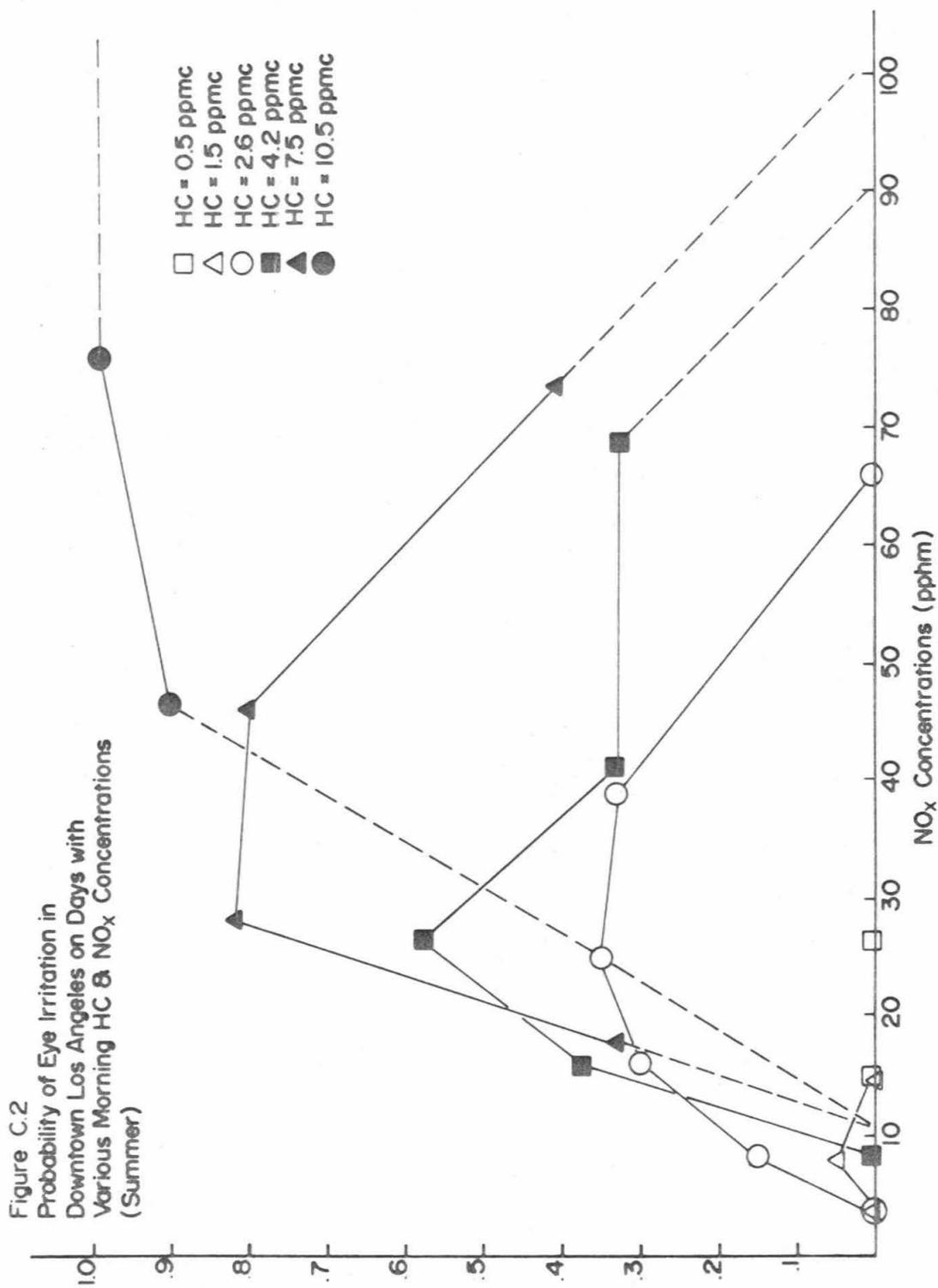
Eye irritation is taken as a 0-1 parameter depending on whether or not the meteorologist at the Downtown air monitoring station recorded eye irritation during that day. From these measurements and the corresponding morning concentration measurements, the probability of eye irritation as a function of (x, y) is determined. Figures C.1 and C.2 present these functions, $P^{o(w)}(x, y)$ and $P^{o(s)}(x, y)$.

C-IV. Results and Conclusions

From the measured functions, $N^{o(w)}(x, y)$, $N^{o(s)}(x, y)$, $P^{o(w)}(x, y)$, and $P^{o(s)}(x, y)$, the number of winter and summer days of eye irritation in Downtown Los Angeles is calculated as a function of RHC and NO_x emission levels in L. A. County according to equation (4-12). The total number of days per year of eye irritation in Downtown L. A. versus emission levels is presented in Figures C.3 and C.4. Figure C.3

Figure C.1
Probability of Eye Irritation in
Downtown Los Angeles on Days with
Various Morning HC & NO_x Concentrations.
(Winter)





REACTIVE HYDROCARBON EMISSION LEVEL
AS % OF 1300 TONS/DAY RHC

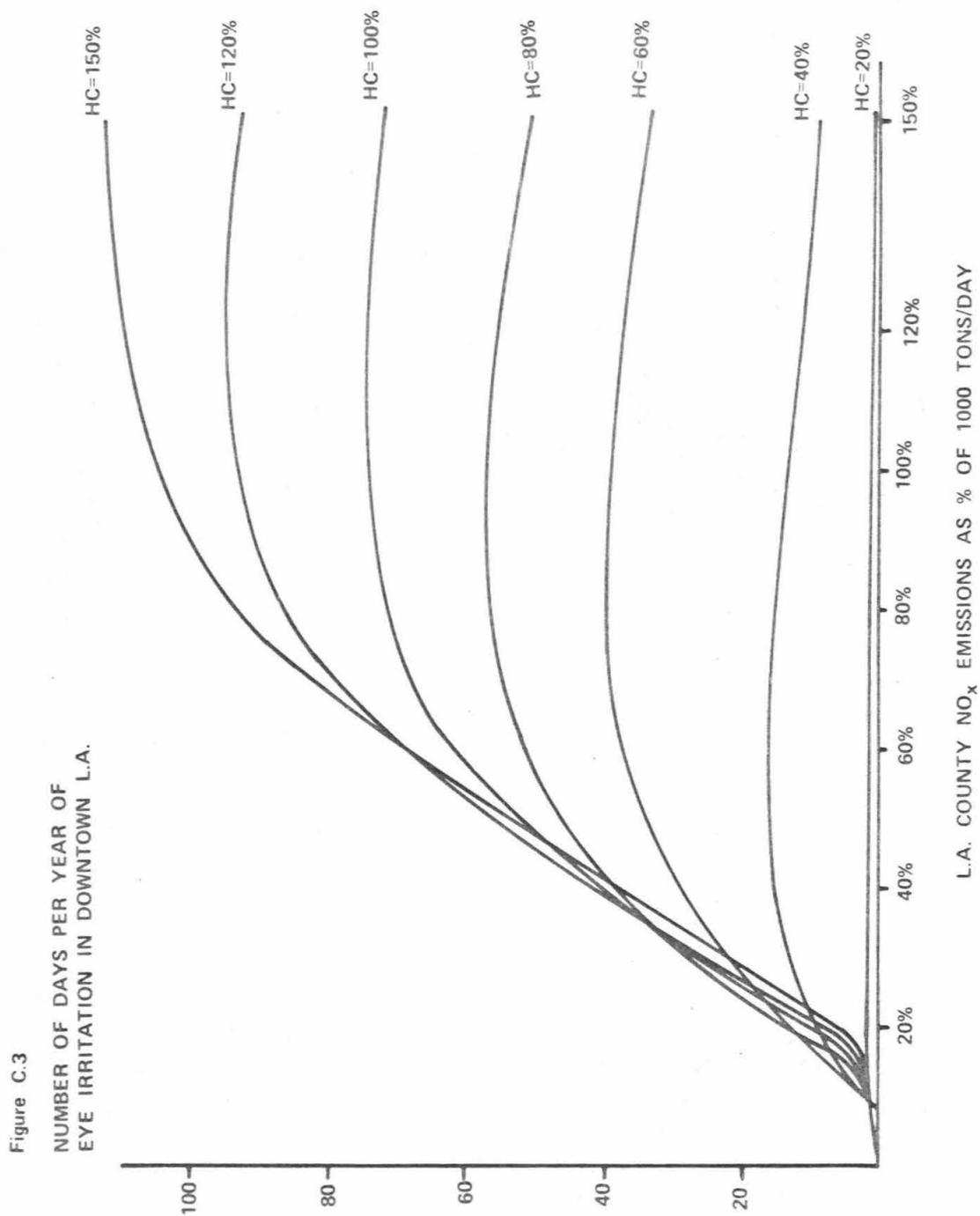
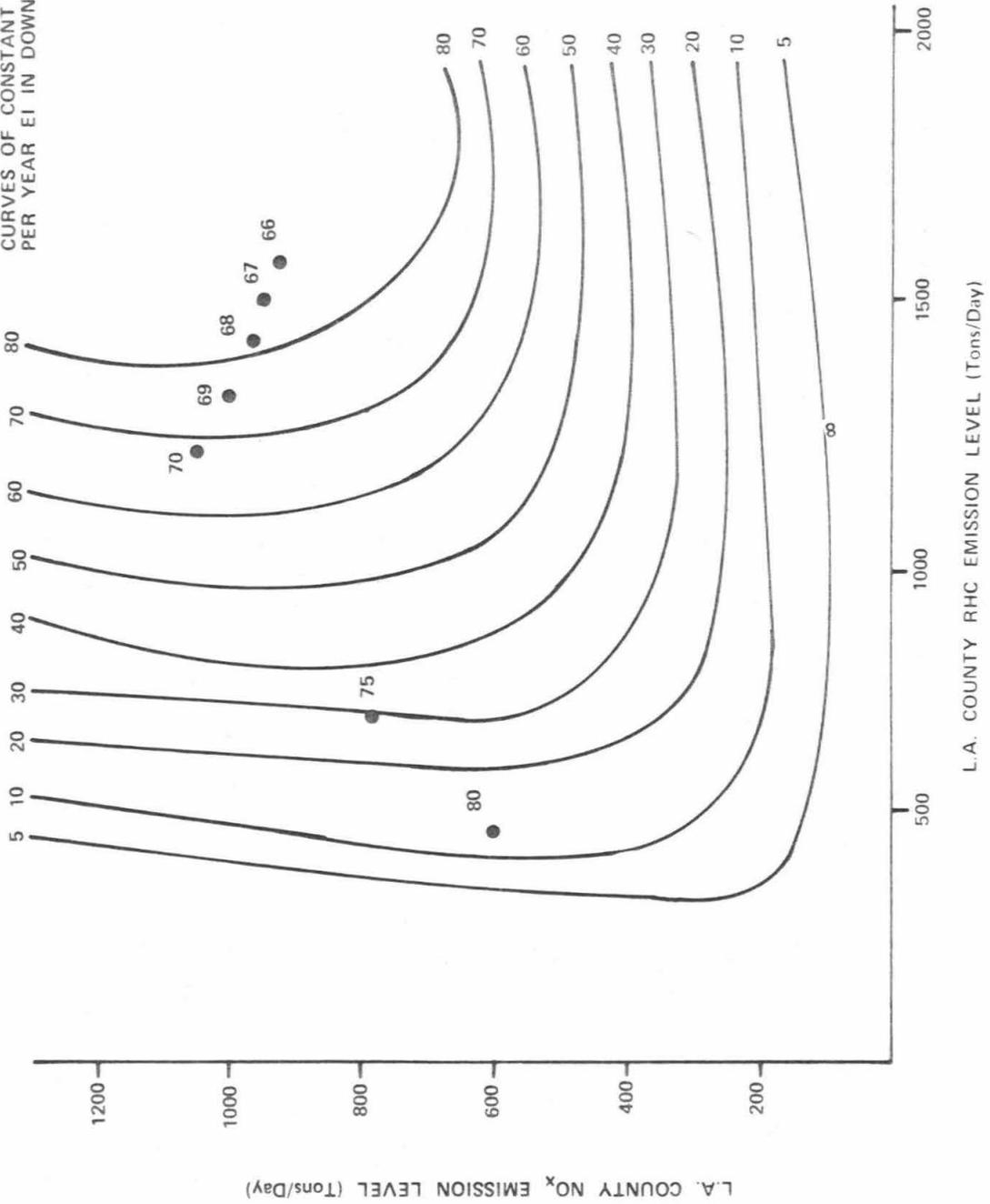


Figure C.4
CURVES OF CONSTANT DAYS
PER YEAR EI IN DOWNTOWN L.A.



gives days per year of eye irritation versus NO_x emissions for various RHC emission levels. Figure C.4 plots eye irritation contours as a function of both emission levels. The 1966-1970 and the presently planned 1975 and 1980 emission levels are marked in Figure C.4 (APCD Profile, 1971; EQL, 1972).

Figure C.4 indicates that in 1966, Los Angeles was near the peak of the "eye irritation hill." The control policy of the late sixties and the seventies take Los Angeles down the low RHC side of the hill, reducing the number of eye irritation days from 90 in 1966 to 68 in 1970, to 30 in 1975, and to 12 in 1980.

C-V. Comparison with Experiment

Several experimental studies have been performed which attempt to quantify the amount of eye irritation produced by the photolysis of HC and NO_x mixtures in order to determine the relationship between eye irritation and the concentrations of the primary contaminants. These experiments have varied in size and composition of chamber, source and intensity of radiation, irradiation time, type of HC, eye irritation index, and concentration range. The main features of five such studies are summarized in Table C-I.*

In attempting to compare the experimental results to the results of the stochastic atmospheric model, several problems are encountered. First, most of the experimental data were taken at concentrations

*Almost all of the information for Table C-I is condensed from Hamming and Dickinson, 1966.

TABLE C-1
Summary of Experimental Eye Irritation Studies

Study Agency and Reference	Eye Irritation Index Used	Radiation Intensity	Irradiation Time	Number of Exp. Points	Type of HC Used	Range of Exp. Data	
						NO _x	HC
1. Western Oil & Gas Association and APCD, (Hamming et al., 1961)	"Response-delay" method... The time (in seconds) between exposure of subjects to the gas and the report of eye irritation by the subjects.	~ ½ noon sunlight — or ~	3 hrs.	12	Auto Exhaust	70-300 pphm	0.6-6.0 ppm (as Hexane by IR-2 method)
2. Western Oil & Gas Association and APCD, (Hamming et al., 1961)	"Response-delay" method... The time (in seconds) between exposure of subjects to the gas and the report of eye irritation by the subjects.	~ ½ noon sunlight — or ~	3 hrs.	15	Olefins	70-350 pphm	0.15-0.9 ppm (Bromocoulo-metric)
3. APCD Solvent Project, (Brunelle et al., 1964)	"Response-delay" method... The time (in seconds) between exposure of subjects to the gas and the report of eye irritation by the subjects.	~ noon sunlight	4 ½ hrs.	17	Auto Exhaust	80-400 pphm	0.5-2.0 ppm (as Hexane by IR-2 method)
4. California Department of Public Health and APCD, (Mader et al., 1963)	"Response-delay" method... The time (in seconds) between exposure of subjects to the gas and the report of eye irritation by the subjects.	~ noon sunlight	4 hrs.	17	Auto Exhaust	30-220 pphm	0.25-2.0 ppm (as Hexane by IR-2 method)
5. U. S. Public Health Service (Korth et al., 1964)	"Intensity" method... The intensity of eye irritation reported by subjects exposed to the gas on a 0, 1, 2, 3 scale.	~ noon sunlight	2 hrs.	9	Auto Exhaust	50-200 pphm	3.0-7.0 ppmc (flame ionization)

considerably higher than those found in the atmosphere. This can be seen by comparing the NO_x ranges (the difficulty in comparing HC measurements will be the second problem). In the atmospheric model, 90% of the points have NO_x concentrations less than 50 ppm. Experiments 1, 2, 3, and 5 of Table C-I have no points within this range. Experiment 4 does, however, have points in the higher part of the atmospheric range. It will be used for the comparison.

The second problem arises in attempting to compare the HC data. Experiment 4 used auto exhaust, measured HC concentrations by infrared spectroscopy, and expressed HC as hexane equivalent ppm. The atmosphere contains auto exhaust, evaporated gasoline, and a whole range of hydrocarbons of varied reactivity from stationary sources. It also contains geophysical and anthropomorphic methane in considerable concentrations. Measurements are made by gas chromatography (flame ionization) and expressed as ppm Carbon.

Some means of reducing the experimental HC measurements to atmospheric equivalents must be found. (This has proved to be a great problem in interpreting smog chamber studies.) This estimate is made here as follows:

Let x = ppm hexane of auto exhaust in experiment

1st, to correct for the IR-2 vs. flame ionization method,
multiply by 1.9 (Hamming and Dickinson, 1966)

$$x \rightarrow 1.9 x$$

2nd, to correct for ppm hexane to ppmc, multiply by 6

$$1.9 x \rightarrow 6 (1.9) x$$

3rd, assuming that the non-methane part of the atmospheric total HC is equivalent in reactivity to auto exhaust, since (after 1 ppm is subtracted for background methane) approximately 35% of the remainder of atmospheric HC is methane, multiply by $100/65 = 1.54$

$$6 (1.9) x \rightarrow 1.54 (6) (1.9) x = 17.5 x$$

Thus,

$$17.5 \text{ (experimental ppm hexane by IR-2)}$$

$$\approx \text{atmospheric ppmc by flame ionization}$$

The third problem in comparing Experiment 4 and the atmospheric model is that they each measure different things. The experiment measures the time for subjects who are exposed to the gas to say they have experienced eye irritation. The atmospheric model measures the probability of eye irritation on a day with given morning concentrations. These are two different indices obtained under two different sets of conditions, and one thus cannot expect more than "qualitative agreement." The comparison is made with this in mind and only a qualitative comparison based on the shape of the eye irritation hill is looked for.

One of the most serious differences in the conditions of each measurement is that Experiment 4 measures eye irritation 4 hours after irradiation and Downtown L. A. experiences the first eye irritation peak, $1\frac{1}{2}$ hours after irradiation. However, according to

Hamming and Dickinson (1966), the 4 hour eye irritation peak is "about equal" to the $1\frac{1}{2}$ hour peak. Since only a qualitative comparison is being made, this difference may not be too serious.

In order to compare Experiment 4 and the atmospheric results, the probability of eye irritation on a summer day was plotted in contour form as a function of morning HC and NO_x concentrations. This is shown in Figure C.5. Then, in Figure C.6, the two lowest contours in the experimental range of Experiment 4 are plotted for comparison. Figure C.6 reveals that the experiment and the atmospheric model do compare well qualitatively. Both have the peak of the eye irritation hill at about the same HC/NO_x ratio. The atmospheric model seems to show a more highly sloped hill, but the difference is not very great.

Figure C.5
PROBABILITY OF EYE IRRITATION ON SUMMER
DAYS WITH VARIOUS MORNING HC AND NO_x
CONCENTRATIONS

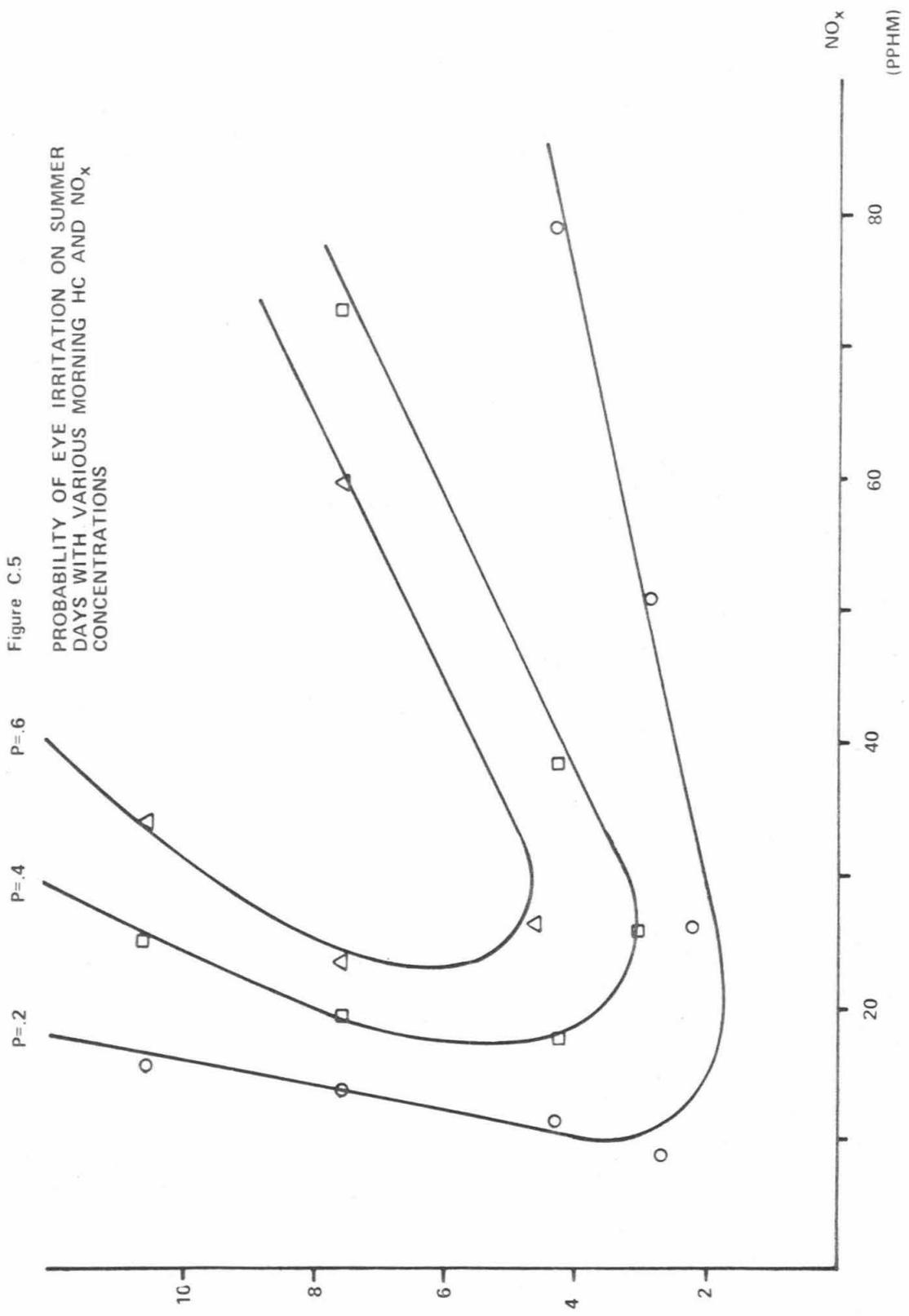
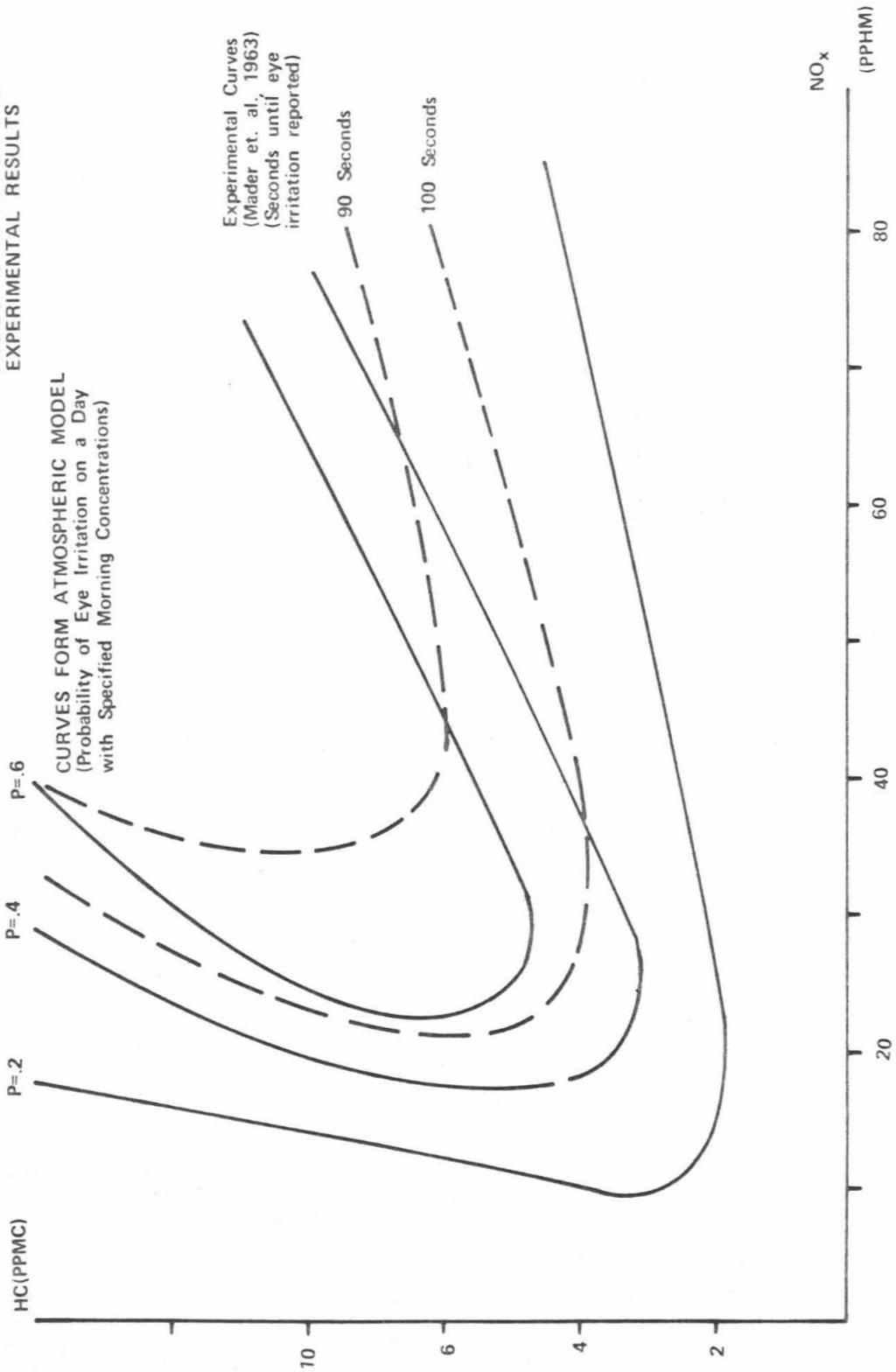


Figure C.6
QUALITATIVE COMPARISON OF THE
ATMOSPHERIC MODEL AND
EXPERIMENTAL RESULTS



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