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Environmental Monitoring Series

DEVELOPMENT OF A METHODOLOGY FOR DESIGNING CARBON MONOXIDE MONITORING NETWORKS

Environmental Monitoring and Support Laboratory
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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound integrated monitoring data base through multidisciplinary, multimedia programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment

- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report discusses the theoretical bases for a method of designing air quality monitoring networks. The method was developed for application to reactive or nonreactive pollutant monitoring. Specific design steps in the report, however, are illustrated for a carbon monoxide monitoring network. Regional or local agencies may find this method useful in planning or adjusting their air quality monitoring networks. The Monitoring Systems Design and Analysis Staff at the EMSL-LV may be contacted for further information on the subject.

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PREFACE

This document is concerned with the development of a methodology for the design of a monitoring network for carbon monoxide (CO). In actuality, the methodology is generally valid for any airborne pollutant. CO was chosen partially because it is a relatively inert pollutant for which the methodology should be presentable in its basic, simplest form. In addition, CO is a pollutant very susceptible to analysis at both the mesoscale and microscale levels. Finally, the first application of the methodology is for CO and will appear as a separate report.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CAMP	--	Continuous Air Monitoring Program
CAT-P	--	concentration area time-product
CO	--	carbon monoxide
EPA	--	U.S. Environmental Protection Agency
g/m^3	--	grams per cubic meter
g/m/s	--	grams per meter per second
HC	--	hydrocarbon
km	--	kilometer
LDV	--	light duty vehicles
LST	--	local standard time
m	--	meters
m/s	--	meters per second
m^2/s	--	square meters per second
mg/m^3	--	milligrams per cubic meter
NAAQS	--	National Ambient Air Quality Standards
NASN	--	National Air Sampling Network
NCC	--	National Climatic Center
NEDS	--	National Emissions Data System
NOAA	--	National Oceanographic and Atmospheric Administration
NO_2	--	nitrogen dioxide
NWS	--	National Weather Service
PHS	--	Public Health Service
ppm	--	parts per million
SAI	--	Systems Applications, Incorporated
SO_2	--	sulfur dioxide
$\mu g/m^3$	--	micrograms per cubic meter
UTM	--	Universal Transverse Mercator
VMT	--	vehicle miles traveled

SYMBOLS

A	--	pollutant concentration averaging area
c(x,y,t)	--	pollutant concentration as a function of distance and time
C_{max}	--	maximum allowable contribution of any one source to the concentration
c^*_{on}'	--	vehicle emission factor
D	--	a specified downwind horizontal distance
d_e	--	exposure class

SYMBOLS, continued

d_w	--	wind speed class
E	--	roadway types
F(j,k)	--	Figure of Merit
G_{max}	--	desired maximum concentration gradient away from the roadway
Γ	--	random variable
H	--	hourly percentage of daily traffic
h*	--	average height of the roughness element within a grid element
k	--	von Karman constant
Kx, Ky, Kz	--	turbulent eddy diffusivities in the x,y and z directions
K_{z_i}	--	vertical diffusivity at height z_i
L	--	Monin-Obukhov length
$m^*_{on'}$	--	adjusted annual travel distance
p_{oT}	--	temperature correction factor
Q(x,y,t)	--	pollutant emission rate
$q_{oTw'}$	--	cold start correction factor
ρ	--	sensor location at some downwind horizontal distance
s	--	downwind horizontal distance
S	--	stability function which is a digital version of the Pasquill stability category
s*	--	exposure silhouette area
S*	--	lot area
S_i	--	downwind position of i-th particle
σ_z	--	standard deviation of a Gaussian plume in the vertical
t*	--	pollutant concentration time-averaging interval
θ	--	angle between wind and line source
u	--	wind speed in the x-direction
U	--	horizontal wind speed
u_*	--	friction velocity
U_r	--	reference horizontal wind speed
u'c'	--	pollutant flux in the x-direction
v'c'	--	pollutant flux in the y-direction
w'c'	--	pollutant flux in the z-direction
v	--	wind speed in the y-direction
$v^*_{os'}$	--	speed correction factor
w	--	wind speed in the z-direction
z*	--	height of instrument inlet
Z_i	--	height of stable layer capping mixing layer or height above which pollutant concentrations level off to background values
z_i	--	height of particle i
z_o	--	surface roughness
Z_r	--	reference height

CHAPTER I

MONITORING OF AMBIENT AIR QUALITY

The monitoring of ambient air quality is probably the single most important activity in the study and control of air pollution. Without reliable measurements, a legitimate data base cannot be established for assessing either the degree of deterioration of ambient air or for enforcing Federal and local regulations, nor can a firm and valid basis be obtained for examining the cause-effect relationship between the emissions from the pollutant sources and the quality of ambient air. It is thus not surprising that prior to the early sixties, when recognition of air pollution as a national problem began to emerge, the primary concern of most air pollution studies focused on the monitoring of ambient air quality.

In 1953, the U.S. Public Health Service (PHS) set up the National Air Sampling Network (NASN) to measure particulates in air. In 1962, an intensive effort, the Continuous Air Monitoring Program (CAMP), was initiated by the PHS to measure gaseous pollutants in typical urban areas. Since then, numerous governmental and private investigations related to air quality measurements have been carried out. With the passage of the Clean Air Act in 1971, ambient air monitoring programs became an indispensable part of State implementation plans. Thus, there exists a need to set up guidelines for planning and siting of established or prospective air monitoring stations. As discussed later, there have been a number of attempts in the past to provide such guidelines. However, a rigorous guideline with a sound theoretical basis that is operationally effective is lacking. In light of the recent advances in the theory of systems design and in the current understanding of the distribution of the various pollutants, an in-depth study that will lead to the development of an objective methodology for siting monitoring stations is apparently feasible. The present project is devoted to this goal.

REVIEW OF PREVIOUS WORK

Guidelines or rules previously used by designers of monitoring networks were largely based on accumulated experience derived from practice. A brief review of these efforts is presented below.

In September 1963, a symposium on environmental measurements was sponsored by the PHS at Cincinnati, Ohio. Several papers presented there dealt in part with the objectives of measuring systems and the design of such systems. However, information resulting from that symposium was unsuitable for specific applications.

Common practices in the design of air monitoring networks before 1969 were summarized in a survey made by Yamada (1970). Based on this study, Yamada and Charlson (1969) found that differences in the measurement parameters of the air sampling devices between networks of stations and between stations within a single network can be a potential source of error. They thus pointed out the need for standardization of location and design of air quality monitoring stations. Charlson (1969) further pointed out that the siting criteria depend on the particular objective of interest and that the question of "representativeness" of measured air quality was an important consideration.

At a U.S. Environmental Protection Agency (EPA) workshop held in January 1970 (U.S. EPA, 1970), four major objectives of a regional air quality monitoring program were cited:

- To measure and document a region's progress toward meeting ambient air quality standards.
- To determine ambient air quality in nonurban areas of the region.
- To improve the reliability of dispersion models.
- To provide air quality data during air pollution episodes.

Four criteria were recommended to ensure that data to be collected satisfy all of the above stated objectives:

- Monitoring stations must be pollution-oriented.
- Monitoring stations must be population-oriented.
- Monitoring stations must be located so as to provide areawide representation of ambient air quality.
- Monitoring stations must be source-category and/or source-magnitude oriented.

With these qualitative criteria in mind, the following guidelines were suggested for the distribution of monitoring stations:

- Heavily polluted or "dirty" areas--in most cases 3 to 5 stations will suffice.
- Nonurban stations--2 to 4, depending upon size of the area.
- Population-oriented stations--3 to 7.
- Source-oriented stations--3 to 5.
- Reference (center city) station--1.
- Any available stations not accounted for by above should be placed

where the concentration gradation is greatest (as predicted by dispersion models).

The above recommendations were only speculative in nature and did not define the criteria for locating monitoring stations.

More recently, guidelines on siting monitoring stations were provided in U.S. EPA(1971) and U.S. EPA(1975). Quantitative rules for designing a minimally adequate surveillance system were suggested in these documents. For example, as shown in Figure I-1, the number of stations that are required to implement such a system can be determined once the total population and the type of measuring systems are known. Also, formulae were proposed that use previous air quality records as an aid in determining the number of stations needed. Guidelines were provided for locating these stations. For the most part, the conclusions drawn were based on the analysis of air quality from stations sited with little knowledge of the essential ingredients that must be considered in planning their locations.

Of more interest, however, are several theoretical studies carried out (e.g., Morgan et al., 1970; Seinfeld, 1972; Darby et al., 1974) where the concept of systems design was applied. The design of an air quality monitoring network was treated in these theoretical studies as an optimization problem where a set of well-defined constraints related to monitoring objectives were prescribed.

OBJECTIVES OF AIR QUALITY MONITORING PROGRAMS

Reflection suggests that consideration of the objectives of a monitoring program must precede the actual design of the monitoring network and the siting of the stations. Various objectives of past and present air quality monitoring programs can be classified into three categories:

General Air Quality Monitoring Programs

The goal of general monitoring programs is to provide the two-dimensional air pollutant distribution near the ground in the region of interest. Judging from the specific objectives stated below, it can be concluded that State or local agencies are likely to be primarily concerned with this type of monitoring program.

Compliance with Air Quality Standards

As summarized in Table I-1, the Clean Air Act Amendment of 1971 specified two types of air quality standards: the primary standards for the public health, and the secondary standards for the public welfare (Barth, 1970). In addition to these Federal standards, many State and local agencies have set up their own air quality standards. Compliance, progress toward compliance, or lack of compliance with these standards can be determined from the measured air quality. When excessive concentration levels are registered by the monitoring network, indicating the occurrence of an air pollution episode, the collected data can be used in activating emergency control measures.

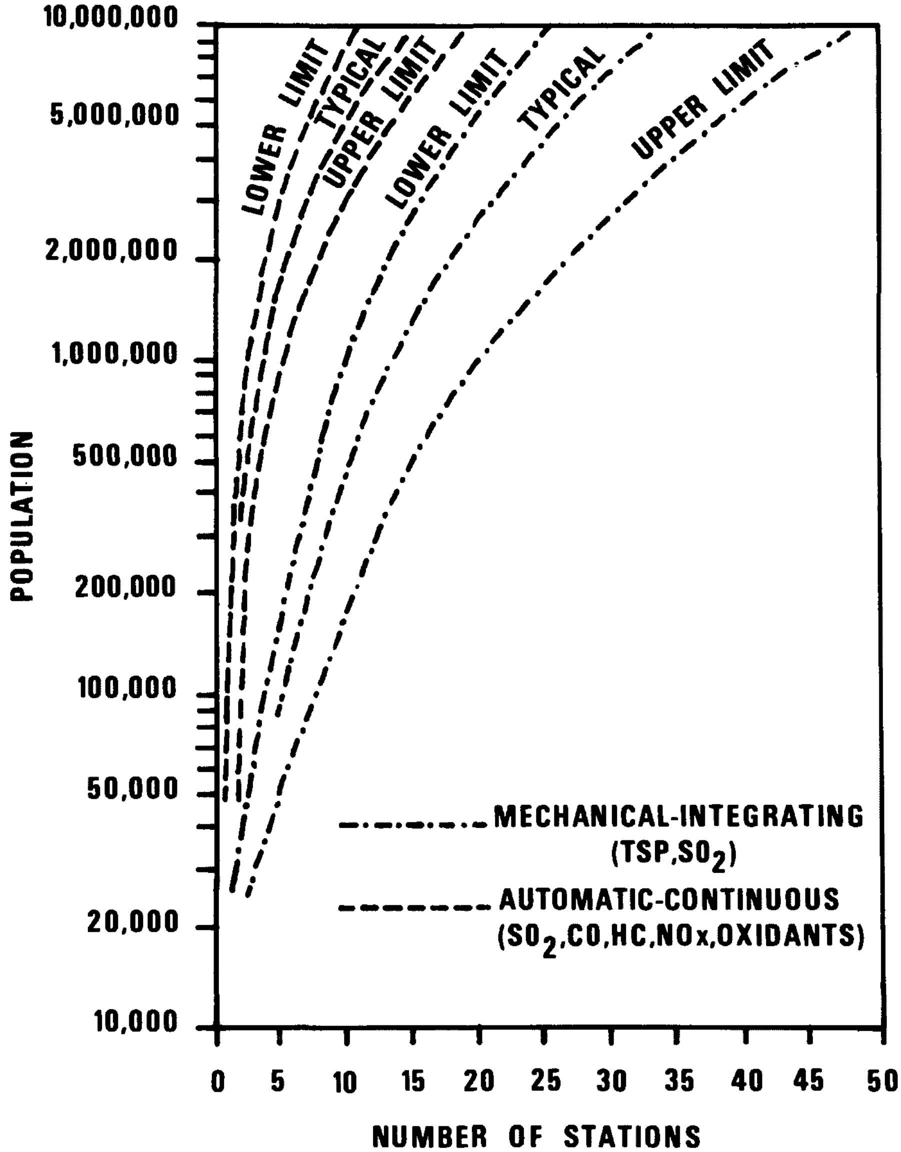

Figure I-1. Number of stations per air quality control region as a function of population (U.S. EPA, 1971).

TABLE I-1. NATIONAL AMBIENT AIR QUALITY STANDARDS

Pollutant	Primary Standards	Secondary Standards	Averaging Times
SO_2	80μg/m^3 (0.03ppm)		Annual arithmetic mean
	365μg/m^3 (0.14ppm)		24 hours
	- -	1300μg/m^3 (0.5ppm)	3 hours
Particulate matter	75μg/m^3	60μg/m^3	Annual geometric mean
	260μg/m^3	150μg/m^3	24 hours
CO	10mg/m^3 (9ppm)	10mg/m^3 (9ppm)	8 hours
	40mg/m^3 (35ppm)	40mg/m^3 (35ppm)	1 hour
Photochemical oxidants	160μg/m^3 (0.08ppm)	160μg/m^3 (0.08ppm)	1 hour
HC	160μg/m^3 (0.24ppm)	160μg/m^3 (0.24ppm)	3 hours
NO_2	100μg/m^3 (0.05ppm)	100μg/m^3 (0.05ppm)	Annual arithmetic mean

ppm = parts per million

Source: Code of Federal Regulations, Title 40, Part 50, pp. 3-28, July 1, 1975.

Determination of Long-Term Air Pollution Trends

The implementation of realistic air pollution control strategies will inevitably take time. The effectiveness of these strategies, as reflected by the gradual changes in air quality, can be evaluated through painstaking comparisons of historical records of measured air quality data. In addition, the effects of increases in population and changes in land use on air pollution can also be assessed by scrutinizing the long-term trends or patterns.

Perimeter Monitoring Programs

In the general air quality monitoring programs described above, "areawide" measurements are being sought. By contrast, perimeter monitoring programs are designed primarily to obtain source-oriented measurements. The eventual goal is the calculation of pollutant fluxes. The need for this type of program can arise out of the following concerns by State or local agencies.

Enforcement of Air Pollution Control Regulations

Federal or local regulations usually restrict the amount of air pollutants emitted by any given industrial installation. Although in-stack monitors can be used to ensure that these regulations are being met, enforcement can also be accomplished by source-oriented monitoring. The emission flux can be calculated from data obtained from simultaneous monitoring of the concentration levels and wind speed and direction along the perimeter of the industrial plant. This flux can in turn be used to estimate whether the regulations are being violated. For example, see Sperling (1975).

Estimation of Regional Air Pollutant Fluxes

"Line-wise" types of measurements can also be used to settle legal disputes regarding pollutant fluxes across the boundaries of regions under different jurisdictions. For example, a perimeter monitoring program can provide the data necessary to quantify the transport of airborne pollutants into a county from an adjacent upwind county.

Special Monitoring Programs

This type of monitoring program is topic- and project-oriented. The measurements are made over a short time span, on the order of weeks or months, and are of interest only to a special group. Some of the more important goals of this type of program are:

Procurement of a Data Base for Regional Model Development

Regional models will eventually become an indispensable part of air pollution control programs. Measured air qualities at a series of monitoring stations comprise an important part of the data base for validating such models. The monitoring data can also aid in the refinement of regional models.

Air Quality Impact Studies

A special monitoring program may be needed to establish the baseline pollution levels when the construction of a new roadway or shopping center is contemplated. The information can be used in transportation control or land use planning.

Special Research Studies

Special measuring programs can be initiated to investigate certain speculated cause-effect relationships. Examples are studies correlating indoor air pollution with outdoor air pollution and carbon monoxide concentration on the roadway with the driver's blood hemoglobin level.

FACTORS PERTINENT TO MONITORING NETWORK DESIGN

Once the objectives of a monitoring network have been ascertained, an investigator will be confronted (in the process of planning and designing the network) with a variety of factors that will affect the final network design. As it turns out, many of these factors are not necessarily technical. Most of the technical aspects will be considered in detail later in this report. For an overview, it is of interest to briefly summarize both the technical and nontechnical factors.

Technical Factors

Included here are factors that can be either evaluated or quantified; these are:

Emissions

Because air pollution is a consequence of emissions from sources, this is probably the most important parameter.

Atmospheric Dispersion and Transformation

The concentration levels of air pollutants at any receptor point are determined not only by the emission sources, but also by transport, diffusion, and chemical and physical transformations that take place in the atmosphere. These factors can be extremely important in the selection of the monitoring sites.

Costs

Both the fixed (capital investment) and variable (recurring) costs for the construction and maintenance of the monitoring network can also figure prominently in the decision-making.

Hardware and Software

A variety of factors concerning the instrumentation (such as precision, response time, and operating conditions) and data reduction procedures may also affect the overall design of a monitoring network.

Nontechnical Factors

A number of nontechnical factors exist that can also be important in the deliberation of site selection. These include:

- Accessibility of the monitoring site.
- Safety of personnel and security of equipment.
- Availability of utilities (electricity, water, etc.).
- Ability to accommodate future modifications or expansions.
- Compatibility of purpose with other surveillance networks.

The important role played by these factors in the final decision of monitoring sites should not be underestimated. In Yamada's (1970) statistical survey of past practices in the design and siting of monitoring stations, the reasons given for locating stations were as follows:

Locating Reason	Percentage
Compatibility with station purpose and availability of site	50.0
Compatibility with station purpose only	25.0
Availability of site only	12.5
Others	12.5

The importance of factors other than technical can be clearly seen from analysis of the information presented in this table.

CHAPTER II

DESIGN OF A NETWORK FOR AIR QUALITY MONITORING

Concentration levels of air pollutants are observed not only to fluctuate with time, but also to vary significantly from one location to another even within the same proximity. This variability in observed concentrations is the consequence of both the complex emission pattern and atmospheric dispersion and transformation processes in a region. Since most conventional measuring techniques allow only "point" sampling, the measured data at any arbitrarily chosen site may or may not adequately represent the air quality in a larger area surrounding the monitoring site. It is thus clear that a critical problem in the siting of air quality monitoring stations is to establish the degree of "representativeness" of the station measurements. In the first section of this chapter, major components in the design of an air quality monitoring network are discussed. This is followed by a section delineating the various issues regarding this question of representativeness of station measurements. Also described is the methodology adopted in this study for siting monitoring stations.

COMPONENTS IN THE DESIGN OF AN AIR QUALITY MONITORING SYSTEM

The establishment of an air quality monitoring system, either for operational use or for special studies, is not a small undertaking. Usually, it commits enormous monetary and human resources. Therefore, the planning and design of such a system require the utmost in care.

The concentration of pollutants in a region and the flux of contaminants into, within, and out of the region are highly variable quantities in space and in time. The location of the limited number of stations permitted by financial resources requires careful planning so that measurements that are not typical of the region as a whole can be avoided. Errors due to local disturbances or instrument malfunctions can be minimized by an assessment of the site characteristics, the limitations of the instrumentation, and by establishment of an adequate instrument calibration and maintenance program.

The design of a system can be conveniently divided into three parts:

Monitoring Station Selection

The success of a monitoring program depends heavily on the appropriate design of the monitoring network. This design consists of the following important components:

Estimation of the Number of Monitoring Stations

This is one of the factors that must be decided early in the planning stage. Quantitative rules for reaching this decision are extremely useful. Ideally, the minimally required number of monitoring stations should be determined from a cost-effectiveness analysis based upon optimization techniques. This was apparently not the past practice. As we have discussed in the review, Figure I-1, which was based on statistical data, correlates the number of monitoring stations required with the population of the region. Despite the fact that people are admitted polluters, their distribution and number may not reflect the distribution and strengths of problem pollutants. Therefore, any judgment concerning the number of stations should be based on more direct factors, such as emissions distribution patterns.

Determination of the Mode of Monitoring Stations

In the past, air pollution monitoring has been primarily accomplished by fixed-station measurements. This practice is probably related to the fact that instruments used in these measurements were mostly of a wet-chemical type, requiring a stable and highly controlled environment. With the rapid advances in instrumentation hardware, mobile monitoring stations have become an important monitoring mode. Although mobile stations usually serve as complementary methods in general air pollution monitoring programs, for perimeter monitoring or for special monitoring programs mobile stations may outperform fixed stations, either on economical or operational grounds. A typical description of the design and test of a mobile station mounted on a van can be found in a report by Ingram and Golden (1969). Other platforms, such as airplanes or even satellites, have also emerged recently as good candidates for the mobile monitoring of air pollution.

Selection of Monitoring Sites

This is, or course, the crucial part of the entire planning process. How close the measurement will fulfill the intended mission of the monitoring program will be judged by the "representativeness" of the measured data, which is in turn critically dependent on the selection of monitoring sites. This issue will be discussed in detail later.

Instrumentation System Selection

Proper selection of the instrumentation system plays an essential role in assuring a successful monitoring program. Among the more important elements are the following:

- Determination of species to be measured.
- Selection of measuring devices, i.e., choice between manual or automated systems.
- Scheduling of sampling frequencies and duration.

Data Acquisition and Analysis

The final link in the measuring system is the transmission and translation of data registered by a sensor. The following considerations should, therefore, be included:

- Establishment of data acquisition and processing system.
- Formulation of procedures for data reduction and analysis, including quality assurance.

The foregoing constitutes a brief outline of the three major components in the design of an air quality monitoring system. However, only the first one, i.e., site selection, is addressed in this report.

SELECTION OF MONITORING SITES

A rational definition of "representativeness" can be made in relation to the objectives of the monitoring program. Therefore, this chapter first presents a set of quantitative definitions of the representativeness of station measurements in terms of some of the objectives discussed in the first chapter. Most air quality standards state that specified maximum concentration levels must not be exceeded more than a certain number of times during specific time periods. Therefore, for air monitoring programs that have compliance with air quality standards as their primary objective, a measure of the representativeness of the data collected at a station would be defined according to the ability of the measured data to reflect true peak concentrations in the region being monitored. In this case, it is important to locate monitoring stations at maxima in the spatial concentration distributions. On the other hand, if the detection of long-term trends is a major monitoring objective, the station measurements can be considered as representative if they are sensitive to the effect of changes in regional source emissions on air quality. It is clear that, to achieve this goal, the ability to measure the rate of change of concentration levels with respect to time--rather than the concentration maxima themselves--is most critical in assessing representativeness. Similarly, other criteria can be established for different monitoring objectives. It should be noted, however, that only the first one--compliance with, or progress toward attainment of, air quality standards--is considered in this study.

In order to locate monitoring stations to identify concentrations which exceed the national ambient air quality standards (NAAQS), one must first make some extremely important interpretations of the standards. First, one must decide what constitutes a violation. Clearly, if we measure close to the tailpipe of an automobile, ambient air quality standards for several pollutants are likely to be violated at all times, even if the vehicle is operating well within emission standards. Therefore, one reaches the conclusion that the standards do not apply directly to air spaces which are close to the tailpipe. In fact, there is no single definition of where standards should apply. Similarly, if one were to measure concentrations at curbside along a busy street, the chances are good that a large number of measurements exceeding the standard could also be expected. Clearly we cannot measure all of them, nor is it necessary. It is thus important to clearly define under what situations the NAAQS are exceeded. Obviously this question cannot be resolved without other considerations, such as population exposure.

In the present study, the method used for identifying concentrations which exceed the NAAQS can be expressed in terms of a Concentration Area Time-Product (CAT-P).

$$\text{CAT-P} = \int_{t^*} \left(\iint_{A} c(x,y,t)\,dx\,dy \right) dt \qquad \text{(II-1)}$$

where A represents an area and t* a time interval for averaging the concentrations. A concept similar to this was proposed by Duckworth (1967) for describing the severity of air pollution episodes. The time intervals can be selected to match those as specified in the ambient air quality standards (for example, 1 hour and 8 hours for carbon monoxide). The choice of averaging area A is dictated by considerations including the spatial resolution of emissions inventory, the size of the region under consideration, and the storage capacity of the computer to be used.

Once a clearly defined interpretation is obtained, the next problem in the selection of monitoring sites is the determination of pollutant concentration variations. Since air pollution is the direct consequence of emissions from sources, an inventory of emissions, including magnitudes and temporal variations, is clearly one of the most important inputs. Meteorological parameters, such as wind speed, wind direction, and atmospheric stability as derived from vertical temperature profiles, are also indispensable in determining the distribution of air pollutants. With the application of a mesoscale air quality simulation model, pollutant distributions on a regional scale can be obtained for varying emission and meteorological conditions.

Finally, since pollutant concentrations are measured only at particular points in a region under consideration, the measurements can be expected to be strongly affected by environmental factors in the immediate vicinity of monitoring sites as selected by the mesoscale model. For example, the measurements on a local scale can be affected by localized sources that can cause local concentration levels to be significantly higher than the average for the area. Local structures can also influence either the air flow field or pollutant dispersion in the vicinity of the monitoring site. At this microscale level, important parameters that are expected to influence the pollutant distributions include:

- Relative magnitude of the local sources.
- Distance from local sources.
- Microscale meteorology.

- Natural topography or man-made structures in the neighborhood of the monitoring site.

Thus it is clear that the actual siting of a monitoring station requires the knowledge of pollutant distributions on the microscale. This problem is discussed in detail in Chapter IV.

APPROACH ADOPTED IN THIS STUDY

The primary goal of the monitoring network to be designed is to identify concentrations which exceed the NAAQS. Therefore, stations are to be located in such a fashion as to minimize the probability of not detecting a violation. Carrying out this objective requires interpretation of a number of related issues.

The first issue, as discussed in the previous section, concerns the interpretation of the NAAQS. A Concentration Area Time-Product (CAT-P), given by equation II-1, is used for identifying the concentrations which exceed the NAAQS. Assuming that this is appropriate, the use of a mesoscale model would be ideally suited for computing the CAT-P as follows:

$$\text{CAT-P} = c(x,y,t)\Delta x\Delta y\Delta t \qquad \text{(II-2)}$$

where

$c(x,y,t)$ = computed concentration

$\Delta x, \Delta y$ = step size in the x- y- directions

Δt = step size in time.

Although, in principle, the mesoscale model can be used to obtain annual or long-term averages, it is not practically feasible. Because it is implicitly assumed that the monitoring system is to be designed for long-period operation, the question then arises as to how to include the long-term fluctuations in the pollutant concentrations due to not only daily but also seasonal variations of the meteorological parameters in the area. The problem can be treated by using a frequency-weighted concentration expressed as an index called the Figure of Merit.

The Figure of Merit for a particular point can be defined in general as the sum of the products of the ground-level concentrations and the associated frequencies of occurrence. Two types of Figures of Merit are of particular interest to the present study--one for exceeding ambient air quality standards and one for general air quality monitoring.

For each of the grid points in the modeling region, the Figure of Merit for exceeding standards can be defined as follows:

$$F(j,k) = \sum_{\ell} \begin{pmatrix} 1, \text{ if AAQS are exceeded at grid point } j,k \text{ under meteorological pattern } \ell \\ 0, \text{ if not} \end{pmatrix} \cdot \begin{pmatrix} \text{probability of meteorological pattern } \ell \end{pmatrix} \qquad \text{(II-3)}$$

Thus, this Figure of Merit is a measure of the probability that each grid point is likely to indicate when an air quality standard is exceeded.

Similarly, a Figure of Merit for general air quality monitoring can be defined as

$$F(j,k) = \sum_{\ell} \begin{pmatrix} \text{concentration at grid point } j,k \text{ under meteorological pattern } \ell \end{pmatrix} \cdot \begin{pmatrix} \text{probability of meteorological pattern } \ell \end{pmatrix} \qquad \text{(II-4)}$$

This index represents an average pollutant concentration at each grid point as weighted by the frequency of occurrence.

In order to implement the scheme, it is necessary to specify a set of scenarios which completely describe the meteorological conditions in the area of concern. This can be accomplished by examining climatological data in the region of interest.

Once a set of meteorological scenarios is determined, the mesoscale model can be exercised to provide the corresponding pollutant distributions. The resultant ground-level concentration distributions, in conjunction with the associated frequencies of occurrence, can then be used to compute the Figure of Merit for siting potential monitoring stations. A computer program has been prepared to perform these calculations. To illustrate the use of this program, values for Figure of Merit defined by equation II-4 were computed using simulated surface carbon monoxide (CO) distributions in ppm for a 1-hour period during peak traffic for two separate days (see Figures II-1 and II-2) for a hypothetical region with 1- by 1-km grid squares. Figure of Merit values were calculated under the assumption that these situations have an equal probability of occurrence. An isopleth plot of these values is presented in Figure II-3. The computer program also takes the resultant values for the Figure of Merit and searches for the highest values which are not adjacent to other higher values without an intervening trough. As shown in Figure II-4, locations for the 16 highest Figures of Merit were identified, ranked, and plotted.

In conclusion, it should be emphasized that the procedures described above are by no means definitive. They are proposed here only to illustrate an idealized concept for the objective and systematic determination of air quality monitoring stations as outlined in this chapter. Modifications of the basic approach are certainly possible and probably desirable. For example,

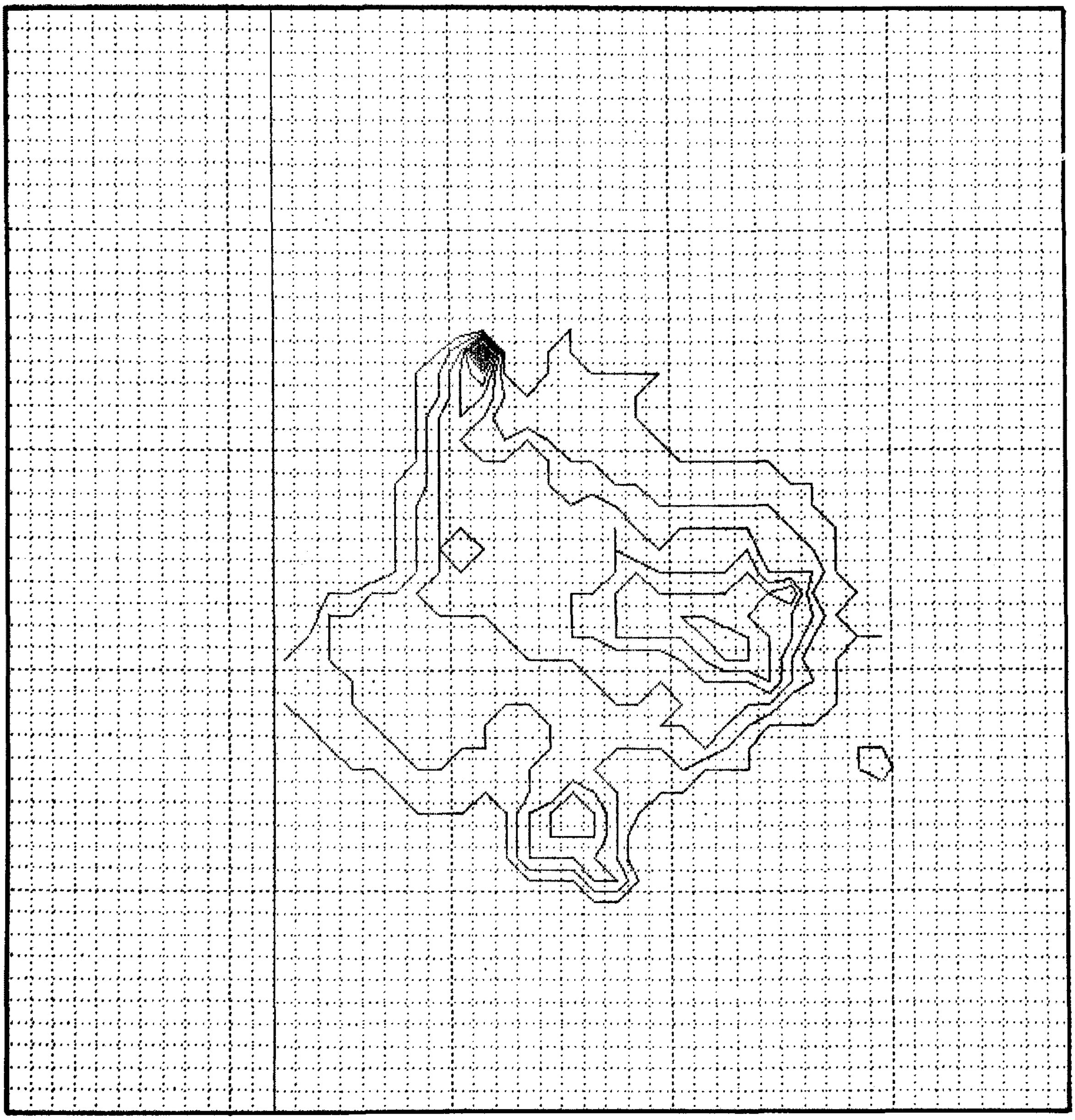

Figure II-1. Simulated surface carbon monoxide distribution across a hypothetical region for the hour of peak traffic for a particular day. Grid squares are 1 km and isopleth increment is 1 ppm. (Day 1)

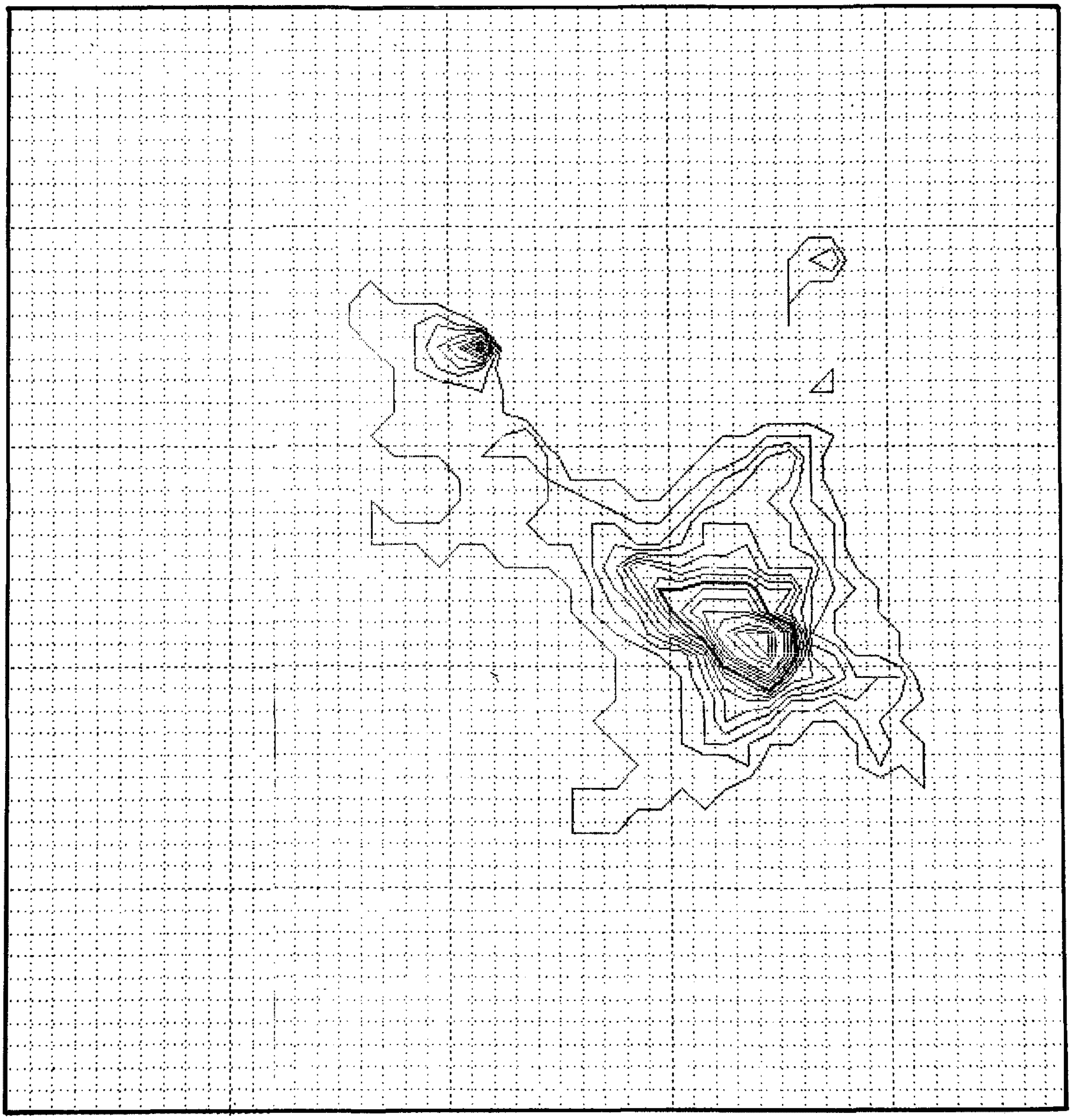

Figure II-2. Simulated surface carbon monoxide distribution across a hypothetical region for the hour of peak traffic for a particular day. Grid squares are 1 km and isopleth increment is 1 ppm. (Day 2)

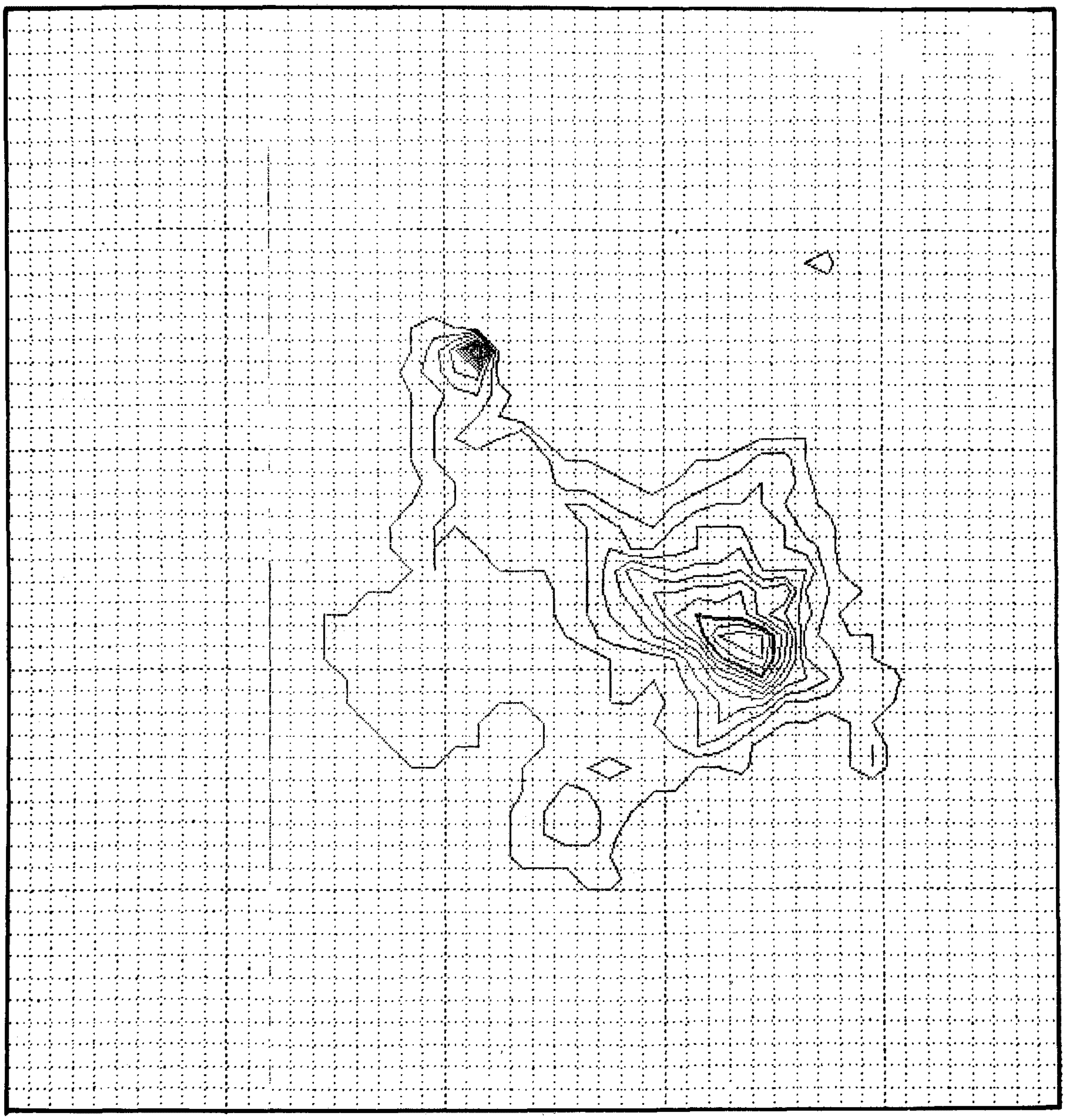

Figure II-3. Figure of Merit distribution for data in Figure II-1 and II-2. Isopleth increment is 1 ppm.

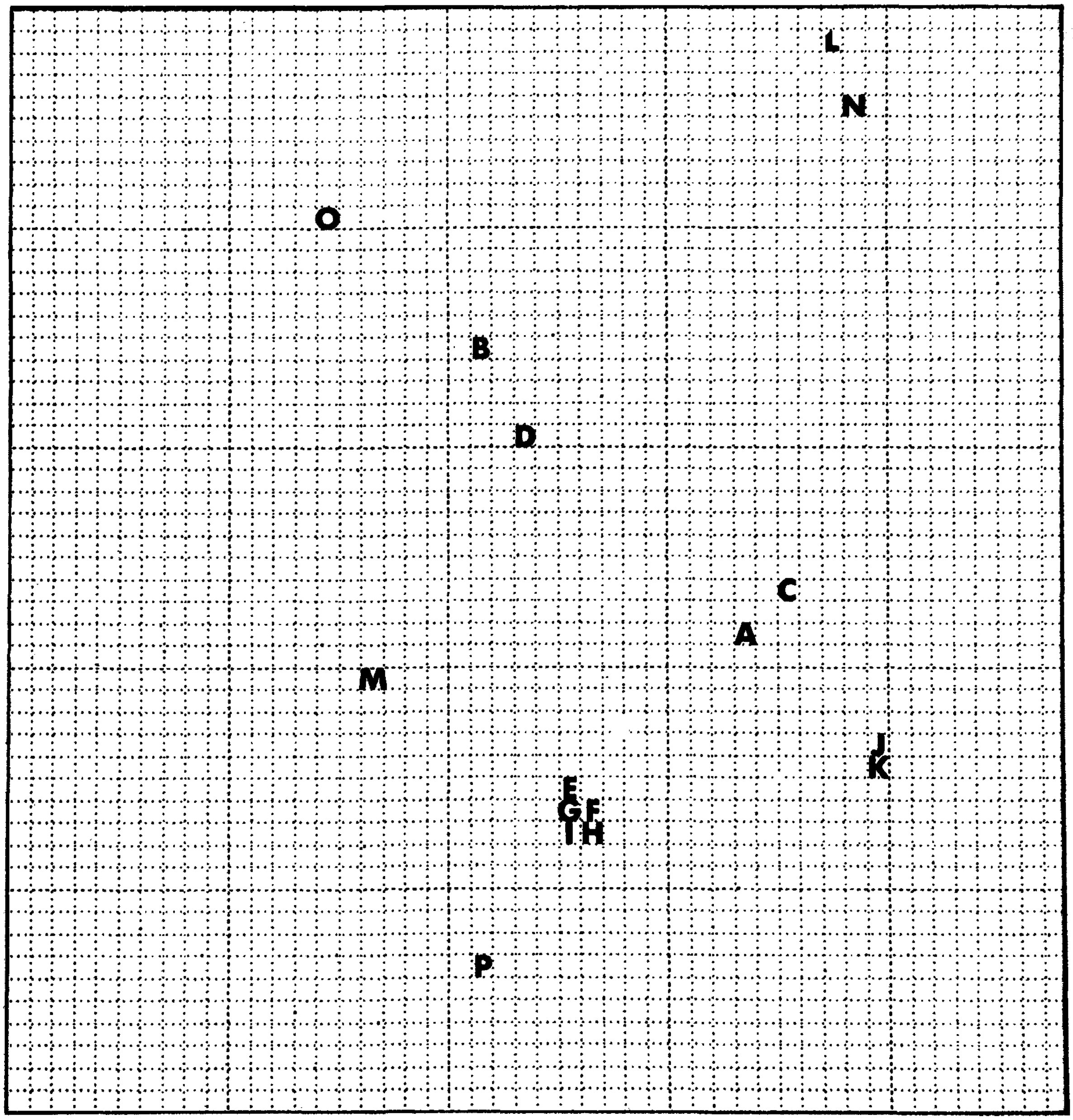

Figure II-4. Ranking of the potential monitoring sites by Figure of Merit for data in Figure II-3.

normalization of the Figure of Merit as defined by equations II-3 and II-4 or inclusion of demographic information may yield new definitions which are intuitively more appealing. On the other hand, a close examination of the averaging time is required to clarify certain ambiguities in the definitions of the Figure of Merit. These questions apparently warrant future considerations.

CHAPTER III

ANALYSIS AT THE MESOSCALE LEVEL

The approach adopted in this study for siting monitoring stations is based on the concept of a CAT-P for identifying the locations of grid areas in a region whose concentrations exceed the NAAQS. Since grid models normally compute space- and time-averaged pollutant concentrations, it appears that this type of air quality simulation model is ideally suitable for such an application. The first section of this chapter is thus devoted to a discussion of the mesoscale or regional model selected for this project. The second section then addresses the very important question concerning the incorporation of an improved vertical diffusivity algorithm into the model.

A DESCRIPTION OF THE MESOSCALE AIR QUALITY SIMULATION MODEL

The goal of the mesoscale analysis is the accurate determination of pollutant distributions on the regional scale under a variety of emission and meteorological conditions. This can be achieved by use of a mesoscale air quality simulation model. The model selected for the present project was developed by Systems Applications, Inc., (SAI) (Reynolds et al., 1973; Roth et al., 1974; Reynolds et al., 1974). The model is based on the following simplified form of the equation of mass balance for an inert pollutant species like carbon monoxide (CO):

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) \qquad \text{(III-1)}$$

where: c is pollutant concentration; t is time; x,y, and z are the space coordinates; u,v,w are wind speeds in the x,y, and z directions; and K_x, K_y, and K_z are turbulent eddy diffusivities in the x,y, and z directions.

This partial differential equation in four dimensions (x,y,z,t) is solved by a finite-difference technique. The method of fractional steps (Yanenko, 1971) is applied by splitting the original 4-dimensional equations into three, 2-dimensional equations in (x,t), (y,t), and (z,t), respectively. The solution is explicit and direct in the line (x,t) and (y,t) fragments and implicit and iterative in the (z,t) fragment. The emissions from areal and point sources within the region under consideration enter the model equation as boundary conditions, via the following expression:

$$-K_z \frac{\partial c}{\partial z}\bigg|_{z=0} = Q\ (x,y,t) \qquad \text{(III-2)}$$

where:

Q (x,y,t) is the pollutant emission rate.

The top of the modeling region is usually set at the base of an elevated inversion or stable layer capping the atmospheric mixing layer. With the modified diffusivity scheme, which is discussed in the next section, this condition can be relaxed. For example, under a stably stratified atmosphere, the top of the modeling region can be chosen at a height above which pollutant concentrations level off to the background values.

The 3-dimensional wind field (u,v,w) as a function of time is considered as an input that must be prescribed. In the present model, the 3-dimensional wind field is calculated based upon surface wind measurements via an interpolation algorithm (Liu et al., 1973). The generation of ground-level wind speed and direction at a particular grid cell in time is based on the interpolation of the field measurements using a weighted inverse square of the distance between station locations and the grid cell under consideration. Once the surface wind is computed, the wind speeds and directions in upper levels can be calculated based on the continuity equation of mass.

One of the important assumptions invoked in the derivation of the model equation discussed above is the gradient transfer approximation, also known as the K-theory. This approximation is tantamount to assuming that the turbulent transfer of pollutants in the atmosphere is proportional to the gradient of the mean concentration. For the SAI model, according to a sensitivity study carried out by Liu, et al., (1975), an order-of-magnitude change in the horizontal eddy diffusivity will only affect the predicted surface concentration by less than 3 percent. Thus, a constant value of 50 m^2/s is used which is compatible with a grid square up to a few kilometers on a side.

In a previous study, a simple scheme incorporating a height and wind-speed dependence was used for the prescription of the vertical eddy diffusivity (Reynolds, et al., 1973). It was found to be satisfactory for the Los Angeles basin during daylight hours. However, the application of the model to other regions of interest and for other diurnal periods of the day requires the use of a more generalized diffusivity algorithm. The following section is devoted to a discussion of the basic limitations of the K-theory and development of such an algorithm.

APPROXIMATION OF TURBULENT TRANSFER BY EDDY DIFFUSIVITIES

Like many other related studies of the atmosphere, a difficult and also crucial part in the simulation of pollutant dispersion is the attainment of a reasonable scheme to represent the turbulent processes. Theoretical studies based on higher closure schemes for hierarchies of turbulence moment equations have recently been carried out (e.g., Deardorff, 1970, 1972). However, these have been restricted in application to certain special cases and require considerable computational effort. Thus, an alternative based on the simple concept of turbulent eddy diffusivities--the K-theory--is adopted in most atmospheric dispersion models of the type used here. Analogous to the molecular diffusion, the K-theory speculates that a pollutant flux in the direction of decreasing concentration is established as a result of turbulent fluctuations. The magnitude of this flux is proportional to the gradient of the average concentration. Thus:

$$\overline{u'c'} = - K_x \frac{\partial c}{\partial x} \qquad \text{(III-3)}$$

$$\overline{v'c'} = - K_y \frac{\partial c}{\partial y} \qquad \text{(III-4)}$$

$$\overline{w'c'} = - K_z \frac{\partial c}{\partial z} \qquad \text{(III-5)}$$

The limitations of models based on the K-theory or the gradient transport theory are well known. They can be generally grouped into the following two categories:

- Length and time-scale constraints;
- Directional constraints.

The first type is related to the spatial and temporal homogeneity of the mean concentration field. Corrsin (1974) summarized the conditions necessary for satisfying such constraints:

- The transport mechanism length scale must be much smaller than the distance over which the curvature of the mean transported field gradient changes appreciably.
- The transport mechanism time scale must be much smaller than the time during which the mean transported field gradient changes appreciably.
- The transport mechanism length scale must be essentially constant over a distance for which the mean transported field changes appreciably.

The second constraint arises when, for example, the Reynolds stress, a second-order tensor, is replaced by an inner product of a second rank tensor and a vector. The conditions for satisfying this constraint are more difficult to delineate. However, qualitative estimates for the validity of the mesoscale model based on the equation of mass balance for a pollutant species were obtained by Lamb and Seinfeld (1973). The result seemed to indicate that the gradient-transport approach is plausible under a variety of conditions.

Based on a comprehensive review of the literature, an algorithm for prescribing the eddy diffusivity in the vertical was adopted. In the surface layer, the following general formula was used:

$$K_z = \frac{ku_* z}{\phi\left(\frac{z}{L}\right)} \quad , \qquad (z_0 \leq z \leq |L|) \qquad \text{(III-6)}$$

where

k = von Karman constant (= 0.35)

u_* = friction velocity

z = height

L = Monin-Obukhov length

z_0 = surface roughness

$\phi(\ )$ = a functional relationship to be specified.

This formula is the result of the similarity theory for the constant-flux surface layer (Businger et al., 1971). For the neutral case, the ϕ-function equals unity. For the stable or unstable case, the ϕ-function is greater or less than one respectively. The following empirical expressions for the ϕ-function were proposed by Businger et al., based on observational data.

For the stable case ($L > 0$)

$$\phi\left(\frac{z}{L}\right) = 1 + 4.7\left(\frac{z}{L}\right) \qquad \text{(III-7)}$$

For the unstable case ($L < 0$)

$$\phi\left(\frac{z}{L}\right) = \left(1 - 15\frac{z}{L}\right)^{-\frac{1}{4}} \qquad \text{(III-8)}$$

The friction velocity was determined by the following equation,

$$u_* = \frac{kU_r}{f} \qquad \text{(III-9)}$$

where U_r denotes a reference horizontal wind speed measured at a reference height, Z_r, and

$$f = \ln \left(Z_r / z_o \right) + 4.7 \left(\frac{Z_r - z_o}{L} \right) \qquad \text{(III-10) (stable)}$$

or

$$f = \ln \left[\frac{1 - \phi\left(\frac{Z_r}{L}\right)}{1 + \phi\left(\frac{Z_r}{L}\right)} \right] - \ln \left[\frac{1 - \phi\left(\frac{z_o}{L}\right)}{1 + \phi\left(\frac{z_o}{L}\right)} \right]$$

$$+ 2 \tan^{-1} \left[\frac{1}{\phi\left(\frac{Z_r}{L}\right)} \right] - 2 \tan^{-1} \left[\frac{1}{\phi\left(\frac{z_o}{L}\right)} \right] \qquad \text{(III-11) (unstable)}$$

Above the surface layer ($|L| \leq z \leq Z_i$), a second-order interpolation formula first proposed by O'Brien (1970) was utilized:

$$K_z(z) = K_{z_i} + \left(\frac{Z_i - z}{Z_i - |L|} \right)^2 \cdot \left\{ K_z(|L|) - K_{z_i} + (z - |L|) \cdot \left[K_z'(|L|) + 2 \left(\frac{K_z(|L|) - K_{z_i}}{Z_i - |L|} \right) \right] \right\} \qquad \text{(III-12)}$$

where Z_i = height of stable layer capping mixing layer or height above which pollutant concentrations level off to background values (stable conditions).

K_{z_i} = vertical diffusivity of height i.

$$K_z'(|L|) = \left. \frac{d\, K_z(z)}{dz} \right|_{z = |L|}.$$

The implementation of the proposed diffusivity scheme requires an estimate of the Monin-Obukhov length. The Monin-Obukhov length can be in general related to the Richardson number which can be, in turn, determined experimentally (McElroy, 1969). The estimate of this length was, however, accomplished in the present study via the following formula which relates the Monin-Obukhov length to the surface roughness, z_o, and the stability function, S,

$$L = \left\{ (a_1 S + a_2 S^3) \; z_o^{-(b_i - b_2|S| + b_3 S^2)} \right\}^{-1} \qquad \text{(III-13)}$$

where

$a_1 = 0.004349$

$a_2 = 0.003724$

$b_1 = 0.5034$

$b_2 = 0.2310$

$b_3 = 0.0325$

This formula is a result of the best-fit of observational data reported by Golder (1972). The stability function, S, a digital version of the Pasquill stability category (see Table III-1), can be calculated as follows:

$$S = \frac{1}{2} (3 - d_w + |d_e|) \cdot \text{Sign } (d_e) \qquad \text{(III-14)}$$

where

$$\text{sign } (d_e) = \begin{cases} 1 & d_e > 0 \\ 0 & d_e = 0 \\ -1 & d_e < 0 \end{cases}$$

and d_w and d_e are the wind speed class and exposure class. These are defined as follows:

$$d_w = \begin{cases} \frac{U_r}{2} & 0 \leq U_r \leq 8 \text{ m/s} \\ 4 & U_r \geq 8 \text{ m/s} \end{cases}$$

$$
d_e = \begin{cases} 3 & \text{strong} \\ 2 & \text{moderate} \\ 1 & \text{slight} \end{cases} \text{ daytime insolation}
$$

$$
d_e = \begin{cases} 3 & \text{strong} \\ 2 & \text{moderate} \\ 1 & \text{slight} \\ 0 & \text{heavy overcast} \\ -1 & \geq \frac{4}{8} \\ -2 & \leq \frac{3}{8} \end{cases}
\quad
\begin{array}{l} \text{daytime insolation (3, 2, 1)} \\ \text{day or night (0)} \\ \text{nighttime cloudiness. (-1, -2)} \end{array}
$$

TABLE III-1. PASQUILL CATEGORY AND STABILITY FUNCTION

Pasquill Category*	Stability Function, S
A	-3
B	-2
C	-1
D	0
E	+1
F	+2

*Turner (1969)

The prescription for the computation of the vertical eddy diffusivity is now completed. The primary inputs are the wind speed, the reference height Z_i, the exposure class, and the surface roughness. The result of a sample calculation is included in Figure III-1. Note that an approach for the determination of vertical eddy diffusivities generally similar to the above was suggested by Myrup and Ranzieri (1975).

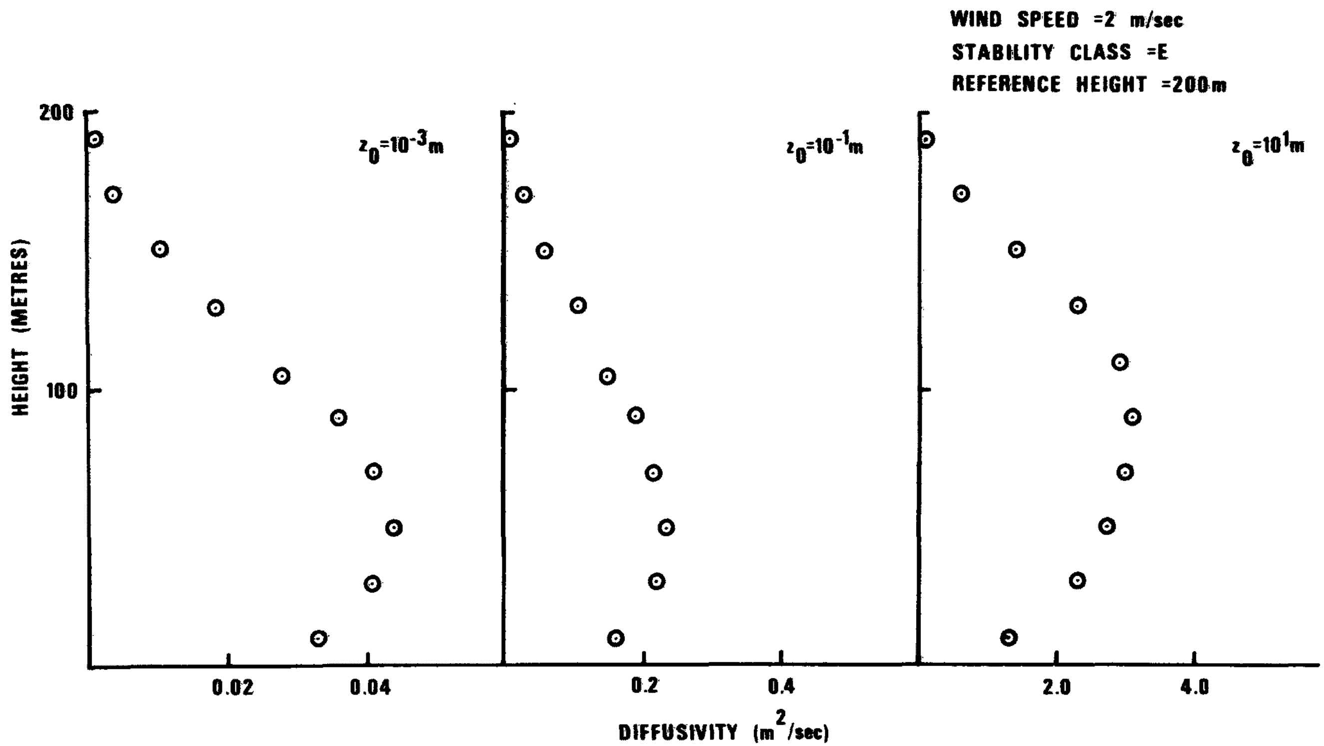

Figure III-1. Calculated vertical diffusivity as a function of height.

CHAPTER IV

ANALYSIS AT THE MICROSCALE LEVEL

The primary objective of the microscale analysis is to pinpoint the monitor in a microscale environment within the area identified by the mesoscale analysis. The major task is to find a sensor location at which the sensor's readings are not unduly influenced by local sources.

OVERVIEW

The problem of selecting monitoring sites on the microscale arises because the mesoscale model predictions only provide an average estimate of the pollutant concentration over a large geographical area (typically this area represents a 1-km by 1-km square), while a conventional sensor measures only a point value at some arbitrary location within the grid square. Depending on the emissions and meteorology pattern and the relative sensor location, the sensor may or may not provide a measurement which can be considered as a representative value for the grid square. Clearly, what is needed is an analysis at the microscale to establish a methodology for locating the sensor on the microscale and a method for relating its readings to a mesoscale average value.

The only previous work related to the siting of monitors on a local scale was that of Ludwig and Kealoha (1975) which forms the basis of the current EPA siting guidelines for CO (U.S. EPA, 1975). The essential feature of their analysis consisted of defining a variety of locations at which a monitor could conceivably be placed (street, canyon, corridor, neighborhood, etc.) and the various types of measurement one could make (peak, average, etc.). As a criterion for siting for corridor and neighborhood stations, Ludwig and Kealoha characterized the roadway as a Gaussian line source,

$$c = \frac{2Q}{\sqrt{2\pi}\, U\sigma_z \sin\theta} \exp\left[-\frac{1}{2}\left(\frac{z^*}{\sigma_z}\right)^2\right] \qquad \text{(IV-1)}$$

where:

c = concentration (g/m^3)

Q = source strength (g/m/s)

U = horizontal wind speed (m/s)

σ_z = standard deviation of a Gaussian plume in the vertical (m)

θ = angle between wind and line source (degrees)

z^* = height to instrument inlet (m).

The dispersion coefficient, σ_z, was represented by the equation

$$\sigma_z = as^b \tag{IV-2}$$

where a and b are functions of the Pasquill stability class and s is downwind horizontal distance. When the conditions that either the contribution from any one source be small or that the gradients of such contributions be small were imposed, the following inequalities were derived,

$$\frac{2Q}{\sqrt{2\pi}\, U\sigma_z \sin\theta} < C_{max}$$

$$\left| \frac{1}{c \sin\theta} \; \frac{\Delta c}{\Delta s} \right| < G_{max}$$

where C_{max} is the maximum allowable contribution of any one source to the concentration and G_{max} is the desired maximum concentration gradient away from the roadway. With the following typical values for the various parameters,

θ = 40 degrees

U = 1 m/s

C_{max} = 0.001 g/m^3

G_{max} = 0.002/m

Q = 0.07 g/m/s

they were able to determine the minimum distance between a large roadway and a neighborhood monitoring site. Given the uncertainties in the Gaussian model and the assumptions involved in its implementation, this approach may have furnished a qualitative analysis, but it did not provide quantitative information on pollutant concentrations at such site locations under a variety of atmospheric and emission conditions. In addition, the method failed to provide information on the representativeness of data obtained from stations located at places other than their suggested locations.

REPRESENTATIVENESS OF MEASUREMENTS ON THE MICROSCALE

Fundamental to the microscale analysis is the concept of the representativeness of the measurements; i.e., given a point-measurement value, at what monitor location can the measured value be considered as representative of an average concentration value over a predetermined length scale? Schematically, this situation is illustrated in Figure IV-1 for a single roadway with emission rate, Q, and sensor at distance, ρ, downwind and height, z*, above the roadway.

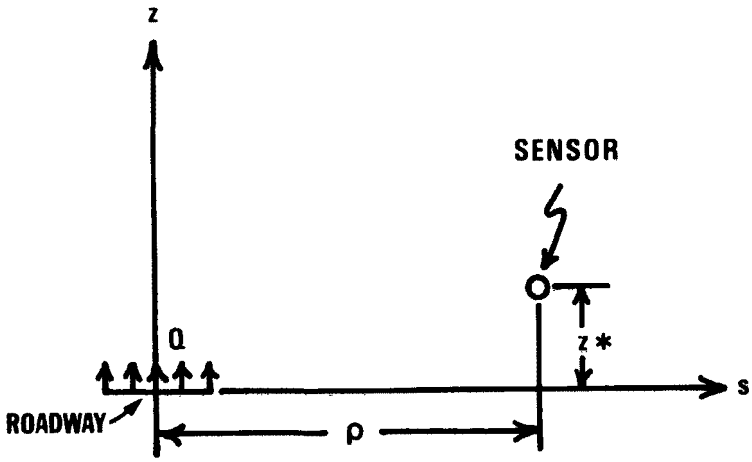

Figure IV-1. Schematic diagram of roadway and sensor location.

To simplify the analysis, a steady state condition was assumed for an infinite line source normal to the s-direction. The wind was assumed to blow in the s-direction and have a speed varying with height. For this case, the equation of mass balance for a species reduced to:

$$U \frac{\partial c}{\partial s} = \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) \qquad \text{(IV-3)}$$

in which both wind speed, U, and vertical diffusivity profiles must be specified a priori. In addition, the emission rate enters the equation as a boundary condition:

$$K_z \left.\frac{\partial c}{\partial z}\right|_{z=0} = -Q. \qquad \text{(IV-4)}$$

Since most sensors are located at a recommended height of 3 meters above the ground (z^* = 3 meters), variations in the vertical were eliminated in the final analysis by merely examining those concentration profiles at the 3-meter level.

To mathematically quantify the meaning of representativeness, the mean value theorem of calculus expressed as

$$c(\rho,3)\,D = \int_0^D c(s,3)\,ds \qquad 0 < s < D \qquad \text{(IV-5)}$$

D = distance downwind of roadway

was used, from which the mean value of the concentration in the interval [0,D] can be computed and the location of the sensor ρ predicting this value obtained. Graphically, these two quantities are illustrated in the following figure:

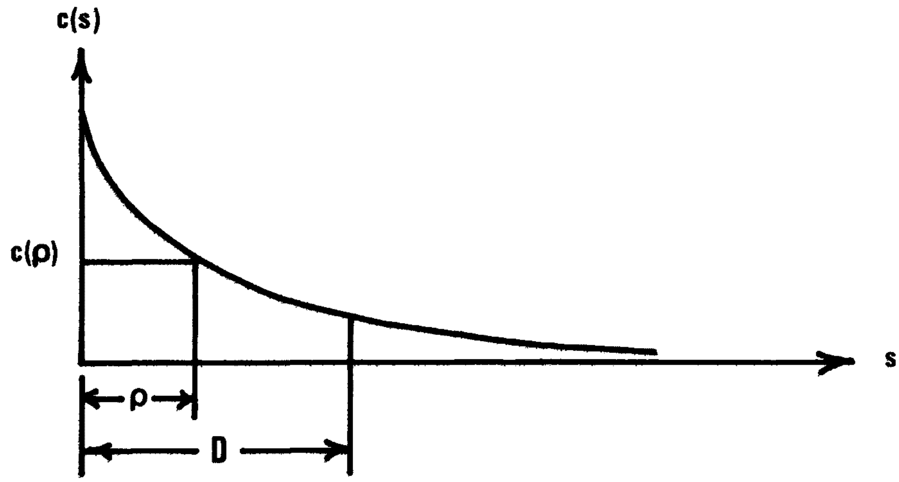

Figure IV-2. Relationship of sensor location to measured concentration.

For various emissions rates, wind profiles, and Pasquill stability classes, a series of charts can be constructed relating ρ to D.

SOLUTION METHODOLOGY

Two basic difficulties were encountered in trying to solve the governing equation:

$$U \frac{\partial c}{\partial s} = \frac{\partial}{\partial z} \left(K_z \frac{\partial c}{\partial z} \right) \qquad \text{(IV-6)}$$

to predict the downwind pollutant concentration profiles. The first of these was related to the inherent mathematical difficulties associated with the prediction of concentration values within 10 meters of the ground surface and the second was associated with the assumptions concerning the velocity and diffusivity profiles at these same heights.

Although a variety of mathematical methods are available to solve parabolic differential equations, the particle-in-cell method was adopted. It is best suited for highly accurate solutions in cases where near ground-level values are important. Unlike computing finite differences which are limited by cell-size considerations and plagued by numerical instabilities in regions with steep gradients, the particle-in-cell formulation is capable of providing stable and accurate solutions when a sufficiently large number of particles are used. Originally developed by Harlow and Welch (1965) and modified by Hotchkiss and Hirt (1972), the method was used successfully by Sklarew et al. (1971) to predict mesoscale pollutant values for nonreactive pollutants. Following the practices of Sklarew, particles were generated in proportion to the emissions rate, Q, and advected laterally via the relationship

$$S_i(t + \Delta t) = S_i(t) + U(z_i)\ \Delta T \qquad \text{(IV-7)}$$

where

S_i = downwind position i-th particle

$U(z_i)$ = wind speed at height z_i

Δt = time step

z_i = height of particle i.

To account for vertical diffusion, the algorithm of Hotchkiss and Hirt (1972) was used in which vertical height was computed via the expression

$$z_i(t + \Delta t) = z_i(t) + \sqrt{4K_{z_i}\ \Delta t\ \Gamma} \qquad \text{(IV-8)}$$

where

K_{z_i} = vertical diffusivity at height z_i

Γ = normally distributed random variable between $\pm \infty$ with mean zero and unit standard deviation

Wind speed profiles near the ground may be represented by a power law model of the form

$$\frac{U}{U_r} = \left(\frac{z}{Z_r}\right)^n \qquad \text{(IV-9)}$$

in which the exponent n is a function of stability and r refers to parameter values at a reference height. The n values calculated as a function of atmospheric stability can be related to Pasquill stability classes. Table IV-1 lists stability dependent values of mass provided by DeMarrais (1959). The n values were assumed applicable to Pasquill classes in the manner shown in this table. Since automobiles generate a wake as they move, it could be anticipated that the wind speed does not smoothly decay to zero as the surface is approached as predicted by the power law model. According to a study carried out by the California Department of Transportation (Ranzieri and Ward, 1975), the movement of a vehicle gives rise to a 4-meter-high mixing cell "above the roadway" in which both dispersion and meteorological parameters are roughly uniform. For this reason, the wind speed profile was modified in such a way that in the range between 0 and 4 meters above the ground the speed would be set to the 4-meter value.

TABLE IV-1. EXPONENTS FOR WIND PROFILE

Pasquill Stability Class	Exponent n
A	0.1
B	0.15
C	0.20
D	0.25
E	0.35
F	0.30

Finally, estimates of the eddy diffusivities were computed from algorithms discussed earlier in Chapter III as based on the semi-empirical theory discussed earlier which includes the effects of wind speed, surface roughness, stability class, and vertical height.

To facilitate the computations in the microscale analysis, the Monin-Obukhov lengths for typical values of surface roughness around a roadway were estimated. These lengths as a function of prevailing atmospheric stability class are listed in Table IV-2. As was the case with the wind speed profiles, the diffusivity values were assumed to be uniform in the interval between zero and 4 meters above the surface and equal to the 4-meter value.

TABLE IV-2. MONIN-OBUKHOV LENGTH VERSUS PASQUILL STABILITY CLASS

Stability Class	Monin-Obukhov Length L (m)
A	-9.09
B	-22.9
C	-133.3
D	∞
E	159.2
F	16.0

Although the methodology developed here was for the simple case of a single roadway, this method may be extended to more complex situations in which the same type of analysis is possible. For example, if several roadways have to be dealt with, the contributions of each roadway must be superimposed.

CHAPTER V

FIELD MEASUREMENT PROGRAM

Application of mesoscale analysis requires that the validity of the model used be demonstrated for the region to which it is applied. Accordingly, an observational program must be developed to support the verification effort. One approach toward establishing such a program proceeds as follows:

Various attributes of the area are considered such as the size of the region, land use, population density, emission patterns, topography, etc. Examinations of historical information and current data collection activities are made in order to determine their completeness. Based on this examination, any supplemental monitoring needs can be identified. Thus, pollutants to be monitored and meteorological conditions to be observed can be specified. A decision is made on the number of meteorological and air quality monitoring sites, the specific locations, and the instrumentation required. Other requirements are specified such as resolution, frequency, duration, and extent of observations and required accuracy, specificity and precision of the measurements.

MODELING REGION

To provide a reference system for measurement site locations, a grid structure should be developed for the modeling region selected. The boundaries of the modeling region must be defined. A grid size is to be specified for the area which would be oriented on the Universal Transverse Mercator (UTM) grid system. The UTM coordinate system is suggested in order to conform to the format of available data. This grid also provides a reference for topographic information and emission source locations.

In a modeling region such as the Las Vegas Valley, the ridgelines of the surrounding mountains define the boundaries for which a grid structure could be developed. A map of this region (Figure V-1) shows the flat, gradually sloping valley surrounded by the Las Vegas Range to the north, Frenchman and Sunrise Mountains to the east, the Spring Mountains to the west, and the McCullough Range to the south. The urban area consists of vacant desert scattered among the residential developments. The population of over 300,000 people is distributed over a larger area than other urban communities of equivalent population. Note that a limited access interstate highway traverses the city and major highways crisscross the valley providing access from Arizona to northwestern Nevada, and from California to Utah. A large grid of four-and-six-lane arterial streets and an intermeshed network of secondary roadways accommodate local traffic in the valley.

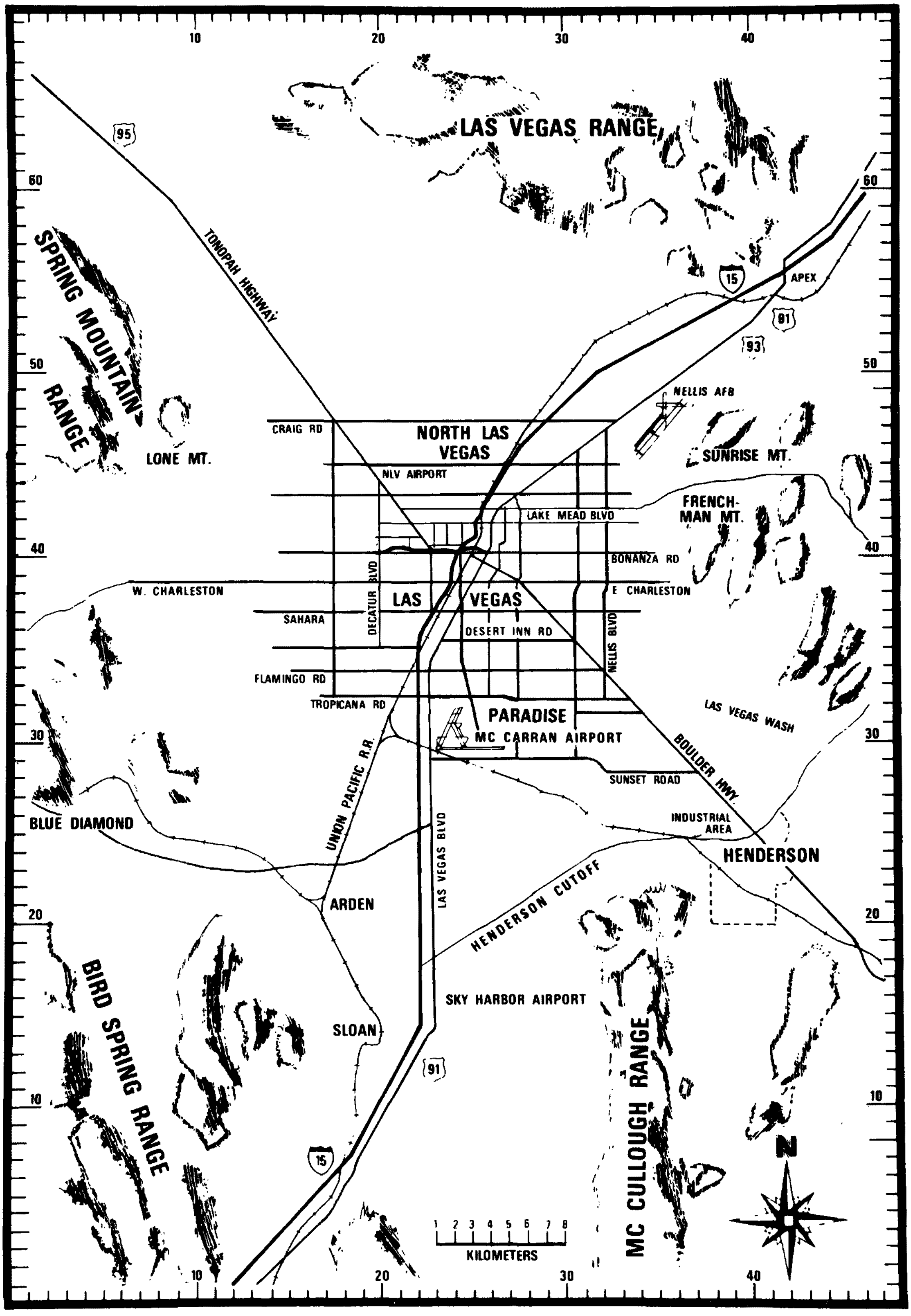

Figure V-1. Map of Las Vegas Valley.

HISTORICAL INFORMATION

A survey and preliminary analysis of available aerometric data are necessary for planning of the field measurement program. For example, this will provide guidance for locating field sampling equipment, developing meteorological scenarios, and determining periods of field-data collection for both continuous monitoring and intensive measurement efforts.

Region-wide aerometric data may be available from Federal, State, and local agencies, particularly with regard to the monitoring and other provisions of the Clean Air Act. These agencies and private concerns may also have such data for specific areas in the region regarding environmental impact assessments. Many of the programs may be ongoing and yield quantitative information useful in developing pollutant emission inventories.

Usually, meteorological data are collected routinely by the National Weather Service (NWS) at a local airport station or by the military at their installations. In some regions, the NWS has data available for locations in metropolitan areas. In addition, weather stations are operated in cooperation with the NWS by other Federal agencies often at small airports and military establishments. Data from these and other sources are compiled and stored at and are available from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Center (NCC) in Asheville, North Carolina. Inquiries should be made to the NCC regarding such data including climatic and other summaries and results of special studies using the data.

NWS airport stations providing near-surface weather information are located about 90 km apart. They nominally report at 1-hour intervals weather information including that on cloud cover, visibility, barometric pressure, air temperature and moisture, precipitation, and wind speed and direction. Some NWS, military, and cooperative stations operate on less than a 24-hour per day schedule and/or report only certain of the above weather elements.

NWS stations providing upper air data on temperature, moisture, and wind speed and direction are situated about 370 km apart. Vertical soundings of these parameters are made nominally at 0000 and 1200Z (international standard time). Some military installations also take such soundings on this time schedule. Additionally, some NWS and military weather stations, including many of the above, take vertical soundings of only wind speed and direction; the frequency and schedules for these soundings are often dependent upon the local station responsibilities and, hence, may be irregular.

SAMPLING RATIONALE AND PLAN

A period of sampling must be chosen both for the continuous monitoring and the intensive measurement programs. The examination of historical aerometric data may allow a determination of both the primary season(s) of interest and the meteorological situations for which abnormally high levels of air quality are likely to occur in the region under consideration.

In a region such as the Las Vegas Valley, the period for full scale sampling of CO both for the routine and intensive programs would be November through February, inclusive. From a meteorological standpoint the conditions potentially conducive for high CO concentrations occur most frequently during this period. This might be expected since CO is emitted primarily from near ground-level sources and the ventilation rate, which is comprised of the products of mixing depth and the average wind speed through the depth, is smallest during this period. The available historical data on CO levels in the Las Vegas Valley indicate that the CO values are in phase with this meteorological pollution potential.

Las Vegas, which is situated in semi-arid terrain, experiences a desert-type climate characterized by nearly clear skies, a large diurnal temperature change, and a strong nocturnal surface-based inversion. Periods of minimal pollutant dispersal, both horizontally and vertically, are associated with the occurrence of the nocturnal inversion, especially with the normally decoupling of air from upper levels with higher wind speeds from the air within the inversion layer. The inversion begins to dissipate and its base begins to rise shortly after sunrise. Because of the relatively large temperature increase in the portion of the inversion nearest the ground, its base rises slowest in the first few hours after sunrise. The inversion normally reforms at the surface beginning around sunset. The times of sunrise and sunset on an annual basis for the local area are shown graphically in Figure V-2. As is shown in this figure, sunrise occurs later and sunset earlier during the November through February period than during the rest of the year. Where it is demonstrated that motor vehicles generate the major portion of the emissions of CO, times of peak emission are critical. Locally, these occur between 0630-0830 and 1600-1800 local standard time (LST). Thus, the times of peak emissions coincide most often with diurnal periods of minimal pollutant dispersal in the November through February period. Hence, highest short-term (on the order of a few hours) concentrations of CO can reasonably be expected to occur most frequently during this part of the year.

Periods for short term intensive sampling can usually be chosen on the basis of forecasts of synoptic scale weather patterns over the region of interest. In the Las Vegas Valley, days with particularly limited atmospheric dilution could be selected. Such situations generally occur when the valley is under the direct influence of a slowly moving or stagnant high pressure area. A major constraint on intensive sampling in the valley would be the elimination of weekends for which an adequate CO emission inventory cannot be established from available data.

Weather forecasts for intensive sampling can be made using facilities available at the nearest NWS station. Here, surface and upper air data described previously and special aircraft and ship weather reports for at least the contiguous U.S. are routinely collected by teletype. Usually, charts are available covering this area plus portions of the adjacent oceans. They contain observed and forecast weather information for ground level and various constant pressure surfaces above ground. Additionally, special forecast information is available, generally resulting from simulations with synoptic-scale meteorological models.

Specific forecasts in this manner are developed for periods up to 72 hours in advance. In reality, forecasts for periods 48 to 72 hours in advance

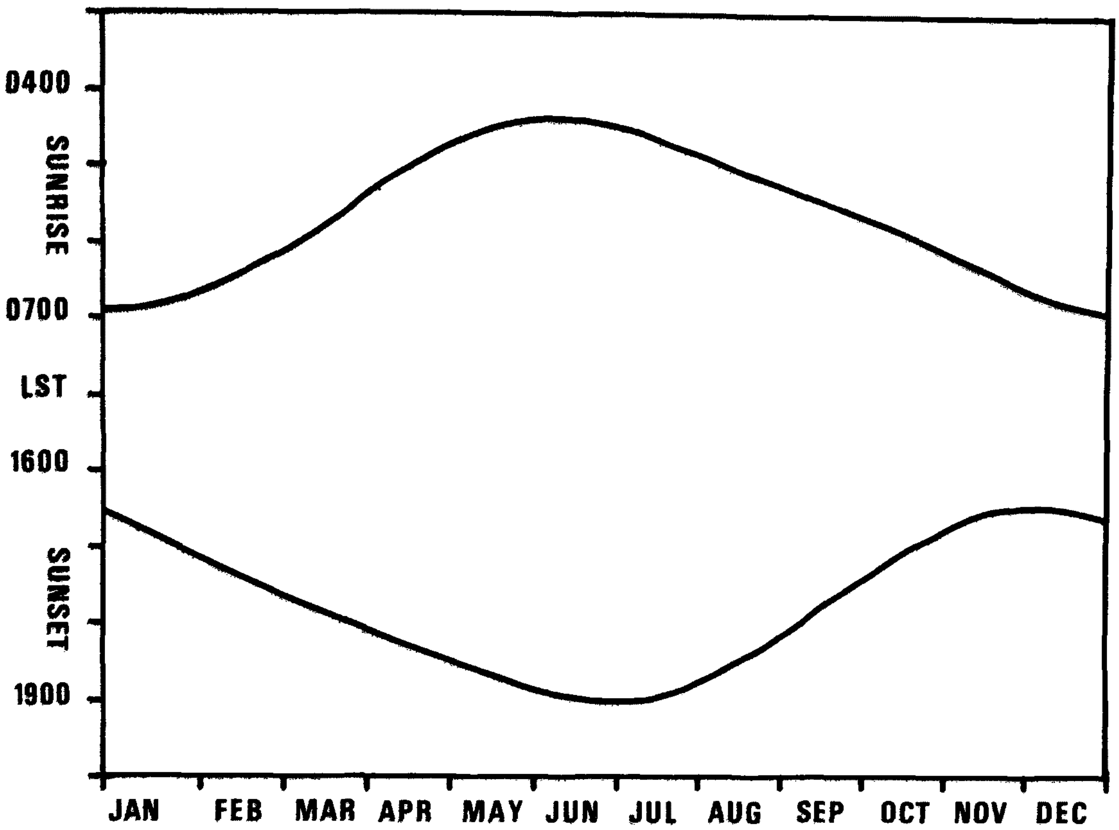

Figure V-2. Sunrise and sunset times for Las Vegas (Local Standard Time).

normally provide guidance regarding general circulation periods. Those for periods less than 24 hours can usually be expected to provide reasonably accurate information on details and timing of specific weather events. Hence, only one day's notice can normally be expected for intensive periods. Such a constraint requires personnel on a standby status based on the longer term forecasts.

Based on predominant synoptic-scale and locally induced wind patterns (i.e., upslope and downslope winds), topography, and traffic data, initial sampling sites can be selected to provide data for model verification and supplementary data for use in the design of a CO monitoring network. If cooperative arrangement can be made with other monitoring agencies, only a few new sites may be required to supplement those existing.

QUALITY ASSURANCE

Quality assurance takes on several aspects in the field project. First, if field data are collected by several agencies working cooperatively, it will be necessary to ensure that measurements within the individual programs are comparable. Second, data and data handling procedures must be compatible and as error-free as possible.

A significant way to ensure uniformity in air quality measurements is to require that all span gases used in field instrumentation be calibrated against the same National Bureau of Standards standard reference gas. A lead agency should provide a cylinder of known concentration to be used as a blind sample for each agency for data correlation purposes.

Routine and preventive maintenance and frequent instrument calibrations should also be carried out by each agency. Standardized check lists and log books should be kept for all instrumentation. Routine maintenance schedules should be specified in an operator's manual developed for the project. To ensure proper identification, strip charts should be labeled at each calibration with the site name, the span value, time, date, and other information as is applicable.

A complete quality assurance plan should be developed for the field program following procedures and format suggested in the EPA (1976b) publication, Quality Assurance Handbook for Air Pollution Measurement Systems.

CHAPTER VI

APPLICATION FOR SELECTION OF CARBON MONOXIDE MONITORING SITES

An air quality simulation model is an essential component of planning studies in air pollution control because there commonly exists a need to establish a quantitative relationship between effluent emissions rates and the magnitude of ground-level contaminant concentrations that result from these emissions. Because each region may have unique topographical and meteorological conditions, and specific pollutant emissions patterns, the model is a useful tool in the design of a monitoring network to detect concentrations exceeding the NAAQS. This chapter discusses the development of a design for an ambient air monitoring network for carbon monoxide using the techniques developed in earlier chapters.

GENERAL METHODOLOGY

Since the primary objective of the air monitoring network is to document compliance with or progress toward meeting of the NAAQS, the CAT-P is used to identify the locations where concentrations in excess of the ambient CO standards are most likely to be found. These are computed with the use of the mesoscale air quality simulation model. A field measurement program is established to provide air quality and meteorological data for model validation, and for simulation to yield projected space-time average concentration distributions of CO.

Prevailing meteorological patterns as well as the frequency of occurrence associated with each can be applied, with the projected concentration distributions, to yield a frequency weighted average of concentrations called Figure of Merit. A mapping of these values provides the basis of selection of the locations and number of sites.

MODEL INPUT REQUIREMENTS

The SAI model, developed as a nonlinear, second-order partial differential equation, requires a numerical solution with the aid of a digital computer. The overall and specific operational characteristics of the computer programs which make up the model are discussed in a separate document as a User's Guide (EPA, 1977). The program package consists of a data preparation portion and a simulation portion. As a general use model, inputs to the programs are parameters which specify the characteristics of the region to be modeled. Because of the number and types of parameters involved, only a major set of input requirements is discussed. The User's Guide should be consulted for further details on specific input parameters.

Emissions Inventory for Carbon Monoxide

The emissions inventory can be developed in accordance with the EPA (1973) publication, Guide for Compiling a Comprehensive Emissions Inventory. Emission factors are compiled in EPA (1976a) AP-42, Compilation of Air Pollutant Emission Factors, second edition, and its five supplements. Essentially, the inventory involves the summing of emissions from point sources, area sources, and mobile sources, resulting in emissions per hour per grid square.

The emissions factors given in AP-42 can be used to compute total emissions. How the emissions might be spatially distributed throughout the day, week or year, must be developed from other data such as traffic patterns and densities.

An emissions inventory depends upon quantifiers such as the number of kilowatts produced per hour or the number of automobiles traveling at a certain speed. For light duty vehicles, emissions have also been shown to depend on ambient temperature. Thus, a temperature correction factor and a cold-start correction factor which is a function of temperature must be applied to their emissions. For example, over the temperature range from 0° to 20°C the temperature correction changes from 1.57 to 1.06 and the cold-start correction factor from 1.3 to 1.1 (for 30% cold starts). This dependence on temperature suggests that any one inventory cannot completely characterize emissions. A special inventory is necessary for each different set of temperature conditions. The result is an inventory of emissions organized into separate parts with emissions for which possible temperature dependence has not been quantified, making up one subtotal and temperature-dependent emissions making up the other. For this latter part, a computer code can be developed to apply temperature and cold-start corrections for the given series of temperatures that describe each hour of the day chosen. After the corrections are applied, the various subtotals can be added, giving an emissions inventory specific to a given day.

For an emissions inventory in the Las Vegas Valley, the following would be considered: point sources (power plants and industrial plants); area sources (space heating); and mobile sources (railroads, airplanes, and automobiles). It was noted that total mobile sources in the Las Vegas Valley were responsible for 93 percent of the total emissions, with 84 percent attributed to gasoline-powered vehicles.

Much of the point source data required for most regions is available through the National Emissions Data System (NEDS). For industrial sources, the assumption is usually made that emissions are uniform over all operating hours. For power plants, emissions can be estimated from data obtained on hourly fuel oil and natural gas use from several chosen consecutive days during the CO season, the first of which is chosen randomly. These values, averaged for each hour and with emission factors applied, yield emissions per hour. Natural gas not supplied to power plants and industrial users can be assumed to be used for space heating. Local natural gas suppliers can provide estimates of residential, commercial, and industrial sales. Using these data, calculated emissions can then be parceled out to each grid square according to population density.

Aircraft emissions can be calculated for local airports with scheduled commercial flights from data listed in the Official Airline Guide, North American Edition. This semimonthly publication contains up-to-date airline schedules, including times, flight numbers, and aircraft used. Information on unscheduled charters and light plane traffic may be available through the local Federal Aviation Agency. Application of emission factors by engine type and number of landing-takeoff cycles per hour determines the actual emissions.

Data on actual vehicle miles traveled (VMT) at different speeds, on each type of roadway per grid square, and on diurnal traffic variations can often be supplied by the State Department of Highways. Heavy duty vehicle emissions are not considered to be temperature-dependent and are handled according to procedures outlined in AP-42.

For light duty vehicles, the equation (from EPA, 1976a, AP-42) for CO emissions is

$$Q_{LDV} = \frac{1}{1000} \left[\frac{H}{100}\right] \left[\sum_{E} (VMT_E \; LDV_E \sum_{o=1963}^{1975} c^*_{on'} \; v^*_{os'} \; m^*_{on'} \; p_{oT} \; q_{oTw'})\right] \quad \text{(VI-1)}$$

where

Q_{LDV} = total carbon monoxide emissions (kg/hour/grid square)

H = hourly percentage of daily traffic

E = roadway types

VMT_E = vehicle miles traveled for each roadway type E

LDV_E = percent light duty vehicles for roadway type E

$c^*_{on'}$ = Federal test procedure average emission factor for model year o, calendar year n

$v^*_{os'}$ = speed correction factor for speed s', model year o

$m^*_{on'}$ = adjusted annual travel for model year o, calendar year n'

p_{oT} = temperature correction factor for model year o, temperature T

$q_{oTw'}$ = percent cold start correction factor for model year o, temperature T and percent cold starts w'.

There are two sets of temperature and cold-start correction factors for the above equation. One set applies to model years 1963 through 1974 which do not use catalytic converters. The other set applies to model years 1975 and later. The equation then becomes

$$Q = \frac{1}{1000} \left[\frac{H}{100}\right] \left[(pq) \sum_E \left(VMT_E \; LDV_E \sum_{o=1963}^{1974} c^*_{on'} \; v^*_{os'} \; m^*_{on'}\right) + (p'q') \sum_E \left(VMT_E \; LDV_E \sum_{o=1975} c^*_{on'} \; v^*_{os'} \; m^*_{on'}\right) \right] \quad \text{(VI-2)}$$

where

p,q are the correction factors for the years 1963 through 1974

p',q' are the correction factors for 1975

With this equation, emissions from light duty vehicles can be calculated for a reference temperature. Adjustments for specific temperatures can be made during simulations, using data collected at the nearest NWS or military weather observing station.

Topography

Ground elevation information can be derived from standard U.S. Geological Survey topographic maps (1:62,500 scale). A map mosaic can be prepared using a clear plastic grid overlay of some specified grid size oriented over the area using UTM coordinate designations. Grid square elevations can be visually estimated taking into account features of the terrain.

Initial and Boundary Conditions

The model program takes measured and specified air quality data at a number of sites throughout the modeling region and, via an interpolation/extrapolation procedure, computes both initial and boundary concentration distributions. The input data requirements for the program are:

a. The grid coordinates for each measurement site.

b. Hourly air quality data for each pollutant of interest at each station.

Initial conditions are given for 1 hour prior to the hour of simulation while boundary conditions are input for each hour of simulation.

Atmospheric Thermal Structure

Data on the diurnal character of reference height Z_i, i.e., the atmospheric mixing height, are required at hourly intervals. This information is generally determined through analysis of vertical profiles of air temperature. Such profiles can be obtained from soundings using free or tethered radiosondes, or from vertical spirals using fixed wing, helicopter, or drone aircraft as measurement platforms. Data collected using remote sounding devices such as a LIDAR or monostatic acoustic sounder can often be used for this purpose. Vertical profiles of air quality, dewpoint temperature, visual range (with an integrating nephelometer), and wind speed and direction can often be useful as supplementary information.

Special measurement programs may be required to ascertain the necessity of allowing for spatial variability in mixing height across the modeling region. This is especially true for areas which contain large urbanized sections or severe topographical features, or are under the direct influence of large bodies of water.

Surface Wind Speed and Direction

Information on the 3-dimensional wind for each of the grid cells in the model region is required at hourly intervals. The interpolation algorithm described in Chapter III provides this data from values of horizontal wind speed and direction reported for the grid locations of each of the surface wind stations in the field network.

Vertical Eddy Diffusivity Requirements

Profiles of vertical eddy diffusivity for each grid column are computed by model algorithms (see Chapter III) from values of near surface horizontal wind speed, roughness parameter, height of reference level (i.e., mixing height), cloud cover and exposure class. The information on cloud cover may be obtained from hourly weather observations made at the nearest NWS or military station. Exposure class may be determined in daytime from the sun angle which is in turn obtained by an algorithm using latitude, longitude, time of day, and Julian date as input parameters.

Values of the surface roughness parameter, z_0, for inclusion into the diffusivity scheme can be estimated using the aerodynamic technique developed by Lettau (1969). Basically, the technique considers the height, surface area, and distribution of roughness elements exposed to the wind. This technique was developed from field measurements of the aerodynamic properties and wind profiles for various geometric configurations of roughness elements placed on a frozen lake surface. The explicit formulation is

$$z_0 = \left(\frac{h^*}{2}\right) \cdot \left(\frac{s^*}{S^*}\right) \qquad \text{(VI-3)}$$

where h* is the average height of the roughness elements within a grid element; s* is the silhouette area of the elements exposed to the wind; and S* is the lot area. The lot area is the quotient of the total surface area over which the elements are being considered divided by the number of elements within the area.

Average values of z_0 can be computed for each of the horizontal areal grid elements of the model area within the region of interest. Percentages of the land-use types within each of the grid elements can be established using street maps, real estate maps, aerial photographs, and results of visual ground surveys, etc. A value of z_0 for each of the grid elements can then be computed by appropriate weighting of the percent coverage of land-use type existing within the grid elements.

Variations in silhouette area and hence of z_0 as a function of season of the year and of wind direction may need to be considered. The former is especially true for areas with significant deciduous tree cover and/or agricultural activity. The latter is particularly important for areas with relatively heterogeneous land-use tracts and the above-mentioned tree cover.

Scenario Selection

Selection of optimal locations for CO monitoring stations by the Figure of Merit technique is accomplished using simulations with the mesoscale air quality simulation model as a data base. The simulations can be run on meteorological scenarios developed from historical weather data supplemented by historical air quality data and current meteorological information collected during the field sampling program.

Analysis of historical air quality data in relation to the prevailing meteorological situation or pattern should provide definitive information on the types of such situations likely to produce high pollutant concentrations. This is particularly important since the function of the CO monitoring network is for monitoring to detect concentrations exceeding the NAAQS.

Classification of meteorological situations into types may be accomplished through statistical analysis of sea level pressure charts and upper air constant pressure charts applicable for the area as available from the NCC of the NWS. Objective classification may be accomplished in the manner outlined by such investigators as Lund (1963) and Roach and MacDonald (1975). Basically, this is done for a large sample size, on the order of 5 to 10 years of data, by linear correlation of the heights on a constant pressure surface (or pressures on a constant height surface) at regular grid intervals. The maps correlating highest with each other are grouped together and form classes. The percentage frequency of each class establishes its probability of occurrence. Alternatively, visual examination of such charts may allow a subjective classification of meteorological situations with the frequency of occurrence of each establishing its probability of occurrence.

Meteorological information on winds, surface air temperature, mixing depths, and atmospheric stability for input into the model for each such class may be obtained from historical surface and upper air data for reporting stations within the region. Where the appropriate stations are not available locally, selective use may be made of data for stations normally within the same air mass. Diurnal mixing depths, for instance, may be estimated from the 1200Z radiosonde profile and hourly surface air temperature values in the manner of Holzworth (1972).

Statistical analysis of the resultant meteorological data for the particular dates corresponding to the various classes can lead to the selection of the scenarios to be utilized. For example, averages and/or percentiles of frequency distributions of the various parameters may be selected. Alternatively, typical cases for subsets within the basic classes may be chosen.

In regions containing significant topographic features, under the direct influence of large bodies of water or containing large urbanized areas, it may well be necessary to use supplementary weather data to assist in establishing meteorological input for the model. Here, large spatial variations in certain of the parameters may persist across the region. Objective analysis or other statistical models may be used to develop fields of such variables based upon the historical and supplementary data. In areas where the meteorology for the relevant scenarios is determined almost exclusively by local effects due to large bodies of water or complex topography, it may even be necessary to use meteorological simulation models to develop the relevant inputs.

CHAPTER VII

SUMMARY

This document has presented a methodology for designing an air monitoring network which has as its objective the identification of pollutant concentrations that exceed the NAAQS. Emphasis has been placed on the theoretical development of mathematical expressions which describe the behavior of pollutants that have been emitted in an urban environment. Computer solution of these equations under specified meteorological conditions form the data base from which predicted pollutant concentrations can be mapped, which in turn provide the bases for the selection of monitoring sites for a network.

A procedure has been described for applying this methodology to a design for selecting carbon monoxide monitoring sites. Application of the methodology requires the establishment of a field measurement program, the development of an appropriate historical data base, the assembly of a complete emissions inventory, and the development of other pertinent data required as input to the solution of the mathematical model.

This document contains only the rationale behind the air monitoring network design methodology and a procedure for applying this methodology. The instructions for implementing and executing a computer solution of the mathematical model is published separately as a User's Guide. A complete example of the application of the methodology including details of an executed field program, emissions inventory development, meteorological scenarios development, simulation results, and recommended network design for the Las Vegas Valley are presented in a separate publication.

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16. ABSTRACT

A methodology is presented for designing a carbon monoxide monitoring network based on the objective of identifying concentrations that exceed the national ambient air quality standards (NAAQS). The basis for identifying concentrations in excess of the NAAQS is the Concentration Area Time-Product, where the concentrations are integrated over an area (i.e., a grid square in a gridded system) and integrated over a time interval for averaging the concentrations. These are computed with a mesoscale air quality simulation model formulated as a 4-dimensional (x,y,z,t), partial differential equation of mass balance for the pollutant species which yields space-time average concentration distributions. A frequency-weighted average of concentrations called Figure of Merit is determined from these projected concentration distributions, prevailing meteorological patterns, and the frequency of occurrence associated with each of the meteorological patterns. A mapping of these Figure of Merit values provides the basis of selection of the locations and number of sites in the network.

The methodology was applied in a design of an ambient air monitoring network for carbon monoxide. The establishment of a field measurement program is described which would provide air quality and meteorological data for model validation and simulation as required in development of the specifications for the number and location of sites in the network design. Discussions are limited to the design methodology. Actual field data, simulation exercises, pollution concentration isopleths, and mappings are presented in a separate report.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Monitoring Networks	05H
Mathematical Models	Air Quality Monitoring	13B
Systems Analysis	Monitoring Sites	14A

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