NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 200

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TRANSPORTATION RESEARCH BOARD
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MONITORING CARBON MONOXIDE CONCENTRATIONS IN URBAN AREAS

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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation
Research Board

This report presents methodologies that use considerably less than a full year of data for estimating the two critical annual statistics of the carbon monoxide levels at a proposed highway site—the annual second maximum 8-hour average and the annual second maximum 1-hour average. Therefore, it is of substantial interest to highway professionals responsible for preparation of environmental impact statements. Among such professionals are engineers, meteorologists, and statisticians. They will find step-by-step procedures for applying the methodologies, for various conditions of data availability, to determine magnitudes of CO concentrations and their confidence limits. An example application is provided.

The estimation of the existing worst-case, background levels of carbon monoxide is one requirement for an environmental impact report for major highway improvements. At present, there is no widely accepted justification for less than a full year of CO monitoring to measure background; such extensive monitoring is expensive and can cause significant delays in highway construction. The major objective of this study was to determine a method of estimating the two critical annual statistics of the carbon monoxide levels at a proposed highway site—the annual second maximum 8-hour average and the annual second maximum 1-hour average—that would use considerably less than a full year of data. Specifically, the possibility of sampling for one month was investigated along with other sampling plans. In the extrapolation from this small data set, three separate possibilities were considered: (1) having auxiliary CO data available (from existing monitoring stations), (2) having auxiliary meteorological data available, and (3) having no auxiliary data available.

The research approach taken by Technology Service Corporation was, first, to document current practice and sampling preferences through telephone interviews and reviews of environmental impact statements for highway construction. From such documentation, the requirements of a methodology were determined and applied in the development of two alternative methodologies. Data bases from five U.S. cities were explored for trends and distributions. The estimation methods were developed using data from two cities and then used for estimation in three other cities. The methods were found to have acceptable accuracy. The simplest method proved the most accurate. For each method, confidence intervals were determined as a function of the availability of auxiliary and meteorological data and the length of the sampling period. The recommended method is simple to apply, requiring at most a desk calculator. Therefore, the practitioner will find the material needed to predict the required annual CO background statistics and the variability associated with those predictions.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 20-14 by the Data Sciences Division of Technology Service Corporation. Dr. William S. Meisel, Manager of the Data Sciences Division, was Principal Investigator for the project and principal author of the report. Dr. Ted Dushane, Member of the Research Staff, was the principal co-author.

Development of the study methodology was primarily the responsibility of Dr. Meisel, Dr. Leo Brieman, Exclusive Statistical Consultant to TSC, and Dr. John Trijonis, Air Pollution Specialist. They were assisted by Dr. Yuji Horie, Senior Scientist, and Dr. Dushane. Consultation on meteorological questions was provided by Mel Zeldin, Senior Scientist and Meteorologist.

The major programming effort was performed by Susan Hartman, Technical Engineer, and Dennis Bicker, Member of the Technical Staff, assisted by Harry Knobel, Member of the Research Staff. Martin Cohen, Member of the Senior Staff, wrote the software for performing the nonlinear plots used throughout.

Numerous traffic engineers, highway personnel, and air pollution experts helped in gathering and interpreting the data used in this study. Grateful acknowledgment is extended to all of them for sharing their knowledge about CO data and CO monitoring for production of proposed highway environmental impact reports.

MONITORING CARBON MONOXIDE CONCENTRATIONS IN URBAN AREAS

SUMMARY

The estimation of the existing worst case levels (background levels) of carbon monoxide is one requirement for an environmental impact report on a new highway. At present, there is no widely accepted justification for less than one full year of CO monitoring to measure background; such extensive monitoring is expensive and can cause significant delays in highway construction. The major objective of this study was to determine a method of estimating the two critical annual statistics of the carbon monoxide levels at a proposed highway site, the annual second maximum 8-hr average and the annual second maximum 1-hr average, using considerably less than one full year of data. Specifically, the possibility of sampling for one month was to be investigated along with other sampling plans. In the extrapolation from this small data set, three separate possibilities were to be considered: having auxiliary CO data available (in the form of existing monitoring stations), having auxiliary meteorological data available, and having no auxiliary data available.

The main result of this study was the following. As long as it is possible to monitor during a part of the CO season (October to January, possibly February), the two statistics mentioned can be accurately estimated from one month of sampling. The restriction of monitoring to the CO season represents a change from some current practices. The most accurate of the methods tested was the simplest—use the highest 8-hr average observed during the period of monitoring at the highway site as the estimate of the annual second maximum. It must be verified that the monitoring period contained enough meteorologically adverse days to make the estimate valid. Such adverse days must be determined using an existing monitoring station nearby which has been operating for at least a year, by a meteorological index, or, less persuasively, by typical rates of occurrence of adverse days for the months encompassed by the monitoring period.

An approach based on using an estimated statistical distribution to estimate the annual statistics from limited measurements was less accurate than the observed-maximum approach.

Simple methods for obtaining annual average CO levels were recommended; however, this statistic seems to be more sensitive to meteorology than to emissions, and does not appear to be a useful statistic to estimate.

The degree to which the error in the estimation process creates uncertainty in the estimate was quantified. Means for assessing confidence intervals were recommended.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

This chapter discusses the objectives of this project. An overview of the problems involved in predicting CO levels is given, and current approaches, both recommended and actual, to CO monitoring are reviewed.

OBJECTIVES OF THE STUDY

When a proposed highway is to be built through an urban area, environmental impact statements are usually required. In particular, the impact on carbon monoxide (CO) levels of the addition of the highway must be assessed. As part of this assessment, the highway agency must estimate the existing background levels of CO at a proposed urban highway site that are due to areawide CO emissions prior to the addition of the highway. An estimate of peak highway contributions is then added to this background level to determine compliance with CO air quality standards. This study is directed at the problem of estimating the background concentration of CO at a proposed highway site under existing conditions. The problem of adjusting the background concentration for some future year, such as the estimated time of completion or the design year, is not addressed here.

Some states currently recommend monitoring at the proposed site for a full year to determine background levels. Such extensive monitoring is expensive and can cause significant delays in the proposed highway project. This report examines the degree to which this requirement can be reduced to a shorter sampling period or, at least, to an intermittent sampling plan. Procedures are developed for estimating, from such limited monitoring data, the background concentrations that would be obtained from a full year of monitoring.

The standards for CO are currently for the running 8-hr-average concentration and the 1-hr-average concentration. The standards are stated in terms of the value of these quantities that may be exceeded no more than once a year. Thus, compliance with the standards results when the second highest 8-hr average and the second highest 1-hr average for the year are below their respective standards. To determine if the highway contribution plus the background contribution meets the standard, the measurement of background that is required is an estimate of the second highest 8- and 1-hr averages for the year. (For brevity, the annual maximum 8- and 1-hr-average CO concentration values are referred to as the "8-hr max" and the "1-hr max," respectively. Similarly, the second highest annual values will be referred to as the "8-hr second max" and the "1-hr second max".) In addition, the annual average of carbon monoxide levels is also of interest, largely because there has been some discussion of an eventual standard based on this quantity. The objective of this study is to determine and evaluate methods for estimating these quantities for urban locations.

Two kinds of results emerge from the present study:

1. A practical procedure for extrapolating measurements taken in a limited sampling period to annual standard-related values.
2. Justification for the procedure chosen and a measure of its accuracy.

Figure 1 shows the way in which the procedure developed would be used. Carbon monoxide measurements at the proposed highway site (target site) for a limited sampling period are required inputs into the procedure. Two types of auxiliary data may possibly be available to improve the estimate of annual standard-related CO values: (1) data from existing monitoring stations in the area, and (2) meteorological data relevant to the general locale of the target station. Either or both types of auxiliary data can conceivably be available. In some cases, there may be no relevant auxiliary data. The procedure developed provides a methodology for each case. The results of applying the procedure to available data are, as shown in Figure 1, estimates of the three standard-related annual quantities, as well as the confidence in those estimates (i.e., the range of error implicit in those estimates).

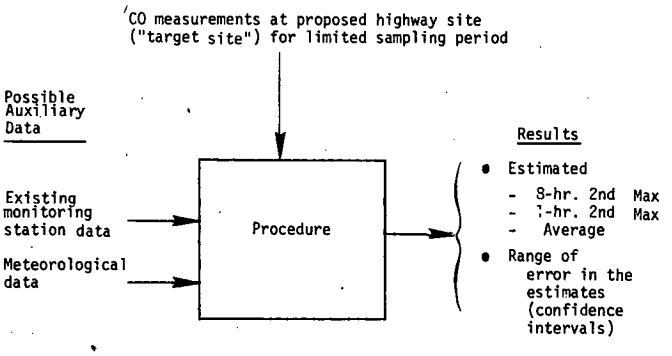


Figure 1. Intended use of the procedure developed.

Note that, in Figure 1, there is no specific statement that the CO measurements are required to be at a location where the levels measured are background levels. In fact, the procedure derived can be applied to a number of related air quality problems where data are missing and one wishes to extrapolate to the standard-related annual values. However, the specific problem context plays an important role in choosing the procedure recommended in this study. In particular, the problem of estimating background as part of estimating highway air quality im-

pact is easier than the more general problem in two major ways:

1. The estimate of background level is to be added to a model-generated estimate of the contribution due to the highway. This contribution will generally be larger than the background level, and the models themselves have some error. Thus, the accuracy of the background estimate will not be the sole determinant of the accuracy in the over-all estimate of CO levels.
2. Almost by definition, background levels will tend to have less variability and take less extreme values than CO measurements at more source-affected locations.

The development of a practical and easily implemented methodology for the present application did not require examination of detailed methodological refinements and theoretical considerations, which might be justified by the more general problem of extrapolating annual standard-related values from limited measurements.

THE CO PROBLEM

CO data are usually recorded in the form of hourly averages, and all of the data in this study are of this type. The purpose of this section is to give an overview of the problem in predicting CO levels, with special emphasis on the kind of variability exhibited by CO data.

Examining hour-by-hour plots of CO data reveals wide variation in the pattern of CO hourly averages observed. Figure 2 shows a plot of hourly CO averages for a day with extreme variability in Las Vegas, Nev. The extreme day in Las Vegas has much more variation than even a normally high day, with a 1-hr maximum of over 50 ppm. The values on that day should be put into perspective. The second highest 1-hr average in the period 1974–1976 at that station was 39.6 ppm. The particular CO concentration shown was a result of an extremely low and strong inversion that settled over the city for almost exactly one hour in the morning, coinciding with the peak traffic hour and with the clock hour. If the peak inversion had been from 7:30 to 8:30 in the morning, the resulting maximum 1-hr-average value would probably have been less than 40 ppm, because averaging is done over the clock hour. Although such extreme behavior is rare, there are many examples among the highest few days in each station-year that are commonly believed to be a result of similarly anomalous conditions. Such data, valid but inconsistent with other data, make analysis difficult.

More typical examples of the diurnal variation of CO concentrations are shown in Figures 3 and 4 for Newark, N.J., and Burbank, Calif. (Los Angeles area), respectively. The percentage of the time in which the daily 1-hr maximum occurs in a given hour is shown, as well as the annual average CO concentration for each hour. The rush-hour traffic contributions to peak CO levels are apparent for Newark. In Burbank, regional meteorology eliminates the afternoon peak. A relatively unexpected phenomenon that can be seen rather consistently for both Los Angeles and New Jersey is the high CO levels in the evening. Note, particularly, the large value of CO after 10 p.m. reflected in both graphs of Figure 4. There are stations, in fact, where the annual 8-hr second max has occurred in a period around midnight.

Looking at the CO data from day-to-day gives another picture of their variability. Figure 5 shows a plot of the 8-hr daily maximum CO for the city of Reseda, Calif., in

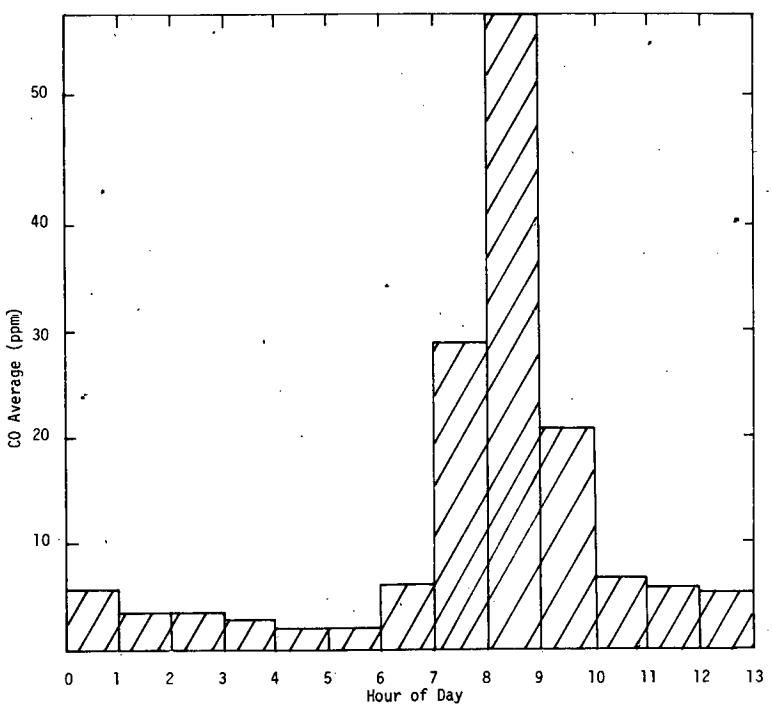
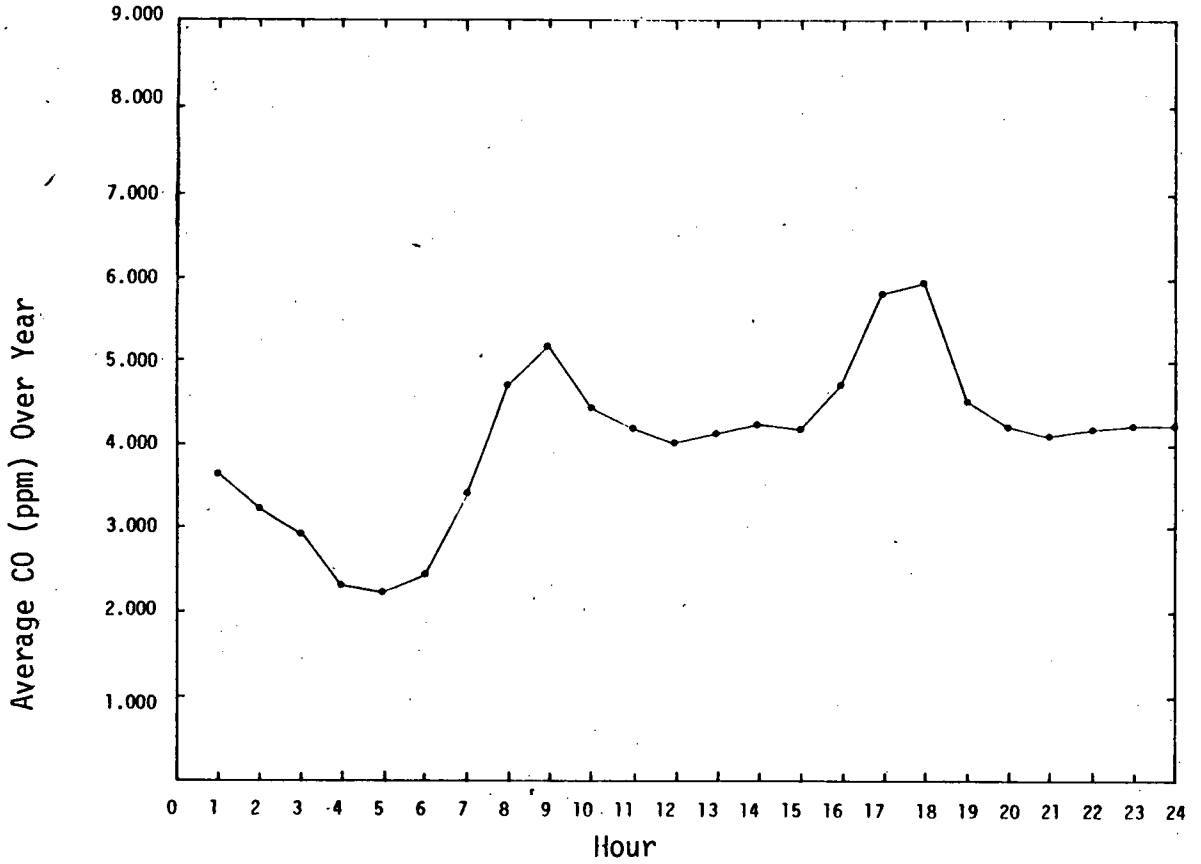


Figure 2. Extreme CO day, Jan. 29, 1974, Las Vegas, Nev. (EPA site 290320001).



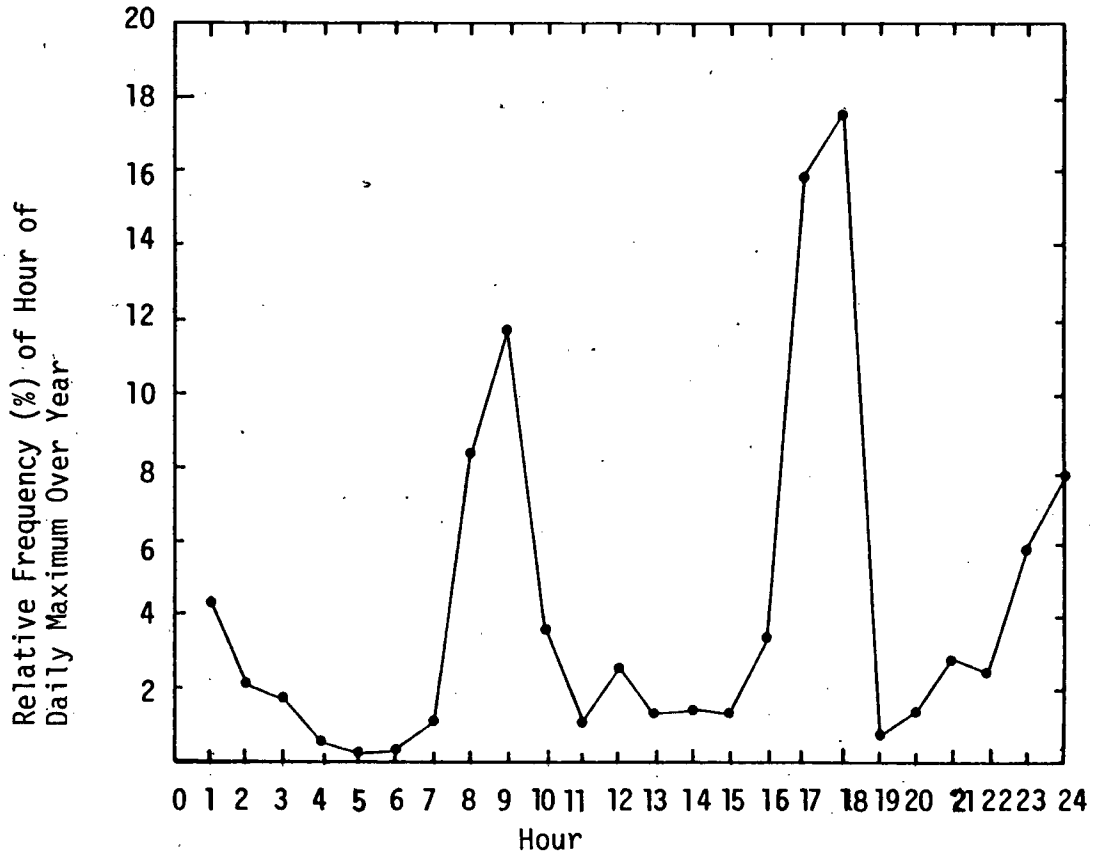
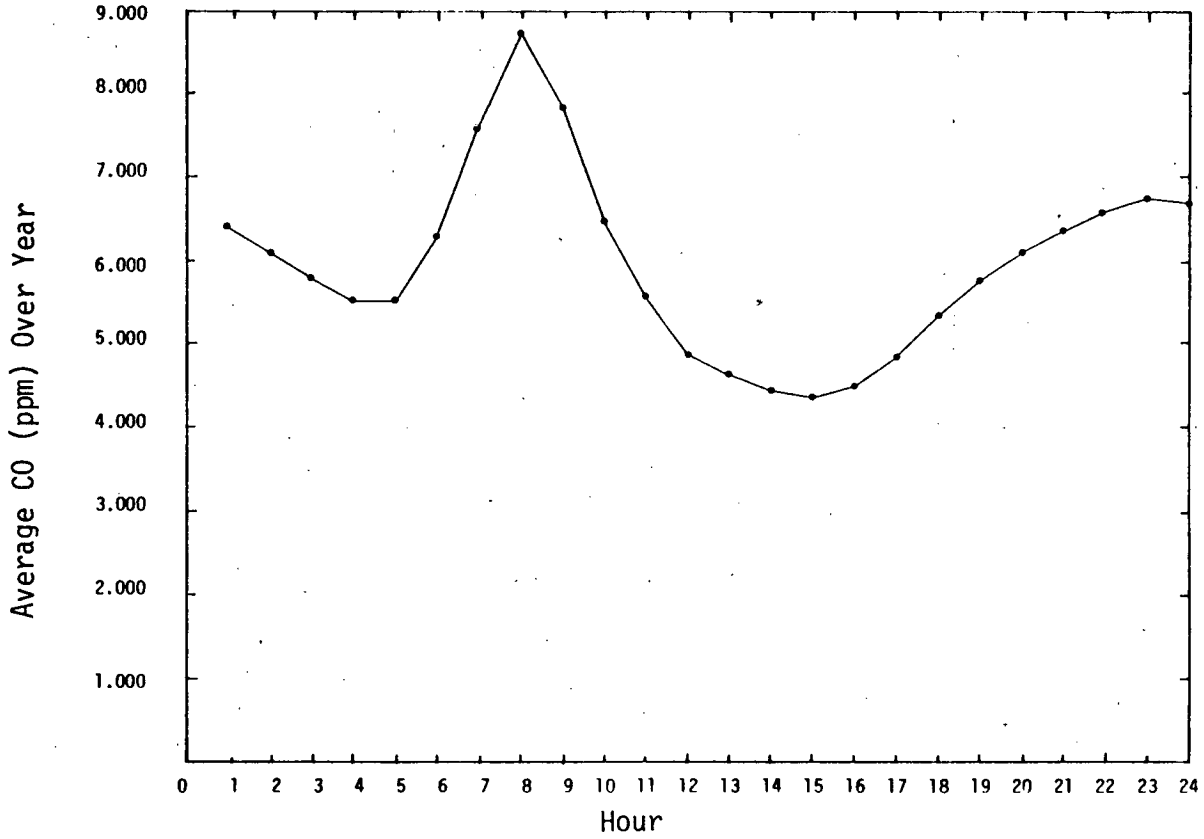


Figure 3. Hour of occurrence of 1-hr maximum and diurnal variation at Newark, N.J., 1974.



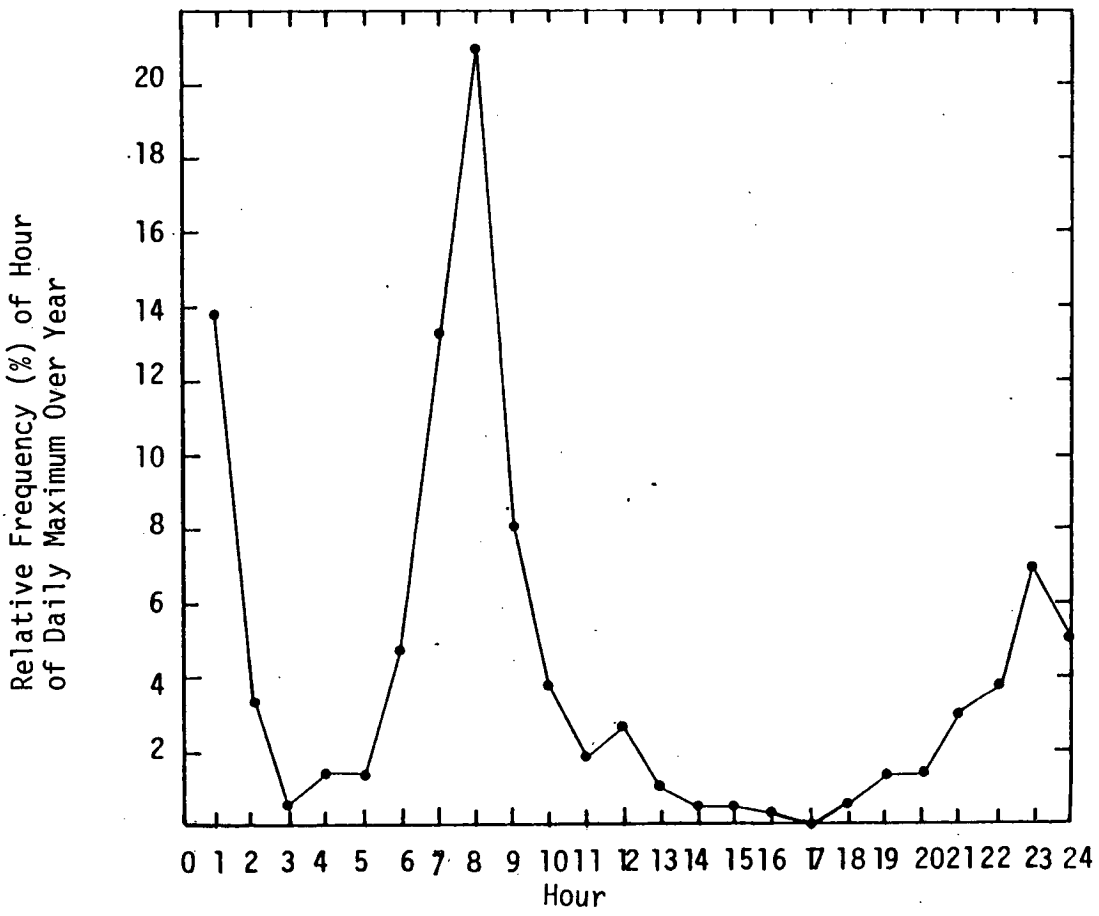


Figure 4. Hour of occurrence of 1-hr maximum and diurnal variation at Burbank, Calif., 1974.

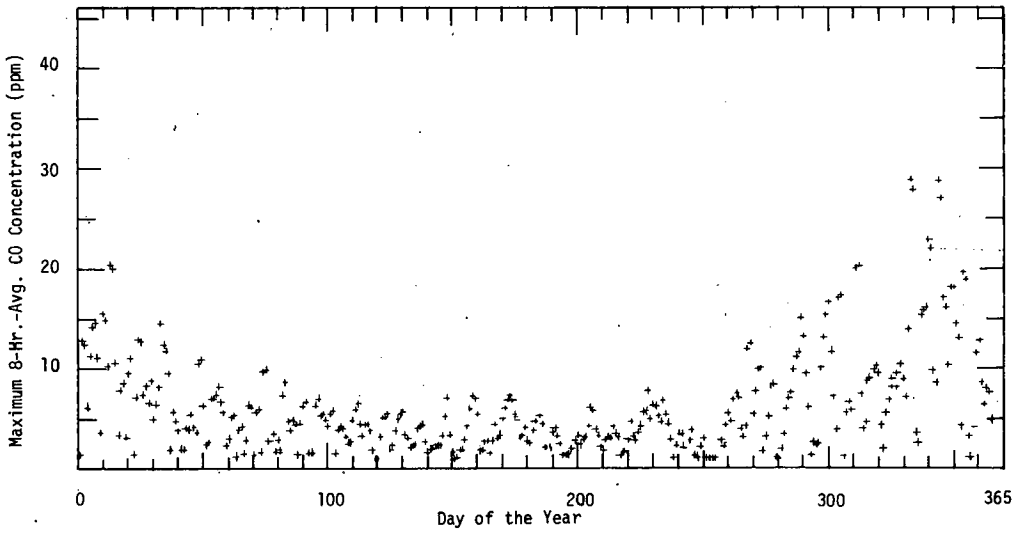


Figure 5. Plot of 8-hr daily maximum for Reseda, Calif., 1973.

the year 1973. It is interesting to note that, although the apparent minimum value of CO attainable is about the same throughout the year, the maximum varies considerably. Hence, there is a wider variation in some periods of the year than in others.

This pattern was repeated in many other cities examined. From looking at such time-series plots, it is clear that the bulk of the variability in the CO distribution can be explained by the behavior of CO observed during the CO season. For a given station, the summer values are much more nearly constant than the CO-season values from year-to-year. Also, interstation differences are considerably less, in magnitude and percentage, during the non-CO season than during the CO season. These observations led the research team early to abandon the non-CO season in attempting to extrapolate to maximum statistics from small data sets.

CO also varies with the day of the week. Since automobile traffic is the main source of ambient CO, it is natural to expect the nonholiday weekdays to have higher levels of CO than the weekends or holidays. To verify this, the high-CO days were examined in the CO season to see if there was a tendency for the higher CO days to be nonholiday weekdays. Specifically, the following were considered. First, the highest 20 percent of the days of the year were determined according to their daily 8-hr maximum. Then, among such days occurring in October, November, December, and January, the percentage occurring on nonholiday weekdays was computed for each station-year. It was found that the over-all average percentage was 78 percent. This is larger than the expected value of 71 percent if all days of the week had uniform levels of CO.

Certain general seasonal effects should be noted about the behavior of CO data. Concentrations are higher, all other factors being equal, in colder areas and during the winter season. These high concentrations occur as a result of both direct and indirect effects of meteorology.

The direct influence of meteorology is the production of conditions conducive to keeping the concentration of CO high after it has been released in the ambient air. The concentration tends to stay high when there are low wind speeds and limited morning mixing, both characteristic of winter weather. Thus, regions that tend to show the meteorological pattern typical of winter mornings to a greater extent and/or more often will tend to have higher maximum levels of CO.

Indirectly, meteorology tends to produce greater amounts of CO emissions because of the effect of cold weather on automobile emissions. On cold mornings, people spend more time in warming up their cars. This "cold-start" effect contributes in part to the tendency towards high CO during cold weather.

Because of these effects, the CO problem is largely seasonal, peaking in the winter months. Table 1 gives the frequency of occurrence of the first and second maximums by month for four diverse locations. November, December, January, and, to a lesser extent, October are by far the most likely months in which to find extreme CO concentrations.

This section has looked at the variability of CO within a given year. One could ask further what the intrinsic variability in maximum CO levels from year-to-year would be simply as a result of changes from year-to-year in over-all meteorology (from a "bad" year to a "good" year, for example). Since emission changes from one year to the next are not substantial, one can simply look at the magnitude of the percentage change from year-to-year in values of interest, such as the annual 8- and 1-hr second maximums. Table 2 tabulates, for four diverse areas, the average magnitude of the year-to-year percentage change in these standard-related values. The result is remarkably consistent, averaging about 13 percent to 17 percent.

If one monitored at the target location for a full year with no missing data, one would have obtained the exact annual second maximum. As an estimate of the second maximum, this value would have an intrinsic error of about

TABLE 1

PERCENTAGE OF DAYS HAVING FIRST AND SECOND HIGHEST (NONOVERLAPPING) 8-HR CO AVERAGES OCCURRING IN EACH MONTH, AVERAGED OVER EACH LOCALE'S NONSOURCE-AFFECTED STATIONS

Locale	Number of Station-Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Los Angeles	21	21.4	0	0	0	0	0	0	0	2.4	9.5	28.6	38.1
New Jersey	21	28.6	0	0	2.4	2.4	0	2.4	14.3	7.1	4.7	21.4	16.7
Denver	11	27.3	0	0	0	0	0	0	0	0	0	27.3	45.4
San Francisco	27	18.4	7.4	0	0	0	0	3.7	0	5.6	7.5	29.6	27.8
St. Louis	4	0	0	0	12.5	0	0	0	0	0	50.0	25.0	12.5
OVERALL*	84	22.0	2.4	0	1.2	0.6	0	1.8	3.6	4.2	8.3	26.7	29.2

*Overall averages are weighted by the number of station-years.

TABLE 2

INTRINSIC VARIABILITY OF 8-HR AND 1-HR ANNUAL SECOND MAXIMUMS DUE TO YEAR-TO-YEAR CHANGES IN METEOROLOGY

Locale	No. of Year-to-Year Changes Considered	Average Magnitude of Year-to-Year % Change	
		8-Hour Second Max	1-Hour Second Max
LA	28	12.8%	13.6%
NJ	14	17.6	16.7
Denver	12	13.5	13.1
San Francisco	20	16.4	16.9
OVERALL	74	14.8%	15.5%

15 percent due to the year-to-year change in meteorology. However, a complex analysis of the meteorology over a number of years to determine the meteorological propensity for high CO levels in the given year, as related to other years, is required to treat the multiyear problem. The methodology developed in this report is intended to estimate what the second maximum would be in the given year from a limited sampling plan taken in that year.

To the degree that the estimate of background concentration is sufficiently critical to merit consideration of year-to-year changes in meteorology, the results given in Table 2 will allow an approximate consideration of this factor. In particular, a rough approach to handling this problem is to make the background estimate some 15 percent higher to compensate, on the average, for possible underestimation of the long-term background levels. Chapter Four indicates generally how the methodology developed in this report can be extended in a natural way to include year-to-year effects to handle this problem more precisely.

These results also add further perspective to the accuracy requirements on the developed procedure. Since monitoring for the full year has an intrinsic error with respect to underlying background levels on the order of 15 percent, an elaborate methodology for estimating background CO for the year in question—one that attempts to go beyond this accuracy—is overkill if the result is substantial complication of the procedure or substantially increased monitoring requirements.

CURRENT PRACTICE

Before proceeding to the formulation of an extrapolation method for the second 8-hr max, second 1-hr max, and the annual average, the investigators of this study felt it imperative to confine proposed methodologies to practical and feasible approaches. What is currently done is certainly an indicator of what is feasible. In this section, the current recommended and actual practices are reviewed, and the implications for the consideration of sampling plans are discussed.

Current Recommended Practice

A primary motivation for this study is the commonly held assumption that continuous monitoring for one year is considered, if not a requirement, a virtual necessity for estimating the relevant standards for CO concentrations. Although there is no formal EPA requirement that the monitoring be done for one year, there is such a recommendation in the State of California (see Beaton et al. (*1*)).

Some Shortcuts That Have Been Taken

In order to determine what kinds of monitoring practices are currently being used, two sources of information were investigated. First, a telephone survey was conducted of highway agencies in states where urban highways have been recently constructed or are currently being constructed. Inquiries were made about practices, particularly in states where controversial urban highway projects are underway or will be underway soon. The second source of information was a sampling of environmental impact reports filed for highway construction.

The results of the inquiries showed that essentially three methods of estimation are currently in use for estimating the existing CO levels at a target site. The first is to

monitor continuously during the CO season (approximately October through January) for a period of three weeks to three months, take the second highest nonoverlapping value obtained for the 8-hr and 1-hr averages, and use these numbers as estimates for the desired annual 8-hr and 1-hr second maximums. A variation on this approach is to use Larsen's log-normal model (*2*) to extrapolate from such a limited data set to the appropriate annual statistics (for example, see Holland et al. (*3*) and Mecherikoff et al. (*4*)).

The second method is to sample continuously for a period of one to two months at a target site, use the data from a nearby monitoring station, and then do a linear or log-linear regression of the target station hourly CO values as a function of the nearby monitoring station's hourly values. This relationship derived from the regression is then extrapolated to the entire year by substituting the hourly values from the nearby station into the regression equation and examining the resulting estimates of the year's hourly averages. From these estimated hourly averages at the target site, 8-hr averages are computed. The second highest nonoverlapping 8-hr average, or the second highest nonoverlapping average among those that do not cross midnight, is computed. Either of these is the estimate of the 8-hr second maximum. The 1-hr second maximum of the predicted values is taken as the estimate of the 1-hr second maximum at the target station. Finally, the annual average, if needed, is estimated as the average of the resultant predicted values.

The third method in common practice involves using auxiliary meteorological data such as the Pasquill stability class (*5*), wind direction, wind speed, and the inversion base in a linear regression application. The wind speed is often treated by using separate regressions for small groups of adjacent wind directions observed (for example, see Meece et al. (*6*)).

In short, the current methodology either assumes that the worst case CO has been found during the sampling period, assumes that the data are a random sample from a log-normal distribution, or uses an extrapolation of some form of linear or log-linear regression of hourly values against a nearby CO station or meteorological data.

Relationship of Sampling Plan to Monitoring Practice

A singularly important result of the survey of highway agencies and environmental reports is that random sampling, random with respect to either hour or day, is not used in practice. The telephone survey indicated that it was considered uniformly the least desirable and most impractical sampling plan. The summary response to inquiries about random sampling was that if one were to go to the expense of monitoring during a given period, the differential cost of "filling out" the data in the period would be small and would outweigh the disadvantage of having to sample in a longer period to obtain an equivalent number of samples.

This means that sampling plans, such as 100 random hourly samples over 30 days or over one year, are not considered reasonable alternative sampling plans to a more-or-less continuous plan, except perhaps for the annual average.

Since the usual sampling plan involves continuous sampling, or in some cases 5-day midweek sampling, the researchers of this project focused on methodologies that either used continuous sampling for a month or more (the minimum continuous sampling time found in practice was three weeks, and that one was in a locale of known low CO concentration) or that would be readily applicable to a 5-day or 3-day midweek sampling plan. For any sampling plan, of course, the methodology must allow missing days due to equipment breakdown or other problems.

CHAPTER TWO

FINDINGS

This chapter summarizes the approaches tested and the results obtained. The definitions, assumptions, and preliminary analyses on which the methodological development is based are discussed. The methodologies are then derived and evaluated.

SUMMARY OF APPROACH AND RESULTS

Outline of Developed Methodology

Two basic categories of approaches were considered in extrapolating from limited data to the annual second maximum:

1. Assume that the measured data arise from an underlying statistical distribution. Estimate, in some manner, the parameters of the distribution (or at least the upper tail of the distribution) particular to the specific locale and the specific year. The percentile of the derived distribution that corresponds to the second highest day yields the annual second maximum.

2. Use an intuitively based approach. For example, take the highest daily 8-hr maximum during the sampling period as an estimate of the annual second maximum. This procedure assumes that the sampling is done in months in which the second maximum is likely to occur; it is based

on the argument that the highest day encountered in a bad month is representative of the value to be expected of the second maximum for the entire CO season.

One would use auxiliary data in a different way, depending on which of these approaches was being used.

The first approach is more scientific; it might be the best approach if all the appropriate assumptions regarding the statistical distribution were correct. However, the second approach is considerably simpler. This simplicity is an attractive aspect of the method if it appears that the accuracy of the two methods is comparable—particularly in light of the limited accuracy required for a background estimate.

The specific approaches that have been adopted in each category are discussed in the following.

Fitting a Statistical Distribution to the Target-Station Data

Figure 6 shows an example of a cumulative distribution of daily maximum 8-hr-average CO concentration for a full year at a particular station. The cumulative distribution shows, for each CO value encountered, the fraction of days in the year on which the daily maximum is less than that value. The scale on which the fraction of days is marked is nonlinear to emphasize the high values. If the distribution for the year at a target station is known, the problem will be quite simple. One would simply read the value that corresponded to the second day out of 365 days to estimate the 8-hr second max.

The upper tail of the distribution is of interest rather than the over-all distribution, because that is the part which is relevant to predicting the extreme values. Since one is interested in the degree of fit in the upper tail, it is not necessarily reasonable to work hard to describe the lower part of the distribution, particularly if it is at the expense of a good fit in the tail. It may be even more appropriate to use only high values in the analysis if it is considered that the upper end of the tail is the result of particular meteorological classes that may be quite distinct from classes yielding lower pollution potential. In other words, the upper end of the tail may result from a significantly different meteorological regime (i.e., physical process) than the lower part of the distribution. In that case, it may be that the distribution of the tail is totally independent of the distribution of the lower values. There is then not only little advantage to extrapolate a fit from lower values to the tail, but it may reduce rather than increase accuracy to use such data.

Given this logic, one can consider fitting the upper end of the distribution; that is, only the days with the highest concentrations. Such high-pollution days have been defined as "adverse days." After inspection of the data, it was chosen to define adverse days as the upper 20 percent of values encountered in the year at a given station. When sampling is done over a limited period rather than over the full year, a determination of these adverse days must be accomplished by (1) the use of an auxiliary CO station for which data are available throughout the year to define adverse days as the upper 20 percent of the days at that station; (2) the use of a meteorological index measuring CO pollution potential, calling a day an adverse day if the values of the index on that day are among the top 20 percent of its values during the year; or (3) in the absence of auxiliary data, defining adverse days as the highest K days in the sampling period, where K is the expected number of adverse days found in that sampling period for the general region (or nationwide).

The "adverse days" approach is the heart of the method of determining which data points belong on the upper tail of the curve. Once these points are determined, it remains to fit the tail of an appropriate distribution to those points and to extrapolate to the second highest day. The usual approach to fitting a probability density to observed data

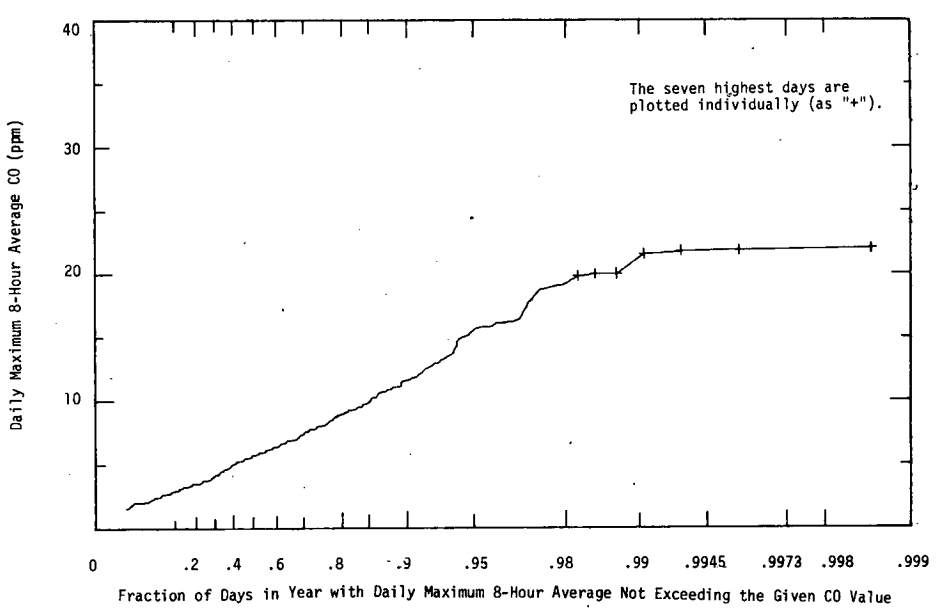


Figure 6. Cumulative distribution for 8-hr daily CO data at west Los Angeles, 1972.

is to estimate the parameters of the distribution from the data and then use the distribution yielded by those parameter values. For example, for the log-normal distribution, the geometric mean and the geometric standard deviation are typically estimated and used.

A more desirable alternative for small sample sizes (e.g., for fitting the tail alone) is that of fitting all the data points to the distribution in a least-squares sense. This fitting makes full use of the limited data available. Further, it has the character of a test of the over-all fit of the data to the distribution; if the fit is good, the distribution represents the data well. In particular, suppose the percentile scaling of the cumulative distribution plot were nonlinear such that, for the appropriate distribution, the cumulative distribution function is linear. Then, points arising from that distribution plot on a straight line, as exemplified for actual CO data in Figure 7. Also one can simply extrapolate linearly to estimate the value of the second maximum, using the percentile corresponding to the second maximum, $364/366 = 0.9945$. (The first maximum, of course, can also be estimated from the same plot, using its appropriate percentile.)

The exponential distribution was chosen to be plotted linearly on the figure because (1) the exponential distribution is a good distribution on the average for the tail of distributions in all locales considered, and (2) the effect of the change in the predicted second maximum caused by a change in assumed distribution of the tail was very small, making fine-tuning of the distribution largely irrelevant for this application.

The method used as a statistical-distribution approach was evolved after extensive examination of the data and consideration of other alternatives. The method and its justification are discussed in more detail in later sections.

An Intuitively Based Approach

There are a number of intuitively based approaches that one might postulate as a reasonable estimate of the second maximum. The one explored in detail in this study is to use as the estimate of the annual second maximum the *maximum* of values in the sampling period. This approach has been used in the past in environmental impact reports (for example, by Mecherikoff (*4*)). The justification for this approach is relatively straightforward. If the monitoring were conducted throughout the CO season (typically 3 or 4 months), one would feel fairly confident in using the second highest value of the estimate of the second maximum. (In Table 1, it can be noted that there is a very high probability that the first or second maximum will occur in a fairly limited season.) Since a more limited monitoring period is being used, such as one month or two months, and since a more conservative estimate is desired, a logical choice is to test the accuracy of using the first maximum in the monitoring period as a predictor.

A more simple statement of this basic argument is possible. Background monitoring can be considered an attempt to find out the typical range of values at the target station in adverse months, assuming that the range of daily maximums at a background station, as opposed to a source-affected station, is very small. Thus, the largest value observed will not be much different from the second maximum.

Overview of Conclusions

So that the reader may make the distinction in later detailed discussions between arguments most relevant and those least relevant to the conclusions of this report, the final results will be outlined as follows.

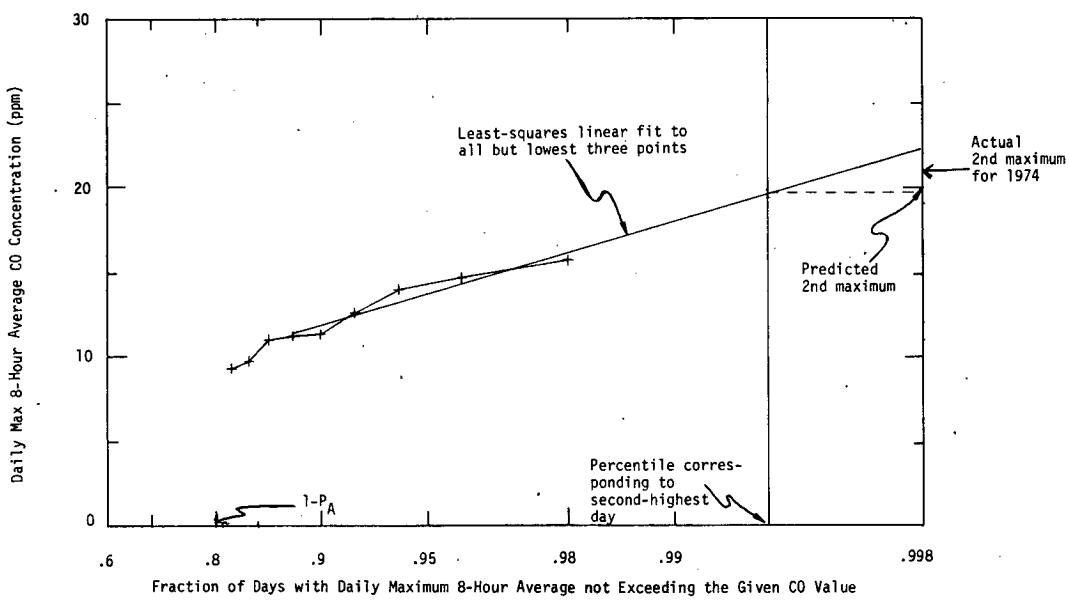


Figure 7. Illustration of methodology when meteorological data are available.

It was found that the observed-maximum method works surprisingly well, in fact better than either the distribution method or the combined method. It was further noted that one month of monitoring yields results of more-than-acceptable accuracy. For the observed-maximum method, there is little increased accuracy in going to two-month sampling. The results for the observed-maximum method are predicated on having at least 6 adverse days within a one-month period or 10 adverse days within a two-month period of sampling.

It was found also that accuracy did not increase in any systematic way with the number of adverse days in the sampling period for any of the methods. The only apparent requirement was that the minimum requirement on number of adverse days be met and that sampling be within the high-CO period of October, November, December, January, and perhaps February.

Thus, the methodologies suggested by the studies in this report indicate that there is little advantage to using a distribution approach over the simple approach of using the observed maximum during the sampling period, provided that sampling is limited to the high-CO season. Since it was concluded that the CO measurements in the off-season are unrelated to annual measurements, one cannot, with any method, extrapolate from data in the low-CO season to the high-CO season. These conclusions are justified in the following sections.

ASSUMPTIONS, DEFINITIONS, AND PRELIMINARY ANALYSES

This section covers some precursors to the methodological analysis:

1. Locale selection.
2. Choice of target and auxiliary stations.
3. Definition of the 8-hr second max.
4. Treatment of the 1-hr second max and the annual average.
5. Treatment of missing data.
6. Sampling plans.

Locale Selection

In determining requirements for the data base of this study, certain characteristics were required of the data—characteristics that the development of any methodology for background estimation would need. The key statistics to be estimated are the 8-hr and 1-hr second maximums. In order to test any methodology, complete or nearly complete years of CO data at urban sites in the study must exist. In order to conform to usual practice, the second maximums estimated have been defined in calendar years, thus requiring not only full years of data, but, ideally, full calendar years.

In addition to this basic requirement, another requirement that is nearly as fundamental, to test the approach of using an auxiliary CO station, is the need for the existence of data at both the target station and the auxiliary station simultaneously for at least one year. Not only are data required at both candidate target and auxiliary stations, but the auxiliary station CO data should have some relevance, even superficially, to the CO data at the target station. The data base of Chicago, described later, provides an example of a failure of this criterion.

There is also the over-all requirement that the methodology developed have as wide an applicability as possible. Thus, in choosing urban locales for the present study, two conflicting needs were apparent:

1. The requirement for complete, accurate, and long-term data, including auxiliary CO stations and extensive meteorological data, in order to allow the exploration of a wide variety of potential indices that could be developed, of tradeoffs between various algorithms, and of a variety of sampling plans.
2. The requirement that the study be widely applicable and not area-specific.

These needs pose a conflict because of the poor quality of historical CO data in most locales. Although data quality has improved recently, the requirement for a minimum of one complete calendar year of accurate data at a number of monitoring locations in each locale, along with accurate meteorological data for the same period, is seldom satisfied.

Development of methodology requires a level of accuracy considerably greater than that needed for the testing of a given algorithm. The testing, in turn, necessitates a more accurate data base than that required for implementation of any given extrapolation technique. For example, in this study, it is shown that, in many situations, one month of sampling at a target site during the CO season, with no auxiliary data, is sufficient to obtain reasonable estimates of second maximum statistics. However, even though only this much sampling is needed to implement such an approach, obviously many station-years would be required to verify its accuracy.

The basic approach to achieving both objectives was to consider two types of locales: primary and secondary. Primary locales were used for extensive methodological development and comparison. Los Angeles and New Jersey (New York City area) were used as primary locales. Secondary locales were used to verify the methodology developed to determine its generality and to extend results on confidence intervals to a broader geographical area. Data at secondary sites need not be as complete or accurate as at primary sites, because they are used in a more limited manner. The locales used as secondary locales were San Francisco, Denver, and St. Louis (RAPS data). The Chicago locale was considered, but had to be dropped from the study for reasons explained in the following.

Table 3 lists the locales studied and the stations used within these locales. The precise definition of the classification scheme used with these stations is given in a later section. Specific comments on each locale are as follows:

1. *Los Angeles*—Los Angeles has a reputation for high-quality CO data. It is the most studied of all cities, and the meteorological data are of high quality. It is one of the principal study locations.
2. *New Jersey*—The New Jersey data are also quite good. The sites in New Jersey can be divided into three groups: nonurban sites, sites near Philadelphia, and sites near New York. The group near New York is of primary

TABLE 3

LOCALES USED IN THE STUDY

Locale	Station	Classification	Period of Data
Los Angeles (primary)	Downtown L.A.	Intermediate	1/70-12/74
	Burbank	Intermediate	1/70-12/74
	Lennox	Source-Affected	1/70-12/74
	West L.A.	Intermediate	1/70-12/74
	Whittier	Intermediate	1/70-12/74
	Reseda	Intermediate	1/70-12/74
	Newhall	Background	4/70-12/74
New Jersey (primary)	Bayonne	Background	1/70-12/74
	Elizabeth City	Intermediate	8/70-12/74
	Elizabeth Trailer	Intermediate	5/72-9/72,1/73-3/73 7/73-12/74
	Newark	Intermediate	1/70-12/74
	Jersey City	Intermediate	8/70-12/74
	Hackensack	Intermediate	8/70-12/74
	Paterson	Intermediate	8/70-12/74
San Francisco (secondary)	Richmond	Background	3/72-12/73
	Redwood City	Background	1/70-12/74
	Burlingame	Background	5/72-12/74
	San Jose (4th St.)	Intermediate	8/72-12/74
	Sunnyvale	Background	9/73-12/74
	Oakland	Background	1/70-1/74
	Fremont	Background	1/71-12/74
	San Francisco (Ellis St.)	Background	1/70-12/73
Denver (secondary)	Arvada	Intermediate	1/74-12/76
	CAMP	Source-Affected	1/74-7/74,10/74-12/76
	CARIH	Intermediate	1/74-12/71
	NJH	Source-Affected	1/74-8/75,11/75-12/76
	Overland	Intermediate	1/74-12/76
	Welby	Intermediate	1/74-12/76
St. Louis (secondary)	Carr Square	Intermediate	1/76-12/76
	Norfolk & Western	Intermediate	1/76-12/76
	Newstead & N. Market	Intermediate	1/76-12/76
	Washington Univ.	Intermediate	1/76-12/76

interest because it is a heavily industrialized urban area and has typical east coast meteorology. The sites near Philadelphia were fewer in number than those near New York and were not in as close proximity to each other. Of course, the nonurban sites were inappropriate for the study. Therefore, the New York-metropolitan-area New Jersey stations were chosen.

3. *San Francisco Bay Area*—This set of stations turned out to be a good testing ground for the methodology of this study because it contains a relatively large number of background stations. One consequence of this large number is that stations tended to show somewhat irregular correlations with each other—stations quite far apart sometimes evidenced higher correlations than stations closer together. Nevertheless, the results from this site were consistent with those from Los Angeles and New Jersey.

4. *Denver*—This locale provides a very difficult test of any CO estimation technique. It has mixing heights that are typically low in the morning and very high in the afternoon, particularly in winter, which has the effect of causing extreme peaks in CO concentrations. In addition, the siting in Denver is such that all the stations were classified as intermediate or source-affected; the sites were evidently chosen to obtain estimates of near worst-case health effects rather than of general background.

The data from Denver were of very high quality. The editing process usually performed by the research team turned out to be a redundant effort because the data were obtained directly from the State of Colorado Department of Health, which had previously edited them.

5. *St. Louis*—The St. Louis SAROAD data lack a significant number of values, and, in particular, have several entire months missing from most of the station-years. Because of the large number of RAPS stations, the RAPS data were used. After a preliminary look at the data, the four stations listed in Table 3 were chosen. Unfortunately, the fact that the CO in the RAPS project is monitored using a gas chromatograph (G-C) technique, rather than the nondispersion infrared (NDIR) technique used at most stations and in all the other locales in this study, seemed to make the RAPS data anomalous. As part of the RAPS study, an informal comparison of five nearby CO monitors, one G-C and the others NDIR, revealed anomalies in both the magnitude of the data (by nearly a factor of 2) and in the shape of the distribution of values.

6. *Chicago*—The Chicago SAROAD data obtained for this study were not used for two reasons. First, among the three stations showing data simultaneously for one year (CAMP, Cermak, and Polk St.), the local air pollution officials expressed minimal confidence in the data, especially in its SAROAD form. Second, an examination of the correlations between stations indicated unusual behavior of the data. The correlation matrix of the three Chicago stations considered is compared in Table 4 with one for a subset of the Los Angeles data base. These circulation matrices are presented to show, in a gross statistical sense, the enormous variation between locales and, in particular, the difficulty with the data in Chicago.

The four Los Angeles stations chosen include three that are within 15 mi of each other (downtown Los Angeles, Burbank, and west Los Angeles) along with a station (Newhall) that is over 20 mi away and is located in a considerably different meteorological region. Newhall was included in order to show that even an unrelated station had higher correlations with downtown Los Angeles stations than those correlations observed among some of the Chicago stations, all located in downtown Chicago and relatively close to each other.

Choice of Target and Auxiliary Stations

Carbon monoxide stations are subject to being source-affected. The monitoring sites used in this study need to be classified because the degree to which they are source-affected can markedly influence results. The sensitivity of carbon monoxide measurements to a variety of factors, including distance to the nearest roadway, vertical placement, and the existence or nonexistence of nearby structures, has been noted by a number of authors (*7, 8*).

It is the objective of this study to formulate and test sampling plans that will allow highway engineers to use less than one full year of continuous data from a target site to extrapolate to annual statistics at that site. The following situation is to be modeled: a CO monitoring station is placed at a proposed highway site, which has been called the target station; data are taken at the target station for less than one year, nominally for one or two months. Car-

bon monoxide monitoring data and/or meteorological data from an existing monitoring network are used to extrapolate the data taken from the target site. In this study, no actual monitoring at an hypothetical highway site was performed. Rather, some existing monitoring sites were used as though they were target sites.

Thus, a distinction must be made between source-affected and background stations to determine how well an existing station used in this study is similar to a target station that would be used in a proposed urban highway corridor. Such a target station in an urban area is likely to be near some streets because urban highways have many cross streets. At the same time it often will be placed at some distance (at least 20 to 50 ft) from any major cross street.

After discussing CO monitoring sites with a number of state and municipal monitoring agencies, the research team concluded that the monitoring sites studied could be described by three categories: (1) background, (2) intermediate, and (3) source-affected. For the purposes of this study, a background site is preliminarily defined as a site far from any major roadway or point source of CO ("far" defined as in excess of 200 ft, following Ott (*9*)). Ott's figure of 200 ft, as well as the slightly less conservative figure of 115 ft from Kinosian and Simeroth (*7*), is referenced in the EPA guideline (*10*) for air quality monitoring network siting. This type of background site is like most target sites actually used in preparation of environmental impact reports (see, for example, Holland (*3*)) and, as was discovered, is a type of site not commonly found among existing urban monitoring stations. A source-affected site is preliminarily defined, for the purposes of the study, to be one that is near a large roadway ("near" being closer than 50 ft or close to parking lots or other major sources of CO). Finally, the remaining stations were preliminarily categorized as intermediate. These definitions roughly correspond to the intuitive ideas that most highway engineers have about site classification.

Following this preliminary look, a study was then undertaken to see if certain numerical parameters of the data could be found that would reflect the definition monitoring agencies use to differentiate between target stations that are source-affected from those that are background. The principal motivation for using inherent numerical properties of the data is that the definitions of background currently in use imply a large measure of subjective judgment on the part of the classifier. Such phrases as "significant point-source effect" are in fact vague. This investigation is discussed in Appendix A. In short, the results of some numerical explorations and of numerous contacts with monitoring agencies led the researchers of this project to the conclusion that the levels of CO encountered at the site were, in fact, the determinant of site classification. In practice, an 8-hr second annual maximum less than 12 ppm will almost certainly be a background station by any definition. Some stations that would appear to be appropriately considered intermediate stations (lightly source-affected) get near an 8-hr second max of 12 ppm. The specific site characteristics, therefore, were carefully studied around this level. The heavily source-affected stations show high peak values; therefore, stations were classified as source-affected (more accurately, heavily source-affected) when high values were observed and the site characteristics verified this assessment.

TABLE 4

COEFFICIENTS OF CORRELATION OF DAILY 8-HR MAXIMUM FOR SELECTED STATIONS FROM THE DATA BASE OF THIS STUDY

Selected L.A. Stations (Average of 1970-1974 Annual Correlations)

	Downtown L.A.	Burbank	West L.A.	Newhall
Downtown L.A.	1.00	.84	.79	.23
Burbank	.84	1.00	.83	.38
West L.A.	.79	.83	1.00	.26
Newhall	.23	.38	.26	1.00

Selected Chicago Stations (Average of 1974-1975 Annual Correlations)

	CAMP	Cermak	Polk St.
CAMP	1.00	.19	.19
Cermak	.19	1.00	.64
Polk St.	.19	.64	1.00

Definition of the 8-Hr Second Maximum

The air quality standards require that the 8-hr average CO concentration not exceed 9 ppm more than once a year. In developing the distribution of 8-hr averages, the daily 8-hr max will be used, the maximum running 8-hr average within each day. Thus, averages that cross midnight are not considered, and statistics are not considered other than the maximum 8-hr average during the day in estimating the annual 8-hr second maximum. The second highest daily maximum in a year is the quantity used in the evaluation of the developed procedure. This choice was motivated by theoretical considerations (largely the approximate independence of the daily maximums) discussed later.

The use of this definition of the second maximum requires justification on two grounds:

1. The method of computing the 8-hr second maximum recommended by the Environmental Protection Agency (EPA) allows averaging over midnight.
2. The method of computing the second maximum recommended by the EPA allows the second maximum to occur in the same day as the first maximum.

With respect to the first point, averages through midnight have not been included. The problem context requires not an estimate of whether a standard is violated at the target site, but an estimate of the background level to be added to the estimated highway contribution. Because the peak contribution from the highway model will be estimated for peak traffic loads, it would not make sense to add a highway contribution to a background level estimated for a time of day when traffic is minimal. Therefore, by not including averages through midnight, the potential has been minimized for a mismatch in the time of occurrence of peak

levels estimated by a highway model and the maximum background estimate.

When the second maximum for the year occurs near midnight (which it can), there is typically another daytime maximum within the year that is very close in value to the nighttime peak. Thus, the value estimated by the procedure is typically nearly the same whether or not averages crossing midnight are used. On the other hand, if one allows averages crossing midnight, the maximum on one day can include all but one of the hours in the 8-hr maximum for the adjacent day, clearly destroying the day-to-day independence. As will be seen in the discussion of method development, the independence significantly reduces the difficulty of treating the present application.

Regarding the first and second maximums within one day, there are at least three ways of defining the second maximum running 8-hr average:

1. The second maximum running 8-hr average, allowing the first and second maximums to overlap. (This would most likely result in the first and second maximums' including 7 common hours.)
2. The second maximum 8-hr average excluding the 8 hours that represent the first maximum.
3. Given all possible pairs of nonoverlapping 8-hr periods in the year, each of these pairs is assigned the value of the lesser of the two 8-hr averages of that pair. The 8-hr annual second maximum is then the maximum of this set of numbers. As an example, Figure 8 shows a year in which the 8-hr periods designated "A" and "B" are the nonoverlapping pair where the highest lesser value of the 8-hr average is 16.3. Note that, as shown in Figure 8, the second 8-hr maximum thus defined overlaps the single highest 8-hr average in the year. The EPA (*11*) recommends this definition.

The distinction between the last two cases is rather subtle, but the distinction is relevant in isolated cases (see Fig. 8 for an example to clarify the distinction between the definitions). In general, the second and third definitions will most often result in the same second maximum except for these isolated cases. When the third definition yields overlapping first and second maximums, the first and second maximum will be highly dependent because they must both occur within a 15-hr time interval.

The computational complexity of using this latter definition, along with the possible resulting dependence between the first and second maximums, does not make direct estimation of the second maximum under this definition attractive.

If one uses the second definition—that of the nonoverlapping second maximum—in conjunction with the restriction against averaging across midnight, this definition is in practice equivalent to defining the second maximum as the daily maximum of the second highest day for all the data analyzed in the current study. None of the data contained a case where the second maximum for the year occurred as a nonoverlapping 8-hr average within the same day as the first maximum.

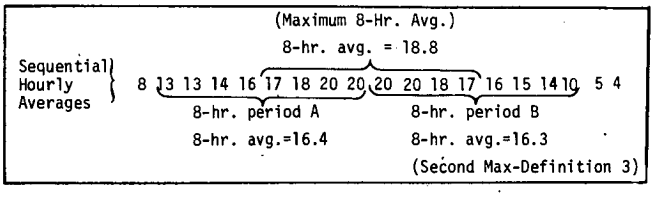


Figure 8. Example illustrating how the EPA-recommended definition of the 8-hr second max can result in an overlapping 1st and 2nd maximum.

The 8-hr second max used in the derivation and evaluation of the methodology is the second highest of the maximum, within-day, 8-hr averages—that is, the second highest daily 8-hr maximum. The method also directly estimates the annual maximum 8-hr average (with the assumption that the annual maximum does not cross midnight). The values of the second maximum yielded by the three definitions given are bounded by these two values. The first definition yields a second maximum close to the first maximum. The third definition yields a value close to the first maximum when there is overlap and one close to (usually the same as) the second daily maximum when there is no overlap. The second definition will almost always yield a value equal to the second daily maximum (particularly if 8-hr averages crossing midnight are excluded). Since the method of this study allows estimation of the daily maximum and the second daily maximum, the uncertainty in the definition can be translated into an increase in the uncertainty interval of the predicted result. This point will be discussed at greater length in discussing methodology, but the main point to be made here is that, by dealing with the second daily maximum, one is not eliminating the use of any of the choice of standards; one is merely translating the choice of standard definition into the choice of relative weights on the predicted first and second daily maximums.

To the already complicated definition of the second maximum, a further complication must be added. When one takes into account the fact that no monitoring station has complete data, the potential alternatives in defining the 8-hr second max increase. The simplest alternative is to say that one will only consider data when there are 8 consecutive hours and perhaps limit the considerations only to stations where at least 75 percent of the 8-hr averages for a given year exist. Because of missing data, the measured second maximum in the year will be less than the true second maximum, which, in general, will be unknown except for stations with essentially 100 percent complete data. The treatment of missing values is discussed further later.

Treatment of the 1-Hr Second Max and the Annual Average

In the methodology developed, the 1-hr maximum is not estimated directly, but it is related to the estimate of the 8-hr maximum. Also, an exhaustive test is not performed of the procedure for the estimation of the annual average. This section discusses the motivation for the foregoing limitations in this study.

Treatment of the 1-Hr Second Max

The air quality standards require that the 1-hr-average CO concentration not exceed 35 ppm more than once per

year. There is no particular difficulty in defining the 1-hr second maximum because the question of overlap does not arise as in the case of the 8-hr average. However, the second maximum 1-hr average has a high likelihood of occurring on the same day as the maximum 1-hr average; therefore, one cannot assume independence between the 1-hr first and second maximums.

Another problem in treating directly the 1-hr second max is the fact that the second highest 1-hr value in a year is very likely to be caused by an anomalous event. An extreme example is the known case of a repair truck parked with the engine running directly under the monitor for an hour. This sort of anomalous event, of course, cannot be considered part of a normal statistical process. For that matter, such occurrences do not represent an honest measure of background. Similar considerations are relevant to peak 1-hr values that are not source-affected, such as the example given earlier for Las Vegas in Figure 2.

Fortunately, these difficulties in treating the 1-hr maximum are ameliorated by the fact that the 1-hr standard is not the dominant CO standard. In all cases where there is not an anomalous source-affected event, an area in which there are violations of the 1-hr standard will also have violations of the 8-hr standard. Table 5 gives, for the stations reporting at least 75 percent complete data for the year of 1974 throughout the country, the number reporting 1-hr and 8-hr violations. There were 116 stations reporting at least one 8-hr violation during the year, and only 22 stations reporting any 1-hr violations during the year. All of the stations with 1-hr violations had at least one 8-hr violation as well. In fact, for the 22 stations with 1-hr violations, the median number of 8-hr violations during the year was 257. Hence, it is reasonable to assume that the 1-hr standard will be met if the highway impact analysis suggests that the 8-hr standard will be met.

The level of the 1-hr annual maximum was chosen to be estimated from the estimate of the 8-hr second max through a simple linear equation to significantly reduce the complexity of the procedure resulting from this study. The specifics of this technique are reserved for later discussion.

The Annual Average

Since the annual average is not a standard, it is not currently required as part of a highway impact analysis. Note that, except for a negligible difference arising from the first and last days of the year, and some small differences due to missing values, the annual 1-hr average is equal to the annual 8-hr average. If it becomes required, it would not be a difficult quantity to estimate, simply because it does not vary greatly in value. For the 85 SAROAD stations reporting 90 percent complete data in 1974 (from 82 cities), the mean of the annual averages was 2.6 ppm. The standard deviation was 1.1 ppm. The minimum and maximum values were 0.3 ppm and 5.5 ppm, respectively. Two highly source-affected stations with annual averages of 11.5 ppm and 16 ppm were eliminated from these statistics, but many source-affected stations are included. Thus, using the value of 2.6 ppm as the estimate of the annual average irrespectively of any measurements would result in the standard deviation of the error in the estimate of 1.1 ppm. However, a somewhat more complicated technique is suggested in a later section.

TABLE 5

COMPARISON OF NUMBER OF STATIONS REPORTING 1-HR AND 8-HR VIOLATIONS FROM 153 SAROAD (1974) STATIONS REPORTING 75% DATA OR MORE (REPRESENTING 150 CITIES)

1-Hour Violations	8-Hour Violations: NONE	8-Hour Violations: AT LEAST ONE
NONE	37	94
AT LEAST ONE	0	22

Treatment of Missing Data

In defining the 8-hr second maximum, it is evident that, for each day, it is necessary to determine the maximum 8-hr average not crossing midnight (i.e., from within-day 1-hr averages). Even for the best of data sets, such as the Denver data base set, there will be missing 1-hr values. If all 8-hr averages were declared missing if any 1-hr value were missing, much data would be needlessly lost. On the other hand, if the 8-hr average were defined as the average of whatever hours in the 8-hr period were valid, some serious problems could result. An example of this is shown in Figure 9. The 8-hr average from 4 to 11 is 17.7. If hours 4, 5, 10, and 11 are missing, the average of the remaining 4 hours is 23.5. If they were filled in by averaging, the resulting 8-hr average would be 18.5, closer to the original.

Toward the end of preserving as much of the data as possible, a study was performed of how to interpolate missing CO data. The study is described in Appendix B. The conclusion of this study is that, for the data base investigated, the best data base-independent method was to use averaging of adjacent hours. Even though more sophisticated methods were explored in this study, they were found only marginally more effective than the adjacent-hour averaging.

As a result of the foregoing findings, the following somewhat conservative criteria were formulated for filling in missing 1-hr values. For a given 8-hr period, no more than three hours were allowed to be missing; and, among the eight hours, no more than two adjacent hours were allowed to be missing. If either one of these criteria failed, the 8-hr average was defined to be missing. The following (where X stands for data, and M stands for missing values) demonstrates some sequences of missing data in 8-hr periods that were determined acceptable and some that were not:

Acceptable 8-Hr Time Periods
M M X M X X X X
M X M X M X X X
Unacceptable Time Periods
X X X X M M M X
M X M X M X M X

Interpolation on the resulting values was performed as follows:

1. If one value was missing or two values in a row were missing, the missing values were first filled in by linear interpolation. Then, the average of the resulting eight values was taken.
2. If more than two hours in a row were missing, which can happen in the first or last 8-hr period in a given day, the 8-hr average in that time period was defined as the average of the remaining six hours, where one of the six was allowed to have been filled in by an averaging of adjacent values.

As a result of filling in missing values, most days have an 8-hr daily maximum defined, even with some 1-hr values missing. This is important in estimating the "true" second maximum in the year. With too many missing days, the second maximum would be second among a significantly smaller set of numbers, and, hence, would correspond to a different percentile than that of the second highest of 365 days. The resulting second maximum would be below the true second maximum. Thus, with this method of filling in missing values, the data are nearly complete as a set of daily maximums; for most of the stations of interest in this study, not more than 4 or 5 days are missing out of 365 in the year. On the other hand, as a set of hourly values, 4 percent to 8 percent of the 8,760 hourly values in the year were routinely missing.

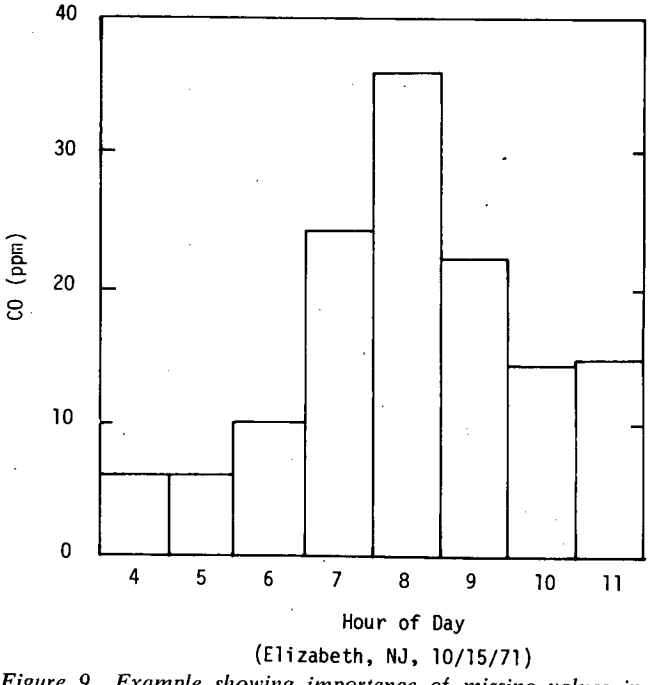


Figure 9. Example showing importance of missing values in determination of 8-hr averages.

Sampling Plans

In developing the methodology, the research team focused heavily on the 1-month continuous sampling plan, and on the 2-month plan as an extension. The first reason for this is that this approach is already the most common one in use, and it is considered the most practical, according to the telephone survey conducted of state highway agencies and environmental impact reports. Taking the short-time continuous sampling plan as a given, the research team sought a reasonable and justifiable extrapolation methodology that would put existing practice, or something as close to it as possible, on more solid footing.

Some state highway agencies also reported using 5-day and 3-day midweek sampling plans. Therefore, the research team adopted the constraint that the methodology developed for the 1-month and 2-month sampling plans be readily extendable to the 5-day midweek or 3-day midweek sampling plans. This constraint is satisfied by the proposed methodology.

Random hourly sampling was not considered a desirable sampling method by the respondents in the aforementioned telephone survey. No effort was made to develop methodology that would encompass random hourly sampling. The final methodology does encompass random sampling of entire days.

DERIVATION AND EVALUATION OF METHODOLOGY

Determining Adverse Days

The motivation for emphasizing high pollution potential days—what have been called "adverse" days—has been indicated. If one had data at the target station for the full year, the adverse days would be defined as the days resulting in the highest 20 percent of days at the target station, measured by daily 8-hr maximums in the year. Since limited monitoring is being done at the target site, one must determine indirectly which of those days are adverse days. For the distribution method, it is necessary to identify those days in order to identify the values arising from the upper tail of the distribution. For the observed-maximum method, it is desirous to use the number of adverse days to verify that a sufficient sampling has been performed within a high pollution potential period for the method to be valid; one also wishes to determine if the accuracy of the method is related to the number of adverse days in the sampling period.

Part of the motivation for using a method that involves using adverse days is methodological. It is easier to classify days as "adverse" or "nonadverse" with accuracy than it is to determine a specific predictive relationship between a meteorological index and a target station or between an auxiliary monitoring station and a target station. Part of the reason for this statement can be discerned from Figure 10. In that figure, 8-hr daily maximums at an auxiliary station are plotted versus 8-hr daily maximums at a target station. Although there is some correlation between the two stations, the best linear fit does not predict the high values well. This is the rule rather than the exception. There is a danger in using a regression-type result to extrapolate to high values when (1) there are a small

number of samples for the regression (e.g., a month of daily data); and (2) many of the points used in the linear fit arise from meteorological classes that are not closely related to those causing the adverse days.

Determining Adverse Days with no Auxiliary Data

If one has no auxiliary data, the number of adverse days in a sampling period can be estimated by the number of adverse days in the period, based on regional statistics or nationwide statistics. Table 6 gives the number of days, on the average, that were adverse days in each month for the entire data base, along with a breakdown by locale. The average numbers of adverse days in the table were computed as follows: (1) the average percentage of adverse days in the month was computed—that is, the average, by locale and over-all station-months, of the number of adverse days divided by the number of days with valid data in month; and (2) the resulting average was multiplied by the appropriate number of days in the month (28¼ for Feb., otherwise 30 to 31) to obtain the number recorded in the table. These numbers may be used to determine, for a given month, what fraction of the month can be expected to be adverse days.

For the distribution-based method, the highest percentage of days in the sampling period, with the percentage equaling the expected percentage of adverse days for that period, yields the data plotted as arising from the upper 20 percent of the distribution. For the observed-maximum technique, the number of adverse days is used simply to confirm that sampling is done in a month with sufficient samples for the results to hold (as discussed in a later section).

For randomized sampling plans, where sampling is not continuous, the number of adverse days can be estimated by calculating the percentage of days that would be encountered with continuous sampling during the total sampling period and reducing that by the ratio of the number of days sampled to the total number of days in the period.

If a weekday-only sampling plan is used, these percentages must be adapted to reflect the fact that adverse days do not fall on the weekend in the ratio of 2 to 7, or 29 percent. In fact, on the average, only about 23 percent of adverse days for intermediate stations and 21 percent for background stations occur on the weekend during the high-CO months. Thus, weekday-only sampling strategies require the adjustment of the number of adverse days using this fraction. These procedures are discussed in more detail in Chapter Three of this report.

Determining Adverse Days Using Auxiliary Monitoring Stations

When there are monitoring stations in the area that have been operating continuously for the full year (excluding some missing data), such stations can be used to determine the adverse days. The simplest procedure is to use as the auxiliary station that station with the daily 8-hr maximum that correlates best with the target station during the sampling period. The highest 20 percent of days in the

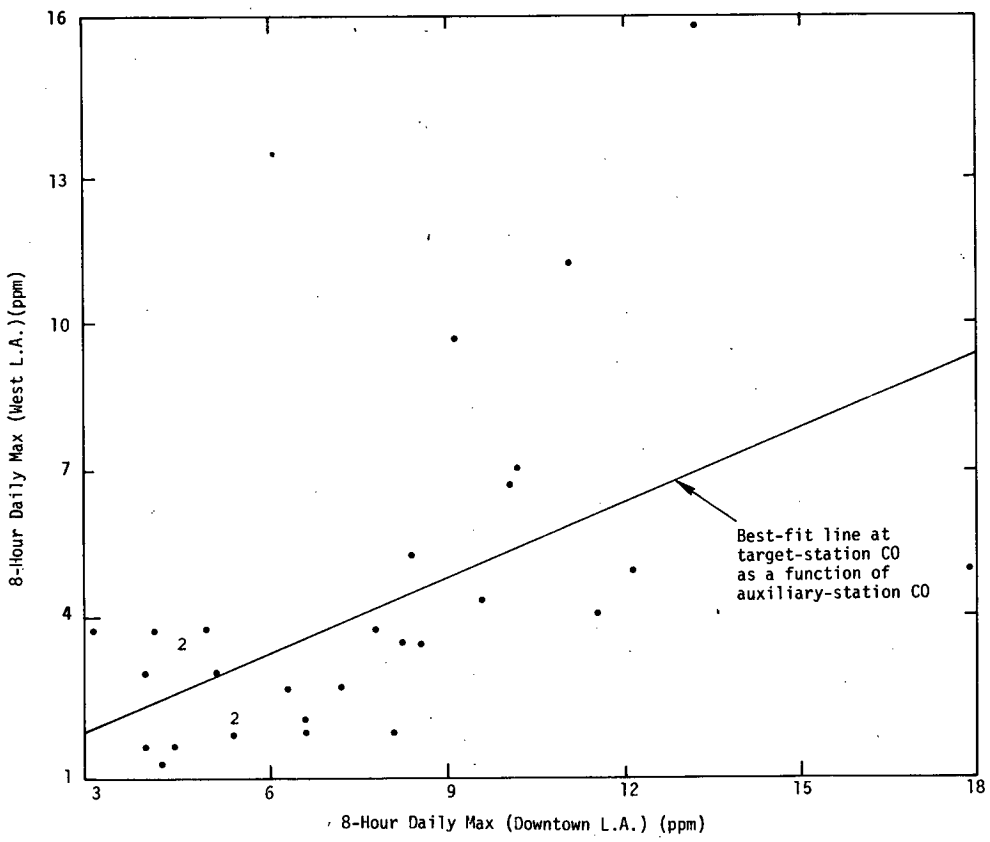


Figure 10. Target CO station vs. auxiliary CO station for October 1974.

TABLE 6

AVERAGE NUMBER OF ADVERSE DAYS BY MONTH, FOR ENTIRE STUDY DATA BASE AND BY LOCALE

Locale	Number of Station-Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Los Angeles	21	14.4	7.9	2.7	1.3	0.7	0.7	1.5	1.1	3.7	8.6	13.8	14.4
New Jersey	21	9.6	4.3	5.5	4.1	4.5	4.9	3.5	5.9	6.9	7.4	8.7	8.5
Denver	18	14.4	7.6	3.1	1.4	0.1	0.8	0.7	1.7	4.5	9.5	13.8	13.8
San Francisco	19	11.1	9.5	4.9	2.2	2.0	2.5	1.9	1.2	3.4	11.7	9.8	13.6
St. Louis	4	4.8	7.4	2.9	4.1	4.2	2.9	2.5	3.2	6.0	10.5	9.8	11.2
TOTAL*	83	12.0	7.2	3.9	2.3	2.0	2.5	2.0	2.5	4.7	9.3	11.4	12.8

*This is averaged by station-month and hence is the weighted average of the locale averages with weights proportional to the number of station-years represented.

year, measured by the daily 8-hr maximum, are the adverse days. Those adverse days that occur during the sampling period are the ones whose daily maximums are used for the distribution-based method or the number of which are used to assess the credibility of the observed-maximum method.

One might use data from several stations to refine the estimate of adverse days. One might combine stations by creating an index using "factor analysis" (using standard statistical software); the resulting index is a weighted average of the values of the daily 8-hr maximum at the individual stations. However, on investigating this approach, it was found that the possible improvement in accuracy resulting from this procedure does not justify the effort. This lack of significant improvement in using several CO stations as opposed to one station results from the fact that stations may be added that are less correlated with the target station than the single best auxiliary station.

Using a Meteorological Index

The development of a meteorological index is of importance in the situation where either no auxiliary CO site is present or the sites in existence are either too source-affected or too far away from the target site to be useful. A meteorological index summarizes the pollution potential of a given day as a function of several meteorological variables on that day. Given the values of a meteorological index, it can be treated as one would treat an auxiliary CO station—days with the highest 20 percent of daily values in the year as adverse days. This requires that meteorological data be available for the full year.

As a first step in investigating the feasibility of development of a meteorological index, an attempt was made to use surface meteorological data only. This was done because surface meteorological data are readily available to a highway engineer almost anywhere, whereas upper-air data are not. In this regard, two variables were selected for investigation: the difference between the maximum and minimum daily temperatures, abbreviated ΔT; and the average morning wind speed, MWS, the average of the 6 a.m., 9 a.m., and noon wind speeds.

In order to describe why ΔT is a variable that one might expect to be related to elevated levels of CO concentration, it is necessary to discuss some of the meteorological conditions that tend to produce high CO concentrations. Tiao et al. (*12*) showed a relationship between CO concentrations in Los Angeles and inversion base height, maximum mixing height, and wind speed as follows: Low wind speeds and limited morning mixing resulted in higher CO values. Low wind speeds and limited morning mixing (and therefore dilution) are typical of a certain type of weather pattern. Such a pattern is usually typified by clear, windless nights causing significant radiational cooling. Thus, in the wintertime, lower-than-average minimum surface temperatures result. The lack of winds is a result of weak pressure gradients, most likely due to a surface high-pressure center in the vicinity. Warming aloft usually begins. The net effect of these phenomena is a vertical temperature profile such that there are surface inversions (see Fig. 11). The combination of warming aloft and daytime surface heating results in larger-than-average maximum-minimum daily temperature spread, ΔT.

A first look at the potential for these surface observation meteorological variables to estimate CO levels was performed. Table 7 gives CO values at downtown Los Angeles as a function of the temperature difference, ΔT, and the average morning wind speed, MWS. The meteorological data were also taken at downtown Los Angeles. In each box of the table is shown the average values of the CO 8-hr maximum on days having the ΔT and MWS values indicated in the appropriate row and column, respectively, of the table. Also shown are the unbiased standard deviations of the entries along with the number of sample points on which each average is based. For example, on 19 days with ΔT between 10 F and 15 F and MWS between 3 mph and 4 mph, the average 8-hr maximum was 8.8 ppm with an unbiased standard deviation of 3.0 ppm. It is evident from looking at this table that there is a trend in CO values such that they increase as the ΔT increases and as the MWS decreases. It is also clear that the standard deviations of the values are relatively large.

At this point, several formulations of a CO index were tried using these surface observation variables. Multiple regression and stepwise linear regressions were performed with the CO 8-hr maximum as a dependent variable and the following independent variables: ΔT; the maximum of ΔT

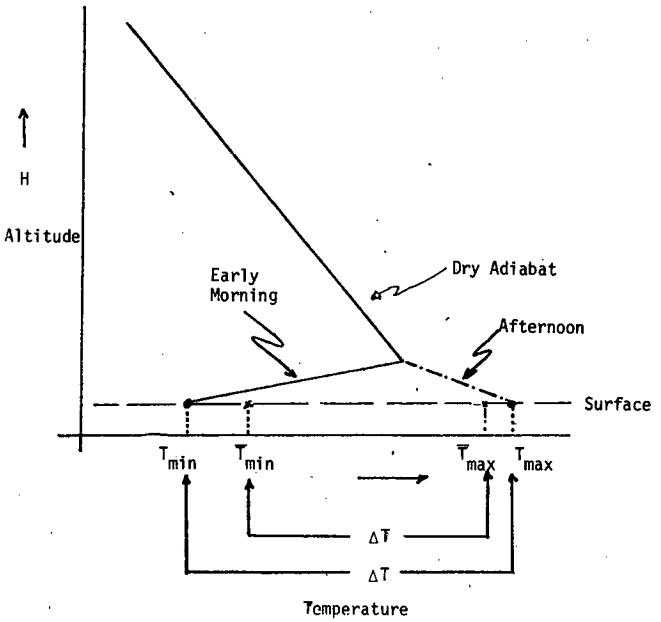


Figure 11. Vertical temperature profile conducive to CO build-up.

on the day before, on the given day, and on the day after; the minimum temperature; the minimum of morning and afternoon wind speeds; and the morning wind speed. The result of these tests was that, although some general relationship between these variables and resulting CO concentrations exists, the correlations were generally so low (less than 0.45) that the research team concluded that any index formulated from these variables would probably be no more effective than using no auxiliary data at all.

Dropping the constraint of using only surface meteorological observations, the research team then investigated existing meteorological indices for carbon monoxide to see what could be done if more elaborate meteorological models were used. One index, whose computation is described in Figure 12, was developed by a practicing meteorologist for the Los Angeles APCD. The methodology for formulating such indices is described by Zeldin and Meisel (*13*). As can be seen from Figure 12, this method requires the use of the following upper-air variables: temperatures taken at specified altitudes and temperatures taken at the base and top of the inversion layer. It was derived heuristically by looking at CO and meteorological data in Los Angeles over a period of several years. Presumably, such an index could be worked out for other locales, as long as upper-air data were available.

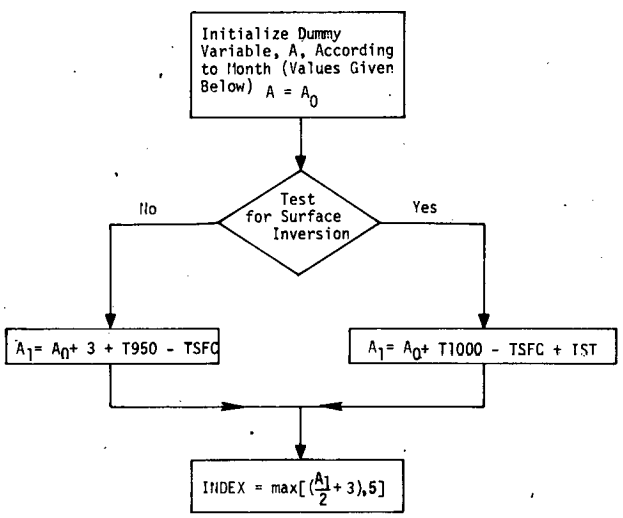
A test of the use of this index in monthly sampling was performed on a subset of the Los Angeles stations. Before describing the method in detail, it is important to note a fundamental difference between using an auxiliary CO station and an auxiliary meteorological station to extrapolate. A CO index, consisting of auxiliary station CO data, will reflect the fact that, in general, high CO values tend to occur on weekdays because traffic contributions to CO are generally higher on weekdays. However, meteorological indices are independent of this weekend/weekday effect,

TABLE 7

AVERAGES OF 8-HR DAILY MAXIMUMS FOR CERTAIN COMBINATIONS OF ΔT AND MWS FOR DOWNTOWN L.A. CO DATA AND DOWNTOWN L.A. METEOROLOGICAL DATA

Max-Min Temp ΔT (°F)	Morning Wind Speed, MWS--Average of 6 A.M., 9 A.M., and 12 Noon Windspeeds (mph)					
	0-3	3-4	4-5	5-6	6-8	8+
5-10		7.1 (N=1)	2.5 (N=1)		7.0+6.3 (N=2)	
10-15	9.6+2.1 (N=8)	8.8+3.0 (N=19)	7.8+2.2 (N=5)	8.6+3.0 (N=4)	7.8 (N=1)	
15-70	12.7+6.0 (N=10)	8.0+3.0 (N=9)	8.1+2.0 (N=8)	7.3+1.8 (N=2)	8.0+4.4 (N=7)	
20-25	15.1+4.3 (N=4)	11.0+3.4 (N=8)	10.3+2.2 (N=8)	8.8+4.5 (N=8)	7.4 (N=1)	
30-35	15.9 (N=1)	13.2 (N=1)	12.4+3.4 (N=4)	10.9+2.1 (N=3)		
35+			13.7 (N=1)			

so that using a meteorological index to select high-CO days on both weekends and weekdays would introduce a problem. To avoid this difficulty, the research team decided to use a sampling plan that omitted weekends and holidays (which amounts essentially to a 5-day midweek sampling plan).



Definition of Met Data Variables

T950 = 950-millibar temperature (°C)
T1000 = 1000-millibar temperature (C°)
TSFC = surface temperature (C°)
IST = inversion strength
= $T_{top\ of\ inversion} - T_{bottom\ of\ inversion}$

Initialized Values, A_0, for A

Month	A_0
Jan	15
Feb	10
Mar	6
Apr	3
May	-3
June	-3
July	-3
Aug	-3
Sept	-3
Oct	9
Nov	12
Dec	15

Figure 12. Flow chart of meteorological index computation. Los Angeles meteorological index postulated by experienced meteorologist.

The index was used as though it were an auxiliary CO station. The adverse days in the month in which the sampling occurred were defined as those days in the month among the nonholiday weekdays in the top 20 percent of the year's nonholiday weekdays, where the nonholiday weekdays of the year were ranked according to the value of the meteorological index on each day. Then, the values of the CO 8-hr maximum on those days at the target station were plotted on exponential graph paper, and extrapolation to the appropriate percentile for the second highest day of all the days of the year was performed.

The results obtained by using the meteorological index are discussed subsequently. In summary, it is noted that the results were comparable to those obtained using an auxiliary CO station. This fact suggests that the use of a meteorological index as an alternative to an auxiliary station is possible. However, the derivation of a meteorological index is difficult and area-specific.

Combining the Meteorological Index and Auxiliary Monitoring Data

The meteorological and CO indices, according to the results outlined in the previous section, are comparably effective. It is then natural to ask that if the two are combined, does one obtain additional information that would allow better extrapolations from limited data sets?

In order to investigate this question, the research team obtained special scatterplots of the Los Angeles stations on which the meteorological index was tried. These scatterplots (see Figs. 13 and 14) were designed for the following situation. Consider auxiliary station B and the meteorological index, both of which are designed to help extrapolate at a given target station A. The values of the 8-hr daily maximum at station B, the CO index at station B, and the meteorological index for the nonholiday weekdays were plotted, with each point representing one day. The symbols used were a "1" for nonadverse days at station A and an "A" for adverse days at station A.

The plot shows how the adverse days at the target station are distributed. By looking at the plot, one can see at a glance if there is some linear combination of the two indices that will better select the adverse days at the target station from the nonadverse days (i.e., separating the A's from the 1's) than a threshold of either index alone.

Figure 13 is an example using downtown Los Angeles as a target station with west Los Angeles and the meteorological index as candidate auxiliary indices for 1973 data. It is evident from the plot that the two indices are reasonably well correlated to each other, that they do an approximately equal job of separating adverse from nonadverse days, and that there is no combination of the two indices, such as a weighted average of the two, that would produce a better classification of adverse from nonadverse days than that achieved from either index alone.

Although downtown Los Angeles and west Los Angeles are both intermediate stations, much of the same pattern was demonstrated for the background station of the Los Angeles data base, Newhall. Figure 14 is a plot of the adverse and nonadverse nonholiday weekdays at Newhall (shown with A's and 1's) plotted at points corresponding to the values of two auxiliary indices: Burbank, an auxiliary CO station; and the meteorological index.

In general, for the stations studied, it was found that the graphs showed little promise of any new information from the use of an auxiliary CO station combined with a meteorological station. Therefore, it was concluded that, if a plausible meteorological index such as the one in Los Angeles could be constructed, the choice of meteorological vs. CO index could be made on the basis of cost, assuming that an auxiliary index was to be used to determine whether or not a month qualified as being an adverse month in order to use the monthly maximum estimation for the second annual 8-hr max.

Fitting a Statistical Distribution to the Data

Many parameterized distributions have been suggested for air pollution data. The earliest and most common was the log-normal distribution, based on pioneering work by Larsen (*2, 14-16*). Arguments for the basis for this observed distribution were offered by Benarie (*17*), Gifford (*18*), Kahn (*19*), and Knox and Lange (*20*). Hunt (*21*) and Neustadter and Sidik (*22, 23*), among others, have shown the usefulness of the approach. Mage and Ott (*24*) argued, on both empirical and theoretical grounds, for the appropriateness of the censored log-normal distribution. Lynn (*25*) compared the gamma, Weibull, and beta distributions to the log-normal and found the latter marginally better. Pollack (*26*) similarly asserted the suitability of the log-normal distribution. Curran and Frank (*27*) indicated that the apparent suitability of the log-normal might not extend well to the highest values, a fact they suggested was often masked by the plotting of the log of CO concentration in showing empirical results. They indicated the suitability of the one- and two-parameter exponential distribution for some cases in modeling high values.

These studies were oriented toward fitting an entire distribution of values, including the low values, and were thus largely oriented to the over-all goodness of fit to the data (with the exception of the work of Curran and Frank). In most of the foregoing studies, however, it was recognized that the upper end of the distribution is usually of greatest interest. Therefore, rather than fitting the data by paremeters such as the geometric mean and standard deviation for the log-normal distribution, it is common to extract these parameters using values at the upper end of the data, such as the median and 90th-percentile values, which results in the distribution fitting these percentiles exactly, as in Figure 15. Despite this qualification, most of the referenced research is not oriented toward the problem of extrapolating measurements as limited as those in this report. Because the number of measurements is so limited, the research team felt it necessary to use a method of fitting the data that utilizes all of the data at the upper end of the tail.

Thus, all the data for adverse days (the upper 20 percent of the distribution) are chosen to be fitted in a least-squares sense; that is, the distribution is chosen with parameters that best fit data from the upper tail of the distribution in a

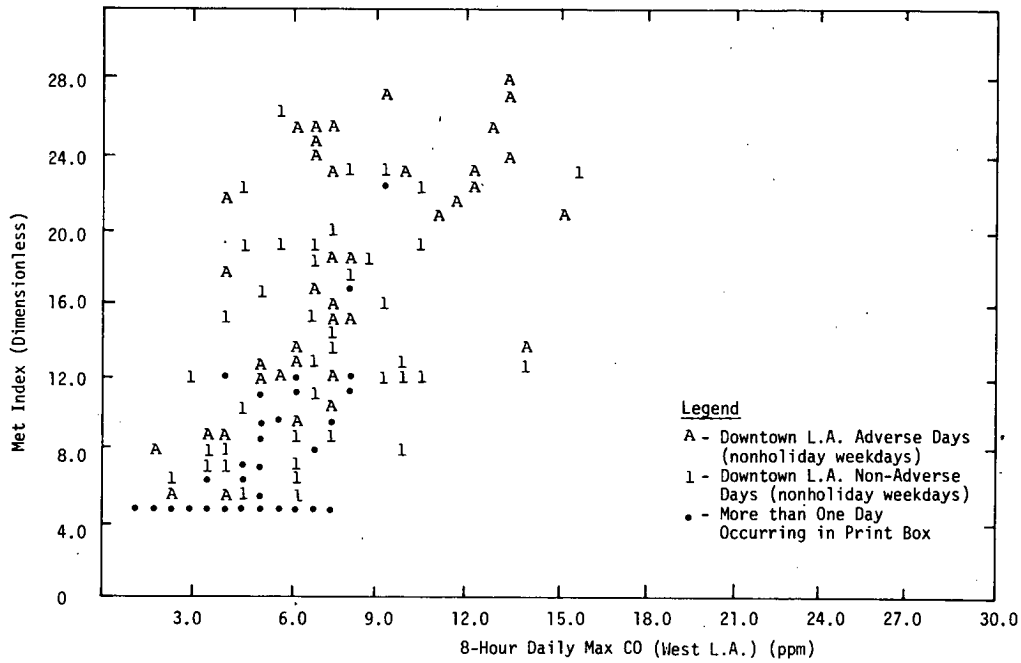


Figure 13. Downtown L.A. adverse and nonadverse nonholiday weekdays plotted on west L.A. vs. meteorological index scatterplot.

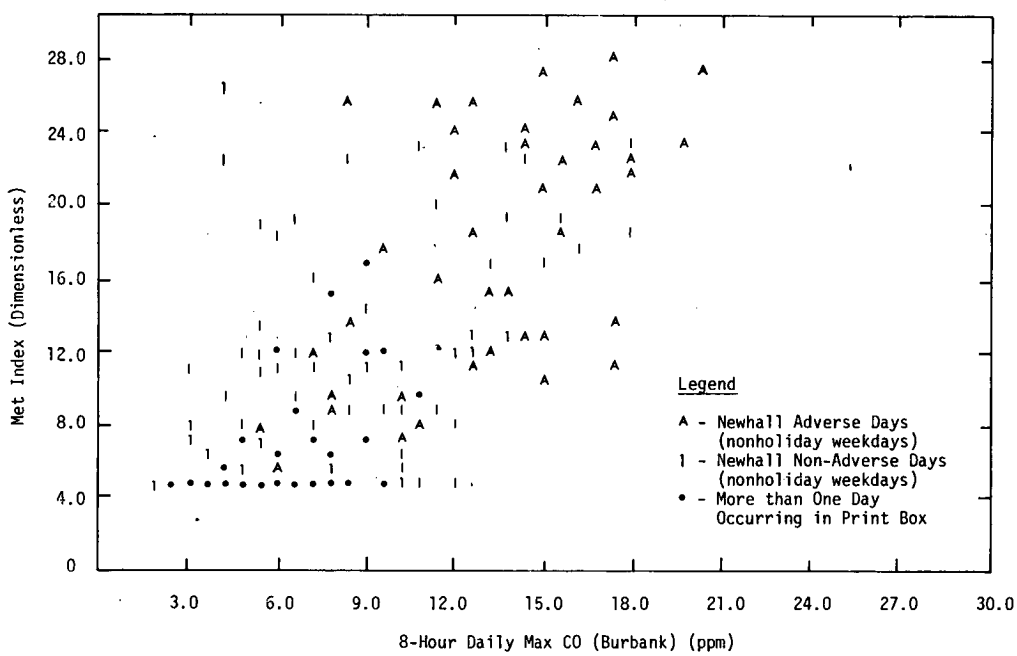


Figure 14. Newhall adverse and nonadverse nonholiday weekdays plotted on Burbank vs. meteorological index scatterplot.

least-squares sense, minimizing the sum of the squared error in the approximation.

If the adverse-days data are plotted on a scale chosen so that it plots approximately as a straight line, the least-squares fit becomes a simple linear regression, with the slope and intercept of the line determining the parameters of the distribution. A linear fit has the further advantages of being easily visualized and extrapolated. The accuracy of the fit can be visually inspected. For most distributions, the percentile scale can be nonlinearly plotted so that data that fit the given distribution will plot linearly. In fact, the degree of linearity of the plot is a measure of how well the distribution models the data. Thus, it is desirable to find a suitable distribution that can be nonlinearly scaled to plot linearly. Figure 16 provides an example of this characteristic.

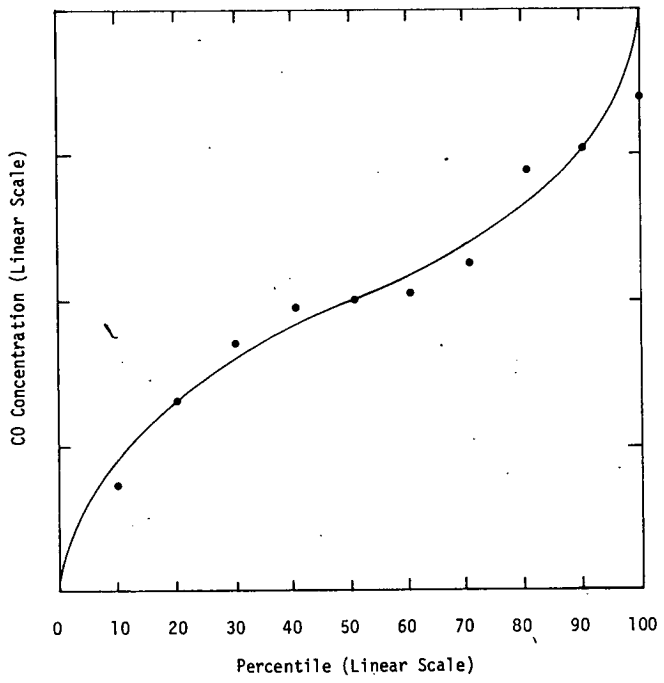


Figure 15. Theoretical distribution that fits the data exactly at the 50th and 90th percentiles.

It is also desirable to use a distribution where the vertical axis can be CO concentration, rather than the logarithm of CO concentration. (The log-normal distribution is usually plotted with a vertical log scale and a horizontal scale corresponding to the normal (Gaussian) distribution.) With a vertical log scale, equal-percentage errors appear the same. Thus, a 2-ppm error in predicting 4 ppm at the low end of the scale will appear to be of the same magnitude as a 10-ppm error in predicting 20 ppm at the high end of the scale. As noted by Curran and Frank (*27*), this masks errors in predicting the upper tail.

The exponential distribution fits these criteria. It also tends to be a good approximation to the tail of the distribution over a wide number of locales and stations. The distribution of the tail turns up from linear at the high percentiles as often as it turns down from linear, indicating that the exponential is a good average distribution. Because at the target station one will not have information as to the true distribution throughout the year, and because no single distribution is consistently best (even for a specific monitoring station from year-to-year), the exponential distribution is a reasonable choice to make.

It is worth noting, as shown in Figure 17, that the choice of distribution typically does not have a substantial impact on the estimated second maximum. Choosing a different distribution or adapting the distribution to the particular

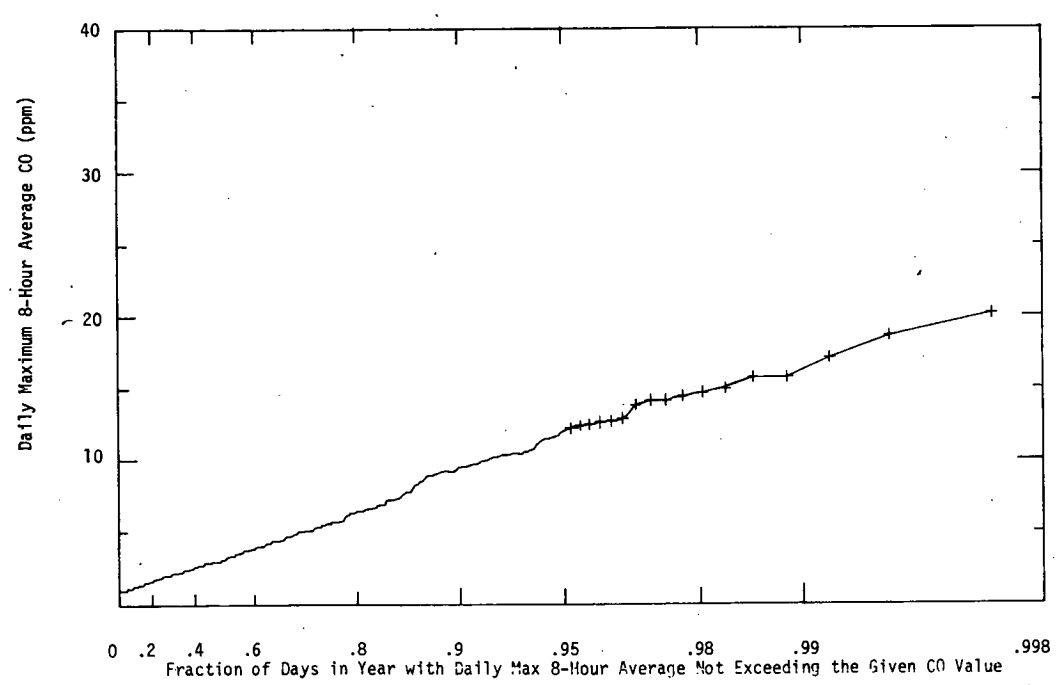


Figure 16. Cumulative distribution plot for west L.A. for the Year 1974 plotted on exponential graph paper.

station would not significantly change the results. Therefore, the results obtained by using the exponential distribution are representative of what would be obtained by using any other reasonable distribution or by choosing a distribution specific to each station. A discussion of how such a plot is created follows.

Suppose one has measured the daily maximum, within-day, 8-hr-average CO concentration for N days, yielding N numbers. Suppose these numbers are placed in increasing order, so that $x_i \leq x_{i+1}$ for $1 \leq i \leq N\text{-}1$. Thus, the value x_N is the 8-hr max for the highest day observed; x_{N-1} is the second highest day; and so on.

Intuition might suggest that the value x_i would correspond to the percentile $100 \cdot (i/N)$ of the day (e.g., the second highest day in the year might correspond to the percentile $100 \cdot (364/365)$; i.e., the 99.73th percentile). However, this same logic would place the highest value at the 100th percentile; this conclusion does not make sense for any distribution with an infinite tail. In fact, the *expected value* of the percentile for the ith value x_i is

$$100 \cdot \left(\frac{i}{N+1}\right) \tag{1}$$

(see, for example, Bury (*28*) or David (*29*)). Thus, using Eq. 1, the second highest daily value in the year would correspond to $100 \cdot (364/366)$ (i.e., the 99.45th percentile); and the highest value for the year, to the 99.73th percentile. Because the distribution of values for adverse days is assumed to arise from the upper 20 percent of the distribution, values for N adverse days would be plotted at the percentiles (expressed as a fraction) of

$$f_i = 0.80 + 0.20\left(\frac{i}{N+1}\right) \tag{2}$$

for $i = 1, 2, \ldots, N$. The best linear fit is then extrapolated to the CO value at 99.45 to obtain the estimated annual second maximum (see Fig. 17). In the limiting case where a full year's monitoring was performed, this choice of plotting percentiles would place the second

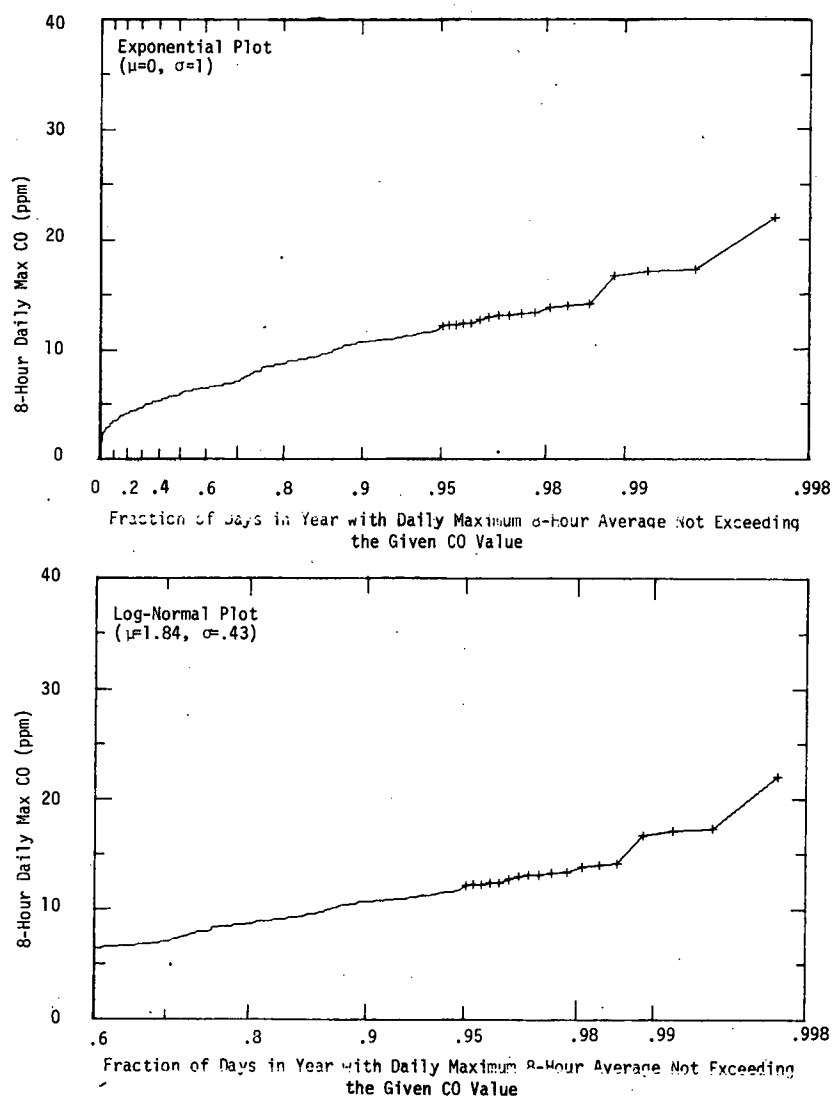


Figure 17. Cumulative distribution plots of 8-hr daily maximum for downtown L.A. (L.A. data base) in 1973 on exponential and log-normal paper.

highest value of the year at the 99.46th percentile, while the second maximum would be estimated at the 99.45th percentile—certainly, this is close enough.

Using the Maximum in the Sampling Period as an Estimator

The motivation for using the maximum daily 8-hr average in the sampling period as an estimator of the annual 8-hr second max has been previously discussed. The major reasons are, first, the simplicity of the approach; and, second, the expectation that the value so obtained will be representative of the annual second maximum if the sampling period is confined to the more adverse months.

One clear disadvantage of the use of the monthly maximum as an estimator is that, if extended to the entire year, it would yield the *first* maximum rather than the *second* maximum. (The distribution method has the attractive quality that, given a full year's data, it will estimate the annual second maximum very closely.) This disadvantage can be overcome by extending the definition of the method to use a weighted average of the first and second maximums observed during the sampling period, where the weight varies depending on the length of the sampling period. This extension of the methodology, however, was not adopted in this research both because of the intention of the researchers to obtain simplicity with the observed-maximum method and because of the likelihood that the maximum sampling period would be two months. For the data being analyzed, it would amount to an unjustified complication and would not substantially change the results.

One aspect of using the observed maximum as an estimator is that auxiliary data, such as a meteorological index or nearby monitoring station, are not used in a *direct* way in the estimate. The way in which auxiliary data would be used with the observed-maximum estimator is to verify that the sampling period contained enough days of an adverse nature to justify the estimate. In particular, the results discussed under the section heading "Performance of the Three Months" require that at least six adverse days be included in the sampling period for any one-month period. Further, because the analysis was limited to the more adverse months, at least 10 adverse days occurred in each two-month period used. Therefore, it is recommended that auxiliary data be used to verify the occurrence of at least 6 adverse days for one month's sampling and 10 adverse days for two months' sampling.

In the case where no auxiliary data are available, it then becomes of critical importance to perform the sampling in the most adverse months, as suggested by Table 6.

A Combined Estimator

In one sense, the two methods discussed might be complementary. The distribution-based estimator will make its largest errors when the first or second maximum occurs in a sampling period with a relatively small number of adverse days. In that case, the method might be extrapolating to a value considerably higher than the actual second maximum.

On the other hand, the observed-maximum estimator will tend to underestimate the second maximum in any month where the actual first or second maximum does not occur. It might then be expected that some sort of weighted average of the two estimates might be at least less biased, if not more accurate, than either alone.

There arises the question of what relative weights to use. The most logical, systematic approach was to use the typical frequency of occurrence of the first or second maximum in a given month to determine the relative weight between the two methods, as determined by the over-all average in Table 6. Suppose that the typical fraction of times the first or second maximum occurs in the sampling period is α. Suppose also that the distribution-based estimate is C_D and the observed maximum estimator is C_M; the combined estimator could then be defined as

$$C_{\mathrm{COMB}} = \alpha\, C_M + (1 - \alpha)\, C_D \qquad (3)$$

In other words, when there is a very high probability that either the first or second maximum occurred in the month, the maximum estimator would be weighted most heavily. When there is a smaller probability of the first or second maximum occurring in the month, the distribution-type estimator would be weighted more heavily.

This combined approach was also tested. The results are described in the following section.

Performance of the Three Methods

This section evaluates performance of the three approaches: (1) the distribution method, (2) the observed-maximum method, and (3) the combined method. The evaluation is divided into three parts:

1. Performance when monitoring is within one month.
2. Performance when monitoring is within two months.
3. The relationship between accuracy and the number of adverse days in the sampling period.

Monitoring Within One Month

The evaluation conducted in this study was limited to the most adverse four months: October, November, December, and January. Both primary and secondary locales were used in the evaluation; the results are thus for geographically diverse sites.

Table 8 presents the performance of the three methods in predicting the 8-hr second max for all target sites, both background and intermediate. Performance is indicated by five measures, each of which measures a somewhat different aspect of the over-all prediction error. The "bias" indicates whether the method overpredicts or underpredicts, on the average (and by how much). The standard deviation measures the root-mean-square error relative to the bias and provides an assessment of the over-all error if the bias is removed. The average magnitude of the error indicates the average absolute error with the bias. The correlation between predicted and actual values gives a dimensionless assessment of the degree to which the observed variation in actual values of the 8-hr second max is explained by predicted values. (A correlation of 1.0 is perfect.) The range of error indicates the extremes of the prediction error, the worst cases of underprediction and overprediction.

TABLE 8

ONE-MONTH MONITORING FOR ALL CASES, BOTH BACKGROUND AND INTERMEDIATE *

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error (ppm)	4.2	3.5	3.9
Bias (Average Signed Error in ppm)	0.5	-2.4	-0.2
Correlation Between Predicted and Actual	0.79	0.84	0.81
Average Magnitude of Error (ppm)	3.3	3.0	3.0
Range of Error (ppm)	22.5 (-9.3 to 13.2)	16.2 (-11.5 to 4.7)	19.9 (-9.5 to 10.4)

* Performance of methodologies by several criteria for 117 cases. Adverse days for the distribution method were obtained with an auxiliary CO station.

Except for the bias, the distribution method is worst by every measure, and the observed-maximum method is best. The monthly maximum method tends to underpredict, on the average, by 2.4 ppm; but, despite this bias, it still has a smaller average magnitude of the error than the distribution method.

In this comparison, adverse days for the distribution method were determined using an auxiliary CO station (the station with the highest correlation to the target station during the sampling period). Comparisons using a meteorological index and no auxiliary data are reported later.

The performance figures in Table 8 are relevant when it is uncertain whether the target station is strictly background or might be somewhat source-affected. Table 9 presents the performance of background stations alone. Again, the observed-maximum approach appears clearly superior; it even has the smallest bias.

On examination of the quality of these estimators in more absolute terms, for background stations, the average size of the error using the observed-maximum method is only 1.0 ppm, and the largest error made is an underestimation of 3.7 ppm. The distribution method is not much worse. In either case, this accuracy is not much different from the potential error in the CO measurements; certainly, as a background estimate to be added to an estimate of the highway contribution, further accuracy is not necessary.

For intermediate stations (Table 10), the average size of the error rises to about 4.0 for both basic methods. Again,

TABLE 9

ONE-MONTH MONITORING AT BACKGROUND STATIONS *

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error	1.6	1.2	1.4
Bias (Average Signed Error)	1.3	-0.5	0.9
Correlation Between Predicted and Actual	0.61	0.76	0.67
Average Magnitude of Error	1.8	1.0	1.5
Range of Error	5.8 (-2.1 to 3.7)	5.7 (-3.7 to 2.0)	5.3 (-2.6 to 2.7)

* Performance of methodologies by several criteria for 36 cases.

TABLE 10

ONE-MONTH MONITORING AT INTERMEDIATE STATIONS *

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error	4.9	3.9	4.7
Bias (Average Signed Error)	0.1	-3.2	-0.7
Correlation Between Predicted and Actual	0.49	0.57	0.52
Average Magnitude of Error	4.0	3.9	3.7
Range of Error	22.5 (-9.3 to 13.2)	16.2 (-11.5 to 4.7)	19.9 (-9.5 to 10.4)

* Performance of methodologies by several criteria for 81 cases.

it would be difficult to justify further effort to improve accuracy in the present problem context, although the maximum errors can get rather large (e.g., 11.5 ppm). If this accuracy is not sufficient to ensure compliance with the CO standards, a longer sampling period can be used to improve accuracy.

Two-Month Monitoring

In testing the extension of the sampling period to two months, a smaller set of data was used. For two-month sampling, the basic methods were comparable (Table 11), with the observed-maximum method having the smallest average magnitude of the error.

The combination method fared worst. Since the combination method was intermediate in performance for the one-month period, the research team concluded that it was not achieving the stated objective of using the best of both basic methods.

By comparing Tables 11 and 12, it can be seen that two-month sampling is clearly more accurate than one-month sampling for the distribution method, but not dramatically better for the observed-maximum method.

The distribution method is not improved relative to the observed-maximum method by the use of a meteorological index instead of an auxiliary CO station. Table 13 presents, for 36 cases in the Los Angeles area (the only area for which a meteorological index was derived), the relative performance of the methods. In general, performance with the meteorological index was closely comparable to performance with an auxiliary monitoring station.

TABLE 11

TWO-MONTH MONITORING AT BOTH BACKGROUND AND INTERMEDIATE STATIONS *

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error	3.6	3.5	4.1
Bias (Average Signed Error)	0.7	-0.8	0.0
Correlation Between Predicted and Actual	0.83	0.82	0.76
Average Magnitude of Error	2.9	2.4	2.9
Range of Error	16.0 (-8.8 to 7.2)	17.4 (-10.8 to 6.6)	21.3 (-14.3 to 7.0)

* Performance of methodologies by several criteria for 42 cases.

Accuracy Versus Number of Adverse Days in Sampling Period

One might expect that the accuracy of either basic method would improve as the number of adverse days in the sampling period increased. And one would suppose that, because the number of adverse days corresponds to the number of points used in extrapolation for the distribution method, increased accuracy for that method should be expected. For the observed-maximum method, one would expect an increased likelihood of actually encountering the first or second maximum in a month and getting a relatively accurate assessment of the annual second maximum.

Tables 14, 15, and 16 give breakdowns of the three major error measures by the number of adverse days in the sampling period. From this array of numbers, no significant and apparently reliable tendency can be seen for the error to become smaller as the number of adverse days in the sampling period increases.

There is one particular case in which a significant improvement in accuracy does appear for the distribution method: when there are 16 or more adverse days in the month. Somewhat of an improvement in the error of the distribution method seems to occur at the highest number of adverse days in the sampling period; however, there is no confidence in the statistical significance of this result,

TABLE 12

ONE-MONTH MONITORING FOR 42 CASES USED IN THE TWO-MONTH ANALYSIS

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error	5.0	3.5	4.5
Bias (Average Signed Error)	1.1	-2.5	0.3
Correlation Between Predicted and Actual	0.68	0.79	0.71
Average Magnitude of Error	4.1	3.2	3.7
Range of Error	21.5 (-8.3 to13.2)	15.6 (-10.9 to 4.7)	19.2 (-8.8 to 10.4)

TABLE 13

ONE-MONTH MONITORING USING METEOROLOGICAL INDEX *

MEASURES OF ERROR	METHOD		
	Distribution	Observed-Maximum	Combination
Overall Standard Deviation of Error	3.3	2.1	2.9
Bias (Average Signed Error)	2.6	0.8	1.8
Correlation Between Predicted and Actual	.88	.90	.88
Average Magnitude of Error	3.4	1.7	2.6
Range of Error	14.6 (-4.0 to 10.6)	9.9 (-5.2 to 4.7)	14.0 (-3.9 to 10.1)

* Performance of methodologies by several criteria for 36 cases, including both background and intermediate stations.

TABLE 14

BREAKDOWN OF ERROR USING THE DISTRIBUTION METHOD BY THE NUMBER OF ADVERSE DAYS IN THE MONTH (ONE-MONTH SAMPLING)

NO. OF ADVERSE DAYS IN MONTH	ALL CASES				BACKGROUND STATIONS			
		Error Measures (ppm)				Error Measures (ppm)		
	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error
6 - 7	20	1.7	4.7	3.8	8	1.5	1.6	1.8
8 - 9	21	-0.6	3.2	2.6	4	2.0	1.2	2.0
10 - 12	18	0.2	4.0	3.0	10	2.1	1.4	2.2
13 - 15	33	0.7	5.1	4.0	6	1.1	1.9	1.8
16 or more	25	0.2	3.4	2.6	8	0.1	1.2	1.0

TABLE 15

BREAKDOWN OF ERROR USING THE OBSERVED-MAXIMUM METHOD (ONE-MONTH SAMPLING)

NO. OF ADVERSE DAYS IN MONTH	ALL CASES				BACKGROUND STATIONS			
		Error Measures (ppm)				Error Measures (ppm)		
	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error
6 - 7	20	-2.2	3.7	2.9	8	-0.8	1.0	1.0
8 - 9	21	-3.3	2.9	3.3	4	-0.9	1.0	0.9
10 - 12	18	-2.2	3.8	2.6	10	-0.0	1.0	0.7
13 - 15	33	-2.4	3.7	3.3	6	-0.1	1.9	1.2
16 or more	25	-1.8	3.3	2.7	8	-1.1	1.3	1.4

given that there does not appear to be a consistent trend in the behavior of the error as a function of the number of adverse days.

Examples of probability plots for the distribution method for various locales, sampling stations, and months are included in Appendix C.

Estimating the 1-Hr Second Max Using the 8-Hr Second Max

Figure 18 is a plot of the annual 1-hr second maximum against the 8-hr second maximum at each of 67 stations for 1974 from the EPA SAROAD data files. The least-squares best-fit line shown presents an equation for estimating the 1-hr second max carbon monoxide, $CO_{1\text{-hour}}$, from the 8-hr second max carbon monoxide, $CO_{8\text{-hour}}$:

$$CO_{1\text{-hour}} = (1.26 \times CO_{8\text{-hour}}) + 4.4 \qquad (4)$$

The correlation coefficient for this best-fit line is 0.92, indicating a very reliable relationship between the two quantities. The standard deviation of the error in the estimate of the 1-hr second maximum by this regression equation is 3.2 ppm. At the point at which the 8-hr standard (9 ppm) is exceeded, an error of 7.2 standard

TABLE 16

BREAKDOWN OF ERROR FOR ALL CASES (TWO-MONTH SAMPLING)

NO. OF ADVERSE DAYS IN TWO MONTHS	DISTRIBUTION METHOD				OBSERVED-MAXIMUM METHOD			
		Error Measures (ppm)				Error Measures (ppm)		
	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error	No. Cases	Bias (Avg. Signed Error)	Std. Dev. of Error	Avg. Mag. of Error
10 - 12	7	1.3	3.5	2.8	7	-1.1	3.1	2.1
13 - 16	10	0.9	3.4	2.5	10	-1.3	1.8	1.3
17 - 21	9	0.7	4.5	3.4	9	-0.8	4.4	3.3
23 - 29	8	-0.1	4.1	2.9	8	-1.0	4.6	2.9
30 or more	7	0.1	2.9	2.2	7	0.2	3.6	2.3

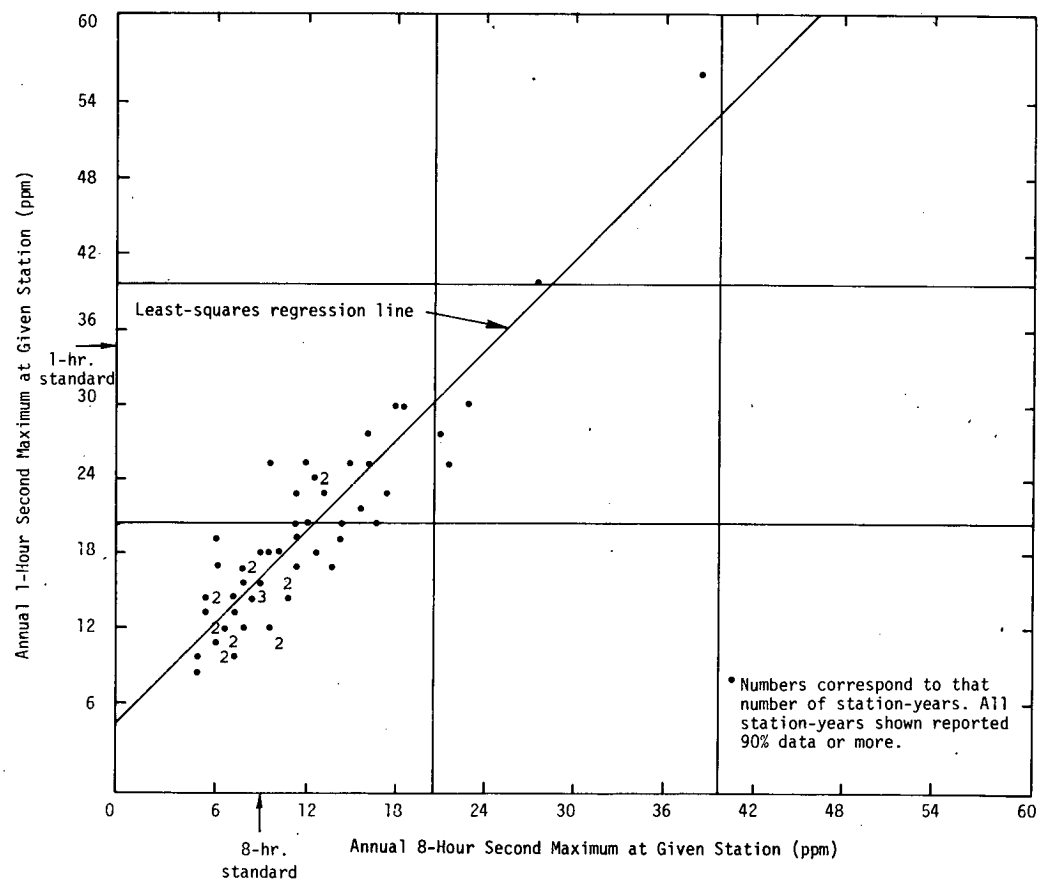


Figure 18. Annual 1-hr second maximum vs. annual 8-hr second maximum for stations reporting 90% data or more (National 1974 SAROAD data).

deviations would be required to exceed the 1-hr standard (35 ppm). It is highly unlikely that such an error would occur and thus predict a violation of the 1-hr standard when the 8-hr standard was not violated.

In the developed procedure, the equation given is used as a means of estimating the 1-hr second maximum, after having estimated the 8-hr second maximum. The standard deviation of the error, in combination with the confidence intervals in the estimate of the 8-hr second max, is used in estimating confidence intervals on the 1-hr second max. This procedure is formalized and restated in Chapter Three.

Estimating the Annual Average

Of the three statistics estimated in this study, the annual average was studied the least. As discussed in a previous section, inspection of the data revealed that variation in the annual average is related more to meteorology than to emissions. Furthermore, actual values of the annual average vary little. Consequently, the annual average would not make a good pollution standard because of its dependence on meteorology and small range.

Nevertheless, if for some reason the annual average is required, there are relatively simple ways of obtaining an estimate of it. For example, Mage and Ott (*24*) have shown that, using random sampling of 100 1-hr values, the annual average can be estimated with a 95 percent confidence interval of 1 ppm for 79 out of a group of 84 U.S. cities studied.

Another method uses an auxiliary index that is required to be available for a full year, such as a CO station or an hourly meteorological index. In this approach, a linear regression is performed on the sample-period 1-hr data, with the target-station 1-hr average as the dependent variable and the auxiliary index as the independent variable. If the hourly values of CO are called CO_h and the hourly values of the index are called I_h, a regression of the form

$$CO_h = aI_h + b \tag{5}$$

can be determined by linear regression. The estimate for the annual average is

$$\overline{CO}_h = a\bar{I}_h + b \tag{6}$$

where $\bar{I}_h$ is the average of the hourly index values over the year.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

In this chapter, the resultant recommendations are stated, in practical terms, for the highway engineer who is interested in monitoring existing CO levels for less than a full year, at a proposed highway site, in order to estimate the annual second 8-hr maximum CO and the annual second 1-hr maximum CO. Side issues and supportive material are contained in Chapter Two and are not discussed here. The following sections focus on the actual methods for estimating the annual second maximum 8-hr average, the annual second maximum 1-hr average, and the annual average.

ESTIMATION OF THE ANNUAL SECOND MAXIMUM 8-HR AVERAGE

Figure 19 shows the over-all recommended approach for estimating the annual second maximum 8-hr average at a proposed highway site. Elements A through E of the diagram are described in the following:

1. *Select Sampling Plan (A)*—There are two principal constraints on sampling imposed by the methodology employed. The sampling must consist of whole-day periods (24 hours) of sampling, and that sampling must be in the CO season (i.e., the months of October through January). The restriction to the CO season represents a change from some current monitoring practices. Also, the number of days should nominally be a minimum of 30; looking at (C), it is evident that a sufficient number of days is needed to obtain six adverse days, so that if more than six adverse days are obtained with fewer than 30 days of sampling, sampling can stop there. On the other hand, the requirement at (C) dictates that, if possible, sampling should start in December rather than in January. There were cases in the data base where, using a CO index as a criterion, fewer than six adverse days were found in January.

2. *Determine Adverse Days (B)*—The details of this are discussed under the heading "Determine Adverse Days." The end result is that an estimate is made of how many of the days sampled are among the 20 percent of the previous year's days most likely to produce high CO levels.

3. *Test for Sufficient Adverse Days in Sampling Period (C)*—The basic requirement for obtaining a confidence interval is six adverse days. This means that by whatever method chosen for obtaining an auxiliary index at (B) or if no auxiliary index is used at all, six days or more designated as adverse must be obtained. If this is not the case, additional sampling must be performed in order to proceed.

4. *Estimate Annual Second Maximum (D)*—This is performed in one of two ways, as described under the heading "Estimate Annual Second Maximum." Either a simple maximum is taken, given that at least six adverse days exist in at least a month of sampling; or the distribution method is used, in case there are fewer than 30 days of sampling with at least six adverse days obtained or there is some other reason for using this method.

5. *Determine Confidence Interval (E)*—This is performed as described under the heading "Determine Confidence Interval." It is essentially a table lookup, depending on how the sampling is performed and the kind of auxiliary index, if any.

Determine Adverse Days

The elements of the determination of adverse days at the target site in the sampling period are shown in Figure 20. Elements B1 through B4 of the diagram are elaborated in the following:

1. *Select Type of Auxiliary Data (B1)*—This selection is dependent, primarily, on the level of accuracy required of the final estimate, as well as on practical considerations of data availability. As outlined under the heading "Determine Confidence Interval," the use of no auxiliary data at all produces confidence intervals comparable to those with the use of auxiliary data. In a situation in which *a priori* information indicates that the station is, indeed, a background station with low levels of CO, the use of no auxiliary data is ideal. Caution must be exercised, however, because the range of error in the no-auxiliary-station case is somewhat larger than that in the case using auxiliary data.

Note that the meteorological index developed in this study is designed to show the feasibility of using meteorological data alone. The formulation of the index, as well as its testing, is very possibly locale-dependent—a situation that warrants additional study. Hence, the biases and confidence intervals obtained for the meteorological index, used in either the distribution or the observed-maximum estimation method, must be taken as rough guesses, at best, for another meteorological index or even for a similar one derived for a different locale.

2. *Select Appropriate Auxiliary CO Station (B2-CO)*—In the case that a CO index is chosen and there is more than one candidate auxiliary station, the choice may be made in two complementary ways, as follows. First, if one site, by examination of typical windfield patterns during the CO season and by virtue of physical proximity, is an obvious choice, designate it as the auxiliary station; if no such obvious analysis can be performed, a check of the correlation of the daily 8-hr maximum (computed without using over-midnight averages) between the target station and the candidate auxiliary stations should be performed, and the one with the highest correlation should be chosen. If two stations have nearly identical correlations, the one should be chosen that has a higher correlation for the higher values of the month (this can often be determined by inspection of a scatterplot of the 8-hr daily maximums at the two stations).

3. *Construct or Obtain a Met Index (B2-Met)*—In some locales, indices formulated by air pollution officials are already in existence for the prediction of CO levels. The meteorological index tested in this study was adapted from one made by a practicing meteorologist for the Los Angeles AQMD. If such an index is not already available, some guidance on index construction can be found in Zeldin and Meisel (*13*).

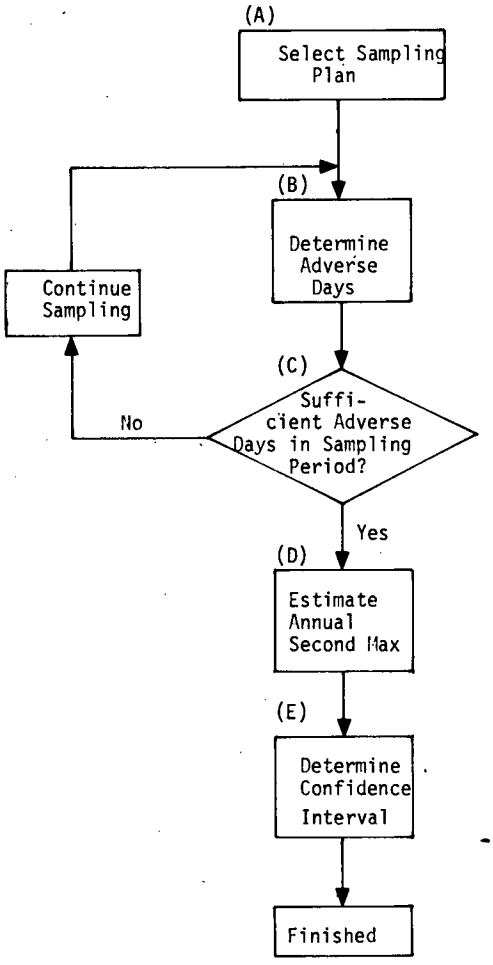


Figure 19. Overview of the suggested method.

4. *Calculate Values of Daily Index for Year Previous to End of Sampling Period; Identify Top 20% of Days (B3-Index)*—In the case of a meteorological index of the type described in this report, the calculation is only performed on nonholiday weekdays because of the weekend/weekday effect previously discussed, and the top 20 percent of the days to be identified are the top 20 percent of the nonholiday weekdays. For the CO index, this step is self-explanatory.

5. *Calculate Expected Number of Adverse Days, K, in Sampling Period (B3-No Aux.)*—Table 6 gives average numbers of adverse days in each month. It is recommended that the over-all averages be used, unless one has some good reason for preferring the averages of one of the locales of the study. Given the average number of adverse days in the month, N_{av}, one computes the expected number of adverse days, K, in the sampling period (assumed nonholiday midweek) as follows:

$$K = (N_{av})(p_{wd})\left(\frac{A}{B}\right) \qquad (7)$$

where p_{wd} is the average percentage of adverse days falling on nonholiday weekdays, A is the number of sample days obtained with good data, and B is the total number of nonholiday weekdays in the month. The value of p_{wd} in the data was 77 percent for intermediate stations and 79 percent for background stations, computed for the adverse days of the CO season (October through January). Eq. 7 may be appropriately modified for two-month periods or periods of other lengths.

6. *Determine Adverse Days in Sampling Period Which are Adverse by Index Definition (B4-Index)*—This simply consists of observing which of the top 20 percent of the days identified in step (B3-Index) are in the sampling period.

7. *Determine Adverse Days in Sampling Period by Taking Highest K Days in Sampling Period (B4-No Aux.)*—The highest days are those with the K highest 8-hr daily maximums.

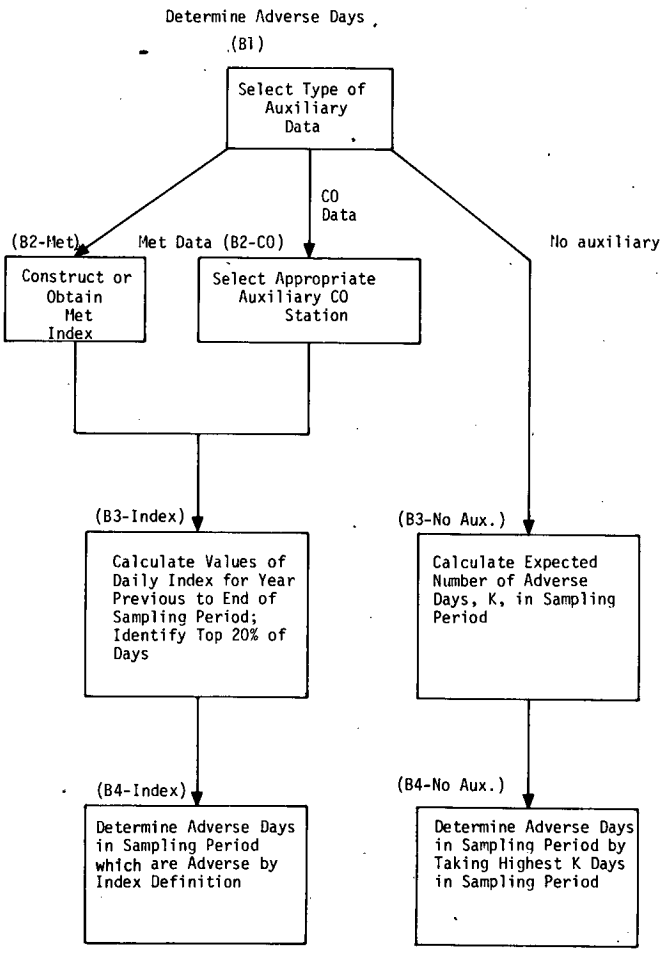


Figure 20. Elements of determining adverse days in the sample period.

Estimate Annual Second Maximum

Two methods of estimating the annual second 8-hr maximum can be used: (1) taking the maximum daily 8-hr maximum during the sampling period, as long as it is at least one-month long, and (2) using the distribution method outlined next. Using either method, one obtains a biased estimate of the annual second 8-hr maximum, $\widehat{CO}$. From this, the appropriate bias must be subtracted. Table 17 presents the biases to be subtracted from $\widehat{CO}$, along with the confidence limits (discussed in the following section).

The distribution method can be described as follows. Suppose one is given J adverse days from a one-month or two-month sampling plan where the adverse days are determined to be among the top 20 percent of the year's values. Then the extrapolation to the percentile corresponding to the annual 8-hr second maximum is performed in the following way:

1. Order the CO 8-hr daily maximums from the J days. Call these $CO_1, \ldots, CO_J$.

2. Using exponential graph paper with percentile scale between 0.6 and 0.998, plot the point x_i for the percentile p_i, where $p_i = 0.8 + (0.2)\left(\frac{i}{(J+1)}\right)$. Explicitly, if the graph is to be D units in horizontal size, the coordinates (x_i, y_i) of the ith-highest point CO are:

$$\left.\begin{aligned} x_i &= \frac{\ell n(1-0.6) - \ell n(1-p_i)}{\ell n(1-0.6) - \ell n(1-0.998)} \cdot D \\ y_i &= CO_i \end{aligned}\right\} i = 1, \ldots, J \qquad (8)$$

The y-scale can be an arbitrary linear scale.

3. Fit the highest J-L points, where $L = 4$ for the one-month plan, and $L = 6$ for the two-month plan, and L is chosen proportionally for plans requiring larger periods of time, using a standard linear regression program to obtain the formula

$$y = ax + b \qquad (9)$$

where a and b in Eq. 9 are chosen to minimize the sum

$$\sum_{i=L}^{J} (y_i - (ax_i + b))^2 \qquad (10)$$

The terms x_i and y_i in Eq. 10 are defined in Eq. 8.

4. Using the a and b from Eq. 9, the biased estimate obtained for the annual 8-hr second max, $\widehat{CO}$, is

$$\widehat{CO} = a(0.9945) + b \qquad (11)$$

since the second highest daily 8-hr max has a percentile of

$$\frac{364}{366} = 0.9945$$

Determine Confidence Interval

Table 17 gives the confidence intervals associated with the various sampling and extrapolation scenarios tested, along with the biases referred to in the previous section. The confidence intervals were computed by assuming the error distribution to be normal and using the unbiased standard deviations from Tables 8 through 16. In summary, for a given scenario, if the bias is B, if the confidence

interval is C with confidence X percent, and if the biased estimate (either from the maximum method or from the distribution method) is $\widehat{CO}_{8\text{-hour}}$, the unbiased estimate of the annual second 8-hr maximum is

$$(\widehat{CO}_{8\text{-hour}} - B) \pm C \qquad (12)$$

with confidence X percent.

In the important case of using an auxiliary CO station with one month's sampling, it is evident that the biases and the confidence interval are quite dependent on the degree of source-affectedness of the target station. If the target station can be easily categorized as background or intermediate, there is no problem in determining the correct entries on the table (see Appendix A on how to categorize stations). If there is doubt, it is safe to assume that the station is intermediate.

Only limited testing of the two-month sampling method was performed. From an examination of the first four rows of Table 17, it is evident that the confidence interval for the two-month sampling is not significantly reduced from that for the one-month sampling. However, the bias is much reduced for the observed-maximum method. Hence, the values stated for the bias and confidence intervals are adequate for any background or intermediate station, using a two-month plan. The values for the confidence intervals are conservative for a background station.

TABLE 17

BIASES AND CONFIDENCE INTERVALS FOR VARIOUS SCENARIOS

SCENARIO	OBSERVED-MAXIMUM METHOD				DISTRIBUTION METHOD			
		Confidence Intervals				Confidence Intervals		
	Bias	80%	90%	95%	Bias	80%	90%	95%
One Month - Background CO Auxiliary	-0.5	1.6	2.0	2.4	1.3	2.1	2.6	3.1
One Month - Background Monthly Maximum	-0.9	1.8	2.4	2.8	0.4	2.9	3.7	4.4
One Month - Intermediate CO Auxiliary	-3.2	5.0	6.4	7.6	0.1	6.3	8.1	9.6
Two Month - Both Background and Intermediate CO Auxiliary	-0.8	4.5	5.8	6.9	0.7	4.6	5.9	7.1
One Month - Both Background and Intermediate CO Auxiliary	-2.4	4.5	5.8	6.9	0.5	5.4	6.9	8.2
One Month - Both Background and Intermediate Met Auxiliary	-0.8	2.7	3.5	4.1	2.6	4.3	5.5	6.5
One Month - Background Met Auxiliary Data	-0.9	1.8	2.3	2.7	0.3	3.0	3.8	4.5

ESTIMATION OF THE ANNUAL SECOND MAXIMUM 1-HR AVERAGE AND THE ANNUAL AVERAGE

For the estimation of the 1-hr second maximum, it is recommended that the approximate functional relationship of the annual 1-hr and 8-hr second maximums, derived earlier under the heading "Estimating the 1-Hr Second Maximum Using the 8-Hr Second Maximum," be used. Given the 8-hr second max carbon monoxide, $CO_{8\text{-hour}}$, the 1-hr second max, $CO_{1\text{-hour}}$, is estimated by Eq. 4, as follows:

$$CO_{1\text{-hour}} = (1.26 \times CO_{8\text{-hour}}) + 4.4$$

The value $\widehat{CO}_{1\text{-hour}}$ has an error standard deviation of 3.2 ppm. The resulting confidence interval for the estimation of the 1-hr second max may conservatively be determined by assuming that the confidence interval of the estimation of the 8-hr second max, $CO_{8\text{-hour}}$, is of the form $\widehat{CO}_{8\text{-hour}} - B \pm C$, with confidence X percent as previously described (Eq. 12). Then, the confidence interval of the estimate of the 1-hr second max, $CO_{1\text{-hour}}$, is

$$\widehat{CO}_{1\text{-hour}} \pm [(1.26 \times C) + C^*] \qquad (13)$$

with confidence X percent, where C^* is equal to 4.1 for 80 percent confidence, 5.3 for 90 percent confidence, and 6.3 for 95 percent confidence.

For the annual average, a standard linear regression approach has been outlined earlier under the heading "Estimating the Annual Average."

AN EXAMPLE

Suppose that the Newhall monitoring site in the Los Angeles area is located at a proposed highway site. Since this report concludes that the monthly maximum method is superior to the distribution method, the monthly maximum method is used in this example.

It is known that sampling must proceed during the CO season; suppose, then, that one has sampled continuously during the month of October 1973. The next step is to select an appropriate auxiliary CO station. In order to do this, one may look at correlations of 8-hr maximums between stations; this requires that the 8-hr daily maximum average for each day be computed for the stations under consideration. Suppose the data base contains Los Angeles (downtown), Burbank, Reseda, and west Los Angeles. The highest correlation between Newhall and the other monitoring stations of the data base in this report occurred at Reseda, and the second highest occurred at Burbank (during the month of hypothetical sampling). Thus, Reseda is chosen as the auxiliary station, because it had the highest correlation with Newhall during the sampling month, and also because the conditions at Reseda more nearly approximate those at Newhall than did those at Burbank.

Then, the daily 8-hr maximums at Reseda, the auxiliary station, are computed for the one-year period November 1972 through October 1973, and the highest 20 percent of the days are identified as adverse days. It is observed that 14 of these days fall in October, easily qualifying the month for the monthly maximum method. Finally, it is observed that the maximum daily 8-hr average during the month of sampling at Newhall, the target station, is 10.1 ppm.

The annual second 8-hr maximum is estimated according to Eq. 12, using Table 17. Newhall is a background station (see Appendix A), and since the monthly maximum is being used, the bias is —0.9. Assuming that a 95 percent confidence interval is of interest, the estimate is then

$$10.1 - (-0.9) \pm 2.8 = 11.0 \pm 2.8 \text{ ppm}$$

The annual second 1-hr maximum is estimated using Eq. 4:

$$CO_{1\text{-hour}} = (1.26 \times 11.0) + 4.4 = 18.3 \text{ ppm}$$

with a 95 percent confidence interval obtained from Eq. 13 of

$$\pm [(1.26 \times 2.8) + 6.3]$$

Thus, the 1-hr second maximum is estimated as 18.3 ± 9.8 ppm.

It turns out, in this case, that the monthly maximum method overestimates both statistics. The 1973 8-hr second maximum at Newhall is 9.9 ppm, and the 1973 1-hr second maximum is 14.0 ppm.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

In this chapter, a brief description is given of the major conclusions and research suggested by this study.

CONCLUSIONS

Two basic methods were evaluated:

1. The distribution method—A statistical distribution was fit to the high CO measurements and extrapolated to the annual 8-hr second maximum.
2. The observed-maximum method—The maximum 8-hr average during the sampling period was used as an estimate of the annual second maximum 8-hr average.

From the results of this investigation, the following conclusions are drawn:

1. Sampling should be limited to the four most adverse months of October, November, December, and January, with the possible inclusion of February. There is insufficient occurrence of adverse days in the other months for either of the methods evaluated to be reliable.
2. For the observed-maximum method, very little accuracy is gained by going from a one-month sampling period to a two-month sampling period. For the distribution method, there is a substantial improvement.
3. Although adverse CO concentrations are encountered less often on weekends than on weekdays (less than in a ratio of 2 to 7), they do occur on weekends fairly often. Thus, sampling on weekends is not irrelevant.
4. The observed-maximum method is clearly better than the distribution method for sampling within a one-month period. For a two-month sampling period, the methods are closely comparable in accuracy. Combining the two basic methods did not result in a method better than either of the two basic methods alone.
5. The accuracy obtained by either method (and by the observed-maximum method in particular) is excellent. Further methodological refinements are not necessary or justified in the context of the application addressed in this study.
6. For the observed-maximum method, the occurrence of at least six adverse days in one-month sampling and ten in two-month sampling should be verified.
7. Beyond the minimum, accuracy did not improve systematically as the number of adverse days in the sampling period increased (for either method).
8. The annual maximum 1-hr-average CO concentration can be estimated from the estimated 8-hr second maximum. Since the 1-hr CO standard is seldom exceeded, this procedure provides more than enough accuracy.
9. The annual average is dominated by meteorology rather than emissions and does not vary greatly from locale-to-locale. For this reason, discussion of estimation of the annual average was limited to the most straightforward approach.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further research is recommended in three areas:

1. Methodology for accounting for year-to-year variation in meteorology.
2. Development of meteorological indices for CO.
3. Development of simplified methods for assessing the impact of highways on other pollutants, such as ozone.

Year-to-Year Variation in Meteorology

As indicated in Chapter One, the average change in magnitude of the annual 8-hr second max from one year to the next is about 15 percent. Given that this is the average, the difference in background CO levels between a "bad" year meteorologically and a "good" year can be quite significant. This study was limited to extrapolation from measurements within a year to the annual second maximum for that year, without consideration of the relative adverseness of that year relative to other years.

As the standards are currently stated, they can be interpreted as requiring by their "thou-shalt-not-exceed" language that consideration be taken of year-to-year variability. When year-to-year variability on the order of 15 percent

leaves a safe margin below the standards for the total highway impact, this year-to-year variability should not be a major problem. However, if compliance with the standards appears marginal, explicit consideration of the year-to-year variability may be advisable to avoid having to assume the worst case.

The methodology developed in this report for CO can be extended in a rather direct manner to year-to-year variation in meteorology, providing that meteorological data or auxiliary-station CO data are available. Furthermore, even in the absence of such auxiliary data, a more detailed study of the typical variation induced by meteorology for various regions could yield general guidelines.

Meteorological Indices for Carbon Monoxide

Both for extrapolating from limited measurements to the second maximum in a given year and for the purposes of measuring year-to-year variability in meteorology and its effect on CO, a deeper treatment of the derivation of meteorological indices for carbon monoxide is merited. Such an investigation would have benefits beyond use in measuring the number of adverse days in a given sampling period and in measuring the meteorological adverseness of a given year. Such a study could provide a means of determining which meteorological conditions should be used with models of the highway contribution to CO concentrations.

Simplified Approaches to Treating Other Pollutants

It was learned in the present study that a very straightforward method for estimating background levels of CO worked as well as a more complicated method, in fact better. The investigators feel that there is considerable simplification possible in procedures for estimating levels of other air pollutants in highway impact studies. Since the vehicle travel patterns estimated for a new highway contain some large modeling uncertainties (predictions of travel demand, etc.), an extremely difficult and expensive analysis translating these traffic levels into oxidant levels is not justified if any practical alternatives exist.

In particular, oxidants provide an example of a particularly difficult estimation problem. The techniques used in the current study are unlikely to be directly transferable to oxidants because (1) background levels of oxidants tend to be quite high where there is an oxidant problem, and (2) oxidants are not primary pollutants but are the results from a chemical reaction of primary pollutants.

However, approaches considerably simpler than those currently employed are possible for estimating the impacts of a highway on oxidant levels. For example, current work by Eldon and Trijonis (*30*) at Technology Service Corporation derives simple relationships between early-morning ambient air quality measurements and late-afternoon oxidant peaks (which may be considerably removed geographically from the morning emissions). Because it is considerably easier to model the relationship of traffic patterns to early-morning concentrations of primary pollutants directly emitted by those vehicles, methodologies that can translate in a straightforward fashion from morning concentrations of primary pollutants to oxidant levels can considerably expedite the oxidant impact analysis.

Approaches similar to those used in the present report can extrapolate from a fairly small number of traffic impact model cases to annual second maximums.

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APPENDIX A

CLASSIFICATION OF MONITORING SITES

Objective approaches were examined in classifying monitoring sites as "background," "intermediate," and "source-affected." One approach to classifying the stations would be elaborate investigations of complete physical models, including at least a three-dimensional time series meteorological and traffic simulation. This sort of approach was considered far beyond the scope of this study and probably impracticable in any case. As an alternative, a numerical approach based on the data from the station itself was attempted. The basic concept used was that a source-affected station should exhibit a higher degree of randomness or variation than the data from a background station. This is roughly equivalent to stating that the carbon monoxide data as a function of time should be smoother for a background station than for a source-affected station. A measure that reflects this is the detrended standard deviation, σ_{detrend}. This statistical measure, defined by Breiman (*31*, p. 348) for a set of n hourly data points is given as follows:

$$\sigma^2_{\text{detrend}} = \frac{1}{n}\sum_{i=1}^{n/2}(x_{2k} - x_{2k-1})^2 \qquad \text{(A-1)}$$

where $x_1, x_2, \ldots, x_n$ are successive hourly readings. Note that for a year, n is nominally 8,760.

As one can see from Eq. A-1, this measure is an average of the squared differences from hour-to-hour. A station exhibiting a lot of variation in the carbon monoxide data should have a large detrended standard deviation, and a station that is relatively smooth should have a small detrended standard deviation.

Also examined were more conventional statistics about the CO data, including the annual 1-hr maximum and the annual 8-hr maximum. Some statistics were taken during the heart of the CO season, the months of November and December, including the average of the daily 1-hr maximum during those two months and the average of the daily 8-hr maximum. In addition, as will be explained later, the possibility of classifying stations with only CO-season data was investigated.

The statistics cited for the stations in the Los Angeles data base are given in Table A-1. Each of the statistics in the table is computed for each station in each of the years 1972, 1973, and 1974. Then, the resulting three values are averaged. The numbers in parentheses are the unbiased standard deviations of the resulting statistics. Judging from this table, one sees that the detrended standard deviation very clearly indicates Newhall as a background station, Lennox as a source-affected station, and the other stations as more or less intermediate. Similar results were obtained for the other locales of the study. It was found that stations clearly "background," which were between 100 ft and 200 ft from the nearest roadway, exhibited much smaller detrended standard deviations than the other stations exhibited. Stations "source-affected" appeared showing large detrended standard deviations.

This classification was checked by comparing it to the classification used by the monitoring agencies at the locales of the study. The monitoring agencies were asked if their ordering of stations as source-affected or urban-background conformed to the ordering produced by the detrended deviation. For the locales of the study, the ordering produced by the detrended standard deviation was in excellent agreement with that of the monitoring agencies.

Looking at Table A-1 again, however, it is evident that the detrended standard deviation is reflecting the magnitude of the CO data at the stations as much as anything else.

TABLE A-1

STATISTICS FOR URBAN L.A., CO MONITORING SITES, AVERAGE 1972–1974

STATIONS	ANNUAL STATISTICS		NOVEMBER-DECEMBER AVERAGES	
	σ_{detrend}	1-Hour Annual Max	Average of Daily 1-Hour Max	Average of Daily 8-Hour Max
Downtown LA	1.17(.08)	31(2.7)	14.3(1.8)	9.4(1.1)
Burbank	1.11(.05)	32(5.0)	15.9(0.6)	11.2(0.5)
Lennox	1.78(.04)	46(3.0)	21.4(1.7)	13.6(1.3)
W.L.A.	1.16(.07)	33(3.2)	12.9(1.4)	7.7(0.6)
Whittier	1.11(.16)	29(3.1)	13.4(2.0)	8.7(1.1)
Reseda	.96(.03)	33(3.2)	13.7(1.0)	8.7(0.4)
Newhall	.68(.11)	16(2.5)	7.0(0.6)	4.7(0.6)

For example, the ratios of the statistics cited for Lennox, a source-affected station, divided by Newhall, a background site, are similar and range from 2.6 to 3.0. Therefore, because the measures of data magnitude, the average of the daily 1-hr or 8-hr maximum in November and December (for any station) or the average of the 1-hr annual maximum, are more readily available and understood than the detrended standard deviation, it was the conclusion of this study that these are preferable, and approximately equivalent, measures to the detrended standard deviation.

On checking again with the monitoring agencies, the research team found that data magnitude, as much as anything else, was the ultimate test of the extent to which a station was considered background vs. source-affected. Stated otherwise, high values of CO are assumed, at least by the agencies contacted, to be *prima facie* evidence of source-affectedness, and low values (of peak statistics) are regarded as *prima facie* evidence of an absence of point sources—evidence that underscores the use of indicators of data magnitude, especially extreme-value statistics, in site classification.

APPENDIX B

ANALYSIS OF THE TREATMENT OF MISSING VALUES

In this appendix, a study is described that was performed to investigate the question of how to interpolate missing values. The CO hourly data have a significant number of missing values, ranging from 3 percent to 40 percent of the year's 8,760 hours at the sites considered in this study. In addition, the CO data are slowly varying as a function of time. Therefore, it is reasonable to interpolate to fill in some of these values, at least those that are preceded and succeeded by one or two hours of good data. In this appendix, such an hour surrounded by one or two hours with good data values is called an "isolated missing value."

In order to interpolate isolated missing values, the approach taken was to assume that the isolated missing value was functionally related to the two nearest or four nearest neighbors. To describe these functionalizations, a little notation is helpful. If x_0 is an isolated missing value, let x_1 be the next hour's value; x_2, the hour after next hour's value; x_{-1}, the value from the hour before; and x_{-2}, the value from the hour two hours before the hour to be filled in. Each sequence of five hours' values may be written $x_{-2}, x_{-1}, x_0, x_1, x_2$.

The first technique was to investigate a functionalization, F, of the form

$$F = ax_{-2} + bx_{-1} + cx_1 + dx_2 + e. \qquad \text{(B-1)}$$

The function F was determined by using a stepwise linear regression on 100 percent valid data with x_0 as a dependent variable; and x_{-2}, x_{-1}, x_1, and x_2 as independent variables.

The second technique involved the use of the average of the four nearest neighbors as one independent variable

$$\bar{x} = \frac{1}{4}(x_{-2} + x_{-1} + x_1 + x_2) \qquad \text{(B-2)}$$

and the four additional dimensionless variables

$$\frac{x_{-2}}{\bar{x}}, \frac{x_{-1}}{\bar{x}}, \frac{x_1}{\bar{x}}, \frac{x_2}{\bar{x}}, \text{ and } \bar{x}$$

with x_0 as a dependent variable in a stepwise linear regression. Hence, a functionalization, G, of the form

$$G = a\left(\frac{x_{-2}}{\bar{x}}\right) + b\left(\frac{x_{-1}}{\bar{x}}\right) + c\left(\frac{x_1}{\bar{x}}\right) + d\left(\frac{x_2}{\bar{x}}\right) + e\,\bar{x} + f \qquad \text{(B-3)}$$

was investigated.

Finally, the technique of averaging the two nearest neighbors, which amounts to a functionalization, H, of the form

$$H = \frac{1}{2}x_{-1} + \frac{1}{2}x_1 \qquad \text{(B-4)}$$

was tried. Here, no regression was needed.

These analyses were performed on a data base made from five Los Angeles stations during the period 1970-1974. The data base was constructed in the following manner. First, for each station and in each year, every other day was selected. Then, among the 24 hours for that day, a list of hours was made which was surrounded by four good values. From the list of good hours, one hour was selected at random. This resulted in about 180 five-dimensional (for $x_{-2}, x_{-1}, x_0, x_1, x_2$) data sets per station-year.

For each of the three methods, the RMS error, the absolute error, and the maximum error were computed for the data points from each year and averaged over the five-year period 1970-1974. The final averages are given in Table B-1. The values given in the table are averages of annual values. For the stepwise linear regression, the errors were defined to be the errors at the final step of the stepwise regression, when all variables were entered.

The principal result of the missing-value study is that averaging of the nearest neighbors, method three, performed nearly as well as methods one and two, which allowed the coefficients of the nearest neighbors to be free

TABLE B-1

COMPARISON OF DIFFERENT INTERPOLATION TECHNIQUES, LOS ANGELES STATIONS

Stations	R.M.S. Errors			Maximum Absolute Errors			Average Absolute Errors		
	L.R.*	N.L.R.**	Avg.	L.R.	N.L.R.	Avg.	L.R.	N.L.R.	Avg.
Los Angeles	1.02	1.17	1.08	5.25	6.17	5.70	.65	.75	.65
Lennox	1.42	1.73	1.53	6.91	8.51	7.60	.94	1.16	.95
Reseda	.84	.96	.87	4.56	4.96	4.70	.53	.62	.51
Newhall	.63	1.00	.65	2.55	3.98	2.60	.45	.72	.44
Whittier	1.05	1.21	1.11	6.34	7.12	6.70	.61	.72	.61

*Linear Regression (using four nearest neighbors as independent variables)

**Normalized Linear Regression (using normalized variables at independent variables)

parameters. This is significant especially because methods one and two, therefore, have more free parameters. This result is significant for the implementation of the main study because it says that averaging, an interpolation method whose parameters do not need to be determined from the data, can be used as effectively as more sophisticated interpolation methods requiring historical data for their definition.

APPENDIX C

EXAMPLE OF APPLICATION OF THE DISTRIBUTION METHOD

Included in this appendix are four examples of use of the distribution method. Figure C-1 shows an accurate estimation at a background station. Figure C-2 shows the kind of overshooting that can occur when the annual second maximum occurs in the sampled month. Figure C-3 shows a very large error at an intermediate station. For the same station pair, the distribution method underpredicted by 7.7 ppm in October, overpredicted by 3.3 ppm in November, and overpredicted by 15.2 ppm, as shown in Figure C-3, in December. This type of result occurs when there is an abnormally uneven distribution of the highest CO days among the months of the CO season. Figure C-4 shows an accurate estimation at an intermediate station.

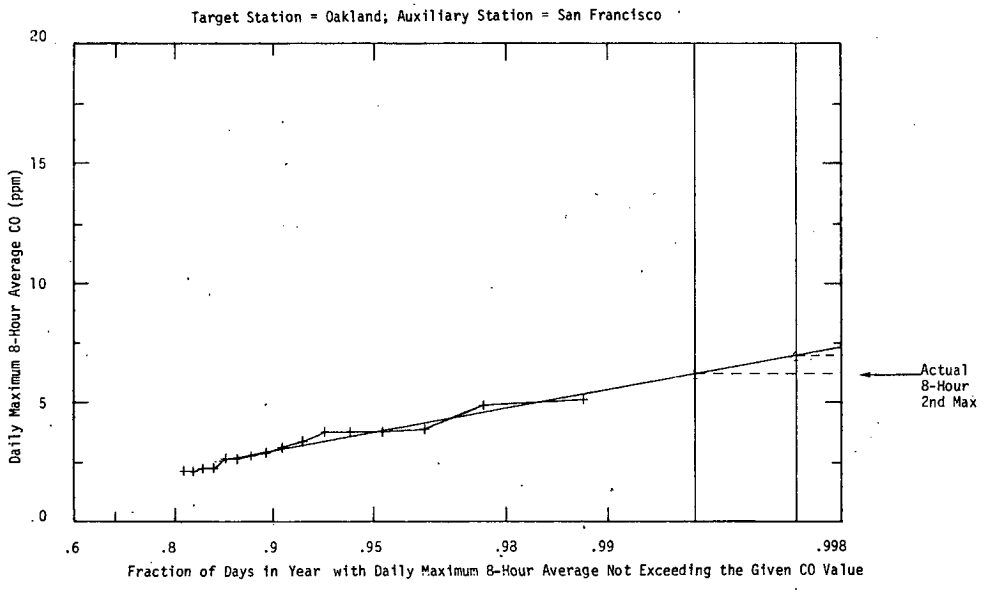

Figure C-1. One-month sampling at background station from San Francisco data base, January 1972.

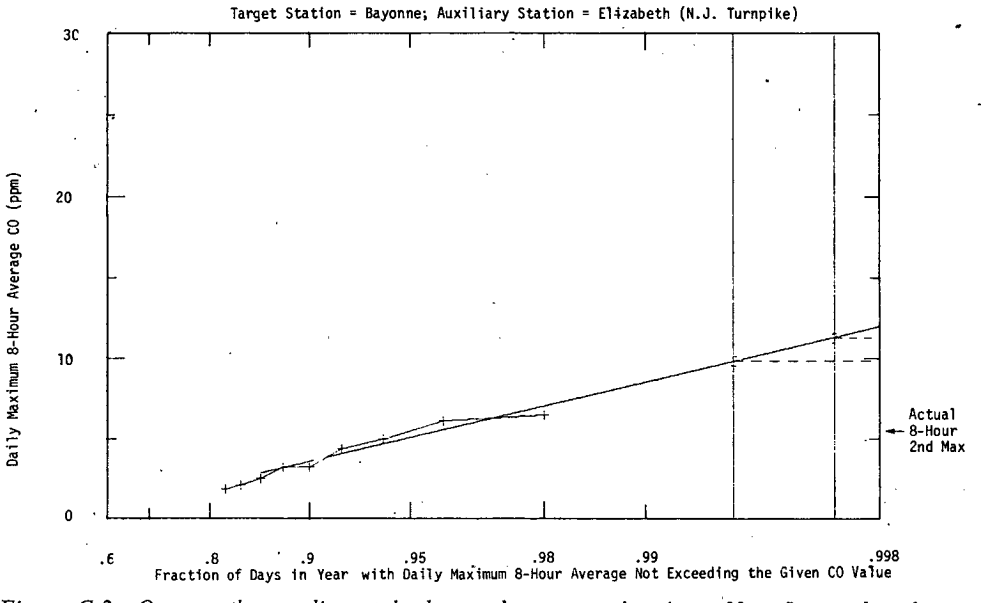

Figure C-2. One-month sampling at background target station from New Jersey data base, December 1974.

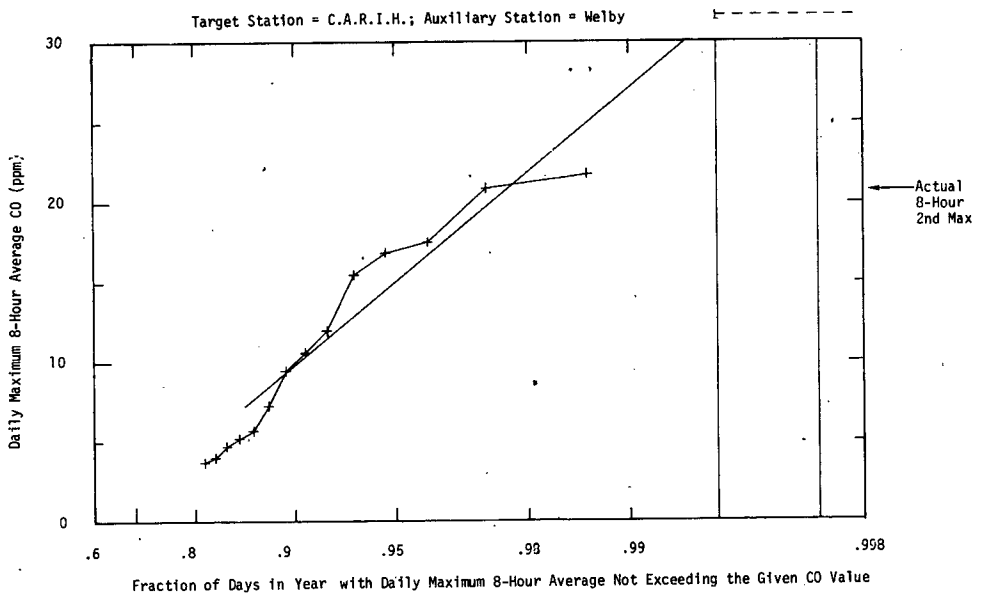

Figure C-3. One of the one-month sampling cases with largest error (December 1975)—at intermediate station from the Denver data base.

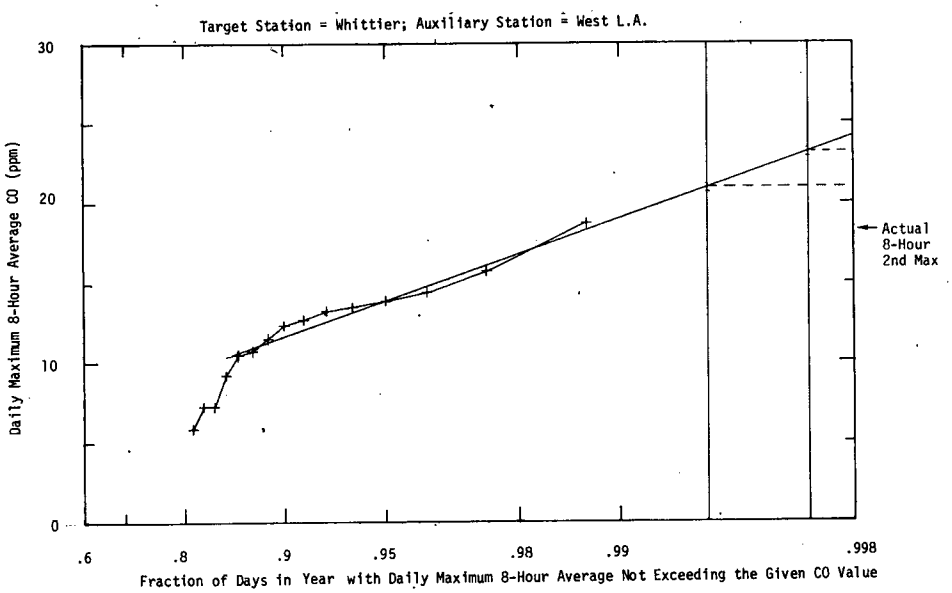

Figure C-4. One-month sampling at an intermediate station from Los Angeles data base, December 1973.

THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 150 committees and task forces composed of more than 1,800 administrators, engineers, social scientists, and educators who serve without compensation. The program is supported by state transportation and highway departments, the U.S. Department of Transportation, and other organizations interested in the development of transportation.

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The National Academy of Sciences was established by a congressional act of incorporation signed by President Abraham Lincoln on March 3, 1863, to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance. It is a private, honorary organization of more than 1,000 scientists elected on the basis of outstanding contributions to knowledge and is supported by private and public funds. Under the terms of its congressional charter, the Academy is called upon to act as an official—yet independent—advisor to the federal government in any matter of science and technology, although it is not a government agency and its activities are not limited to those on behalf of the government.

To share in the tasks of furthering science and engineering and of advising the federal government, the National Academy of Engineering was established on December 5, 1964, under the authority of the act of incorporation of the National Academy of Sciences. Its advisory activities are closely coordinated with those of the National Academy of Sciences, but it is independent and autonomous in its organization and election of members.

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