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Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

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Clean Air Act Ozone Design Value Study: Final Report

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A Report to Congress

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The Clean Air Act Ozone Design Value Study

Final Report

Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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1 EXECUTIVE SUMMARY

INTRODUCTION

This report responds to the requirements of Section 183(g) of the Clean Air Act Amendments (CAAA) of 1990, which requires that

> "The Administrator shall conduct a study of whether the methodology in use by the Environmental Protection Agency as of the date of enactment of the Clean Air Act Amendments of 1990 for establishing a design value for ozone provides a reasonable indicator of the ozone air quality of ozone nonattainment areas. The Administrator shall obtain input from States, local subdivisions thereof, and others. The study shall be completed and a report submitted to Congress not later than 3 years after the date of the enactment of the Clean Air Act Amendments of 1990. The results of the study shall be subject to peer and public review before submitting it to Congress." (PL 101-549, Sec. 183 (g))

Ground-level ozone, the primary constituent of smog, causes several adverse health and environmental effects, such as respiratory problems, crop loss and materials damage. EPA has established a national ambient air quality standard (NAAQS) for ground-level ozone. According to EPA regulations, an area is not meeting the ozone standard ("nonattainment") if the expected number of days per year with daily maximum 1-hour concentrations greater 0.12 ppm is greater than 1. As of October 1994, there are 91 areas of the country that are designated as nonattainment areas for ozone.

The ozone design value is a surrogate measure of attainment status, a measure of progress, and an indicator of how much concentrations must be reduced to meet the standard. The EPA design value method yields an estimate for the ozone design value that is consistent with the current ozone NAAQS. The current EPA design value method is simply to select the fourth highest daily maximum 1-hour concentration as the design value during the 3-year compliance period (Laxton, 1990). The fourth highest value is the design value, since if the fourth highest day is reduced to the level of the standard, then there will be one day per year above the level of the standard assuming three years of data.

With passage of the Clean Air Act Amendments (CAAA) of 1990, added emphasis was placed on ozone design values. In addition to designating areas as nonattainment for ozone, the CAAA introduced a classification process to further categorize nonattainment areas according to the extent of their ozone problem. As shown in Table 1-1, this area classification was based upon the ozone design value. The CAAA stated that the design value "shall be calculated according to the interpretation methodology issued by the Administrator most recently before the date of the enactment." Before the 1990 CAAA, designation of nonattainment areas simply involved a yes/no determination as to whether the area met the standard. The additional classification step introduced by the 1990 CAAA

placed greater emphasis on ozone concentration observations and on the methodology used to determine the design value.

TABLE 1-1. Ozone classifications specified in the 1990 Clean Air Act Amendments.

Area Class	Design Value*	Attainment Date**
Marginal	0.121 up to 0.138	3 years
Moderate	0.138 up to 0.160	6 years
Serious	0.160 up to 0.180	9 years
Severe	0.180 up to 0.280	15 years
Extreme	0.280 and above	20 years

*The design value is measured in parts per million (ppm).
**The primary standard attainment date is measured from the date of the enactment of the Clean Air Act Amendments of 1990.

Another reference to the use of design values is contained in Section 181(b)(2) of the Act, which states that EPA "shall determine, based on the area's design value (as of the attainment date), whether the area attained the standard by that date." EPA's preliminary interpretation of this Section is that the "average number of exceedances per year shall be used to determine whether the area has attained" which is the attainment test for the ozone National Ambient Air Quality Standard (NAAQS) (Federal Register, 1992).

National Ambient Air Quality Standard for Ozone

In 1979, EPA promulgated the ozone NAAQS at a level of 0.12 ppm that is attained "when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 part per million (235 $\mu g/m^3$) is equal to or less than 1 as determined by Appendix H" (40CFR 50.9). The attainment test specified in Appendix H states that the "expected number" of days with concentrations above 0.12 ppm ("exceedance" days) is to be estimated by calculating the average number of exceedances during the most recent three years. Additional information is contained in Appendix H and the EPA Ozone Guideline on procedures for dealing with missing data (EPA, 1979). The Guideline makes it clear that the expected exceedance criterion is to be applied independently to each monitoring site. For areas with multiple monitoring sites, all sites within the nonattainment area must meet the standard for the area to be designated in attainment of the ozone NAAQS.

Ozone Design Values

As noted above, compliance with the ozone NAAQS is judged on the basis of expected exceedances, and becomes a "yes/no" decision. However, once it is established that an area exceeds the standard, the next logical question to ask is, "By how much?" The air quality design value is intended to provide a measure of how far concentrations must be reduced to achieve attainment or, equivalently, how far out of attainment the area represented by a monitoring site is. In this respect, the design value can be viewed as an air quality indicator for a given location.

Given the expected exceedance form of the ozone NAAQS, the design value for this standard is defined in the EPA guideline document as "the concentration with expected number of exceedances equal to one" (EPA, 1979). Note that in this context the ozone guidelines are referring to the unknown "true" number of expected exceedances per year rather than the estimate of expected exceedances determined using the Appendix H calculations. In statistical terms, this is the value which is exceeded once per year on average. If the daily maximum ozone concentrations are assumed to be independent and have the same distributions every day throughout the year, then the design value is the characteristic largest value (CLV) of that distribution. The Ozone Guideline described several different options for estimating design values, including a table look-up approach, graphical procedures, and fitting statistical distribution. The current EPA design value method is simply to select the fourth highest daily maximum 1-hour concentration as the design value during the 3-year compliance period (Laxton, 1990). The fourth highest value is the design value, since if the fourth highest day is reduced to the level of the standard, then there will be one day per year above the level of the standard assuming three years of data.

Strictly speaking, the design value is an unknown quantity depending on the underlying distribution of ozone concentrations, and the EPA design value and alternatives are estimators of the (true) design value. To retain the readability of this document the term "design value" may refer to either the unknown population value or an estimator, depending on the context in which it is used. Where appropriate, the term "true design value" is used for clarification. The "EPA design value" always refers to the table look-up value.

Regulatory History of Design Values

Beginning in the 1970's, air quality design values were used as the primary input to simple air quality models, such as the "rollback model" and the Empirical Kinetic Modeling Approach (EKMA) (deNevers and Morris, 1975; Meyer et al., 1977). These models were used to estimate emission reductions needed to attain the NAAQS and to evaluate alternative control strategy options (deNevers and Morris, 1975; Meyer et al., 1977; Wilson and Scruggs, 1980). This use of ozone design values diminished following the development of more complex photochemical modeling approaches (EPA, 1981; EPA, 1991b). In some applications, design values used in estimating emissions reductions have been adjusted to

account for factors such as the level of transported ozone, or air quality reductions expected from future control measures (Meyer, Gipson, and Freas, 1977; Wilson and Scruggs, 1980). Such adjusted design values have come to be known as "control strategy values" to differentiate them from "air quality" design values, which are estimated directly from the ambient monitoring data (Rhoads and Tyler, 1987).

To support the passage of the Clean Air Act Amendments, EPA began issuing annual lists of areas failing to meet ozone and carbon monoxide NAAQS which contained their corresponding air quality design values (EPA, 1987, 1988, 1989, 1990, 1991a, 1992b). It is clear from the language of the CAAA of 1990, and the legislative history of the Act, that the initial area classifications were to be based on the air quality design value, which is the primary focus of this study (EPA, 1993). However, issues such as adjusting ozone design value for transport, emissions trends, and meteorological variability are addressed in this study within the context of "control strategy values."

EPA Design Value Methodology

The design value associated with the ozone NAAQS is an abstract quantity that can only be estimated from available data. The Ozone Guideline suggests several methods for estimating the design value, including a simplified table look-up procedure, approaches using statistical distributions, and techniques based on conditional probabilities. No single approach was required by the Guideline.

The table look-up procedure, summarized below in Table 1-2, has been designated as the EPA design value estimation method (Laxton, 1990). Basically, the tabular method identifies the lowest observed concentration that was not exceeded more than an average of once per year during the measurement period. This methodology is essentially unchanged from the State Implementation Plan (SIP) guidance issued in 1981, and is the method that was used for all of the annual design value lists issued by EPA and the initial ozone area classifications (EPA, 1981, 1987, 1988, 1989, 1990, 1991a,b, 1992, 1993; 40CFR58). Using the tabular method focuses attention on a concentration that was actually observed, as compared to a statistical fitting technique that could yield a design value that does not correspond to a concentration observed on a particular day. The tabular approach has several additional advantages not always shared by more complex statistical procedures. First, estimates can be made quickly, and directly, from existing summaries of air quality data. Second, the design value estimates are reproducible and verifiable with actual monitoring data. Third, it provides a uniform approach for all areas. It is also worth noting that current monitoring regulations do not require the reporting of hourly ozone data for all sites across the nation (Federal Register, 1991). Thus, statistical approaches which require fitting distributions to all the data, or even the upper 10 percent of the distribution, are not applicable for sites that only report summary statistics and not the individual hourly concentrations, or daily maximum 1-hour values.

TABLE 1-2. Ozone design value rank based on number of years of data.

Number of Valid Years (at least 75% of days during designated ozone season)	Ozone Design Value Rank (daily maximum 1-hr concentration)
less than one valid year	highest daily maximum
1 year of data	2nd highest daily maximum
2 years of data	3rd highest daily maximum
3 years of data	4th highest daily maximum

THE OZONE DESIGN VALUE STUDY

Section 183(g) of the Act directs EPA to conduct a study of the methodology currently in use for calculating design values to determine if the calculated design value "provides a reasonable indicator of the ozone air quality of ozone nonattainment areas." Thus, the focus of the study is on the design value methodology as initially developed in the Ozone Guideline and later defined in current EPA guidance (40CFR50.9; EPA, 1979; Laxton, 1990). Issues concerning the form of the current ozone NAAQS are more properly treated within the existing mechanism for NAAQS review. EPA is in the midst of reviewing the ozone NAAQS. The Agency intends to propose any change to the standard by Spring 1995 and, after taking public comment, will promulgate the final decision in Spring 1997.

The "reasonable indicator" evaluation is dependent on the intended application of the design value. It is quite possible that a design value estimation procedure that provides a reasonable indicator for the purpose of determining the nonattainment classification of a small geographic area surrounding a monitoring site may not be suitable for the purpose of estimating the required degree of emission reduction needed to achieve attainment or for the purpose of estimating health risks to nearby populations. Therefore, it is necessary to indicate the intended application of a design value estimation procedure before judging whether it yields a reasonable air quality indicator. This issue can be examined in both a temporal and a spatial framework.

Spatial Representativeness

Design values are estimated individually for each monitor in an area, and the maximum value is used to determine the nonattainment classification of the entire area. Ozone concentrations can also be locally depressed immediately downwind of a source of nitrogen oxides (NO_x) due to scavenging by nitric oxide (NO). Key concerns are (1) whether the monitoring network is sufficiently dense and monitors are appropriately located to represent air quality over the area in question and (2) how spatially uniform are design value

estimates across metropolitan areas. The study examined the spatial distributions of ozone ambient concentrations from existing monitoring networks within urban areas. Figure 1-1 shows the variability in 1987–89 ozone design values calculated for all monitoring sites in the northcentral states of Indiana, Illinois, Michigan, and Wisconsin. As illustrated, design values can vary from levels near the standard to levels near 0.20 ppm at sites across these states. The study also described regional-scale ozone episodes and examined large-scale features using spatial concentration distributions calculated by photochemical dispersion models.

Temporal Representativeness

A major concern with respect to the temporal representativeness of design values is the number of years of data used to calculate the design value. Current EPA guidance calls for the use of three years of data, if available (40CFR50.9). The use of three years of data is a compromise between the need to include as much data as possible to arrive at an accurate estimate and the need to recognize nonstationarities in the data record resulting from precursor emission trends. Setting the time period for judging compliance also sets an upper limit on the number of exceedances that a site can experience in any one year and the area still remain in attainment of the NAAQS.

Wide year-to-year variations in weather conditions can result in significant differences in estimated design values from one three-year period to the next, even in the absence of emission changes, as shown in recent design value lists that include 1988 ozone data. Meteorological conditions in 1988 were highly conducive to ozone formation, especially in the eastern half of the nation. Summer 1988 was the third hottest summer on record (Heim, 1988). Adding 1988 data to the three-year data window increased the number of areas not meeting the ozone standard to 98, an increase of 37 areas (EPA, 1989, 1990). More recent summers have been less conducive to ozone formation than the summer of 1988. In the East, the period from January through July 1989 was among the wettest on record (Heim, 1988). In the Northeast, summer 1990 also had above-average precipitation (Heim, 1990). However, summer 1991, which was the eighth warmest summer on record, saw the return of ozone conducive conditions, especially in the Northeast (Heim, 1989). In addition to these meteorological differences, volatile organic compound emissions have been reduced since 1988 levels. The volatility of gasoline, measured as Reid Vapor Pressure (RVP), was reduced 11 percent between 1988 and 1989, and an additional 3 percent between 1989 and 1990 (Federal Register, 1989; MVMA, 1988a, 1988b, 1988c). As a result of both changing meteorological conditions and emissions reductions, the latest design value listing, based on 1991–93 data, showed that 55 of the initial 98 nonattainment areas now meeting the ozone NAAQS (EPA, 1994). This is the fourth update that does not include data from the 1988 peak ozone year. Seven of the original 98 nonattainment areas have already been redesignated to attainment. Thus, factors such as the sequence of meteorological conditions, and reductions in emissions can introduce temporal variability in design values.

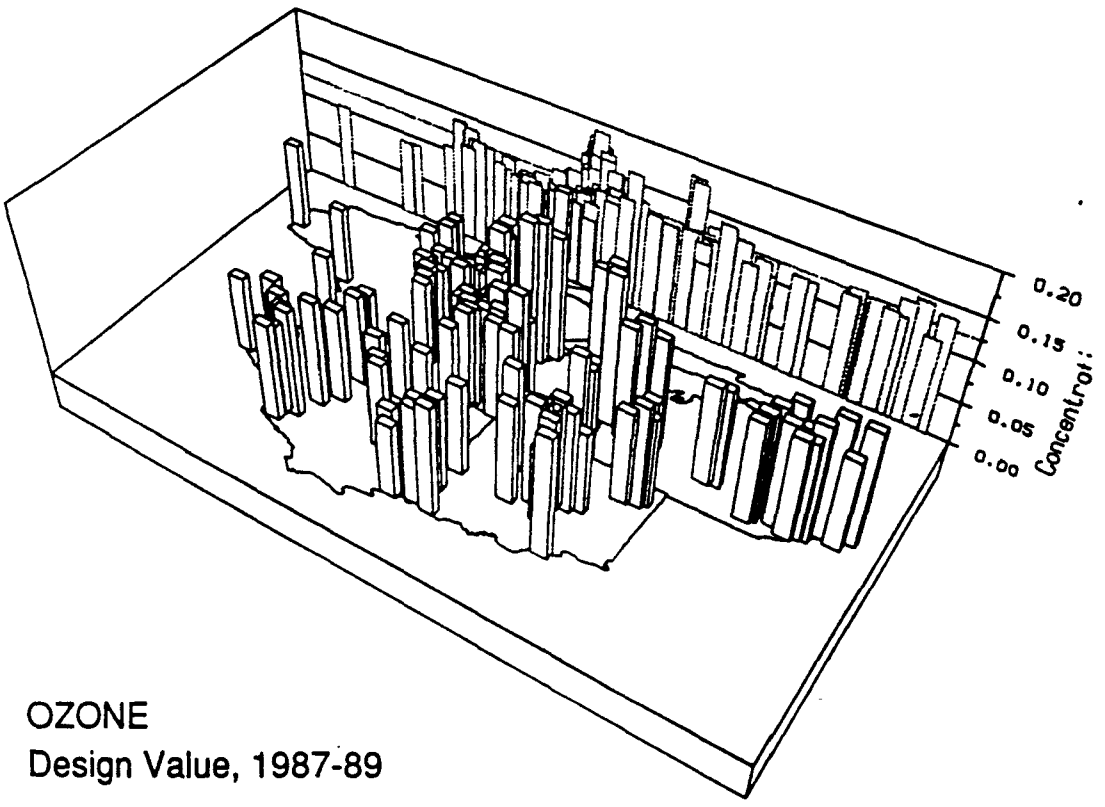

Figure 1-1. Map depicting ozone design values at all sites in Indiana, Illinois, Michigan, and Wisconsin, 1987–89.

As another measure of temporal variability, Table 1-3 summarizes ozone area classifications that would result from increasing the number of years used in the EPA design value method. The table focuses on data windows ending in 1989, because most of the area classifications were based on data from that period (40CFR58). However, to maintain historical consistency, Consolidated Metropolitan Statistical Areas (CMSAs), Metropolitan Statistical Areas (MSAs), and counties are used to define the geographic area, and not the nonattainment area boundaries of the currently designated nonattainment areas. Table 1-3 shows that the largest differences in ozone area classifications are associated with design values based on a single year of data. There is close agreement between classifications based on 3 and 4 years of data, while the longer data windows (5 and 6 years) have fewer nonattainment areas (4 and 7 fewer, respectively) than the 3-year estimates. There is some downward movement in area classifications evident in the longer time periods. That is, severe areas have moved downward to serious, serious areas to moderate, and moderate areas to marginal.

TABLE 1-3. Impact on ozone area classifications of varying the number of years when estimating the ozone design value using the EPA tabular method.

Clean Air Act Ozone Classification	Number of Areas (CMSA/MSA/County)							
	Single Year Design Value			Multi-year Design Value				
	1987	1988	1989	1988-1989	1987-1989	1986-1989	1985-1989	1984-1989
Extreme	1	1	1	1	1	1	1	1
Severe	6	11	4	7	9	9	7	6
Serious	17	23	4	20	16	15	14	15
Moderate	22	45	12	36	33	33	33	29
Marginal	22	32	18	35	39	37	39	40
Total	68	112	39	99	98	95	94	91

ALTERNATIVE OZONE DESIGN VALUE ESTIMATION METHODS

The Ozone Guideline introduced several techniques that could be used to estimate design values including (1) a table look-up procedure (which evolved into the current EPA method), (2) the use of fitted statistical distributions, and (3) the use of a conditional probability approach.

There are two distinct approaches to fitting distributions to air quality data: (1) fitting parametric distributions to raw hourly or daily concentrations, and (2) fitting extreme value distributions to the highest concentrations. A review of the literature conducted for this study, including the reported goodness-of-fit results, suggests that a growing consensus appears to favor the use of the tail exponential distribution to fit the annual maximum hourly ozone concentrations. The use of the lognormal distribution to fit the hourly and, possibly, daily maximum hourly, ozone concentrations was another popular method (Mage, 1984; Curran and Frank, 1975). The selection of a "best" statistical distribution for calculation of ozone design values may not be possible because such a distribution probably varies according to the location studied and the time period of interest. An approach developed by Breiman for EPA fits an exponential distribution to the upper 5 to 10 percent of the concentration distributions for each year (Breiman et al., 1978). Ozone design values are estimated by combining the tail-exponential distributions for the three-year compliance period. Another approach is to combine data years and fit a parametric distribution to the upper tail of the three-year distribution. The tail exponential approach developed by Larsen and others at the California Air Resources Board (CARB, 1992b) was developed in response to the 1988 California Clean Air Act which allows highly irregular or infrequent violations of the state ambient air quality standards to be excluded from the attainment/nonattainment designation process (Larsen and Bradley, 1991; CARB, 1992a; Larsen, 1991). In June 1990, the California Air Resources Board (CARB) determined that exceedances expected to recur less frequently than once in seven years could be excluded. The tail exponential approach was proposed as a method of estimating the one-in-seven-year concentration. More recently, the CARB revised the exclusion frequency to be one in one year (CARB, 1992b).

Comparisons have been made of design values estimated using the EPA tabular approach and those estimated using exponential and Weibull distributions. These distributions were fitted to the upper 5 percent of the three-year distribution for 1987–89 at all ozone sites in the historical database using the Breiman tail-exponential procedure and by a procedure that estimated the parameters by maximum likelihood using a Newton-Raphson algorithm (Breiman et al., 1978; SAS; Freas, 1992a). The tabular method design value estimates tended to be lower than those obtained with the tail-exponential and other distribution fitting methods. Differences in the several parts per billion range were found among the various distribution fitting methods. Table 1-4 presents the results for the Chicago, New York and Los Angeles metropolitan areas of using five different methods for estimating design values: (1) the EPA tabular approach, (2) simply using the appropriate percentile from the empirical distribution, (3) the Breiman tail-exponential fitted to the upper 5 percent of the data, (4) a 10 percent tail-exponential fit, and (5) the CARB tail-exponential approach developed by Larsen. The CARB approach was applied both with and without the empirical calibration factor used with the method. The calibration factor was determined by Larsen in a way that recognized the expected discrepancy between the tail-exponential method and the EPA tabular method, since the EPA method is expected to be biased low on theoretical grounds. According to the CARB (McGuire, 1994), the calibration factor estimate recommended by Larsen is based on ozone data from monitoring sites throughout

California and was selected to produce design value estimates at a "suitable midpoint" between the uncalibrated method and the EPA method.

Average and maximum values across all monitoring sites in these areas are listed in Table 1-4. Details of the calculations, including the percentile definitions and confidence intervals, are provided in Section 6. The maximum values indicate the design value which would be assigned to the nonattainment area, assuming that design values from any monitors not included in this analysis are smaller. Except for design values based on the 10 percent tail exponential (and the 5 percent tail exponential in Los Angeles), the various methods produced estimated average design values that are within 0.01 ppm of each other. This is also true of the maximum design values in each area, except in Los Angeles where the differences were as large as 0.02 ppm. Of course, results at individual monitors may show wider variations. Design values obtained by fitting a tail exponential distribution to the top 10 percent of the data values are higher than even the third highest concentration in each area, both on average and for the maximum values. Lower design values were obtained from tail exponentials fitted to the top 5 percent of the ozone values although, on average, they are still higher than the third highest for the New York and Los Angeles areas. These results indicate that the portion of the distribution of daily maximum concentrations to which the tail exponential is fitted can have a significant impact on the estimated design value. This is the primary motivation for using Larsen's approach, which uses multiple tails fitted to various portions of the upper end of the distribution and weights the results toward those tails which best fit the available data.

If design values are to be estimated by fitting distributions, the tail-exponential distribution approach, using either the Breiman formulation or the CARB method, seems preferable on the basis of its simplicity, ease of fitting, robustness and goodness of fit. The goodness of fit for a large number of sites is likely due to the property that a wide variety of daily maximum ozone concentration distributions have an approximately exponential tail.

TABLE 1-4. Average and maximum estimated (ppm) design values for the period 1989-91 using each estimation method (4th High = fourth highest concentration, 3d High = third highest concentration, Pcntl = percentile method, 5%TlExp = 5 percent tail exponential, 10%TlExp = 10 percent tail exponential, Larsen = CARB method, LarNoCal = CARB method without calibration factor).

					5% TlExp 95% Confidence Interval			10% TlExp 95% Confidence Interval			
	4th High	3rd High	Pcntl	5%TlExp	Lower Bound	Upper Bound	10%TlExp	Lower Bound	Upper Bound	Larsen	LarNoCal
Chicago Area											
Average:	0.118	0.122	0.118	0.123	0.113	0.137	0.126	0.116	0.138	0.113	0.118
Max:	0.151	0.164	0.152	0.161	0.146	0.183	0.168	0.153	0.187	0.151	0.158
New York Area											
Average:	0.140	0.146	0.140	0.150	0.138	0.168	0.159	0.146	0.177	0.144	0.151
Max:	0.165	0.175	0.166	0.175	0.159	0.199	0.185	0.167	0.209	0.166	0.175
Los Angeles Area											
Average:	0.21	0.22	0.22	0.25	0.22	0.30	0.26	0.23	0.30	0.21	0.22
Max:	0.28	0.30	0.30	0.32	0.29	0.38	0.34	0.31	0.39	0.28	0.30

USE OF TIME-SERIES MODELS

In this study, time-series models were used as a tool for evaluating alternative design value estimation methodologies. The ambient ozone database was used to develop a time-series model of the behavior of daily maximum ozone concentrations. Given such a model, large numbers of random simulations of single seasons of daily maximum ozone values can be generated that allow the limiting CLV (the "true design value") and design values for any number of methods to be calculated over a large number of years. Thus, both the inherent biases and precision of alternative design value methods can be studied using a wide variety of averaging years. These data sets have no missing values and therefore are free from this source of error.

The time-series model has been applied in five geographically diverse metropolitan areas: Atlanta, GA; Charlotte, NC; Chicago, IL-WI; Houston, TX; and New York, NY-NJ-CT. One hundred three-year sequences of ozone daily maximum concentrations were generated for key sites in each area. The results are similar to those observed with the ambient data comparisons. That is, the EPA tabular method gave lower design value estimates, on average, than Breiman's tail-exponential method. However, tail exponential estimates at some individual sites can be lower than the EPA tabular values, depending on the shape of the concentration distribution.

PEER AND PUBLIC REVIEW

Section 183(g) of the CAAA of 1990 requires the EPA to "obtain input from States, local subdivisions thereof, and others." In conducting the Ozone Design Value Study, EPA has made every effort to have an open process and to ensure full public input and participation. These efforts focused on information exchange through participation in professional meetings and conferences, involvement of interested parties on the study working group, and holding a public meeting (Freas, 1992a, 1992b; Curran, 1992a, 1992b; 57FR34133). The study plan and the results of the multi-year analyses were presented in technical papers at the Air and Waste Management Association's Tropospheric Ozone Specialty Conferences. These papers were peer reviewed prior to publication in the Conference Proceedings.

A study review group has been established to provide input on technical issues and policy concerns. The group is composed of representatives from EPA program, research, policy and legal offices. State and local air pollution control agency officials also serve on the review group.

On September 10, 1992, EPA held a public meeting in Arlington, VA to obtain input on technical considerations and on implementation and policy issues to be addressed within the context of the Ozone Design Value Study. The meeting announcement was published in the Federal Register, and to ensure that all interested parties were aware of the public meeting, copies of the meeting announcement were sent to both individuals and organizations that had previously expressed interest in ozone-related issues (57FR34133). At the public meeting, presentations were made on behalf of the Motor Vehicle Manufacturers Association and Ford Motor Company. Written comments were received from ten respondents, representing State and local air pollution agencies, industry and private individual views.

On March 14, 1994, EPA published a *Federal Register* Notice announcing the availability of a draft report on the study for public review and comment. Prior to that announcement, copies of the draft report were mailed to all parties that previously expressed an interest in the study. More than 250 copies of the report were mailed out in response to requests. As of the close of the public comment period on April 14, 1994, comments had been received from only two respondents. Requests were received from several parties to extend the comment period. On April 28, 1994, a second *Federal Notice* was published that extended the public comment period until May 31, 1994. Although many additional requests for copies of the draft report were answered during this period, only eight additional parties submitted comments by the close of the comment period. Technical peer review was conducted under the auspices of the National Institute of Statistical Sciences. The report responds to the public comments and was revised to address the technical corrections identified during peer review.

Comments received during the public meeting and on the draft report can be grouped into two major categories: (1) those relating directly to design value issues and (2) those that

would require changes in legislation or a revision to the form of the ozone standard. Those in the first category include issues concerning (1) the statistical robustness of the current design value methodology, (2) the precision and accuracy of ozone monitoring data, and (3) the use of other statistical techniques, such as fitting a tail-exponential model, for determining the design value. The second category includes issues associated with changing the form of the ozone standard to a more robust air quality indicator, or proposing to modify the attainment test to incorporate a statistical test, such as a "t-test" for judging compliance with the standard (Heuss, 1992; Chock, 1989, 1992; Heuss and Chock, 1992). Such changes are beyond the scope of this study and are more properly addressed during the next ozone NAAQS review.

OTHER CONSIDERATIONS

Many comments received raise issues related to the concept of a "control strategy" design value, not the air quality design value. Adjusting design values for factors such as transported ozone, meteorology, and emissions trends falls within the control strategy design value concept, not the air quality design value methodology used to classify ozone nonattainment areas under the CAAA of 1990.

Adjusting for Transported Ozone Levels

Transport of ozone and ozone precursors generated in one air basin can significantly influence ozone concentrations in neighboring air basins located considerable distances downwind. Some comments received on the original nonattainment area classifications argued that EPA should have considered lowering the classification because of the impact of transport from upwind areas (Federal Register, 1991; EPA, 1992a). The amendments specifically acknowledge that transport across state boundaries plays a major role during high ozone events in the northeastern urban corridor between Washington, D.C. and Boston. Transport of ozone and precursors also plays a significant role in other parts of the country, including the Gulf Coast region and Lake Michigan. Although the amendments call for the establishment of a transport commission to study this issue, the Act does not provide for adjusting the air quality design values for transport. The one instance that transport may be considered during the initial classification process is if the design value is within 5 percent of the classification level.

As a result of the strong influence of transported precursors and ozone in some areas, design values at such locations may be heavily influenced by emission changes occurring many kilometers away in an upwind area. Adjusted design values differ from "current air quality design values" in that they take into account the degree to which transport of ozone and precursors from upwind metropolitan areas contributes to ozone concentrations at the monitoring site in question.

This study described a computer model, Transported Ozone Design Value (TODV),

which has been developed to assist in determining the likely source regions associated with high ozone concentration events (Sabo and Hawes, 1990). TODV can only provide an approximate location of the emissions source region likely to have influenced a particular afternoon ozone peak. No estimate of the relative contributions of upwind vs. local emissions to the peak is provided, and back-trajectory calculations based on routine wind data can contain large uncertainties. Selection of the transport-adjusted design value requires an experienced analyst to interpret the results, which introduces a subjective element to the adjustment process. Application of this approach to 1988–90 ozone data yielded transport-adjusted "control strategy" design values for 35 areas. These transport adjustments ranged from a decrease of 0.05 ppm to increases of 0.04 ppm. Thus, these transport adjustments can lead to both decreases and increases in an area's design value as the downwind impact is attributed back to the source area, or the impact from upwind areas is subtracted out.

Adjusting for Meteorological Variability

Meteorological conditions have been shown to play a key role in explaining variations in daily maximum ozone concentrations. Given similar precursor emissions, the basic differences between days when ozone concentrations are average or below average and days when concentrations are high (i.e., episode days) are in the prevailing meteorological conditions. High ozone concentrations are likely to occur with low wind speeds, elevated temperatures, intense solar radiation (i.e., no cloud cover), shallow mixing depths, and the wind patterns that bring, keep, or return high background concentrations to the region. In some years, such meteorological conditions occur more frequently and with greater intensity than in others, leading to a greater number of high ozone days even if precursor emission levels do not differ significantly from those in other years. Thus, design values determined from a single year of data vary in accordance with weather conditions during the year in question and may or may not be representative of design values that can be expected to occur in the future, even in the absence of any precursor emission trends. To some extent, basing design values on three years of data instead of one eliminates some of the meteorological variability, but a single unusual year such as 1988 can still strongly affect the three-year value. This has raised concern that meteorological variability must be considered when assessing ozone air quality trends and judging progress toward attainment of the ambient standards (NRC, 1991).

The influence of meteorological conditions, particularly temperature, on ozone concentrations has been well established (NRC, 1991; Sweitzer and Kolaz, 1984; Jones, 1985; Jones, 1989; Kolaz and Swinford, 1990; Wakim, 1990; Zeldin and Meisel, 1978; Cox and Chu, 1992). The most successful empirical models used in ozone trends adjustments account for roughly 60–80 percent of the variance in daily maximum ozone concentrations (see for example Kolaz and Swinford, 1990; Wakim, 1990; Cox and Chu, 1992). Due to correlations of temperature with other variables, the daily maximum temperature is often the single most important variable in explaining day-to-day ozone variations. However, since high temperature by itself is not sufficient to produce high ozone concentrations, including other meteorological variables in the analysis often produces better results. This is

particularly true at locations where ozone and precursor materials transported from upwind source regions account for a significant concentration increment on high ozone days. High concentrations at such locations are primarily associated with weather conditions conducive to both ozone formation and transport from the upwind source regions.

Much of the year-to-year variability in ozone design values and other summary statistics is attributable to interannual variations in prevailing weather conditions during the high ozone season. These fluctuations can mask underlying ozone trends associated with changes in precursor emission patterns and can affect estimates of design values. As a result, a great deal of attention has been given to the development of procedures for adjusting summary statistics to remove the effects of meteorological fluctuations (Sweitzer and Kolaz, 1984; Jones, 1989; Jones, 1992; Kolaz and Swinford, 1990; Wakim, 1990; Zeldin and Meisel, 1978; Cox and Chu, 1992). A wide variety of methods have been used, all of which rely on the development of a mathematical relationship between ozone concentrations and meteorological factors. This relationship is then used to estimate (predict) ozone concentrations expected to occur under standardized meteorological conditions. Figure 1-2 illustrates actual and adjusted trends in the number of days the ozone NAAQS was exceeded in Chicago (Kolaz and Swinford,1990). The "adjusted" summary statistics calculated from these predicted concentrations can then be examined for trends. Figure 1-3 shows how an index of ozone conducive days (days with maximum daily temperature greater than 90° F) can be used to adjust the trend in the number of exceedances of the ozone NAAQS (Jones, 1992). Although these approaches are very useful for assessing trends, one must consider how meteorological adjustment affects the intended level of protection for the standard if such an approach were to be used for assessing compliance with the ozone NAAQS.

It may be possible to improve the performance of meteorological adjustment techniques by focusing on meteorological variables that describe the persistence of ozone-conducive conditions over multi-day periods (Cox and Chu, 1992). The importance of persistence and the day-to-day carryover of pollutants has been demonstrated by Kolaz and Swinford among others (Kolaz and Swinford, 1990). EPA has initiated a program to investigate techniques for adjusting ozone trends for meteorological influences. One of the methods being studied is a statistical model developed by Cox and Chu in which the frequency distribution of ozone concentrations is described as a function of meteorological parameters (Cox and Chu, 1992). The results of application of the model to a number of urban areas are encouraging. Figure 1-4 shows the actual and adjusted trends in the 99th percentile concentrations in Chicago. EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS).

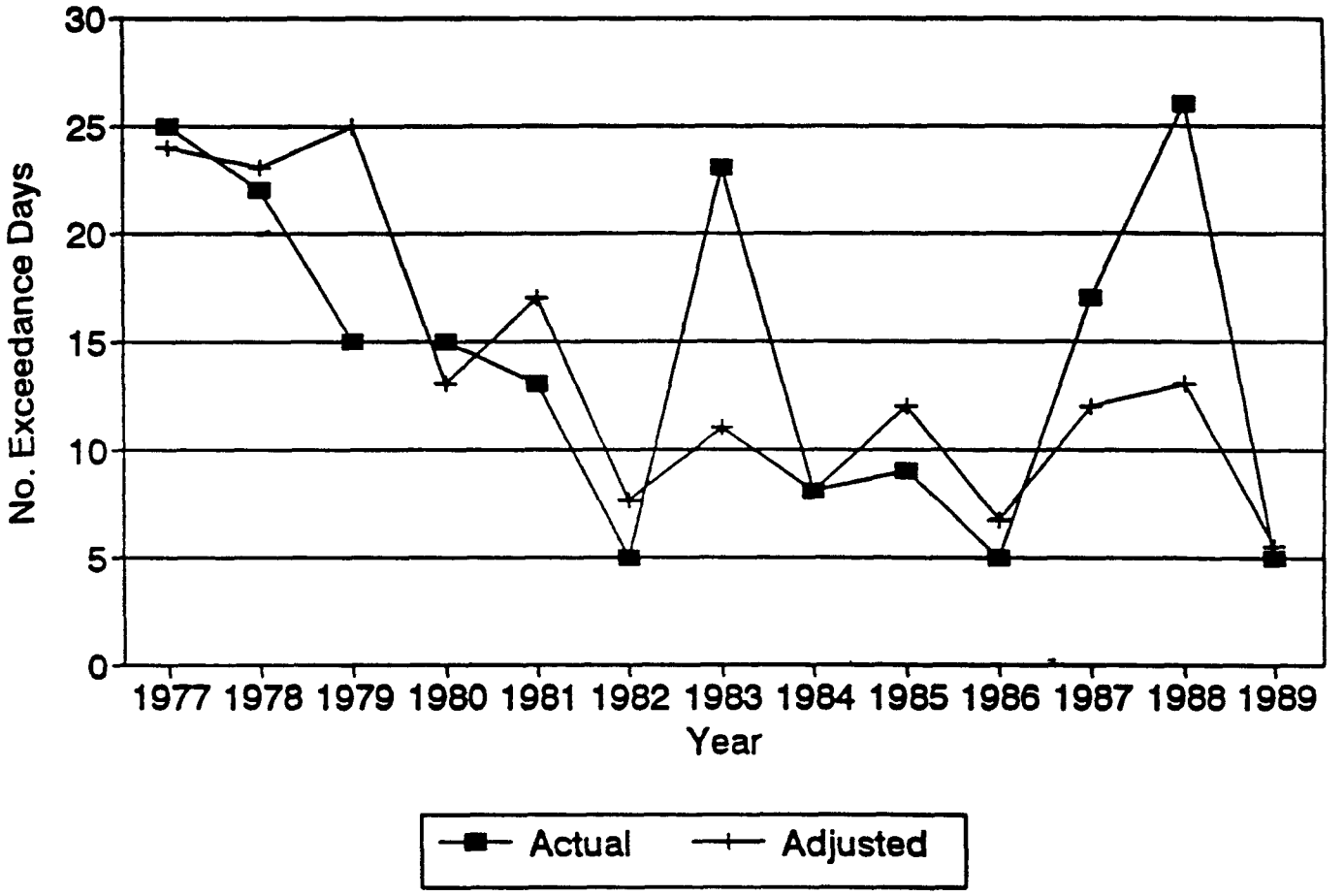

Figure 1-2. Actual and adjusted trends in number of days on which ozone concentrations exceed 0.12 ppm in the Chicago area (adapted from Kolaz and Swinford, 1990).

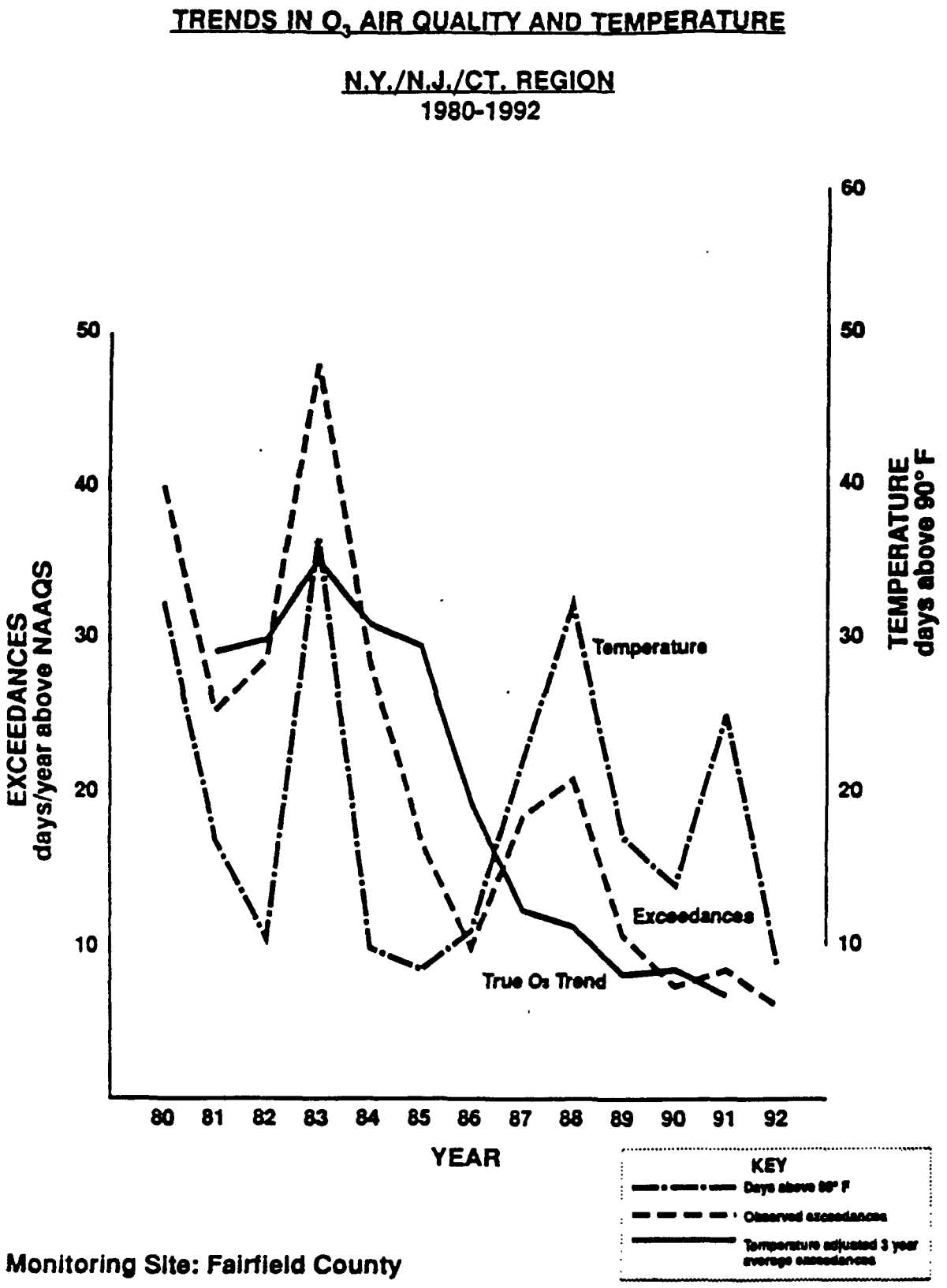

Figure 1-3. Adjustment of ozone trend based on number of days above 90° F (Source: Jones, 1992).

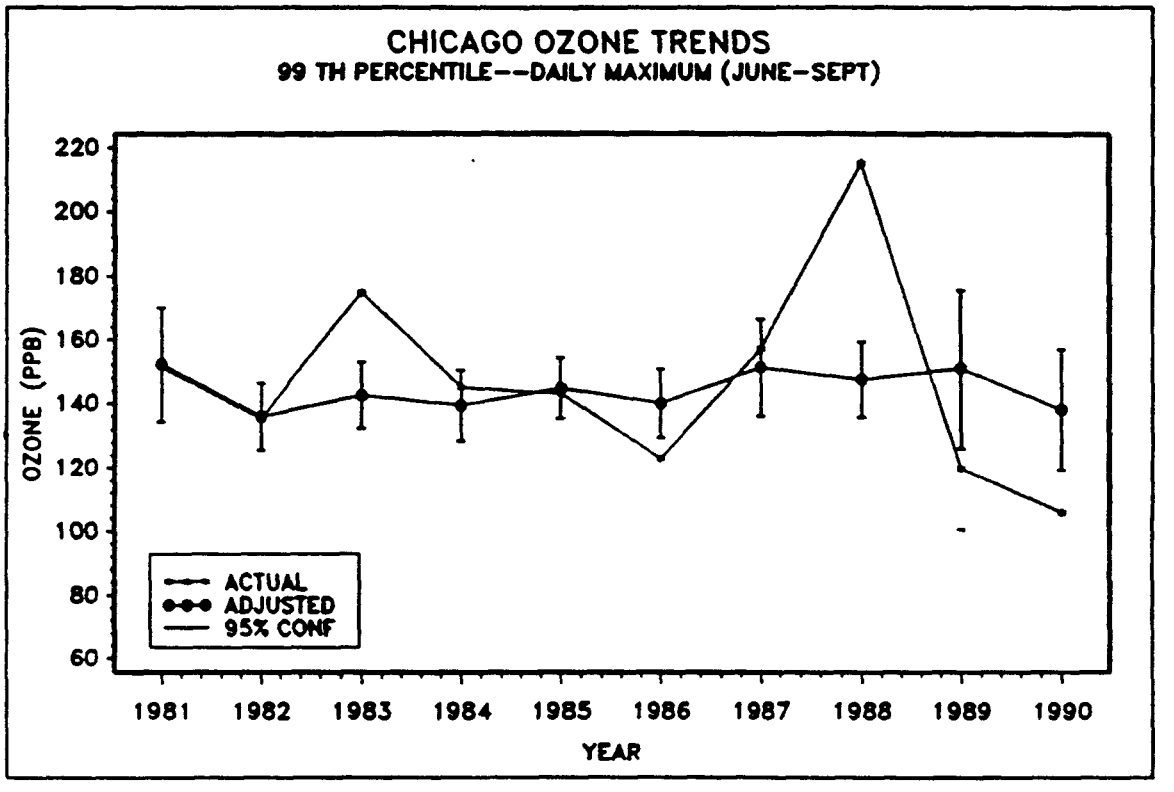

Figure 1-4. Actual and meteorologically adjusted ozone trends in the 99th percentile of the daily maximum 1-hour ozone concentration for Chicago, 1981-1990 (adapted from Cox and Chu, 1992).

MAJOR FINDINGS

The Ozone Design Value Study has examined the current EPA method, as well as alternative approaches, for calculating ozone design values. The key findings of the study are as follows:

1. With passage of the Clean Air Act Amendments of 1990, the primary role of the air quality design value is to establish the ozone classification of ozone nonattainment areas.

2. Although the year-to-year differences in maximum ozone concentrations can be large, all of the different methods examined in this study for estimating air quality design values exhibit less year-to-year variability. The EPA design value is slightly more variable than lower percentile indicators and design values estimated from fitted tail exponential distributions, although it remains highly correlated with these indicators.

3. Increasing the number of years used to estimate the design value reduces the year-to-year fluctuations. Comparisons made for 3-year periods ending in 1988–90 had less variability in the design value estimates than during previous 3-year periods. This is likely due to the fact that there was a single dominant year (1988) for peak ozone levels during the 1988–90 time period.

4. The past decade has seen large year-to-year variability in ozone concentrations. However, the relative variation in ozone concentrations recorded among monitoring sites throughout large urban areas can be as great as, or greater than, the year-to-year variation in ozone concentrations recorded at a particular monitoring location. Spatial variations in ozone concentrations at smaller, sub-metropolitan-length scales are not well defined in many areas due to the sparsity of ozone monitors.

5. The EPA tabular design value method tends to give lower, but more variable estimates for the ozone design value than some of the statistical modeling methods, such as the Breiman tail exponential approach. Results of the time series modeling analysis suggest that the tail exponential approach provides the best compromise regarding bias and precision in the estimate of the "true" design value.

6. Given the database available at the time, generally data through 1989, the use of more robust (less variable) methods such as the tail exponential approach would not have significantly changed the initial ozone nonattainment area designations and classifications. Use of more years of data (i.e., 4 or 5 years) in estimating the design value would have resulted in lower classifications in only a limited number of cases. However, more recent data periods that do not include 1988 yield significantly different results. For the years 1989–91, the first 3-year compliance period that excludes the 1988 data, 42 of the original classified 98 nonattainment areas have ambient ozone meeting the standard. Seven of these areas have been redesignated to attainment. The most recent compliance period, 1991–93,

has 48 of the remaining 91 classified nonattainment areas also meeting the ozone standard.

7. Since the "true" design value is in the tail of the ozone concentration distribution, the EPA tabular design value method and more robust alternatives are perforce subject to greater variability than estimators of the central part of the distribution. Like any statistical estimator, errors in these estimated design values can lead to 1990 CAAA misclassification of nonattainment areas, just as errors in the Appendix H estimated expected exceedance rate can lead to misclassification of attainment areas as nonattainment areas and vice versa. Analyses included in this study provide estimates of the theoretical misclassification rates, but for a given site and monitoring period it is impossible to determine whether the estimated classification is the (unknown) true classification.

8. The "air quality" design value differs in concept and application from the "control strategy value." The former is based solely on the actual measured ozone air quality data and relates directly to the form of the ozone NAAQS. Control strategy design values have historically been used to evaluate emission control strategies, and may incorporate adjustments for factors such as transported ozone levels and meteorological variability. Use of the control strategy value concept to judge attainment under the Act would require EPA to revise its preliminary interpretation of Section 181(b)(2) published in the General Preamble to Title I.

9. For thirty-five areas modeled, the transport contribution to design values in areas subject to transport was found to be as large as 0.05 ppm. Increases in the design value of up to 0.04 ppm were estimated when the downwind impact was attributed back to the source area.

10. EPA has initiated a program (Cox and Chu, 1991) to investigate techniques for adjusting ozone trends for meteorological influences. One method being studied is a statistical model in which the frequency distribution of ozone concentrations is described as a function of meteorological parameters. EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS). Preliminary results suggest that the bias and uncertainty associated with long-trend estimates can be significantly reduced by including meteorological covariates as parameters in the statistical modeling process.

11. The use of a simple linear function of the 95th percentile of the distribution of daily maximum ozone concentrations as a surrogate design value is less satisfactory than any of the four more direct estimators of the design value. It fails to significantly reduce the variability of the associated estimated characteristic largest value (CLV) below that achieved with the more direct methods. (From another perspective: controlling the 95th percentile fails to improve control of the underlying CLV.) At the same time it introduces substantial biases which vary with the site. The bias problem would result in uneven treatment of sites relative to what would be achieved with the more direct measures. Nor would the use of the 95th percentile obviate the need to use 3-year data sets.

CONCLUSIONS

The question for the Ozone Design Value Study is "Does the EPA design value methodology provide a 'reasonable indicator of ozone air quality in ozone nonattainment areas'?" The answer depends on the intended application of the design value. Each nonattainment area was classified as a Marginal Area, a Moderate Area, a Serious Area, a Severe Area, or an Extreme Area based on the design value for the area. The area's classification establishes the primary standard attainment date and the requirements for State Implementation Plans.

In responding to Section 183(g), EPA sought to focus this study on whether the design value serves as a reasonable indicator of attainment status as defined by the current NAAQS, progress in reaching attainment, and of how much concentrations must be reduced to meet the standard. The EPA design value method yields an estimate for the ozone design value that is consistent with the current ozone NAAQS. Given the findings of this study, the EPA design value yields a "reasonable" estimate of the "true" air quality design value for the area and of peak ozone levels within the nonattainment area for the initial three year compliance period.

The EPA design value provides a reasonable estimate of peak levels within the urban area, and the degree of nonattainment of the area. However, the design value cannot describe the spatial variability in ozone concentrations across the area. More robust indicators based on specific monitoring sites also have large spatial variability. Ozone design values calculated with the EPA design value method are highly correlated with other more robust indicators. However, due to the spatial variability observed across urban areas, one cannot expect a single numerical value to adequately describe complex concentration gradients across large metropolitan areas.

The current EPA design value method may not provide a reasonable indicator of ozone levels in future years due to the large year-to-year variability in meteorological conditions, or to reductions in emissions following implementation of control measures. However, other more robust air quality indicators also exhibit similar year-to-year variability.

The method used to adjust for meteorological influences on long-term ozone trends could be adapted for use in calculating meteorologically adjusted exceedance rates and design values. While such adaptations are technically feasible, and would reduce the year-to-year variability, the use of adjusted exceedance rates in NAAQS attainment and adjusted design values for classification purposes would represent a major departure from current EPA policy and NAAQS implementation guidelines. Also, a meteorologically adjusted design value may not be the best indicator of the air that people breathed during a specific calendar year.

Concerns about the current ozone standard were raised during the public review process. Although changes to the form of the ozone standard were outside the scope of this

study, they are being considered within the context of the current review of the ozone NAAQS. The knowledge gained from the input of all parties to this study during the public review process will be used to address issues concerning the form of the ozone standard and design value methodologies.

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2 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 specified that each nonattainment area in the U.S. be classified with regard to the severity of the ozone problem on the basis of the ozone design value concentration. In the terminology of air quality analysts, a design value is the concentration that must be reduced to the level of the standard to achieve attainment of the standard. Classifications range from marginal to extreme depending on how far above 0.12 ppm the design value is. In addition, the amendments call upon EPA to conduct a study of the methodology currently in use for calculating design values to determine if the calculated design value "provides a reasonable indicator of the ozone air quality of ozone nonattainment areas" (CAAA, 1990).

This section provides background information on technical issues associated with the formulation of the ozone NAAQS, and procedures for defining, calculating, and interpreting ozone design values. This section concludes with a discussion of the scope of the Ozone Design Value Study.

OZONE STANDARDS AND DESIGN VALUES

National Ambient Air Quality Standard for Ozone

In 1979, the U.S. Environmental Protection Agency (EPA) promulgated a National Ambient Air Quality Standard (NAAQS) for ozone at a level of 0.12 parts per million (ppm). This standard is attained "when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 part per million is equal to or less than 1 as determined by Appendix H" (40CFR50.9). Appendix H describes the manner in which the "expected number" of days with concentrations above 0.12 ppm ("exceedance" days) is estimated. Additional information is contained in the EPA Ozone Guideline document (EPA, 1979). Appendix H and the Ozone Guideline specify procedures for dealing with missing data and make it clear that the expected exceedance criterion is to be applied independently to each monitoring site. For areas with multiple monitoring sites, all sites must meet the standard for the area to be designated in attainment.

The formulation of the ozone standard is designed to take into account the fact that daily maximum ozone concentrations vary widely from one day to the next in response to changing weather conditions. This in turn causes year-to-year variations in the number of exceedances recorded at a monitoring site. A larger number of exceedances are recorded in years when weather conditions conducive to ozone formation occur more frequently than other years. In recognition of this variability, the ozone NAAQS is written in terms of an <u>expected</u> exceedance rate. This is a statistical term which can be defined as the value approached by the average number of exceedances per year as the number of years included

in the average is increased without limit.[1] For this limiting average to exist, it must be assumed that the random processes which cause the number of exceedances to vary from one year to the next are stationary, i.e., that there is no change in their nature over time that causes the number of exceedances per year to permanently increase or decrease; instead, the exceedances simply fluctuate randomly about some long-term, fixed average value which is defined as the expected exceedance rate.

Since the amounts of precursor emissions can be expected to vary over time as a result of emission control programs, and economic and demographic trends, the number of exceedances per year observed at a monitoring site can be expected to exhibit nonstationarities such as long-term trends. Thus, the expected exceedance rate at a given point in time is the expected exceedance rate associated with emission levels prevailing at that time. If emissions change (e.g., following implementation of a control program), the expected exceedance rate is also likely to change. This raises an issue concerning the representativeness of data collected in previous years when emission levels may have differed from current values.

Implementation of the Ozone NAAQS: Estimating the Expected Exceedance Rate

From the above discussion it is clear that the expected exceedance rate is a mathematical abstraction that cannot be directly observed (and is therefore unknown) but must instead be estimated from what data are available. As required by Appendix H, the simplest estimate is obtained by averaging exceedances over a three-year period, that is, by adding up the number of exceedances observed during the three-year period and dividing by 3 (assuming no data are missing; see below). If there are no nonstationarities during the data collection period, then the more years included in the average, the more accurate the estimate of the underlying exceedance rate will be. In most cases, however, inaccuracies arise if more than a few years of data are used since emission patterns cannot reliably be assumed to remain unchanged over longer time periods. Taking this tradeoff into account, EPA formulated procedures for estimating the expected exceedance rate in Appendix H and in the Ozone Guideline that call for the use of a three-year averaging time. The procedure was selected as a reasonable compromise between the need to use the longest possible time period and the need to limit the number of exceedances that would be allowed in a single year and still have the area remain in attainment. It must be kept in mind, however, that the average number of exceedances over a three-year period is only an approximation to the expected exceedance rate and that it varies randomly from one three-year period to the next just as the annual number of exceedances varies from one year to the next, although the variations tend to be of a smaller magnitude. As noted, the actual expected exceedance rate (which is

[1]Appendix H to 40CFR50.9 states that the expected exceedance rate is to be determined by calculating the average number of exceedances over a three-year period, with suitable adjustments for missing data. A statistical definition of the term "expected exceedance rate" is not provided. The three-year period was selected to limit the number of exceedances that can occur in a single year and the area still remain in attainment of the NAAQS.

unknown) does not vary over time so long as the random processes generating the exceedances are stationary.

Ozone Design Values

As noted above, compliance with the ozone NAAQS is judged on the basis of the estimated expected exceedances, and becomes a "yes/no" decision. However, once it is determined that an area exceeds the standard, the next logical question to ask is, "By how much?" The design value is intended to provide a measure of how far concentrations must be reduced to achieve attainment or, equivalently, how far out of attainment the area represented by a monitoring site is. In this respect, the design value can be viewed as an air quality indicator for a given location.

Given the expected exceedance form of the ozone NAAQS, the design value for this standard is defined in the EPA guideline document as "the concentration with expected number of exceedances equal to one" (EPA, 1979). Note that in this context the ozone guidelines are referring to the unknown "true" number of expected exceedances per year rather than the estimate of expected exceedances determined using the Appendix H calculations. In statistical terms, this is the value which is exceeded once per year on average. If the daily maximum ozone concentrations are assumed to be independent and have the same distributions every day throughout the year, then the design value is the characteristic largest value (CLV) of that distribution. Given that there are 365 days in a year (ignoring leap years) and assuming independent identically distributed daily maximum ozone concentrations, the CLV is simply the value which is exceeded with probability 1/365. Conceptually, if the CLV is less than or equal to the level of the standard (0.12 ppm) for all monitoring sites in an area, then the expected exceedance rates at all monitors will be less than or equal to one per year as required by the ozone NAAQS.[2] Thus, the air quality indicator (design value) which the formulation of the ozone NAAQS identifies as being of significance is the CLV. By limiting the CLV to a value not exceeding 0.12 ppm, the ozone NAAQS indirectly limits the frequency and magnitude of peak daily maximum ozone concentrations. That is to say, although an area just in attainment may experience an occasional year with several daily maximum concentrations in excess of 0.12 ppm, these will be balanced out by years with no exceedances such that, on average, no more than one day per year exceeds 0.12 ppm. More precisely, a Poisson distribution approximation implies that only 8 percent of years have three or more exceedances of 0.12 ppm for a site just in attainment. If the CLV is significantly above 0.12 ppm, then in most years a number of days can be expected to have concentrations well in excess of 0.12 ppm.

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[2] It must be noted, however, that in some cases with incomplete monitoring data the CLV estimated from monitoring data will be less than the NAAQS and yet the site will be designated nonattainment based on a calculation of the estimated expected exceedance rate (which is the actual basis of the attainment test called for by the NAAQS). This situation can occur because the CLV and true expected exceedance rate are unknown, and are estimated by the design value in Appendix H procedures, respectively, which are both subject to error.

Strictly speaking, the design value is an unknown quantity depending on the underlying distribution of ozone concentrations, and the EPA design value and alternatives are estimators of the (true) design value. To retain the readability of this document the term "design value" may refer to either the unknown population value or an estimator, depending on the context in which it is used. Where appropriate, the term "true design value" is used for clarification. The "EPA design value" always refers to the table look-up value.

Estimating Design Values

Initial EPA Guidance

Just as the expected exceedance rate is a mathematical abstraction that cannot be directly observed but must instead be estimated from available data, the design value associated with the ozone NAAQS is also an abstract quantity that can only be estimated. The Ozone Guideline suggests several methods for estimating the design value, including a simplified table look-up procedure, techniques incorporating statistical distributions, and techniques based on conditional probabilities. No single approach was required by the guideline, so that the initial guidance contained a fair degree of flexibility in how these design values could be estimated. However, both the Ozone Guideline and Appendix H made clear that *attainment/nonattainment determinations are to be based on estimates of the expected exceedance rate, not on comparisons of the design value with the level of the standard.* Once an area has been determined to be in nonattainment on the basis of the expected exceedance rate, then estimated design values can be used to assess the degree of nonattainment for the purpose of formulating emission control strategies. Thus, the flexibility in design value estimation techniques incorporated into the ozone guidelines did not extend to flexibility in attainment determinations.

Additional EPA Guidance

In 1981, EPA issued guidance on the determination of ozone design values for the purpose of precursor emission control strategy development (EPA, 1981). This guidance is based on use of the Empirical Kinetic Modeling Approach (EKMA) to estimate the degree of precursor emission controls needed to reduce the ozone concentration observed on a particular high ozone day to the level of the standard. According to the guidance, EKMA is to be used to calculate the percentage emission reduction (control requirement) required on each of the five highest ozone days. The control requirement to be used in State Implementation Plans (SIPs) should then be the day with the fourth highest control requirement assuming three valid seasons of daily ozone measurements are available. The third highest control requirement is used if two seasons are available, and the second highest is used if only one valid season is available. The guidance is based on the fourth highest control requirement as opposed to the fourth highest ozone concentration since the nonlinear relationship between emission reductions and ozone concentrations raises the possibility that the day with the fourth highest concentration may not always correspond to the day with the fourth highest control requirement. In most cases, however, the two days are the same.

Thus, the 1981 guidance indirectly suggested that the design value for the current ozone NAAQS could be estimated as the $(n+1)$th highest daily maximum concentration given n valid seasons of monitoring data.

Using the $(n+1)$th highest concentration as the design value focuses attention on a concentration that was actually observed, as opposed to a statistical fitting technique that could yield a design value that does not correspond to a concentration observed on a particular day. The advantage of using an observed value as the estimated design value is that the day on which the value was observed can be used as the basis for a computer model exercise to determine the degree of emission controls needed to reduce the daily maximum concentration on that day to the level of the NAAQS. However, the $(n+1)$th highest concentration design value may be more variable and less desirable than alternative design values, based on a statistical fitting technique.

During the late 1980s, EPA issued ozone design value lists that used a table look-up approach patterned after the 1981 SIP guidance (e.g., EPA, 1987). This approach is summarized in Table 2-1. Basically, it results in the identification of the lowest observed concentration that was not exceeded more than an average of once per year during the measurement period.

TABLE 2-1: Ozone design value rank.

Number of Valid Years[3]	Ozone Design Value (Based on Rank-Ordered List of Daily Maximum Concentrations)
0	highest
1	2nd highest
2	3rd highest
3	4th highest

On June 18, 1990, EPA issued a memorandum signed by William G. Laxton, Director of the Technical Support Division, documenting the procedures used in determining both ozone and carbon monoxide design values (Laxton, 1990). This memorandum essentially maintained the status quo and documented the table look-up procedure summarized above as the EPA design value estimation method. This was the last EPA policy statement on design values prior to enactment of the 1990 Clean Air Act Amendments. Table 2-2 reproduces the

[3]A valid year is one in which valid daily maximum ozone concentrations are available on at least 75 percent of days during the officially designated ozone season. A valid daily maximum concentration requires that at least nine hourly concentrations were collected between 9:00 a.m. and 9:00 p.m. local standard time. These restrictions ensure that missing data do not result in significantly underestimated design values.

example contained in the Laxton memo for an area with two ozone monitors to illustrate the basic points in ozone design value estimation. This example indicates that the design value methodology is applied independently to the two sites in the area and that the highest design value for the sites becomes the design value for the area. The memorandum discusses additional details for special cases, but the general methodology is essentially unchanged from the SIP guidance issued in 1981.

TABLE 2-2. Hypothetical example of ozone design value determination (case with two ozone sites in an area, each year at least 75 percent complete).*

		Four Highest Daily Maximum Values			
		Max	2nd Hi	3rd Hi	4th Hi
SITE 1	1986	.127	.123	.122	.110
	1987	**.129***	.124	.121	.116
	1988	.142	.136	.134	.115

* The design value for Site 1 is 0.129 ppm, the fourth highest daily maximum value during the three-year period.

		Four Highest Daily Maximum Values			
		Max	2nd Hi	3rd Hi	4th Hi
SITE 2	1986	.110	.100	.095	.090
	1987	.110	.100	.095	.090
	1988	.180	.175	.160	**.110***

* The design value for Site 2 is 0.110, the fourth highest value during the three-year period. Note that any of the days with .110 could have been selected.

0.129 ppm would be the design value for the area.

1990 Clean Air Act Amendments

With passage of the 1990 CAAA, a new dimension was added to the use of ozone design values. In addition to designating areas as nonattainment for ozone, the CAAA introduced a classification process to further categorize nonattainment areas according to the extent of their ozone problem. As shown in Table 2-3, this classification was based upon the ozone design value. The CAAA stated that the design value "shall be calculated according to

the interpretation methodology issued by the Administrator most recently before the date of the enactment." Thus the June 18, 1990 Laxton memo determined the methodology underlying the ozone classifications published in the November 6, 1991 *Federal Register*. These classifications, shown on the map in Figure 2-1, resulted in 37 marginal areas, 34 moderate areas, 17 serious areas, 9 severe areas, and 1 extreme area—Los Angeles.

TABLE 2-3. Ozone classifications specified in the 1990 Clean Air Act Amendments.

Area Class	Design Value*	Attainment Date**
Marginal	0.121 up to 0.138	3 years
Moderate	0.138 up to 0.160	6 years
Serious	0.160 up to 0.180	9 years
Severe	0.180 up to 0.280	15 years
Extreme	0.280 and above	20 years

*In parts per million (ppm).

**Measured from the date of the enactment of the Clean Air Act Amendments of 1990.

Before the 1990 CAAA, designation of nonattainment areas simply involved a "yes/no" determination as to whether the area met the standard. The additional classification step introduced by the 1990 CAAA placed greater emphasis on ozone concentration observations and on the methodology used to determine the design value.

THE OZONE DESIGN VALUE STUDY

In addition to the new use of ozone design values imposed by the 1990 CAAA described above, Section 183(g) of the CAAA required EPA to conduct an Ozone Design Value Study. In particular, Section 183(g) states:

> The Administrator shall conduct a study of whether the methodology in use by the Environmental Protection Agency as of the date of enactment of the Clean Air Act Amendments of 1990 for establishing a design value for ozone provides a reasonable indicator of the ozone air quality of ozone nonattainment areas. The Administrator shall obtain input from States, local subdivisions thereof, and others. The study shall be completed and a report submitted to Congress not later than 3 years after the date of the enactment of the Clean Air Act Amendments of 1990. The results of the study shall be subject to peer and public review before submitting it to Congress.

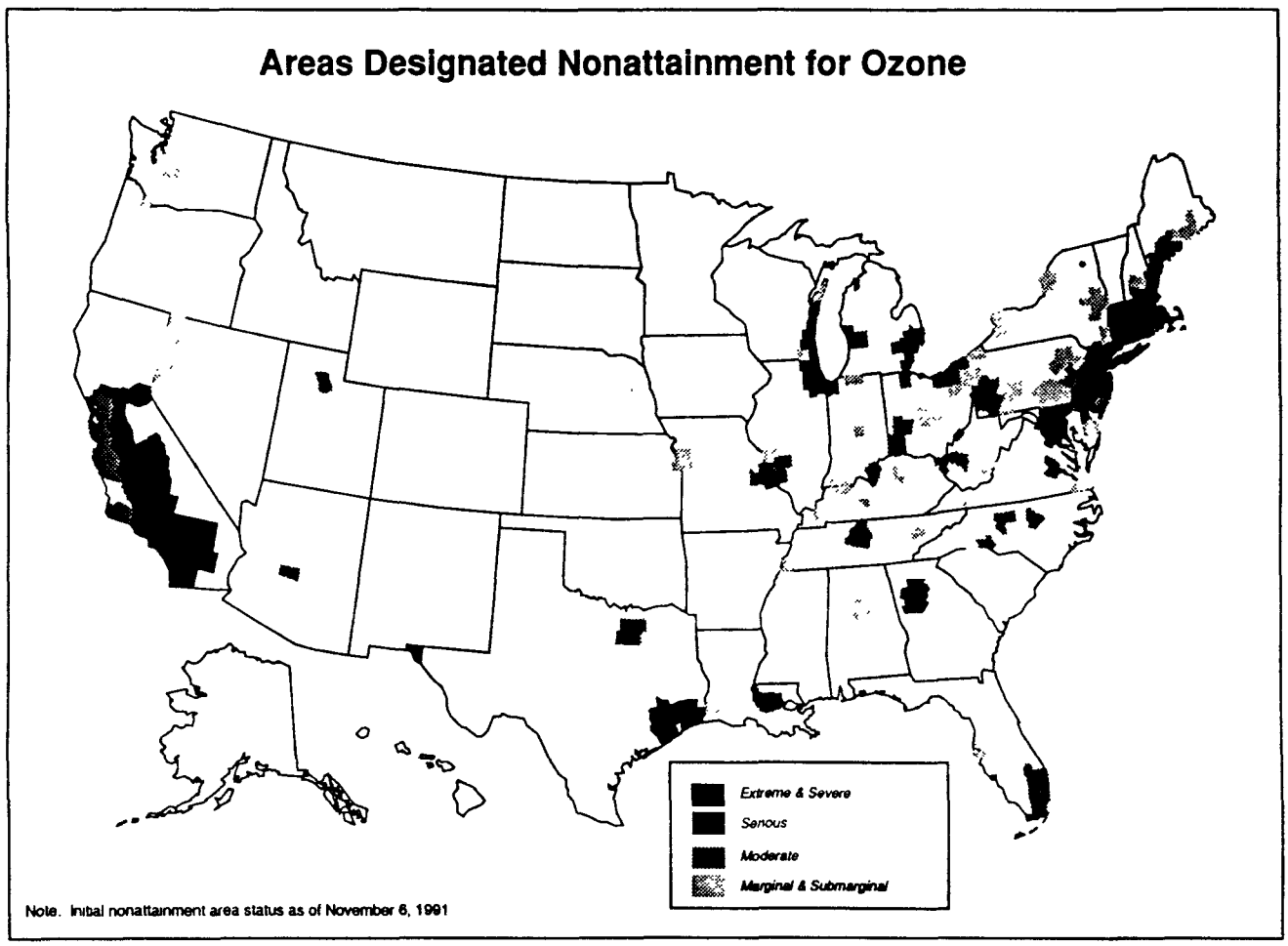

Figure 2-1. Initial ozone nonattainment area designations and classifications under the Clean Act Amendments of 1990.

On the basis of this language, it is assumed throughout this report that the focus of the Ozone Design Value Study is on EPA's design value methodology "as of the date of enactment of the Clean Air Act Amendments of 1990." Concerns regarding the level of protection provided by the current ozone NAAQS are more properly treated within the existing mechanism for NAAQS review, and the wording of Section 183(g) clearly establishes that Congress was interested in examining EPA's ozone design value methodology, not the ozone NAAQS. With this viewpoint, it is possible to delineate the scope of the design value study as an examination of EPA's design value methodology within the framework of the existing ozone NAAQS. Thus, EPA has sought to focus this study on whether the design value serves as a reasonable indicator of attainment status as defined by the current NAAQS, progress in reaching attainment, and of how much concentrations must be reduced to meet the standard.

As required by the 1990 CAAA, the design value study is to consider the extent to which the design value estimation procedure "provides a reasonable indicator of the ozone air quality of ozone nonattainment areas." This issue can be examined in both a temporal and a spatial framework. One issue common to both frameworks is that the "reasonable indicator" evaluation is dependent on the intended application of the design value. It is quite possible that a design value estimation procedure which provides a reasonable indicator for determining the nonattainment category of a small geographic area surrounding a monitoring site may not be suitable for the purpose of estimating the required degree of emission reduction needed to achieve attainment or for the purpose of estimating health risks to nearby populations. Therefore, it is necessary to indicate the intended application of a design value estimation procedure before judging whether it yields a reasonable air quality indicator.

Spatial Representativeness

Currently, design values are estimated individually for each monitor in an area, and the maximum value is used to determine the nonattainment category of the entire area. Thus, the question is "How representative is the design value measured at an individual monitoring site of 'air quality of the nonattainment area' at large?" There is also the issue of whether or not the monitoring network is sufficiently dense to represent air quality over the area in question. This study examines typical spatial distributions of ozone concentrations. Large-scale features can be determined by examining monitoring data. To identify smaller-scale features, it may be necessary to examine spatial concentration distributions calculated by photochemical dispersion models or the results of special, intensive field monitoring programs.

Transport of ozone and ozone precursors generated in one air basin can significantly influence ozone concentrations in neighboring air basins located considerable distances downwind. Title I of the 1990 Clean Air Act Amendments prohibits any activity from emitting pollutants that contribute significantly to nonattainment in another state or interfere with Prevention of Significant Deterioration requirements. The amendments

specifically acknowledge that transport across state boundaries plays a major role during high ozone events in the northeastern urban corridor between Washington, D.C. and Boston. The amendments call for the establishment of a transport commission to study this issue.

Temporal Representativeness

A major concern with respect to the temporal representativeness of design values is the number of years of data used to calculate the value. Current EPA guidance on estimating ozone design values calls for the use of three years of data, if available. As discussed, the use of three years of data is a compromise between the need to include as much data as possible to arrive at an accurate estimate of the underlying expected exceedance rate and the need to limit the number of exceedances allowed in a single year and still have the area remain in attainment. However, year-to-year variations in weather conditions can result in significant differences in estimated design values from one three-year period to the next, even in the absence of emission changes, as shown by McCurdy and Atherton (1990).

Reasonable Indicator Criteria

To judge whether or not various design value estimation procedures provide a reasonable indicator of air quality, criteria for determining what is reasonable need to be developed. In addition to concerns about spatial and temporal representativeness, these criteria must also address issues such as:

Symmetry: This concept is best explained by example. Consider a proposal to incorporate information on the uncertainty in an estimated design value when judging attainment status. If, for an area actually in attainment, the probability of being falsely judged in nonattainment on the basis of the estimated design value is to be considered, then, for an area actually in nonattainment, the probability of being falsely judged in attainment must also be considered, and, conversely, if the probability of a false attainment determination is considered, then so would the probability of a false nonattainment determination.

Consistency/Equity: A design value estimation procedure should be consistent from one area to the next. People in different locations should all receive the level of health protection intended by the NAAQS. Any procedure that results in different treatment for areas with similar air quality problems should be viewed with caution.

Clarity: Technical details of a design value estimation procedure should be sufficiently clear so that there is no ambiguity about how the procedure is to be applied. It is also desirable that the results of the procedure can be easily communicated to the general public.

Other Design Value Issues

Another reference to the use of design values is contained in Section 181(b) of the Act, which states that EPA "shall determine, based on the area's design value (as of the attainment date), whether the area attained the standard by that date." EPA's preliminary interpretation of this Section is that the "average number of exceedances per year shall be used to determine whether the area has attained," which is the attainment test for the ozone NAAQS and not the ozone design value (EPA, 1992). Thus, design values will not be used to make this determination, although for complete monitoring data the two determinations may be the same.

STRUCTURE OF THE REPORT

The remaining sections of this report include:

Section 3. BACKGROUND—background information on the nature of the ozone problem.

Section 4. OZONE DESIGN VALUE METHODOLOGIES—discussion of alternative methods for estimating ozone design values.

Section 5. EVALUATION APPROACHES FOR OZONE DESIGN VALUE METHODS—ambient data base and time series modeling.

Section 6. COMPARISONS AMONG ALTERNATIVE DESIGN VALUE METHODS—comparisons of alternative design value methodologies using the ambient database and time series modeling approach.

Section 7. THE ROLE OF METEOROLOGY IN OZONE FORMATION—an assessment of the impact of meteorology on ozone formation and methods for adjusting ozone trends for meteorological variability.

Section 8. ASSESSING THE ROLE OF TRANSPORTED OZONE AND PRECURSORS—an assessment of the impact of transported ozone and methods for adjusting ozone design values for transport.

Section 9. DETECTING TRENDS IN OZONE DESIGN VALUES—methods for determining trends in ozone design values.

Section 10. ALTERNATIVE AIR QUALITY INDICATORS—a review of alternative air quality indicators and their relationship to ozone design values.

Section 11. PUBLIC OUTREACH EFFORTS—a summary of the public outreach efforts, including public meetings, technical conferences and technical review.

Section 12. SUMMARY OF FINDINGS.

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3 BACKGROUND

In this section, background information on the tropospheric ozone problem is presented to familiarize the reader with the basic technical issues concerning the nature of the ozone problem. Brief discussions are presented concerning the chemistry of ozone formation, the spatial and temporal distribution of ozone, and the relationship of ozone to meteorological conditions. A more extensive review of these topics is provided by NRC (1991).

Ozone is a trace constituent of the earth's atmosphere that is produced in small amounts through natural processes. In the higher atmospheric region known as the stratosphere, a layer of relatively high concentrations (peaking at a mixing ratio of about 12 parts per million or ppm) exists at elevations ranging between about 25 to 45 km. This naturally occurring stratospheric ozone layer serves the vital function of shielding the earth's surface from harmful ultraviolet radiation emitted by the sun. Ozone is also found in smaller amounts within a few kilometers of the earth's surface (the lower troposphere). In remote locations far removed from human influence, these concentrations are quite small (roughly 0.02–0.04 ppm) and of little concern. In and around urban areas, however, relatively high near-surface concentrations are often produced (as high as 0.2–0.3 ppm in Los Angeles, the city with the most severe ozone problem in the U.S.). Exposure to concentrations encountered within and downwind of many major U.S. urban areas is known to produce adverse health effects in humans and is harmful to plant life as well. The following discussion focuses on the characteristics of these elevated tropospheric ozone levels.

Tropospheric ozone is a secondary pollutant. That is to say, it is not emitted directly into the atmosphere. Instead, the elevated ozone concentrations found within and around major urban areas are the result of a complex series of photochemical (light driven) reactions involving two types of precursor gases: nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Both NO_x and VOCs are emitted by transportation and industrial sources. VOCs are emitted from automobiles, chemical manufacturing facilities, dry cleaners, paint shops, and other sources where solvents are used. NO_x is emitted when fuel is burned at high temperatures such as in automobiles or at stationary sources such as utility power plants and industrial steam boilers. Motor vehicles are the single biggest source category of ozone precursors in many urban areas. Natural sources of VOCs and NO_x have also been identified. Under certain conditions, potentially significant quantities of VOCs are emitted by plants, and NO_x may be emitted as a metabolic byproduct of organisms living in the soil. In recent years, much attention has focused on the contribution of such biogenic VOC emissions to the ozone problem in certain parts of the U.S.

Ozone is a reactive gas that can cause health problems because it damages lung tissue, reduces lung function, and sensitizes the lungs to other irritants. Scientific evidence indicates that ambient levels of ozone affect not only people with impaired respiratory systems, such as asthmatics, but healthy adults and children as well. Exposure to ozone for 6 to 7 hours at relatively low concentrations has been found to significantly reduce lung function in normal,

healthy people during periods of moderate exercise. This decrease in lung function often is accompanied by such symptoms as chest pain, coughing, nausea, and pulmonary congestion (EPA, 1993). Studies continue on what length of exposures under what circumstances and to what concentration levels are harmful to humans. Although these studies provide new insights into the effects of exposure to ozone, the ozone design value study mandated by the 1990 CAAA, which is the focus of this report, is based on the current NAAQS. The ozone design value study is not intended to address issues related to the degree of health protection afforded by the current NAAQS.

CHEMISTRY OF OZONE FORMATION

Although a detailed description of the chemistry of ozone formation is beyond the scope of this section, a brief discussion of the basic chemical mechanisms involved is provided to assist the reader in understanding the factors that determine the magnitude and distribution of ozone concentrations and hence ozone design values.

The chemistry of ozone formation is described in detail by Whitten (1990); a general review can also be found in the recent National Research Council Report (NRC, 1991). The brief and simplified description given here presents the most important reactions in ozone formation. First, ozone is created by the photolysis of NO_2, as follows:

$$NO_2 + h\nu \rightarrow NO + O \qquad (1)$$

$$O + O_2 + M \rightarrow O_3 + M \qquad (2)$$

where $h\nu$ represents the ultraviolet light energy input and M is an inert compound. At the same time, however, ozone is destroyed by the NO created in reaction 1:

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad (3)$$

Under steady-state conditions, ozone concentrations would not increase, since one ozone molecule would be created and one would be destroyed for each NO_2 molecule photolyzed. However, ozone accumulates in the atmosphere because another set of reactions involving VOCs can preclude reaction 3 by converting the NO of reaction 1 to NO_2 (which then undergoes photolysis, leading to additional ozone formation):

$$\text{"VOC"} + OH \rightarrow RO_2 \qquad (4)$$

$$RO_2 + NO \rightarrow RO + NO_2 \qquad (5)$$

where R is an organic fragment or hydrogen.

Finally, NO_2, rather than being photolyzed as in reaction 1, may be removed from further atmospheric reactions by the following reaction:

$$NO_2 + OH \rightarrow HNO_3 \qquad (6)$$

An important consequence of these reactions is that reductions in VOC concentrations will always result in reduction of the rate of ozone formation and the peak ozone concentration in a manner similar to that illustrated in Figure 3-1. However, reductions in NO_x concentrations will either decrease or increase the ozone peak at a specific location. The determining factor is the relative probabilities of the reaction of VOC with the hydroxyl radical (the presence of which requires sunlight) and the reaction of NO_2 with the hydroxyl radical. Reactions of VOC with OH lead to the formation of the RO_2 radical, which, in turn, converts the NO portion of the NO_x to NO_2 (reaction 5); it is the photolysis of NO_2 that leads to ozone formation (reactions 1 and 2). However, this same photolysis reaction (reaction 1) also yields NO, which, in turn, might remove the ozone just formed (reaction 3) unless further RO_2 is available to sustain the reactions leading to ozone formation (reactions 5, 1 and 2). Moreover, when NO_2 reacts with OH to form HNO_3 (nitric acid), NO_2 is removed from the ozone formation process (reaction 6).[1]

One approach to understanding the complex behavior of NO_x reductions toward ozone formation, therefore, is to consider the competition between VOC and NO_2 for hydroxyl (OH) radicals, which is represented by reactions 4 and 6, restated again below with their rate coefficients:

$$\text{"VOC"} + OH \rightarrow RO_2 \qquad k_1 = 3{,}100\ \text{ppmC}^{-1}\ \text{min}^{-1} \qquad (4)$$

$$NO_2 + OH \rightarrow HNO_3 \qquad k_2 = 17{,}000\ \text{ppm}^{-1}\ \text{min}^{-1} \qquad (6)$$

The rate coefficient for reaction 4 represents a VOC-weighted average for a VOC mix considered representative of a typical urban atmosphere, i.e., one containing approximately 56 percent paraffinic carbon, 7 percent olefinic carbon, and 21 percent aromatic carbon (Baugues, 1986).[2] It is evident from the rate coefficients for reactions 4 and 6 that the

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[1]It is also useful to note that while VOC, NO_x and sunlight are required to generate ozone, only sunlight (energy) and VOC are consumed when ozone is formed. The amount of ozone formed is proportional to the NO_2:NO ratio; VOC and sunlight govern the magnitude of this ratio. The loss of NO_x (e.g., to HNO_3) does not lead to ozone formation.

[2]For an atmosphere that contains a greater fraction of paraffinic carbon (e.g., alkanes), the weighted-average rate coefficient for reaction 4 would be less, causing the VOC:NO_x ratio, which balances the probabilities of reactions 4 and 6, to be greater. Similarly, an atmosphere that contains more olefinic carbon or aromatic carbon would have a larger weighted-average rate coefficient, causing the VOC:NO_x ratio that balances the probabilities of reactions 1 and 2 to be smaller.

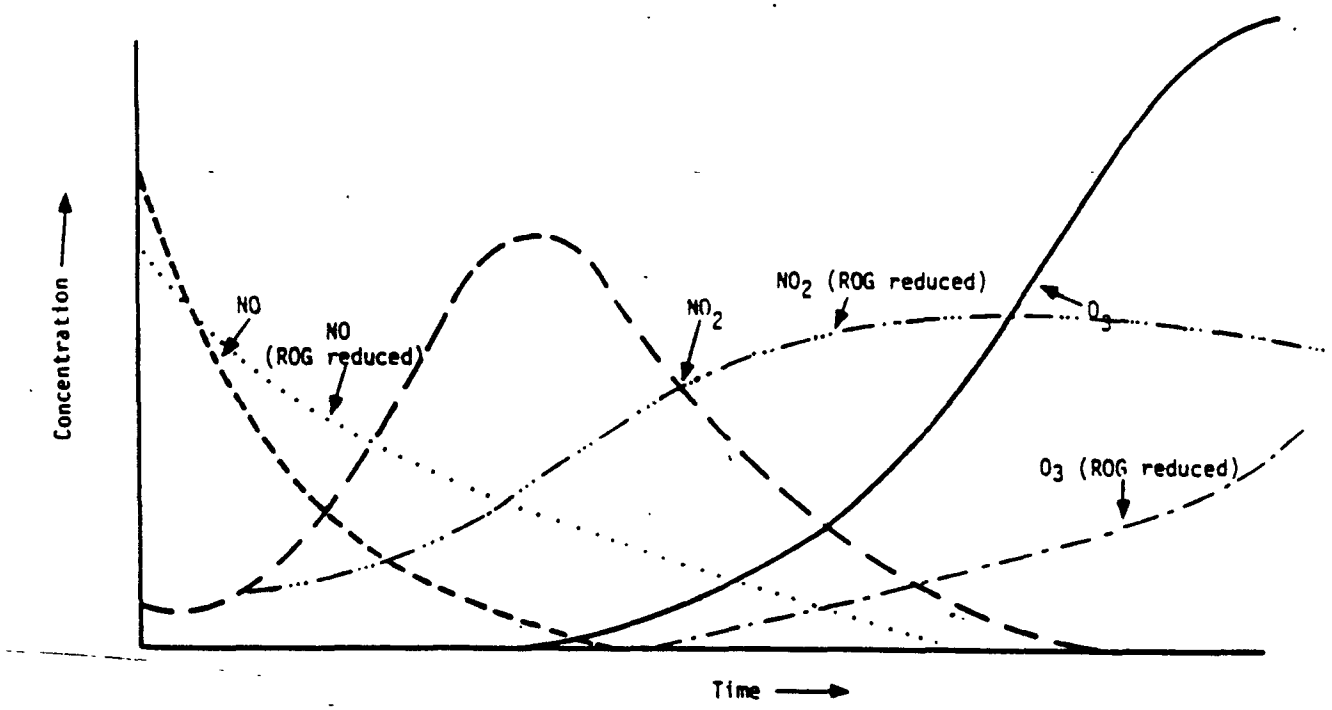

Figure 3-1. Typical base ozone chemistry evolution profiles for NO, NO_2, and ozone, and ozone chemistry with reduced reactive organic (ROG) emissions.

probability per unit time that the NO_2 molecule reacts with OH is approximately 5.5 (=17,000/3,100) times greater than the probability that "average" VOC molecule reacts with OH. Thus, when the VOC concentration is approximately 5.5 times the NO_x concentration, the probability per unit time that VOC reacts with OH is equal to the probability per unit time that NO_2 reacts with OH.

From the foregoing discussion, it can be seen that when the VOC:NO_x ratio is substantially greater than 5.5 reaction 4 is favored. Under these conditions, a shortage of NO exists that can be oxidized by the RO_2 radicals thus formed, such that the probability that these radicals react with each other (to form peroxides) is greater than the probability that they react with NO to produce NO_2, and thus ozone. Under these conditions--large VOC:NO_x ratios—ozone production is limited by the amount of NO_x available; thus reductions in NO_x concentrations lead to reductions in ozone concentrations. However, when VOC:NO_x ratios are approximately 5.5 or less, the ubiquitous NO_x retards ozone formation. Under these conditions, NO_2 reacts faster with the OH to form nitric acid than VOC with OH to eventually form ozone. Reduction of NO_x concentrations under these circumstances increases the efficiency of ozone formation and accelerates the sequence of chemical reactions, which, in turn, can result in increases in the peak ozone concentration.[3] It should be noted that the influence of changes in NO_x emissions on ambient ozone concentrations in urban areas is subject to numerous factors and can only be predicted by application of photochemical grid models.

Before deriving any generalizations from this brief description of the dependence of ozone formation on VOC and NO_x levels, a refinement must be added to the foregoing discussion. The "critical" VOC:NO_x ratio also depends on the duration of the photolytic period (the period in the day with sunlight). When this is taken into account, the critical VOC:NO_x ratio that governs whether peak ozone levels will increase or decrease when NO_x reductions occur changes from approximately 5.5 to approximately 11 (which is approximately equal to the prevailing ratio observed between 6:00 a.m. and 9:00 a.m. at monitoring sites in the Los Angeles basin).

In summary, both theory and experimental evidence show that reductions in VOC concentrations will always reduce the rate of ozone formation and decrease ozone peaks. However, reductions in NO_x concentrations may cause ozone levels to go up or down, depending on the ambient VOC:NO_x ratio.

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[3] The efficiency of ozone formation is increased because the reaction rate that removes the OH radical (reaction 6) is reduced, resulting in more hydroxyl radicals being available to produce RO_2 radicals to oxidize NO to NO_2, which in turn leads to ozone formation. See Figure 3 in Chock and Heuss (1987), which illustrates the location of the 5:1 NMHC:NO_x ratio on so-called ozone isopleth curves.

DISTRIBUTIONAL CHARACTERISTICS OF TROPOSPHERIC OZONE

Monitoring Ambient Ozone Concentrations

Routine observations of urban ozone concentrations were begun in Los Angeles in the 1950s. Today, most major urban areas are served by networks of monitors operated by state and local government agencies and various federal agencies that routinely report hourly ozone concentration measurements. Data collected at most of these monitoring sites are reported to EPA's Aerometric Information and Retrieval System (AIRS) on a regular basis. AIRS serves as a national archive of ambient air quality data.

Each monitoring site is classified into one of three categories: NAMS, SLAMS, or SPMS. The NAMS, or National Air Monitoring Stations, were established to ensure a long-term national network for urban-area-oriented ambient monitoring information and to provide a systematic, consistent database for air quality comparisons and trends analysis. The SLAMS, or State and Local Air Monitoring Stations, were established to allow state or local governments to develop monitoring networks tailored more to their immediate ambient air monitoring needs. The SPMS, or special purpose monitoring stations, are stations used by state or local agencies to fulfill specific, short-term monitoring needs. Figure 3-2 shows the distribution of NAMS, SLAMS, and other ozone monitor types across the U.S. As of 1990, a total of 812 ozone monitors in 467 counties reported data to the AIRS. A total of 590 sites reported data in each year from 1988 to 1990; a total of 471 sites reported data in at least 8 of the 10 years from 1981 to 1990 (EPA, 1991).

Spatial Distribution

Since ozone is formed over a period of hours from a mixture of primary pollutants that are emitted by numerous widespread sources, its spatial distribution is more uniform than that of many primary pollutants such as carbon monoxide. Unfortunately, information on typical spatial gradients in ozone concentrations is limited due to the sparsity of the monitoring network. Of course, concentration gradients decrease as one moves away from major precursor source regions as a result of mixing within the atmosphere.

In discussing the spatial distribution of ozone, it is useful to conceptualize a series of concentric rings encompassing areas of different sizes. Such a conceptual model of ozone distribution—adapted from a recent National Research Council Report (NRC, 1991) in which five canonical regions are identified—is defined as follows:

> Urban Core: Comprises the primary business/commercial district of an urban area; dominated by primary emissions from stationary sources with some mobile source impacts. Ozone concentrations are depressed as a result of NO scavenging and young air mass age.

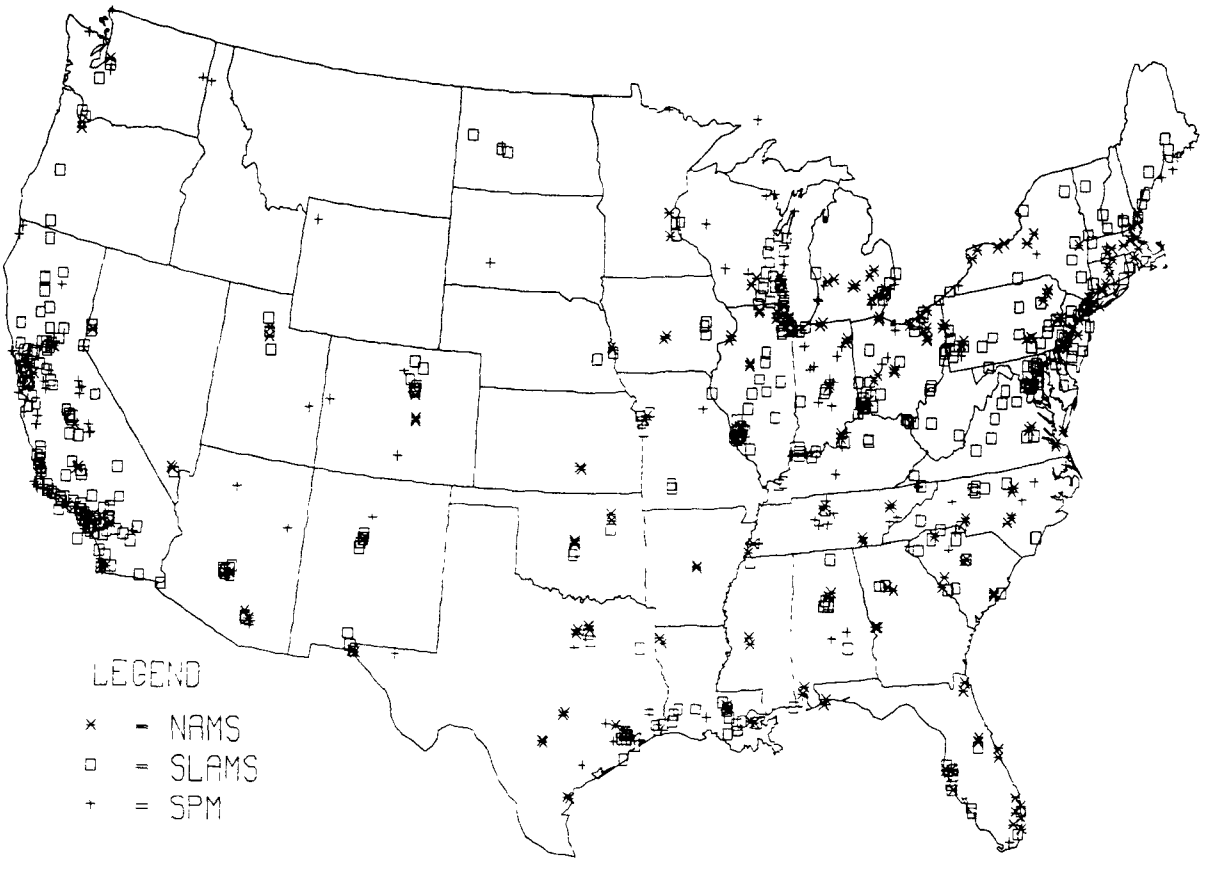

Figure 3-2. Ozone monitoring network in the continental United States, 1990.
Urban Perimeter: Includes the heavily populated area immediately adjacent to the urban core; typically characterized by major transportation arteries and high mobile source emission densities. This area experiences the primary ozone impacts resulting from urban core precursor emissions.

Mesoscale Transport Region: The entire region affected by emissions from one or more urban core areas. This region may be defined by topographical boundaries such as mountains or shorelines. In some cases, it may be defined by the outer perimeter of a major metropolitan area encompassing several urban cores. In other cases, the outer boundary of this region may not be well defined. Under the sluggish atmospheric circulation systems typically associated with high ozone episodes, pollutants emitted in the urban core can stay within the mesoscale transport region for several days at a time.

Synoptic Transport Region: Regions associated with long-range transport of ozone and precursors usually controlled by the synoptic-scale atmospheric flows associated with high and low pressure systems. These systems typically control areas measuring several hundred to a thousand kilometers across—large enough to transport polluted air masses a considerable distance.

Global Background Region: Remote areas far removed from the direct influence of major source regions that are representative of planetary-scale background conditions. Since photochemical pollutants in urban air masses are relatively short-lived, planetary-scale background ozone concentrations are primarily a function of biogenic precursor emissions and stratospheric ozone intrusions (see NRC, 1991 and Lefohn et al., 1992).

Rural locations in the eastern U.S. occasionally experience extended periods of widespread elevated ozone concentrations. On the other hand, western rural ozone concentrations tend to be much lower (NRC, 1991). Exceedances of the NAAQS are generally confined to areas within the mesoscale transport region associated with major urban areas. It is these regions, therefore, that are the primary focus of this report; information on rural ozone can be found in numerous references (e.g., Lefohn et al., 1992, and references therein).

On the basis of both routine ozone observations and tracer experiments, it has been demonstrated that there can be a significant impact of precursor emissions from one urban core on downwind population centers within either the same mesoscale or synoptic-scale transport region but which may be in different topographically or politically defined air basins. For example, it is generally recognized that transport along the urban corridor stretching from Washington, D.C. to New York and Boston contributes significantly to the severity and geographic extent of ozone episodes along the eastern seaboard (Pollack et al., 1988; Cleveland et al., 1976; Wackter and Bayly, 1987; Samson and Shi, 1988; and Possiel et al., 1990). Tracer experiments conducted in California have identified interbasin transport there as well (CARB, 1990).

Within the outer perimeter of a large urban area, distributions of daily maximum ozone concentrations can vary markedly from one location to the next. For example, Figure 3-3 shows the year-to-year variations in the annual second highest daily maximum 1-hour concentrations at monitoring locations in the Los Angeles metropolitan area. On this figure,

a different symbol (letter or number) is used to identify each individual monitoring site. Missing symbols for specific monitoring sites may indicate that either (1) the monitoring site stopped sampling during this period or (2) its symbol may be hidden from view, because only one symbol can be displayed at a given concentration level. In the westernmost (coastal) parts of the Los Angeles basin, average concentrations are low while in the more inland parts of the basin (Glendora/Pomona, downwind of the major urban core source regions), concentrations are higher and variability is greater. Figure 3-4 reveals that the spatial variability among monitoring sites in the basin is similar for the 95th percentile concentrations, but the magnitude of the annual differences is smaller than that found for the annual second maximum concentrations. Figures 3-5 through 3-14 present these same two ozone statistics for five additional Consolidated Metropolitan Statistical Areas (CMSAs); Boston, Chicago, Dallas, Houston, and New York. As these figures illustrate, the relative variation in ozone concentrations recorded among monitoring sites throughout these large urban areas can be as great as or greater than the year-to-year variation in ozone concentrations recorded at a particular monitoring location.

Spatial variations in ozone concentrations at smaller, sub-metropolitan length scales are not well defined in many areas due to the sparsity of ozone monitors. Ambient monitoring data from the Los Angeles basin indicate that concentrations are fairly uniform over distances on the order of 10 km. However, ozone concentrations can be locally depressed immediately downwind of a NO_x source due to NO scavenging (NRC, 1991). Because ozone design values are estimated individually for each monitor in an area, and the maximum value is used to determine the nonattainment category of the entire area, key concerns are (1) whether the monitoring network is sufficiently dense and monitors are appropriately located to represent air quality over the area in question and (2) how spatially uniform are design value estimates across metropolitan areas. Figures 3-15 and 3-16 show, respectively, the spatial variability in 1987–89 ozone design values at all monitoring sites in the four northcentral states of Indiana, Illinois, Michigan, and Wisconsin and for the four northeastern states of Connecticut, Massachusetts, New York, and Rhode Island. As illustrated, design values can vary from levels near the standard to levels near 0.20 ppm at sites across these states.

Temporal Distribution

Seasonal Patterns

Since ozone is formed through photochemical processes, sufficient sunlight is required to produce appreciable quantities. In the latitudinal band covering most of the continental U.S., wintertime solar input is low and cool temperatures reduce reaction rates. As a result, ozone concentrations remain low. It is only between late spring and early fall that the sun is high enough in the sky for enough hours each day and temperatures are warm enough to generate ozone concentrations that exceed the NAAQS. In southern cities such as Los Angeles and Houston, however, exceedances can occur during any month, although they are much more limited during the winter. Several other factors contribute to the summertime

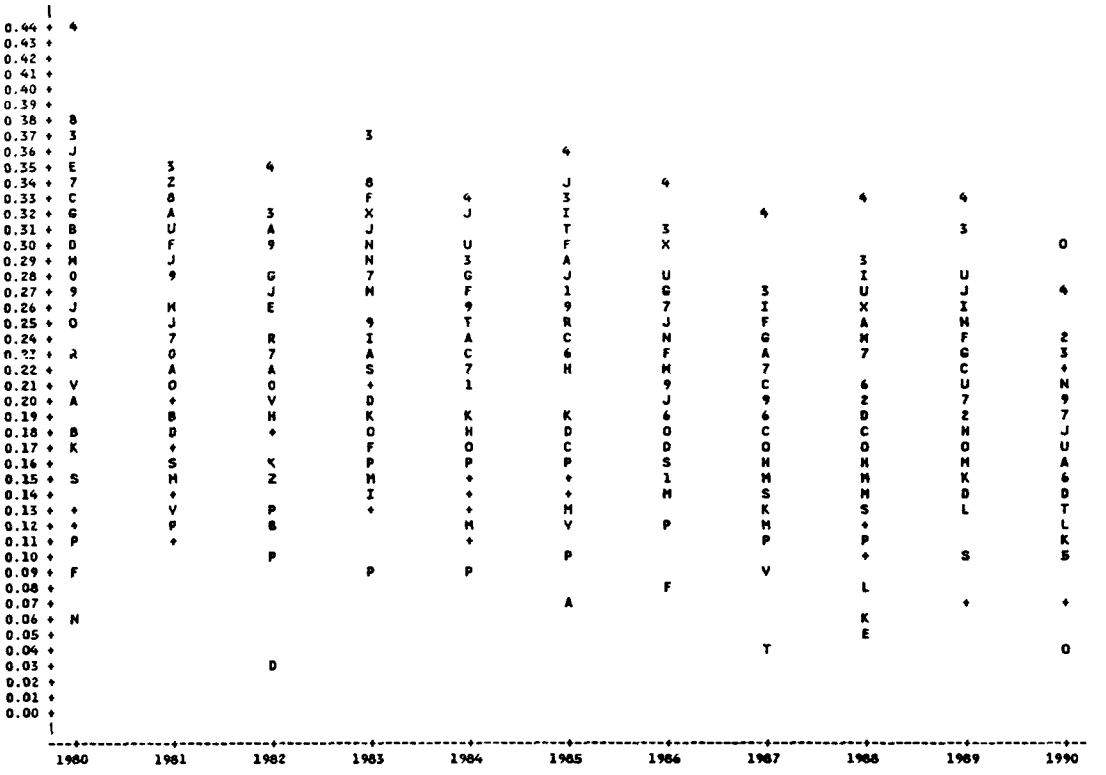

Figure 3-3. Second highest daily maximum 1-hour ozone concentration by year for all sites in the Los Angeles-Anaheim-Riverside, CA CMSA.

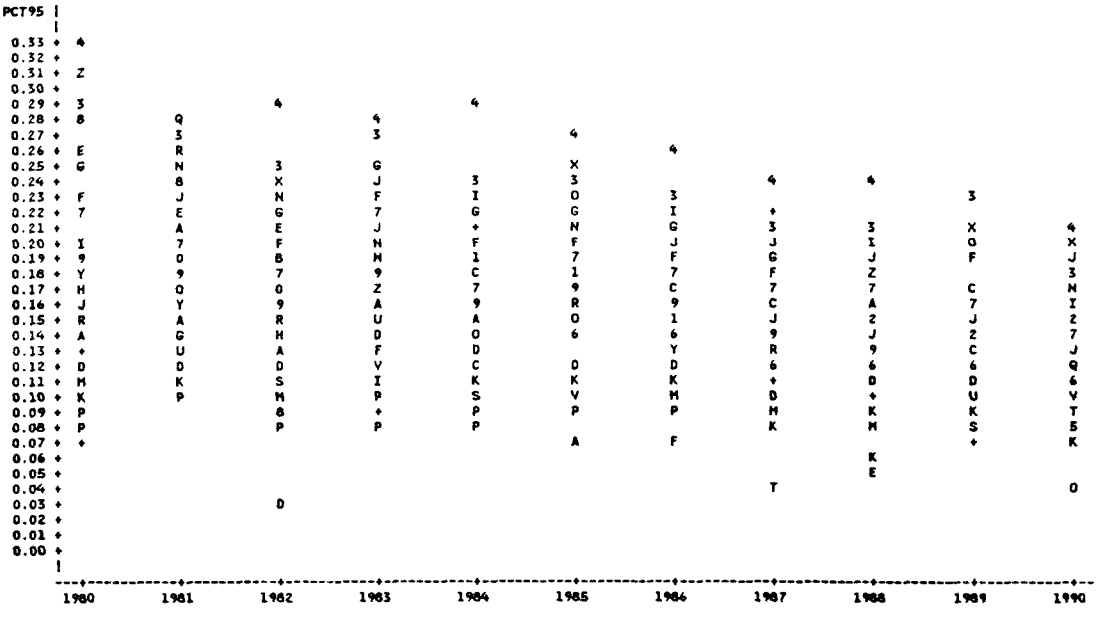

Figure 3-4. 95th percentile ozone concentration by year for all sites in the Los Angeles-Anaheim-Riverside, CA CMSA.

Figure 3-5. Second highest daily maximum 1-hour ozone concentration by year for all sites in the Boston-Lawrence-Salem, MA-NH CMSA.

Figure 3-6. 95th percentile ozone concentration by year for all sites in the Boston-Lawrence-Salem, MA-NH CMSA.

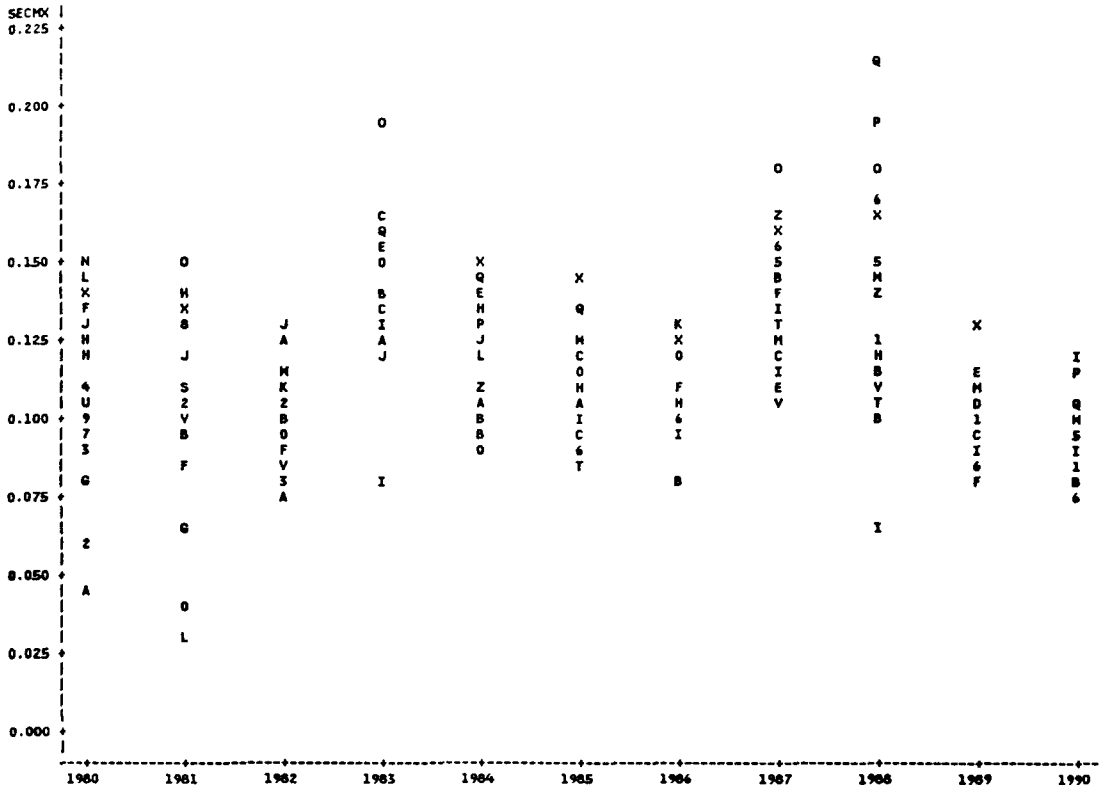

Figure 3-7. Second highest daily maximum 1-hour ozone concentration by year for all sites in the Chicago–Gary–Lake County, IL-IN-WI CMSA.

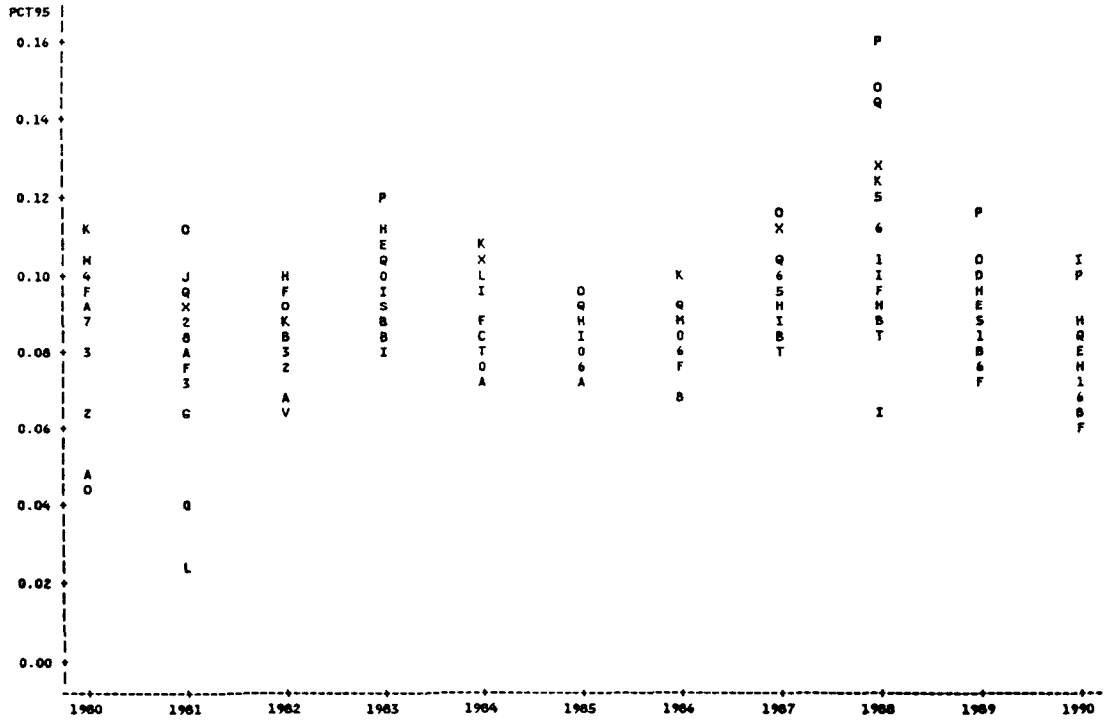

Figure 3-8. 95th percentile ozone concentration by year for all sites in the Chicago–Gary–Lake County, IL-IN-WI CMSA.

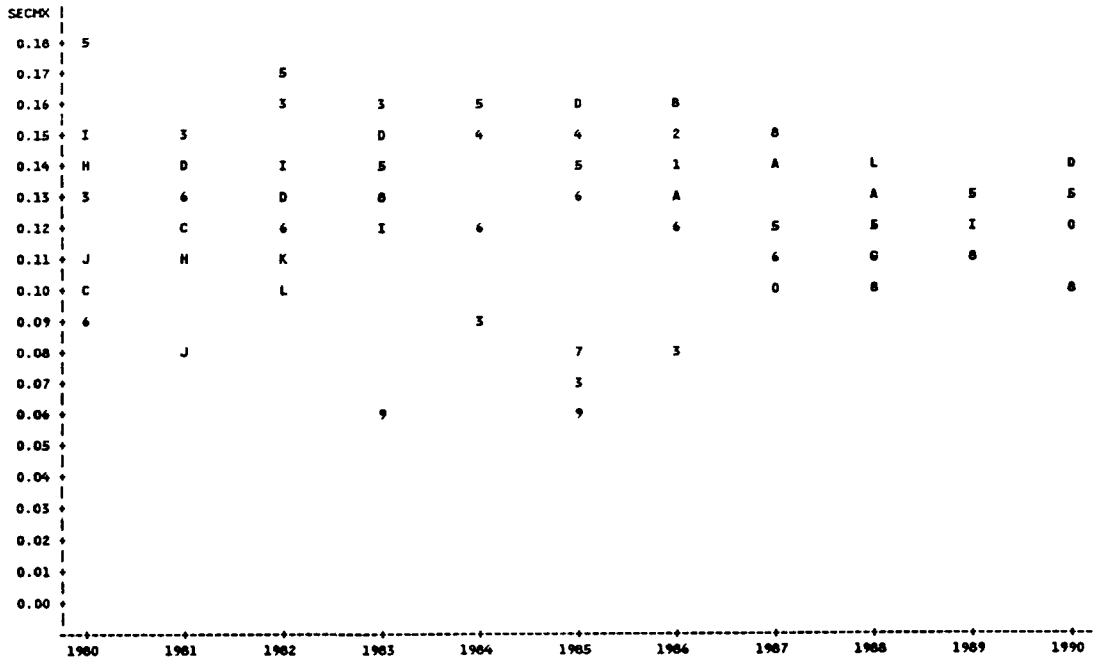

Figure 3-9. Second highest daily maximum 1-hour ozone concentration by year for all sites in the Dallas–Ft. Worth, TX CMSA.

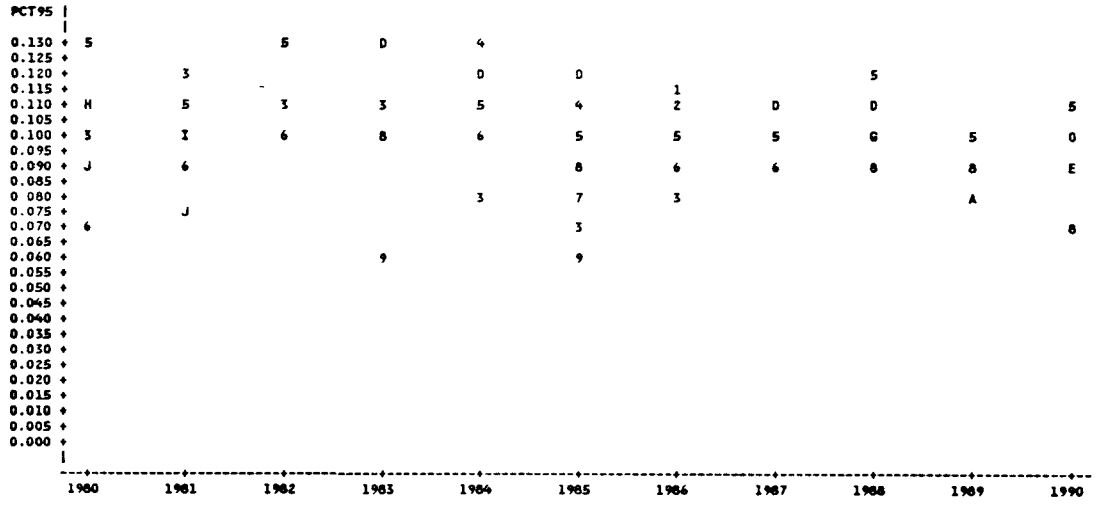

Figure 3-10. 95th percentile ozone concentration by year for all sites in the Dallas–Ft. Worth, TX CMSA.

Figure 3-11. Second highest daily maximum 1-hour ozone concentration by year for all sites in the Houston-Galveston-Brazoria, TX CMSA.

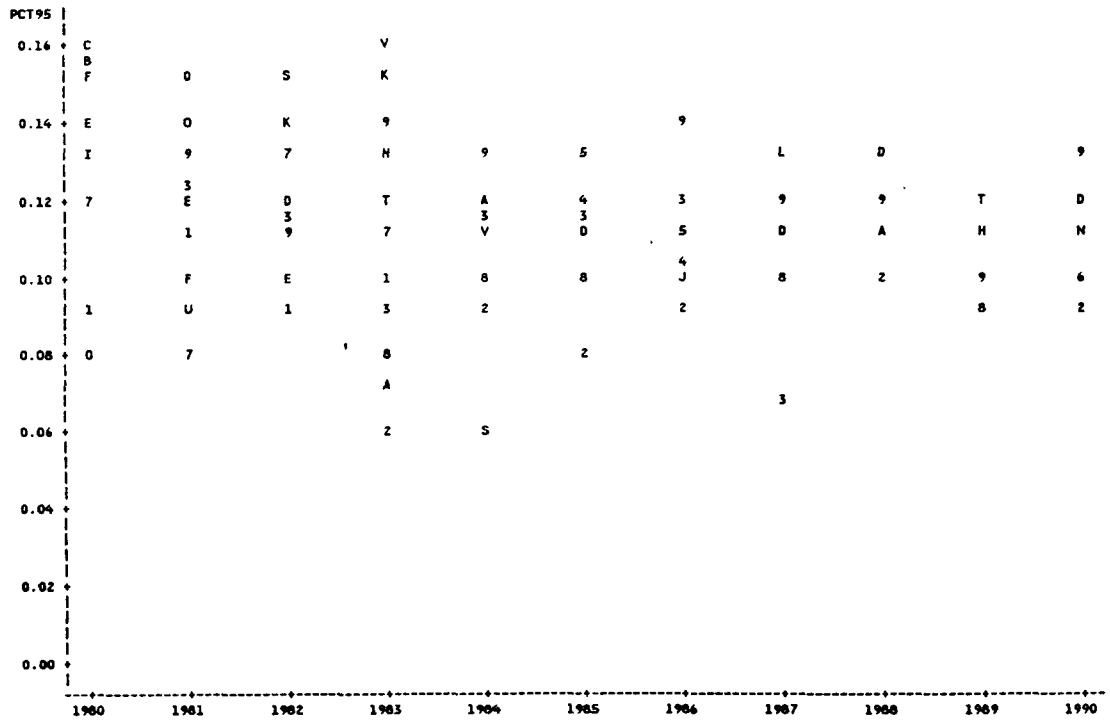

Figure 3-12. 95th percentile ozone concentration by year for all sites in the Houston-Galveston-Brazoria, TX CMSA.

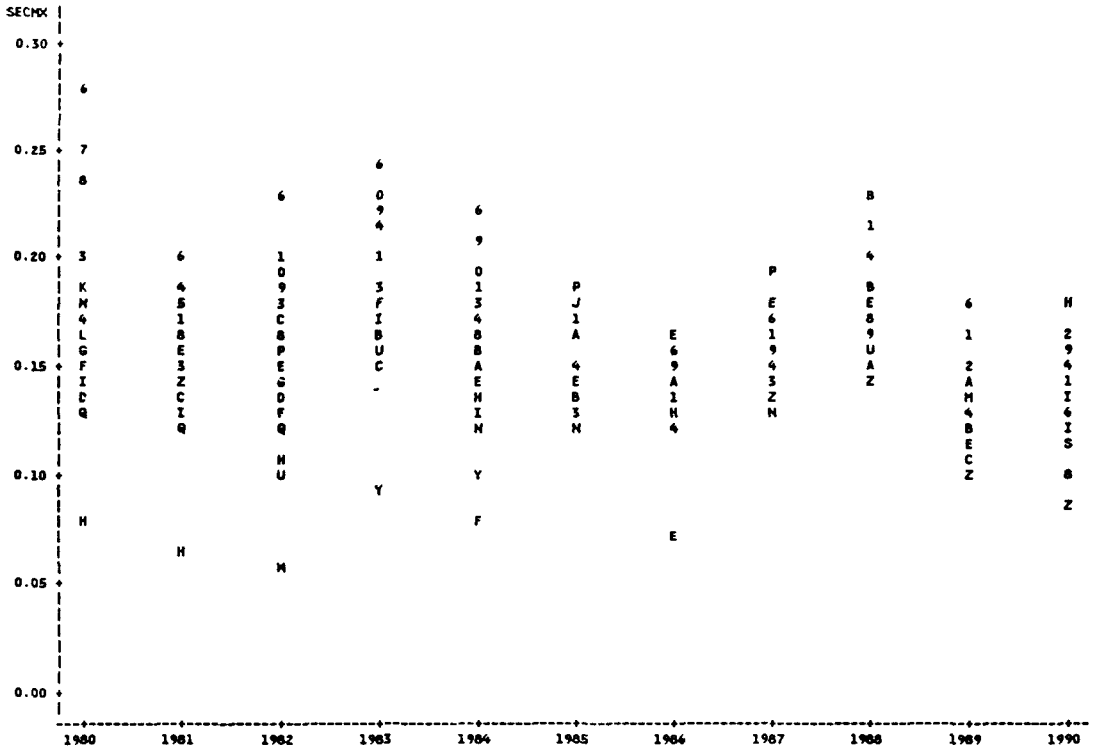

Figure 3-13. Second highest daily maximum 1-hour ozone concentration by year for all sites in the New York–Northern New Jersey–Long Island, NY-NJ-CT CMSA.

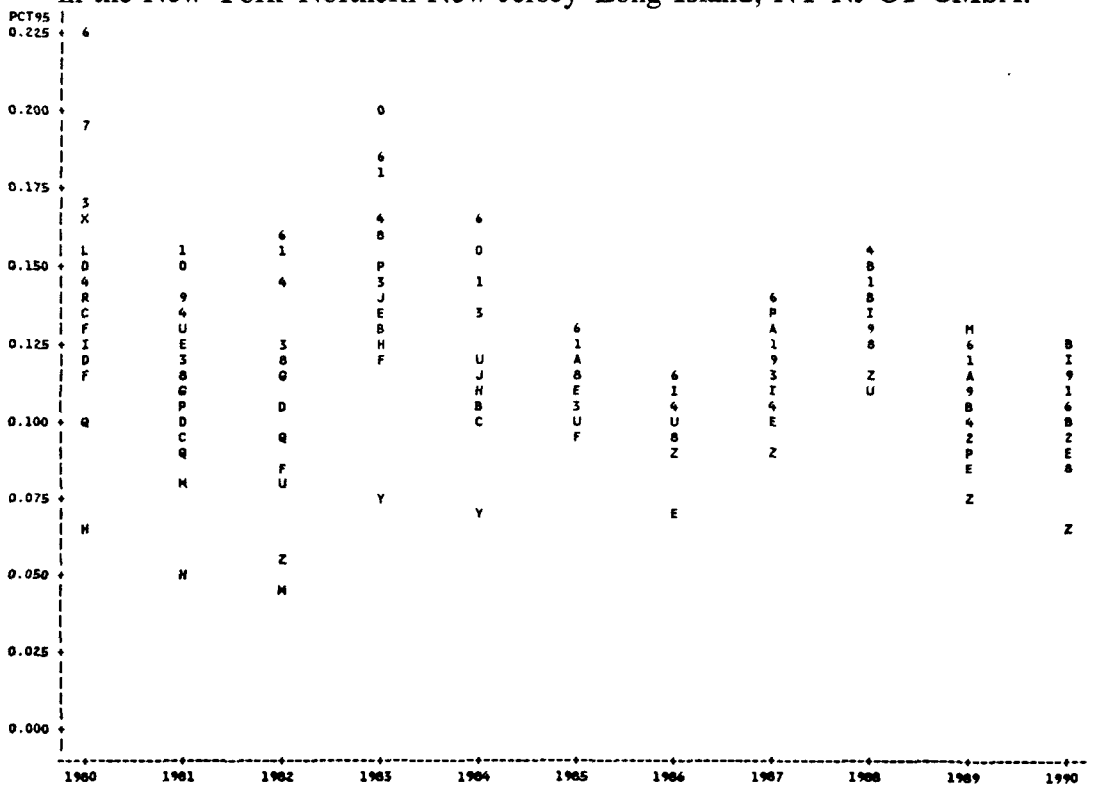

Figure 3-14. 95th percentile ozone concentration by year for all sites in the New York–Northern New Jersey–Long Island, NY-NJ-CT CMSA.

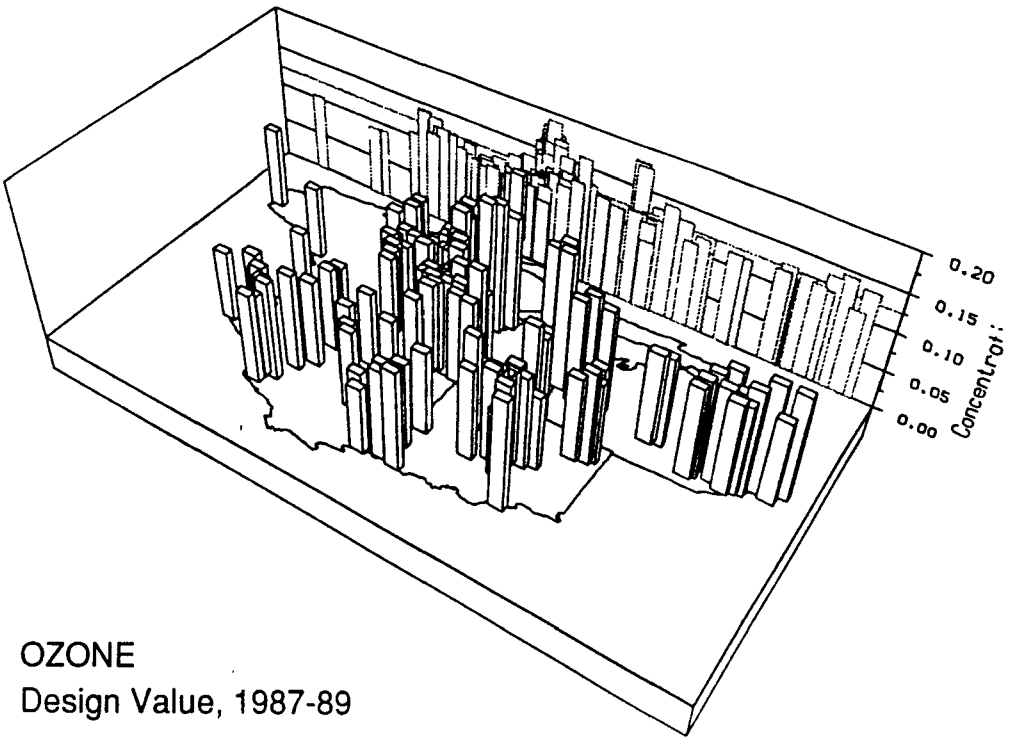

Figure 3-15. Ozone design values at all sites in Indiana, Illinois, Michigan, and Wisconsin, 1987-89.

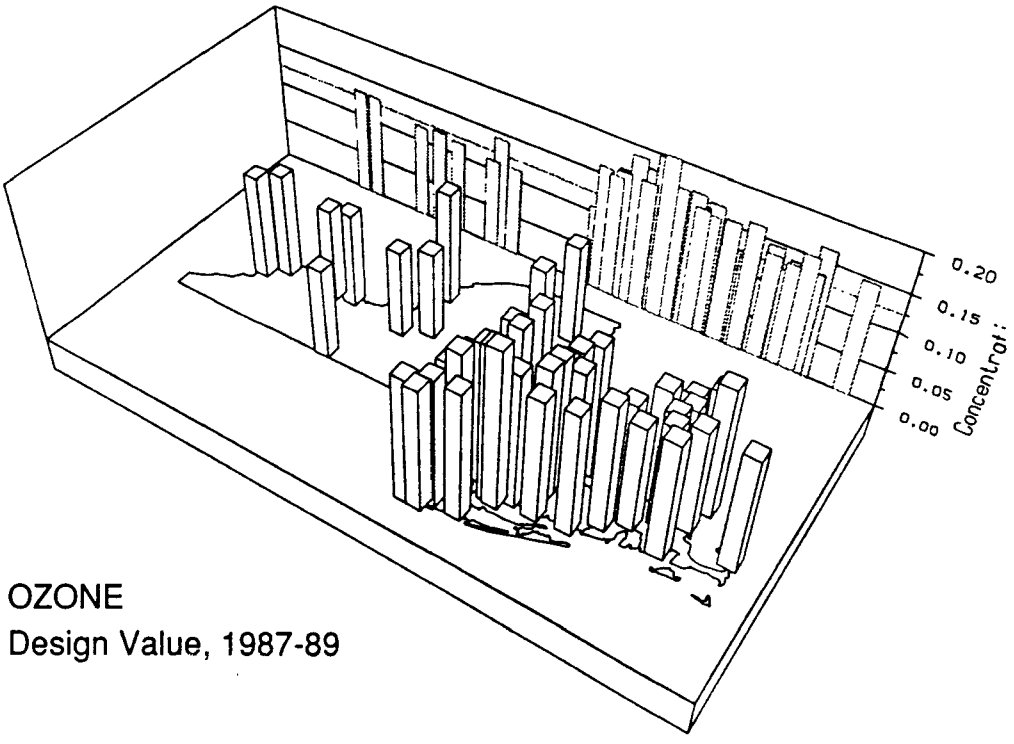

Figure 3-16. Ozone design values at all sites in Connecticut, Massachusetts, New York, and Rhode Island, 1987-89.

ozone maximum, including increased biogenic emissions, increased evaporative emissions from motor vehicles and other sources, and increased fuel combustion required to power air cooling systems that are associated with higher temperatures in some locations. To account for this seasonal ozone pattern and to accommodate differences in local climates, EPA has designated specific "ozone seasons" for each State consisting of a contiguous set of months during which minimal ambient air quality monitoring requirements must be met (see Table 3-1). In southern locales such as Los Angeles and Houston, the official ozone season spans all 12 months, while in northern states such as Montana, the monitoring season spans only the summer months June through September.

Diurnal Patterns

Ozone concentrations in most locations follow a predictable pattern over the course of a day. Maximum concentrations occur in the afternoon when solar radiation peaks and the morning emissions have had sufficient time to react and build up a reservoir of ozone. In some cases, the afternoon maximum may be further enhanced by the downward transport of ozone from aloft as the layer of well-mixed air near the ground thickens during the day in response to increased solar heating of the earth's surface. The ozone being transported down may have formed the previous day and become trapped above the mixed layer during the evening as the amount of mixing decreased after sunset or it may have been transported aloft from other locations overnight.

An ozone minimum is typically observed at night when there is no photochemical production and ozone is lost both through dry deposition (i.e., reaction on surfaces such as vegetation) and reaction with freshly emitted NO. Near strong nighttime NO source regions, sufficient NO may exist to essentially eliminate all ozone in the shallow nighttime mixed layer.

Year-to-Year Variation

Daily maximum ozone concentrations vary widely from one day to the next primarily as a result of changes in weather conditions. Given similar precursor emissions, the basic differences between days when ozone concentrations are average or below average and days when concentrations are high (i.e., episode days) are in the prevailing meteorological conditions. High ozone concentrations are likely to occur with low wind speeds, elevated temperatures, intense solar radiation (i.e., no cloud cover), shallow mixing depths, and the wind patterns that bring, keep, or return high background concentrations to the region. In some years, such meteorological conditions occur more frequently and with greater intensity than in others, leading to a greater number of high ozone days even if precursor emission levels do not differ significantly from those in other years (see Figures 3-3 through 3-14). Thus, design values determined from a single year of data vary in accordance with weather conditions that occurred during the year in question and may or may not be representative of design values that can be expected to occur in the future, even in the absence of any

TABLE 3-1. Ozone monitoring season by state.

State	Begin Month	End Month
Alabama	March	November
Alaska	April	October
Arizona	January	December
Arkansas	March	November
California	January	December
Colorado	March	September
Connecticut	April	October
Delaware	April	October
District of Columbia	April	October
Florida	January	December
Georgia	March	November
Hawaii	January	December
Idaho	April	October
Illinois	April	October
Indiana	April	October
Iowa	April	October
Kansas	April	October
Kentucky	April	October
Louisiana	January	December
Maine	April	October
Maryland	April	October
Massachusetts	April	October
Michigan	April	October
Minnesota	April	October
Mississippi	March	November
Missouri	April	October
Montana	June	September
Nebraska	April	October
Nevada	January	December
New Hampshire	April	October
New Jersey	April	October
New Mexico	January	December

Continued

TABLE 3-1. Concluded.

State	Begin Month	End Month
New York	April	October
North Carolina	April	October
North Dakota	May	September
Ohio	April	October
Oklahoma	March	November
Oregon	April	October
Pennsylvania	April	October
Puerto Rico	January	December
Rhode Island	April	October
South Carolina	April	October
South Dakota	June	September
Tennessee	April	October
Texas AQCR 4, 5, 7, 10, 11	January	December
Texas AQCR 1, 2, 3, 6, 8, 9, 12	March	October
Utah	May	September
Vermont	April	October
Virginia	April	October
Washington	April	October
West Virginia	April	October
Wisconsin	April	October
Wyoming	April	October
American Samoa	January	December
Guam	January	December
Virgin Islands	January	December

precursor emission trends. To some extent, basing design values on three years of data instead of one eliminates some of the meteorological variability, but a single unusual year such as 1988 can still strongly affect the three-year value. Numerous procedures designed to take into account the meteorological component of ozone concentration variability have been proposed. These procedures are reviewed, and a more detailed description of meteorological influences on ozone is provided, in Section 7.

Other Technical Issues

As pointed out by Heuss and Chock (1991), year-to-year variations in the number of exceedance days can introduce significant uncertainty into attainment determinations and design value calculations. For locations that typically record no more than a handful of exceedances each year, the number of exceedances can vary widely from one three-year period to the next even if emissions remain stable. However, an area just in attainment will only have a 23 percent chance of being differently classified in two consecutive years, according to one reviewer's calculations using a Poisson approximation. In theory, these areas could jump in and out of attainment of the NAAQS (i.e., have fewer than or greater than three exceedances in three years) as each new year is incorporated into the running three-year averaging period used to determine the attainment status. In practice, however, areas do not routinely jump in and out of attainment after each new year because (1) there has been a historical pattern of a dominant peak year and (2) that peak year remains in the attainment test period for three years. Javitz (1980) calculated that an area that is just in attainment (i.e., has a true expected exceedance rate of exactly one per year) will experience four or more exceedances (and thus be falsely designated nonattainment according to the attainment criteria described in Appendix H) in 35 percent of all three-year periods. In the past, this has generally not been a major issue since most areas were well above or well below the standard. Of course, this percentage decreases as the true expected exceedance rate drops below one per year. It should also be noted that an area that is just out of attainment (i.e., has a true expected exceedance rate greater than or equal to 1.05) will experience an even more significant number of periods during which the three-year average exceedance rate turns out to be less than 1.05, thus resulting in a false determination of attainment.[4] Using a Poisson approximation, this probability is approximately 61 percent.

Several investigators (Chock and Heuss, 1987; Heuss and Chock, 1991; Chock, 1989; Fairley and Blanchard, 1991) have pointed out that more stable seasonal summary statistics can be formulated, such as the seasonal mean daily maximum concentration or the 90th or 95th percentile of the daily maximum concentration (i.e., the concentration exceeded on 10 percent or 5 percent, respectively, of days during the season). These statistics are based on a larger number of daily observations and are therefore less variable. However, as illustrated

[4] Appendix H includes a rounding convention that requires the estimated expected exceedance rate to be specified to within one decimal place. Thus the minimum estimated expected exceedance rate required for nonattainment is 1.1, which corresponds to a true expected exceedance rate of 1.05 or greater.

by Figures 3-4, -6, -8, -10, -12, and -14, these upper percentiles also exhibit relatively large year-to-year variation in concentration levels. It should also be noted that these other indicators bear no direct relationship to design values for the current ozone NAAQS. Therefore, use of these indicators as design values for ozone nonattainment area designations and classifications would require revision to the current NAAQS and to Section 181 (a) of the CAAA of 1990. For example, Chock (1989) suggested a revised standard requiring the 95th percentile to be less than or equal to 0.095 ppm. The design value for this standard would be the 95th percentile, which could be estimated in a number of different ways. According to Chock, this standard would be "equivalent" in some sense to the current NAAQS. As pointed out by Curran and Freas (1991), however, "equivalency" can be defined in many ways and does not mean that the two standards would result in identical attainment/nonattainment determinations in all cases. In other words, there is no deterministic, one-to-one relationship between design values for the current NAAQS and the 95th percentile that could be used to calculate one given the other. The two design values can only be linked via statistical relationships, which may be inadequate for some locations. If a universally applicable statistical relationship can be shown, then a function of the 95th percentile, rather than the 95th percentile itself, might serve as a useful estimated design value for the current NAAQS.

SUMMARY

This section has provided background information on technical issues associated with the tropospheric ozone problem. The chemistry of ozone formation was described as well as its relationship to emission control strategies. The spatial and temporal characteristics of ambient ozone data were presented and their consequences for estimating ozone design values was discussed.

The past decade has seen large year-to-year variability in ozone concentrations. However, the relative variation in ozone concentrations recorded among monitoring sites throughout large urban areas can be as great as or greater than the year-to-year variation in ozone concentrations recorded at a particular monitoring location. Spatial variations in ozone concentrations at smaller, sub-metropolitan length scales are not well defined in many areas due to the sparsity of ozone monitors.

Finally, the issues raised by Chock and other researchers concerning the attainment test for the current ozone NAAQS and the use of alternative indicators or standards were described.

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4 OZONE DESIGN VALUE METHODOLOGIES

Appendix H to Part 50 discusses how to determine whether the standard is attained and cites the Guideline for Interpretation of Ozone Air Quality Standards (EPA, 1979) as providing additional implementation details. Both Appendix H and the Guideline were issued simultaneously with the National Ambient Air Quality Standard (NAAQS) for ozone when it was revised by EPA in 1979. As discussed in Section 2, the guideline defines the ozone design value in probabilistic terms as that concentration with an expected exceedance rate of once per year. This is referred to in statistical literature as the characteristic largest value (CLV) (Gumbel, 1958). After these discussions on the definition of a design value, the guideline introduced several techniques that could be used to estimate design values. These included a simplified table look-up procedure, different statistical distributions, and the use of a conditional probability approach.

OZONE GUIDELINE DESIGN VALUE METHODS

EPA Table Look-up Method

In 1981, EPA issued the Guideline for the Use of City-specific EKMA in Preparing Ozone SIPS, which used a table look-up approach for selecting the appropriate control estimate as determined from photochemical modeling of peak ozone days (EPA, 1981). The Empirical Kinetic Modeling Approach (EKMA) required that the design value be a concentration that was actually measured in order to obtain the necessary modeling parameters. Thus, the simple tabular procedure shown in Table 4-1 was selected because it gave a design value that was observed, as opposed to a statistical fitting technique that could yield a design value that was not actually measured, but rather a statistical estimate. The tabular approach has several practical, implementation advantages as compared to more complex statistical techniques. First, ozone design value estimates could be made quickly, and directly, from existing ambient data reporting systems. Second, it was understandable by control agency personnel, and the actual ambient air quality values could be reaffirmed through existing quality assurance procedures. Third, the approach could be applied using reported summary statistics which were readily available. This last feature was important given the existing ambient air quality data reporting requirements in the monitoring regulations (40CFR58). The reporting requirements for the State and Local Ambient Monitoring Stations (SLAMS), as specified in the regulations, only require the reporting of the four highest daily maximum 1-hour concentrations, the number of observations, and the number of estimated exceedances in the Annual SLAMS Report. Hourly data were not required to be reported to EPA. Thus, distribution fitting techniques that required daily maximum data were not feasible for such sites. With the advent of newer, automated data reporting and capture methods, most of the hourly ozone data collected in this country are now reported to EPA.

TABLE 4-1. Ozone Design Value Rank Based on Number of Years of Data

Number of Valid Years (at least 75% of days during designated ozone season)	Ozone Design Value Rank (daily maximum 1-hr concentration)
Less than one valid year	Highest daily maximum
1 year of data	2nd highest daily maximum
2 years of data	3rd highest daily maximum
3 years of data	4th highest daily maximum

During the late 1980s in support of the Clean Air Act debate, EPA issued ozone design value lists that continued to use this tabular technique (EPA, 1987, 1988, 1989, 1990, 1991). On June 18, 1990, EPA issued a memorandum documenting the table look-up approach as the EPA design value estimation method (Laxton, 1990). This policy memorandum essentially maintained the status quo and documented the tabular approach shown in Table 4-1 as the EPA design value method. The memorandum provided specific example calculations and clarified several technical details. It restated that air quality design values are estimated on a site-by-site basis, and that the design value for the "area" is the highest design value estimated at any site within the area. This was the last EPA policy statement issued prior to passage of the CAAA of 1990.

Use of Statistical Distributions

This section contains a review of important articles dealing with the fitting of statistical distributions to air quality data. Appendix A contains a quick reference tabular summary of each numbered reference which appears in brackets "[ ]". This section also summarizes the parametric distributions fitted to the data, the fitting method, and the applicability of the method to the current ozone NAAQS.

The Ozone Guideline (EPA, 1979) allows the use of fitted distributions to calculate design values, provided that the fit is acceptable. In this case, the design value is often estimated as the $100 \times 364/365$th percentile of the distribution of the daily maximum since that value is exceeded an average of once per 365 days (assuming that the distribution is the same throughout the year). In general, if the parametric distribution is correct, or a very good approximation to reality, then the use of the fitted distribution is likely to lead to better estimates of the expected number of exceedances, and of the design value, than estimates using the empirical distribution (raw data). As in the case of the tabular design value approach, design values estimated from ambient monitoring data by this statistical modeling approach may be less than the level of the standard even though the area has failed the attainment test based on estimated exceedances. However, in contrast to the tabular

approach, these statistical methods can also yield design values that are greater than the NAAQS even though the area has an expected exceedance rate less than or equal to 1.

There are two distinct approaches to fitting distributions to air quality data. In the first, one of the standard parametric distributions, such as the lognormal distribution, is fitted to the raw concentrations. The second approach is based on extreme value theory, which uses the fact that if we have a large number of approximately independent measurements with approximately the same distribution, there are only three types of limiting parametric distributions for the highest concentrations (maximum, second maximum, etc.) and for the upper tail of the distribution. The limiting extreme value distribution depends on two or three unknown parameters.

Both approaches (fitting parametric distributions to raw hourly or daily concentrations, or fitting extreme value distributions to the highest concentrations) assume weak serial dependence and only small trends in the raw concentration data (i.e., approximate stationarity). Weak serial dependence means that two consecutive daily maximum concentrations may be highly correlated, but daily maxima separated by a long time interval are almost independent. The proviso of "small trends" means that the distribution, and in particular the mean, of the daily maximum is almost constant in time. Alternative approaches that directly take dependence and trends into account are described elsewhere in literature reviews of time series and trend modeling.

The extreme value theory approach is particularly important for ozone NAAQS issues because it focuses attention on the extreme (maximum) concentrations that are primarily responsible for determining the design value. Furthermore, the applicability of the extreme value approximations across a variety of raw concentration distributions, even in the presence of serial dependence (Leadbetter et al., 1983) and small trends, is an advantage over approaches that fit parametric distributions to the raw data or that use the observed concentration distribution. The main limitation of the theory is the requirement for large numbers of raw concentrations, or for only using those concentrations in the extreme upper tail of the distribution. In particular, use of the extreme value distribution for the annual maximum is based on applying the asymptotic theory to 365 daily maxima instead of an infinite number (assuming a 365-day ozone season). It is possible that 365 (or the length of the ozone season) may not be large enough for the extreme value approximation to be sufficiently accurate since convergence to the limiting extreme value distribution is typically very slow (see, for example, Cohen, 1982). However, Cohen (1982) demonstrated that in many cases a much better approximation can be obtained using the three-parameter extreme value distribution rather than the two-parameter extreme value distribution (Gumbel) even if the Gumbel distribution is the theoretical limiting distribution. Furthermore, the fitted distribution may give an even better approximation than the theoretical limiting distribution using the shape parameters calculated for an assumed raw concentration distribution.

Given this literature review, including the reported goodness-of-fit results, a growing consensus appears to favor the use of the tail exponential distribution to fit the annual

maximum hourly ozone concentrations. The use of the lognormal distribution to fit the hourly and, possibly, daily maximum hourly ozone concentrations is another popular method. This discussion primarily focuses on these two statistical distributions. Other statistical distributions that have been used for air quality data include the normal, gamma, Weibull, beta, powers of normal distributions (Box-Cox transformations), and exponential distributions. A comparison of distributions for hourly ozone data in Wisconsin ([4]) found that the lognormal distribution fit best. A comparison for daily mean ozone concentrations in Australia ([15]) found that the gamma distribution fit best. In any case, the selection of a "best" statistical distribution for calculation of ozone design values may not be possible because such a distribution probably varies according to the location studied and the time period of interest.

Fitting Methods

The first step in fitting statistical distributions to air quality data is the selection of the parametric family. The second step is the fitting method in which the specific distribution in the family that best fits the available data is selected. The specific distribution is usually defined by specific values of location, scale, and/or shape parameters. For example, the selection of a lognormal distribution defines a family of distributions with different location and scale parameters. The maximum likelihood method ([4, 8, 9, 10, 12, 14, 15, 16, 19, 20, 21, 22, 25]) has certain well-known optimal properties, particularly when the number of observations is very large. In this method the values of the parameters are selected so as to maximize the joint density at the observed data values (very roughly speaking, the probability of obtaining the observed concentrations). A less powerful but often simpler approach is the method of moments ([9, 10, 16, 26]) in which the sample moments (means, variances, etc.) are matched to the theoretical moments based on the fitted parametric form. A similar method is the method of quantiles, in which the sample quantiles or percentiles (median, 90th percentile, etc.) are matched to the theoretical quantiles ([1, 2, 7, 9, 10, 11, 13, 16, 17, 24]).

In many cases the fitted distribution can be transformed so that the unknown parameters are scale and location parameters. The method of quantiles is then equivalent to creating a probability plot for the transformed distribution and fitting a straight line. For example, the lognormal probability plot is usually created so that one axis contains the concentrations plotted on a logarithmic scale and the other axis contains percentages (or probabilities) plotted on a scale that converts the percentage $100p$ to the value x that is the corresponding standard normal percentile (i.e., the value x such that $100p$ percent of values from a standard normal distribution are less than x). Essentially, the ith highest concentration is plotted against the probability i/n. Improved fits can be obtained by using alternative plotting positions to i/n (see Cunnane, 1978). The optimal plotting position for the ith highest concentration depends on the statistical distribution to be fitted and the properties required of the parameter estimates. Cunnane (1978) shows that replacing i/n by $(i - \alpha)/(n + 1 - 2\alpha)$, with $\alpha = 3/8$ for the normal case and $\alpha = 0.44$ for the exponential

or Gumbel (extreme value) distributions, gives approximately unbiased minimum mean square error estimates for quantiles.

The method of fitting two quantiles ([1, 2, 9, 10, 24]) is based on drawing a line through two points on the probability plot to estimate the scale and location parameters. Some of the investigators fitted the straight line using least squares to more than two quantiles ([13, 16]), or to all the quantiles ([7, 11, 17, 24]). An approach that uses a plot of the distribution function rather than the inverse distribution function is described in paper 24.

In general, selection of the fitting method is less crucial to the ultimate use of the results than selection of the parametric form. A problem that is common to all of the methods described in the cited papers is the use of the inherent assumption that all the observations used in the distributional fit are independent and identically distributed. (The maximum likelihood method does not explicitly require these assumptions, but all of the reviewed articles that used maximum likelihood methods also used these two assumptions in deriving the likelihood function.) Alternative methods that allow for nonstationarity and dependence are discussed in the time series and trends literature reviews. Because ozone design values are expressed in terms of concentrations in the upper tail of the distribution (i.e., extreme values), it is reasonable to assume that the applications that fit the concentration distribution to the entire hourly concentration data will be less consistent with the ozone NAAQS than are the applications that fitted the distribution to the upper tail only. (Extreme value theory shows that the limiting distribution of the highest values depends only on the extreme upper tail of the distribution.) However, the accuracy of the fitting method decreases if fewer upper tail concentrations are used. Thus for the purpose of estimating design values, the maximum likelihood method, least-squares fitting to all quantiles method, and the method of moments should be applied only to the upper tail of the hourly concentrations rather than the complete set of concentrations. Furthermore, it is appropriate that the quantile method be applied to the high rather than the low quantiles.

Lognormal Distributions

The pioneering papers by R. Larsen ([1, 2]) describe how the lognormal distribution appeared to fit air pollutant concentration data for a wide variety of cities, pollutants, and averaging times. Furthermore, Larsen found empirically that the median and annual maximum were proportional to powers of the averaging time, and hence was able to derive formulae to convert medians and annual maxima between two different averaging times.

Several authors have criticized the Larsen paper. In particular, Patel ([3]) commented on the invalidity of the independence assumption. Patel also commented on the invalidity of Larsen's equating the expected log maximum with the log expected maximum, which Larsen used to derive the conversion formulae.

Perhaps the most crucial issue is the inconsistency of Larsen's approach caused by the fact that if the distribution is lognormal for one averaging time, and if the concentrations are independent, then the distribution for a longer averaging time cannot theoretically be lognormal. One resolution of this issue is to argue as in Larsen's response to Patel ([3]) that Larsen's results are just simply observations about the approximate behavior of air quality data and are not intended to provide a theoretical model. A second response is found in the paper by Bencala and Seinfeld ([17]) in which the lognormality of CO data is derived assuming a lognormal wind speed distribution. Further, we have found arguments made in several papers not included in this survey that the concentrations can be thought of as products of a large number of independent variables, which implies a limiting lognormal distribution by the central limit theorem (see, for example, some of the papers and discussions in EPA (1974)).

A most interesting treatment of this problem appears in the article by Mitchell ([18]), in which a lognormal distribution is shown to fit averages of a small number of independent lognormal concentrations better than the normal distribution. One reason for this effect is probably that although the central limit theorem implies the normality of an average of a large number of independent lognormal concentrations, for small samples the lognormal distribution is better at fitting the skewness of the distribution of the average. (The average cannot be symmetric since it ranges from 0 to plus infinity.) In practice, another reason for this may be the effect of autocorrelation: Bencala and Seinfeld ([17]) give an example to show the approximate lognormality of the average of correlated lognormal concentrations.

One difficulty with the lognormal distribution is the problem of estimating the moments (such as the mean) of the lognormal concentrations from the parameters of the normal distribution fitted to the logged data. If the concentrations are lognormal, then the obvious approach is to exponentiate the mean of the log concentrations, which gives the geometric mean concentration. However, it is shown in [22], for example, that the geometric mean is biased for the true mean concentration. An unbiased estimate would be given by the arithmetic mean concentration, but this estimate does not use the assumed lognormality and is not the best (minimum variance unbiased) estimate.

Extreme Value Theory Approximations

The theory of extreme values (see [6], [7], and the textbooks cited in the reference section) stems from the result that if we have a large number of approximately independent measurements with approximately the same distribution, then there are only three types of limiting parametric distributions for the highest concentrations (maximum, second maximum, etc.). In particular, the limiting distribution of the maximum is either the two-parameter Gumbel distribution or the three-parameter Type II or Type III extreme value distribution. This result provides theoretical support for the use of one of these extreme value theory distributions to fit the annual maximum hourly ozone concentration distribution. Similar extreme value distribution limits apply to the second maximum, third maximum, ... and kth maximum, where k is small. However, it is important to keep in mind the distinction

between the kth highest hourly value and the kth highest daily maximum hourly value. The latter value is more relevant to the present ozone NAAQS.

The papers by Georgopolis and Seinfeld ([9]) and by Johnson and Symons ([13]) present a hybrid approach in which the lognormal or Weibull distribution is fitted to the hourly or daily maximum hourly concentrations and then extreme value theory is applied to estimate the distribution of the annual maximum. The main problem with this approach is that it fails to take advantage of the general applicability property of extreme value theory under which, for a general daily maximum distribution, the limiting distribution of the maximum is restricted to only the three extreme value distributions. This result applies even under mild departures from the independence ([23], Leadbetter et al. (1983)) and identical distribution assumptions. In fact, Leadbetter et al. (1983) showed that under quite strong local dependence (between measurements at most a few days apart), the same limiting distribution applies, although the shape parameters may be shifted. An alternative approach that uses the general applicability property (because it does not use any specific distributions for the daily maximum concentrations) is to directly fit the extreme value distribution to the annual maxima.

Tail Exponential and Related Approaches

An extreme value theory approach that takes advantage of the general applicability property is presented in several papers ([12], an important and frequently cited paper describing original work by Breiman and others performed under contract to the Environmental Protection Agency, and [14], [19], [20], [21], and [25]). These papers use the result that the limiting tail distribution can only be one of three distribution functions known as the family of Generalized Pareto Distributions (GPD--the limiting distribution of the concentrations that exceed a given threshold as the threshold increases). The most commonly used member of this family is the tail exponential distribution, which corresponds to the Gumbel distribution in the first classical extreme value theory approach. The tail exponential extreme value theory approach takes the highest 5, 10, or 20 percent of the daily maximum concentrations and fits an exponential distribution to those concentrations above the corresponding concentration threshold c, the 95th, 90th, or 80th percentile of the entire daily maximum concentration data set. The exponential distribution has the probability density $\alpha \exp\{-\alpha (x - c)\}$. No assumption is made about the distribution below c. The estimated value of α using the maximum likelihood method is the reciprocal of the mean upper tail concentration. Given the tail exponential distribution, the expected number of exceedances per year of the ozone NAAQS is 365 (0.05) [exp $\{-\alpha (0.125 - c)\}$], assuming a 365-day ozone season, a 5 percent upper tail fit, and assuming that 0.125 exceeds the 95th percentile of the daily maxima (i.e., the upper tail threshold). The term in the single brackets is the probability of exceeding 0.125 given that c is exceeded, and 0.05 is the probability of exceeding c. The exceedance threshold used is 0.125 ppm rather than the 0.12 ppm ozone NAAQS since the rounding convention in Appendix H specifies that an exceedance occurs only if the concentration is greater than or equal to 0.125 ppm.

A major advantage of the tail exponential or tail GPD approach is that much more of the data can be used than, say, the annual maxima. The approach has general applicability analogous to those of the classical theory. The crucial choice is the selection of the high concentration threshold, or, equivalently, of the percentage of observations in the tail used to fit the tail exponential (or GPD). Several authors have found fairly good results using the upper 5, 10, or 20 percent tails. Larsen and others ([19, 20, 25]) have used an approach that combines estimates for a range of tail percentages between 5 and 20 percent, either using a simple average ([19]) or using a weighted average that gives greater weight to the better fitting tail exponential distributions ([20]).

Since the GPD includes all the limiting tail distributions, the tail GPD approach may be more robust although the application is more complex than for the tail exponential. Smith ([21]) fit the GPD to 72-hour ozone maxima that exceed the selected thresholds; such an approach takes into account clustering of daily maxima due to very strong serial correlations. A more theoretical study of clustering was given by Leadbetter (1991).

Conditional Probability Approach

The conditional probability approach is described in the Ozone Guidelines (EPA, 1979). This approach is an alterative to the approach of fitting a single distribution to all data collected during the attainment period. Suppose that the attainment period is N years (typically $N = 3$). A statistical distribution is selected and fitted for each year separately using the approaches described earlier in this section. If $F_i(x)$ is the distribution fitted to the ith year of data, and if each year gets equal weight, $1/N$, then the distribution fitted to all N years is

$$F(x) = \sum_{i=1}^{N} F_i(x)/N.$$

The conditional probability approach design value is the solution of the equation $F(x) = 1/365$, which would usually have to be solved by an iterative process.

The same approach could be applied to an even finer subdivision of the attainment period (e.g., into quarters rather than years), which would lead to a larger value of N. One advantage would be that ozone trends within a year could be accounted for. A disadvantage would be that there may be insufficient monitoring data to accurately estimate $F_i(x)$.

A more complex version of the conditional probability approach assumes that the daily maximum ozone distribution is different for different meteorological classes and that the frequencies of the different meteorological classes are known (either the observed frequencies or the expected frequencies according to an appropriate model may be used). It then follows that

$$F(x) = \sum_{i=1}^{K} F(x|class\ i)\ P(class\ i)$$

where $F(x|\text{class } i)$ is the estimated daily maximum ozone distribution for the ith meteorological class and $P(\text{class } i)$ is the relative frequency for the ith meteorological class. The design value would be estimated by iteratively solving the equation $F(x) = 1/365$.

OTHER DESIGN VALUE APPROACHES

California Method for Computing Recurrence Rate Values

The tail exponential approach of Larsen and others ([19, 20, 25]) was developed primarily to implement criteria in the 1988 California Clean Air Act specifying conditions under which highly irregular or infrequent violations of the state ambient air quality standards could be excluded from the attainment/nonattainment designation process. In June 1990, the California Air Resources Board determined that exceedances of the California ozone standard expected to recur less frequently than once in seven years could be excluded. More recently the Board determined that exceedances expected to recur less frequently than once in one year could be excluded. The tail exponential approach was proposed as a method of estimating the one-in-one-year or one-in-seven-year concentration. In [19], the proposed approach used the methods of Breiman and others ([12]) described above to estimate the one-in-seven-year concentration (based on three years of data) for approximately 166 different exponential tails, corresponding to all possible upper tail percentages from the top 5 percent (55 values) to the top 20 percent (220 values). If the exponential tail probability density is $\alpha \exp\{-\alpha(x - \text{threshold})\}$ corresponding to a $100p$ percent upper tail, then the estimated one-in-seven-year concentration for that upper tail is threshold + $(1/\alpha)\log(7(365)p)$ assuming a 365-day ozone season. The implementation in [19] used the simple average of the 166 one-in-seven-year concentration estimates to give the overall one-in-seven-year concentration estimate.

The one-in-seven-year-concentration estimate in [19] ignores the fact that the goodness of fit of the exponential tail model varies with the size of the upper tail. The goodness of fit is affected partly by the overall accuracy of the exponential tail model and partly by the accuracy of the parameter estimates. The exponential tail assumption is an approximation that can be assumed to be more accurate for the more extreme upper tails.[1] The precision of the exponential tail slope parameter increases with the number of observations in the upper tail. It follows that the goodness of fit for a given upper tail percentage is a compromise between the competing errors of the exponential approximation

[1] This assumption is based on extreme value theory, which applies if the daily maximum concentrations can be assumed to be approximately independent and identically distributed with a common distribution that has the appropriate exponential type tail behavior; possible common distributions include the normal and lognormal distributions.

(generally improving with lower upper tail percentages) and of the parameter estimates (improving with higher upper tail percentages). However, McGuire (1994) pointed out that in some cases, the higher upper tail percentiles actually produce better fits to the data than the lower percentages.

The approach in [20] uses a weighted average of the 5 to 20 percent tail exponential estimates of the one-in-seven-year concentration. Each tail exponential estimate of the one-in-seven-year concentration is weighted by the inverse of the corresponding chi-square goodness-of-fit statistic. The chi-square goodness-of-fit statistic is based on partitioning the tail into 10 classes with equal expected frequencies and comparing the observed and expected frequencies. Another modification in [20] of the implementation in [19] was the use of the threshold estimate given by the average of the lowest five tail concentrations and the four concentrations just outside the tail, instead of using the corresponding upper tail percentile (estimated as the highest concentration not included in the upper tail). Although the ideas of giving greater weight to better fitting models and using more than one concentration value to estimate the upper tail percentile are intuitively sound, it should be noted that no theoretical justification is provided in [20] for the particular procedures used.

EPA Tabular Method Extended to Multiple Years

EPA guidance specifies that the three most recent years of ambient ozone monitoring data be used to determine compliance with the ozone NAAQS and to estimate ozone design values. One possible way to reduce the year-to-year variability of the ozone design value estimates is to lengthen the "data window" used with the tabular procedure. The "number of years plus 1" rule is easily extended to more than 3 years, i.e., the design value for 4 years of data is simply the fifth highest daily maximum 1-hour concentration.

While design value estimates based on more years of data may be more stable over time, they also are less responsive to underlying changes in the distribution of ozone concentrations. Nationally, the peak ozone years were 1980, 1983, and 1988. Thus, design values based on the three-year period 1984–86 show much greater decreases in ozone concentrations than 4-, 5-, or 6-year design values which incorporate ozone data from 1983. Conversely, design value estimates based on a longer time period may not increase as much as those based on fewer years of data whenever a peak ozone year occurs. If design values are based on periods longer than three years, a decision may have to be made on the representativeness of design values estimates from monitoring sites that had not operated for several years.

Control Strategy Design Values

Beginning in the 1970's, air quality design values were used as the primary input to simple air quality models, such as the "rollback model" and the Empirical Kinetic Modeling Approach (EKMA). These models were used to estimate emission reductions needed to attain the NAAQS and to evaluate alternative control strategy options (deNevers and Morris,

1975 and EPA, 1977). This use of ozone design values diminished following the development of more complex photochemical modeling approaches (EPA, 1991).

In some applications, design values used in estimating emissions reductions have been adjusted to account for factors such as the level of transported ozone, or air quality reductions expected from future control measures. Such adjusted design values have come to be known as "control strategy values" to differentiate them from "air quality" design values which are estimated directly from the ambient monitoring data (Rhoads and Tyler, 1987). Recent attention has been focused on adjusting ozone design values for the year-to-year fluctuation in meteorological conditions. Meteorological influences on ozone concentrations and adjustment methods are discussed in Section 7. The role of transported ozone and precursors is the subject of Section 8 of this report.

SUMMARY

The Ozone Guideline introduced several approaches that could be used to estimate ozone design values, including a table look-up method, a graphical procedure, the use of different statistical distributions, and the use of a conditional probability approach. No single approach was required by the Guideline, so that the initial guidance contained a fair degree of flexibility in how design values could be estimated. Since the early 1980's, EPA has used a tabular approach for estimating ozone design values that have been reported in annual air quality assessments. Prior to enactment of the 1990 Clean Air Act Amendments, EPA issued a policy memorandum documenting the procedures used in determining both ozone and carbon monoxide design values (Laxton, 1990). This memorandum essentially maintained the status quo and documented the table look-up procedure summarized above as the EPA design value estimation method. This was the last EPA policy statement on design values.

A wide variety of statistical distributions for air quality data have been investigated. For ozone data, the tail exponential and lognormal distributions have been widely used, but the literature does not provide definitive guidance on the best distribution to use for ozone design value calculations. However, there appears to be a growing consensus in favor of the tail exponential, on the basis of its general applicability and good fit, simplicity, and ease of fitting.

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5 EVALUATION APPROACHES FOR OZONE DESIGN VALUE METHODS

INTRODUCTION

Two different but complementary approaches have been taken in the comparisons of alternative ozone design value methodologies. In the first, a database was constructed that contained the daily maximum 1-hour ozone concentrations for all sites in the AIRS database for the years 1980 through 1990. Using this database, design values were calculated for alternative procedures on the same data sets and the results compared. These data, obtained over a variety of sites, give an indication of the variability of each method and suggest the relative biases of the methods. The drawback of this first approach is that the underlying "true design value" is not known and the absolute biases cannot be determined.

The second approach attempts to overcome these difficulties. The ambient air quality database provides the base data for the derivation of a time-series model. Given such a model, large numbers of random simulations of single seasons of daily maximum ozone values can be generated, which allow the limiting characteristic largest value (CLV), and design values for any number of methods, to be calculated over a large number of years. Thus, both the inherent biases and precision of alternative design value methods can be studied using a wide variety of averaging years. These data sets have no missing values and therefore are free from this source of error. Data can be removed from the individual years to study the sensitivity of the methods to missing values.

There are also problems with the time-series approach. First, the study did not develop a single time-series model equally applicable to all site-years of data. Instead, two models were developed, which between them seem to do reasonably well in all cases studied. They tend to bracket the actual behavior in most situations with one of the series usually being the better of the two in a particular case. There may be an inherent problem with fitting a time series to actual ambient data. The parameters of the time series reflect the total behavior of the data, whereas the interest here is in the behavior at the extremes of the seasonal distribution of the ozone data. If the behavior of the extreme values is not a reflection of the random behavior of the data as a whole, then the procedures used to derive the time series will be in question. This does not appear to have been a serious problem with this model.

OZONE AIR QUALITY DATABASE

State and local governments throughout the nation operate ozone monitoring stations that collect actual direct measurements of pollutant concentrations. The vast majority of these measurements represent the country's heavily populated urban areas. These permanent monitoring stations produce hourly concentration data using monitoring instruments that operate continuously, producing a measurement every hour for a possible total of 8,760 hourly measurements per year. These air quality data are submitted to EPA's Aerometric

Information Retrieval System (AIRS) by State and local governments, as well as federal agencies. EPA and other federal agencies also operate some air quality monitoring sites on a temporary basis as a part of air pollution research studies. These data may also be submitted to AIRS.

The national monitoring network conforms to uniform criteria for monitor siting, instrumentation, and quality assurance (40CFR58). The monitoring sites are classified into one of three categories: NAMS, SLAMS, or SPMS. The NAMS, or National Air Monitoring Stations, were established to ensure a long-term national network for urban area-oriented ambient monitoring information and to provide a systematic, consistent database for air quality comparisons and trends analysis. The SLAMS, or State and Local Air Monitoring Stations, were established to allow State or local governments to develop monitoring networks more tailored to their immediate ambient monitoring needs. The SPMS, or special purpose monitors, are stations used by the State and local agencies to fulfill very specific or short-term monitoring goals. Data from all three types of monitoring sites are included in this multi-year database.

Hourly ozone data were retrieved from AIRS for any site that reported data for the years 1980 through 1990. Valid daily maximum 1-hour concentrations were calculated for each day that met the required daily validity criteria as defined in Appendix H to 40CFR, Part 50. That is, a valid daily maximum means that at least 75 percent of the hourly values from 9:01 a.m. to 9:00 p.m. (Local Standard Time) were measured, or at least one hourly value exceeded the level of the ozone standard. Additional summary statistics retrieved from AIRS included in the database are the annual number of estimated exceedances, the required number of sampling days, and the percent data completeness. The estimated exceedances were adjusted for missing data during the ozone season following the prescribed procedures in Appendix H. (See Table 3-1 in Section 3 for a list of the designated ozone monitoring seasons, which generally vary by state.)

Spatial Distribution of Ozone Monitors

The map in Figure 5-1 displays the location of the 1,500 monitors that reported ozone data in at least one year during the study period of 1980 through 1990. The number and location of ozone monitors can vary from year to year due to many factors. New monitors may be added, or existing monitors may be discontinued, as a result of network reviews of monitoring objectives. Some monitoring locations are lost when existing building leases are terminated, or existing space is renovated. The map in Figure 5-2 displays the spatial extent of the 323 monitors that operated in each year during the period 1980–90. A comparison of these two maps reveals a paucity of long-term monitoring sites in the smaller cities and areas throughout the Southeast, West, and Northwest.

The 323 sites that operated continuously each year since 1980 are contained within 221 counties. In contrast, the current monitoring network of 818 monitors that reported data to AIRS for 1990 includes 469 counties.

Trends in Ozone Monitoring Coverage

The number of ozone monitoring sites reporting data to AIRS varied from year to year during 1980–1990. The most recent year with data, 1990, had the largest monitoring network with 818 monitors reporting to AIRS, up 114 monitors or 16 percent, from a low of 704 monitors in 1986. Focusing on counties as the geographical unit of interest, 1990 was again the peak year with 469 counties reporting ozone data to AIRS. This count is up 70 counties, or 18 percent, from the 399 counties reporting data in 1986. A third way of looking at the geographical coverage of the monitoring network is to focus on the number of distinct "areas" reporting data annually to AIRS. For these comparisons, an "area" is defined as the larger of the geographical unit of a county, a Metropolitan Statistical Area (MSA), or a Consolidated Metropolitan Statistical Area (CMSA). In some cases, the geographical scope of the areas designated nonattainment under provisions of the Clean Air Act Amendments of 1990 differ from the boundaries of existing MSAs and CMSAs. To facilitate comparisons using the historical ozone air quality monitoring data, MSAs and CMSAs are used to summarize many of the analyses that follow. However, when the focus is on analyses of current ozone air quality data, summaries are presented using the designated ozone nonattainment areas. The chart in Figure 5-3 shows the temporal pattern in the number of areas reporting ozone data and in the distribution of area types (CMSA, MSA, or county). Even though the number of CMSAs reporting ozone data has remained constant during this period, the mix of sites within these areas may have changed. As expected, most of the variability in the spatial coverage of the ozone monitoring network has occurred in non-metropolitan areas.

TIME-SERIES MODELING APPROACH

This section begins with a literature review of papers that address issues associated with time-series modeling of air quality data. These include discussions of various time-series models used to model exceedance days and ozone hourly and daily maximum concentrations. A tabular summary of the papers included in this literature review is contained in Appendix B. The section concludes with a discussion of time-series models developed for this study to evaluate alternative ozone design value methodologies. Model evaluation results are provided in Appendix C.

Time-Series Literature Review

This literature review is a summary of important articles (cited as bracketed numbers from the list at the end of this section) that address the statistical modeling of ozone concentrations taking into account their serial dependence. Serial dependence implies that the peak ozone concentration on a given day is correlated with the ozone concentrations on previous days; otherwise, the concentrations would be independent. A related literature review of statistical distributions fitted to air quality data focuses on cases where the concentrations are assumed to be approximately independent. The computation of a design value that corresponds to the statistical model for the serially dependent or independent cases

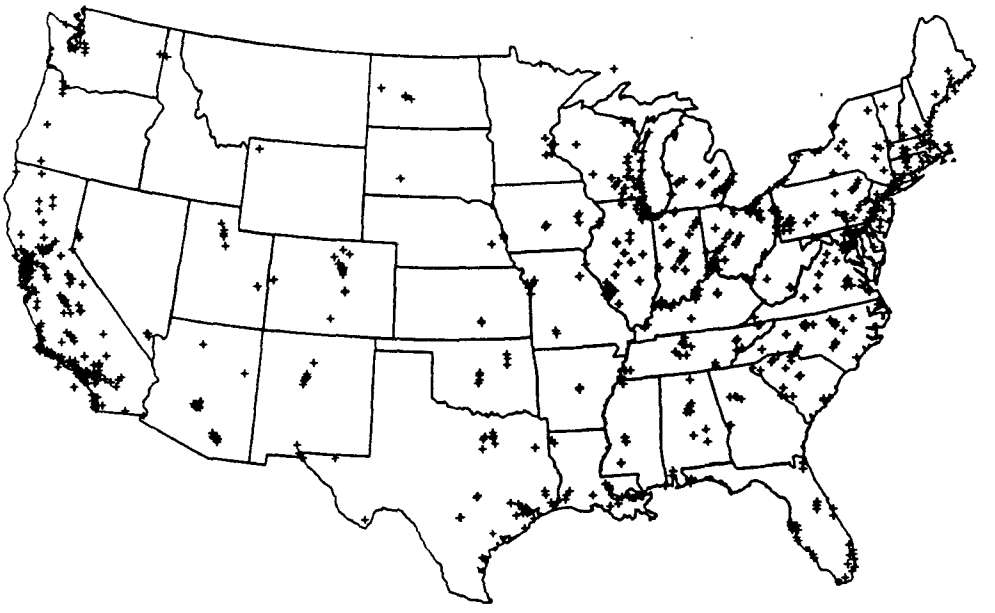


FIGURE 5-1. Ozone monitoring sites that reported hourly ozone concentration data for at least one year during the period 1980–90.

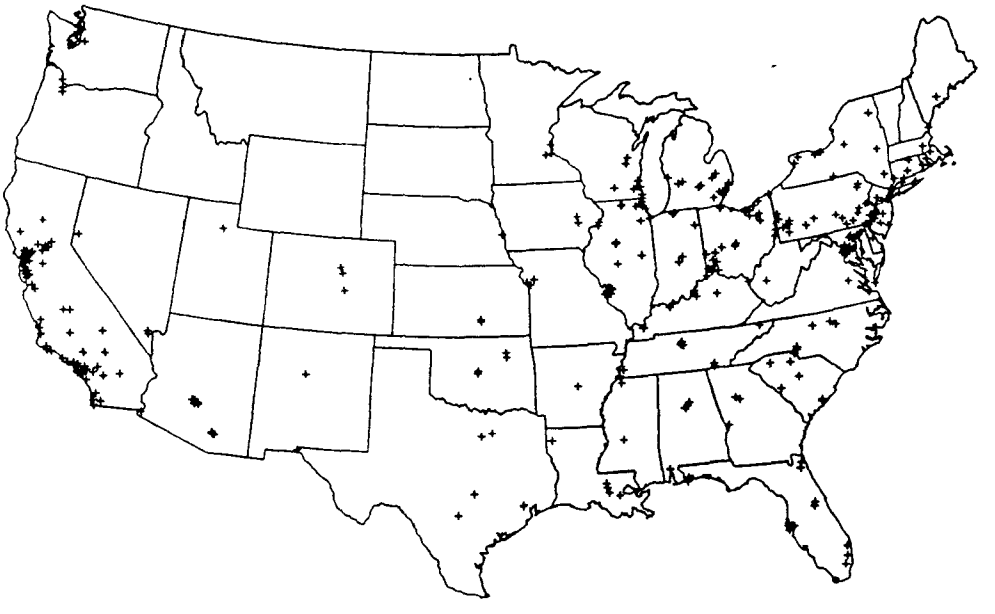
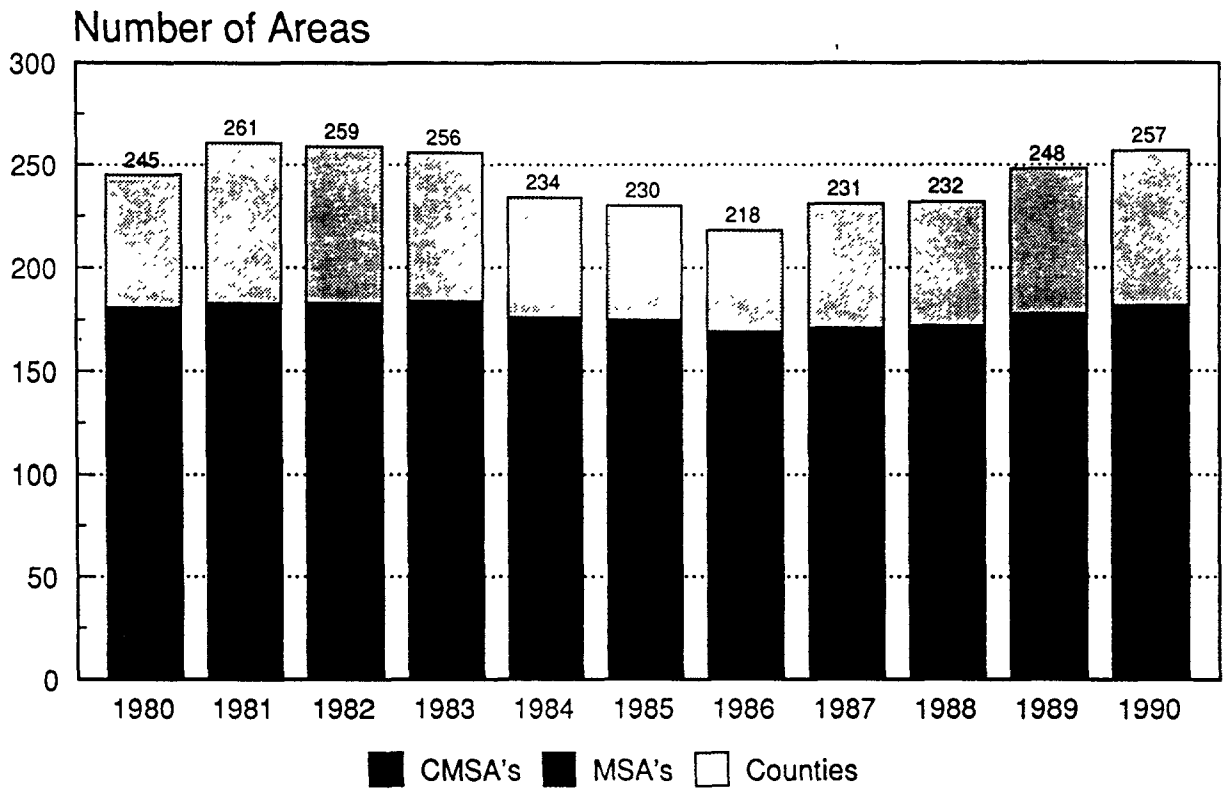


FIGURE 5-2. Location of the 323 ozone monitoring sites that monitored each year during the period 1980–90.



Source: Aerometric Information Retrieval System

FIGURE 5-3. Number of areas (CMSAs/MSAs/counties) reporting ozone data to AIRS by year.

is discussed later on in this summary. This literature review discusses articles in which the main focus is on the time-series model.

The strong serial dependence that has been found in ozone concentrations, and in ozone exceedance days ([1], [4], [11]) has important implications for ozone NAAQS attainment issues. An illustration of the serial dependence in daily maximum ozone concentrations is found in [1]; high concentrations and NAAQS exceedances tend to be repeated on the succeeding day. Design value estimates that realistically take into account the serial dependence are likely to be more reliable, since those estimates are more precise than estimates that assume independence. One problem with the time-series approach is that a multitude of statistical models are available, often with different policy implications (since different time-series models tend to lead to different estimated design values), and the available data are too noisy to allow us to identify any one of these models as providing a clearly superior description of the data. To some extent, the same comment applies to the multitude of statistical distributions that have been fitted to ozone concentration data in cases where independence has been assumed. However, the similarity of the tail behavior of the fitted distributions implies that the design values tend not to be strongly affected by the choice of the common distribution function, at least for a hypothetically independent sequence of hourly or daily maximum hourly concentrations.

Concentration Time Series Models

Several authors have examined the autocorrelations between successive hourly and daily maximum hourly concentrations ([1, 4, 11] for example). Autocorrelation is the statistical correlation between one value and the kth previous value, where k is the order or lag (the first-order autocorrelation is between one value and the previous value). Because of this serial dependence, several authors have considered time-series models that explicitly take the serial dependence into account.

The simplest concentration time series model ([1, 19]) is the stationary normal first-order autoregressive model. The term "stationary" refers to an assumption that the distribution of each concentration is constant (given no information about past or future concentrations) and, more generally, that the joint distribution of any finite number of consecutive values is also constant. The term "normal" corresponds to an assumption that the concentrations have a normal distribution. The term "first-order autoregressive" implies that the concentration on a given day or hour is given by a constant plus a multiple of the previous concentration plus an independent error term.

Various authors have used more complex versions of this model for the daily maximum hourly ozone concentrations. One extension of the model ([2, 12, 16]) is to use a higher-order stationary autoregressive model (so that the present concentration is a linear combination of several previous values and the independent error) or the even more general autoregressive moving average (ARMA) time-series models. A further extension treats the nonstationary cases where the mean is changing in time ([3, 5, 12, 16]). The Box-Jenkins

approach takes day-to-day, month-to-month, and/or year-to-year differences until the resulting difference series appears to be stationary. An alternative approach to nonstationarity is to assume the mean is a certain function (linear, quadratic, or cubic polynomial) of time, which is often estimated using multiple regression.

An important use of ozone time-series models has been in forecasting the daily maximum hourly concentrations ([2, 3, 5, 16]). A typical ozone forecast is an advance estimate of the next day's daily maximum hourly ozone concentration based on the present day's ozone concentrations and meteorological measurements. Such estimates are often used to alert the public about the predicted ozone level so that people particularly susceptible to high ozone concentrations may take appropriate actions. Investigators have found that forecasts based on time-series models using only the daily maximum ozone concentration perform poorly([2]). Significantly improved forecasts include trend terms and various meteorological factors in the time-series models, such as the most recent temperature measurements.

A similar extension of the simple time-series model is in intervention analysis ([17, 18]). In the application of this theory in papers 17 and 18, one of the intervention events was the opening of the Golden State Freeway in 1960, and the model thus assumes that this event caused a step change in hourly ozone concentrations.

Exceedance Time Series Models

An alternative approach to serial correlations between consecutive daily maxima is to ignore the actual measurement and only record whether or not that value is an exceedance of a given threshold. The threshold can be, but does not have to be, the ozone NAAQS. Since the exceedance either occurs or does not occur, this is a binary time series. The serial dependence can be tested by comparing the observed exceedance process with the expected behavior if consecutive exceedances were independent. Runs tests ([1, 4]) or exceedance duration tests ([11]) have shown that there is statistically significant dependence for daily maximum ozone exceedances. A runs test compares the observed number of runs of consecutive exceedances with the expected number in the independent case. An exceedance duration test compares the observed numbers of consecutive exceedances with the expected values in the independent case.

The simplest binary time-series model, apart from independence, is probably the first-order Markov chain model. This model ([1, 4, 6, 7, 8]) implies that the probability of an exceedance depends only on whether or not the previous day had an exceedance, rather than on the complete history of exceedance days.

The theory of extreme values shows that in the case of no trends, under very general conditions, the distribution of the number of exceedances of a high threshold concentration is approximately the compound Poisson distribution ([14]; see also Hsing and others (1988)). Clusters of exceedance days occur "randomly" according to a Poisson process. The number

of daily exceedances in each cluster has some random distribution. In the special cases of independence or weak dependence, the limiting approximation to the exceedance series has exactly one exceedance per cluster and the number of exceedances has a Poisson distribution. A special case of the compound Poisson limiting distribution was investigated by Thrall and Burton ([6]); their approximation corresponds to clusters with a geometrically distributed number of exceedances per cluster.

Davison and Hemphill ([15]) proposed an exceedance model that incorporates meteorological factors. This model, applied to Texas ozone data, assumes that exceedances follow a Poisson process, but the rate of the Poisson process has a logarithm that is a linear combination of meteorological measurements. The proposed application of this model was to estimate the numbers of exceedance days when measurements are missing. This approach differs from the missing value adjustment of Appendix H to the ozone standard, that assumes that the proportions of exceedance days are the same for days with and without valid measurements. However, it is assumed in Appendix H that missing concentrations on days outside the ozone season, and on days sandwiched between valid daily maxima below 75 percent of the standard, are in both cases less than the standard.

Computation of the Distribution of the *k*th Highest Value

The literature on time-series models for ozone includes analyses of the concentration series (hourly or daily maximum hourly) and of the exceedance day binary series. These two approaches are related. In principle we can easily compute the occurrence probabilities of the exceedance days from a time-series model of the daily maximum hourly concentrations. On the other hand, important properties of the concentration series can be computed from the distributions of the numbers of exceedances of various threshold concentrations, rather than simply the exceedances of the ozone NAAQS (0.12 ppm). Several of the cited papers exploit the result that the *k*th highest value is greater than x only if the number of exceedances of x is greater than or equal to k. In particular, it follows that the distribution function of the annual maximum is the same as the probability of zero exceedances of the (dummy) variable x, and the distribution function of the second highest value is the same as the probability of zero or one exceedance of x.

Several papers use a time series model for the daily maximum concentrations to compute the distribution of the annual maximum, second maximum, and so on ([7, 8, 9, 10, 12, 13]). This computation is very difficult to do analytically, and is more easily done either by simulation ([8, 8a, 12]) or by using an extreme value approximation ([8, 9, 10, 12, 14]).

As discussed in the paper [8a], the calculations in the papers [7] and [8] contain mathematical errors because the first-order Markov chain model for exceedances is inconsistent with the assumption that the daily maximum concentrations form a Markov process. The Markov chain model for *exceedances* roughly states that the conditional probability of an *exceedance* given the previous exceedance record depends only on whether or not the previous day had an exceedance. The Markov process model for *daily maximum*

concentrations, which is a basic assumption in [7] and [8], roughly states that the conditional probability distribution of the *daily maximum* given the past monitoring record depends only on the record for the previous day. A fallacy that is easily made assumes that the Markov process assumption implies the Markov chain assumption. Although the calculations in [7] and [8] are not mathematically exact, because of this issue, Chock [8a] reported the results of a small simulation study that implied that the calculations in [8] were approximately correct.

The most relevant feature of extreme value theory is that if the dependence is weak and there is little or no trend, the limiting distribution of the maximum, second maximum, and so on, is the same as the limit in the independent case ([7, 8, 8a, 13]). The accuracy of the extreme value approximation for the *k*th highest value has been investigated by Chock ([8, 12]) and others (see [20] for example). Chock found that the approximation is best when the rank is low (i.e., for the *k*th highest for small *k*) and when the autocorrelation is low. (Using the results from Berman's paper [13], the dependence in the AR(1) process is weak enough that the limiting distribution does not depend on the autocorrelation.) If the dependence is too strong (so that the condition D′ of Leadbetter and others (1983) is not satisfied) but there is little or no trend, then the limiting distribution is affected by the clustering of exceedances ([6, 14]). Typically the general form of the limiting extreme value distribution of the maximum is the same as for the independent case, but the shape parameters that define the specific limiting distribution is different from the independent case. However, the distribution of the second highest, third highest, etc., have quite a different form from the independent case if clustering occurs ([4]).

If the dependence is weak and there is a significant trend (i.e., the mean concentration is not constant in time), then the limiting distribution depends on the trend and has been derived by Horowitz and others ([9, 10]). Note, however, that Leadbetter and others [20] have shown that the theoretical results in [9] and [10] do not apply to all trend functions described in Horowitz's exposition, because a mathematical error resulted in the use of the wrong normalizing constants for rapidly increasing trends.

Time-Series Model Development

The above literature review and the strong serial correlation of daily maximum ozone concentrations, as illustrated by Figure 5-4, provide the motivation for developing a time-series model as a tool for evaluating alternative ozone design value methodologies. Given such a model, large numbers of random simulations of ozone seasons can be generated in which the "true" design value is known. Thus, the inherent biases and precision of alternative design value methods can be determined. These data sets have no missing values and therefore are free of this source of error.

The following sections discuss the two time-series models developed in this study. They are relatively simple but appear in most cases to adequately capture the significant behavior of daily maximum ozone concentrations over a variety of sites. In this section we

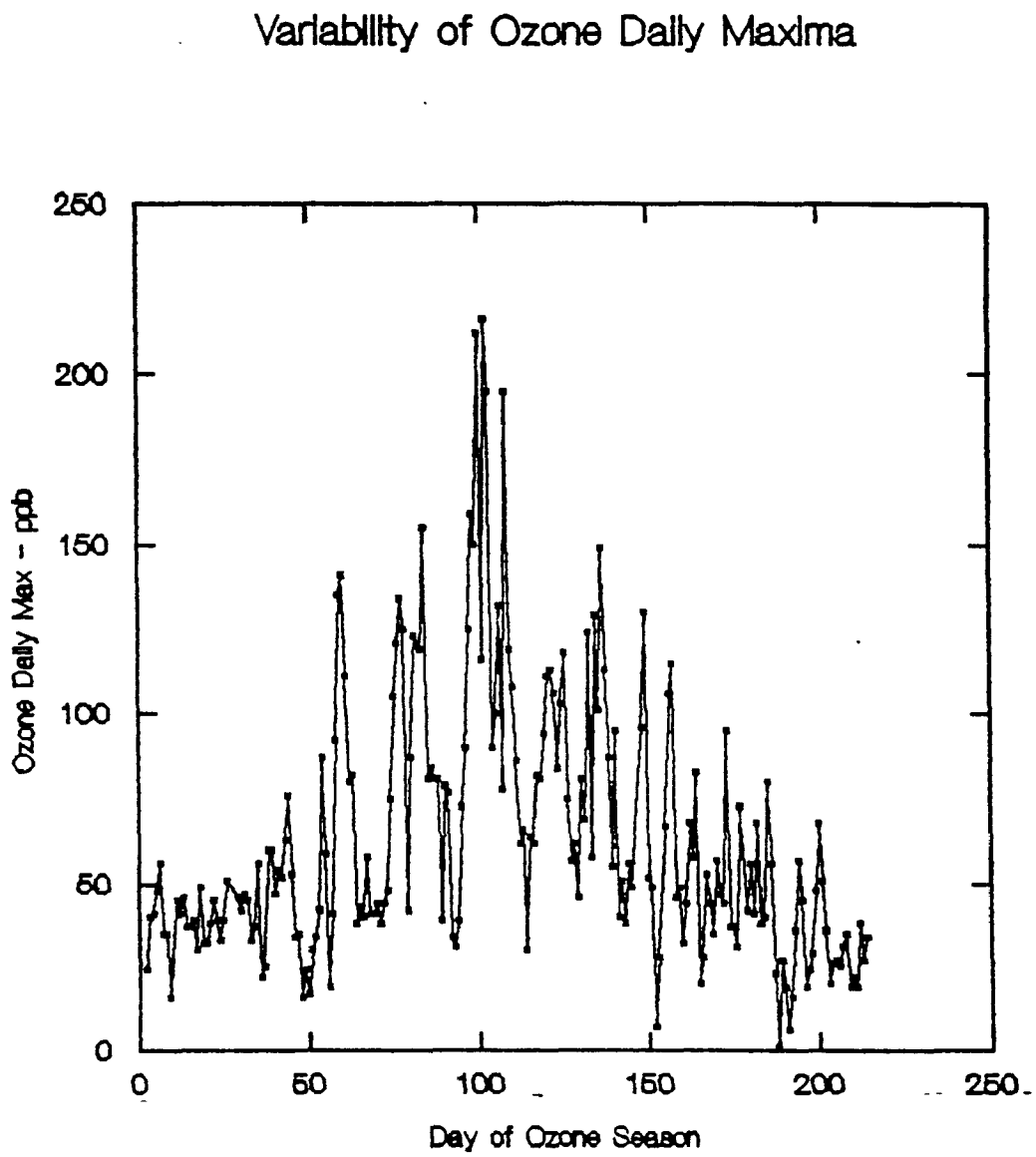


Figure 5-4. Example of variability of ozone daily maximum 1-hour concentrations.

describe the application of the time-series models for two site years only. In Section 6, a more complete analysis applies these time series to 11 sites.

Basic Form of the Daily Maximum 1-hour Ozone Time Series Model

The two time-series models have the same basic form. They differ only in the probability distribution associated with the shock term. The base model represents an autoregressive random process of order one designated by AR(1). This process is applied after the daily maximum concentrations are transformed to their natural logarithms and the seasonal effect is removed. Each season a given monitor site generates a single realization of daily maximum 1-hour ozone concentrations:

$$c(1),\ c(2),\ \ldots,\ c(t-1),\ c(t),\ \ldots,\ c(n)$$

where $c(t)$ is the daily maximum 1-hour ozone concentration on day t of an ozone season containing n days. A time-series model that appears to apply to monitor sites in a variety of geographic areas is as follows:

$$x(t) - m(t) = \phi(x(t-1)-m(t-1)) + z(t)\sigma \quad , \tag{1}$$

where

$$x(t) = \ln c(t) \quad , \tag{2}$$

and $m(t)$ is the expected value at time t. The term $m(t)$ is estimated by $\bar{x}(t)$, a moving average, which subtracted from the corresponding $x(t)$ removes the seasonal effect, that is, the tendency of daily maximum ozone concentrations to increase as the days become warmer and sunlight intensity increases and then fall again as summer ends (Figure 5-4). The coefficient ϕ is a measure of the autocorrelation between the adjusted log daily maximum concentration on a given day and the previous day's adjusted log daily maximum concentration. The term $z(t)\sigma$ is the shock term. In the model it generates a random shock which added to the previous day's autocorrelated contribution yields the current day's adjusted log concentration. The term $z(t)$ is a standardized variate which is randomly sampled each day from a distribution, with zero mean and unit standard deviation; σ is the standard deviation of the resulting random shocks.

The time-series model given in equations 1 and 2 has three major features. First, the daily maximum concentrations are transformed to their natural logarithms. Second, a running average log daily maximum concentration is subtracted from each log daily maximum to adjust for the seasonal effect. Third, the present day's adjusted log daily maximum is obtained as the sum of an autoregressive term of order 1 which accounts for the previous day's contribution plus a random shock term generated from a defined probability distribution.

The use of the log transform is suggested by the increasing variability of the daily maximum concentrations as the concentrations increase (see Figure 5-4). Figure 5-5 shows how the variability tends to be more uniform over the season under the log transform.

Several approaches to computing the moving average for a season $\bar{x}(t)$ were studied including simple running averages and fitting second and third and fourth order polynomials to a season of log daily max data. These were all abandoned in favor of the LOWESS procedure, which employs distance-weighted least squares to produce a smoothed average. The power of this method is that a tension factor can be adjusted to give complete control over the degree of smoothing achieved. After considerable experimentation, a tension factor of 1/3 was applied to all sites studied. Figure 5-6 shows the generated LOWESS curve for the same site-year featured above. Lowering the tension produces increasing fine structure in this curve, while increasing the tension leads to an increasingly smooth curve. Figure 5-7 shows the LOWESS fits for the years 1981 through 1990 for the same site. There is a substantial yearly effect on the shapes and heights of the fitted curves. Only a portion of this variation can be accounted for by day-to-day variability in the adjusted log concentrations.

The terms ϕ and σ are obtained by application of standard statistical software which fits the Box-Wilson ARIMA (AutoRegressive Integrated Moving Average) model to a set of time ordered data. In this case the series was the adjusted log daily maximum concentrations for single seasons. This analysis permits a thorough exploration of the complex ARIMA random process which includes both autoregressive and moving average processes of any order as well as taking into account trends and seasonal effects. The exploration clearly showed that a simple AR(1) process was sufficient in all cases studied. The inclusion of moving average processes and higher order autoregressive and moving average processes occasionally improved fit but never enough to justify inclusion of additional terms. Seasonal effects were not investigated because of the large differences in seasonal effect from one year to the next. The appearance of the series plots, autocorrelation function plots (ACF) and partial auto correlation function plots (PACF) all strongly signaled the predominance of an AR(1) process.

It is customary in fitting a time series to think in terms of the standardized variate z as being associated with the normal distribution N(0,1). If so, the residuals from the ARIMA fit should be normally distributed. Figure 5-8 is a probability plot of the residuals from the ARIMA fitted to the same example site-year. The plot assumes the standardized variate is normally distributed (or a lognormal distribution of the untransformed daily maximum concentrations). In this case a straight line should fit the data in the figure. Clearly this is not the case. However, in many cases the fit is quite good, as shown in Figure 5-9 for another site in a different geographic area for the same year. In the former case it was found that the use of a modified extreme value distribution provided a good representation of the data. The success of the extreme value distribution is an indication that the daily maximum concentrations approximately have Weibull distributions. This is because the logarithm of a variate that has a Weibull distribution has an extreme value distribution.

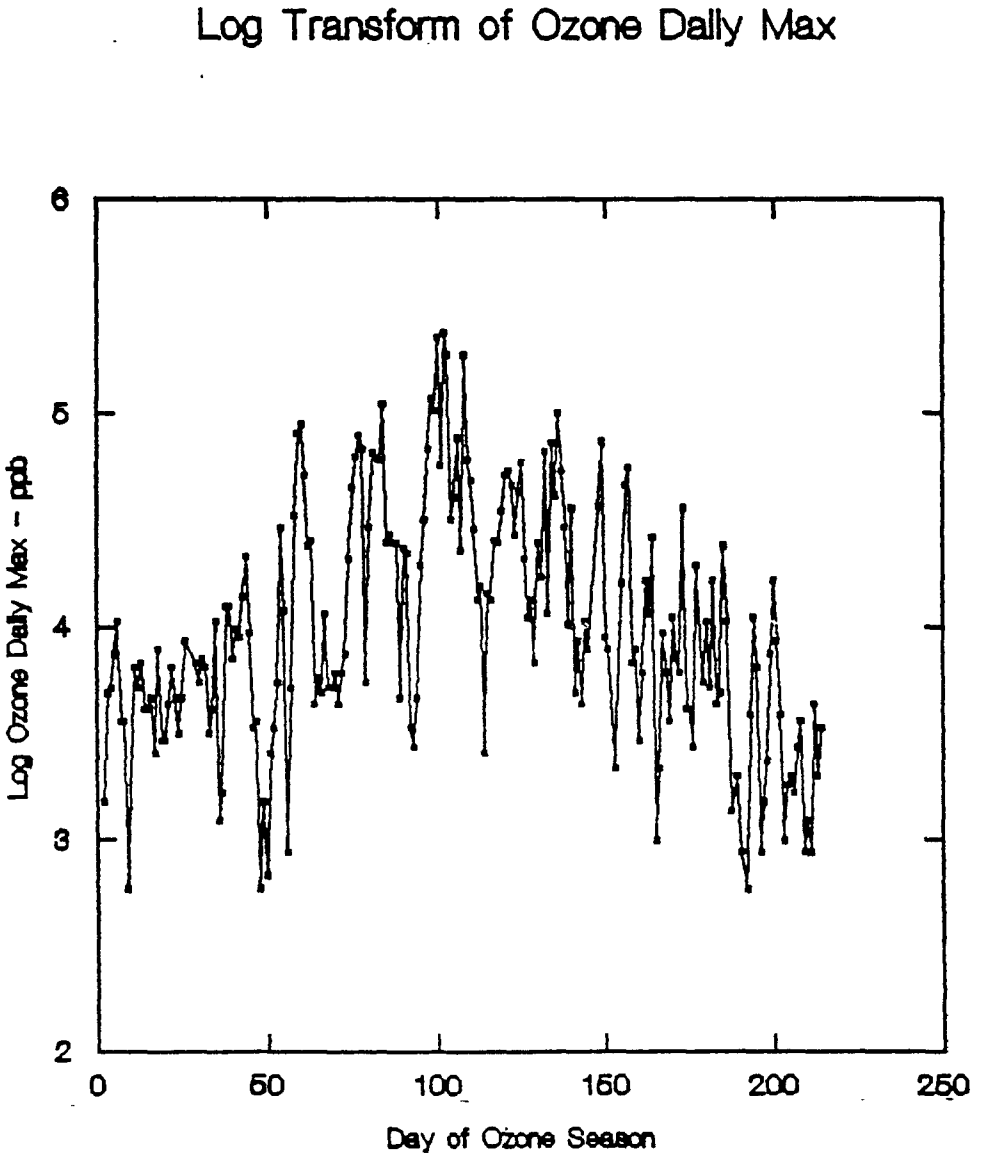


Figure 5-5. Log transform of daily maximum 1-hour concentrations at sample site.

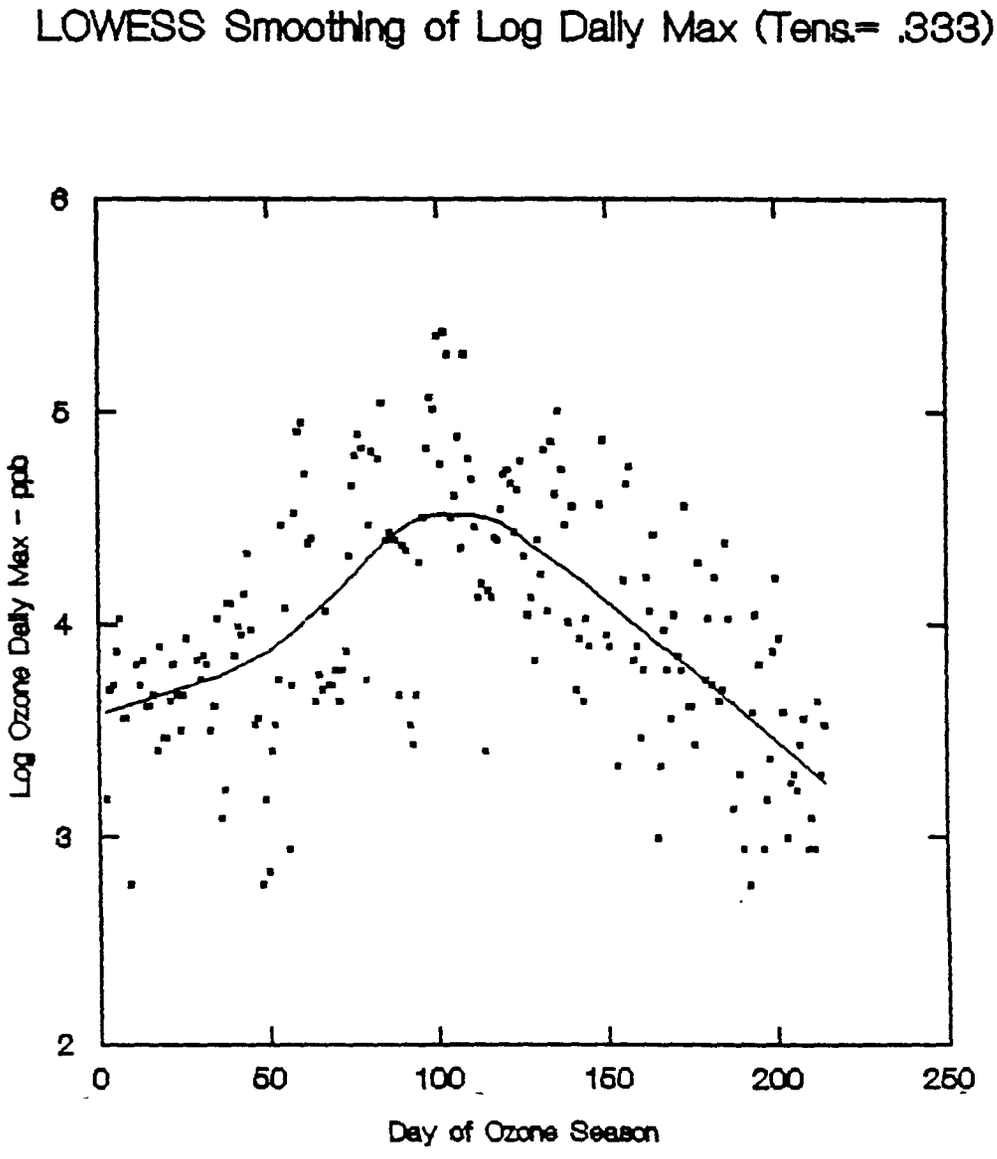


Figure 5-6. LOWESS smoothing of the log of the daily maximum 1-hour concentrations at the sample site.

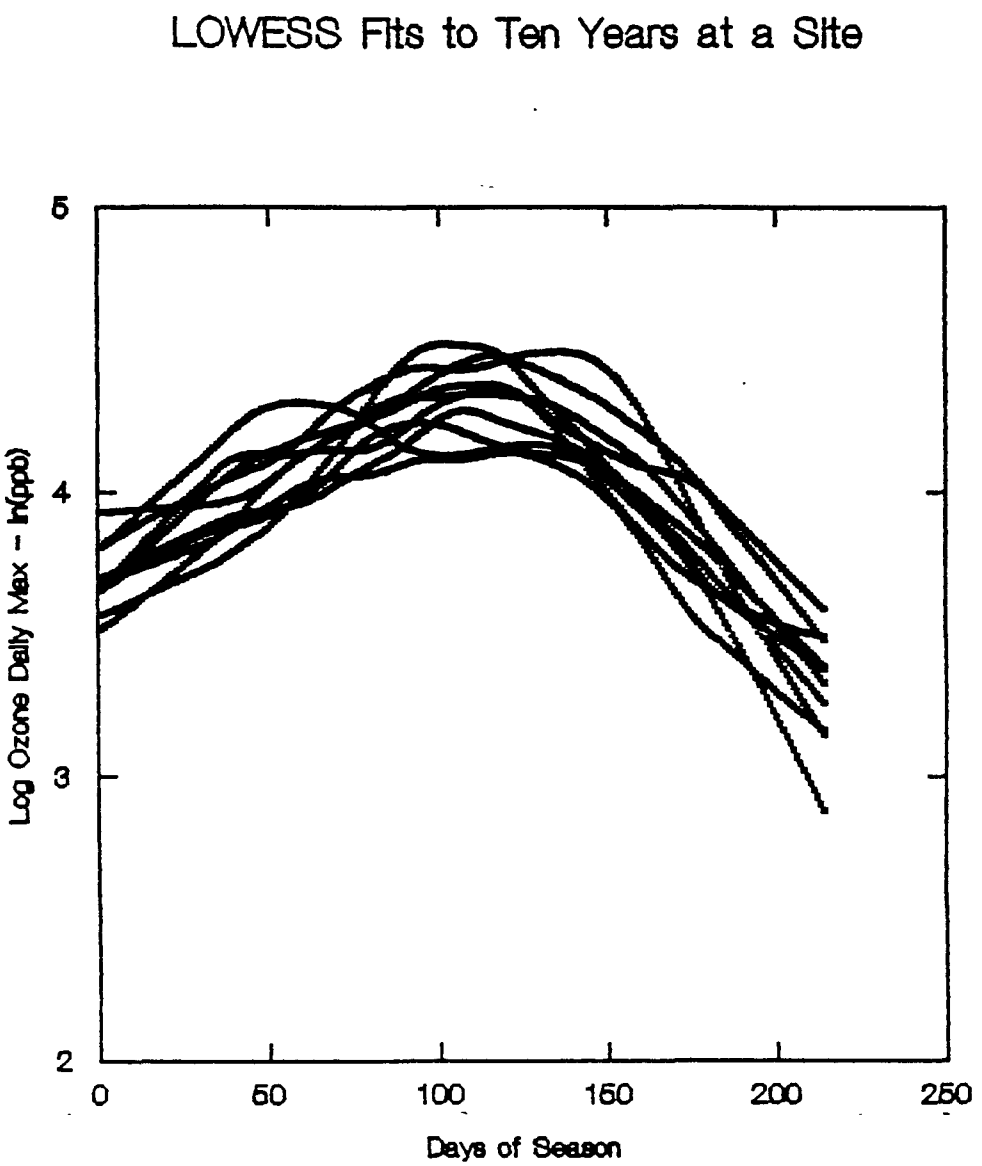


Figure 5-7. LOWESS fits to ten years of ozone data at the sample site.

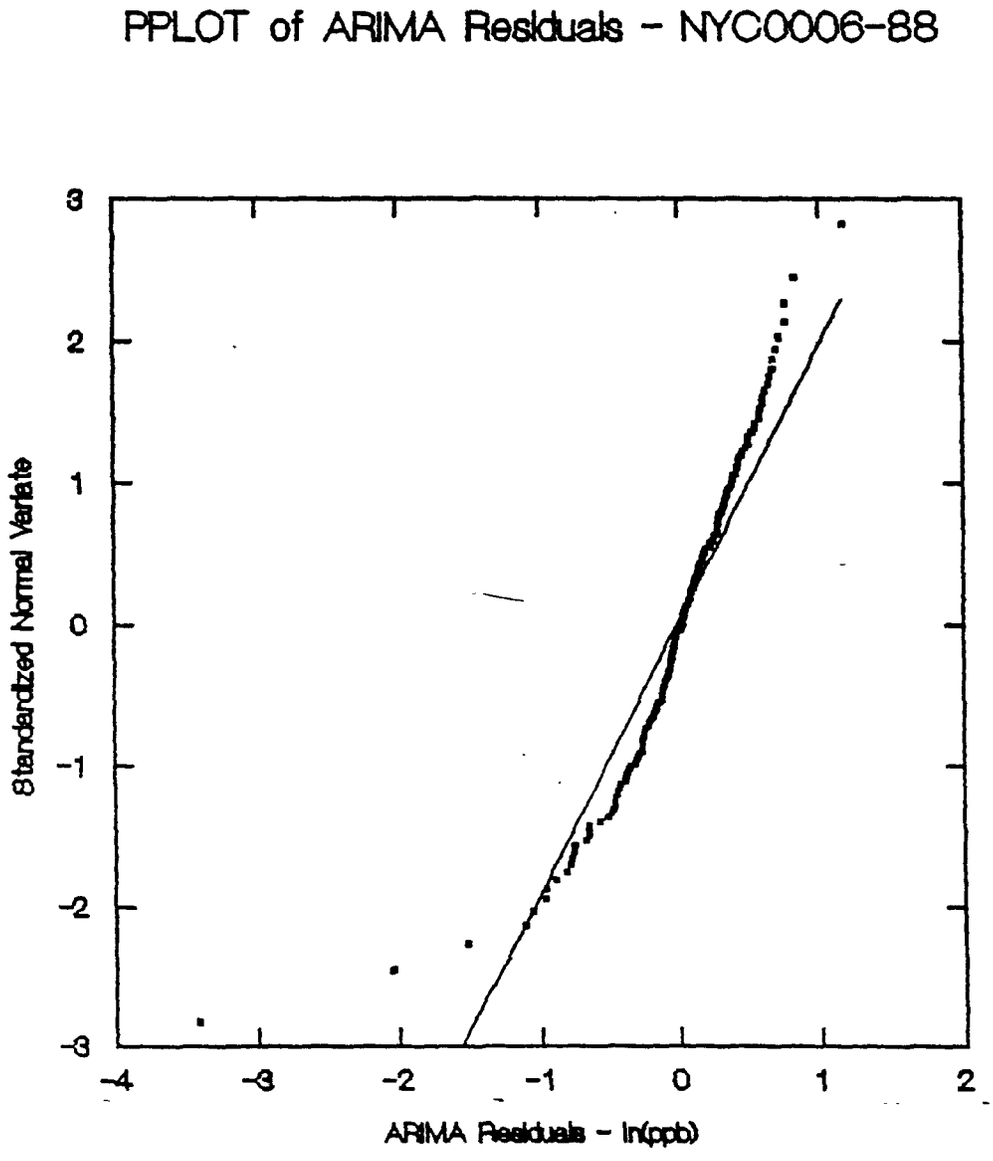


Figure 5-8. Probability plot of ARIMA residuals at a site in the New York metropolitan area.

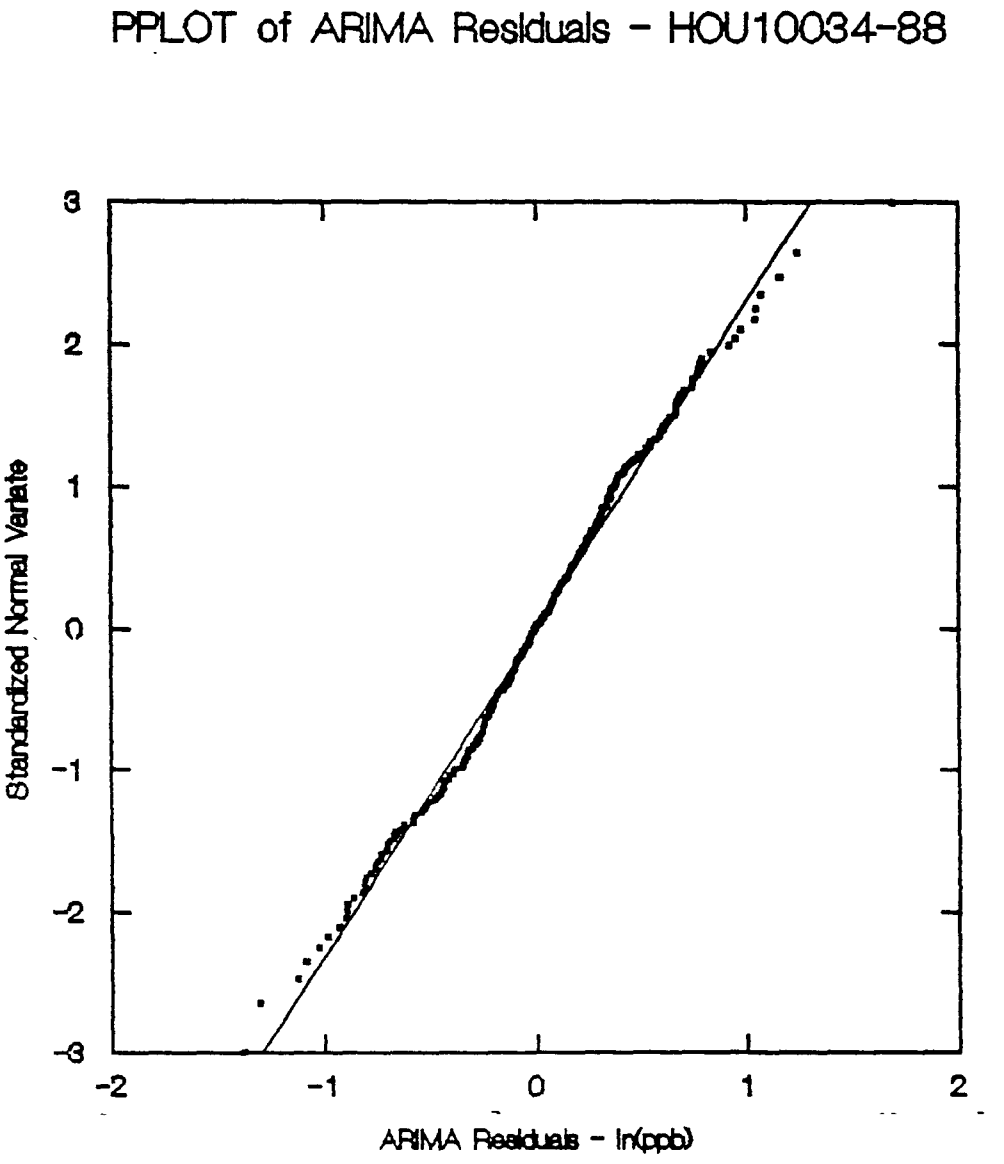


Figure 5-9. Probability plot of ARIMA residuals at a site in the Houston metropolitan area.

It was found that all the site years studied could be represented by one or the other or both distributions within a standard deviation of the design value. This finding is reasonable since a single season's ozone daily max concentrations can usually be fitted by a lognormal or Weibull distribution with one or the other fitting better.

Model Evaluation

Table 5-1 compares several alternative design values measures for two different site-years computed first from the ambient ozone database (AIRS) and then from a simulation using the ARIMA and LOWESS fits. Each simulation produced 250 realizations. Several alternative design value measures were computed for each realization and then averaged over the 250 realizations. Standard deviations of individual realizations from the mean values were also calculated. The design value designated by EPA is the EPA table look-up procedure. Since the application here is to single years and there are no missing data, the second largest concentration is the EPA table look-up design value. The columns headed by EXPO5 and EXPO10 are tail-exponential design values which take into account the behavior of the upper 5 percent and 10 percent of the data respectively. The PCNT95 and PCNT90 columns are the 95-percentile and 90-percentile points on the distribution of the daily maximum concentrations. These are potentially less variable surrogates for the design value. Here they are used as a measure of how well the upper tail of the distributions are simulated. The CHV column has two interpretations. It is the annual largest concentration. When averaged over the 250 simulations it is the most reliable estimate of the "true" design value, and thus a basis for calculating the biases of the other measures. The averaged simulated design values are in excellent agreement with the ambient measurements at these sites. In all cases the single season AIRS values are within a standard deviation of the averaged simulated values. It is noted that single-season comparisons are appropriate in comparing simulated average values and design values computed from the ambient ozone database. If the comparison is good for single years, it will be good for averages of multiple years of real data. Appendix C contains example time-series model simulation results for 30 years and summary statistics for the entire set of 250 simulations.

SUMMARY

Two basic approaches have been proposed for evaluating alternative methodologies for estimating ozone design values: (1) comparing ozone design value estimates using historical ambient ozone data, and (2) comparing ozone design value estimates using time-series models. The first approach allows us to compare alternative design value estimates on a national basis using historical ozone monitoring data. In the time-series approach, the "true" design value is known from the underlying time series, and we can get an estimate of the precision and bias associated with each method for a limited number of cities.

Table 5-1. Comparison of simulated and ambient ozone design values for sites in New York and Houston, 1988.

SITE	RUN	DATA	CHV	EPA	EXP05	EXP10	PCNT95	PCNT90
HOU1034	AIRS	O3DV	.220	.190	.186	.197	.110	.090
	LOG SIM	O3DV	.215	.183	.191	.190	.113	.093
		STDV	.042	.025	.022	.019	.008	.005
NYC0006	AIRS	O3DV	.216	.212	.220	.205	.135	.119
	EVD SIM	O3DV	.214	.192	.200	.206	.140	.118
		STDV	.031	.023	.023	.024	.012	.009

Notes:

1. Single year of daily maximum ozone data.
2. LOG SIM is AR(1) process with lognormal shock term.
3. EVD SIM is AR(1) process with extreme value shock term.
4. In each case 250 simulations were run.
5. In the data column, the rows labeled O3DV are the design value estimates. STDV is the standard deviation for the 250 simulations.
6. In the AIRS runs, CHV is the largest daily maximum in one year. In the simulations, this number is the best estimate of the "true" design value.

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6 COMPARISONS AMONG ALTERNATIVE DESIGN VALUE METHODS

The Ozone Guideline defines the ozone design value as that concentration with a true expected exceedance rate of once per year. Thus, the design value associated with the ozone NAAQS is an abstract quantity that can only be estimated from available data. The Ozone Guideline suggests several methods for estimating the design value, including a simplified table look-up procedure, approaches using statistical distributions, and techniques based on conditional probabilities.

The EPA ozone design value method in effect as of the date of enactment of the 1990 Clean Air Act Amendments is the table look-up procedure. As noted previously, for monitoring stations meeting the 75 percent data completeness criterion in each of the three most recent years, this method consists of selecting the fourth highest daily maximum 1-hour concentration during the three-year period.

This section describes the results of the two complementary approaches used within this study to evaluate alternative ozone design value methods: (1) comparisons of design values estimated from ambient ozone data and (2) comparisons of alternative design values derived from a time-series model. Details of the historical ambient ozone air quality database, and the ozone time-series model development are described in Section 5 this report.

ALTERNATIVE DESIGN VALUE METHODS

The Ozone Guideline allows the use of fitted distributions to calculate ozone design values, provided the fit is acceptable. The steps involved in fitting statistical distributions to air quality data include selecting the specific distribution and selecting the fitting method. There are two distinct approaches to fitting distributions to air quality data: (1) fitting parametric distributions to raw hourly or daily concentrations and (2) fitting extreme value distributions to the highest concentrations. Since the ozone design value is expressed in terms of concentrations in the upper tail of the distribution, most applications have focused on methods which fit the upper 5 to 10 percent of the distribution.

Breiman Tail Exponential Method

Under this method, two parameter tail exponential distributions were fitted to the upper $100p$ percent of the daily maximum concentrations using the maximum likelihood estimators as described by Breiman et al. (1978). Separate calculations were performed for 5 percent and 10 percent exponential tails. Approximate 95 percent confidence bounds for design values were obtained from each of the tail exponential distributions. Assuming that the upper tail distribution is approximately exponential, it follows that the mean upper tail concentration has approximately a gamma distribution. Therefore, an approximate 95 percent confidence interval for x_p is given by

$$lower\ limit = \hat{x}_{P_0} + \frac{m\hat{a}\ \log(p_0/p)}{G^{-1}(0.975)}$$

$$upper\ limit = \hat{x}_{P_0} + \frac{m\hat{a}\ \log(p_0/p)}{G^{-1}(0.025)}$$

where $G^{-1}(\theta)$ is defined as the 100 θth percentile of the gamma distribution, with density proportional to $x^{m-1}\ e^{-x}$ (the sum of m independent exponentially distributed variables, each with mean 1).

California Air Resources Board Method

This method, developed by Larry Larsen of the California Air Resources Board (see CARB, 1992), is an extension of the tail exponential approach developed by Breiman in which multiple tail exponential distributions are fitted to the top 100p percent of the daily maximum concentrations for 100p ranging from 5 percent to 20 percent. A separate design value is estimated for each distribution by calculating the 100 $\times$ (364/365)th percentile of the distribution. A weighting factor is assigned to each tail estimate based on a chi-square goodness-of-fit statistic for the tail. The final design value estimate is then taken to be the weighted average of the individual estimates. Software for implementing this method was obtained directly from Larsen. The software includes a provision for applying a calibration factor to the estimated design value. The calibration procedure consists of raising the estimated value (in pphm) to the 0.983 power. The calibration factor was determined by Larsen in a way that recognized the expected discrepancy between the tail-exponential method and the EPA tabular method, since the EPA method is expected to be biased low on theoretical grounds. According to the CARB (McGuire, 1994), the calibration factor estimate recommended by Larsen is based on ozone data from monitoring sites throughout California and was selected to produce design value estimates at a "suitable midpoint" between the uncalibrated method and the EPA method. For comparison purposes, the Larsen method was applied both with and without this calibration factor.

Distribution Fitting Method

The Breiman and Larsen methods are just two possible approaches to fitting parametric distributions to the upper tail of air quality distributions. In the comparisons that follow, exponential and Weibull distributions were fitted to the upper 5 percent of the three

year distribution for 1987–89 using a procedure that estimated the distribution parameters by maximum likelihood using a Newton-Raphson algorithm (SAS, 1990).

Percentile Method

Although not widely used, this method was included for purposes of comparison with the other methods. The 100 × 364/365th percentile was estimated directly from the sorted daily maximum concentrations using the SAS UNIVARIATE procedure. This method is identical to the table look-up method if no days are missing during the ozone monitoring season.

COMPARISONS USING AMBIENT OZONE DATA

A database was constructed that contained the daily maximum 1-hour ozone concentrations for all sites in the AIRS database for the years 1980 through 1990. Daily maximum concentrations were extracted from these data. This database was used for those comparisons that focused on the changes in attainment status and on the impact of varying the number of years used to estimate the design value. Since the "true" design values are unknown, design value estimates obtained from each method can only be compared relative to each other.

This database was supplemented with additional ozone monitoring data from the period 1989–91 to provide an indicator of current status (EPA, 1992). For the metropolitan area comparisons using the 1989–91 data subset, only stations with valid daily maxima on at least 75 percent of days during the federally designated ozone season (April - October for both areas) were used. All other stations were dropped from the analysis to focus attention on how the various design value estimation procedures differ when reasonably complete data sets are available. For stations meeting the seasonal data completeness criteria, any daily maxima not meeting the above validity criteria were set to missing if they occurred during the ozone season.

Selected Metropolitan Area Results, 1989-91

Design values were estimated for four different design value estimation methods: (1) the EPA tabular method, (2) the percentile method, (3) the Breiman tail-exponential method, and (4) the California Air Resources Board (CARB-Larsen) tail-exponential method. For the Breiman method, estimates were made using both the upper 5 percent (5% tail) and upper 10 percent (10% tail) of the concentration distributions. For the CARB method, estimates were obtained both with and without the calibration factor. These comparisons were made using monitoring data from three groups of nonattainment areas:

1. New York–New Jersey–Long Island and Greater Connecticut nonattainment areas

2. Chicago–Gary–Lake County and Milwaukee-Racine nonattainment areas.

3. Los Angeles-South Coast Air Basin nonattainment area.

Design values were calculated by the above methods for monitoring sites in the three selected areas. Only data for the high ozone season (May through October) were used for the South Coast Air Basin analyses, although the designated ozone season is the entire year. Average and maximum values across monitoring sites in each region are listed in Table 6-1 and depicted graphically in Figures 6-1 through 6-3. Differences in the average value obtained by each method are equivalent to the mean of the differences between the methods across sites, while the maximum values indicate the design value which would be assigned to the nonattainment area, assuming design values from any monitors not included in this analysis are smaller.

Except for design values based on the 10 percent tail exponential (and the 5 percent tail exponential in Los Angeles), the various methods produced estimated average design values that are within 0.01 ppm of each other. This is also true of the maximum design values in each area, except in Los Angeles the differences were as large as 0.02 ppm. Of course, results at individual monitors may show wider variations (see Appendix D for a tabular summary of the estimates for each monitoring site in these three metropolitan areas). A review of Figures 6-1 through 6-3 indicates that the percentile method produces results essentially identical to the fourth highest. This result is expected since the selection criteria were established so that missing data would not be a major factor. Design values obtained by fitting a tail exponential distribution to the top 10 percent of the data values are higher than even the third highest concentration in each area, both on average and for the maximum values. Lower design values were obtained from tail exponentials fitted to the top 5 percent of the ozone values although, on average, they are still higher than the third highest for the New York and Los Angeles areas. These results indicate that the portion of the distribution of daily maximum concentrations to which the tail exponential is fitted can have a significant impact on the estimated design value. This is the primary motivation for using Larsen's approach, which uses multiple tails fitted to various portions of the upper end of the distribution and weights the results toward those tails which best fit the available data.

Larsen's method, on average, produces estimated design values that fall between the third and fourth highest concentration in the New York area, are equal to the fourth highest in Los Angeles, while in the Chicago area, the Larsen method produces slightly lower values on average. In all cases, maximum values from the Larsen method are essentially identical to those of the fourth highest. Recalculation of design values using Larsen's method with the calibration factor removed yields estimated design values that fall between the third and fourth highest concentrations in Chicago, equal the third highest in Los Angeles, but are higher, on average, than the third highest concentration in New York.

A further comparison of Larsen's method with the fourth highest concentration is presented in Figure 6-4, which depicts the results for each monitoring site in the New York and Chicago areas both with and without Larsen's calibration factor. The effect of excluding the calibration factor is simply to shift the cloud of points a little to the right, with the large

TABLE 6-1. Average and maximum estimated design values (ppm) for the period 1989–91 using each estimation method (4th High = fourth highest concentration, 3d High = third highest concentration, Pcntl = percentile method, 5%TlExp = 5 percent tail exponential, 10%TlExp = 10 percent tail exponential, Larsen = CARB method, LarNoCal = CARB method without calibration factor).

					5% TlExp 95% Confidence Interval			10% TlExp 95% Confidence Interval			
	4th High	3rd High	Pcntl	5%TlExp	Lower Bound	Upper Bound	10%TlExp	Lower Bound	Upper Bound	Larsen	LarNoCal
Chicago Area											
Average:	0.118	0.122	0.118	0.123	0.113	0 137	0.126	0.116	0.138	0.113	0.118
Max:	0.151	0 164	0.152	0.161	0.146	0.183	0.168	0.153	0.187	0.151	0.158
New York Area											
Average:	0.140	0.146	0.140	0.150	0.138	0.168	0.159	0.146	0.177	0.144	0.151
Max:	0.165	0.175	0.166	0.175	0.159	0.199	0.185	0.167	0.209	0.166	0.175
Los Angeles Area											
Average:	0.21	0.22	0.22	0.25	0.22	0.30	0.26	0.23	0.30	0.21	0.22
Max:	0.28	0.30	0.30	0.32	0.29	0.38	0.34	0.31	0.39	0.28	0.30

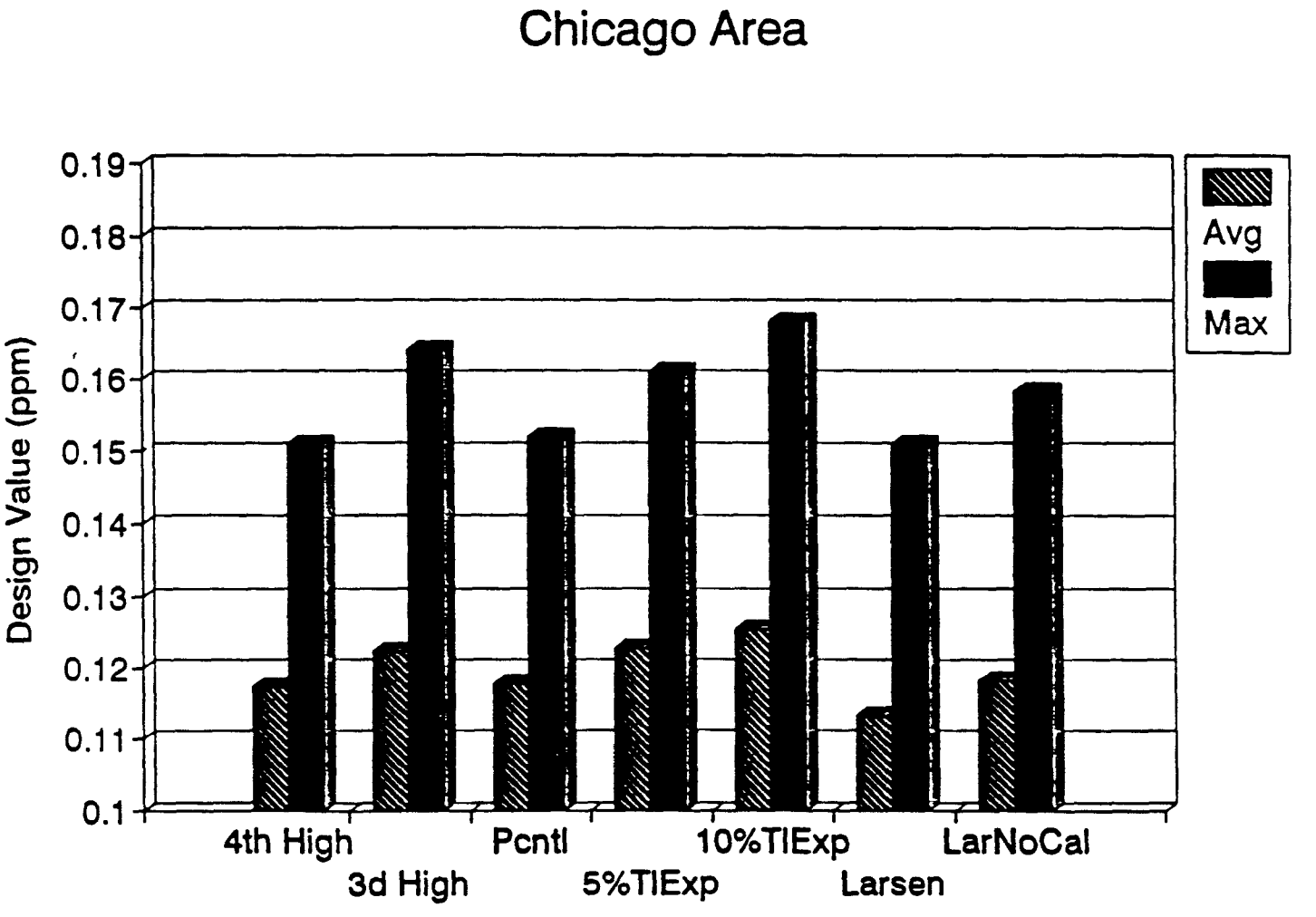


Figure 6-1. Average and maximum design values for monitors in the Chicago metropolitan area for alternative design value estimation methods.

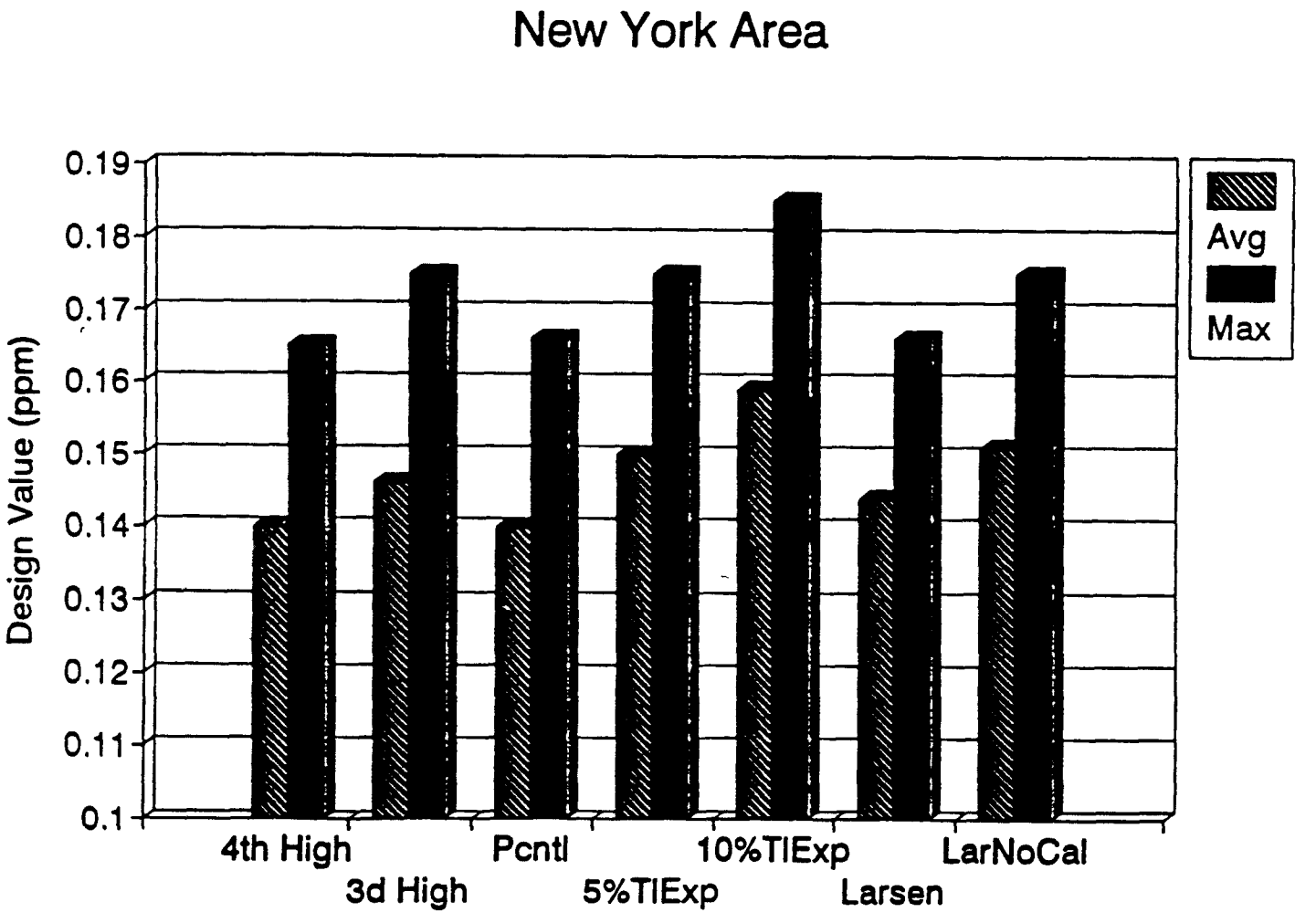


Figure 6-2. Average and maximum design values for monitors in the New York metropolitan area for alternative design value estimation methods.

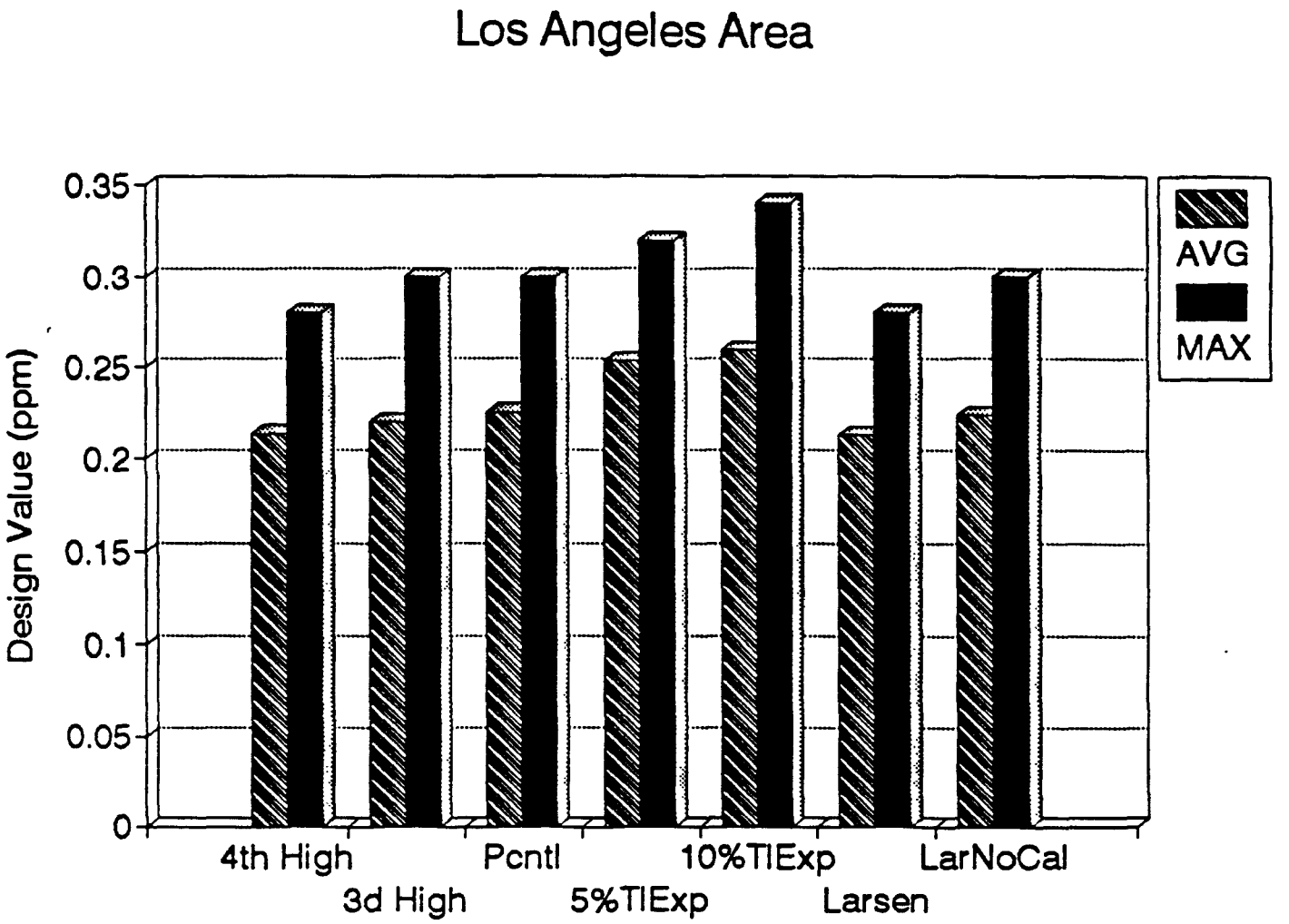
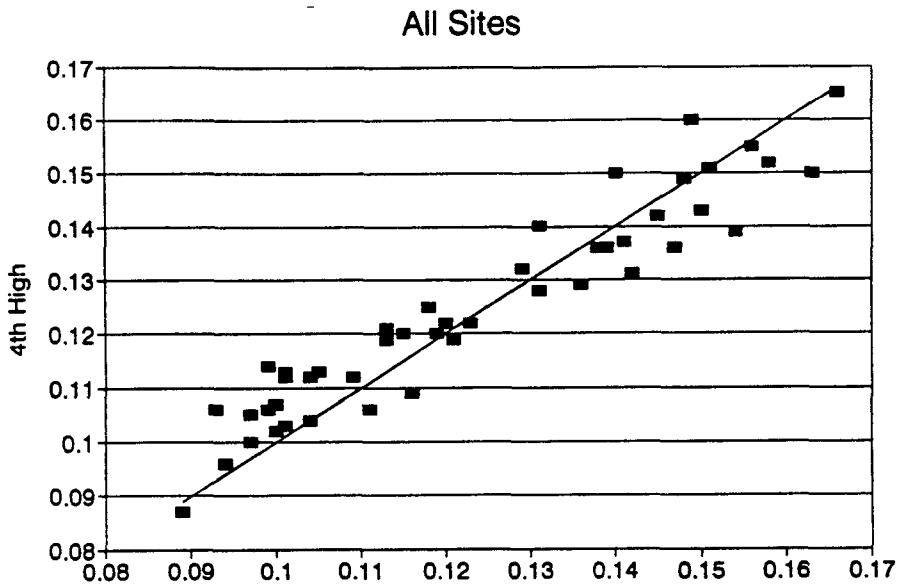


Figure 6-3. Average and maximum design values for monitors in the Los Angeles-South Coast Air Basin area for alternative design value estimation methods.

(including calibration adjustment)



(excluding calibration adjustment)

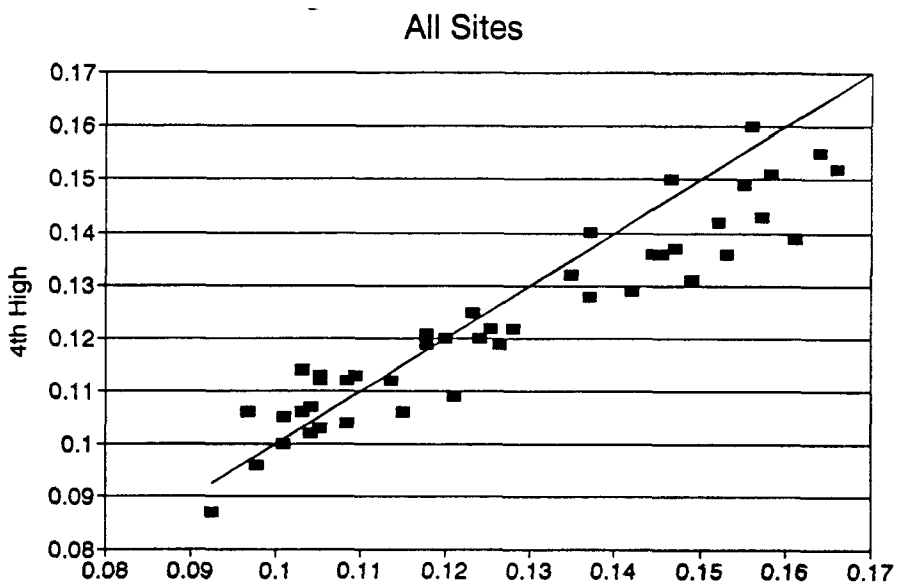


Figure 6-4. Comparison of design values estimated using the California Air Resources Board (CARB - Larsen) method with the fourth highest daily maximum 1-hour concentration at all sites in the Chicago and New York metropolitan areas, 1989-91.

values being shifted farther than the small values. (The Los Angeles data are not shown due to the scaling that would be required to accommodate their higher concentration values.) Recall that Larsen's calibration factor is incorporated into the CARB method as a means of targeting the EPA fourth high concentration, on average. In interpreting these figures, it is important to keep in mind that the spatial correlation in ozone concentrations implies that each point is not an independent observation. With this caveat in mind, these results suggest that, at least for the cases examined here, Larsen's method produces design value estimates that tend to be slightly lower on a site-by-site basis than the fourth highest concentration for values below about 0.13 ppm and slightly higher for values above 0.13 ppm. Removing the calibration factor from Larsen's method results in smaller differences for the lower design values but greater differences in values above 0.13 ppm.

Comparisons for All Ozone Sites, 1987-89

Because almost all of the ozone nonattainment area classifications were based on 1987-89 ozone data, design value estimates were made for all sites for this three-year period. Figure 6-5 presents the 5th and 95th percentile differences for comparisons among 1987-89 design values estimated using the EPA tabular method, the Breiman tail exponential approach, and Weibull and exponential distributions, which were fitted to the combined three-year distribution of ozone concentration data using the maximum likelihood approach

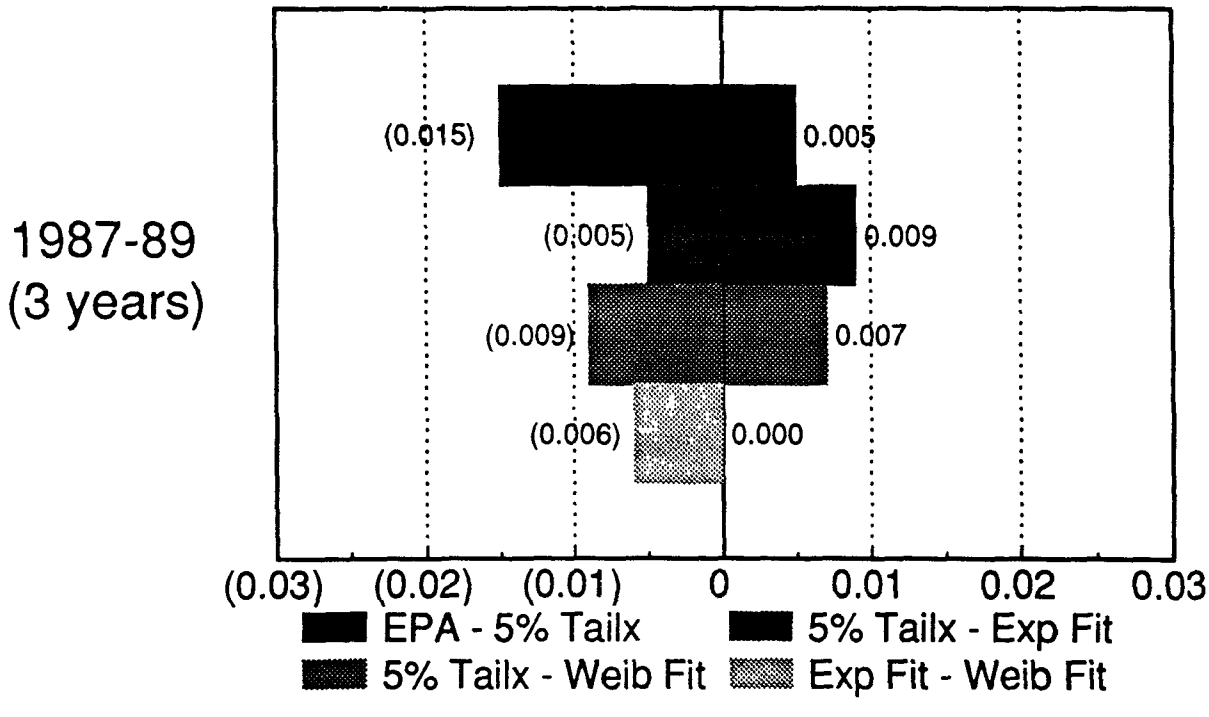


Figure 6-5. 5th and 95th percentile differences for comparisons among alternative ozone design value estimation procedures.

described above. Differences in the several parts per billion range were found among the various distribution fitting methods. As the figure indicates, the tabular method yields design values that tend, on average, to be less than those obtained with the tail exponential method. Design values estimated using the Breiman tail exponential approach, which fits a separate distribution to each year prior to estimating the design value, tend to be slightly higher than those obtained from an exponential distribution fitted to the combined three-year distribution. The Weibull fit gave higher estimates than the exponential fitted to the combined distribution.

Comparisons Among Multi-year Tabular Method Design Value Estimates

Appendix H to the ozone standard specifies that the three most recent years of ambient ozone data should be used to judge compliance with the standard. EPA guidance also requires that design values be estimated for the same three-year compliance period. As noted previously, one potential way to reduce the year-to-year variability in design values is to use more years of data. Several different evaluation criteria can be used to compare the results of varying the number of years of data in the tabular method of estimating ozone design values. One measure is to examine the variability in the ozone design value concentration at a site, among sites, and among geographical areas.

Figure 6-6 presents the 5th and 95th percentile differences for the comparisons between the 3-year estimate of the ozone design value and the estimates based on 4, 5, and 6 years of data at all sites reporting data. The site differences are grouped by the three end years of 1988, 1989 and 1990. Ninety percent of the differences fall within the range shown on the chart. Differences plotted to the right of zero indicate that the 3-year design value was larger than the 6-year estimate, and conversely, differences to the left of zero indicate that the 6-year estimate was larger. The largest differences are found for the period ending in 1988, with the three-year estimate ranging from 0.01 ppm greater than the longer periods, to 0.023 ppm less than the longer-term estimates. The largest differences are found between the 3-year and 6-year estimates ending in 1988, likely due to the fact that the 6-year estimates ending in 1988 span two peak ozone years, 1988 and 1983. In every case except one (i.e., 3-year versus 4-year ending in 1989) the 3-year ozone design value estimates tend to yield lower values than the estimates based on longer time periods.

The previous comparisons have looked at the variability among monitoring sites of design values estimated using the multi-year tabular method. Table 6-2 shows the variability in the number of areas (i.e.. CMSAs, MSAs, and counties) with design values equal to or greater than 0.125 ppm ozone as estimated by the multi-year tabular method. In these comparisons, the highest design value at any site in the area is selected as the design value for the area for that time period. All sites reporting data for the period 1980 through 1990 are included in the analysis, even if they stopped reporting data at some point during this time period. The results are also presented graphically in Figure 6-7. In both the table and the graph, the number of areas with design values greater than or equal to 0.125 ppm is displayed at the end-year of the designated time period.

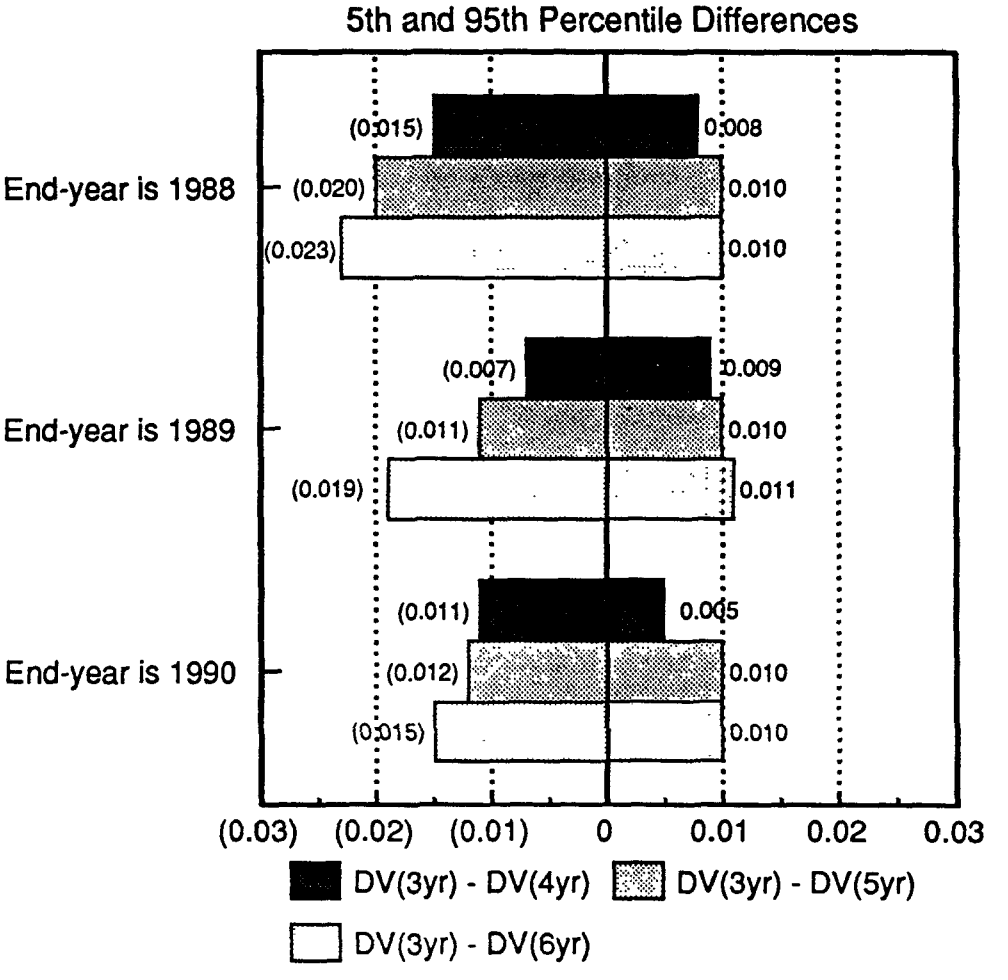


Figure 6-6. 5th and 95th percentile differences among multi-year ozone design value estimates.

Table 6-2. Comparison of Number of Areas with Multi-year Tabular Method Ozone Design Values Equal to or Greater than 0.125 ppm

Number of Years in Ozone Design Value Estimate	Number of Areas With Ozone Design Values Greater Than NAAQS										
	End-year of Time Period Used to Estimate Design Value										
	80	81	82	83	84	85	86	87	88	89	90
1-YEAR	97	73	61	90	53	49	53	68	112	39	48
2-YEARS	-	97	75	85	77	56	55	69	108	99	55
3-YEARS	-	-	98	88	80	74	59	70	104	98	98
4-YEARS	-	-	-	101	86	75	74	71	103	95	96
5-YEARS	-	-	-	-	98	83	74	82	100	94	93
6-YEARS	-	-	-	-	-	96	84	84	104	91	92

Given the pattern in ozone data that we have seen during the past 11 years—several peak years followed by years with much lower ozone concentrations—it is not surprising that the greatest variability in the number of areas with design values greater than or equal to 0.125 ppm is associated with the 1-year estimates. The largest number of such areas is associated with the 1-year design values for 1988, and the smallest with the 1-year estimate for 1989. The number of areas with 1-year ozone design values greater than or equal to 0.125 ppm in 1983 is also larger than the number of areas for the 2-year and 3-year estimates. The reason the number of areas based on the 4-year design values for 1983 is greater than the estimates for shorter time periods is that two peak ozone years (1980 and 1983) fall in this time period. Finally, it is worth noting that there is less variability in the number of areas with design values greater than the level of the ozone NAAQS for the periods ending in 1988–90 than during previous years. This is likely due to the fact that there was a single dominant year (1988) for peak ozone levels for all multi-year data periods (except the 6-year period ending in 1988, which includes the 1983 peak ozone year).

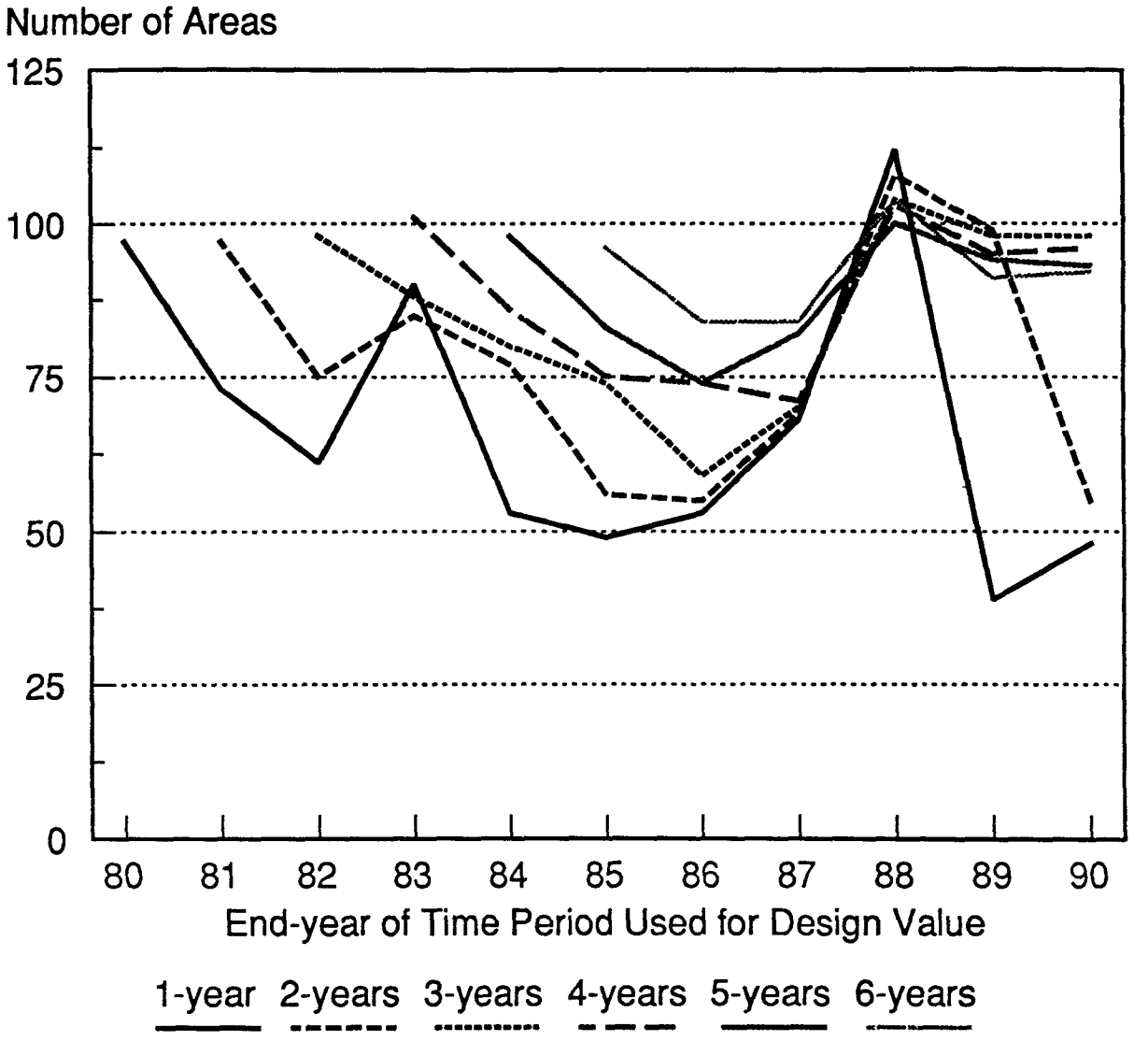


Figure 6-7. Number of areas with multi-year tabular method ozone design values greater than or equal to 0.125 ppm.

The Clean Air Act Amendments of 1990 required that each nonattainment area for ozone be classified as a Marginal Area, a Moderate Area, a Serious Area, a Severe Area, or an Extreme Area based on the design value for the area. These nonattainment area classifications define the primary standard attainment date and the emissions control requirements for the area. The design value levels associated with each classification were listed below in Table 6-3. The attainment dates associated with each classification were listed previously in Table 1-1.

Table 6-3. Ozone Nonattainment Area Classifications

Area Class	Ozone Design Value (ppm)
Marginal	0.121 up to 0.138
Moderate	0.138 up to 0.160
Serious	0.160 up to 0.180
Severe	0.180 up to 0.280
Extreme	0.280 and above

On November 6, 1991, EPA published the ozone nonattainment area designations and classifications (40CFR Part 81). In most cases, the area classifications were based on ozone design values estimated using the tabular method with data from 1987-89 (3 years of data). A few areas had already submitted their 1990 ozone data, and the area's classification was based on data from 1988-90. The potential variability in ozone nonattainment area classifications resulting from varying the number of years of data used to estimate design values was examined. Table 6-4 presents the impact on ozone area classifications of varying the number of years used in the multi-year tabular design value method. The table focuses on data windows ending in 1989, because most of the area classifications were based on data from this period. However, to maintain consistency with the summary presented in Table 6-2, this table continues to use CMSAs, MSAs, and counties to define the geographic area, and not the nonattainment area boundaries of the designated nonattainment areas.

As in the case of the other indicators, the largest differences in ozone area classifications are associated with design values based on a single year of data. There is close agreement between classifications based on three and four years of data, while the longer data windows (5- and 6-year) have fewer nonattainment areas (four and seven fewer, respectively) than the 3-year estimates. There is some downward movement in area classifications evident in the longer time periods; that is, severe areas have moved downward to serious, serious areas to moderate, and moderate areas to marginal.

Table 6-4. Impact on Ozone Area Classifications of Varying the Number of Years when Estimating the Ozone Design Value Using the EPA Tabular Method

Clean Air Act Ozone Classification	Number of Areas (CMSA/MSA/County)							
	Single Year D.V.			Multi-year Design Value				
	1987	1988	1989	1988-1989	1987-1989	1986-1989	1985-1989	1984-1989
Extreme	1	1	1	1	1	1	1	1
Severe	6	11	4	7	9	9	7	6
Serious	17	23	4	20	16	15	14	15
Moderate	22	45	12	36	33	33	33	29
Marginal	22	32	18	35	39	37	39	40
Total	68	112	39	99	98	95	94	91

The potential variability in area classifications resulting from changing the three-year data window used to assess compliance is shown dramatically in Table 6-5, which contrasts the initial nonattainment area classifications (which were generally based on 1987–89 data) with those that would result from the 1989–91 air quality update, which is the first 3-year compliance period to exclude 1988. Of the original 98 nonattainment areas, 42 nonattainment areas have 1989–91 ozone data that demonstrate compliance with the standard; 12 of 33 moderate and 30 of 42 marginal nonattainment areas meet the ozone standard based on 1989–91 data (EPA, 1992). Since that listing, seven areas have been redesignated to attainment; Charleston, WV, Greensboro–Winston–Salem–High Point, NC, Kansas City, KS-MO, Knoxville, TN, Parkersburg, WV, Raleigh-Durham, NC and Cherokee County, SC. For the current 1991–93 period, 48 of the remaining 91 nonattainment areas meet the ozone standard (EPA, 1994). A complete listing of 1991–93 ozone design values for the original 98 nonattainment areas can be found in Appendix E.

Table 6-5. Comparison of number of nonattainment areas in Clean Air Act classification categories with number of areas in classification ranges based on 1989-91 ozone monitoring data.

Clean Air Act Classification	Number of Areas with 1990 CAAA Classification	Number of Areas in Classification Range for 1989-91 Design Values
Extreme	1	1
Severe	9	2
Serious	12	7
Moderate	33	21
Marginal	43	24
Less than O_3 NAAQS	n/a	42
Incomplete data	n/a	1
Total	98	98*

* Kansas City and Cherokee County, SC have already been redesignated to attainment.

Multi-year Design Value Estimates in Selected Cities

The above comparisons have focused on differences in design value estimates at the individual site level and among geographic areas. Figures 6-8 through 6-10 display multi-year (2-, 3-, 4-, and 5-year) table look-up ozone design value estimates for the period 1980 through 1990 in three large metropolitan areas; Atlanta, Chicago, and New York. These areas were selected because they each have several sites in their monitoring networks that have operated during this time period, and because they illustrate several different design value scenarios.

Atlanta

The trend in multi-year ozone design values in Atlanta is displayed in Figure 6-8. The ozone design values were estimated using all sites that reported data to AIRS for the years 1980 through 1990. The overall trend appears relatively flat during this period. The 2-year design value estimates exhibit the largest year-to-year differences. Focusing on the last three time periods, those ending in 1988, 1989 and 1990, reveals that the 2-year design value estimate was higher than the three longer-term estimates for 1988 and 1989, but significantly lower than the other three values in 1990, due to dropping 1988 out of the data window. The ozone design values based on three or more years track closely together during this 11-year period. The 3-year ozone design value estimates in 1989 and 1990 are slightly lower than the design values based on four and five years of data.

Chicago

Figure 6-9 presents the trend in multi-year ozone design values in Chicago for all sites reporting data to AIRS for 1980 through 1990. The "fishbone" pattern in the early years arises because the longer-term data windows continue to capture a special study site with the highest concentration recorded in 1980, that stopped monitoring early in 1981. The design value estimates are the same level in 1988 and 1989 for all four multi-year periods. The 2-year estimate for 1990 is significantly lower (by more than 0.02 ppm) than the longer-term estimates, reflecting the absence of the 1988 peak values and the much lower values recorded in 1989 and 1990.

New York City

Figure 6-10 presents the trend in ozone design values for all sites reporting data for the years 1980 through 1990 in the New York CMSA. As in Chicago, the "fishbone" pattern results from a discontinued site that recorded peak ozone levels in 1980. This becomes apparent when one focuses on the additional plot that displays ozone design values estimated only at sites with data in each year of the 11-year period. This latter plot also reveals a general downward trend in ozone design values in New York City. As in the other two cities, the 2-year design value estimates for 1988 and 1989 are greater than, or equal to, the 3-, 4-, and 5-year estimates. However, unlike these other two cities, in New York City, the 5-year design value for 1990 is lower than the 3-year and 4-year estimates.

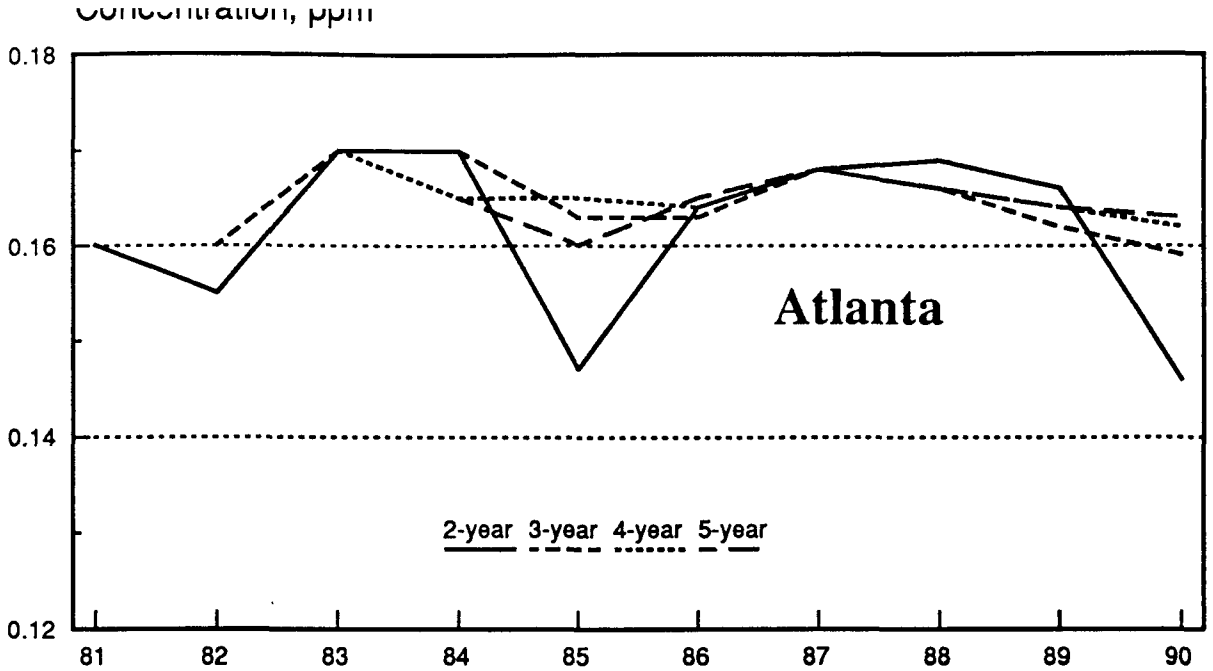


Figure 6-8. Trends in multi-year table look-up ozone design values in Atlanta, GA, 1980–90.

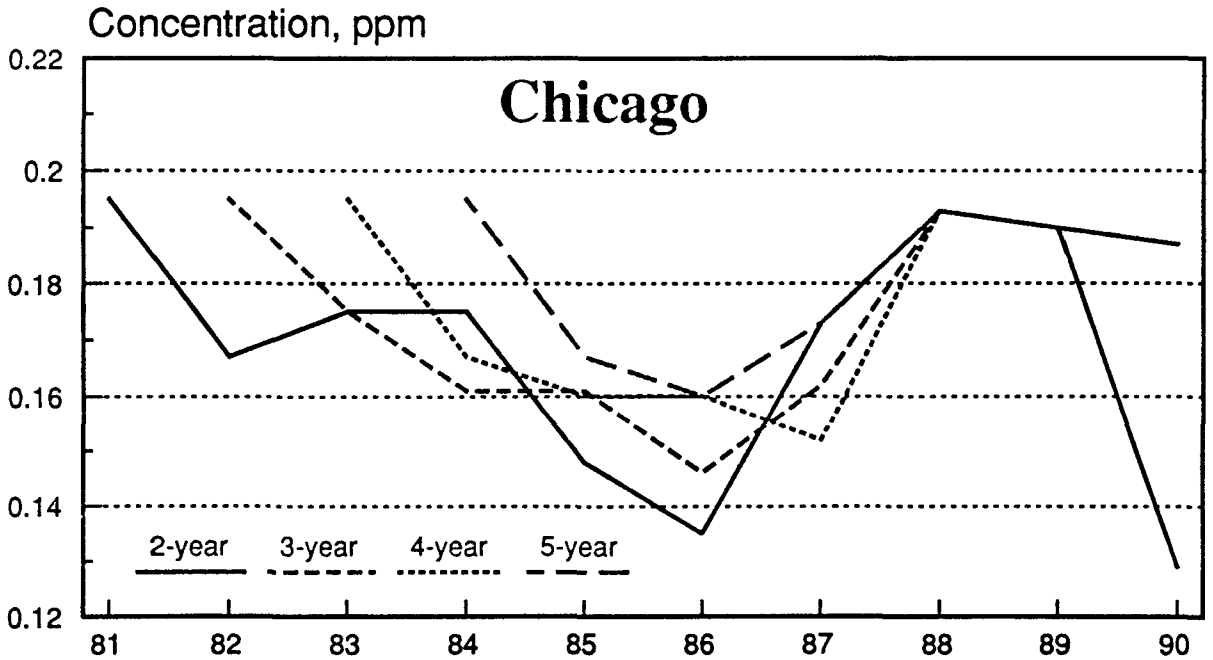
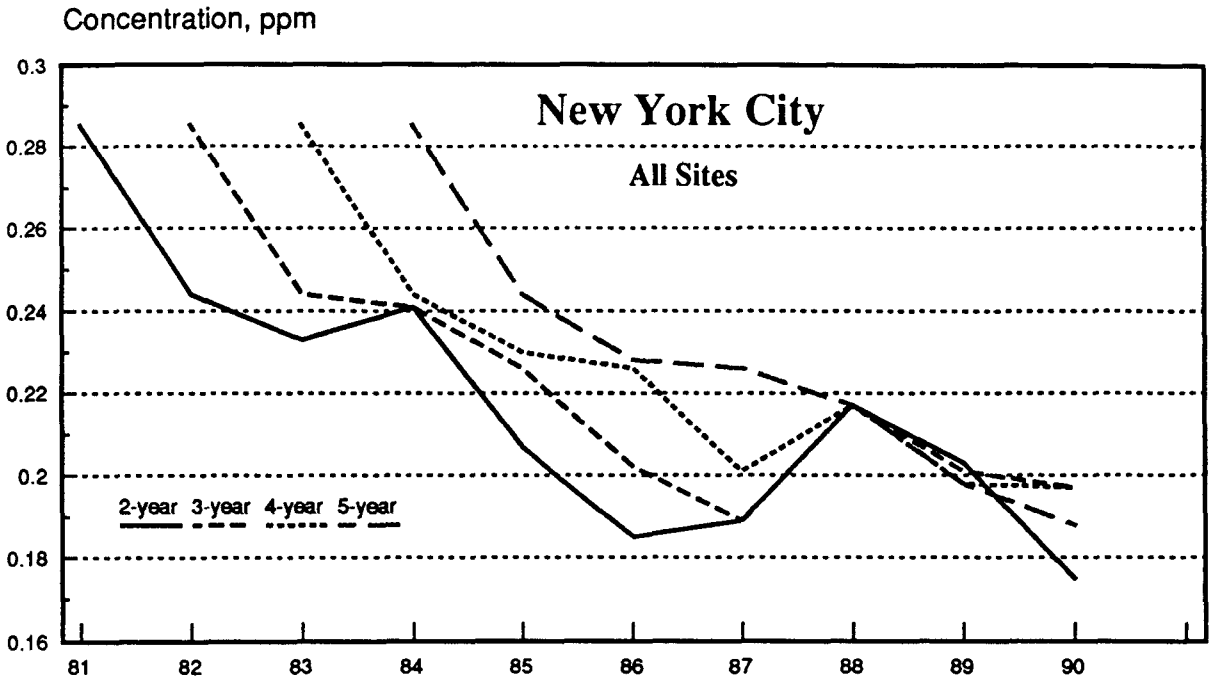


Figure 6-9. Trends in multi-year table look-up ozone design values in Chicago, 1980–90.



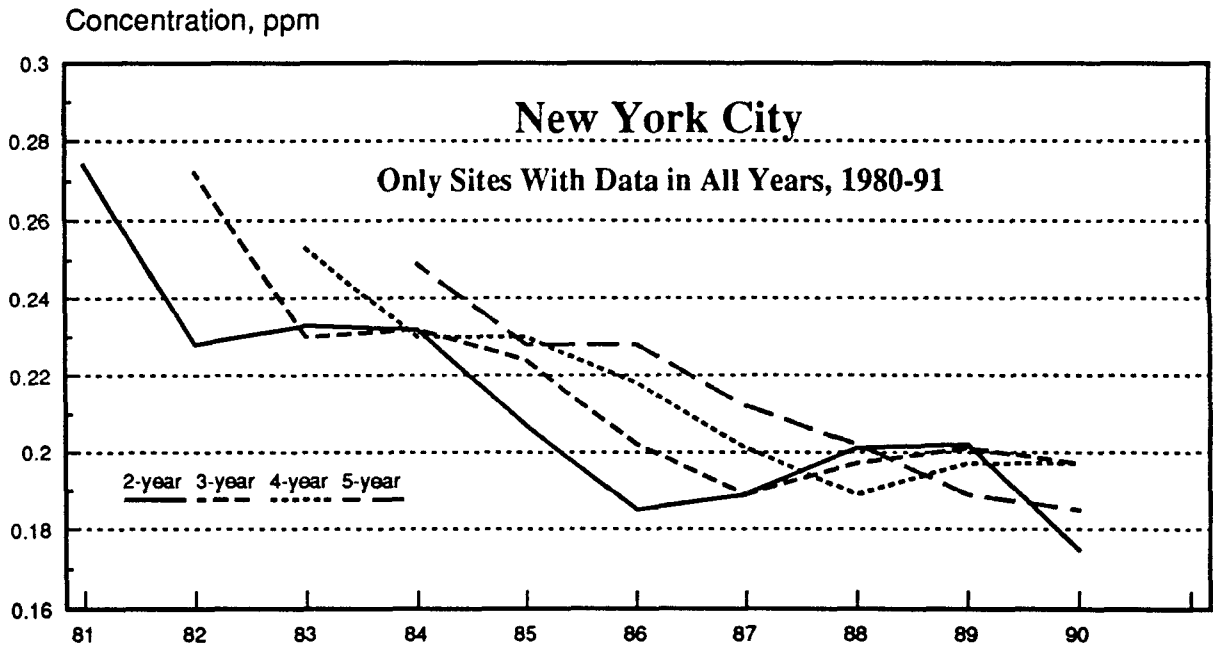


Figure 6-10. Trends in multi-year ozone design values in New York for all sites and sites with 11 years of data.

Summary of Findings from the Air Quality Design Value Comparisons

1. Although the "true" design value is not known, air quality monitoring data can be used to examine the relative differences among alternative methods for estimating ozone design values.

2. The EPA tabular design value method tends to give lower but more variable estimates for the ozone design value than some of the statistical modeling methods, such as the Breiman tail exponential approach. The tail exponential approach developed by the California Air Resources Board (CARB-Larsen) includes a calibration factor that was estimated to target the annual fourth highest concentration. In the selected study areas, the CARB-Larsen method was applied both with and without this adjustment. These comparisons suggest that, at least for the cases examined here, Larsen's method produces design value estimates that tend to be slightly lower on a site-by-site basis than the fourth highest concentration for values below about 0.13 ppm and slightly higher for values above 0.13 ppm. Removing the calibration factor from Larsen's method results in smaller differences for the lower design values but greater differences in values above 0.13 ppm.

3. Design values were estimated for all ozone monitoring sites that collected data during the three-year period 1987–89, the time period used for most of the original ozone nonattainment area designations/classifications. Comparisons made among the EPA tabular method and more robust approaches (e.g., Breiman tail exponential, fitting Weibull and exponential tail distributions using maximum likelihood) revealed that the tabular approach tended to give slightly lower estimates of the design value.

4. Increasing the number of years used to estimate the design value reduces the year-to-year fluctuations in its value. Comparisons made for 3-year periods ending in 1988–90 had less variability in the design value estimates than during previous 3-year periods. This is likely due to the fact that there was a single dominant year (1988) for peak ozone levels during the 1988–90 time period.

5. Given the database available at the time, generally data through 1989, the use of more robust methods such as the tail exponential approach would not have significantly changed the initial ozone nonattainment area designations and classifications. Use of more years of data (i.e., 4 or 5 years) in estimating the design value would have resulted in lower classifications in only a limited number of cases. However, more recent data periods that do not include 1988 yield significantly different results. For the years 1989–91, the first 3-year compliance period that excludes the 1988 data, 42 of the original 98 nonattainment have ambient ozone meeting the standard. Seven of these areas have been redesignated to attainment. The most recent compliance period, 1991–93, has 48 of the remaining 91 nonattainment areas also meeting the ozone standard.

TIME-SERIES MODELING SIMULATION RESULTS

In this study we are using time-series models as a tool for evaluating alternative design value estimation methodologies. The ambient ozone database was used to develop a time-series model of the behavior of daily maximum ozone concentrations at key monitoring sites in selected metropolitan areas. This approach yields a time-series model that is representative of the variability of ozone concentrations at a site during the 11 year period 1980–1990. Given such a model, large numbers of random simulations of single seasons of daily maximum ozone values can be generated which allow the "true" design value and estimated design values for any number of methods to be calculated over a large number of years. The true design value is also known as the characteristic largest value and is abbreviated as "CLV" throughout this section. The CLV is the concentration exceeded once per year on average over a hypothetically infinite monitoring period. Thus both the inherent biases and precision of alternative design value methods can be studied using a wide variety of averaging years. These data sets have no missing values and therefore are free from this source of error.

Methodology

The time-series simulation model described in Section 5 was applied to monitoring sites in five geographically diverse metropolitan areas: Atlanta, GA; Charlotte, NC; Chicago, IL-WI; Houston, TX; and New York, NY-NJ-CT (Table 6-6). Three sites each were examined in the Charlotte, Chicago, and New York areas and a single site each in the Atlanta and Houston areas. Of the eleven sites, six were best described by a time series with a shock term that has an extreme value distribution and five sites by a normally distributed shock term. The site-years at a given site, and the sites in a given metropolitan area, tended to be dominated by a single shock term distribution type. As discussed in Section 5, the extreme value shock term implies that the daily maximum ozone concentrations have Weibull distributions. The normal shock term implies a normal distribution of the daily maximum ozone concentrations.

The behavior of six design value estimation methods and one surrogate design value estimation method was studied using time-series models derived for each site. A single simulation generated one ozone season of daily maximum ozone concentrations. To compute a single design value required N years (seasons) of daily maximum data. The EPA table lookup method is a 3-year method. But for the purposes of this study cases with N = 1, 2, 3, 4, 5, 6, 10, and 250 were studied. In each of these cases about 3,000 seasons of simulated data were generated. Contiguous simulations would be grouped into N simulations each and N-year design values calculated by each method. The average and standard deviation of the N-year design values were calculated from the N-year simulations for each site. The first 35 calculated N-year design values for each method were also recorded. These data are displayed in Appendix C.

Table 6-6. Sites studied in time-series comparisons of design values.

Metropolitan Area	States Covered	Site Code	Shock Term Distribution	Site Years
Atlanta	GA	13 089 0002	Extreme Value	11
Charlotte	NC	37 119 0034	Extreme Value	10
		37 119 1005	Extreme Value	10
		37 119 1009	Extreme Value	11
Chicago	IL-WI	55 059 0002	Lognormal	11
		17 097 1002	Lognormal	11
		17 031 7002	Lognormal	11
Houston	TX	48 201 1034	Lognormal	10
New York	NY-NJ-CT	34 023 0006	Extreme Value	10
		36 085 0067	Extreme Value	11
		09 001 3007	Lognormal	11

The 250-year design values were taken as sufficiently accurate estimates of the limiting values for each of the computed design values. Their standard errors were about 0.0003 ppm (0.2% of the design value) for the six extreme value shock sites and about 0.001 ppm (0.5-0.7% relative standard error) for the normal shock sites.

Two table look-up design value estimation methods were studied: the EPA designated procedure which in the case of no missing data takes the $(N+1)$th largest value in N years of daily maximum ozone data as the design value estimate and an alternative procedure which takes the Nth largest value in N consecutive years of data. Four different methods of estimating the tail-exponential design value were studied. A method was defined by whether it used the upper 5 percent or 10 percent of the distribution of daily maximum ozone concentrations and which of two methods it used to handle N years of data. The two methods were (1) combining the N years into a single distribution and (2) fitting a tail-exponential distribution to each year of data, expressing the N-year distribution as a sum of equally probable individual year distributions, and iteratively determining the concentration whose expected exceedance rate is once per year. The second method is the conditional probability approach detailed in the 1979 EPA Guideline for the Interpretation of Ozone Air Quality Standards (EPA, 1979) and described in Section 4.

In the case of both table look-up methods the limiting design value as N increases without limit is the true underlying ozone design value, the characteristic largest value (CLV). The limiting design values for the tail-exponential methods are not necessarily the CLV since the 5 percent and 10 percent upper tails in general are only approximated by an exponential distribution.

A single surrogate design value, the 95th percentile of the daily maximum distribution, was investigated. A surrogate design value does not directly estimate the underlying design value. Instead, a parameter of the underlying distribution of daily maxima is estimated which has less variability than the direct design value estimators. The less variable surrogate estimator can then be used either in place of the direct estimators or to calculate a more stable estimate of the underlying design value, the CLV.

For any site the design value estimates for the same N years are calculated from the same simulated data set. Thus, the pattern of design value estimates within a site is quite sensitive to subtle differences.

Comparison of Alternative Design Value Estimation Methods

Table 6-7 compares the 3-year design value estimates for the eleven study sites using the EPA table look-up, the alternative table look-up, and the 5 percent and 10 percent tail-exponential employing the conditional probability method to compute multi-year design values. The four methods, for the most part, are in fair agreement both in average value and standard deviation. The EPA table look-up design value is always the smallest. When the time series shock term for a site has an extreme value distribution, the 10 percent

Table 6-7. Results from 1,000 time-series simulations of three-year design value estimates from alternative design value estimation methods in five selected metropolitan areas.

Metropolitan Area	Site	Distribution Characteristic Largest Value CLV	Average EPA Tabular Method Design Value w/(std. dev.)	Average Alternate Tabular Method Design Value w/(std. dev.)	Average Breiman 5% Tail-Exponential Design Value w/(std. dev.)	Average Breiman 10% Tail-Exponential Design Value w/(std. dev.)
Atlanta	0002	0.156	0.152 (.015)	0.157 (.017)	0.157 (.015)	0.159 (.015)
Charlotte	0034	0.133	0.128 (.011)	0.132 (.011)	0.131 (.010)	0.133 (.010)
	1005	0.130	0.126 (.011)	0.129 (.012)	0.129 (.011)	0.131 (.011)
	1009	0.139	0.135 (.010)	0.138 (.011)	0.138 (.010)	0.140 (.010)
Chicago	0002	0.157	0.149 (.025)	0.157 (.028)	0.155 (.025)	0.154 (.024)
	1002	0.132	0.128 (.014)	0.134 (.016)	0.132 (.014)	0.133 (.013)
	7002	0.137	0.132 (.015)	0.138 (.018)	0.136 (.016)	0.136 (.015)
Houston	1034	0.218	0.212 (.030)	0.225 (.035)	0.217 (.028)	0.215 (.025)
New York	0006	0.172	0.166 (.018)	0.172 (.020)	0.171 (.018)	0.174 (.018)
	0067	0.160	0.154 (.014)	0.159 (.015)	0.159 (.014)	0.162 (.014)
	3007	0.218	0.206 (.032)	0.217 (.035)	0.213 (.033)	0.213 (.032)

() indicates standard deviation

tail-exponential design value exhibits the largest design value. The alternative table look-up design value tends to be the next highest, while the 5 percent tail is either equal to the alternative table look-up value or slightly smaller. When the shock term is normally distributed the alternative table look-up design value is always the largest. The 10 percent tail-exponential value is next highest. The 5 percent tail-exponential is either equal to the 10 percent exponential tail value or slightly smaller.

Comparison of Biases of 3-Year Design Values

The bias of the design values in any row (site) of Table 6-7 is obtained by subtracting the CLV from the design value in the same row. The biases appear to vary with size of the design value, nature of the shock term distribution, and possibly other site characteristics. The largest biases occur with the New York #3007 and Houston #1034 sites, both of which exhibit design values above 0.20 ppm. The biases for the other sites form a more consistent pattern and are summarized in the following table:

Summary of Biases of Alternative Ozone Design Value Estimates
(Sites with design values below 0.20 ppm)

	Median	Range*
EPA Table Look-up	-0.005	-0.004 to -0.008 ppm
Alt. Table Look-up	0.000	-0.001 to 0.002 ppm
5% Tail-Exponential	-0.001	-0.002 to 0.001 ppm
10% Tail-Exponential	0.001	-0.003 to 0.003 ppm

*New York #3007 and Houston #1024 sites excluded

Inclusion of the New York and Houston sites does not affect the median biases but significantly extends their range. The EPA tabular method displays a consistent negative bias. The other three measures exhibit relatively little bias. There is a suggestion that the 5 percent tail-exponential bias tends to be slightly negative and the 10 percent tail-exponential slightly positive. The range over sites of the 10 percent tail-exponential bias is slightly greater than that of the 5 percent tail-exponential and the alternative table look-up. This observation suggests a slight advantage of the 5 percent tail-exponential over the 10 percent tail-exponential in that it leads too greater uniformity in design value over sites.

Figure 6-11 provides another view of the data in Table 6-7. The four design value biases for the same site fall along the same vertical line in the figure since the CLV has a single value for each site. To obtain separation between the Houston and New York sites the Houston site's CLV was offset slightly to 0.22 ppm. The regression lines in Figure 6-11 serve primarily as visual aids. The biases tend to vary with site and possibly with the

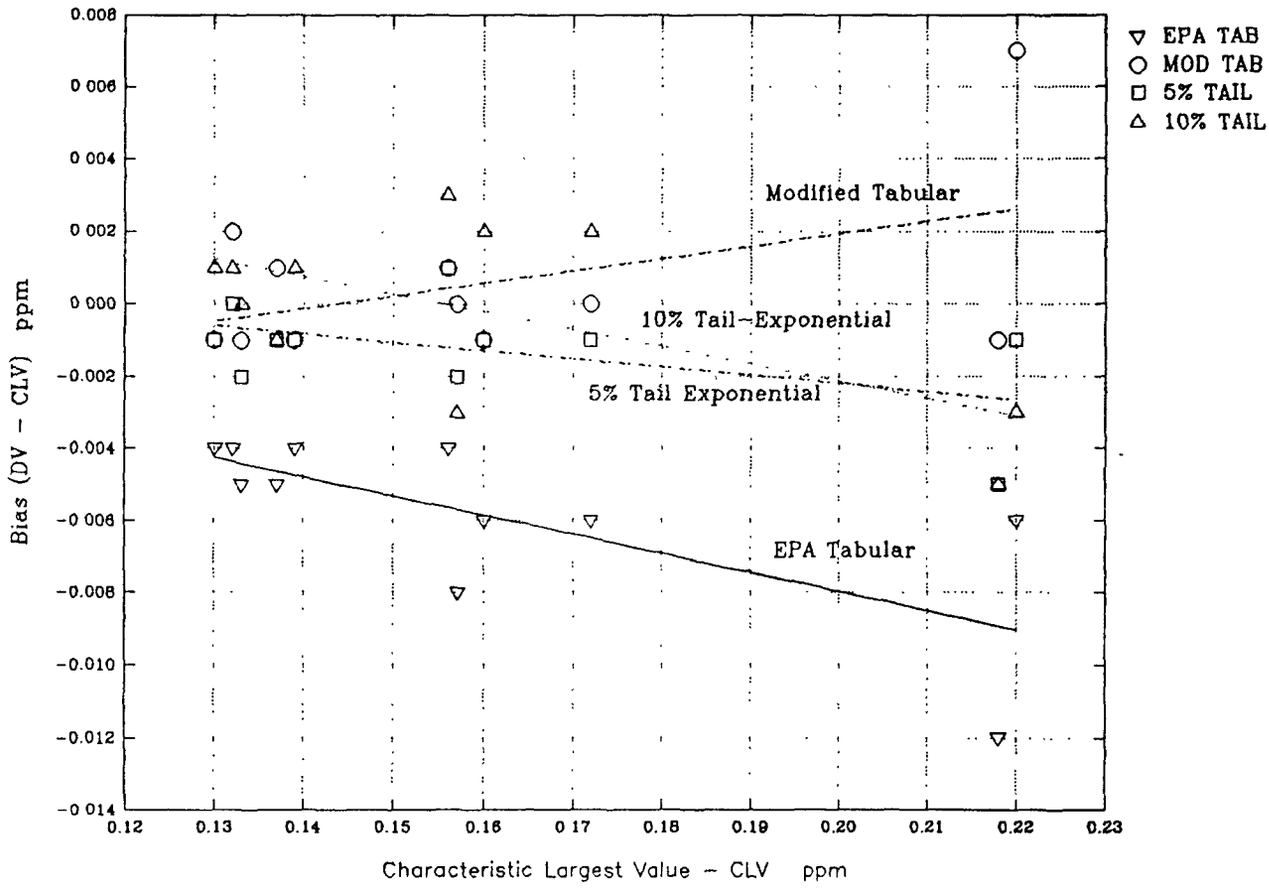


Figure 6-11. Design value bias versus characteristic largest value.

magnitude of the design value. The figure clearly shows the consistent negative bias of the EPA table look-up procedure. For CLV values below 0.18 ppm the alternative table look-up design value exhibits the least bias. The 5 percent and 10 percent tail-exponential design values biases are only slightly greater. At design values above 0.20 the spread in biases may be bigger than at levels closer to the ozone NAAQS design value (0.12 ppm). However, too few sites have been tested at these levels.

Comparison of Standard Deviations of 3-Year Design Values

The 3-year design value standard deviations in Table 6-7 are plotted against their respective design values in Figure 6-12. There is a strong dependence of standard deviation on the magnitude of the design value: the larger the design value the larger the associated standard deviation. The data points for a given city tend to cluster together in the figure because the four design values methods are estimating the underlying design value fairly well, and because the standard deviations are primarily a function of the magnitude of the design values. There is also an effect of shock term distribution type. A wider spread exists in the standard deviations of the different design values at sites whose shock term is normally distributed compared to sites whose shock term has an extreme value distribution.

At the normal shock term sites, the greatest standard deviation belongs to the alternate table look-up design value, which also produces the largest design value of the four methods. The 10 percent tail-exponential design value has the smallest standard deviation. The EPA table look-up and 5 percent tail-exponential have intermediate standard deviations and on average have close to the same standard deviation.

At the extreme value sites, the alternate table look-up procedure continues to exhibit the largest standard deviation but not the largest design value. The standard deviations of the EPA table look-up and the 5 percent and 10 percent tail exponential design values are all about equal.

The relative positions of the data points in Figure 6-12 for both the alternative and EPA table look-up methods roughly conform to the slope of the regression line. The difference is largely explained by the relative magnitudes of the respective design values. The positions of the data points of the 5 percent and 10 percent tail-exponential design values relative to the two table look-up design values do not conform to the slope. Their standard deviations are clearly lower than expected based on their design values. In this comparison the relative standard deviation of the 10 percent tail-exponential design value is smaller than that of the 5 percent tail exponential design value.

These observations are consistent with the expectation that the tail-exponential methods are more robust measures of the design value than the table look-up methods. The computation of tail-exponential methods uses the largest 5 percent or 10 percent of the daily maximum data to compute design vales whereas the table look-up procedures are based on the location of a single daily maximum value in the distribution. The tail-exponential

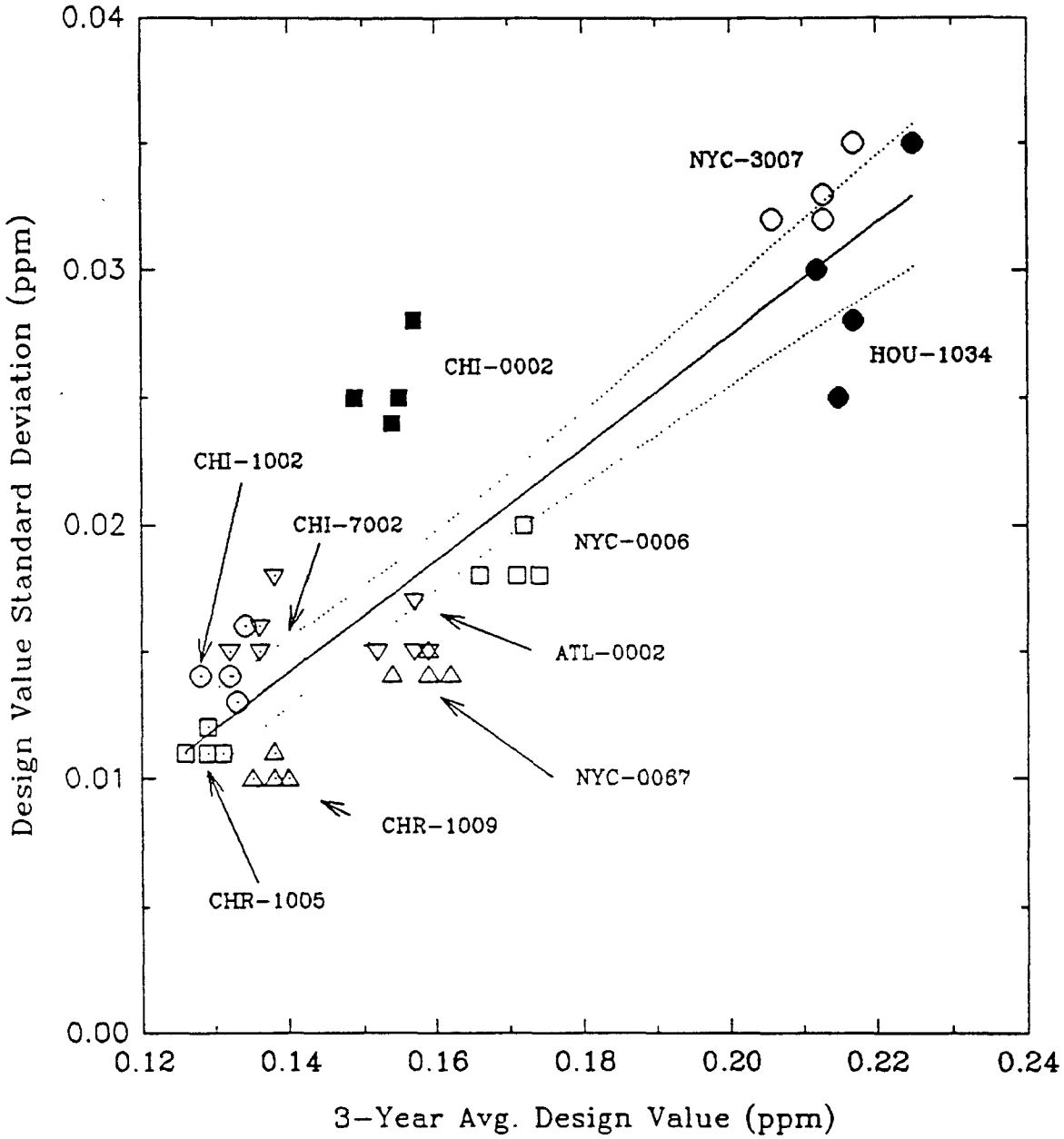


Figure 6-12. Standard deviation of design value affected by site and design value magnitude and method of computation.

methods can be said to make greater use of the available data. The fact that the 10 percent tail-exponential uses twice the data used by the 5 percent tail-exponential accounts for it being the more robust of the two measures.

The improvement in robustness over the EPA table look-up is not large, however. Part of the reason is that the tail-exponential method provides a larger, less biased estimate of the design value than the EPA table look-up method. The smaller EPA table look-up value means a somewhat smaller standard deviation than it would otherwise have. The greater robustness of the tail-exponential measures is more clearly seen when comparison is made with the alternative table look-up procedure, which exhibits very little bias error.

The other reason probably has to do with the fact that the upper 5 percent and 10 percent tails do reflect to a fair extent the fluctuations in the sampled extreme values from one period to the next. They are to some extent measuring the three-year sample design value. This effect is illustrated in the section below, which treats a surrogate design value measure.

Considering bias and standard deviation together, the tail-exponential yields a relatively small but demonstrable improvement in robustness over the tabular methods and has a smaller bias than the EPA table look-up method. The 5 percent tail exponential method has a slightly smaller bias but slightly greater standard deviation than the 10 percent tail-exponential method. While the alternative table look-up procedure appears to exhibit the least bias, it has the greatest standard deviation and is therefore the least robust measure.

Comparisons of Tail-Exponential Multi-Year Methods

Table 6-8 compares the two methods for treating *N* years of daily maximum ozone data in application of the tail-exponential method: (1) fitting separate tail-exponential distributions to each year of data and solving iteratively for the concentration that corresponds to the estimated CLV (conditional probability method) and (2) fitting one tail-exponential distribution to the combined *N* years of data (*N*-year distribution method). Comparing the two sets of 5 percent tail-exponential values in the table, the conditional probability method yields design values from 0.000 to 0.003 ppm higher than the 3-year distribution method. In six of the eleven cases the difference is 0.001 or less. There are three cases in which the difference is 0.003. Two of these cases are accounted for by the Houston 1034 site and the New York 3007 sites, which have 0.22 ppm design values. Comparing the two sets of 10 percent tail-exponential design values, the 3-year distribution method is lower than the conditional method by 0.000 to 0.004 ppm. In six of the eleven cases the difference is less than or equal to 0.002 ppm. Two cases differ by 0.003 ppm and one by 0.004 ppm. The latter case is the Houston 1034 site.

As with the conditional probability 3-year 5 percent and 10 percent tail-exponential methods, the 3-year distribution 10 percent tail-exponential design values are somewhat

Table 6-8. Comparison of two methods of applying the Breiman tail-exponential method to estimation of three-year design values (1,000 three-year simulations).

Metropolitan Area	Site	Distribution Characteristic Largest Value CLV	- Conditional Probability - Average Breiman 5% Tail-Expo. Design Value w/(std. dev.)	Average Breiman 10% Tail-Expo. Design Value w/(std. dev.)	--- 3-Year Distribution --- Average Breiman 5% Tail-Expo. Design Value w/(std. dev.)	Average Breiman 10% Tail-Expo. Design Value w/(std. dev.)
Atlanta	0002	0.156	0.157 (.015)	0.159 (.015)	0.155 (.014)	0.158 (.014)
Charlotte	0034	0.133	0.131 (.010)	0.133 (.010)	0.131 (.010)	0.133 (.010)
	1005	0.130	0.129 (.011)	0.131 (.011)	0.128 (.011)	0.130 (.011)
	1009	0.139	0.138 (.010)	0.140 (.010)	0.137 (.010)	0.140 (.010)
Chicago	0002	0.157	0.155 (.025)	0.154 (.024)	0.152 (.023)	0.151 (.022)
	1002	0.132	0.132 (.014)	0.133 (.013)	0.131 (.013)	0.131 (.013)
	7002	0.137	0.136 (.016)	0.136 (.015)	0.134 (.015)	0.135 (.015)
Houston	1034	0.218	0.217 (.028)	0.215 (.025)	0.214 (.025)	0.211 (.021)
New York	0006	0.172	0.171 (.018)	0.174 (.018)	0.170 (.018)	0.172 (.017)
	0067	0.160	0.159 (.014)	0.162 (.014)	0.158 (.014)	0.161 (.014)
	3007	0.218	0.213 (.033)	0.213 (.032)	0.210 (.032)	0.210 (.031)

() indicates standard deviation

larger than the 5 percent tail. The differences at individual sites closely parallel those observed with the conditional probability set.

The bias of the conditional probability 5 percent tail-exponential was smaller in eight cases, the same in one, and larger in two of the eleven cases. The conditional probability 10 percent tail-exponential has a smaller bias in four cases, the same in three cases, and larger in four cases. The conditional probability 5 percent and 10 percent exponential tail biases were uniformly small for sites with normal shock terms. The standard deviations are generally in good agreement between the two sets. In those few cases where the design values differ by 0.003 to 0.004 ppm, the higher of the two design values exhibits a slightly higher standard deviation.

Summarizing, the two methods for combining 3 years of data yield essentially the same design values in most cases. The conditional probability method is slightly superior with respect to small bias.

Effect of Averaging Period on Alternative Design Value Methods

The time-series simulations are a particularly convenient way to study the effect on estimated design values of the time period over which design values are estimated. Simulations were run for 1, 2, 3, 4, 5, 6, 10, and 250-year periods for each of the sites. For each *N*-year period approximately 3,000 simulations were run of an ozone season of data. The 250-year design values (10 250-year simulations) are taken as equal to the limiting values of their respective design values. Both the EPA table look-up and the alternate table look-up methods converge to the CLV value. The results for the New York area site 34 023 0006 are given in Table 6-9. Results for the remaining sites, which include all the measures studied, can be found in Appendix C. From the table it is seen that the standard deviations fall to roughly two-thirds of their 1-year value in three years and one-third their one-year values at 10 years for all but the 95th percentile surrogate. Its initial decline is more rapid.

The design value data for three estimation methods at each of four sites are plotted in Figure 6-13. The EPA table look-up shows the greatest change in average estimated design value with increasing years. The alternative table look-up procedure exhibits the least drift in bias from 1-year to 250-year periods.

Table 6-10 compares the estimated limiting design values of four estimators. These numbers are actually the average of 10 runs each of 250-year simulations (involving 2,500 annual simulations). Their standard errors vary from 0.0003 to 0.0006 ppm. The limiting design values of EPA and modified table look-up are the same and equal the CLV. The limiting *N*-year 5 percent and 10 percent tail distributions are closer to their respective CLVs that those computed from the iterative conditional probability method. In each case the 5 percent tail-exponential is slightly closer to the CLV than the 10 percent tail-exponential.

Table 6-9. Simulation comparison of the effect of averaging period on New York area site 340230006 design values estimated by various methods.

Averaging Period (years)	Average EPA Tabular Method Design Value w/(std. dev.)	Average Alternate Tabular Method Design Value w/(std. dev.)	Average Breiman 5% Tail-Exponential Design Value w/(std. dev.)	Average Breiman 10% Tail-Exponential Design Value w/(std. dev.)	Average Distribution 95-Percentile Surrogate D.V. w/std. dev.)
1	0.157 (.027)	0.172 (.033)	0.166 (.029)	0.169 (.029)	0.121 (.016)
2	0.164 (.021)	0.173 (.024)	0.170 (.021)	0.173 (.021)	0.121 (.011)
3	0.166 (.018)	0.172 (.020)	0.171 (.018)	0.174 (.018)	0.120 (.009)
4	0.169 (.016)	0.173 (.017)	0.173 (.016)	0.176 (.016)	0.122 (.008)
5	0.168 (.015)	0.172 (.016)	0.172 (.014)	0.175 (.014)	0.121 (.007)
6	0.170 (.013)	0.173 (.014)	0.173 (.013)	0.176 (.013)	0.121 (.006)
10	0.171 (.011)	0.173 (.011)	0.174 (.010)	0.177 (.010)	0.121 (.005)
250	0.171 (.002)	0.172 (.002)	0.174 (.002)	0.176 (.002)	0.121 (.001)

() indicates standard deviation

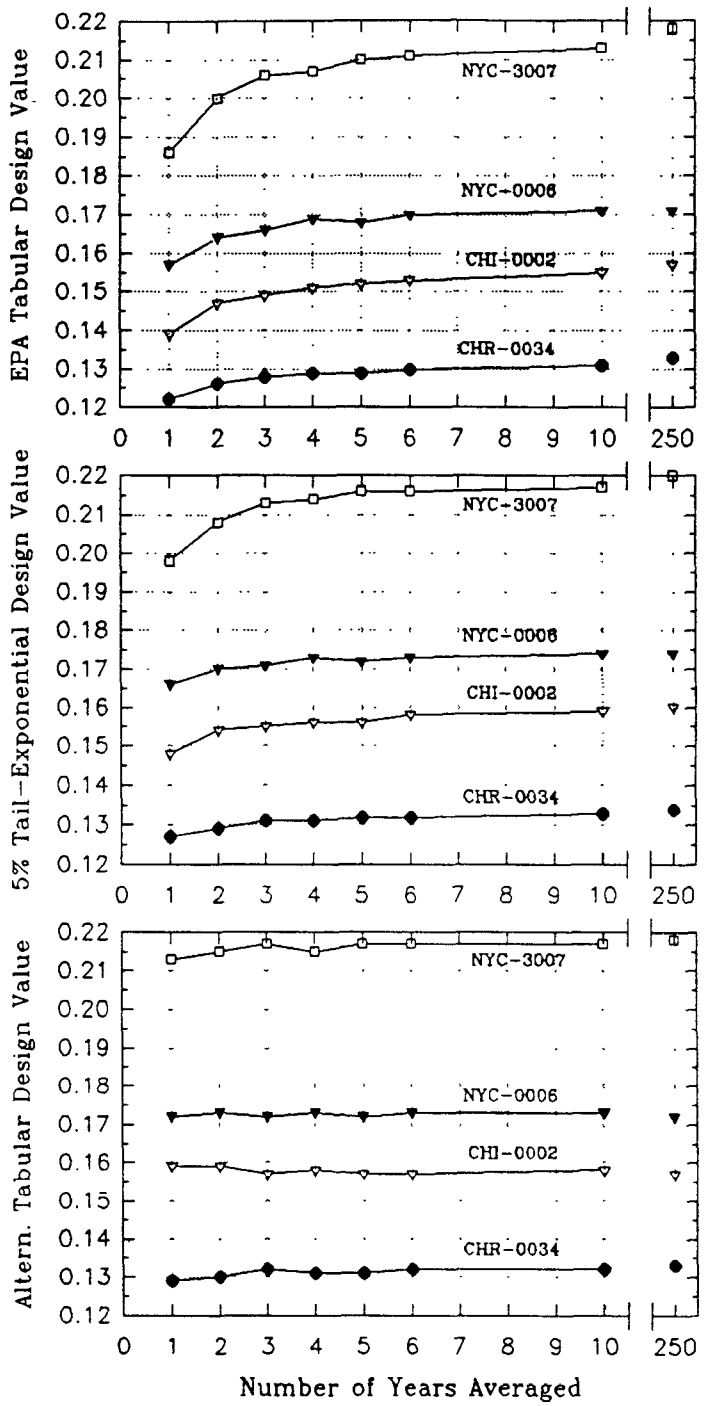


Figure 6-13. Effect of averaging time on design value estimated by three different methods at four locations.

Table 6-10. Comparison of limiting values for alternative design value estimators from alternative design value estimation methods in five selected metropolitan areas.

Metropolitan Area	Site	Alternate Tabular Method	EPA Tabular Method	N-Year Distribution 5% Tail-Exponential Method	N-Year Distribution 10% Tail Exponential Method	Conditional Probability 5% Tail-Exponential Method	Conditional Probability 10% Tail Exponential Method
Atlanta	0002	0.156	0.156	0.157	0.159	0.159	0.162
Charlotte	0034	0.133	0.133	0.133	0.135	0.134	0.136
	1005	0.130	0.130	0.131	0.132	0.131	0.133
	1009	0.139	0.139	0.139	0.141	0.140	0.142
Chicago	0002	0.157	0.157	0.156	0.155	0.160	0.159
	1002	0.132	0.132	0.132	0.132	0.134	0.134
	7002	0.137	0.137	0.137	0.137	0.139	0.139
Houston	1034	0.218	0.218	0.214	0.211	0.219	0.217
New York	0006	0.172	0.171	0.172	0.174	0.174	0.176
	0067	0.160	0.160	0.161	0.163	0.163	0.165
	3007	0.218	0.218	0.217	0.216	0.220	0.220

All limiting values are the average of 10 runs of 250-year simulations

Surrogate Design Values

The current ozone NAAQS has been criticized as specifying statistical measures of attainment whose estimators exhibit an unnecessarily high degree of variability. It has been argued that the ozone NAAQS should be specified in terms of a statistical measure whose estimators exhibit less variability. A NAAQS specifying the 95th percentile of the distribution of daily maximum ozone concentrations has been proposed. Its estimators would exhibit less variability than estimators of the expected exceedance rate. The standard level for the suggested NAAQS would be set at a value that gives protection equivalent to that provided by the present standard. This suggestion assumes that such a standard level exists.

The consideration missed in this argument is that the form of a NAAQS should be determined by the nature of the adverse effects it is intended to protect against. An efficient NAAQS specifies that particular aspect of air quality which best correlates through an exposure-response relationship with the adverse effect(s) it is designed to protect against. Such a standard provides a solid basis for establishing a level of air quality at which the risk of adverse effects is reduced to an acceptable minimum. (A multiple number of possible adverse effects for a given criteria pollutant may require a multiple number of NAAQS.) It also provides the same degree of protection to all sites just in attainment.

The current primary ozone NAAQS is designed to protect against rapidly reversible adverse health effects caused by short term exposure to ambient ozone. Since the greater the concentration of a pollutant the greater the chance of adverse effects and the greater their intensity, the ozone NAAQS seeks to control the magnitude of the extreme values which can occur at a location. To control the extreme values it sets an upper limit on the concentration level whose expected annual exceedance rate is equal to once per year.

A 95th percentile NAAQS, because it is a more central measure than the point on the distribution of daily maximum ozone concentrations represented by the current standard, would not necessarily be a more efficient NAAQS for controlling extreme values even though the variability of its air quality measure is decidedly smaller than that of the current standard. Since it is the extreme values which must be controlled, a 95th percentile standard needs to be judged by how well it controls the extreme values.

Since this report is primarily concerned with the design value of the current form of the ozone NAAQS, the appropriate way to consider the 95th percentile is as a potential surrogate measure of the ozone design value. The question is: does the estimation of the 95th percentile lead to an indirect estimation of the ozone design value (the CLV) that exhibits less bias and more precision than other more direct estimators? If the answer is to be yes, there minimally must be a reasonably tight relationship between the 95th percentile and the CLV that holds over all sites.

Table 6-11. The 95-percentile as a surrogate ozone design value (3000 one-year and 1000 three-year simulations).

Metropolitan Area	Site	Distribution Characteristic Largest Value CLV	Average EPA Tabular Method Design Value w/(std. dev.)	Average One-Year 95-Percentile Surrogate w/(std. dev.)	Estimated Average Characteristic Largest Value w/(std. dev.)
Atlanta	0002	0.156	0.152 (.015)	0.111 (.012)	0.165 (.023)
Charlotte	0034	0.133	0.128 (.011)	0.103 (.010)	0.149 (.019)
	1005	0.130	0.126 (.011)	0.100 (.011)	0.144 (.021)
	1009	0.139	0.135 (.010)	0.109 (.010)	0.161 (.019)
Chicago	0002	0.157	0.149 (.025)	0.099 (.016)	0.142 (.030)
	1002	0.132	0.128 (.014)	0.089 (.010)	0.123 (.019)
	7002	0.137	0.132 (.015)	0.094 (.012)	0.132 (.023)
Houston	1034	0.218	0.212 (0.30)	0.115 (.013)	0.172 (.025)
New York	0006	0.172	0.166 (.018)	0.121 (.016)	0.183 (.030)
	0067	0.160	0.154 (.014)	0.116 (.014)	0.174 (.027)
	3007	0.218	0.206 (.032)	0.133 (.028)	0.206 (.053)

Note 1: () indicates standard deviation

look-up design value as an estimator of the CLV. The 95th percentiles based on both one and three years of data were calculated (only the one-year values are shown). It is seen that the standard deviations for the one-year 95th percentiles are close in size to those of the EPA table look-up method. Since there is no advantage in precision, the one-year 95th percentile will not be considered further. The three-year 95th percentile on average has a standard deviation of about half that of the table look-up method for the same site. It is therefore a candidate surrogate. Figure 6-14 displays the CLV versus the average 3-year 95 percent percentile for the eleven sites. A regression line and 95 percent confidence limits are fitted to the data. It is apparent there is no one-to-one relationship between the variables. As would be expected, the 3-year 95th percentile increases as the CLV increases, but the scatter of the points indicates a strong dependence on site. The regression line may be the best that can be done without introducing added factors. Thus the use of the 95th percentile surrogate leads to significant uneven treatment among sites.

To complete the analysis of the 95th percentile as surrogate measure, the regression analysis was used to predict the average of the 3-year design value based on the average three-year 95th percentile at a site. The results of the calculation are given in Table 6-12. For comparison purposes the CLV, the average EPA look-up design value and the average 3-year 5 percent tail-exponential design value are included in the table. The design value derived from the 95th percentile using the regression model is not an accurate estimate of the CLV, exhibiting both positive and negative biases of varying magnitudes. The average three-year tail-exponential is less biased. The EPA table look-up design value is more biased than the regression estimate because of the strong tendency of the EPA design value to underestimate the CLV. The standard deviations of the 3-year 95th percentile derived design values are somewhat smaller than those of the EPA look-up and 3-year 5 percent tail exponential. But this advantage in lower variability is largely related to the negative biases at several of the sites, and does not compensate for the larger bias of this estimate compared to the other estimates. It is possible that a much more complicated nonlinear function of the 95th percentile would lead to a more accurate estimated design value.

An interesting feature noted by one reviewer is that the regression line is close to the theoretical line CLV = 2*S* applicable if the tail exponential model was precisely valid.

Summary of Conclusions from the-Time Series Modeling Study

1. The time series for individual years of the same site were dominated by a single shock term distribution type: either normal or extreme value. These distributions imply that the respective distributions of the daily maximum ozone concentrations are approximately lognormal or Weibull. The shock term was a normal distribution for five of the eleven sites studied and an extreme value distribution for six of the eleven sites. The time-series models of sites associated with a given metropolitan area tended to have the same shock term type.

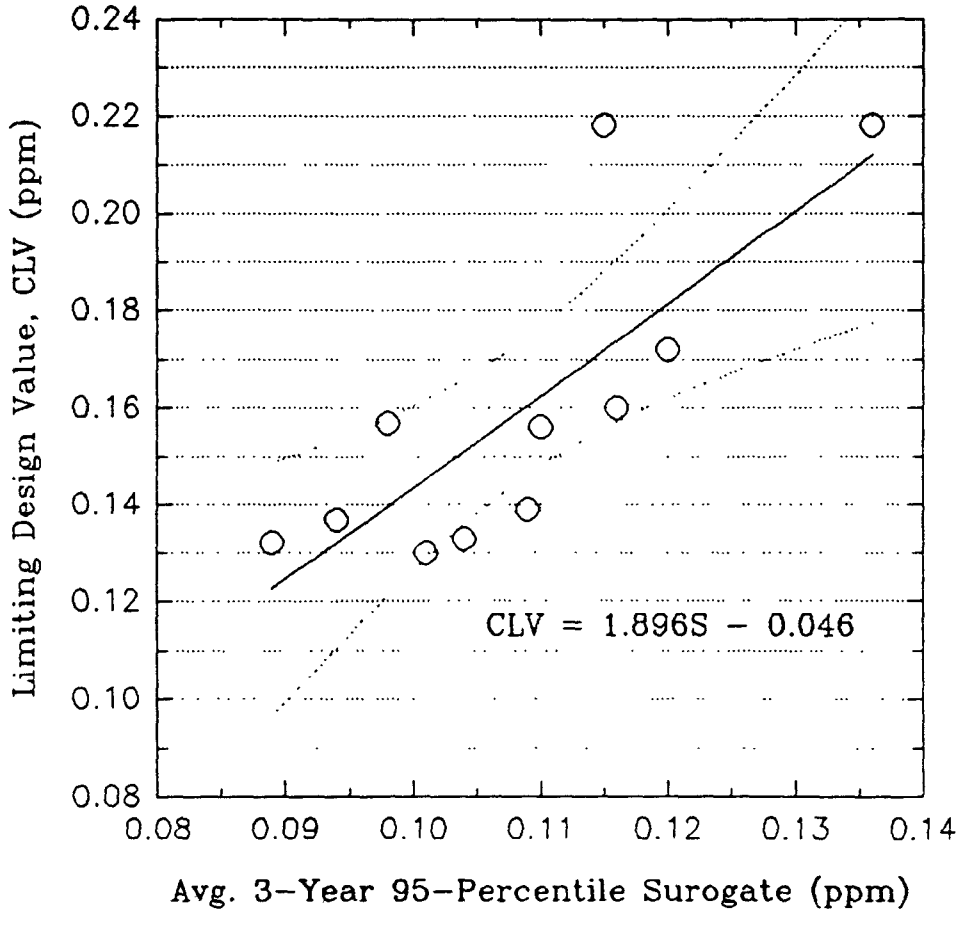


Figure 6-14. Limiting design value (CLV) versus average 3-year 95th percentile.

Table 6-12. Estimation of ozone design value from the 95th percentile surrogate.

Metropolitan Area	Site	Distribution Characteristic Largest Value CLV	Average EPA Tabular Method Design Value w/(std. dev.)	Average Three-Year 5% Tail-Expon. Design Value w/(std. dev.)	Estimated Average Design Value From Three Year 95-Percentile w/(std. dev.)
Atlanta	0002	0.156	0.152 (.015)	0.157 (.015)	0.163 (.013)
Charlotte	0034	0.133	0.128 (.011)	0.131 (.010)	0.151 (.011)
	1005	0.130	0.126 (.011)	0.129 (.011)	0.145 (.013)
	1009	0.139	0.135 (.010)	0.138 (.010)	0.161 (.011)
Chicago	0002	0.157	0.149 (.025)	0.155 (.025)	0.140 (.017)
	1002	0.132	0.128 (.014)	0.132 (.014)	0.123 (.011)
	7002	0.137	0.132 (.015)	0.136 (.016)	0.132 (.013)
Houston	1034	0.218	0.212 (0.30)	.217 (.028)	0.172 (.013)
New York	0006	0.172	0.166 (.018)	0.171 (.018)	0.182 (.017)
	0067	0.160	0.154 (.014)	0.159 (.014)	0.174 (.015)
	3007	0.218	0.206 (.032)	0.213 (.033)	0.211 (.032)

Note 1: () indicates standard deviation
2: Estimated design value: DV = 1.896*S - 0.046 where S is the 3-year 95-percentile.
3: Standard deviation of estimated design value is 1.896 times the standard deviation of the 3-year 95-percentile.

2. The bias of a given design value estimation method can vary with the nature of the shock term and other unidentified characteristics of the site. If the estimator is biased, the bias may tend to increase in the negative or positive direction with increasing magnitude of the design value. Bias can also vary with the number of years over which the design value is estimated.

3. The year-to-year variability of estimated design values increases as the magnitude of the design value estimate increases. The variability is also affected by the type of shock term associated with the site and other unidentified site characteristics. The variability decreases as the number of consecutive years over which the design value is estimated increases. The standard deviation decreased by 31–39 percent in proceeding from one- to three-year measures, 44–52 percent in five years, and 59–67 percent in ten years over four different measures at one site.

4. Based on 1,000 simulations of 3-year sets of daily maximum ozone data, the table look-up method has significant negative bias. For design values below 0.2 ppm, the alternative table look-up method is essentially an unbiased estimator. The 5 percent and 10 percent tail-exponential procedures have small to negligible biases comparable to the alternative table look-up procedure.

5. The alternative table look-up procedure exhibits the least precision of the methods tested but is not substantially less precise than the other methods. The 5 percent and 10 percent tail-exponential and EPA table look-up procedures have essentially the same precision. Given that the magnitudes of the 5 percent and 10 percent tail-exponential design values are greater than the EPA table look-up design value and closer to the unbiased alternative table look-up procedure, it is clear that the tail-exponential methods are comparatively more robust measures than the two table look-up methods.

6. The EPA table look-up method exhibits somewhat higher precision than it would otherwise have because of its negative bias, which results in smaller design value estimates than the other methods.

7. To achieve the precision level of the present EPA table look-up procedure, all the alternative methods would need to be based minimally on 3 years of daily maximum ozone data.

8. Given the preceding conclusions and the observation that the bias of the 3-year 5 year tail-exponential design values are somewhat less variable over sites than the 10% tail-exponential design values, it is concluded that the 3-year 5 percent tail-exponential represents the best compromise of bias and precision of the four methods tested.

9. The conditional probability method of estimating 3-year 5 percent tail-exponential design values exhibits slightly less bias than the combined 3-year distribution method. As the

number of years over which the estimate is computed increases the situation reverses. Both methods are essentially equivalent.

10. The use of the 95th percentile of the distribution of daily maximum ozone concentrations as a surrogate design value is less satisfactory than any of the four more direct estimators of the design value. It fails to significantly reduce the variability of the associated estimated characteristic largest value (CLV) below that achieved with the more direct methods. (From another perspective: controlling the 95th percentile fails to improve control of the underlying CLV.) At the same time it introduces substantial biases which vary with the site. The bias problem would result in uneven treatment of sites relative to what would be achieved with the more direct measures. Nor would the use of the 95th percentile obviate the need to use 3-year data sets.

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7 THE ROLE OF METEOROLOGY IN OZONE FORMATION

A major issue in the development and application of ozone design value estimates centers on the influence of meteorological conditions. High ozone concentration events are known to be associated primarily with certain combinations of meteorological factors. In general, warm, clear days with light winds that bring, keep, or return high precursor and ozone concentrations into an area coincide with the highest ozone concentrations. Ozone design values estimated from data collected in years during which such conditions are unusually frequent are unusually high due to the greater frequency of high ozone days. Conversely, in years during which such weather conditions are infrequent, estimated design values are lower. This effect can be quite pronounced, as evidenced by the large number of high ozone days observed during the unusually warm summers of 1983 and 1988 (EPA, 1990). Meteorological influences of this sort tend to obscure ozone trends resulting from trends in precursor emissions and can cause areas to fluctuate between attainment and nonattainment in the absence of any changes in precursor emissions.

The following sections present a brief review of the literature on meteorological influences on ozone concentrations and methods for adjusting annual ozone summary statistics (such as design values) to account for meteorological influences. Much has been written on this subject. This review is not intended to cover all of these publications, but rather to describe those which, from a historical perspective, are of primary importance to our current understanding of meteorological influences and adjustment methods. This section begins with a discussion of the meteorological factors that have been found to correlate with ozone concentrations, and then surveys the various adjustment methods that have been devised.

In the following sections, numbers enclosed in square brackets refer to the numbered references in the tabular summary of studies on trend adjustment methods in Appendix G. Full citations are provided in numerical order at the end of this review. Unnumbered references do not appear in the table; full citations for these appear in alphabetical order at the end of this section.

METEOROLOGICAL INFLUENCES ON OZONE CONCENTRATIONS

Numerous studies of the relationship between meteorological variables and ozone concentrations have been conducted (see in particular the summaries of Zeldin and Meisel (1978) and Pollack et al. (1988; [16]), from which much of the following material is adapted). These studies have shown that the particular meteorological conditions most closely associated with high ozone events vary somewhat from one location to the next. In general, however, high ozone has been found to be associated with high temperatures, clear skies, and light winds. Contrary to the expectations of most investigators, analyses of the effect of mixing height on ozone concentrations have been inconclusive. Chock et al. (1982; [10]) pointed out that this may be a result of the fact that accurate

measurements of mixing height are difficult to make and that ozone may be carried over from one day to the next in layers of stable air above the inversion top, thus confounding the relationship between mixing height and surface ozone concentrations.

Meteorological variables can be classified according to their role in the ozone formation process as indicated in Table 7-1. Since there is a strong interrelationship between many of the variables (e.g., daily maximum temperature and average wet bulb temperature), the variables could have been grouped in many ways; the classifications shown in Table 7-1 are merely one example. Each of the variables can also be expressed in many forms (e.g., daily maximum temperature, daily average temperature, etc.). Pollack et al. (1988; [16]) discussed the relative merits of several possible forms. Each of the groups of meteorological variables and their relationship to ozone is briefly described in the following sections.

Insolation

Ozone formation is governed by the amount of solar radiation that is available for NO_2 photolysis. NO_2 photolysis rates can be obtained from Demerjian et al. (1980) for each daylight hour, and adjustments for cloud cover can be made according to the method of Maul (1980) as adapted by Scire et al. (1983). These values can be integrated over the 0800–1400 LST "ozone formation period" suggested by EPA (1985) or, alternatively, over all daylight hours. Ceiling height is loosely related to the amount and type of clouds and therefore the amount of solar radiation reaching the lowest layers of the atmosphere. The number of daylight hours provides a measure of the extent of solar insolation in the day and also serves as an indicator of time of year.

Ventilation

Certain variables are associated with the advection and dispersion of ozone and precursors. Previous studies (Zeldin and Meisel, 1978; Langstaff and Pollack, 1985; Pollack et al., 1988; [16]) have shown an inverse relationship between wind speed and ozone concentrations. Wind speed is a measure of the rate of advection and transport, and wind speed and wind direction are often good indicators of the weather regime affecting an area. Whether wind speed is a good indicator of transport and dispersion depends on wind direction. Low wind speeds are typically associated with slow-moving high pressure systems and stagnant air masses, which are often characterized by above average ozone concentrations. High wind speeds are often associated with weather disturbances or the advection of new air masses into an area; both are characterized by relatively low ozone concentrations. Wind speed may affect both the early morning buildup and afternoon dispersion of ozone and precursors. To account for differences in wind direction, a vector average wind speed defined as the magnitude of the resultant vector can be calculated in addition to the scalar average wind speed.

TABLE 7-1. Meteorological variables potentially associated with ozone formation.

Insolation

Sky cover
Integrated clear sky photolysis rate
Integrated cloudy sky photolysis rate
Ceiling height
Number of daylight hours

Ventilation

Vector average wind speed
Scalar average wind speed
Wind fluctuation (ratio of scalar to vector average wind speed)
Mixing height
Ventilation coefficient (mixing height times wind speed)

Transport

Wind direction

Indirect Measures

Previous day's daily maximum ozone concentration
Temperature (daily maximum, range)
Humidity indicators: dewpoint temperature, wet bulb temperature, relative humidity
Surface pressure (corrected to sea level)
Surface pressure range (daily max. minus min. surface pressure)
Precipitation
850 mb temperature
1000 mb–850 mb temperature difference
500 mb temperature
850 mb height
500 mb height
850 mb dewpoint
Synoptic weather pattern type

A measure of the persistence of wind direction during the day is provided by the wind fluctuation ratio, which is defined as the ratio of the scalar average wind speed to the vector average wind speed. The scalar average wind speed is the average of the numerical wind speeds ignoring the wind direction. The vector average wind speed is calculated by averaging the northerly and easterly components and computing the length of the resultant vector. A ratio near one indicates a highly persistent wind direction whereas a larger ratio indicates variability in wind direction.

Mixing height describes the vertical dimension of the volume through which dispersion of ozone and precursors can occur. Generally, restricted mixing depths are conducive to the buildup of pollutants, resulting in higher ozone concentrations. Elevated mixing heights allow a relatively large amount of vertical dispersion to occur, resulting in lower ozone concentrations. As in the case of wind speed, the mixing height may affect both the nocturnal buildup and afternoon dispersion of ozone. The degree of difference between morning and afternoon mixing heights may provide an indication of the type of diurnal weather pattern to which a particular day belongs. Mixing height in many areas and on many occasions may be hard to define because there is no sharp discontinuity in lapse rate.

Ventilation, which is defined as the product of the mixed layer wind speed and depth of the mixed layer, is a measure of the overall ability of the atmosphere to transport and disperse pollutants, both vertically and horizontally. It is not a primary meteorological variable, but it has a strong influence on the buildup of pollutants during the night; during the day, atmospheric ventilation directly influences the maximum concentrations of ozone in the mixed layer.

Transport

Trajectories of polluted air masses are a function of wind speed and direction. Ozone and precursors may be transported both into and out of a particular region. High ozone concentrations at sites outside an urban area can occur only when trajectories are such that a polluted air mass is advected toward the site. As a result, concentrations at such sites are highly correlated with wind speed and wind direction.

Indirect Measures

Many meteorological variables are associated with combinations of factors that either promote or hinder the formation of high ozone concentrations, although they are not a direct measure of any of the factors themselves. For example, the daily range of surface pressure does not in itself affect ozone concentrations. However, large pressure ranges are most likely indicative of windy days with possible frontal passage and associated precipitation. Such days generally have low ozone concentrations due to the dispersing action of the winds, lack of solar insolation, scavenging of pollutants by precipitation, and low temperatures. Conversely, high ozone days may be characterized

by small pressure ranges. In particular locations (such as the Los Angeles Basin), pressure differences between two stations (e.g., coastal and inland) are correlated with ozone concentrations because of their effect on local wind patterns.

One of the most significant meteorological variables in this group is temperature. Nearly all studies of ozone-meteorology relationships identify temperature as the single most important factor associated with fluctuations in ozone concentration levels. While some photochemical reactions do proceed more rapidly as temperatures increase, resulting in a net increase in ozone formation (Whitten and Gery, 1986), temperature is also (and perhaps most significantly) related to a number of other factors that influence ozone formation. For example, very warm days generally occur only in conjunction with clear skies and light winds, both of which are conducive to high ozone concentrations. In addition, high temperature may promote changes in the amount and chemical nature of precursor emissions (e.g., an increase in evaporative VOC emissions) which may also promote ozone formation. In certain locations, such as in the Los Angeles basin and, to some extent, other coastal air basins in California, 850 mb temperature[1] has been found to correlate strongly with ozone. This is thought to be a result of the fact that the 850 mb temperature over Los Angeles provides a measure of the strength and height of the subsidence inversion normally located over the region. The condition of this inversion exerts a particularly strong influence on ozone concentrations in the basin.

Humidity indicators (dew point, wet bulb temperature, and relative humidity) may be related to observed ozone concentrations because they are indicative of overall weather patterns that either promote or hinder ozone formation. Humidity also plays a role in the photochemical reactions that result in ozone formation (Whitten and Gery, 1986). Humidity can affect the rate of ozone destruction during the night, but its primary effect is on ozone production during the day. Pollack et al. (1988; [16]) found a significant relationship between ozone and relative humidity: ozone concentrations in excess of 0.08 ppm were significantly more likely (in a statistical sense) to occur in conjunction with relative humidities below 80 percent. Cox and Chu (1991; [20]) also identified a negative correlation between relative humidity and ozone. However, scatter plots presented by Pollack et al. for monitoring sites in the Northeast suggest that this relationship is reversed for relative humidities below about 55 percent. This may reflect the fact that such low humidities are associated with the advection of relatively dry, cool, and clean continental air masses over the region. For relative humidities above 55 percent, it is likely that the inverse relationship with ozone reflection of the inverse relationship between relative humidity and temperature at constant mixing ratios. Humidities at the lower end of this range are likely to be associated with higher temperatures and lack of precipitation—both of which are indicators of high ozone.

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[1]Air temperature at the height above ground at which the atmospheric pressure is equal to 850 millibars (typically at an altitude of about 5000 feet).

At least one account of a positive relationship between ozone and seasonal precipitation levels has been published. Sandberg et al. (1978; [9a]) described a regression of the number of high ozone days against total precipitation from the preceding two winter rainy seasons in the San Francisco Bay Area. The apparently strong relationship between summer ozone and rainfall during the two preceding winters identified by the regression was hypothesized to result from an increase in summer biogenic emissions from trees whose growth was stimulated by the winter rains. A later report (Sandberg et al., 1991; [9b]) indicated that the relationship, while still significant, has weakened in recent years, possibly as a result of changes in anthropogenic emission patterns.

A number of other variables can be included in the "indirect measures" group. The inclusion of the previous day's ozone concentration is based on the fact that weather patterns tend to persist from one day to the next and the possibility that ozone is carried over from one day to the next. Temperature lapse rates (e.g., 1000–850 mb, 1000–700 mb temperature differences) are indicative of overall weather patterns and atmospheric stability. The presence of precipitation (occurrence of thunderstorm, rain or drizzle) generally reduces ozone concentrations due to increased cloudiness, decreased solar insolation, washout by rain, higher ventilation by increased winds, and lower temperatures. Atmospheric thickness (e.g., the vertical separation between the 850 and 500 mb pressure surfaces) is a direct function of the mean temperature in the layer and is thus related to ozone concentrations for the reasons discussed above.

Although it is possible to demonstrate that many of the meteorological factors discussed above are correlated with ozone, peak ozone concentrations are typically observed to occur in conjunction with certain combinations of these factors. Thus, temperature is correlated with ozone, but high temperature by itself is not a sufficient condition for the occurrence of the highest ozone concentrations. The situation is further complicated by the fact that temperature is typically correlated with a host of other meteorological variables such as insolation, wind direction, etc. Many investigators have suggested that the various combinations of weather conditions observed at a particular location can best be summarized in terms of synoptic-scale weather patterns; therefore, these patterns control a significant fraction of the day-to-day variability in ozone concentrations. Synoptic weather systems, such as blocking high pressure systems and stationary fronts and troughs are key indicators of regional ozone buildup. For local high ozone, local effects should also be considered. Pollack et al. (1988; [16]) and Stoeckenius (1991) evaluated two synoptic classification systems that have been proposed for the northeastern United States. Although a statistically significant relationship between the patterns and daily maximum ozone concentrations at individual locations was confirmed, only a small fraction of the day-to-day variability in ozone was accounted for by the patterns due to the lack of specific information on conditions at a particular monitoring site. Since these findings are by no means conclusive, further research is needed.

ADJUSTING OZONE CONCENTRATIONS TO ACCOUNT FOR METEOROLOGICAL INFLUENCES

As summarized above, ozone concentrations are affected by meteorological conditions in a variety of ways, and therefore meteorology exerts a significant influence on annual ozone summary statistics such as design values. By definition, the actual ozone design value (i.e., the value which is exceeded once per year on average) is representative of the full distribution of meteorological conditions, including normal as well as unusually warm or cool years. However, estimates of the design value based on data collected during an unusually warm or cool period may not be representative of the underlying design value in years closer to the long-term climatic norm. Thus, an estimate based on 1988 data may be significantly higher than one based on a cooler year such as 1986, even though precursor emission levels, and therefore the actual, underlying design value, may have remained unchanged. One way around this problem is to average the annual summary statistics over a time period sufficiently long to be representative of typical meteorological fluctuations. Unfortunately, the 3-year attainment test specified in Appendix H to the ozone standard (40CFR50) and described in the Ozone Guideline (EPA, 1979) is not always sufficient for this purpose. However, averages over longer time periods are likely to include years with significantly different emission levels and thus obscure any emissions-related trend. The National Academy of Sciences (NRC, 1991) has recommended the development of methods to normalize ozone trends for meteorological variation.

Numerous papers and reports have been written on methods for adjusting ozone concentration data to a common meteorological basis (see Appendix G for the listing of the numbered references). Most of these investigations were motivated by the need to detect underlying trends in ozone concentration data that would provide a historical indication of the effectiveness of emission control programs relative to increases in emissions generating activities. These trends are frequently obscured by the "noise" induced by meteorological fluctuations and are therefore difficult to detect. Although trends in estimated design values are of particular interest, various other summary statistics have been used in these studies, as described more fully in Appendix G.

Zeldin and Meisel (1978) surveyed a number of alternative trend adjustment methods. Most methods rely on the development of an empirical model (linear regression models and classification systems are the most common) that relates ozone concentrations to meteorological conditions. The influence of changing precursor emission levels is either incorporated into the model explicitly in the form of a term involving a time index, or implicitly via multiple sets of model parameters, with each set estimated from data collected over a short (one- to three-year) time interval during which emissions are assumed to remain constant. The model is then used to estimate (i.e., predict) ozone concentrations under a fixed set of meteorological conditions. These conditions may represent those observed in a particular reference year or they may be averages representative of "normal" or "typical" conditions. Assuming the model fits the

data well, any year-to-year changes in the predicted ozone values indicate the influence of changes in precursor emission patterns.

The most successful empirical models used in ozone trends adjustments account for roughly 60 to 80 percent of the variance in daily maximum ozone concentrations. Fluctuations in annual summary statistics adjusted using the models (see, for example, Stoeckenius and Hudischewskyj, 1990; [17]) exhibit a residual correlation with the unadjusted summary statistics, thus suggesting that not all of the meteorological influences have been fully accounted for by the model. Cox and Chu (1991; [20]) presented adjusted summary statistics that vary smoothly in time and do not appear to be correlated with unadjusted values. Adjustment methods can be categorized as being based on regression models, classification models, and other models as indicated in Table 2 of Appendix G and described in the following sections.

Regression Methods

Many trend adjustment studies are based on the use of linear regression models to relate ozone concentrations to meteorological conditions ([2], [6], and [10-13] in Los Angeles and ([9], [16], and [18] in other cities). Regression models are of the form:

$$Y = a + \Sigma\, b_i X_i + b_t T + e \quad .$$

where

Y is the daily or seasonal ozone summary statistic (e.g., daily maximum hourly average or seasonal mean of the daily maximums);

X_i are daily or seasonal meteorological variables (e.g., daily maximum temperature or seasonal mean temperature);

T is a time index (e.g., year);

e is the error term (residual); and

b_i, b_t, and a are regression parameters determined via the least-squares fitting procedure.

The regression parameter for the time index term (b_t) is interpreted to represent the (assumed) linear, meteorologically adjusted trend. This interpretation is based on the assumption that the $b_i X_i$ terms in the regression equation fully account for the meteorological influences on ozone concentrations (i.e., the residuals, e, are independent of meteorology). If this is not the case, then b_t may be subject to meteorological influences and give a false indication of the effects of changes in precursor emissions. In the extreme, if no attempt is made to account for meteorological influences in formulating the model, then the "adjusted" trend is simply the slope of the least-squares regression line obtained using the time index as the only regressor. Generally speaking, such

trends, when calculated over time periods of five years or less, may be an artifact generated by the presence of one or more years with unusual meteorological conditions.[2] An additional problem with this approach is that it only handles linear trends, although other smooth trends (i.e., quadratic) can be treated through appropriate transformation of the time index.

Most authors do not include a time index term in the regression model and instead fit a separate set of regression parameters using data from each year. Differences in parameters from one year to the next are assumed to result from differences in precursor emissions, although in practice sampling error results in additional differences. This approach eliminates any a priori assumptions about the nature of the underlying trend and does not assume that errors are independent of meteorology; the adjusted trend is simply interpreted as the trend that appears when that portion of the meteorological variability explained by the regression model is eliminated. Thus, although the adjusted trend may still incorporate some meteorological variability, it is not subject to the sort of potential misinterpretation noted above.

Zeldin et al. (1990; [6]) developed a regression equation for daily maximum ozone using data from a 3-year base period. For subsequent periods, differences between ozone predicted from the equation and observed ozone concentrations were assumed to indicate the influence of deviations in precursor emissions from base period levels.

Chock et al. (1982; [10a]) and Kumar and Chock (1984; [10b]) developed separate linear regression equations for each year during 1971–79 in which daily maximum ozone concentration was the dependent variable and five different meteorological variables served as regressors. These equations were then used to predict daily maximum ozone concentrations using a standardized set of values for the meteorological variables. The resulting trends in annual average daily maximum ozone were interpreted to represent trends resulting from precursor emission changes. A similar method was employed by Duckworth et al. (1980; [11]) and Davidson et al. (1985; [12]).

Kuntasal and Chang (1987; [13]) took a slightly different approach to trend adjustment. They regressed monthly mean daily maximum ozone against 850 mb temperature using data from the entire trend period (1968–85). Adjusted ozone concentrations for each month were then obtained by substituting the climatological mean temperature into the regression equation and adding in the residual for that month. Thus, in effect, the slope of the temperature term is used to adjust the observed ozone concentration to the value one would expect to observe under climatological mean temperature conditions. Wakim (1990; [18]) employed a similar approach using multiple

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[2]Longer-term trends are much less likely to be influenced in this way since the effects of a few unusual years are spread out over a longer time period.

linear regression and annual mean residuals to adjust the annual mean of the 30 and 60 highest daily maximum ozone concentrations.

Pollack et al. (1988; [16]) pointed out that linear or log-linear regression of daily maximum ozone against meteorological variables may lead to underprediction on high ozone days (i.e., the expected value of the error term on high ozone days is not equal to zero). Since high ozone days are of particular importance from a regulatory viewpoint, this bias could produce undesirable results. To mitigate the bias, Pollack et al. attempted to develop an improved regression fit on high ozone days (defined as days with maximum concentrations greater than 0.08 ppm) by identifying a joint set of meteorological criteria which a day must satisfy to be put into the high ozone category. A multiple log-linear regression was then developed using only data from the high ozone days. Thus, Pollack et al. employed a two-stage model consisting of a screening stage and a regression stage. A separate set of regression parameters was estimated for each year in the study period to allow for variations in the ozone-meteorology relationship resulting from changes in precursor emissions. Adjusted ozone concentrations were calculated by substituting daily meteorological conditions corresponding to a particular (reference) year into the regression equations. As a result, the meteorologically adjusted exceedances calculated by Pollack et al. are interpreted as the number of exceedances that would have been observed had meteorological conditions in each year been identical to those in the reference year. Any remaining year-to-year changes in ozone are interpreted to result from changes in precursor emissions.

Classification Methods

As pointed out above, regression models can underestimate concentrations on high ozone days and, furthermore, they do not lend themselves easily to the calculation of meteorologically adjusted trends in exceedance summary statistics such as the number of days per year exceeding the ozone NAAQS. Given the regulatory significance of high ozone days and exceedance summary statistics, alternative models for use in trends adjustment have been considered by a number of investigators. A common approach is to classify days on the basis of meteorological conditions into two or more categories that define their ozone formation potential ([3-5], [15]). Thus, warm stagnant days may be assigned to a high ozone category while cool, windy days are assigned to a low ozone category.

Various methods used to define such categories are described below. This discussion is followed by a description of the procedures used to calculate adjusted trends based on these categories.

Methods for Defining Categories

Meteorological categories of ozone formation potential can be identified in a number of different ways. Burkhart et al. [17] defined years with similar numbers of

days exceeding a preset temperature threshold as having similar ozone formation potential ("similar summers" concept). Changes in the annual ozone summary statistic from one such season to the next are then presumed to arise almost entirely as a result of changes in precursor emissions. Other investigators define ozone formation potential on a daily basis. Jones developed one of the earliest approaches (Jones, 1985, 1989) which classified any day with a temperature in excess of 90°F (32.2°C) as an ozone-conducive day. Pollack and Moezzi (1985; [15]) defined an ozone-conducive day as any day in which the temperature exceeds, and wind speed and cloud cover do not exceed, preset cutoff values. Cutoffs are independently determined for each variable by noting the value exceeded (or not exceeded) on 90 percent of high ozone days (defined as days above 0.10 or 0.12 ppm). Although this method is both objective and simple, it results in the identification of many more ozone-conducive days than actual high ozone days since it does not consider the joint distribution of meteorological conditions on high ozone days.

Sweitzer and Kolaz (1984; [4]) recognized the importance of the effect of joint conditions on meteorological variables and developed a two-category system consisting of "ozone-conducive" days and non-ozone-conducive days using a set of joint criteria (arrived at by inspection) based on typical values of five different meteorological variables characteristic of high ozone events in Chicago. Kolaz and Swinford (1990; [5]) extended this approach to include a numerical measure of the degree of conduciveness associated with each ozone-conducive day.

Zeldin and Breiman (1979; [2]) employed a slightly different approach, regressing daily maximum ozone against various meteorological variables and then defining categories of meteorological conditions based on ranges of ozone concentrations predicted by the regression equation. This approach is less likely to be affected by subjective judgment than the method of Sweitzer and Kolaz but requires careful selection of the predicted ozone ranges assigned to each category and an analysis of the regression results (including an analysis of residuals) to ensure that the selected categories are appropriate.

Zimmerman et al. (1987; [3]) presented an example of categories developed on the basis of a synoptic typing scheme that seeks to relate ozone formation potential to each of several synoptic weather patterns. This approach requires judgments by a meteorologist familiar with the synoptic weather patterns characteristic of the region under study but is potentially powerful in that it deals directly with the atmospheric processes responsible for generating ozone-conducive conditions on a regional scale.

Most of the category development procedures described above rely on a meteorological classification of days by ozone formation potential which is arrived at through an inspection of joint distributions of ozone and key meteorological variables. The selection of key variables and category definitions is a manual process involving some subjective judgment that cannot be consistently applied in an automated fashion to different locations since ozone-meteorology relationships vary from one location to the next. Stoeckenius and Hudischewskyj (1990; [17]) demonstrated the use of a subjective,

automated procedure for generating meteorological categories. Their method is based on an alternative regression model developed using the Classification and Regression Tree (CART) methodology of Breiman et al. (1984). In this model, a data set consisting of daily maximum ozone concentrations and daily meteorological variables is subdivided into a finite number of categories corresponding to different regions in the *n*-dimensional data space defined by the meteorological variables. The divisions are constructed by the CART software to minimize the within-category mean square deviations while maximizing the between-category mean square deviations. Thus, a high temperature, low wind speed category might be identified within which primarily high ozone days can be found together with a low temperature, high wind speed category associated with primarily low-ozone days.

Adjustment Procedures Based on Meteorological Categories

A number of different approaches for obtaining meteorologically adjusted annual summary statistics from a classification model have been developed. Sweitzer and Kolaz (1984; [4]) calculated a meteorologically adjusted trend in the number of days on which ozone concentrations exceeded 0.12 ppm by noting the ratio of the number of exceedance days to the number of ozone-conducive days in each year. The number of exceedances per conducive day was found to decrease between 1977 and 1983, thus suggesting a decrease in ozone independent of meteorological factors. A similar approach has been used by Jones (1992a, b [21]; see also CEQ, 1985, 1989; NRC, 1991, pp. 62-63), in which ozone-conducive days are simply defined as days with temperatures in excess of 90°F. However, as pointed out in the NRC report and by Stoeckenius and Hudischewskyj (1990; [17]), large year-to-year variations were observed in this ratio, making trend detection difficult. Jones presented his adjusted exceedances in terms of running 3-year averages, thus producing a smoother trend (Figure 7-1). Years especially conducive to ozone formation such as 1983 and 1988 are readily identifiable by this method even though it is less reliable than more sophisticated approaches.

Another simple approach to calculating meteorologically adjusted trends using a classification model is to compare an annual summary statistic from one year to the next only on days with similar meteorological conditions. Chock et al. (1982; [10]) used days matching meteorological criteria that define "high," "moderate," and "low" ozone formation potential and calculated the year-to-year trend on days falling in each category. Pollack and Moezzi (1985; [15]) used a similar approach. Burkhart and co-workers (1990, 1991, 1992; [7]) attempted to account for meteorological variability by grouping years according to the frequency of occurrence of ozone-conducive days and calculating the trend in annual summary statistics only for those years with similar numbers of conducive days.

Several authors (Zeldin and Thomas, 1975; [1], Zeldin and Breiman, 1979; [2], Wackter and Bayly, 1987; [14]) used meteorological categories in regression relationships to develop adjusted trends. Zeldin and Thomas (1975; [1]) defined a seasonal

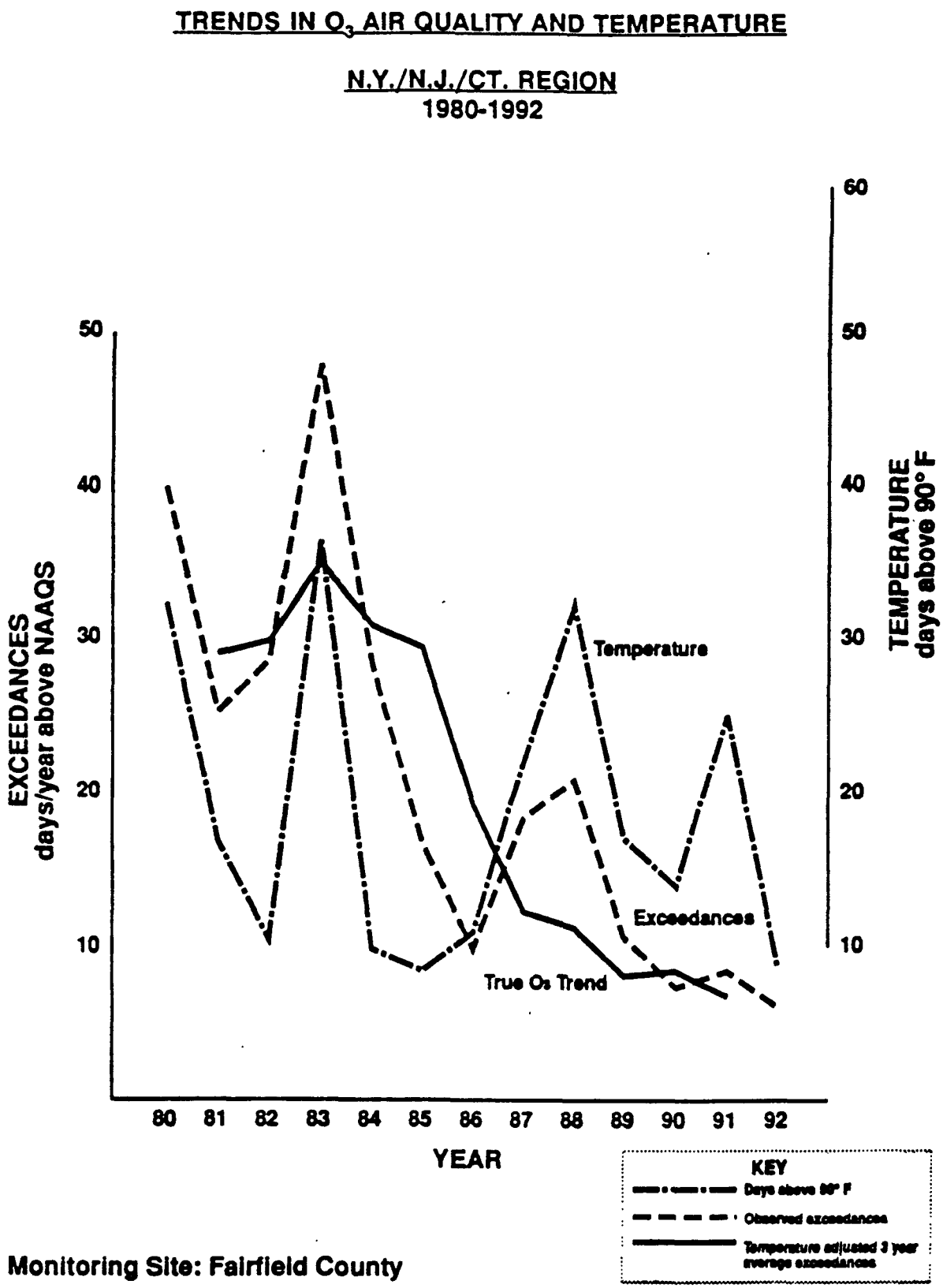


Figure 7-1. Adjustment of ozone trend based on number of days above 90°F (Source: Jones, 1992).

meteorological index based on the average value of a daily score of ozone potential. The daily ozone potential score is determined on the basis of 10 categories representing combinations of atmospheric stability, temperature, inversion height, horizontal pressure gradient, day of week, and month. Zeldin and Thomas regressed the number of hours exceeding 0.20 ppm against the seasonal mean score for a three-year base period and used the resulting relationship to predict the number of hours exceeding 0.20 ppm during each year of the study period. Differences between the predicted and actual trends indicate the influence of meteorology.

Wackter and Bayly (1987; [14]) developed a definition of "ozone-conducive days" based on a combination of temperature, wind speed, and wind direction conditions. A linear regression was then used to relate the annual ozone summary statistic to the number of ozone-conducive days. An additional variable representing the current year was included in the regression equation to model the trend assumed to be associated with changes in precursor emissions. The regression parameter for the year variable was interpreted as representing the meteorologically adjusted trend. As noted in the previous section, this interpretation assumes that the regression model fully accounts for all meteorological influences on ozone concentrations.

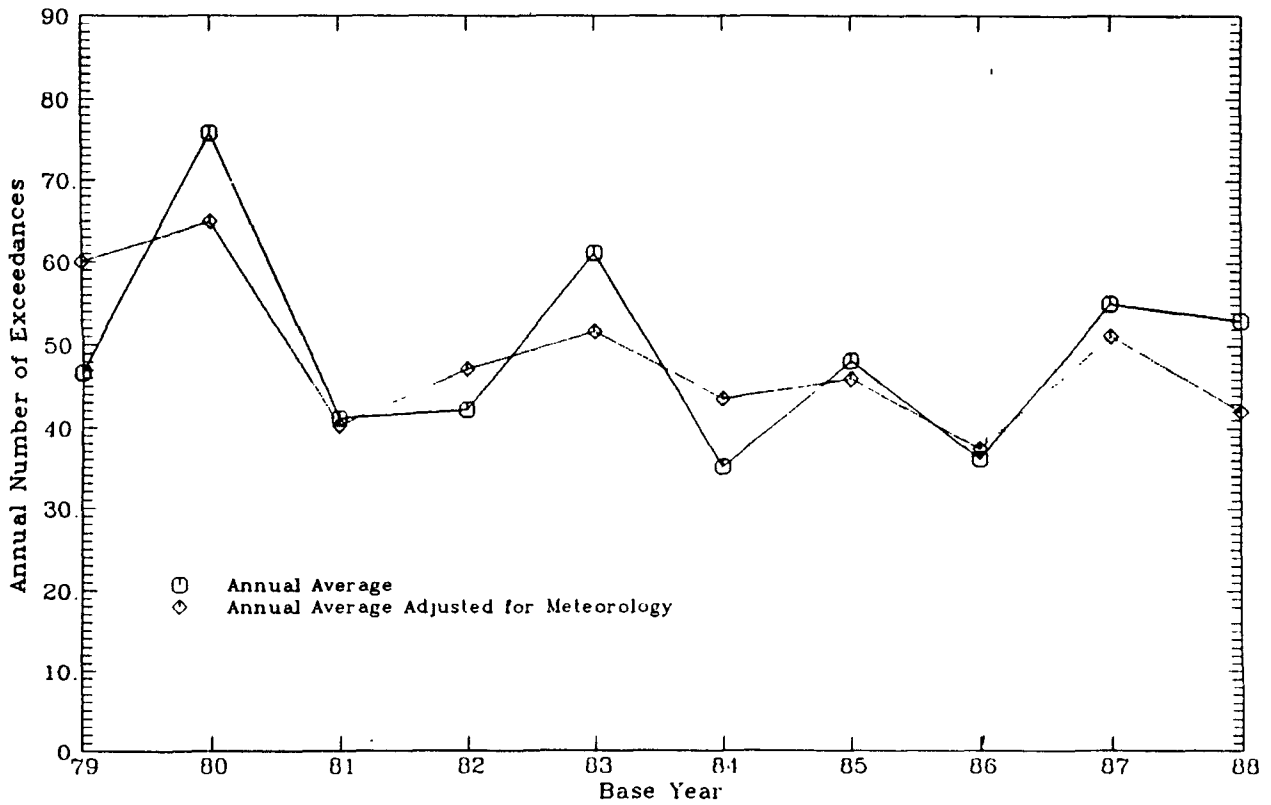
Stoeckenius et al. (1986), in an independent derivation similar to that presented by Zeldin and Breiman (1979; [2]), presented a generalized framework for using meteorological categorization schemes comprising two or more categories to compute adjusted trends in exceedances. This method is based on the use of the conditional probability approach for estimating ozone design values described in the Ozone Guideline. An adjusted exceedance trend is obtained by multiplying the probability of exceedance in each meteorological category (conditional probabilities) by the long-term average (i.e., climatological) frequency of occurrence of each category and summing over all categories. If the categorization scheme does a good job of accounting for meteorological influences, the conditional probabilities vary only in response to non-meteorological factors, and the adjusted exceedance rate is a good estimate of the number of exceedances that one would have expected to observe if meteorological conditions during the year in question had been "typical" or "average." Assuming a multinomial distribution for the exceedances, it is shown how the adjustment method partitions the variance in exceedance rates into within-category and between-category components.

The fact that the adjusted annual summary statistics developed via the above method can be interpreted as the values that would have been observed had meteorological conditions during the year followed a "typical" or "normal" pattern represents an advantage over other adjustment procedures that do not allow for such an interpretation. For example, meteorologically adjusted exceedances calculated in this way can be interpreted as a reasonable estimate of the expected (i.e., long-term average) exceedance rate since, at least to some extent, any peculiarities in meteorological conditions during the year in question have been accounted for.

Other Adjustment Methods

While the adjustment methodology demonstrated by Stoeckenius and Hudischewskyj (1990; [17]) is theoretically sound, flexible, and easy to implement, the meteorologically adjusted trends calculated with this method, as well as those based on linear regression models (with residuals added back in), exhibit some remaining correlation with the unadjusted trends, suggesting that the models do not account for all of the meteorological variability they seek to explain. A typical example of this is shown in Figure 7-2, which presents results obtained by Stoeckenius and Hudischewskyj for Philadelphia. The unadjusted exceedances of 0.085 ppm in this figure show the influence of unusually warm weather in 1983 and 1987–88. However, unless one believes that emission increases unrelated to the unusual weather conditions occurred in these years, it appears that not all of the increase in exceedances in these years are properly accounted for by the adjustment method. Kolaz and Swinford (1990; [5]) attempted to address these shortcomings by calculating the probability of exceeding 0.12 ppm as a function of a meteorological index of ozone potential defined on the basis of wind speed, temperature, and solar radiation. These probabilities are then used in conjunction with long-term average index values to compute an adjusted exceedance trend. This extension of the meteorological categorization procedure provides a means of taking into account not just fluctuations in the frequency of ozone-conducive conditions, but also in the intensity of those conditions, while at the same time avoiding reliance on simple linear relationships such as those used in the regression-based methods discussed earlier. Results obtained by Kolaz and Swinford using this method are presented in Figure 7-3. Although the adjusted trend is considerably less "noisy" than the unadjusted trend, some of the remaining year-to-year fluctuations, particularly the increases in exceedances in 1983, 1985, 1987, and 1988, match fluctuations in the unadjusted trend during those years, suggesting that the meteorological influences are not fully accounted for by this method either.

Alternative statistical models that also seek to address the shortcomings noted above have been proposed by Shively (1990; [19]) and Cox and Chu (1991; [20]). In both papers, a statistical distribution is selected to describe the daily maximum ozone concentration. Parameters of the distribution are written as functions of meteorological conditions and a time index (to allow for gradual trends such as those that might be associated with changes in precursor emission patterns). Shively (1990; [19]) modeled exceedances of 0.12 and 0.16 ppm as a nonhomogeneous Poisson process in which the log of the intensity parameter (equal to the log of the number of exceedances occurring in a given time interval) is a linear function of several meteorological variables and a year index. Model parameters for the meteorological variables and the year index are determined via maximum likelihood. Given the standard errors of the parameter estimates, the null hypothesis that the parameter for the year index is equal to zero can be tested. Rejection of the null hypothesis indicates a statistically significant underlying trend unaffected by fluctuations in meteorological conditions (or at least those fluctuations accounted for by the model). Shively did not calculate meteorologically adjusted annual



= Annual Average (unadjusted)
= Annual Average Adjusted for Meteorology

Figure 7-2. Annual number of days on which the average daily maximum ozone concentration in the Philadelphia Ozone Network exceeds 0.085 ppm based on yearly data run down the CART tree grown on 1979–88 data (adapted from Stoeckenius and Hudischewskyj, 1990).

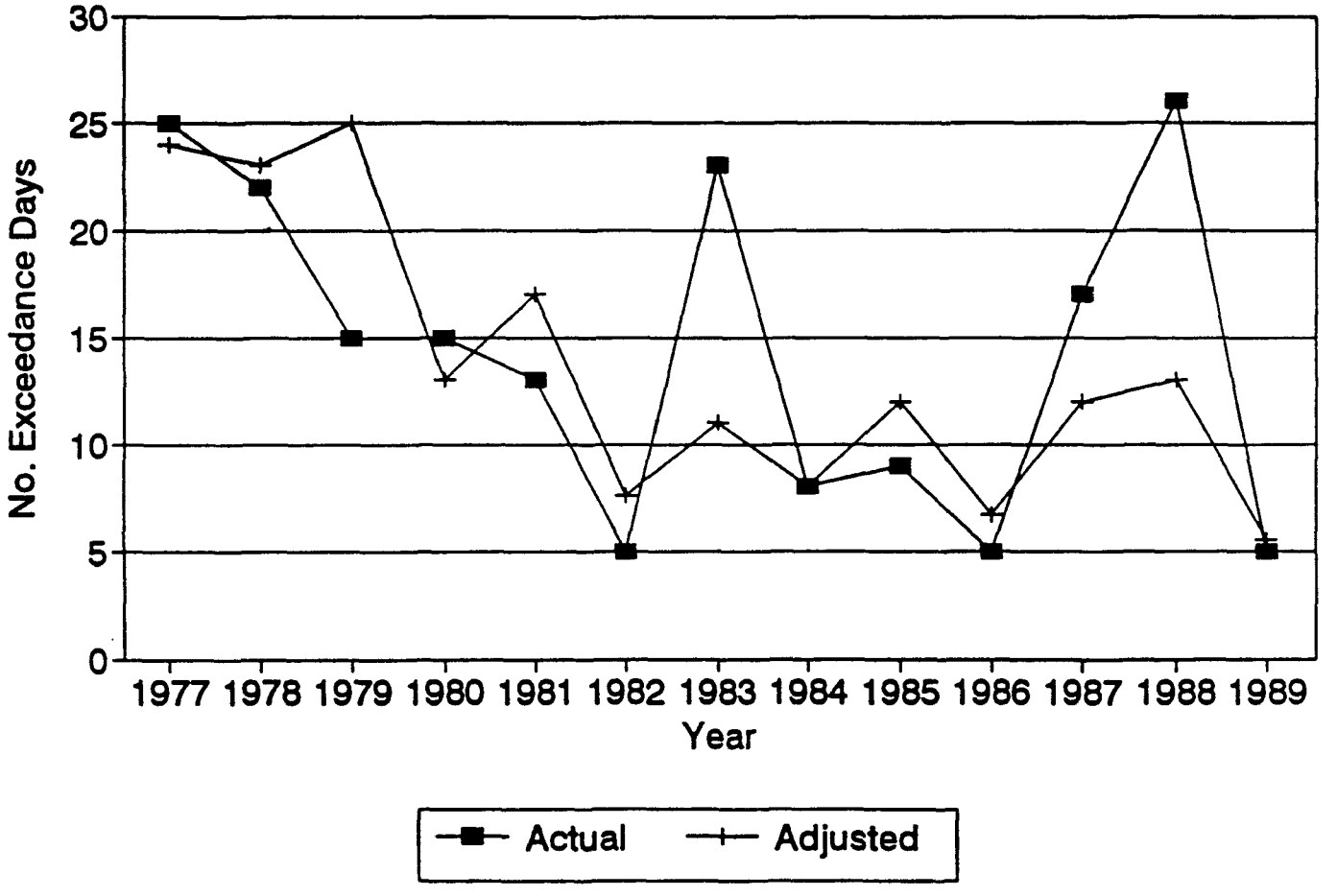


Figure 7-3. Actual and adjusted trends in number of days on which ozone concentrations exceed 0.12 ppm in the Chicago area (adapted from Kolaz and Swinford, 1990).

summary statistics and therefore his results cannot be directly compared to year-by-year results obtained via regression or classification procedures.

Cox and Chu (1991; [20]) modeled the daily maximum ozone concentration using a Weibull distribution with a fixed shape parameter and a scale parameter the logarithm of which varies as a linear function of several meteorological variables and a year index. Model parameters are fitted via maximum likelihood. The fitted distribution can be used to estimate percentiles and threshold exceedance probabilities for the daily maximum ozone concentration given a fixed set of meteorological conditions. Cox and Chu tested for a statistically significant trend term to determine if an underlying meteorologically adjusted trend can be detected. They also used their model to calculate "meteorologically adjusted" estimates of the upper percentiles of daily maximum concentrations in each year. These estimates are obtained by substituting a one-year sequence of adjusted daily meteorological variables into the Weibull scale parameter equation and finding the concentration value exceeded on 1 percent of days over the course of the year. The adjusted meteorological variables are obtained by normalizing each of the actual daily values observed over the 10-year period being analyzed with respect to their long-term mean and standard deviation. This process rescales each meteorological variable so that it becomes centered over its long-term distribution. Cox and Chu demonstrated both that year-to-year variations due to sampling effects are minimal, and that the adjusted 95th percentiles are primarily influenced by the trend term for the 31 cities shown in Figures 7-4 through 7-11. The smoothing introduced by the meteorological adjustment is especially evident in the ozone trends for eastern cities where peak ozone years, such as 1983 and 1988, have been followed by years less conducive to ozone formation. Results of application of the model to a number of urban areas are encouraging. EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS).

SUMMARY AND CONCLUSIONS

The influence of meteorological conditions, particularly temperature, on ozone concentrations has been well established. Meteorology has been found to account for as much as 80 percent of the variance in daily maximum ozone concentrations at many locations in the eastern and midwestern U.S. and in California coastal cities. Although the particular combination of meteorological variables most closely associated with high ozone events varies from location to location, high temperatures, clear skies, light winds and limited vertical mixing generally result in the highest ozone events. Due to correlations of temperature with other variables, the daily maximum temperature is often the single most important variable in explaining day-to-day ozone variations. However, since high temperature by itself is not sufficient to produce high ozone concentrations, including other meteorological variables in the analysis often produces better results. This is particularly true at locations where ozone and precursor materials transported from upwind source regions account for a significant concentration increment on high

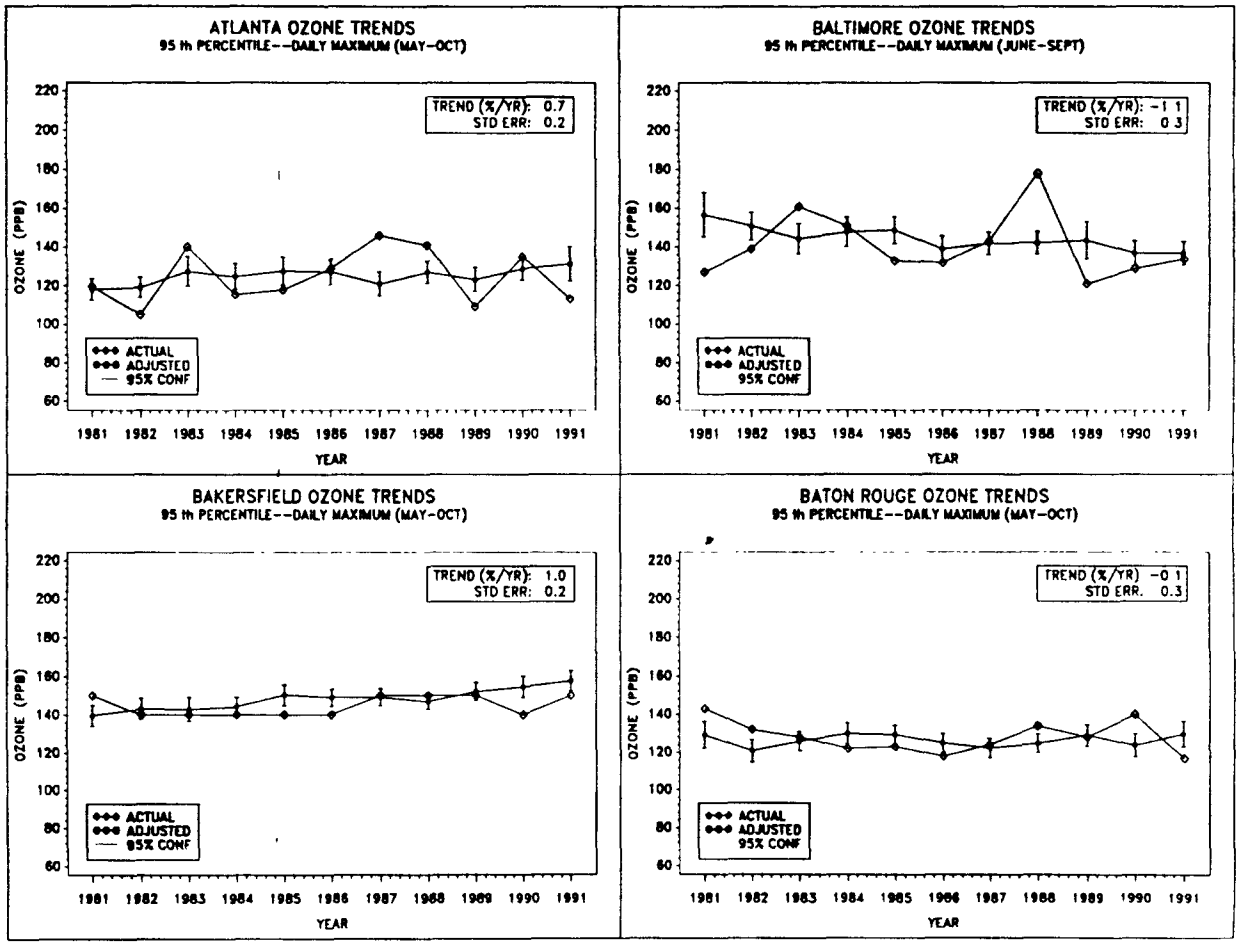


Figure 7-4. Actual and meteorologically adjusted ozone trends in Atlanta, Baltimore, Bakersfield, and Baton Rouge, 1981-91 (adapted from Cox and Chu, 1991).

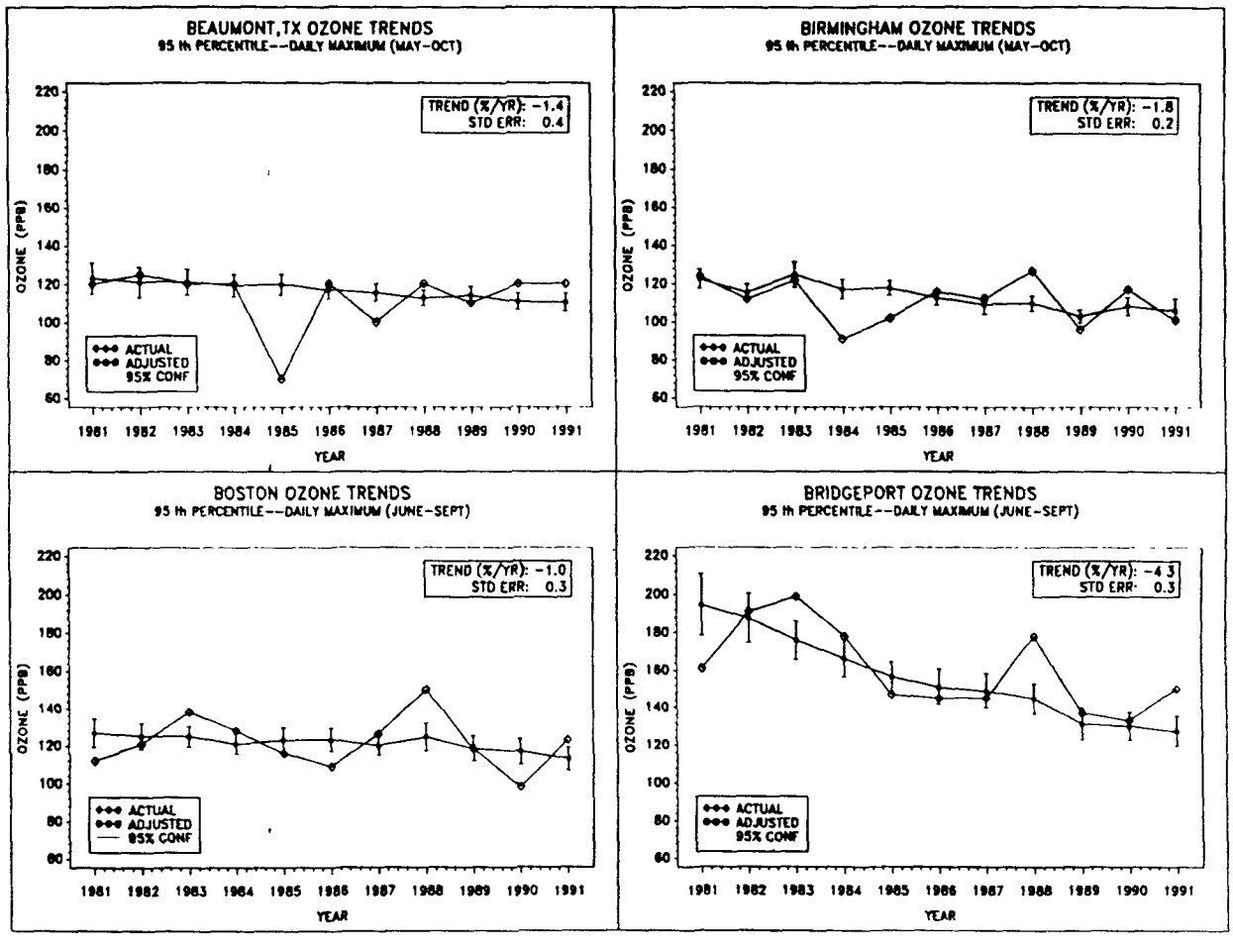


Figure 7-5. Actual and meteorologically adjusted ozone trends in Beaumont, Birmingham, Boston, and Bridgeport, 1981-91 (adapted from Cox and Chu, 1991).

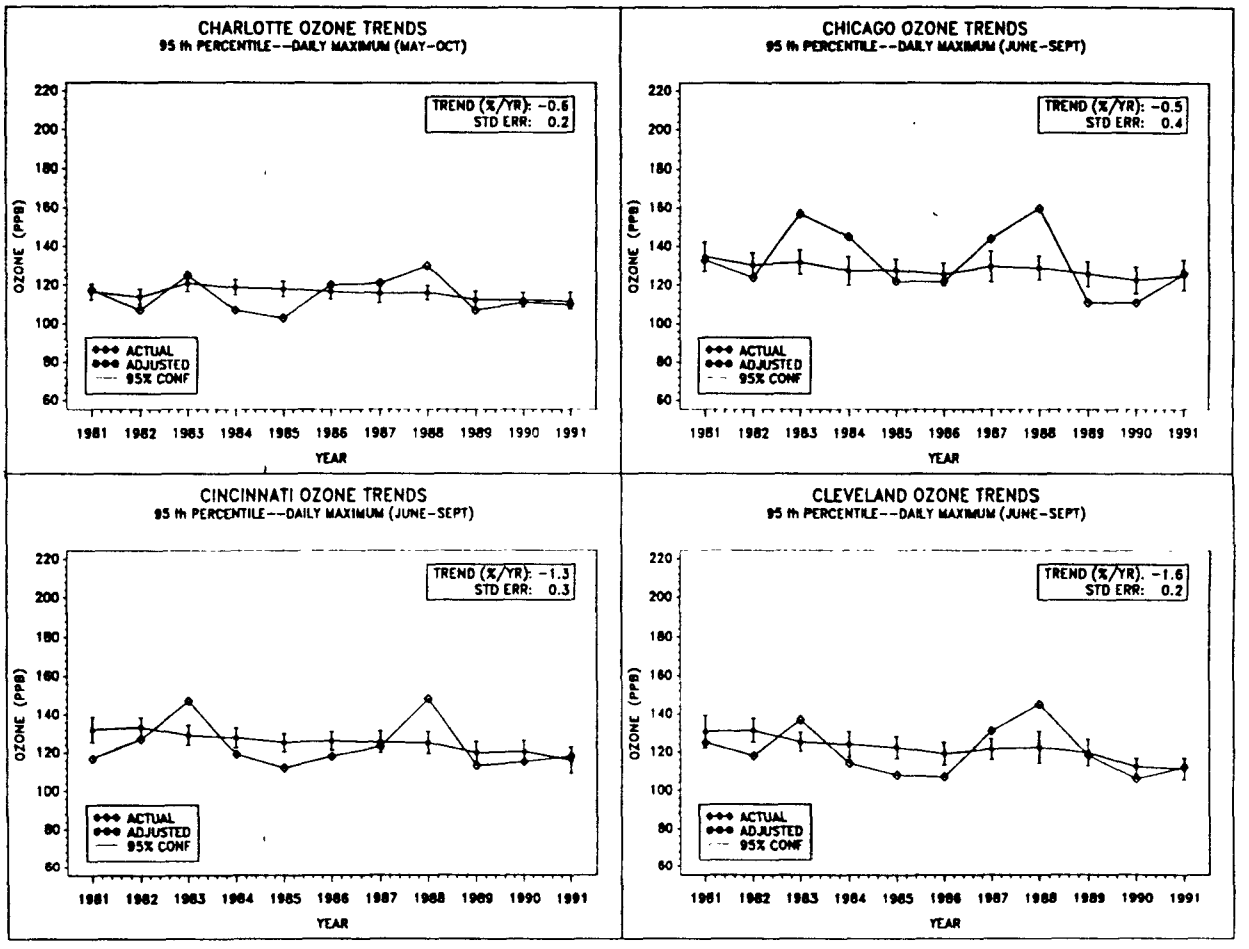


Figure 7-6. Actual and meteorologically adjusted ozone trends in Charlotte, Chicago, Cincinnati, and Cleveland, 1981-91 (adapted from Cox and Chu, 1991).

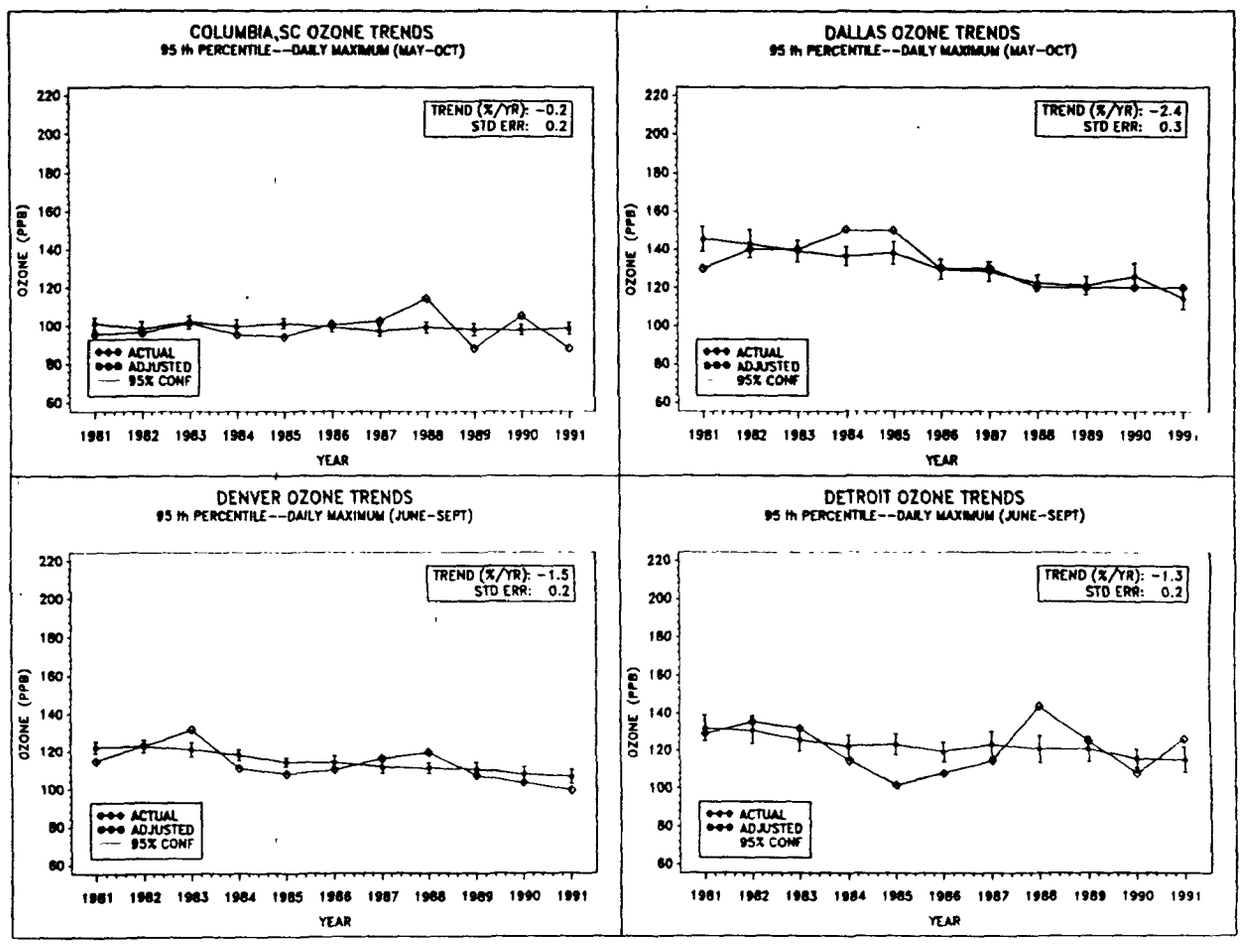


Figure 7-7. Actual and meteorologically adjusted ozone trends in Columbia, Dallas, Denver, and Detroit, 1981-91 (adapted from Cox and Chu, 1991).

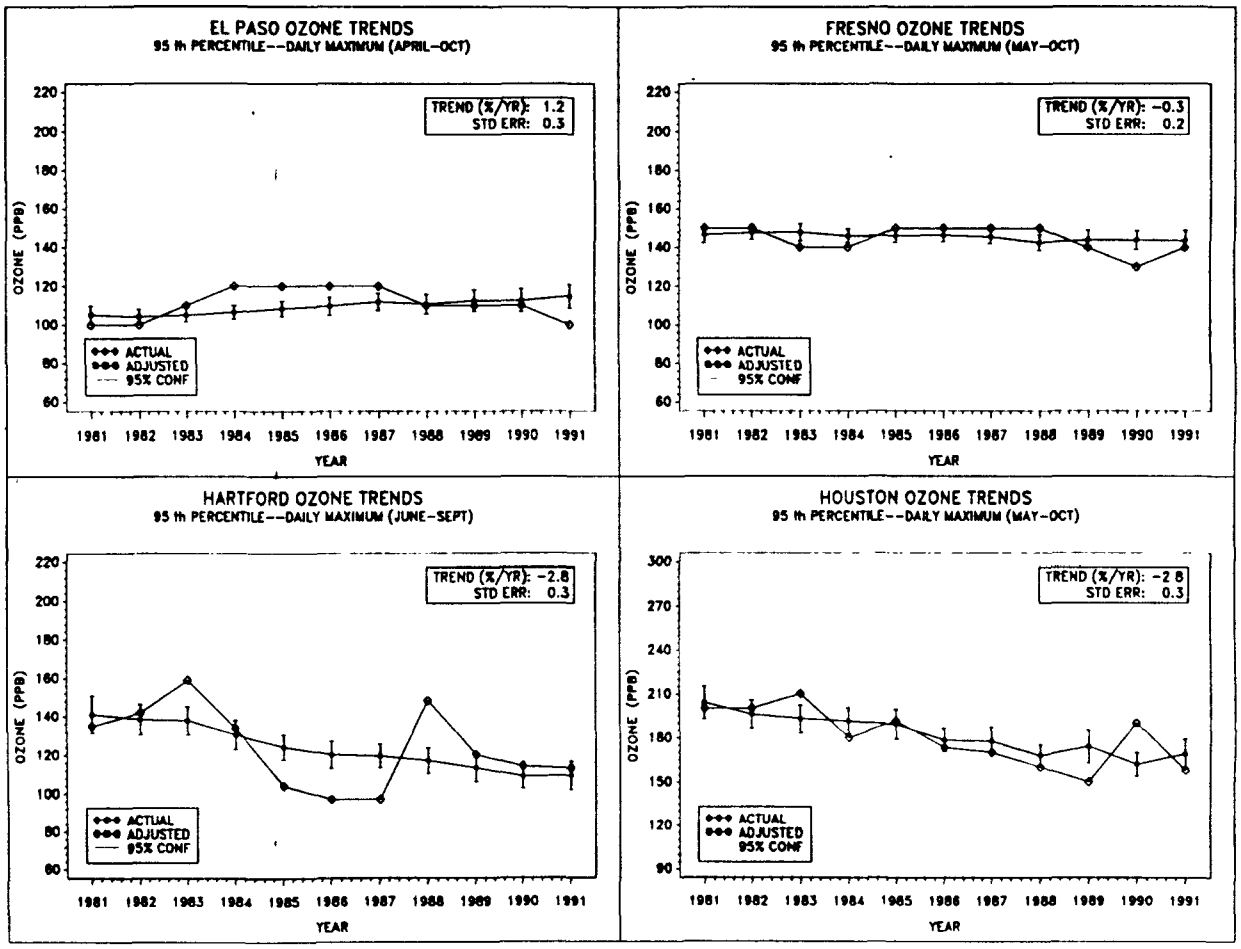


Figure 7-8. Actual and meteorologically adjusted ozone trends in El Paso, Fresno, Hartford, and Houston, 1981-91 (adapted from Cox and Chu, 1991).

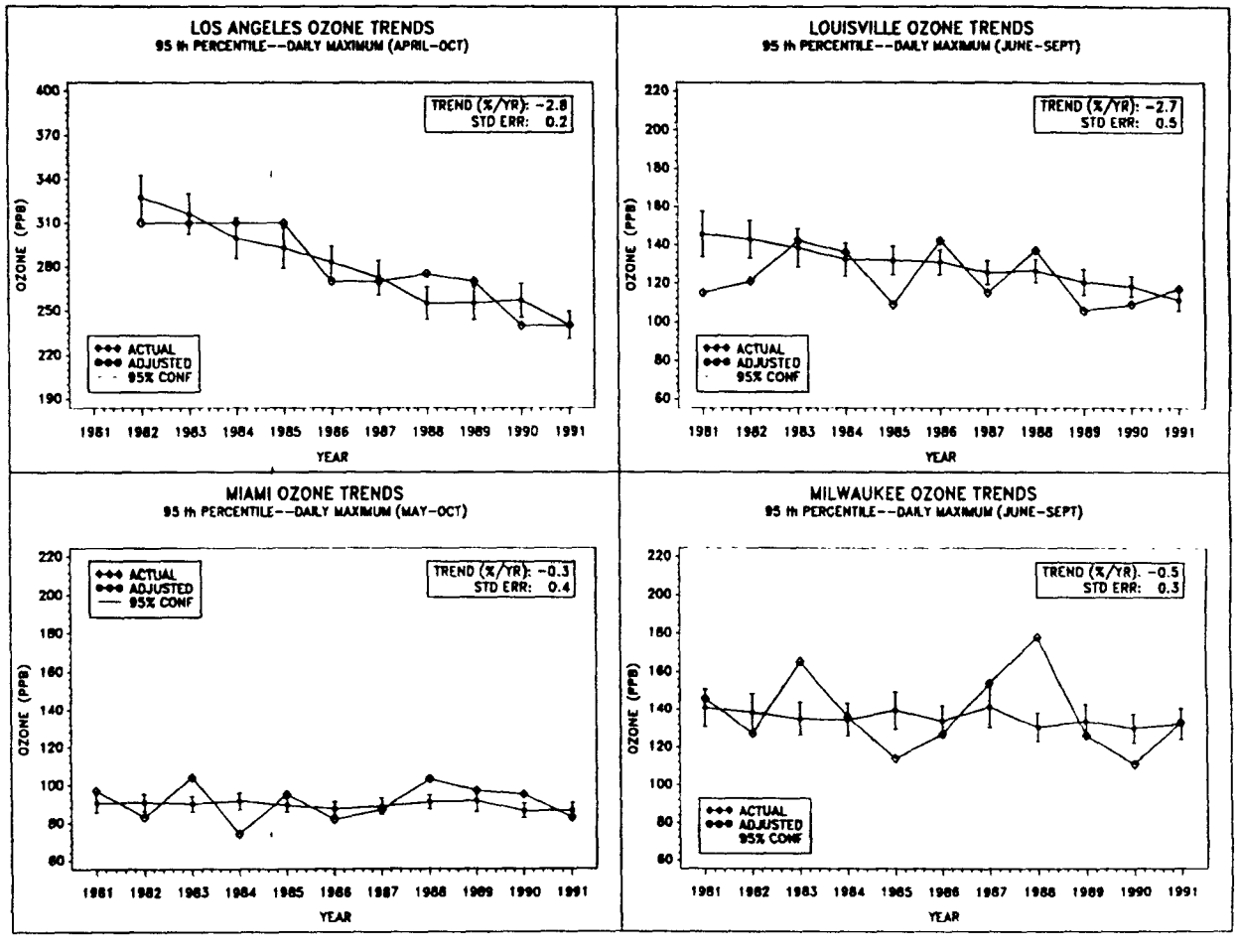


Figure 7-9. Actual and meteorologically adjusted ozone trends in Los Angeles, Louisville, Miami, and Milwaukee, 1981-91 (adapted from Cox and Chu, 1991).

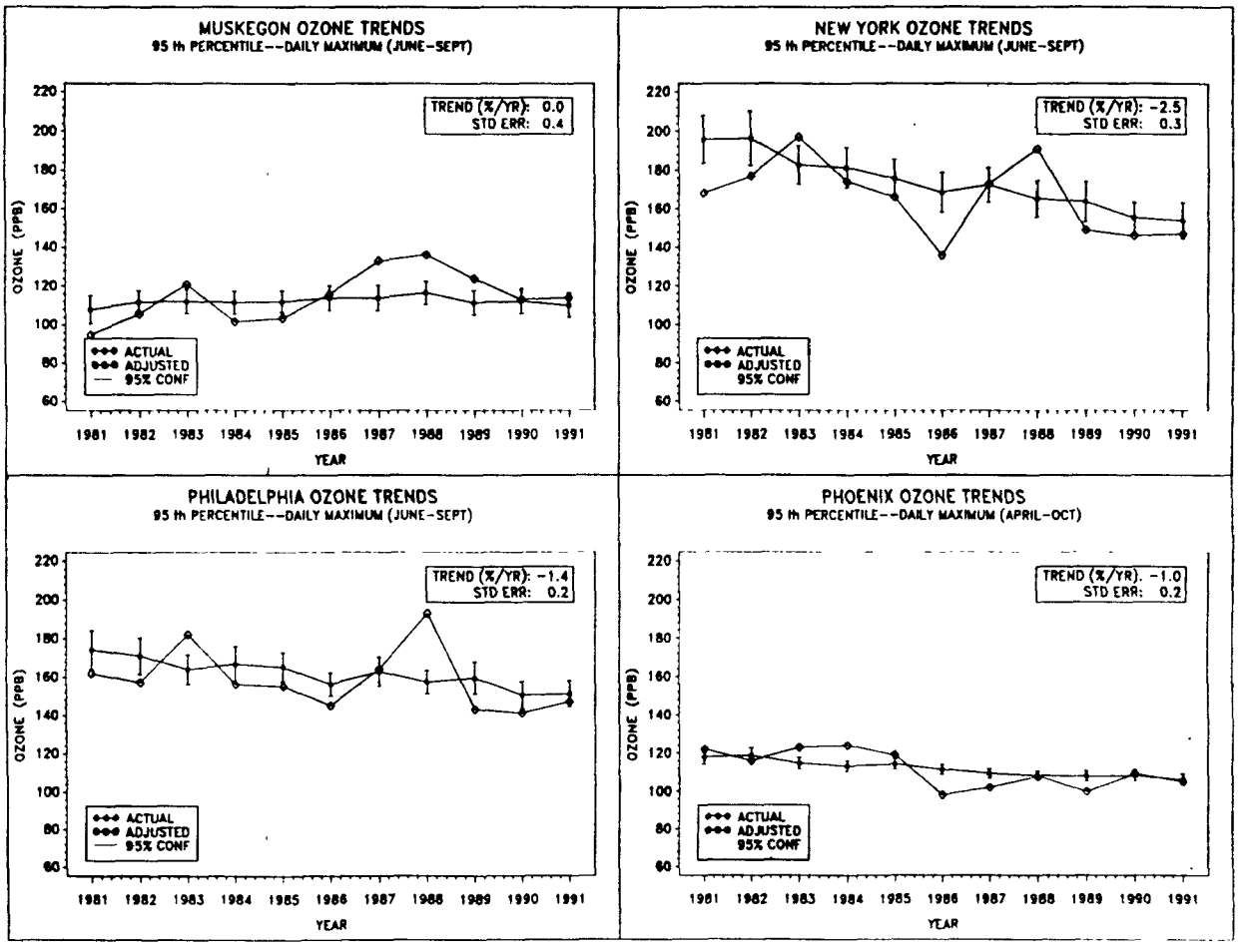


Figure 7-10. Actual and meteorologically adjusted ozone trends in Muskegon, New York, Philadelphia, and Phoenix, 1981-91 (adapted from Cox and Chu, 1991).

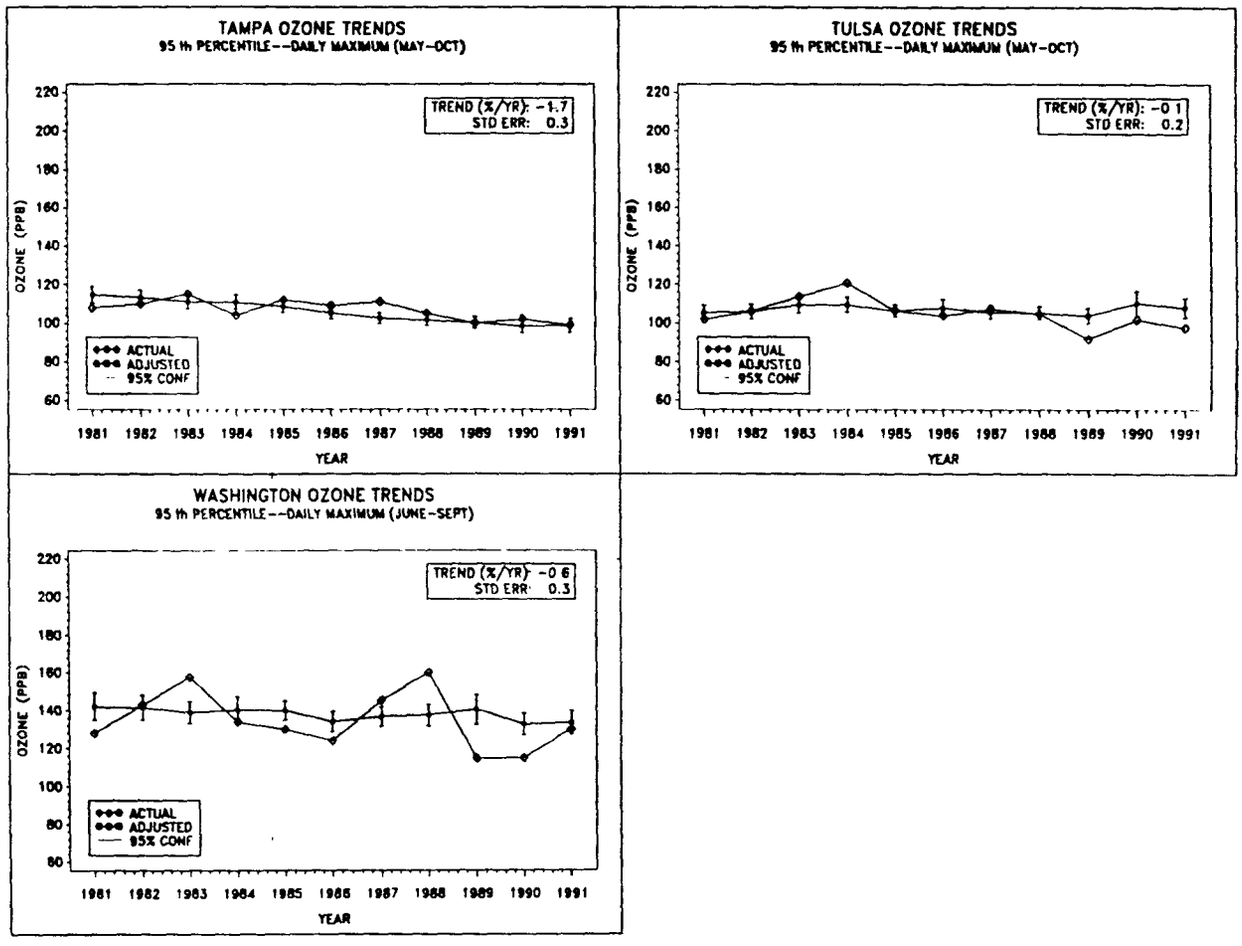


Figure 7-11. Actual and meteorologically adjusted ozone trends in Tampa, Tulsa, and Washington, D.C., 1981-91 (adapted from Cox and Chu, 1991).

ozone days. High concentrations at such locations are primarily associated with weather conditions conducive to both ozone formation and transport from the upwind source regions.

The year-to-year variability in prevailing weather conditions during the high ozone season can mask underlying ozone trends associated with changes in precursor emission patterns and can distort estimated design values. As a result, a great deal of attention has been given to the development of procedures for adjusting summary statistics to remove the effects of meteorological fluctuations. A wide variety of methods have been used, all of which rely on the development of a mathematical relationship between ozone concentrations and meteorological factors. This relationship is then used to estimate (predict) ozone concentrations expected to occur under standardized meteorological conditions. "Adjusted" summary statistics calculated from these predicted concentrations can then be examined for trends or, if the standardized meteorological conditions are representative of typical or average conditions, to provide estimates of design values less affected by year-to-year meteorological fluctuations.

Regression models have been widely used as the basis for calculating meteorologically adjusted summary statistics. These models are particularly well suited for concentration summary statistics such as the annual mean daily maximum but are more difficult to apply to exceedance summary statistics such as the number of days exceeding the ozone NAAQS.

Classification models require fewer assumptions concerning the form of the relationship between meteorological factors and ozone concentrations than do regression models and allow for greater flexibility in defining summary statistics. They are particularly well suited for calculating adjusted exceedance summary statistics. However, development of the category definitions requires at least some manual inspection of data and subjective judgment.

EPA has initiated a program (Cox and Chu, 1991) to investigate techniques for adjusting ozone trends for meteorological influences. One of the methods being studied is a statistical model in which the frequency distribution of ozone concentrations is described as a function of meteorological parameters. EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS). Preliminary results suggest that the bias and uncertainty associated with long-trend estimates can be significantly reduced by including meteorological covariates as parameters in the statistical modeling process.

The method used to adjust for meteorological influences on long-term ozone trends could be easily adapted for use in calculating meteorologically adjusted exceedance rates and design values. While such adaptations are technically feasible, the use of adjusted exceedance rates in NAAQS attainment and adjusted design values for classification purposes would represent a major departure from current EPA policy and

NAAQS implementation guidelines. Such a major change should be considered within the context of the ozone NAAQS review process.

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8 ASSESSING THE IMPACT OF TRANSPORTED OZONE AND PRECURSORS

Since the early 1970's, there has been a growing awareness that ozone and ozone precursors are transported beyond the political jurisdiction of source areas and can significantly influence ozone concentrations in neighboring air basins located considerable distances downwind. To address this aspect of the problem, the 1990 Clean Air Act Amendments established a transport commission for the Northeast, and they allow the establishment of commissions in other parts of the country. The transport of ozone concentrations generated from urban manmade emissions of precursors in numerous areas to locations downwind can result in elevated levels of ozone across regional spatial scales.

Studies of the relationship between high ozone concentrations in downwind impact zones and meteorological conditions have demonstrated that ozone peaks in areas such as southwestern Connecticut are heavily influenced by emissions from upwind sources in neighboring states (see, for example, Possiel et al., 1990; Sampson and Shi, 1988; Wackter and Bayly, 1987). Transport of ozone and precursors also plays a significant role in other parts of the country, including the Gulf Coast region and Lake Michigan. Transport of material between air basins in California has been recognized as significant by that state and is the subject of an active research program. As is the case with federal law, the California Clean Air Act requires upwind air basins to mitigate downwind impacts.

In response to Section 184(d) of the 1990 Amendments, EPA issued criteria for assessing the role of transported ozone and precursors in ozone nonattainment areas (EPA, 1991). The Act requires States to ensure that prescribed emissions reductions are sufficient to meet the ozone NAAQS in nonattainment areas. It is in meeting the Act's air quality management requirements that proper consideration of transport is important. The guidance describes the use of meteorological and air quality data to support modeling analyses, including the use of trajectory models and the Urban Airshed Model.

CHRONOLOGY OF A MULTI-REGIONAL OZONE EPISODE, JUNE 17-20, 1987

An example of a regional scale ozone episode occurred during June 1987 and is displayed below using a geographic information system (GIS). The system was used to generate isopleths based on the daily maxima of hourly ozone concentrations from all sites in the northeast and north central areas of the United States. Data were also obtained from Canadian sites, in Ontario, during the same time period. The Canadian data helped define the isopleths near the Great Lakes. The GIS was used to display the isopleths as levels of grey shading (Figures 8-1 through 8-4). These isopleths involve a certain amount of smoothing, so that the maps provide a simplified overview and are not intended to provide precise city specific concentrations. The episode begins on Wednesday, June 17 and ends on Saturday, June 20.

Wednesday, June 17: A strong high pressure system is located in southeastern Canada, and the whole study area is experiencing high temperatures from the high 70s to the low 90s, with small amounts of precipitation in New England. Ozone readings above the standard are observed in the Chicago and Milwaukee areas and at one site in Parkersburg, West Virginia (Figure 8-1).

Thursday, June 18: The high pressure system is now over Pennsylvania, and a strong low pressure system has moved into southern Canada. No precipitation has been observed in the entire region. Areas of high ozone concentrations are centered on Chicago, Milwaukee, northwest Indiana, eastern Ohio, western Pennsylvania, and central Maryland (Figure 8-2).

Friday, June 19: The high pressure system has moved off the coast of New Jersey, with high temperatures in the 80s to 90s. Again, no precipitation has been observed in the entire area. High ozone concentrations are now observed in eastern Michigan, western Pennsylvania, and from eastern Pennsylvania through the northeast corridor (Figure 8-3).

Saturday, June 20: A weak cold front moving into the area from the northwest has reached Pennsylvania. Precipitation is observed along this front, and maximum temperatures have reached the mid-90s to the east of the front. High ozone concentrations are observed in central New Jersey, with very high concentrations centered on New York City (Figure 8-4).

These displays indicate an initiation of an episode in the Chicago-Milwaukee area which is followed by a general eastward movement ending in New York City. The episode tracks the basic meteorological events occurring during this period. By Sunday no elevated readings of ozone are reported, and the episode has ended. Recognition of such episodes in the Great Lakes region lead to development of the Lake Michigan Ozone Study (LMOS), a cooperative State and Federal effort to study ambient ozone levels on a regional scale in the Lake Michigan area. The LMOS data collection efforts consisted of a major field study during summer 1991, which collected air quality and meteorological data.

As illustrated by this example, visualizing the regional nature of ozone transport using monitoring data requires spatial interpolation among a discrete number of individual sites which are generally concentrated in or near major cities. Photochemical modeling, which produces three-dimensional predictions of ozone air quality, can provide added insight into transport patterns. Several examples of urban ozone plumes and their interaction on a regional scale are shown from predictions of the Regional Oxidant Model (ROM) for the Midwest and Northeast U.S. in Figures 8-5 through 8-8. Each figure displays ROM ozone predictions for a single hour extracted from simulations that encompass multi-day episodes. On July 17, 1987 (Figure 8-5), urban ozone plumes extend from the major Midwest cities downwind with the southerly wind flow on this day. Note the high ozone predicted along the western shore of Lake Michigan and offshore over the lake resulting from urban areas along

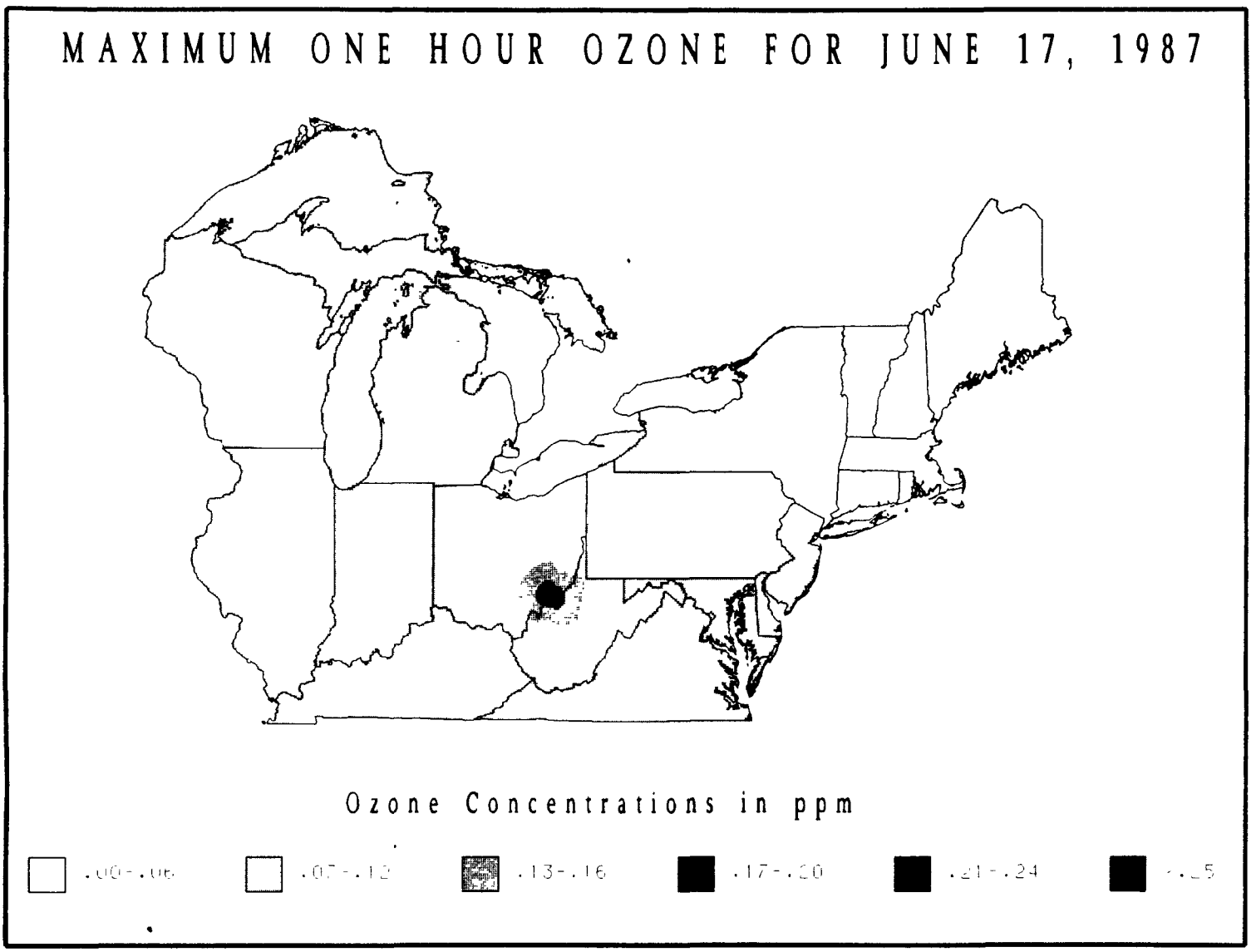

Figure 8-1. Isopleths of ozone daily maximum 1-hour concentrations for June 17, 1987.

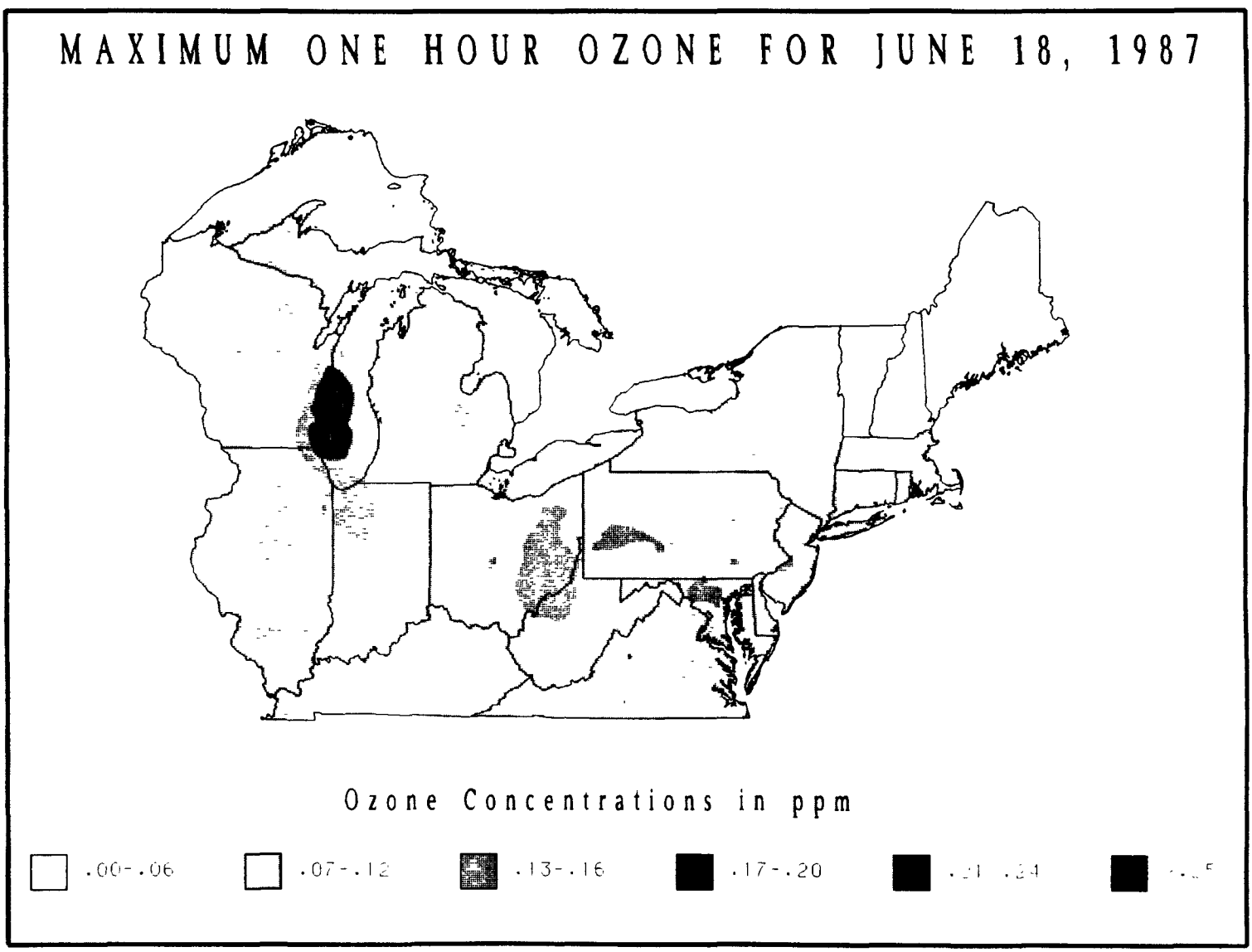

Figure 8-2. Isopleths of ozone daily maximum 1-hour concentrations for June 18, 1987.

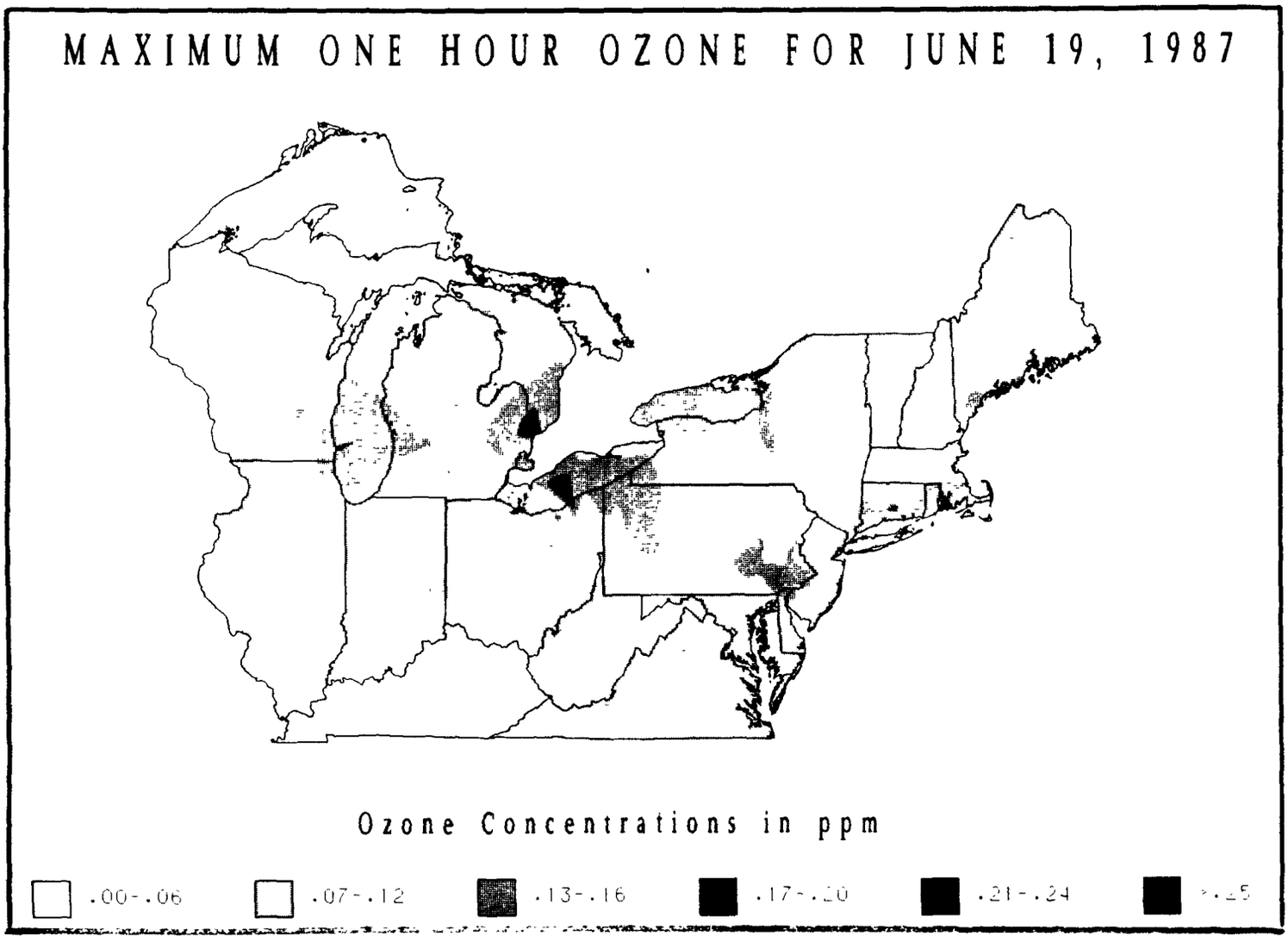

Figure 8-3. Isopleths of ozone daily maximum 1-hour concentrations for June 19, 1987.

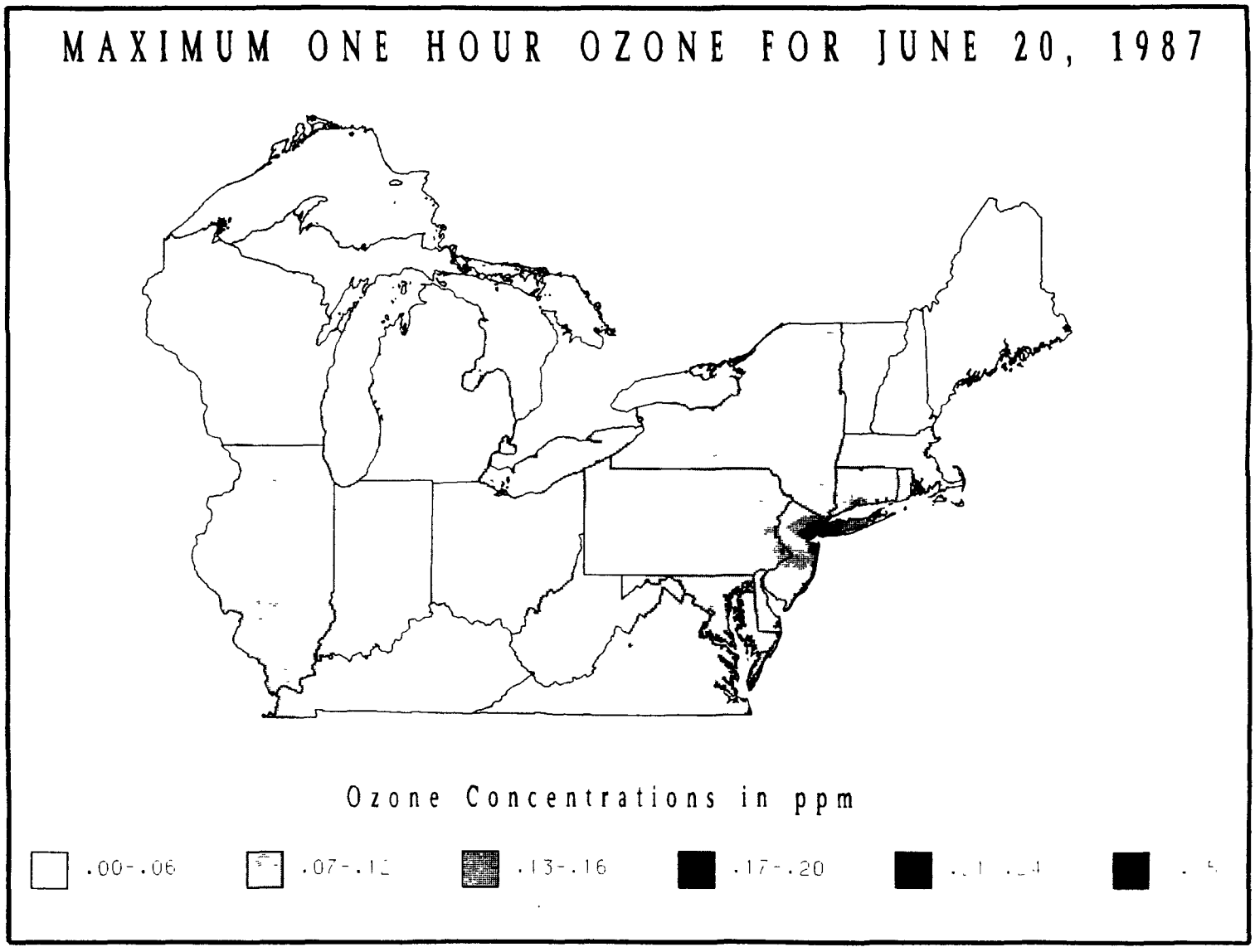

Figure 8-4. Isopleths of ozone daily maximum 1-hour concentrations for June 20, 1987.

the western shore. Also, ozone plumes from cities along the Ohio River extend northward as far as Detroit. In the Northeast, predictions for July 7, 1988 (Figure 8-6) reveal a continuous "river" of moderately high ozone extending from eastern Ohio southeastward to Richmond, VA then northeastward along the Northeast Corridor from Washington, D.C. to coastal Maine. Ozone plumes with concentrations exceeding the level of the NAAQS are embedded within this area over and downwind of major ozone-precursor emissions areas. In fact, a continuous area with ozone levels at or above 0.12 ppm is predicted from southeastern Pennsylvania into Rhode Island. Finally, comparing ozone patterns for 1400 EST and 2300 EST on July 8, 1988 (Figures 8-7 and 8-8) shows the transport of ozone exceeding 0.15 ppm to the Boston area from sources to the southwest during this time period.

The prevailing winds along the eastern seaboard during this episode were out of the southwest as is typical of high ozone days in this region. The long plumes of elevated ozone concentrations stretching downwind from the major urban centers such as Washington-Baltimore and Philadelphia suggest the extent of transport in this region.

ADJUSTING OZONE DESIGN VALUES FOR TRANSPORT

Section 181(a) of the Clean Air Act Amendments of 1990 established ozone classifications for nonattainment areas based on the area's air quality design value. After the initial classification process, EPA could, at its discretion, adjust the classification if the design value was within 5 percent of the level for another category. In making such an adjustment, EPA could consider such factors as the number of exceedances, the level of transport, and the mix of sources and air pollutants in the area. Given this language, and the legislative history including air quality design value lists for urban areas, EPA determined that no direct adjustment for transport was to be made to the ozone design value used for the initial classifications (FR, 1991). However, it is clear that as a result of the strong influence of transported precursors and ozone in some nonattainment areas, design values at such locations may be heavily influenced by emission changes occurring many kilometers away in upwind areas.

In early SIP guidance for the EKMA Model, EPA addressed the issue of how design values are to be used in assessing the need for emissions reductions in both the downwind and upwind areas (EPA, 1977). EPA recognized the need to identify the transport-related component of design values that are to be used for the purpose of designing local emission control strategies (so called "SIP control values"; see Rhoads and Tyler, 1987). These "control strategy" design values may differ from "current air quality design values" estimated in the table look-up procedure in that they take into account the degree to which transport of ozone and precursors from upwind metropolitan areas contributes to ozone concentrations at the monitoring site in question.

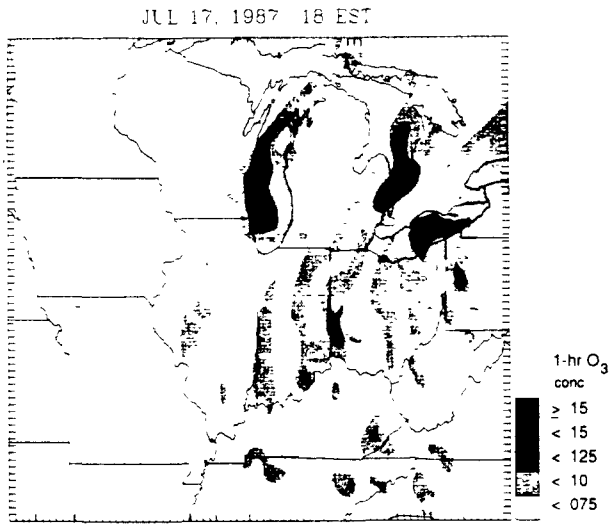

Figure 8-5. Midwest region on July 17, 1987.

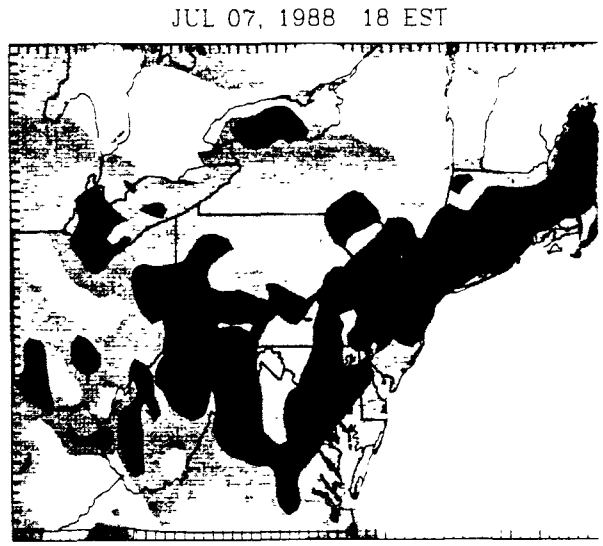

Figure 8-7. Northeast region at 1400 EST on July 8, 1988.

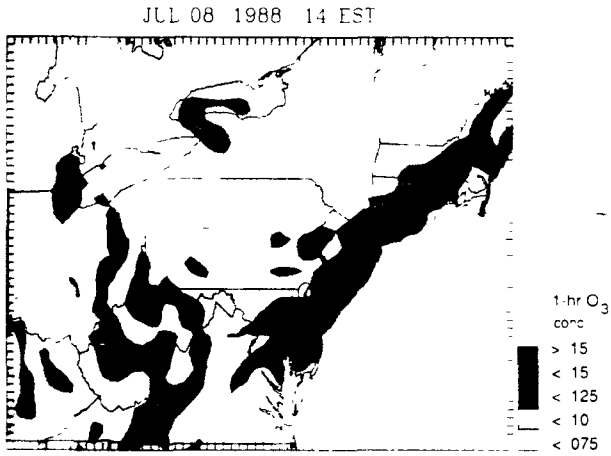

Figure 8-6. Northeast region on July 7, 1988.

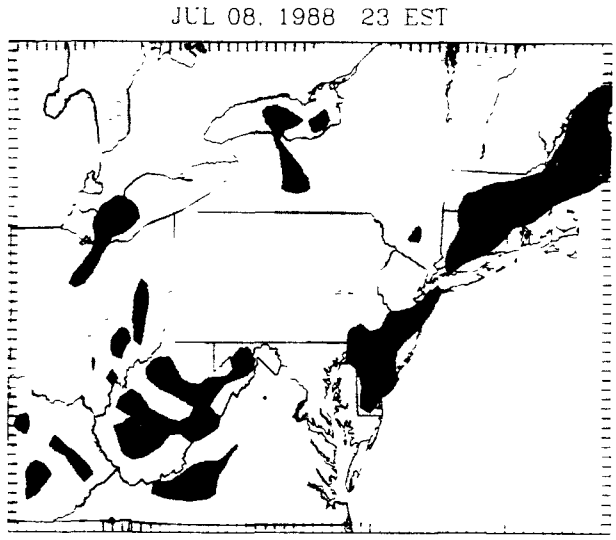

Figure 8-8. Northeast region at 2300 EST on July 8, 1988.

A computer model (TODV: Transported Ozone Design Value; Sabo and Hawes, 1990) has been developed to assist in determining the likely source regions associated with high ozone concentration events. This program uses a combination of hourly ozone concentrations and routine wind speed and direction data to calculate back trajectories and estimate the point of origin (i.e., early morning location) of air parcels arriving at a monitoring site at the time of the afternoon ozone peak on the 20 highest ozone days. This information is then used to determine if the estimated design value at a monitoring site is likely to have been strongly influenced by emissions from upwind metropolitan areas as opposed to the metropolitan area in which the monitor is located. TODV can only provide an approximate location of the emissions source region likely to have influenced a particular afternoon ozone peak. No estimate of the relative contributions of upwind vs. local emissions to the peak is provided, and back trajectory calculations based on routine wind data can contain large uncertainties. Selection of the transport adjusted design value requires an experienced analyst to interpret the trajectory results and concentration estimates, which introduces a subjective element into the adjustment process. A more sophisticated evaluation of the relative contributions of upwind and downwind areas requires application of a photochemical grid model such as the Urban Airshed Model. The TODV model is used here solely for the purpose of demonstrating the *potential* effect of transport on design values.

Application of the TODV Model to 1988-90 ozone data yielded transport adjusted "control strategy" design values for 35 areas. As indicated in Table 8-1, these adjustments ranged from a decrease of 0.05 ppm to increases of 0.04 ppm. Thus, these transport adjustment can lead to both decreases and increases in an area's design value as the downwind impact is attributed back to the source area.

As noted above, the ozone nonattainment area classifications under the 1990 Amendments were determined using the air quality design value, not a "control strategy" value that was adjusted for transport. However, the design values for the 35 areas in Table 8-1 provide an opportunity to ask the question, "What would be the difference in classification if ozone design values were adjusted for transport?" Table 8-2 summarizes the comparison between ozone area classifications that would result from the 1988-90 air quality design value and those obtained from the transport adjusted design value. In twelve of the classified areas (1 serious, 2 moderate, 9 marginal), the area's transport adjusted design value is less than the level for a marginal area. Ten areas recorded increases in design values after accounting for transport, i.e., transport was attributed back to the areas. Only one of these areas with upward adjustments in design values would change classification; Beaumont, TX from moderate to severe.

Table 8-1. Transport Adjusted Ozone Design Values, 1988-90

Area	1988-90 Design Value	Adjusted Design Value	Increase/ (Decrease)
Atlantic City, NJ	0.148	0.119	(0.029)
Beaumont-Port Arthur, TX	0.150	0.190	0.040
Boston CMSA	0.165	0.170	0.005
Charlottesville, VA	0.113	0.106	(0.007)
Chicago CMSA	0.187	0.190	0.003
Cumberland, MD-WVA	0.072	0.107	0.035
Harrisburg-Lebanon-Carlisle, PA	0.131	0.128	(0.003)
Hartford CMSA	0.172	0.158	(0.014)
Janesville-Beloit, WI	0.113	0.096	(0.017)
Johnstown, PA	0.133	0.123	(0.010)
Lake Charles, LA	0.132	0.120	(0.012)
Lancaster, PA	0.122	0.113	(0.009)
Lewiston-Auburn, ME	0.137	0.108	(0.029)
Manchester, NH	0.128	0.105	(0.023)
Milwaukee CMSA	0.187	0.150	(0.037)
Muskegon, MI	0.151	0.125	(0.026)
New Bedford, MA	0.150	0.108	(0.042)
New Haven, CT	0.157	0.153	(0.004)
New London-Norwich, CT-RI	0.151	0.128	(0.023)
New York CMSA	0.197	0.216	0.019
Philadelphia CMSA	0.187	0.196	0.009
Pittsburgh CMSA	0.149	0.157	0.008
Pittsfield, MA	0.102	0.103	0.001
Portland, ME	0.154	0.139	(0.015)
Portsmouth-Dover-Rochester, NH-MA	0.156	0.137	(0.019)
Poughkeepsie, NY	0.134	0.103	(0.031)
Providence CMSA	0.148	0.158	0.010
Rockford, IL	0.105	0.113	0.008
San Diego, CA	0.190	0.170	(0.020)
Sharon, PA	0.128	0.118	(0.010)
Sheboygan, WI	0.153	0.113	(0.040)
Springfield, MA	0.167	0.116	(0.051)
Washington, DC-MD-VA	0.165	0.163	(0.002)
Worcester, MA	0.127	0.107	(0.020)
York, PA	0.129	0.111	(0.018)

Table 8-2. Comparison between Air Quality Design Value and Transport Adjusted Design Value Derived Ozone Area Classifications, 1988-90.

Ozone Classification	Number of Areas	
	1988-90 Ozone Design Value	1988-90 Transport Adjusted Design Value
Severe	5	4
Serious	4	3
Moderate	11	6
Marginal	10	5
Not classified	5	17
Total	35	35

SUMMARY

It is clear that the transport of ozone and ozone precursors generated in one air basin can significantly influence ozone concentrations in neighboring air basins located considerable distances downwind. EPA has issued guidance on criteria for assessing the role of ozone transport in ozone nonattainment. The Amendments call for the establishment of a transport commission to study this issue. Although the Amendments specifically acknowledge that transport across state boundaries can be an important factor during high ozone episodes, Section 181(a) of the Clean Air Act does not include a provision for adjusting the initial ozone nonattainment area classification for ozone transport. Section 181(a)(4) states that the "Administrator may, in the Administrator's discretion, within 90 days after the initial classification" adjust the classification *if the design value in the area is within 5 percent of another category*. "In making such an adjustment, the Administrator may consider the number of exceedances of the national primary ambient air quality standard for ozone in the area, *the level of pollution transport between the area and other affected areas, including both intrastate and interstate transport*, and the mix of sources and air pollutants in the area."

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9 DETECTING TRENDS IN OZONE DESIGN VALUES

This section presents a literature review of articles on the estimation of trends in ozone design values. As discussed in Section 2, design value for ozone can be defined in statistical terms as the concentration that is exceeded once per year on average. Procedures for estimating the design value from ambient ozone concentrations were described in Section 4. For many of the articles in the present literature review, the design value for a given site and year is estimated by the annual highest or second highest daily maximum hourly ozone concentration.

Unless otherwise noted in this review, the term "trend" refers to year-to-year variations in the design value. Ozone design values are typically estimated from three years of data rather than on a single-year basis. However, it is conceptually easier to evaluate trends in single-year design value estimates because estimates based on overlapping multi-year periods are correlated. The assumed trend at some sites may be realistically represented as a constant increase between one year and the following year, or as a constant percentage increase. However, ozone data at some sites have shown long-term increases and long-term decreases for different periods; such nonlinear ozone trends may be due to nonlinear meteorological or emissions trends. The important role of meteorology in ozone formation and trends was addressed in detail in Section 7. Although meteorological variability is not the primary focus of this section, it will be addressed within the context of trends detection.

The methods that have been used for trend detection are in many cases applicable to any annual summary statistic, rather than being restricted to ozone design values. Therefore, this literature review includes articles that discuss trend detection techniques in ozone design values, annual summary statistics and design values for other air pollutants, water quality data, and stratospheric ozone data. Furthermore, various articles on ozone trend detection methods have been based on trends in the annual exceedances of the ozone NAAQS. Although the numerical trend rate for the design value is not simply related to the numerical trend in the annual exceedance rate, a decreasing rate of exceedances implies a decreasing design value; thus approaches based on trends in exceedance rates are included in this literature review.

This summary review begins with a discussion of the definition of the annual design value for a single site or group of sites when there is an annual trend (variation from year to year). Later sections discuss linear regression and general linear model parametric methods of trend estimation, nonparametric methods, methods based on extreme value theory approximations, and methods that use time-series models. A tabular summary of the papers cited in this literature review is provided in Appendix H. The articles are listed by the same reference number (in brackets) used in this summary. The ordering is fairly arbitrary except that related papers tend to appear consecutively.

STATISTICAL APPROACHES TO TREND ANALYSES

Most of the trend analyses in the cited articles use only annual summary statistics in trend estimation. Thus the trend represents overall changes from year to year, and the annual summary statistics incorporate seasonal variation. If, instead, the trend analysis is based on fitting a model to monthly, daily, or hourly concentrations, then the general approach taken in the cited articles is to assume that the concentration distribution varies both seasonally (within the year) and annually (across years). This is usually achieved by allowing the parameters of the fitted distribution to depend on the calendar month and on the year.

In most cases the trend analyses ignore the year-to-year serial dependence; the design values for two consecutive years are assumed to be independent. A general problem is that it is very difficult to distinguish between a trend (not necessarily linear) and serial dependence since both phenomena can lead to very similar concentration series.

It is important to recognize a distinction between methods of trend detection and trend estimation. A trend detection method simply determines whether or not a trend exists. A trend estimation method estimates the size of the trend effect. A trend estimate can often be used for trend detection using the rule that an estimated non-zero trend implies that a trend exists; a trend is usually considered "non-zero" if the appropriate confidence interval for the trend does not contain zeio. The distinction is more important for nonparametric methods rather than parametric methods. Several nonparametric methods (such as the Spearman's rho and chi-square tests described in [18]) are used for trend detection but cannot be used for trend estimation.

Trend analyses often use averages or sums of annual summary statistics across multiple sites. A trend in the composite average across sites does not imply the same trend at every site. Further, it is possible that the site averages do not show a significant trend but there are large increasing and decreasing trends at many sites. One useful result is that the central limit theorem implies that in cases where a large number of site design values are combined, the distribution of the sum or average is approximately normal. The normality of the annual summary statistic is an assumption made for the linear regression and general linear model analyses in the cited articles.

Various types of trends are considered in the cited articles. The simplest type is a linear trend, which means that the annual summary statistic increases or decreases on average by the same amount every year. In this case the mean annual summary statistic is a linear function of the calendar year. In some cases higher order polynomial trend functions for the annual mean have been used, such as a quadratic or cubic functions. These results are usually displayed by simply plotting the observed annual means against the year and superimposing the estimated trend function (a straight line for linear trends).

Instead of making specific assumptions about the form of the trend, a more general approach allowing for arbitrary year effects has also been used. In this approach, a trend is indicated by statistically significant differences between the mean annual summary statistics for a pair of years. An often useful plot is given by graphing the annual means with simultaneous confidence intervals defined such that two means are significantly different if the corresponding confidence intervals do not overlap ([1, 15, 22, 32-40].) For example, Figure 9-1 (from [15]) illustrates simultaneous confidence intervals for four years of data. Since the plotted confidence intervals overlap for years 1 and 2 but not for years 1 and 3, years 1 and 2 are not significantly different, but years 1 and 3 are significantly different.

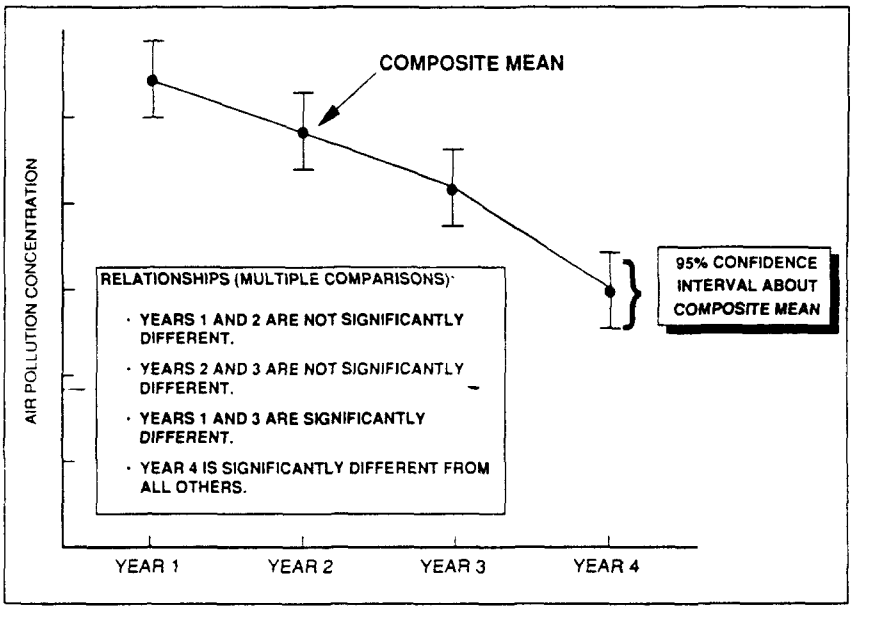

Figure 9-1. Sample illustration of the use of confidence intervals to determine statistically significant changes.

The Tukey studentized range technique used to derive the simultaneous confidence intervals in Figure 9-1 was described by Pollack and others ([15, 22]). Since the number of possible simultaneous comparisons is $k(k-1)/2$, where k is the often large number of years of data analyzed, testing each pair at the usual 5 percent significance level would lead to a high probability that at least one difference would be declared significant when in fact there are no real trends (since each comparison would then have a 5 percent probability of being declared statistically significant). To treat this problem, the confidence intervals were computed in such a way that if there is no real trend, the probability that every pair of annual confidence intervals overlaps is 95 percent. Thus the probability of erroneously determining one or more significant differences is 5 percent. The same Tukey studentized range technique is applicable in other cases where a general linear model is used to estimate the year effects.

If the assumptions of normal distributions and constant variances for every year implicit in the general linear model are not satisfied, then the Bonferroni approach to simultaneous confidence intervals has been used ([15, 22, 32-40]). For example, the constant variance assumption is inappropriate for the number of annual exceedances of the ozone NAAQS. The Bonferroni approach is used in these situations to compute confidence intervals such that the probability of erroneously determining one or more significant differences is 5 percent or less. In general these Bonferroni intervals are wider than the unknown width needed to exactly attain an overall 5 percent error probability, i.e., the Bonferroni intervals are an upper bound approximation to the exact 95 percent simultaneous confidence intervals.

When considering trends in ozone design values, the effects of varying meteorology are important since these effects can often mask underlying trends in the design values that may be attributable to hydrocarbon or nitrogen oxides emissions reductions. Various methods have been used to adjust annual summary statistics for meteorological effects prior to the trend estimation so that the effects of the meteorological "noise" is reduced. These methods are used in some of the papers cited in this literature review ([4, 5, 7-10]) but were described in greater detail in Section 7. The paper by Wackter and Bayly ([10]) also includes adjustments for emissions effects. This literature review focuses on methods of detecting trends in annual summary statistics, regardless of any adjustments made to the annual summary statistics to account for these meteorological or emissions effects.

Linear Model Approaches

One of the simplest methods of trend detection and estimation is simple linear regression ([4, 5, 10, 11, 18]). In this method the expected annual summary statistic is assumed to be linear in the year, so the estimated means plot as a straight line. This statistical model is usually fitted by least squares, which is defined as finding the straight line such that the squared errors about that line (squared differences between the observed annual summary statistic and the estimate from the straight line trend) are minimized.

That method is most appropriate when the annual summary statistics are normally distributed with a constant variance. For ozone concentration data at a single site, the assumption of normality may be less tenable than an assumption of log-normality (see the literature review on statistical distributions), so one can apply simple linear regression to the logged concentrations and then transform from the straight line in log space back to an exponential curve for the mean concentrations ([4, 5]).

Simple linear regression can be used for annual summary statistics from a single site or from a group of sites. If the data set is complete, i.e., if data are available for every site every year, then the straight line fitted by the least-squares method to the complete data set (with one value for each site/year combination) is the same as the line fitted to the yearly means (with one value for each year). In effect the model would assume that for any given year the values for the different sites came from a single distribution. However, if the assumptions of independent, normally distributed errors about the trend line and equal variances for each site/year statistic apply, then the complete data least-squares analysis provides much better estimates of the confidence intervals for the fitted trend line. Under these assumptions it follows that there is an equivalence between the use of simple linear regression for trend estimation and the use of the Pearson correlation coefficient for trend detection: The slope of the straight line is significantly different from zero (indicating a non-zero trend) only if the Pearson correlation coefficient is significantly different from zero.

An alternative to simple linear regression that does not make the assumption of a linear trend is one-way analysis of variance ([15]). In this model the underlying mean value for a given site/year concentration depends only on the year but is an arbitrary value for each year.

If annual summary statistics are available for every site, a better approach than simple linear regression or one-way analysis of variance is the use of two-way analysis of variance ([1, 2, 3, 15, 22, 32–40]). The two-way analysis of variance method assumes that the annual summary statistic for a given site and year is the sum of a site effect, a year effect, and a normally distributed error term. The errors are assumed to be independent, with mean zero and a constant variance. The main advantage of this method is that it accounts for the dependence between annual composite site averages caused by site effects. Simple linear regression and one-way analysis of variance ignore the site-to-site variation by assuming this variation is part of the error; these site effects introduce dependencies between the errors for the same site. A significant trend determined from the two-way analysis of variance corresponds to a statistically significant year effect. The different year effects can be displayed by plotting the composite site averages for each year with Tukey simultaneous confidence intervals (as in Figure 9-1).

The two-way analysis of variance method can also be applied in cases where some annual summary statistics are missing for some sites (often because the available data are insufficient to satisfy the validity criteria for the annual summary statistic). In this case

the approach is equivalent to using the general linear model on the available data to estimate the site and year effects, and then estimating any missing value as the sum of the estimated site and year effects corresponding to the particular missing site and year ([1]). One disadvantage of this method is that data from all sites are used to fill in the missing values, rather than data from local sites. Cohen and Pollack ([2]) provide an extension of the two-way analysis of variance approach that deals with this problem by allowing the year effects to depend on the region. Regions are defined by combining nearby sites in such a way that the mean squared error in the fitted general linear model is minimized.

The two-way analysis of variance approach can be modified to allow for specific trend functions by assuming that the year effects are certain functions of the year, but the site effects are arbitrary. The case of a linear trend but arbitrary site effects is used by Capel and others ([3]).

Nonparametric Methods

The assumptions of independent normally distributed errors with the same constant variance used in several trend analyses may not be applicable. To test for and estimate the trend without making such distributional assumptions, various nonparametric methods have been used. Nonparametric methods proposed in the literature include a simple chi-square test of a step trend ([18]), the use of Spearman's rho ([7, 8, 9, 12, 18]), and Kendall's tau ([13, 14, 21]) for trend detection, and the use of the Theil/Sen slope estimator for linear trend estimation ([13, 21]). Since only very general distributional assumptions are made (concerning the dependence structure), the results are valid under very general conditions but the methods have lower power (trend detection probability) compared to parametric tests in cases where the parametric model assumptions are reasonable approximations. The nonparametric tests can have much greater power than parametric tests when the distributional requirements of the parametric test are violated ([12]). A disadvantage of the nonparametric methods used in the cited articles is that likely site-to-site variability is not included in the analyses.

The chi-square test of trend ([18]) is a simple test to compare exceedance rates for two different years. A simple two-by-two table is created giving the number of NAAQS exceedance days and NAAQS non-exceedance days for each year. If there were no trend, then the proportions of exceedance days per year would be approximately equal for both years. The differences between the observed numbers of exceedance days and the expected numbers in the case of no trend can be used to compute a chi-squared statistic. Because of the minimal amount of information used to compute this trend test statistic, the test has the disadvantage of having a very low trend detection probability which in most cases outweighs the advantage of simplicity.

The Spearman's rho test of trend ([7, 8, 9, 12, 18]) is based on Spearman's rho statistic, which is the standard Pearson correlation coefficient between the rank of the annual summary statistics and the year. The rank is 1 for the highest summary statistic,

2 for the second highest, and so on. If there is no trend and all observations are independent, then all rank orderings are equally likely. This fact is used to calculate the statistical significance of the Spearman's rho statistic; a value significantly different from zero implies a significant trend. If ties in the annual summary statistics are present, then the significance level has to be adjusted to account for the number of ties. In paper 12 a comparison of the power (trend detection probability) of Spearman's rho with the power of simple linear regression shows that the nonparametric test can be almost as efficient as the simple linear regression t test even when the normality assumption holds. The linear regression power calculations in [12] are based on formulae that are incorrect for small samples but approximately correct for large samples (see formula 3b in [12]). Thus the reported results in that paper may be inaccurate for small samples and should be used with caution.

Kendall's tau is an alternative nonparametric statistic that can be used to test for trend ([13, 14, 21]). This statistic can be calculated as the number of possible pairs of years for which the ordering of the years is the same as the ordering of the annual summary statistics (the lower annual statistic occurs in the earlier year) less the number of possible pairs of years with the reverse ordering. If there is no trend and all observations are independent, then all rank orderings of the annual statistics are equally likely; this result is used to compute the statistical significance of the tau statistic. Adjustments for tied annual summary statistics are described in the cited articles.

Adjustments of Kendall's tau for seasonality ([13]) and serial dependence ([14]) have been proposed and investigated in the context of water quality data analysis. A seasonally adjusted Kendall's tau ([13]) allows for different annual means and trends in different calendar months by adding up the 12 Kendall's tau statistics from each month. In paper 13 the null distribution of this statistic (when there are no trends) is calculated assuming that values from different calendar months are independent. In paper 14 the null distribution is calculated assuming that values in different months can be correlated. Both papers include calculations of the power of these tests for simulated data. The power of the seasonal and serial dependence adjusted Kendall's tau is greater than the power of the simpler seasonal dependence adjusted Kendall's tau if there is serial dependence, but is less in the independent case. One difficulty in application of these approaches to ozone design values is that the ozone design value depends upon the highest daily maximum ozone concentrations, and these are more likely to occur in certain calendar months. Possible trends in the maximum concentrations for those months are much more important than trends for other months that tend to have lower maximum concentrations.

Kendall's tau test of trend is related to the Theil/Sen nonparametric slope estimator ([21]), which gives an estimate of the assumed linear trend. This estimator is the median of all possible ratios of the change in the annual summary statistic from one year to a later year divided by the number of years separating the two values. If the trends differ by calendar month, then the same calculation can be applied to the monthly

summary statistics by only considering ratios for values in the same month, i.e., that differ by an exact multiple of 12 months ([13]).

Extreme Value Theory Approaches

The theory of extreme values is summarized in Section 4 and Appendix A. This theory can be used to estimate the distribution of the annual maximum hourly concentration and/or the second up to the *k*th highest daily maximum hourly concentration, and to estimate the distribution of the number of days for which the daily maximum exceeds a high threshold (that may or may not be the ozone NAAQS). This section considers some trend analyses based on these approximations. We first present the use of the Poisson process approximation for the daily exceedances. This relatively simple approach is now being routinely applied for the EPA Trends Reports ([32-40]). Other applications of extreme value theory found in this literature review are also presented. These other methods are potentially very useful in analyzing ozone design value trends but may be too complex for routine application.

The simplest approach that uses extreme value theory is based on the result that exceedance days follow a Poisson process in the limit, provided that the dependence between daily concentrations separated by a given number of days decreases sufficiently fast as the separation increases. Assuming that the numbers of exceedances for different sites are approximately independent, it follows that the total number of exceedance days for a given year (summed over the sites) approximately have a Poisson distribution. A more accurate, but more complex, approach does not assume independence of exceedances between sites, which leads to a compound Poisson rather than Poisson distribution for the total number of exceedances. The Poisson distribution has a variance equal to the mean, and the maximum likelihood estimate of this parameter is the observed number of exceedances. If annual exceedances are averaged across a large number of sites, then the annual average number of exceedances per site are approximately normally distributed, with a mean estimated by the annual average number of exceedance days per site and a variance estimated by the annual average number of exceedance days per site divided by the number of sites. This result can be used to calculate simultaneous confidence intervals for the annual mean number of exceedances per site using the Bonferroni method, as described previously. (The Tukey studentized range method is not applicable in this case because the variance varies from year to year.) This approach is derived in paper 15 and has been applied in several of the annual EPA Trends Reports ([32-40]).

Shively ([20]) used a related approach to estimate the long-term trend in ozone exceedance rates for Houston daily maxima. The sequence of daily exceedances of the selected high ozone threshold was modeled as a nonhomogeneous Poisson process. Thus the exceedances were assumed to follow a Poisson process with a rate that was not constant. The logarithm of the exceedance rate for a given day is the sum of multiples of

certain meteorological measurements for that day and of a multiple of the calendar year. The calendar year multiple gives the estimated trend.

In another paper, Shively ([19]) used the limiting joint extreme value distribution for the k highest daily maximum hourly ozone concentrations for each of several years. This limiting distribution assumes that all daily maxima are approximately independent, and that for each year the daily maxima have the same distribution. These approximations may not be sufficiently realistic. The location parameter (a parameter related to the mean of the limiting distribution) was assumed to change linearly with the year. The maximum likelihood method (described in the literature review on statistical distributions) was used to estimate the parameters, but a bootstrap method was used to determine the statistical significance of the trend, since the amount of data used in the analysis was too small to apply asymptotic theory for the significance test.

The methods of Smith ([6]) use the latest advances in extreme value theory to derive a very complete description of the sequence of daily maxima that incorporates the most general limiting extreme value distribution for the upper tail, the possible clustering of exceedances, seasonal trends (within year), and annual trends (across years). Since exceedance days often cluster together in cases of strong serial dependence (see the time series literature review for more details), Smith fitted the trend model to all hourly ozone concentrations greater than a high threshold separated in time by more than a cluster interval; if more than one hourly exceedance of the threshold occurred within the cluster interval, only the highest of the cluster exceedances was used to fit the model. To fit ozone data from Houston, Texas (1973-86) various thresholds (0.08, 0.10, 0.12, 0.16, 0.20, 0.26, 0.28, and 0.30 ppm) and two alternative cluster intervals (24 and 72 hours) were used with somewhat different results.

According to the limiting extreme value theory model, the cluster exceedances occur according to a Poisson process, and the distribution of the cluster maximum concentration is the tail generalized Pareto distribution (GPD). The tail GPD has a location, scale, and shape parameter. To treat seasonality, which is variation within the year, the scale and shape parameters differ by the calendar month (or pair of months), but are the same for every year. To treat trend, which is variation from year to year, the location parameter was assumed to be an intercept plus a slope parameter multiplied by the calendar year; both intercept and slope vary by calendar month (or pair of months). This complex model was fitted by the maximum likelihood method.

In one application of the model at a relatively low threshold, the annual trend was only significant for February and June. At higher thresholds the trend was examined by comparing the fitted model with no trend term for 1973-80 with the fitted model with no trend term for 1981-86. The results showed that the estimated number of exceedances of each high threshold was lower in the later period, which implies a decreasing trend in the high concentrations. However, Smith found no such trends for the low concentrations.

The extreme value theory model in Smith's paper ([6]) is the most realistic application of extreme value theory to ozone data since it incorporates serial dependence, seasonal dependence, annual trends, and the most general limiting extreme value distribution. This is much more complicated than the independent tail exponential distribution model that is recommended for routine use over short monitoring periods (see the literature review on statistical distributions). The routine application of Smith's model by air quality managers is difficult because of the computational difficulties in fitting the model and the very difficult problem of selecting reasonable choices for the threshold and cluster interval; Smith's selections for Houston are likely to be inappropriate for many other cities. An even more complete analysis would include terms representing meteorological effects into the extreme value theory model and allow for nonlinear trend functions.

The ad hoc approaches of Smith [6] have been investigated on a more formal theoretical basis in several recent papers. In particular, the mean cluster size is the reciprocal of the "extremal index," described in the textbook by Leadbetter and others (1983) and the focus of this theoretical research. Relevant papers are Leadbetter (1991), Leadbetter and others (1989), Rootzen and others (1994), and Smith and Weisman (1994).

TIME-SERIES MODELS

The extreme value model of Smith ([6]) is an example of a model that includes trends and serial dependence (i.e., the mean design value is not assumed to be constant and the hourly ozone concentrations are not assumed to be independent). In principle, any of the time series models described in the literature review on time-series models could be adapted to treat trends using a modification which allows some or all of the parameters of the daily maximum hourly ozone distribution to vary from year to year. Analyses of this type are described in the time-series literature review. Time-series methods including trend analyses have also been applied to stratospheric ozone ([16, 17]); these methods could be adapted to treat tropospheric ozone daily maxima instead of monthly average stratospheric ozone measurements. The analysis in paper 16 is a frequency domain analysis. Such an analysis represents the time series in a more indirect manner as a combination of frequency distributions (low frequencies correspond to long-term trends). A more directly interpretable time-series analysis in the time domain ([17]) represents the series as a first-order autoregressive time series plus sinusoidal terms representing seasonal variation within the year plus a multiple of the number of months from the initial month.

OZONE TRENDS ADJUSTED FOR METEOROLOGY

The important role that meteorological conditions play in determining ground-level ozone concentrations was discussed in Section 7. Because annual variations in these conditions can be substantial, year-to-year fluctuations in ozone concentrations can be quite large. The effect of such variations can be to mask any long-term trends in ozone that might be occurring as a result of changes in precursor emissions.

Methodologies developed to account for meteorological variability within the context of trends assessments were also presented in Section 7. EPA's latest Trends Report (41) featured a comparison of the unadjusted national ozone air quality trend with the composite trend in 43 metropolitan areas based on the model developed by Cox and Chu (42). The "adjusted" trend indicator shown in Figure 9-2 is the composite mean of the meteorologically adjusted 99th percentile daily maximum 1-hour concentrations across each of the 43 individual metropolitan areas. The smoothing introduced by the meteorological adjustment is especially evident in the ozone trends where the peak ozone years, such as 1983 and 1988, have been followed by years less conducive to ozone formation. The general pattern is clear, a steady downward trend. The composite average of the 99th percentile daily maximum 1-hour concentrations in 1992 is 10 percent lower that the 1983 level. This composite trend captures the spatial and temporal variability in meteorological conditions among these 43 metropolitan areas. As illustrated by this figure, the composite trend in the unadjusted 99th percentile daily maximum 1-hour concentration for these 43 metropolitan areas tracks the national composite ozone trend in the second highest daily maximum 1-hour concentration. Thus, the meteorologically adjusted trend is likely to be a reasonable indicator of the composite national ozone trend.

SUMMARY AND CONCLUSIONS

For routine trend analyses of data from a single site, simple linear regression of the annual maximum or second maximum of the daily maximum hourly concentrations against the year is convenient and relatively easy to understand. Nonparametric alternatives using Spearman's rho and Kendall's tau for trend detection, and the Sen/Theil slope estimate for trend estimation, can also be applied to determine the extent to which the results of the parametric trend analysis depend on the normality assumption. With a long series of hourly ozone data at a single site, the complex extreme value theory model of Smith ([6]) yields a more realistic analysis but one that requires a substantial computing and interpretative effort by the investigator. When averages of ozone design values across multiple sites are taken, the central limit theorem provides some theoretical justification for the two-way analysis of variance with site and year effects. Useful year-to-year comparisons can be made using Tukey's simultaneous confidence intervals. To analyze trends in total exceedance days for multiple sites, the use of the Poisson approximation to the distribution and Bonferroni simultaneous confidence intervals is

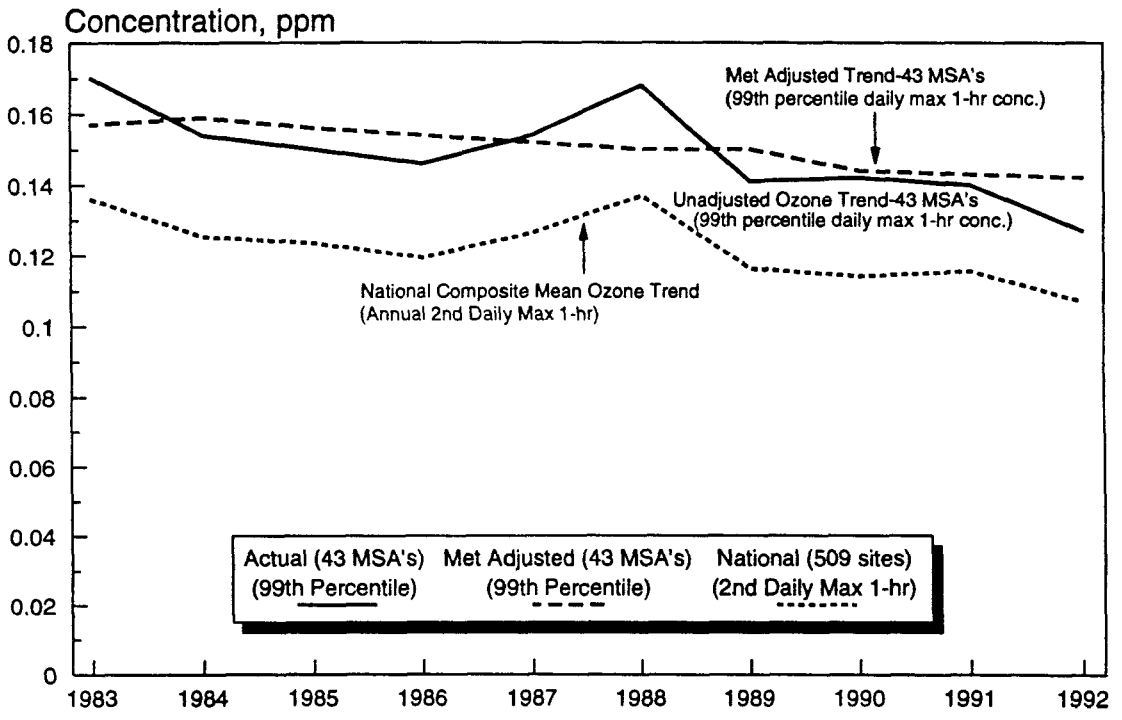

Figure 9-2. Comparison of meteorologically adjusted and unadjusted trends in the composite average of the second highest maximum 1-hour concentration for 43 MSAs, 1983-92.

preferable to the two-way analysis of variance because the variance of the number of exceedances usually varies from year to year.

The important role of meteorology in determining the year-to-year variability in ozone concentrations cannot be ignored. EPA has initiated a cooperative program to review and expand the development of models for meteorological adjustment. Based on initial encouraging results, EPA incorporated a comparison of meteorologically adjusted and unadjusted ozone trends in 43 metropolitan areas in its 1992 Trends Report.

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10 ALTERNATIVE AIR QUALITY INDICATORS

Design values are air quality indicators that may be viewed as a means for characterizing the ozone air quality of a metropolitan area in a single number. The design value can serve as a surrogate measure of air quality status, a measure of progress, and an indicator of how much concentrations must be reduced to meet the standard. However, the design value for an area is, by definition, the highest design value among all sites in the monitoring network. This raises the question of how well the spatial and temporal distribution of ozone concentrations in the area are represented by the design value.

There are two air quality indicators that are directly related to the ozone National Ambient Air Quality Standard (NAAQS): the expected exceedance rate and the air quality design value. Throughout this section the expected exceedance rate is defined as the expected number of exceedances per year estimated using the Appendix H procedures, and the air quality design value is the EPA design value (table look-up procedure). Attainment of the ozone NAAQS is achieved when the expected exceedance rate is less than or equal to 1 at every site within the area. The ozone air quality design value is an estimate of the concentration expected to be exceeded once per year on average. The ambient air quality database was used to examine the relationship among these two NAAQS related statistics and other air quality indicators. The comparisons focus primarily on the 3-year period 1987-89, which was the database used to establish the majority of the initial nonattainment area classifications. However, the comparisons of temporal variability of these indicators include data from the entire 11-year period, 1980-90.

OZONE NAAQS RELATED INDICATORS

The two ozone NAAQS air quality indicators included in these comparisons represent the highest value recorded among all monitoring sites within the area. For the 98 areas initially designated nonattainment for ozone under the Clean Air Act Amendments of 1990 (CAAA of 1990), each statistic was estimated as follows:

Avg Est. Exc:	Estimated exceedances from each of the three years, 1987, 1988, and 1989, are simply averaged to obtain the Appendix H expected exceedance rate for 1987-89.
EPA D.V.	The EPA table look-up procedure was used to estimate the air quality design value for the years 1987-89. With complete monitoring data (i.e., greater than 75 percent of the days during the ozone season), the EPA design value is simply the fourth highest daily maximum 1-hour ozone concentration.

As required by the CAAA of 1990, the EPA ozone design value was used to establish the initial ozone classification of each nonattainment area. Table 10-1 displays these area classifications and the corresponding number of expected exceedances per year at the design

value site in each area. As expected, the general pattern is for decreasing numbers of exceedances as one goes from a higher category to the next lower category. However, there is some overlap between adjoining categories in exceedance rates at the design value monitors. Table 10-2 shows similar statistics for all sites within these nonattainment areas, not just the design value site. Again, the pattern is for lower exceedance rates as one goes from a higher classification to a lower classification category. The wider range in exceedance rates for all sites is likely due to the fact that both downwind and upwind sites are included.

Table 10-1. Number of expected exceedances per year (defined by Appendix H) at design value sites within ozone area classification categories for areas initially designated nonattainment under the Clean Air Act Amendments of 1990.

Clean Air Act Classification	Number of Areas	Number of expected exceedances per year at design value site		
		Maximum	Minimum	Average
Extreme	1	137.5	137.5	137.5
Severe 17	5	59.6	12.2	23.0
Severe 15	4	38.8	8.8	17.7
Serious	12	44.2	3.7	10.6
Moderate	33	9.9	1.5	4.5
Marginal	43	3.8	1.1	2.1

Table 10-2. Average Number of Expected Exceedances at All Sites in Designated Nonattainment Areas, 1987-89

Clean Air Act Classification	Number of Sites	Average Number of Expected Exceedances						
		Max	Min	95th %-tile	90th %-tile	50th %-tile	25th %-tile	Avg
Extreme	40	137.5	0.0	124.2	118.1	46.7	14.7	54.5
Severe 17	79	59.6	0.0	16.6	13.1	7.8	2.0	7.9
Severe 15	43	38.8	0.0	15.6	12.6	7.7	5.4	8.9
Serious	105	44.4	0.0	11.1	8.3	3.4	1.0	4.9
Moderate	187	9.9	0.0	6.7	5.4	1.4	0.3	2.1
Marginal	97	4.4	0.0	3.8	3.1	1.1	0.3	1.4

ALTERNATIVE AIR QUALITY INDICATORS

Five additional air quality indicators were also calculated for each of the 98 nonattainment areas. In each case, these are site-specific indicators; network average indicators are described later in the section on spatial variability. The highest indicator value at any monitoring site in the nonattainment area was calculated as follows:

Avg. 2nd Daily Max:	The average of the second daily maximum 1-hour ozone concentration in each of the three years, 1987, 1988, and 1989.
Avg. 95th %-tile:	The average of the 95th percentile concentration in each of the three years.
5% Tail Exp. D.V.:	The ozone design value estimated by fitting a tail exponential distribution to the upper 5 percent of the annual ozone concentration distribution. The fitting method is the Breiman procedure (Breiman, 1978).
Avg. 10 High Days:	The average of the ten highest daily maximum 1-hour ozone concentrations in each of the three years.
Avg Met Adj 99th %-tile	The average of the 99th percentile ozone concentrations from each year that were adjusted for year-to-year changes in meteorology using the Cox and Chu model (Cox and Chu, 1991). Values are only available for 35 of the 98 areas.

The air quality values for each of the seven air quality indicators are listed below in Table 10-3 in decreasing order of the EPA design value. Table 10-4 presents the linear correlation matrix for these seven indicators. As one would expect, the strongest association is found between the EPA D.V. and the design value estimated using the 5% tail exponential approach since they both target the same statistic. The EPA D.V. is also highly correlated with the average second maximum concentration, the average of the ten highest days, and the meteorologically adjusted 99th percentile concentration. The lowest correlation (0.84) was found for the relationship between the two NAAQS indicators, the EPA D.V. and the expected exceedance rate. Figure 10-1 displays a plot of these two NAAQS related indicators for all monitoring sites that reported data for the period 1987-89.

Table 10-5 lists the relative ranking (from largest [rank=1] to smallest [rank=98]) of each air quality indicator for the original 98 nonattainment areas. Although there is good agreement between the rank of the EPA design value and the ranks of the other air quality indicators, there are several noticeable differences. In Dallas, Seattle, and Monterey, CA,

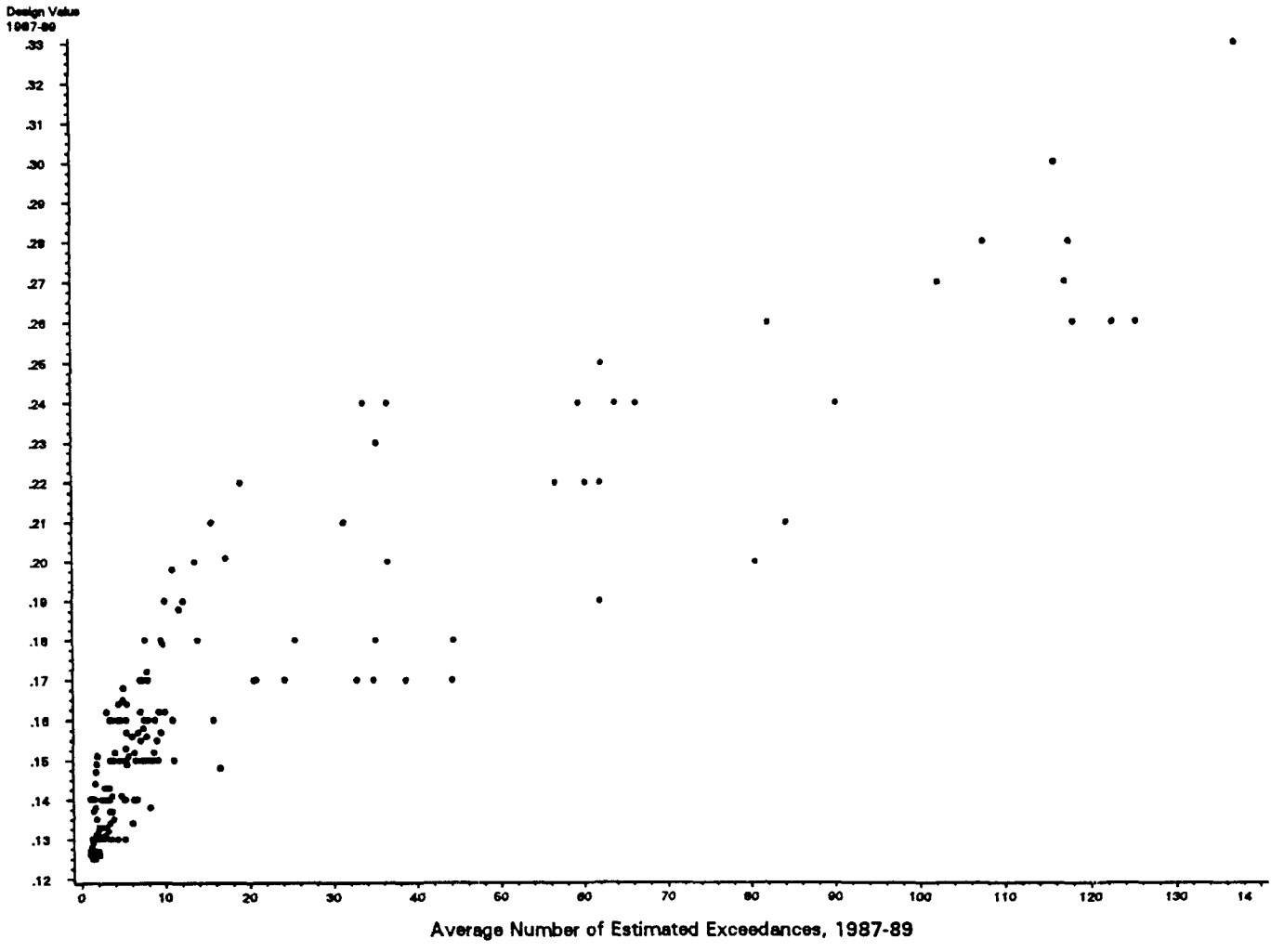


Figure 10-1. Average number of expected exceedances versus the EPA DV for all sites, 1987–89.

Table 10-3. Alternative Air Quality Indicator Values for 1987-89

Nonattainment Area	EPA D.V.	AVG 2nd Daily Max	AVG 95th %-TILE	5% TAIL Expan. D.V.	AVG 10 HI Daily Max 1-hr	AVG MET ADJ Adj. 99th %-tile	AVG Est. Exceed's
Los Angeles South Coast Air Basin	0.330	0.327	0.240	0.343	0.291	0.309	137.5
Southeast Desert Modified AQMD	0.240	0.223	0.170	0.244	0.205	.	59.6
Houston-Galveston-Brazoria NA	0.220	0.203	0.120	0.231	0.166	0.223	14.6
New York-N. New Jersey-Long Is	0.201	0.187	0.140	0.212	0.163	0.211	17.4
Baltimore NA Area	0.194	0.164	0.128	0.192	0.150	0.170	10.7
Chicago-Gary-Lake County NA Area	0.190	0.163	0.128	0.199	0.153	0.154	13.0
Milwaukee-Racine NA Area	0.190	0.174	0.129	0.199	0.153	0.172	13.0
San Diego NA Area	0.190	0.183	0.140	0.222	0.163	0.184	32.9
Philadelphia-Wilmington-Trenton	0.187	0.168	0.135	0.186	0.146	0.191	15.6
Muskegon NA Area	0.181	0.167	0.123	0.184	0.140	0.144	9.5
San Joaquin Valley NA Area	0.180	0.160	0.140	0.173	0.154	0.171	44.4
Sheboygan NA Area	0.176	0.159	0.115	0.182	0.141	.	9.1
Greater Connecticut NA Area	0.172	0.172	0.121	0.179	0.145	0.145	9.0
El Paso NA Area	0.170	0.160	0.100	0.175	0.135	0.134	7.9
Ventura Co NA Area	0.170	0.167	0.140	0.176	0.159	.	38.8
Manitowoc Co NA Area	0.167	0.154	0.121	0.170	0.136	.	9.9
Springfield (W. Mass) NA Area	0.167	0.138	0.110	0.166	0.127	.	6.7
Boston-Lawrence-Worcester NA Area	0.165	0.165	0.124	0.176	0.141	0.149	10.0
Portsmouth-Dover-Rochester, NH	0.165	0.158	0.106	0.166	0.128	.	5.3
Washington NA Area	0.165	0.146	0.120	0.164	0.134	0.164	8.1
Baton Rouge NA Area	0.164	0.154	0.100	0.160	0.128	0.153	4.8
Huntington-Ashland NA Area	0.164	0.144	0.111	0.163	0.129	0.140	5.5
Atlanta NA Area	0.162	0.149	0.110	0.170	0.134	0.149	9.3
Providence (all of RI) NA Area	0.162	0.154	0.115	0.167	0.130	0.147	6.4
Beaumont-Port Arthur NA Area	0.160	0.137	0.100	0.157	0.122	0.145	3.9
Dallas-Fort Worth NA Area	0.160	0.133	0.110	0.143	0.122	0.149	3.5
Sacramento Metro NA Area	0.160	0.153	0.120	0.172	0.146	0.165	15.8
Charlotte-Gastonia NA Area	0.158	0.136	0.112	0.150	0.122	0.134	4.2
Knox Co and Lincoln Co NA Area	0.158	0.137	0.117	0.174	0.121	.	7.4
Cincinnati-Hamilton NA Area	0.157	0.139	0.114	0.159	0.124	0.144	5.4
Cleveland-Akron-Lorain NA Area	0.157	0.143	0.113	0.158	0.126	0.145	5.5
Portland NA Area	0.156	0.148	0.119	0.166	0.127	.	8.7
St. Louis NA Area	0.156	0.147	0.113	0.163	0.132	.	6.2
Parkersburg-Marietta NA Area	0.152	0.142	0.112	0.152	0.123	.	6.7
Greensboro-Winston-Salem-High Pt	0.151	0.151	0.115	0.158	0.133	.	7.2
San Francisco-Bay NA Area	0.150	0.140	0.100	0.148	0.120	.	3.5
Louisville NA Area	0.149	0.134	0.105	0.148	0.118	0.150	3.2
Pittsburgh-Beaver Valley NA Area	0.149	0.142	0.116	0.152	0.125	0.145	7.0
Kewaunee Co NA Area	0.147	0.133	0.111	0.153	0.121	.	5.5
Atlantic City NA Area	0.145	0.135	0.114	0.146	0.126	.	4.0
Detroit-Ann Arbor NA Area	0.144	0.132	0.109	0.153	0.122	0.148	4.4
Smyth Co NA Area	0.144	0.129	0.104	0.146	0.115	.	2.4
Dayton-Springfield NA Area	0.143	0.136	0.109	0.143	0.120	.	3.1
Grands Rapids NA Area	0.143	0.138	0.112	0.143	0.123	.	4.4
Jefferson Co NA Area	0.143	0.129	0.105	0.144	0.120	.	3.4
Salt Lake City-Ogden NA Area	0.143	0.132	0.109	0.147	0.118	.	2.0
Richmond-Petersburg NA Area	0.142	0.133	0.110	0.146	0.121	.	4.4
Jersey Co NA Area	0.141	0.128	0.105	0.139	0.114	0.162	3.7
Raleigh-Durham NA Area	0.141	0.129	0.112	0.145	0.120	0.117	4.2
Reading NA Area	0.141	0.126	0.105	0.142	0.117	.	3.4
Kent County and Queen Anne's Co	0.140	0.117	0.102	0.140	0.107	.	2.2
Memphis NA Area	0.140	0.128	0.102	0.138	0.112	.	2.0
Santa Barbara - Santa Maria -	0.140	0.127	0.080	0.136	0.107	.	1.1
Seattle - Tacoma NA Area	0.140	0.101	0.083	0.111	0.090	0.119	1.4
Toledo NA Area	0.140	0.128	0.100	0.138	0.112	.	2.7
Charleston NA Area	0.138	0.124	0.105	0.143	0.113	.	2.3
Miami-Fort Lauderdale-W. Palm B.	0.138	0.130	0.078	0.136	0.106	0.118	1.7
Monterey Bay Unified NA Area	0.138	0.116	0.092	0.116	0.100	.	8.2
Nashville NA Area	0.138	0.139	0.112	0.141	0.123	.	5.6
Allentown-Bethlehem-Easton NA	0.137	0.129	0.111	0.146	0.118	.	4.4
Lewiston - Auburn NA Area	0.137	0.121	0.097	0.135	0.108	.	1.5
Owensboro NA Area	0.137	0.125	0.108	0.139	0.115	.	3.7

Continued

Table 10-3. Alternative Air Quality Indicator Values for 1987-89—Concluded

Nonattainment Area	EPA D.V.	AVG 2nd Daily Max	AVG 95th %-TILE	5% TAIL Expan. D.V.	AVG 10 HI Daily Max 1-hr	AVG MET ADJ Adj. 99th %-tile	AVG Est. Exceed's
Harrisburg-Lebanon-Carlisle NA	0.136	0.127	0.106	0.138	0.117	.	2.3
Canton NA Area	0.135	0.130	0.106	0.139	0.115	.	2.0
Hancock Co and Waldo Co NA Area	0.135	0.137	0.102	0.157	0.118	.	3.8
Knoxville NA Area	0.135	0.117	0.100	0.133	0.105	.	1.8
Poughkeepsie NA Area	0.134	0.108	0.083	0.130	0.094	.	1.3
Youngstown-Warren-Sharon NA Area	0.134	0.123	0.105	0.136	0.114	.	2.1
Birmingham NA Area	0.133	0.126	0.105	0.141	0.119	0.128	3.0
Johnstown NA Area	0.133	0.120	0.102	0.139	0.110	.	2.5
Cherokee Co NA Area	0.132	0.118	0.098	0.137	0.110	.	2.4
Buffalo-Niagara Falls NA Area	0.131	0.128	0.103	0.139	0.115	.	3.8
Columbus NA Area	0.131	0.124	0.097	0.132	0.107	.	1.7
Lake Charles NA Area	0.131	0.128	0.094	0.140	0.117	.	2.0
Edmonson Co NA Area	0.130	0.114	0.094	0.130	0.106	.	2.1
Norfolk-Virginia Beach-Newport	0.130	0.118	0.099	0.129	0.108	.	2.0
Sussex Co NA Area	0.130	0.127	0.100	0.143	0.113	.	3.6
Altoona NA Area	0.129	0.120	0.099	0.132	0.106	.	2.0
Erie NA Area	0.129	0.132	0.110	0.143	0.120	.	4.0
Scranton-Wilkes-Barre NA Area	0.129	0.120	0.100	0.135	0.110	.	3.0
Tampa-St. Petersburg-Clearwater	0.129	0.124	0.094	0.134	0.109	0.120	1.4
Walworth Co NA Area	0.129	0.115	0.096	0.128	0.104	.	1.3
York NA Area	0.129	0.121	0.105	0.134	0.111	.	1.5
Albany-Schenectady-Troy NA Area	0.128	0.112	0.097	0.134	0.106	.	3.8
Manchester NA Area	0.128	0.112	0.090	0.127	0.101	.	1.4
Essex Co NA Area	0.127	0.112	0.096	0.129	0.105	.	1.8
Lexington-Fayette NA Area	0.126	0.114	0.100	0.128	0.107	.	2.0
Greenbrier NA Area	0.125	0.119	0.103	0.131	0.108	.	1.4
Lancaster NA Area	0.125	0.117	0.106	0.128	0.111	.	1.3
Portland-Vancouver AQMA NA Area	0.125	0.110	0.096	0.131	0.099	.	2.3
Evansville NA Area	0.124	0.119	0.103	0.130	0.111	.	1.1
Paducah NA Area	0.124	0.113	0.096	0.127	0.105	.	1.1
Indianapolis NA Area	0.121	0.120	0.102	0.126	0.109	.	1.1
Phoenix	0.121	0.110	0.093	0.121	0.105	0.122	0.9
South Bend-Mishawaka NA Area	0.121	0.116	0.096	0.128	0.107	.	1.1
Kansas City NA Area	0.120	0.124	0.095	0.130	0.106	0.120	1.2
Reno	0.111	0.096	0.086	0.110	0.088	.	0.0
Door Co NA Area	0.108	0.108	0.096	0.117	0.102	.	0.0

Table 10-4. Correlation Matrix for Alternative Indicators, 1987–89

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / Number of Observations

	DVMAX89	SECMAX89	PCTMAX89	T5XMAX89	HI10MX89	MET8789	EXCMAX89
DVMAX89	1.00000	0.96643	0.89095	0.97224	0.95618	0.93137	0.84195
EPA DV(1987-89)	0.0	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	98	98	98	98	98	35	98
SECMAX89	0.96643	1.00000	0.91855	0.97819	0.98329	0.92046	0.86541
AVG 2NDMX(1987-89)	0.0001	0.0	0.0001	0.0001	0.0001	0.0001	0.0001
	98	98	98	98	98	35	98
PCTMAX89	0.89095	0.91855	1.00000	0.90923	0.95859	0.89142	0.90394
AVG 95%TILE(1987-89)	0.0001	0.0001	0.0	0.0001	0.0001	0.0001	0.0001
	98	98	98	98	98	35	98
T5XMAX89	0.97224	0.97819	0.90923	1.00000	0.97087	0.92273	0.83534
5% TAIL EX(1987-89)	0.0001	0.0001	0.0001	0.0	0.0001	0.0001	0.0001
	98	98	98	98	98	35	98
HI10MX89	0.95618	0.98329	0.95859	0.97087	1.00000	0.92449	0.90477
AVG 10 HI DAYS	0.0001	0.0001	0.0001	0.0001	0.0	0.0001	0.0001
(1978-89)	98	98	98	98	98	35	98
MET8789	0.93137	0.92046	0.89142	0.92273	0.92449	1.00000	0.83855
AVG MET ADJ 99%TILE	0.0001	0.0001	0.0001	0.0001	0.0001	0.0	0.0001
(1987-89)	35	35	35	35	35	35	35
EXCMAX89	0.84195	0.86541	0.90394	0.83534	0.90477	0.83855	1.00000
AVG EST EXC(1987-89)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0
	98	98	98	98	98	35	98

Table 10-5. Relative Ranks of Alternative Air Quality Indicators

Nonattainment Area	RANK FOR EPA D.V.	RANK FOR AVG 2nd Daily Max	RANK FOR AVG 95th %-TILE	RANK FOR 5% TAIL Exp. D.V.	RANK FOR AVG 10 HI Daily Max	RANK FOR Avg MET ADJ 99th %-tile	RANK FOR AVG Est. Exceed's
Los Angeles South Coast Air Basin	1	1	1	1	1	1	1
Southeast Desert Modified AQMD	2	2	2	2	2	.	2
Houston-Galveston-Brazoria NA	3	3	16	3	3	2	9
New York-N. New Jersey-Long Is.	4	4	4.5	5	5	3	6
Baltimore NA Area	5	12	9.5	8	10	8	12
Chicago-Gary-Lake County NA Area	7	13	9.5	6.5	8.5	12	10.5
Milwaukee-Racine NA Area	7	6	8	6.5	8.5	6	10.5
San Diego NA Area	7	5	4.5	4	4	5	5
Philadelphia-Wilmington-Trenton	9	8	7	9	11	4	8
Muskegon NA Area	10	9	12	10	16	24	15
San Joaquin Valley NA Area	11	14.5	4.5	17	7	7	3
Sheboygan NA Area	12	16	22	11	15	.	17
Greater Connecticut NA Area	13	7	13.5	12	13	22.5	18
El Paso NA Area	14.5	14.5	70	15	18	28	22
Ventura Co NA Area	14.5	10	4.5	13.5	6	.	4
Manitowoc Co NA Area	16.5	19	13.5	19.5	17	.	14
Springfield (W. Mass) NA Area	16.5	34	38	23	27	.	26.5
Boston-Lawrence-Worcester NA	19	11	11	13.5	14	16.5	13
Portsmouth-Dover-Rochester, NH	19	17	46.5	23	25	.	35
Washington NA Area	19	26	16	25	20	10	21
Baton Rouge NA Area	21.5	18	70	28	26	13	36
Huntington-Ashland NA Area	21.5	27	34	26.5	24	26	31
Atlanta NA Area	23.5	23	38	19.5	19	16.5	16
Providence (all of RI) NA Area	23.5	20	22	21	23	19	28
Beaumont-Port Arthur NA Area	26	38	70	32.5	38.5	20.5	45
Dallas-Fort Worth NA Area	26	43	38	50.5	38.5	15	52
Sacramento Metro NA Area	26	21	16	18	12	9	7
Charlotte-Gastonia NA Area	28.5	39	28	38	36	27	41.5
Knox Co and Lincoln Co NA Area	28.5	37	19	16	42	.	23
Cincinnati-Hamilton NA Area	30.5	32.5	24.5	29	32	25	34
Cleveland-Akron-Lorain NA Area	30.5	28	26.5	30.5	30	20.5	32.5
Portland NA Area	32.5	24	18	23	28	.	19
St. Louis NA Area	32.5	25	26.5	26.5	22	.	29
Parkersburg-Marietta NA Area	34	29	30.5	36.5	33	.	26.5
Greensboro-Winston-Salem-High Pt	35	22	22	30.5	21	.	24
San Francisco-Bay NA Area	36	31	70	39.5	43	.	53
Louisville NA Area	37.5	42	52.5	39.5	50	14	56
Pittsburgh-Beaver Valley NA Area	37.5	30	20	36.5	31	22.5	25
Kewaunee Co NA Area	39	44.5	34	34.5	40.5	.	32.5
Atlantic City NA Area	40	41	24.5	43.5	29	.	43
Detroit-Ann Arbor NA Area	41.5	46	42	34.5	37	18	39.5
Smyth Co NA Area	41.5	52	57	43.5	58.5	.	62.5
Dayton-Springfield NA Area	44.5	40	42	50.5	46.5	.	57
Grands Rapids NA Area	44.5	35	30.5	50.5	35	.	39.5
Jefferson Co NA Area	44.5	54	52.5	47	44	.	55
Salt Lake City-Ogden NA Area	44.5	47	42	41	49	.	72
Richmond-Petersburg NA Area	47	44.5	38	43.5	40.5	.	37.5
Jersey Co NA Area	49	59	52.5	61	60	11	50
Raleigh-Durham NA Area	49	52	30.5	46	46.5	35	41.5
Reading NA Area	49	64	52.5	54	53	.	54
Kent County and Queen Anne's Co	53	81.5	63	57.5	79	.	67
Memphis NA Area	53	57	63	65	64.5	.	72
Santa Barbara - Santa Maria -	53	60	97	69	81	.	91
Seattle - Tacoma NA Area	53	97	95.5	97	97	33	83
Toledo NA Area	53	57	70	65	64.5	.	60
Charleston NA Area	57.5	68.5	52.5	50.5	62	.	64
Miami-Fort Lauderdale-W. Palm B.	57.5	49.5	98	69	83	34	79
Monterey Bay Unified NA Area	57.5	84	92	96	94	.	20
Nashville NA Area	57.5	32.5	30.5	55.5	34	.	30
Allentown-Bethlehem-Easton NA	61	52	34	43.5	52	.	37.5
Lewiston - Auburn NA Area	61	72	79	71.5	76	.	82
Owensboro NA Area	61	65	44	61	56	.	49
Harrisburg-Lebanon-Carlisle NA	63	61.5	46.5	65	54	.	65.5
Canton NA Area	65	49.5	46.5	61	58.5	.	75.5

Continued

Table 10-5. Relative Ranks of Alternative Air Quality Indicators—Concluded

Nonattainment Area	RANK FOR EPA D.V.	RANK FOR AVG 2nd Daily Max	RANK FOR AVG 95th %-TILE	RANK FOR 5% TAIL Exp. D.V.	RANK FOR AVG 10 HI Daily Max	RANK FOR Avg MET ADJ 99th %-tile	RANK FOR AVG Est. Exceed's
Hancock Co and Waldo Co NA Area	65	36	63	32.5	51	.	48
Knoxville NA Area	65	83	70	76	87	.	77.5
Poughkeepsie NA Area	67.5	96	95.5	82.5	96	.	88
Youngstown-Warren-Sharon NA Area	67.5	70	52.5	69	61	.	68
Birmingham NA Area	69.5	63	52.5	55.5	48	29	58.5
Johnstown NA Area	69.5	75	63	61	70	.	61
Cherokee Co NA Area	71	79	77	67	69	.	62.5
Buffalo-Niagara Falls NA Area	73	57	59	61	57	.	47
Columbus NA Area	73	66.5	79	77.5	77	.	80
Lake Charles NA Area	73	55	89	57.5	55	.	72
Edmonson Co NA Area	76	88	89	82.5	85	.	69
Norfolk-Virginia Beach-Newport	76	80	75.5	85.5	74	.	75.5
Sussex Co NA Area	76	61.5	70	50.5	63	.	51
Altoona NA Area	80.5	73.5	75.5	77.5	84	.	72
Erie NA Area	80.5	48	38	50.5	45	.	44
Scranton-Wilkes-Barre NA Area	80.5	73.5	70	71.5	71	.	58.5
Tampa-St. Petersburg-Clearwater	80.5	66.5	89	74	72	32	85
Walworth Co NA Area	80.5	86	83.5	88.5	91	.	88
York NA Area	80.5	71	52.5	74	67	.	81
Albany-Schenectady-Troy NA Area	84.5	90	79	74	86	.	46
Manchester NA Area	84.5	91	93	91.5	93	.	85
Essex Co NA Area	86	92	83.5	85.5	89	.	77.5
Lexington-Fayette NA Area	87	87	70	88.5	78	.	72
Greenbrier NA Area	89	78	59	79.5	75	.	85
Lancaster NA Area	89	81.5	46.5	88.5	68	.	88
Portland-Vancouver AQMA NA Area	89	93	83.5	79.5	95	.	65.5
Evansville NA Area	91.5	77	59	82.5	66	.	95
Paducah NA Area	91.5	89	83.5	91.5	88	.	93
Indianapolis NA Area	94	76	63	93	73	.	92
Phoenix	94	94	91	94	90	30	96
South Bend-Mishawaka NA Area	94	85	83.5	88.5	80	.	94
Kansas City NA Area	96	68.5	87	82.5	82	31	90
Reno	97	98	94	98	98	.	97.5
Door Co NA Area	98	95	83.5	95	92	.	97.5

contrast, the tail exponential design value ranks for Hancock County, Sussex County, and Erie, PA were relatively higher than the EPA D.V. ranks. Other large differences were found between the relative area rankings based on the EPA design value and rankings obtained for the 95th percentile concentration in some areas, including Houston, El Paso, Beaumont, Portsmouth and Sheboygan.

TEMPORAL VARIABILITY IN OZONE INDICATORS

The National Academy of Sciences (NRC, 1991) recommended that more statistically robust indicators be developed to track progress in reducing ozone. The report described the use of different percentiles as compared to maximum values. Figure 10-2 presents the trend in the peak concentrations and selected percentiles for all sites reporting data during the period 1980–90. The percentiles presented in the figure range from the 50th percentile (the median) to the 95th percentile. The year-to-year variation is similar among all the indicators, with a tendency to become flatter (less variable) in the lower percentiles. Figures 10-3 through 10-7 display the temporal variation in five air quality indicators for ten selected nonattainment areas. The year-to-year variability is similar, especially for the concentration based indicators. Less agreement in year-to-year variation is evident between the concentration based indicators and the expected exceedance rate.

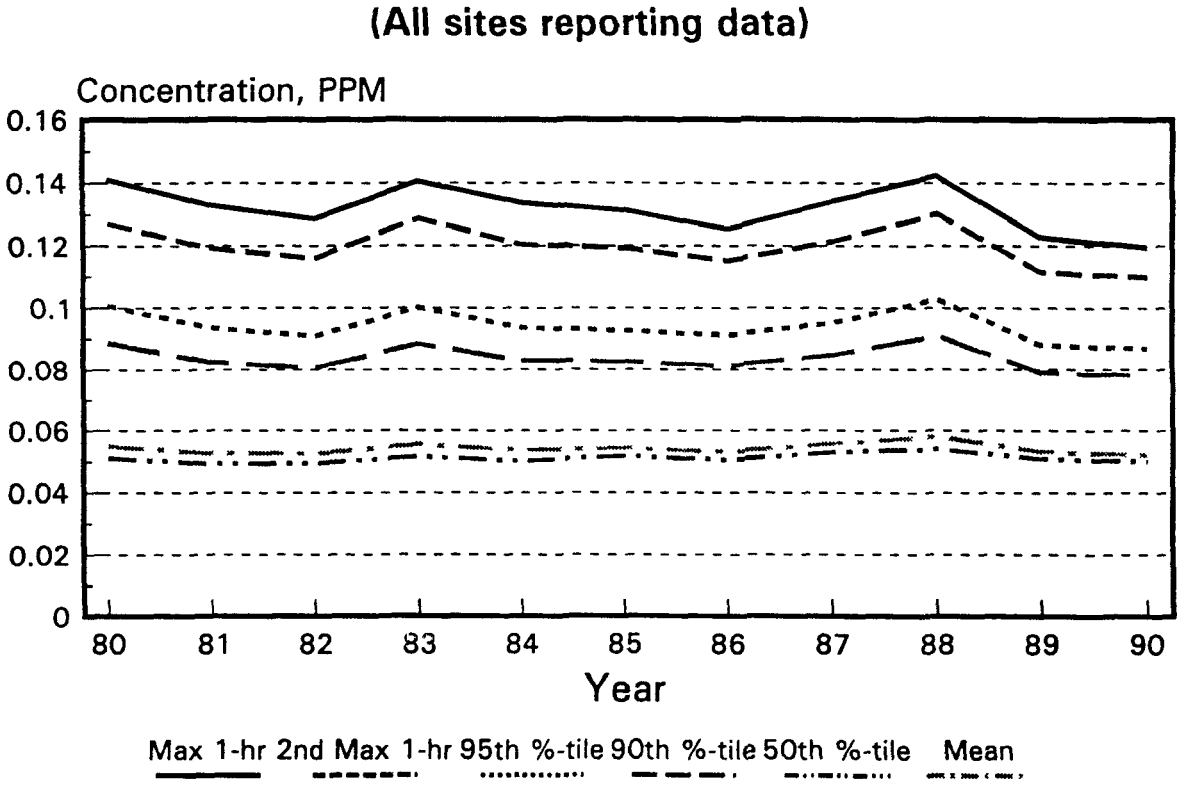
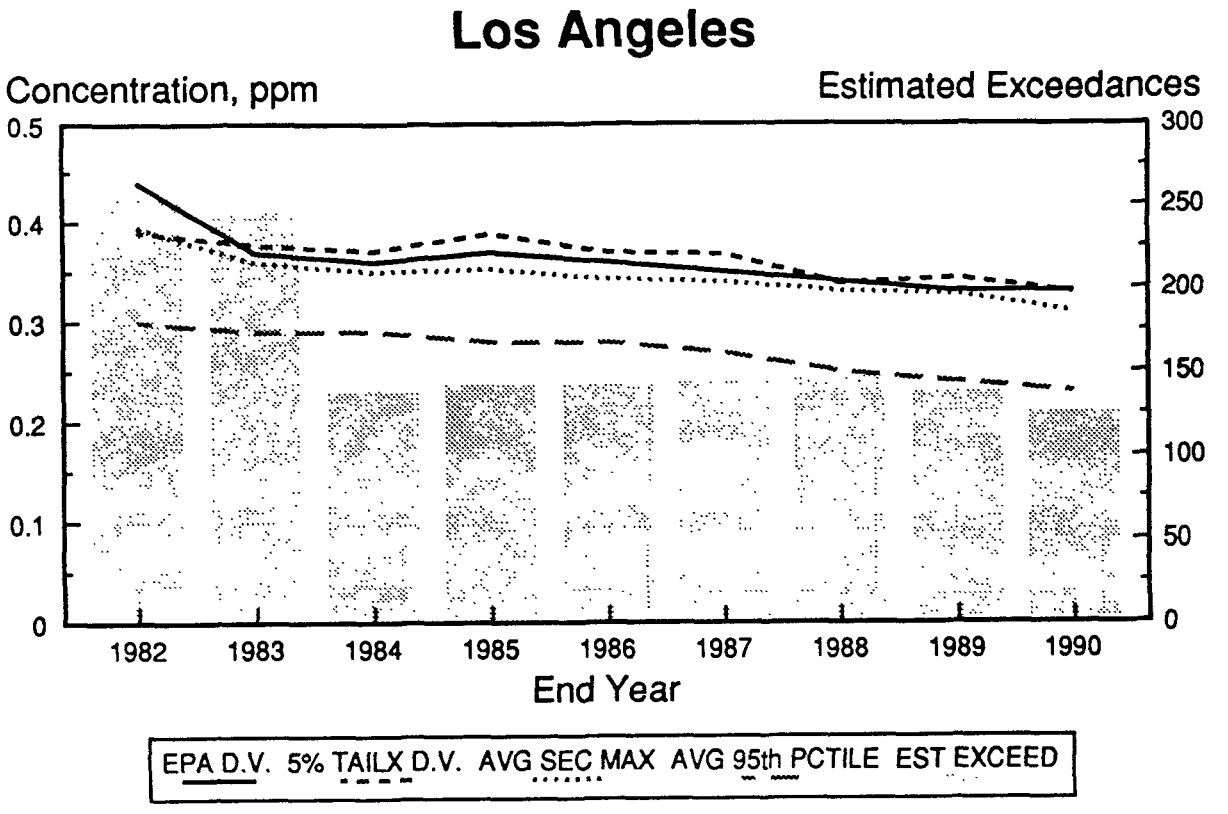


Figure 10-2. Year-to-year variability in selected ozone air quality indicators.



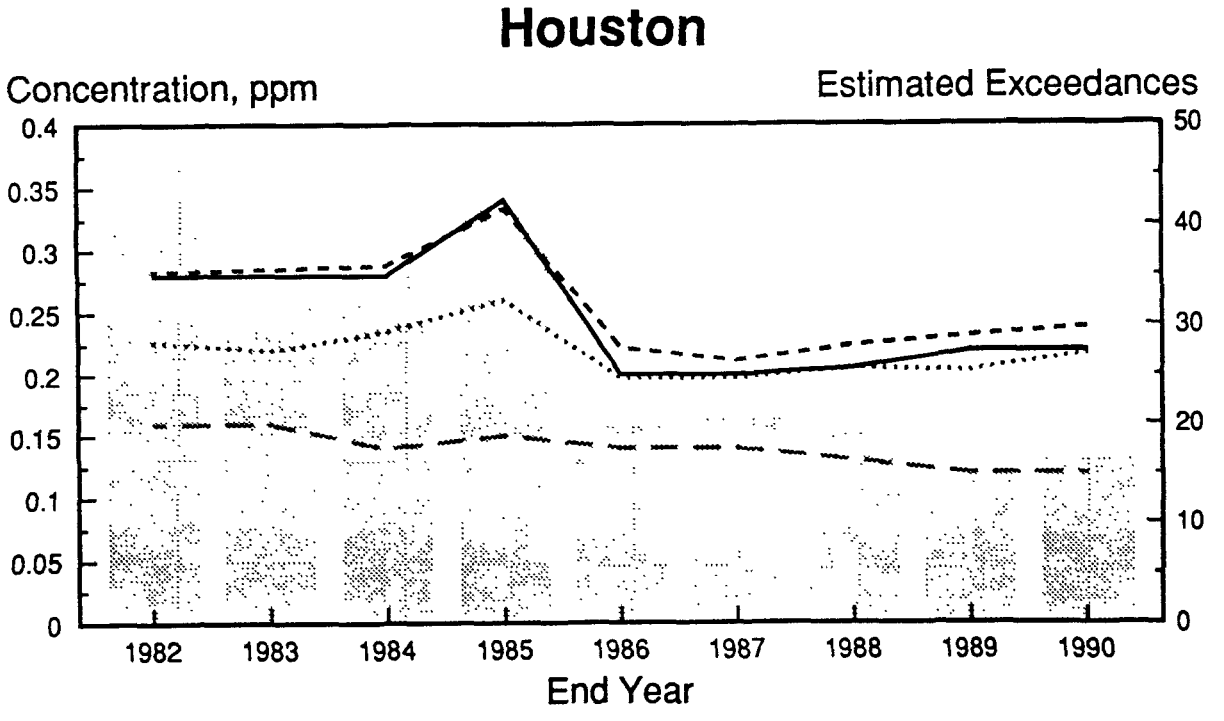


Figure 10-3. Temporal variability in ozone indicators in Los Angeles and Houston.

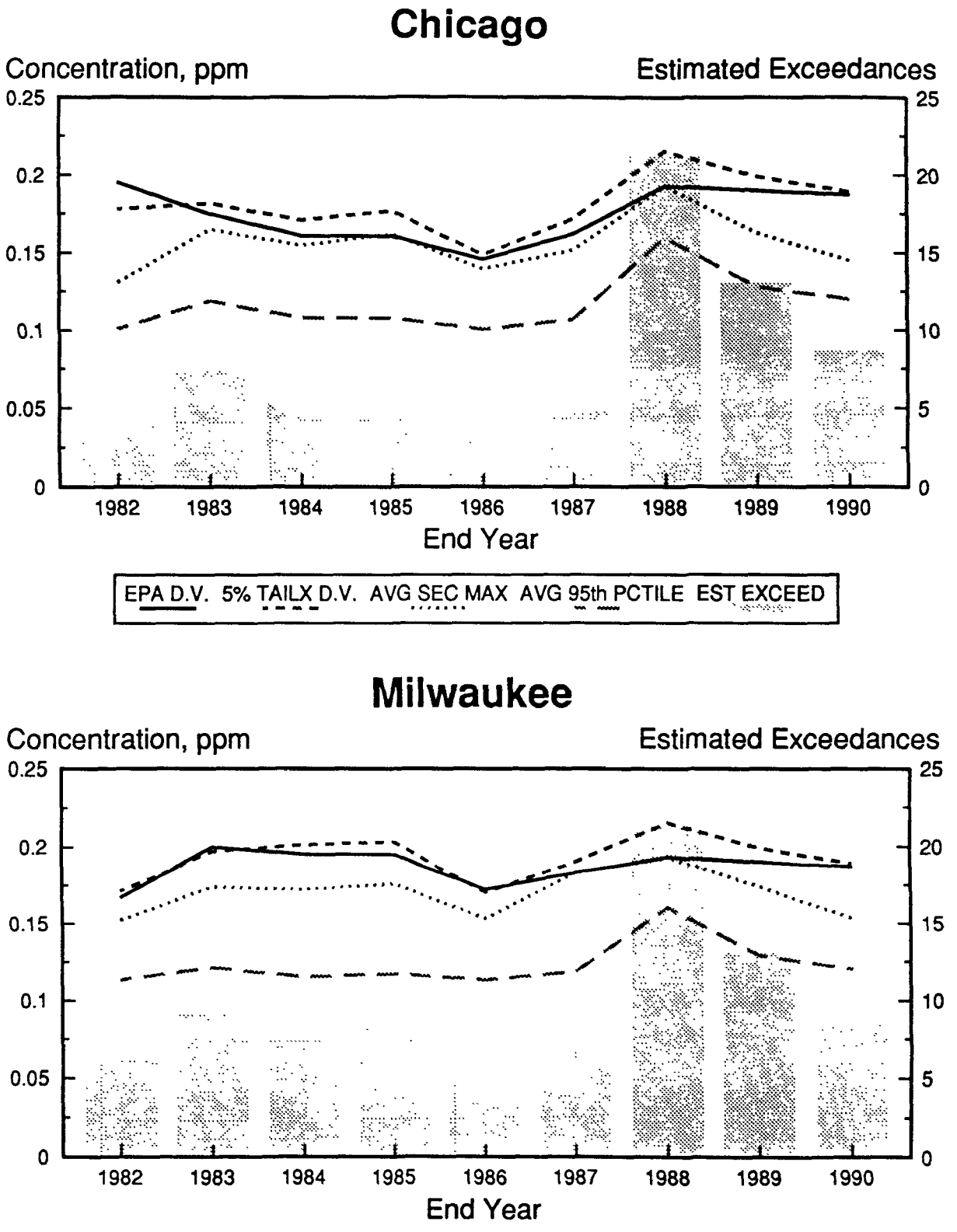
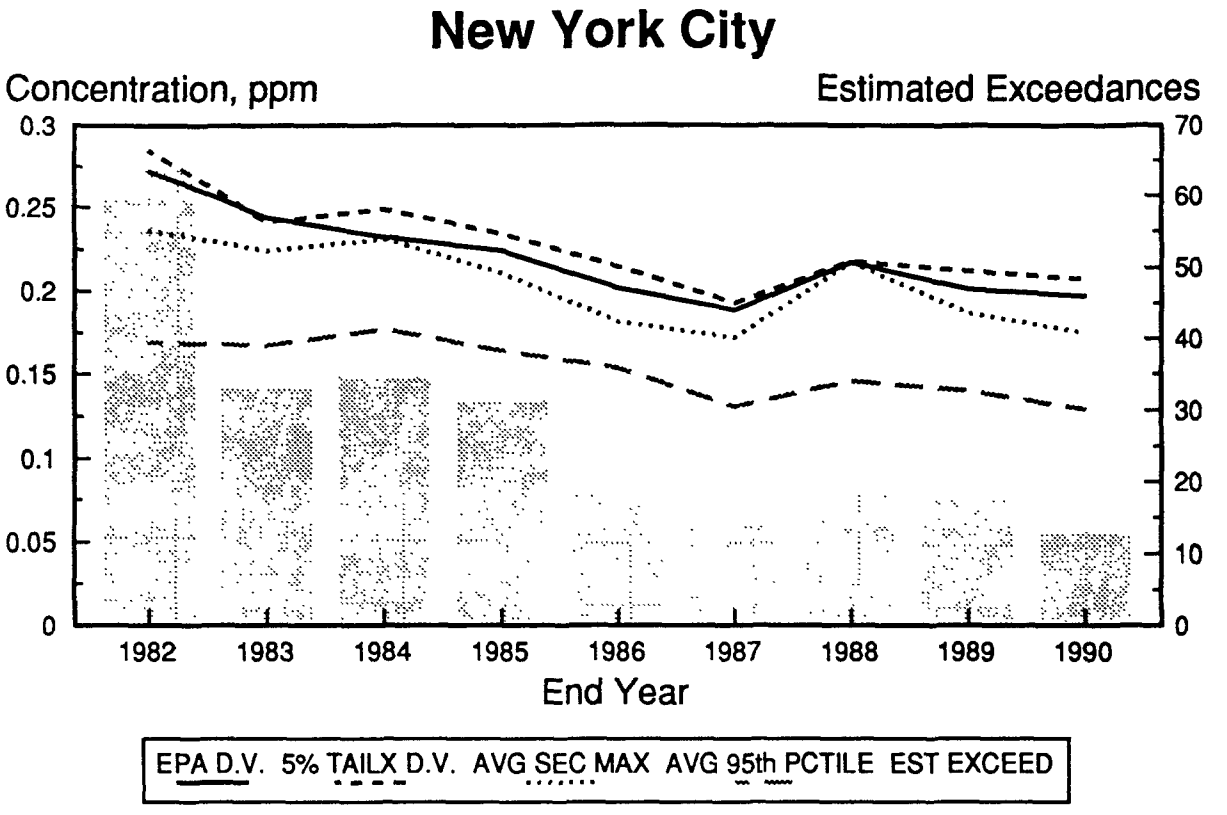


Figure 10-4. Temporal variability in ozone indicators in Chicago and Milwaukee.



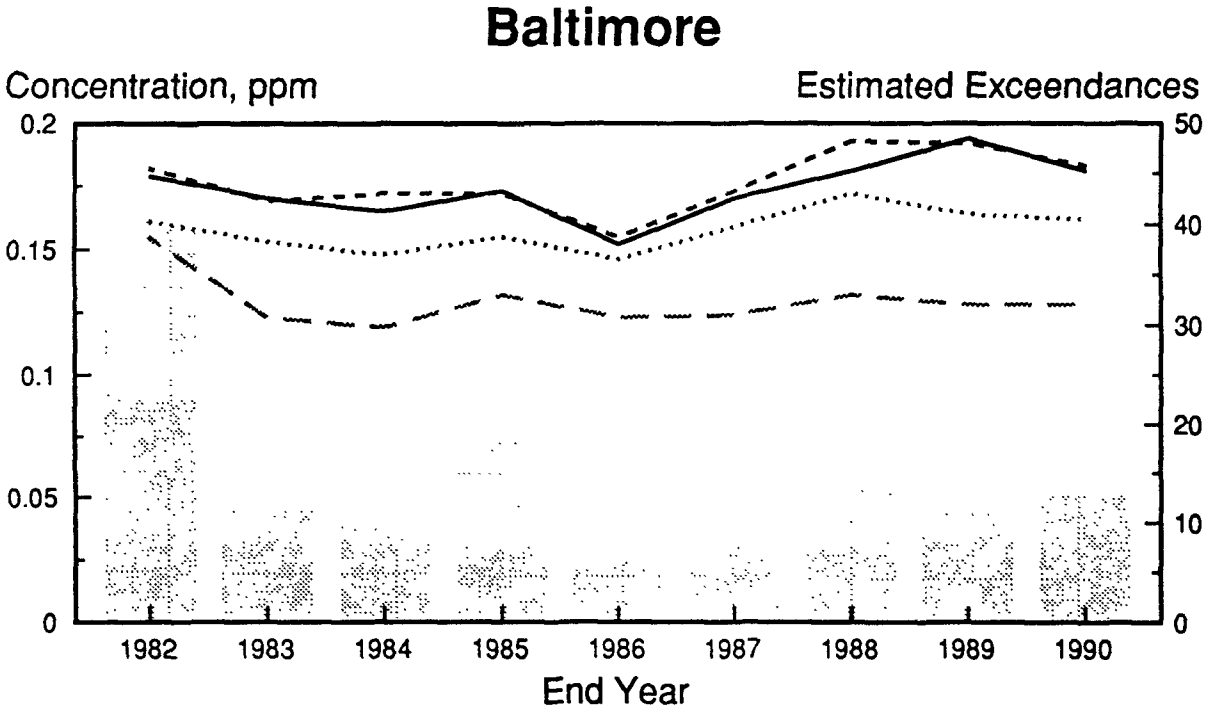


Figure 10-5. Temporal variability in ozone indicators in New York and Baltimore.

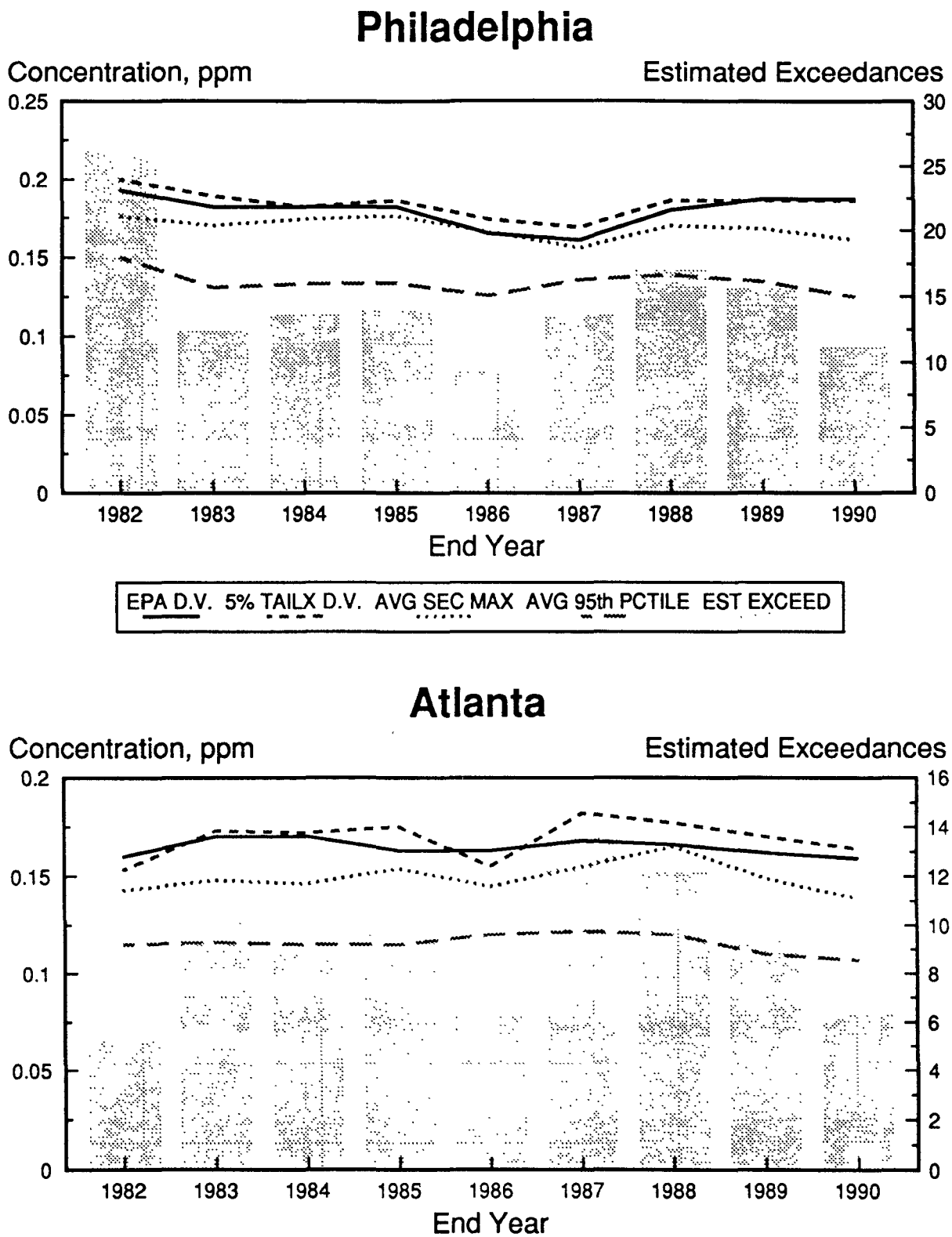
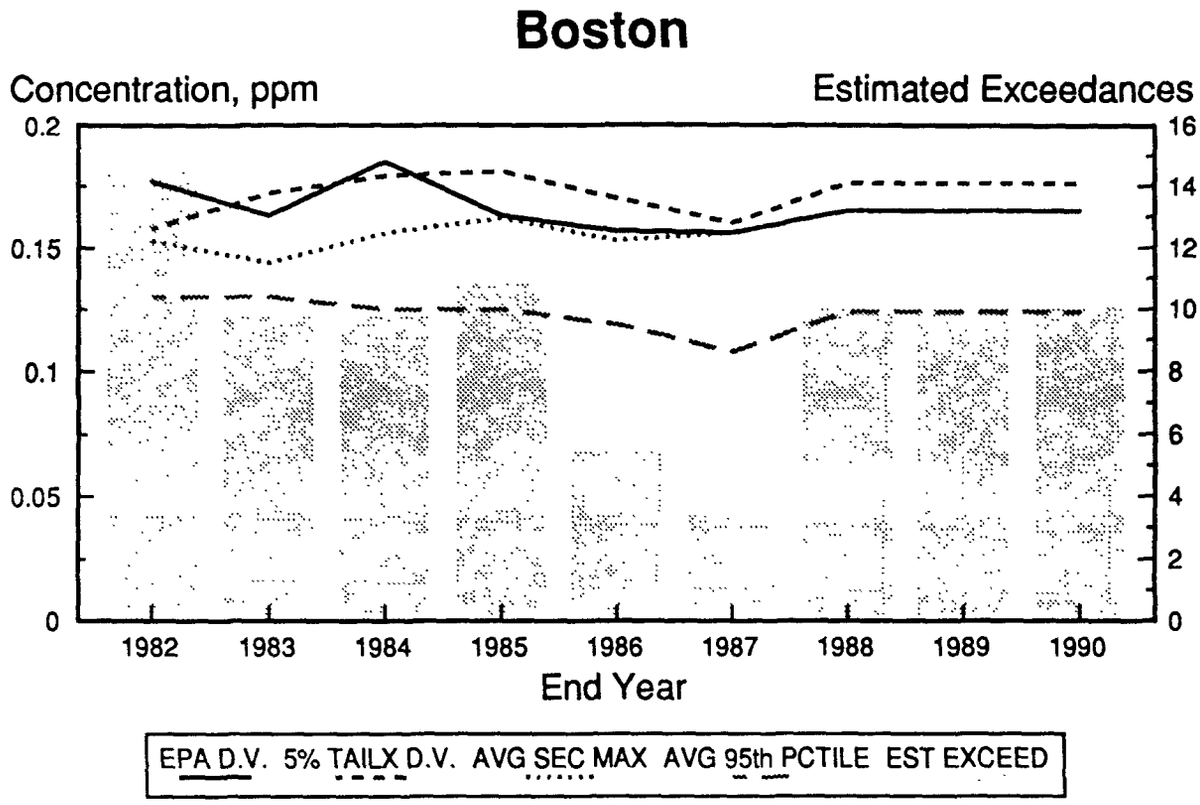


Figure 10-6. Temporal variability in ozone indicators in Philadelphia and Atlanta.



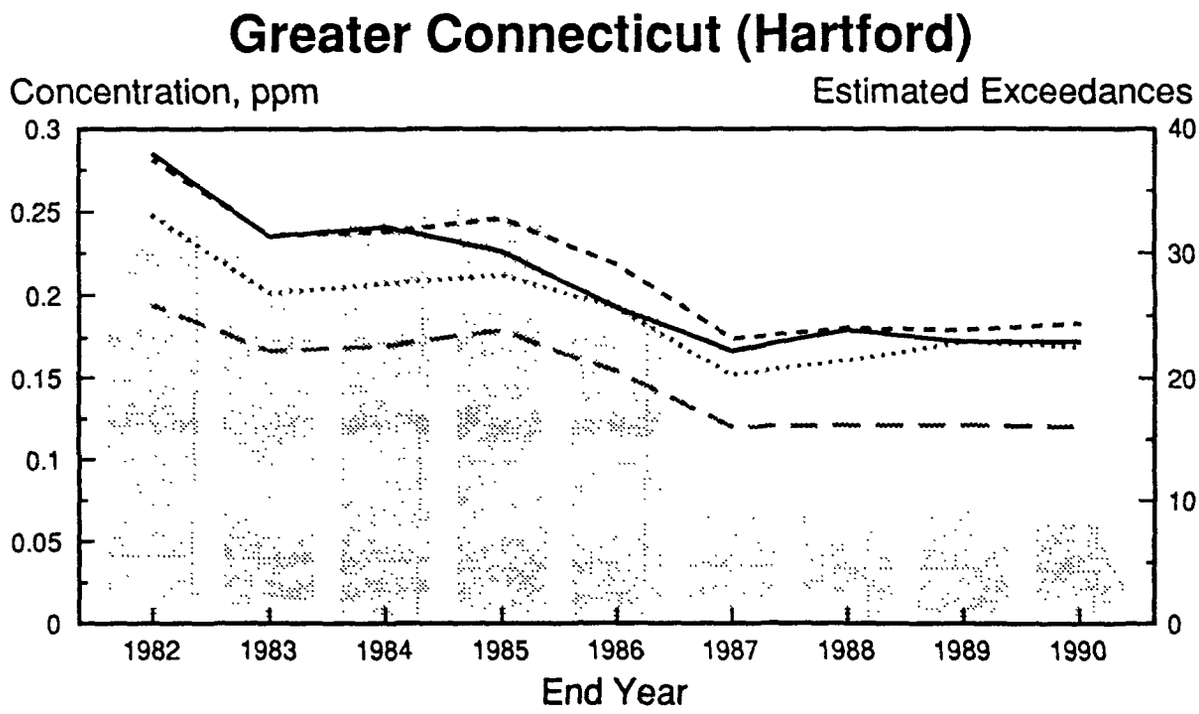


Figure 10-7. Temporal variability in ozone indicators in Boston and Hartford.

SPATIAL VARIATIONS IN OZONE CONCENTRATIONS

Analysis of Monitoring Data

Ozone monitoring networks in most metropolitan areas are quite sparse. A notable exception is the Los Angeles Basin where data are routinely collected over a large network (35 sites in 1989), with 17 sites reporting data to AIRS (as of 1991). Many of these sites have been reporting continuously since 1980, making the South Coast Air Basin (SOCAB) one of the most comprehensively instrumented areas in the world. This extensive database can be used to characterize the spatial variations in ozone concentrations to an extent which is not possible in most other metropolitan areas.

Hourly ozone concentration data at stations in the South Coast (Los Angeles) Air Basin were obtained from AIRS and local sources for the period 1980–91 for the high ozone season (April–October).[1] Daily maximum concentrations were computed and flagged as valid for days with at least nine valid hourly readings between 0900 and 2100 LST. Only stations with at least 75 percent valid daily maximums were retained. Various ozone indicators ("yearly" or "annual" indicators) were calculated for each monitor using the data for each year. Similar indicators were calculated using data combined into overlapping three year periods ("3-year" indicators). These indicators are defined as follows:

EPA DV: The second highest (fourth highest for 3-year) daily maximum concentration.

90%tile: The 90th percentile of the daily maximum concentrations.

95%tile: The 95th percentile of the daily maximum concentrations.

An additional set of ("network") indicators was calculated by combining data for all sites. In this case, EPA DV is the maximum second highest concentration over the monitoring network (fourth highest for 3-year indicators). In addition, two exposure indicators were calculated for the network:

I: The number of pphm-days per station-day above 12 pphm, defined by

$$I = (N_i\, N_j)^{-1} \sum_i \sum_j (D_{ij} - 12)^+$$

where D_{ij} is the daily maximum concentration for the jth monitor (j=1,... , N_j) for the ith day (i=i,... , N_i) and $(D_{ij} - 12)^+$ equals $D_{ij} - 12$ if $D_{ij} > 12$ and equals 0 otherwise.

---

[1]The Federally designated ozone season for the Los Angeles basin is January–December, but peak ozone concentrations are generally confined to April–October period.

I (Pop Wt): A population weighted version of I defined by

$$\left[N_i N_j \sum_j P_j\right]^{-1} \sum_j P_j \sum_i (D_{ij} - 12)^+$$

where P_j is the population associated with the jth monitor.

Figure 10-8 displays the number of days on which concentrations exceeded the NAAQS in 1989. The relatively low concentrations along the coast and high values inland are characteristic of the SOCAB. Spatial variations are also evident in the design values calculated for each station (Figure 10-9). Design values at the coastal and metropolitan stations (North Long Beach and Lynwood) are significantly lower than at stations further inland. In addition, the station with the maximum design value varies from one year to the next and these stations can be located at considerable distances from one another (Pico Rivera and Pomona are 30 km apart, Pomona and Burbank are 50 km apart).

Given the large spatial variations in concentration distributions, care must be taken when interpreting data from sparse monitoring networks. For example, in regions with only a few monitoring stations, a single station located in an area of high concentrations may consistently be the design value station for the region. However, this does not mean that the location of the highest concentrations does not vary from year to the next; it may simply mean that the alternate locations are not near any monitors.

Spatial Indicators of Air Quality

One way of examining the adequacy of the design value as an air quality indicator is to compare the design value with other ozone air quality indicators, including indicators which are more broadly based in both temporal and spatial dimensions. Figure 10-10 compares the design value for the SOCAB (calculated using data from the same stations shown in Figure 10-9) with three other network indicators. This comparison indicates a high degree of correlation between the design value and the broader indices, at least for the period 1980–1988. The design value departs somewhat from the other indicators during the last three years of the period. Linear correlations between the indicators are shown in Table 10-6.

Table 10-6. Correlation Matrix for Spatial Indicators in Los Angeles.

	Design Value	90th Percentile	95th Percentile	I
90th Percentile	.72			
95th Percentile	.822	.975		
I	.842	.939	.967	
I (Pop Wt.)	.825	.926	.962	.992

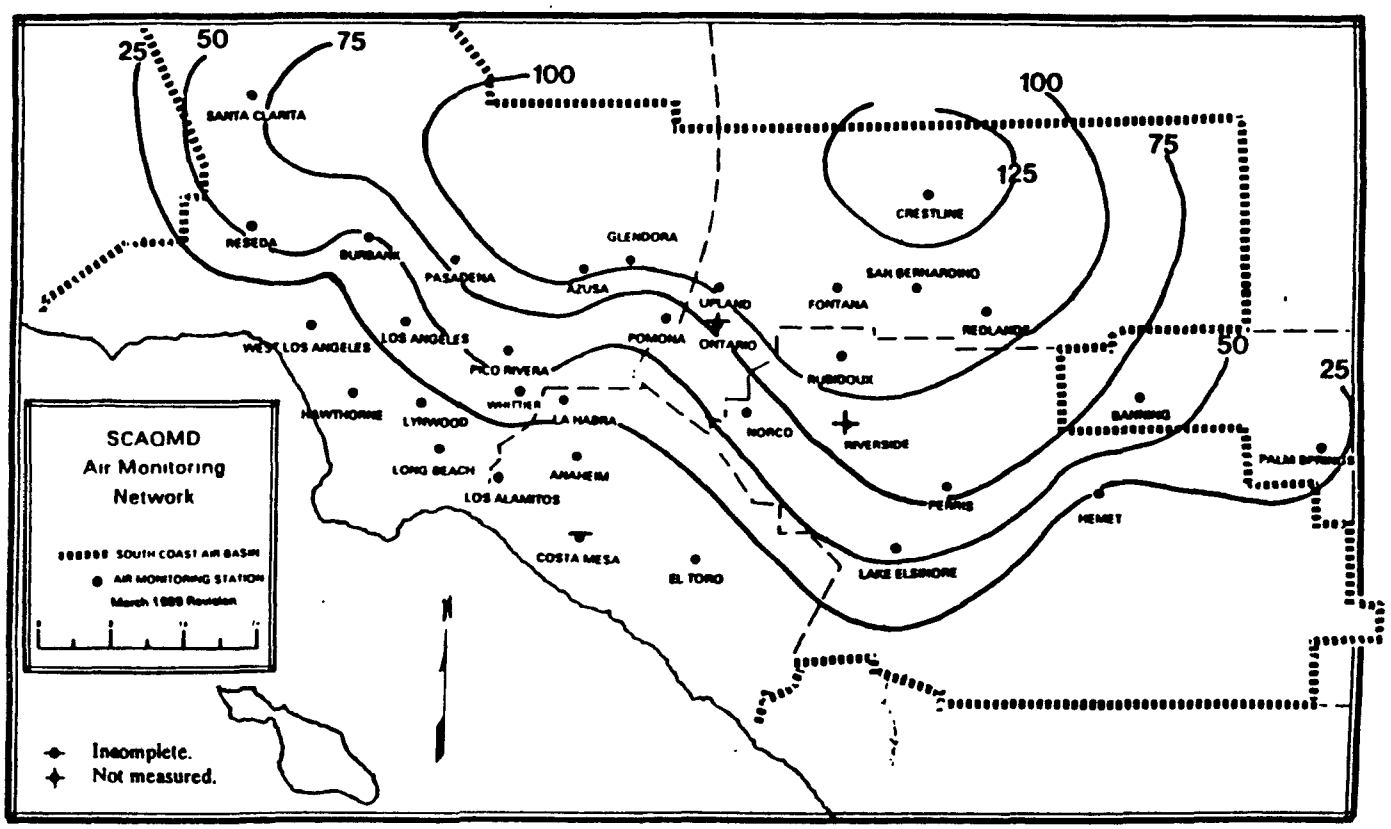


Figure 10-8. Number of days on which the federal ozone standard was exceeded in 1989.

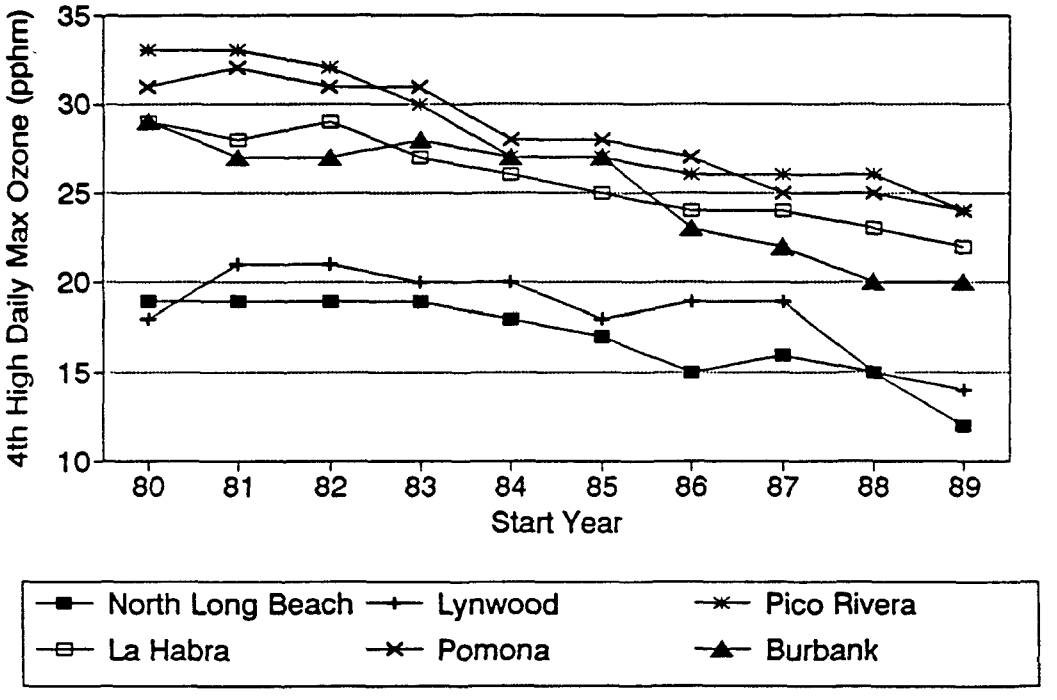


Figure 10-9. Design values (fourth highest value in each three year period) for selected stations.

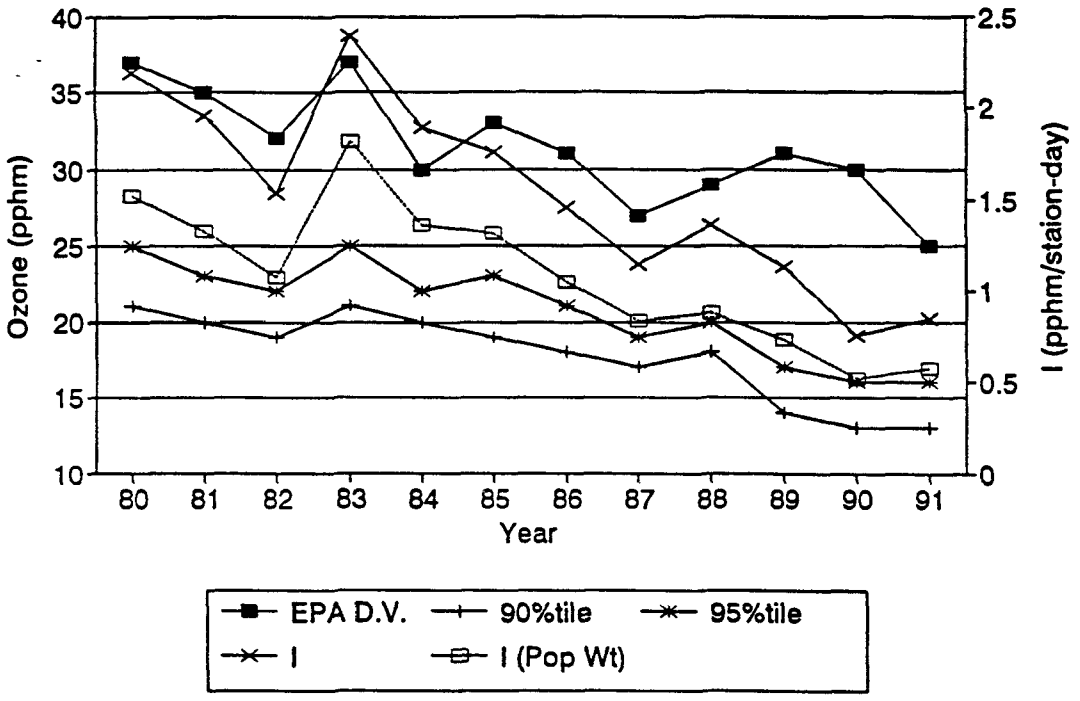


Figure 10-10. Comparison of annual ozone indicators.

These results indicate an overall high degree of association between the design value and the broader air quality indicators for this period in the SOCAB. Indicators based on overlapping three-year periods are significantly less variable than those based on individual years. This point is illustrated in Figure 10-11. As in the yearly results, generally similar trends are evident in each indicator.

Although the yearly design value is highly correlated with the broader air quality indicators, some of the indicators exhibit greater year-to-year variability than others, as indicated in Figure 10-12, which is identical to Figure 10-10 except that the indicator value for each year is plotted as a fraction of its value in 1980. This places the indices on an equal footing and shows that the exposure indicator, *I*, is both the most volatile and exhibits the largest percent improvement since 1980. The design value is slightly more volatile than the 90th and 95th percentiles. The greater volatility and greater overall downward trend in the exposure indicator is characteristic of indicators based on the number of NAAQS exceedances.

These results show that, although all of the indicators follow similar trends in the SOCAB, trends for some indicators may differ from the design value trend in other air basins. For example, in the San Francisco Bay Area, the design value shows no change between 1986 and 1988 while the population-weighted exceedances decreased 50 percent and the 90th percentile and risk-weighted exposures increased. In other words, the number of NAAQS exceedances in heavily populated areas decreased but the occurrences of concentrations slightly below the NAAQS increased. Similar differences in trends between indicators are evident in the other air basins. This suggests that no single indicator can be relied on to fully characterize trends in all of the different aspects of ozone concentrations, which may be of interest to air quality managers.

SUMMARY

Comparisons between ozone design values estimated by the EPA table look-up method and other ozone air quality indicators revealed a high degree of correlation among these alternative indicators. Although the year-to-year variability was similar between the EPA design value and more robust indicators based on lower percentile concentrations, the magnitude of the change in the percentiles was less. The exposure indicators showed a greater degree of year-to-year fluctuations than the concentration-only indicators. Give the spatial variability in ozone observed across urban areas, one cannot expect a single numerical value, such as the design value, to adequately describe concentration gradients.

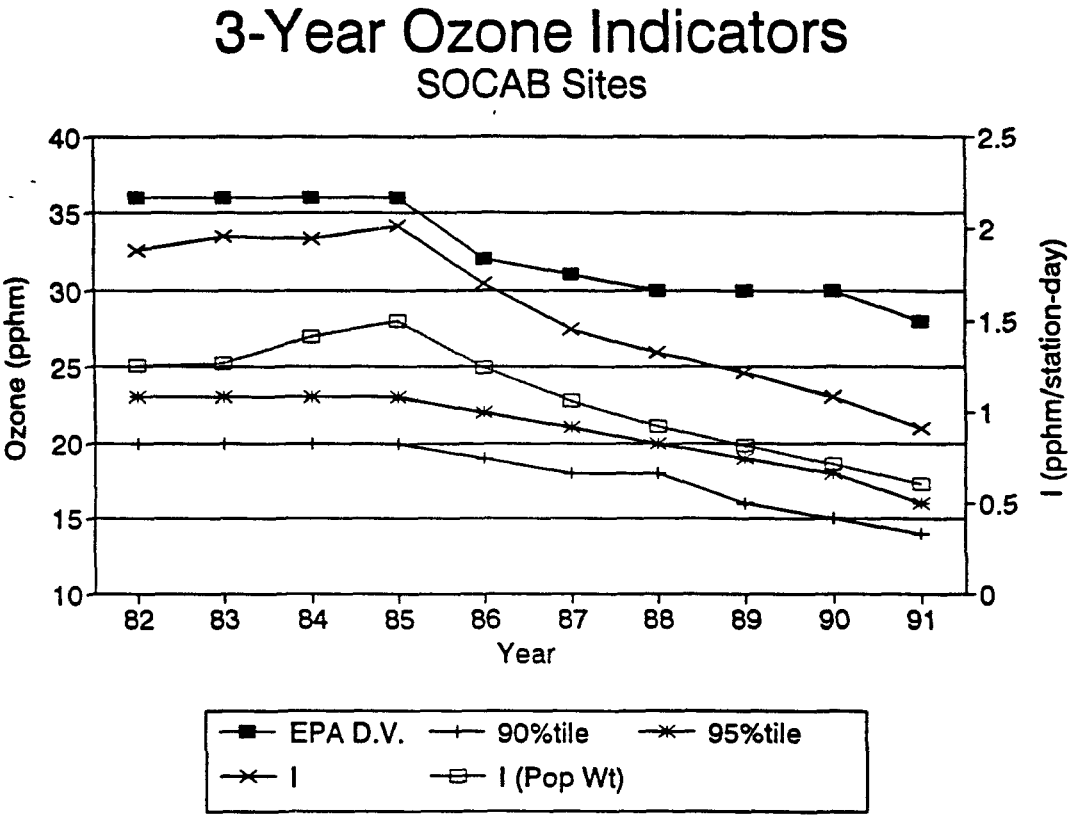


Figure 10-11. Comparison of indicators for overlapping three-year periods.

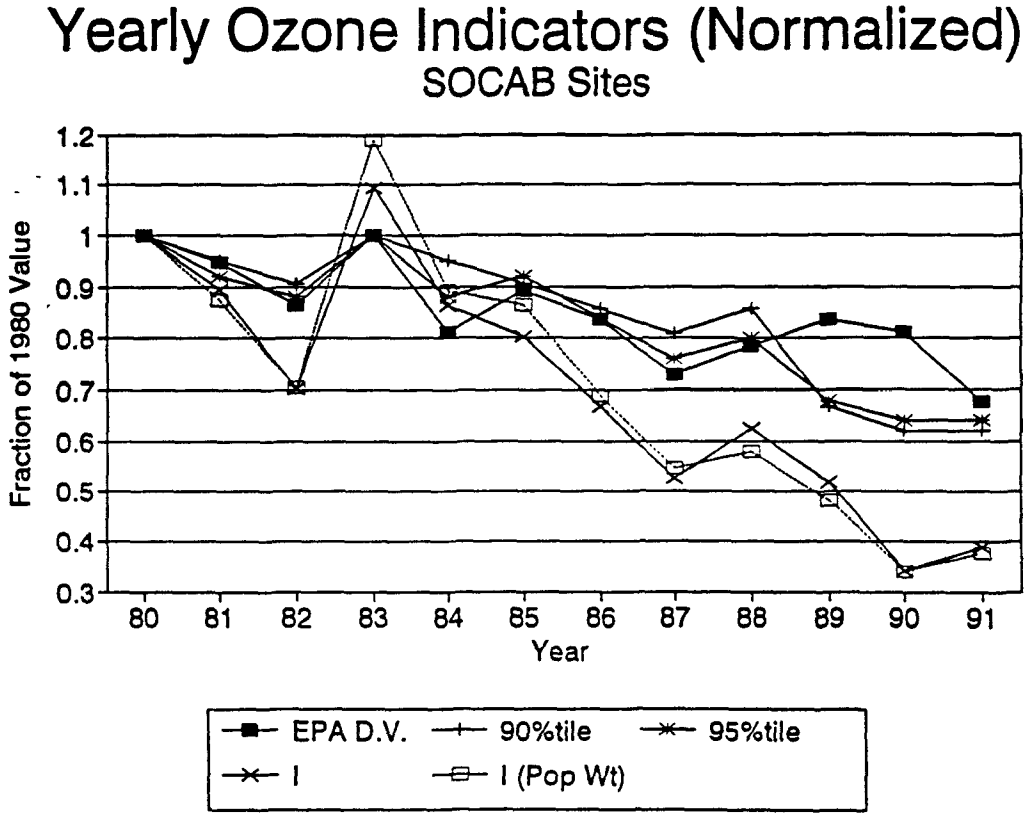


Figure 10-12. Comparison of indicators for overlapping three-year periods normalized to 1980 values.

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11 PUBLIC OUTREACH EFFORTS

Section 183(g) of the CAAA of 1990 requires the EPA to "obtain input from States, local subdivisions thereof, and others." In conducting the Ozone Design Value Study, EPA has made every effort to have an open process and to ensure full public input and participation. These efforts have focused on information exchange through participation in professional meetings and conferences, involvement of interested parties on the study working group, holding a public meeting, and making a draft copy of this report available for public comment. EPA also arranged to have experts at the National Institute of Statistical Sciences conduct a peer review of the draft report.

A study review group has been established to provide input on technical issues and policy concerns. The group is composed of representatives from EPA program, research, policy and legal offices. State and local air pollution control agency officials also serve on the review group. EPA has also sought input from State and local control agency officials through involvement with the Standing Ambient Monitoring Work Group (SAMWG).

Early in the study, EPA staff met with interested parties and participated in technical conferences and meetings. On March 22, 1991, EPA staff met with representatives of the American Petroleum Institute (API), and their member companies, to hear their concerns about the current ozone design value methodology. API representatives expressed their desire to have EPA (1) adopt a more statistically robust form of the ozone standard (i.e., one that is subject to less variability) and (2) use additional indicators, such as measures of exposure, to evaluate control strategy progress. EPA staff have chaired technical sessions, participated in panel discussions, and presented technical papers at the Air and Waste Management Association's Annual Meetings, specialty conferences, and workshops on design value issues (Curran, 1992a,b; Curran and Freas, 1991; Freas, 1991, 1992a,b).

OVERVIEW OF PUBLIC MEETING COMMENTS

On September 10, 1992, EPA held a public meeting in Arlington, VA to obtain input on technical considerations, and implementation and policy issues to be addressed within the context of the Ozone Design Value Study. The meeting announcement was published in the Federal Register, "Notice of Public Meeting" (57FR34133), August 3, 1992. To ensure that all interested parties were aware of the public meeting, copies of the meeting announcement were sent to both individuals and organizations that had previously expressed interest in ozone related issues. At the public meeting, presentations were made on behalf of the Motor Vehicle Manufacturer's Association by Mr. Jon Heuss of General Motors Corporation, and on behalf of Ford Motor Company by Dr. David Chock of Ford. Written comments were received from ten respondents, representing State and local air pollution agencies, industry, and private individual views. The comments received have been grouped into the seven general subject areas listed in Table 11-1. Some of these comments relate directly to issues concerning the methodology for estimating ozone design values, while other comments express concerns about either the form of the ozone standard or implementation of the

Table 11-1. Matrix of Public Meeting Written Comments by Subject Area

	Increase Robustness	Adjust for Annual Meteorology	Compliance Test	Measurement Interference	Design of Monitoring Networks	Transport	Refine Meteoro-logical Models
Motor Vehicle Manufacturer's Association	X	X	X				X
Ford	X	X	X				X
American Petroleum Institute	X			X	X		
US Dept. of the Interior		X			X	X	X
California Air Resources Board		X	X				
Dept. of Environmental Protection, Connecticut	X			X			
Environmental Protection Agency, Illinois		X	X		X		X
New York State Dept. of Environmental Conservation	X	X					
Air Pollution Control District, San Diego						X	
Zephyr Consulting		X			X	X	

CAAA of 1990. A brief summary of each major subject area follows, and an EPA provided synopsis of the public comments can be found in Appendix I. A verbatim transcript of the public meeting, and the written comments and technical papers submitted in response to the Notice, will be included in the public record of this study.

Increase Robustness of the Design Value

Five commenters expressed concern over the reliance on an extreme value for the design value. Several commented on the instability associated with using the fourth highest daily maximum hourly value from the 3-year period and several proposed a summary statistic based on more information such as the 95th percentile, the mean of the three annual 95th percentiles, or the mean of the highest 30 values. The rationale for these proposed modifications is to increase the robustness and the stability in the design value.

EPA comment: The ozone design value is "the value that should be reduced to the standard level thereby ensuring that the site will meet the standard. With the wording of the ozone standard the appropriate design value is the concentration with expected number of exceedances equal to 1." Thus, by definition, the design value is an extreme value. More robust indicators also exhibit year-to-year fluctuations similar to those observed for the design value concentrations (Curran and Frank, 1991; Curran and Freas, 1991; NRC, 1991). It should also be noted that the mean of the highest 30 values is closely related to a tail exponential design value estimate. Furthermore, the alternative "more robust" statistics may not give equivalent public health protection at all sites.

Adjust for Annual Meteorological Differences

Seven commenters said that there is a need for a method to account for temporal variation in meteorology which can mask the underlying ozone trend. Although the 3-year time period used in the current design value method lessens the impact of a particular year when severe heat, low precipitation, and light winds contribute to elevated ozone concentrations, the effect of a year with particularly severe meteorology, such as 1988, is still strongly felt. Several suggested modifying the current procedure, which excludes the three highest values in the 3-year period, to either one that can exclude one or more values each year based on meteorological information or one that selects the second highest from the set of three annual second highest values. Interest was expressed in a method to minimize the temporal variation in ozone design values. Methods were suggested to adjust the design value for the annual variation in the number of ozone conducive days, using temperature data and data for other meteorological parameters. In each case, the intent is to decrease the impact of a single high-ozone year on the design value.

EPA comment: Compliance with the ozone standard is judged on the basis of the actual ambient air quality measurements. The report by the National Academy of Sciences (NAS) stated that more "statistically robust methods be developed to assist in tracking progress in reducing ozone (NRC, 1991)." The NAS did not suggest using meteorologically adjusted air

quality indicators to judge compliance with the ambient standard. Thus, the meteorological adjustments are not appropriate for the "air quality" design value but may be appropriate for a "control strategy" design value. Analyses must communicate trends relevant for the health based standard. EPA has initiated a program to investigate techniques for adjusting ozone trends for meteorological influences (Cox and Chu, 1992).

Compliance Test for Attainment

Concern was expressed for the need to have consistency between the design value and the compliance test for attainment (either to achieve attainment initially or to maintain it). Some commented that the current design value is not the best target because it doesn't incorporate the variability in the ozone measurements and requires compliance 100 percent of the time. Some have suggested modifying this part of the procedure with a two-component testing approach which would be stringent in first accepting an area as in attainment, but for areas that have been in attainment for several consecutive 3-year periods and have no significant increases in ozone-precursor emissions, a less stringent test would be used, which would reduce the probability of misclassifying an attainment area as nonattainment in the test. This modification is intended to reduce the oscillation of areas between attainment and nonattainment due principally to annual fluctuations in meteorological conditions.

EPA comment: The compliance test for the current ozone standard is given in Appendix H to Part 50.9 of the Code of Federal Regulations (44 FR 8220). Changes in the form of the current ozone standard, or the attainment test, are beyond the scope of this study. These issues are more properly addressed within the context of the standard review process.

Measurement Interference and Bias

Two commenters expressed concern about potential measurement interference caused by conditions of high temperature, humidity, and ozone precursor concentrations. Although some factors might cause bias in either direction, commenters felt that most of the factors will result in a positive bias. Two commenters said that both of the major instrument types used for the ozone monitoring networks, the ethylene chemiluminescence (CL) instrument and the ultraviolet absorption (UV) instrument, appear to be affected; the UV instrument interferences seem to be more complex and larger than in the CL instrument.

EPA comment: In accordance with revisions to Appendix A, 40CFR Part 58, site-specific precision and accuracy data have been submitted to EPA beginning in 1987. EPA has studied the issue of interferences from humidity and photochemical pollutants, and based on a 1991 study and earlier studies, EPA does not concur with the commenters' conclusion of widespread interference. EPA is, however, attempting to respond even further to concerns in this area by supporting a project titled "Investigation of Interferences and Other Anomalies in the Measurement of Atmospheric Ozone Concentrations." EPA is looking to jointly conduct this project with the American Petroleum Institute.

Size and Location of Ozone Monitoring Network

Four comments were received stating that there is a need for an ozone monitoring network of adequate size and appropriate locations to characterize ozone measurement variation over small distances, particularly in metropolitan areas. Suggested factors to consider include local terrain features, usual wind roses, proximity to ozone precursor emissions, and seasonal meteorological variation.

EPA Comment: EPA has revised the ambient air quality surveillance regulations (58 FR 8452, February 12, 1993) to include provisions for the enhanced monitoring of ozone and its precursors. Included in these revisions are minimum criteria for network design, monitor siting, monitoring methods, operating schedules, quality assurance, and data submittal.

Transport from Nearby Areas

Three commenters said there is a need to develop techniques to account for transport of ozone and/or precursors from nearby areas. In extreme situations, an air quality region with in-transport may not be able to demonstrate attainment no matter how rigorous the proposed emission control strategy. A modified approach was suggested, such as consideration of a larger regional effort to design control options.

EPA Comment: The air quality design value estimate is determined from the actual ambient monitoring data observed at a monitoring station. In some locations, the transport of ozone and its precursors can have a significant impact on local air quality levels. Section 181(a)(4) gives the EPA Administrator the discretionary authority to modify the area's initial classification if the area's design value is within 5 percent of another category. The Administrator may consider other factors such as "the level of pollution transport." The Act has provisions for treating an ozone nonattainment area as a rural transport area and for establishing Transport Commissions.

Refine Meteorological Models

Four commenters expressed concern about the adequacy of existing meteorological models to perform their role in the current design value methodology. A stated limitation of using photochemical grid models to demonstrate attainment is that the required detailed input information for emissions, initial conditions, boundary conditions, and meteorology may not be available, particularly for a specific design value day in the past. Commenters stated that updated emission inventories are needed in some cases and additional guidance should be developed to clarify this issue. Also, some commenters stated that the Regional Oxidant Model (ROM) outputs are not on a scale sufficient to characterize the more detailed spatial patterns encountered for individual metropolitan areas.

EPA Comment: Research programs to develop/validate models and search for an optimum national ozone strategy are currently under way within EPA. Development and refinement

of the Emission-Based Modeling (EBM) methods required by the Clean Air Act are being pursued within the base research program of EPA. Consistent with expected levels of resources, EPA plans are for extensive field, laboratory, emission inventory and modeling studies to be completed by 1998.

SUMMARY OF PUBLIC COMMENTS ON DRAFT REPORT

On March 14, 1994, EPA published a *Federal Register* Notice announcing the availability of a draft report on the study for public review and comment. Prior to that announcement, copies of the draft report were mailed to all parties that previously expressed an interest in the study. More than 250 copies of the report were mailed out in response to requests. As of the close of the public comment period on April 14, 1994, comments had been received from only two respondents. Requests were received from several parties to extend the comment period. On April 28, 1994, a second *Federal Notice* was published that extended the public comment period until May 31, 1994. Although many additional requests for copies of the draft report were answered during this period, only eight additional parties submitted comments by the close of the comment period. The report was also sent to the National Institute of Statistical Sciences for peer review. This section presents a summary of the public and peer review comments received and EPA's responses.

Several public reviewers provided extensive and detailed comments. In addition, the peer review effort resulted in the formulation of over 90 individual comments and recommendations. A synopsis of all comments made by each organization is presented in Appendix J. Comments of an editorial nature were reviewed and any necessary changes to the text were made. All non-editorial comments were carefully considered and appropriate responses prepared which, in many cases, resulted in changes to the text.

Written public review comments were received from 10 organizations:

Ford Motor Company (Ford)

General Motors (GM)

The Chevron Companies (Chevron)

New York State Department of Environmental Conservation (NYDEC)

Mobile Oil Corporation (Mobile)

E.I. du Pont de Nemours and Company (DuPont)

American Petroleum Institute (API)

California Air Resources Board (CARB)

State of Ohio Environmental Protection Agency (Ohio EPA)

Zephyr Consulting (Dr. Kay H. Jones)

Most of the public comments received on the draft report fall into the same major subject areas as those made during the public meeting, as discussed in the previous section. These are summarized again here and include any significant new aspects raised with regard to the draft report. Additional subject areas were also raised in the public comments and are also summarized below together with EPA's responses. Peer review comments and responses are summarized in a later subsection.

Distinction Between Statistical Population Parameters and Estimated Parameters

At least two commentators (Ford and DuPont) indicated some confusion regarding the distinction between theoretical quantities related to the statistical population of daily maximum ozone concentrations and estimates of these quantities made on the basis of observations from networks of ozone monitors. For example, there appears to be some confusion about whether or not the term "EPA design value" refers to the theoretical quantity known as the characteristic largest value (CLV) or the commonly used estimator of this value, the fourth highest concentration in three years. Ford also makes the comment that the CLV is not directly related to the expected value (i.e., average over many realizations) of the EPA design value.

EPA Response: Changes have been made to the text of the report to make the distinction between population parameters and estimators of those parameters more clear. The "true" design value, or CLV, is an unknown quantity depending upon the unknown true distribution of daily maximum ozone concentrations. The EPA design value is an estimate of the CLV. Similarly, the "true" expected exceedance rate is an unknown quantity which, for compliance purposes, must be estimated using the Appendix H calculations. The "true" design value corresponds exactly to the "true" expected exceedance rate in the sense that the "true" expected exceedance rate exceeds one per year if and only if the "true" design value exceeds the standard. Similarly, the EPA design value and the ozone NAAQS exactly correspond in the case of 100 percent complete three-year monitoring data. Any inconsistency between the CLV and the EPA design value is due to the fact that the EPA design value is an estimator of the CLV, and, like all other design value estimators, is subject to error. Furthermore, while Ford is correct that the expected value of the fourth highest is not the same as the CLV, the accuracy of an EPA design value for a given attainment period is assessed by the difference between the EPA design value and the CLV, rather than by the difference between the EPA design value and the expected value of the EPA design value. The bias of the EPA design value is the expected difference between the EPA design value and the CLV across infinitely many three-year attainment periods, which equals the expected value of the EPA design value minus the CLV.

Increase Stability of the Design Value Estimator

Nearly all commentators discussed concerns related to the year-to-year variability in the current EPA design value estimator (i.e., the fourth highest daily maximum concentration in three years). This variability can cause areas to change attainment status over consecutive overlapping three-year periods, thus leading to uncertainties in the regulatory process.

A number of alternatives designed to reduce variability were suggested, including the three-year mean (or median) of the annual second highest daily maximum, measures based on the 95th percentile of daily maximum concentrations, and the mean of the 10 or 30 highest daily maximums.

Ford commented that the comparison of design values and 95th percentiles in the draft report are not valid due to discrepancies in sample sizes, treating combined instead of individual sites, misinterpretation of correlation diagrams, and misattribution of statistical bias.

Ford also commented that design value estimators based on distributional assumptions are very sensitive to the form of the assumed distribution and that the calibration factor used in the CARB-Larsen tail exponential method to correct an apparent bias between design values estimates obtained from this method and the EPA design value may not be equally applicable to other sites or time periods.

EPA Response: As noted above, the ozone design value is, by definition, "the value that should be reduced to the standard level thereby ensuring that the site will meet the standard. With the wording of the ozone standard the appropriate design value is the concentration with expected number of exceedances equal to 1" (EPA, 1979). Thus, by definition, the design value is an extreme quantity which, inevitably, is subject to variability. The degree of variability is compared to the variability of other air quality indicators in this report. For example, it is noted in Section 3 that the annual 95th percentile exhibits smaller year-to-year differences than the annual second maximum, although the site-to-site variability is similar for both statistics. Furthermore, Finding #6 in Section 12 explicitly points out that "the EPA design value is slightly more variable than the lower percentile estimators." However, the reduced variability comes at the expense of bias relative to the "true" design value and therefore, the alternative indicators cannot serve as a substitute for the design value.

In response to Ford's comments on the comparisons of 95th percentiles and the fourth highest in three years (i.e., the "EPA design value"), we note:

1. As pointed out above, the appropriate comparisons to make are between the 95th percentile and the CLV and between the EPA design value and the CLV, since these indicate the biases of the design value estimators. The CLV has an infinite rather than three-year sample size because the CLV is an unknown population parameter.

2. Fitting the same regression line (CLV against three-year 95th percentile) to all sites is appropriate because it would probably be unacceptable to calculate design values using different regression estimates at different sites; estimating site-specific regressions equations to provide equal public health protection at all sites would be difficult and complex. Although nonlinear regression models might provide a better relationship between the 95th percentiles and the design value, there is no guarantee that a specific relationship would be equally applicable to all monitoring sites.

3. A perfect correlation between the 95th percentile and the CLV at a given site is not expected.

4. Ford's observation that the sign of the bias of the regression estimates depends on which of the two time-series models was fitted is interesting. Ford deduces that the pattern in the estimated CLVs in Figure 14 may be entirely explicable from the properties of the fitted time-series models, rather than reflecting a property of the unknown true CLVs. This may be correct. However, since the best fitting of the two candidate time series models was used at each site, it may instead be reasonable to conclude that Figure 14 demonstrates the difficulty of obtaining a single universally applicable design value estimate based on the 95th percentile because of significant differences in time-series structures at different sites.

With regard to Ford's and GM's suggestion to use the 3-year mean of the annual second highest daily maximum concentrations in place of the fourth highest over three years (EPA design value), we note that this statistic is discussed in Section 10. A problem with this statistic may be that it is more biased with respect to the CLV than the EPA design value. That is to say, this statistic tends to underestimate the CLV more than the EPA design value. This follows from the observation that, if the unknown underlying daily maximum ozone distribution has an approximately exponential tail and the daily maximum values are approximately independent, then the expected value of the $(N+1)$th highest in N years tends to increase with N, approaching the CLV for a sample of size N in the limit as N grows to infinity. Thus in many (though not all) cases, the expected annual second maximum is less than the expected EPA design value, and the expected EPA design value is less than the CLV. The median of the annual second maxima, not specifically discussed in the report, suffers from similar biases, greater variability, and is much less sensitive to the observed air quality. As an extreme example, note that for many areas the median second maximum for 1987–89 would have been the same if the 1988 concentrations had all been ten times as great.

With regard to Ford's comment on the sensitivity of design value estimates to assumptions about the underlying distribution of daily maximum concentrations, we note that it is certainly true that the estimated design value from a fitted distribution may vary significantly depending upon the selected form of the distribution. On the other hand, if a good fit is found (especially in the tail of the distribution), then it is surely more reasonable to use an estimated design value based on a well-fitting distribution than to use a different

estimate based on a poorly-fitting distribution. Discussions in Section 4 include the point that a fit to the tail of the distribution may well be more appropriate for estimating extreme values such as the design value. Several commentators (Chevron, Mobil, CARB) and the NISS peer reviewer support the use of the tail exponential distribution to generate design value estimates.

With regard to Ford's comment about the CARB calibration factor, we note the following comment made by CARB (letter from T. McGuire, May 27, 1994):

> "The calibration factor was not based on data from the Bay Area monitoring network only, although those data played a role along with data from many other sites around the State. The calibration factor was not set so that our method would precisely match EPA's fourth high estimate. In fact, we knew that EPA's method was biased low (theoretically), and we chose not to make the two methods coincide. We also acknowledged the possibility that our method could be biased high, and the Bay Area data along with the other data throughout California helped determine a suitable midpoint between the impressions from the EPA and uncalibrated CARB method."

Attainment Test

A number of commentators expressed concern with the NAAQS attainment test specified in Appendix H of 40 CFR 50. These concerns were generally the same as those expressed during the public meeting, i.e:

- Lack of consistency between the test used to determine attainment/nonattainment status (which is based on exceedances) and comparisons of the design value with the level of the ambient standard (0.12 ppm) which can arise when monitoring records are incomplete (thus requiring the use of the missing data adjustments discussed in Appendix H).

- Lack of consideration for year-to-year fluctuations in the design value in the current attainment test leads to attainment/nonattainment flip-flops and the requirement for a design value target that is "significantly" below the level of the standard (0.12 ppm) to maintain attainment in the long run. In other words, the actual stringency of the standard is greater than the "nominal" stringency implied by the level of the standard.

With regard to the first point, GM suggested that an analysis be included in the report of the extent to which areas are classified as nonattainment as a result of the adjustment of observed exceedances to account for missing values. GM also commented that the study should include analyses of "too close to call" transitional attainment categories. API notes that it supports the development of such a "transitional nonattainment" designation.

With regard to the second point, Ford suggested the use of a statistical attainment test. Such a test, based on the student's-t distribution, has been proposed by Chock (1991).

Alternatively, Fairley and Blanchard (1990) suggested a two-part test based on the number of exceedances in recent years which is designed first to require a high level of proof in demonstrating attainment for the first time, and then shifts to require a high level of proof that attainment is no longer valid, thus reducing the probability of declaring an area that was in attainment as nonattainment if, based on the theoretical value of the expected exceedance rate, the area is actually still in attainment. Mobil suggested using estimates of the value that is expected to be exceeded once in seven years (obtained from the CARB tail exponential fitting procedure) to exclude extreme concentrations from data used to determine attainment.

GM commented that the attainment test applied to areas reaching post-1990 attainment deadlines should be based on a comparison of the area's design value with the level of the standard, and not on the expected exceedance rate, and that, therefore, the Design Value Study should address issues related to the use of design values in determining attainment. GM also suggested that the study should include a discussion of nonattainment area classification methodology.

NYDEC and others commented that variability in design values and attainment determinations could be reduced by increasing the length of the attainment period beyond three years. DuPont suggested using periods of at least six years and noted that this is "conservative" in areas with long-term downward trends in ozone. NYDEC noted, however, that using longer attainment periods would increase the length of time before an area could be declared in attainment. Furthermore, Ohio EPA noted that the use of longer attainment periods would have only limited effect on reducing the influence on design values of an extreme year such as 1988.

EPA Response: As noted above, the test used to determine attainment of the current ozone NAAQS is specified in Appendix H of 40 CFR 50 (see 44 FR 8220). EPA was aware of the "actual" stringency of the standard at the time of promulgation in 1979. EPA selected a three-year attainment period to specifically limit the number of exceedances that could occur in a single year in areas that are in attainment of the standard. Changes in the form of the current standard, including the attainment test, are beyond the scope of this study. These issues will be addressed in the forthcoming Staff Paper being prepared as part of EPA's review of the ozone NAAQS. Thus, the analysis of missing values suggested by GM is beyond the scope of this study. With regard to GM's comment on the attainment test for post-1990 attainment deadlines, we refer to the General Preamble for the Implementation of Title I of the Clean Air Act Amendments of 1990, which states that the attainment test for areas reaching their attainment deadlines will be based on the "average number of exceedances per year" (57 FR 13506).

Adjust Design Values for Annual Meteorological Fluctuations

Ford, GM, NYDEC, Mobil, DuPont, Jones, and API recommended that EPA adjust design value estimates to account for year-to-year fluctuations in meteorological conditions since these fluctuations are not associated with changes in the level of controllable emissions,

cause areas to flip-flop in and out of attainment, and can result in uncertainties about the degree of emission reductions needed to achieve or maintain attainment.

Ford and GM recommended against using the meteorological adjustment method developed by Cox and Chu (1992) as presently formulated since the adjusted annual design values are largely determined by the trend term and the influence of changing emissions over the trend period on the ozone-meteorology relationship is not accounted for. Both Ford and GM recommended using a method that treats each year individually.

EPA Response: As noted in the previous section, compliance with the ozone standard is judged on the basis of the actual ambient air quality measurements. It is the actual ambient air quality, not a hypothetical adjusted value, which is of concern with respect to the potential for adverse health impacts. EPA has long recognized the need to develop reliable meteorological adjustment techniques for the analysis of ozone trends. A trend adjustment procedure is currently under development as described by Cox and Chu (1992). With regard to the concerns about the Cox and Chu method raised by Ford and GM, Cox (1994, personal communication) acknowledges this possibility and notes in a preliminary analysis that relationships between ozone and some meteorological variables do change over time in some of the urban areas studied. Investigation into this issue is ongoing.

Influence of Transport from Nearby Areas

GM and NYDEC commented that the impact of ozone and precursors transported from upwind jurisdictions should be taken into account in attainment/nonattainment determinations. Ford commented that the TODV (Transported Ozone Design Value) model used to separate out the upwind contribution to design values is inadequate and that the UAM (Urban Airshed Model) should be used for this purpose. Ohio EPA noted that some regions may not be able to demonstrate attainment via local emission reductions due to the overwhelming influence of transport from upwind areas. It suggested that control strategy design values that have been adjusted for transport and meteorological effects be adopted for use in classifying nonattainment areas.

EPA Response: As a measure of local air quality, the design value is calculated using data from monitors in the area in question. Section 8 of this report discusses transport issues and notes that local air quality can be significantly affected by transport from upwind areas. As noted above, the Clean Air Act gives the EPA Administrator some discretionary authority to modify the initial design value classification based on factors such as "the level of pollution transport" (Clean Air Act, Section 181(a)(4)). In addition, the Act provides for the identification of rural transport areas and Transport Commissions for dealing with transport-related matters. EPA agrees that the UAM is a more scientifically rigorous (though labor-intensive) approach to estimating the impact of transport; the inclusion of the TODV model results in this study is purely for purposes of illustrating the potential impacts of transport on design values.

Influence of Spatial Variability in Ozone Concentrations

Ford, GM, Chevron, Mobil, DuPont, and API noted that ozone concentrations vary significantly from one part of a nonattainment area to another and that the EPA design value does not adequately account for this variability. They recommended that an alternative design value, based on measures of population exposure, be used. Chevron commented that the design value does not provide reasonable information about current exposures and that trends in design values do not necessarily reflect trends in exposures.

EPA Response: Spatial variability in ozone concentration is discussed extensively in Section 10. EPA agrees that population exposure measures based on data from multiple monitoring sites provide a broader-scale indication of ozone levels than the maximum estimated design value over the monitoring network. However, given the current form of the ozone NAAQS and the Clean Air Act requirement that all population groups must be protected, the ozone design value must be estimated at each monitoring site in an area, and the site with the highest design value determines the level of emission controls required.

Response to Previous Public Comments

GM commented that the draft report did not include an adequate discussion of and response to the public comments received.

EPA Response: The final report includes an expanded review of all comments received (see synopses in Appendix I), and an expanded discussion and response to comments in this section. In addition, a large number of changes have been made to the draft report in response to both the public comments received and the extensive peer review comments (as discussed in the next subsection).

SUMMARY OF PEER REVIEW COMMENTS ON DRAFT REPORT

Dr. Malcom R. Leadbetter of the National Institute for Statistical Studies prepared a detailed peer review of the draft report. A complete synopsis of his comments is presented in Appendix J. Overall, Dr. Leadbetter noted that "The EPA study is an extremely well considered document which addresses issues raised and evaluates them fairly on the basis of their scientific merit." He further noted that the EPA table look-up estimator, although not perfect, is "reasonable" and has the advantages of being simple, statistically valid, and unlike some estimators based on fitting data to parametric distributions, can be applied with equal validity to any monitoring site. Dr. Leadbetter agrees with the public commentators in pointing out that development of more "robust" design value estimators and air quality indicators would be advantageous and suggests that alternative indicators, such as those described in this report, continue to be evaluated and considered for use. He particularly favors indicators based on the tail exponential distribution as these are both simple and robust

but cautions that the universal applicability of the tail exponential distribution to all monitoring situations has yet to be demonstrated.

Additional significant comments provided by Dr. Leadbetter and EPA's responses are discussed below. Where appropriate, changes to the text of the draft report have been made in response to these comments. Dr. Leadbetter supplied numerous additional specific suggestions for changes to the text to improve readability and scientific accuracy as indicated in Appendix J. Changes to the text of the report have been made incorporating these comments.

Comment: One undesirable feature of the table look-up approach is the "higher than desirable" probabilities of misclassifying an attainment area as nonattainment and vice versa (see example calculations in Appendix K. For a given "true" design value, alternative approaches may result in lower misclassification probabilities. However, since misclassification will always be a problem for areas near the attainment/nonattainment boundary, implementation of a "too-close-to-call" (i.e., transitional nonattainment) category would be advantageous.

EPA Response: As noted in Dr. Leadbetter's detailed comments, the high variability (and resulting misclassification probabilities) of the EPA design value and most of the proposed alternative design value estimators is primarily a result of its relationship to the ozone NAAQS, which causes the estimated design value to depend only on the extreme data values. Changes in the form of the current ozone standard, including changes to the 1990 CAAA ozone design value classifications, might lead to lower variability of the estimated design value and reduced misclassification probabilities. Such changes, including the "too close to call" category, are beyond the scope of this study but are being addressed in the forthcoming Staff Paper being prepared as part of EPA's review of the ozone NAAQS.

Comment: A distinction needs to be made between the true design value, expected to be exceeded once per year, and estimated design values.

EPA Response: This comment relates to the apparent confusion in terminology as discussed in connection with some of the public review comments above. The "true" design value is an unknown parameter of the underlying distribution of ozone concentrations and is the value expected to be exceeded with a probability of 1/365 assuming a 365-day ozone season. The true design value, assuming independent, identically distributed daily maximum ozone concentrations, is also known as the characteristic largest value (CLV). The EPA design value (based on the table look-up procedure) is indeed an estimator of this unknown parameter, as are other design value estimators discussed in the study. Changes have been incorporated into the text of this report to alleviate potential confusion between unknown "true" parameters and estimators of those parameters. To retain the readability of the document, the text does not always distinguish estimated and true design values where the meaning is clear from the context. Where there is potential for confusion, the terminology "true design value" is used to indicate the unknown population parameter.

Comment: The study focuses on the fundamental issue of comparing methods of estimating the design value but inadequately treats the important issue of how to take spatial variation into account when using design values at different sites to assess area air quality. In particular, under the current EPA practice of focusing on the monitor with the highest estimated design value, a determination of nonattainment may be more likely for areas with more monitoring sites, thus resulting in potential inequities between areas with different monitor densities.

EPA Response: The spatial variation in ozone concentrations is an important subject for continued research, and several aspects of this problem are considered in the report. The use of the highest monitoring site design value for classification and nonattainment determination is justified by the CAAA requirement to protect public health throughout the attainment area, including the health of people who might be exposed at or near the site with the highest concentrations.

Comment: Comments on alternative forms of the ozone NAAQS may be relevant to the design value study since a revised ozone NAAQS might better correspond to a different design value.

EPA Response: While a NAAQS different from the one currently in place would require the formulation of different design value estimators, EPA's interpretation of section 183(g) of the Clean Air Act is that the design value study is to focus on design value methodologies consistent with the current NAAQS. Thus, design values consistent with alternative NAAQS are beyond the scope of this study. Potential changes to the NAAQS and associated design value issues are being addressed in the forthcoming Staff Paper being prepared as part of EPA's review of the ozone NAAQS. Obviously, findings from this study will be an important consideration in the review process.

Comment: The conclusion section should discuss the crucial issues of the performance of the design value estimates and their ability to accurately classify nonattainment areas.

EPA Response: Appendix K includes some additional analyses of misclassification probabilities prepared by Dr. Leadbetter and the "Major Findings" section has been modified to discuss these issues.

Comment: It is not clear why using alternative design values for nonattainment area designations and classifications would require revision to the NAAQS and the CAAA. Although consistency between the design value and the NAAQS attainment test is "natural, aesthetic, and traditional," departures from this consistency would be justified if improvements in statistical properties (i.e., "robustness") could be achieved. Thus, the arguments made in Section 6 that a poor regression fit between the 95th percentile and the CLV implies that the 95th percentile gives a poor design value estimate are not convincing.

EPA Response: Although the EPA Guideline for the Interpretation of the Ozone NAAQS suggests several alternative procedures for estimating the design value, including the table look-up procedure and methods based on fitting distributions, Appendix H of 40 CFR 50 precisely specifies the calculation of expected exceedances used for the attainment test. Using an alternative design value such as the 95th percentile for the attainment test definition would therefore require a revision to the current ozone NAAQS. Further, the 1990 CAAA specified that the 1990 nonattainment area classifications were to be made using the approved design value methodology in place at the time of enactment, i.e. the EPA tabular approach. Strictly speaking, use of an alternative design value for classifying new ozone nonattainment areas would not require a revision to the ozone NAAQS. However, according to the Ozone Guideline, a design value has to be a reasonable estimator of the value expected to be exceeded once per year ("true" design value). Since most of the summary statistics proposed on page 3-19 of the draft (including the 95th percentile) are not reasonable estimators of the "true" design value, they cannot be used directly as design value estimators. Furthermore, the poor regression fit suggests that a simple linear function of the 95th percentile will not provide a suitable design value estimator applicable over all sites and monitoring periods. The scatter evident in Figure 6-14 suggests that site-specific factors would have to be taken into account, thus a simple method could not be applied with equal validity at all sites and attainment periods.

Comment: At the end of Section 3, the text wrongly implies that a deterministic relationship to the current NAAQS design value, rather than just a statistical relationship, is required to justify the use of the 95th percentile.

EPA Response: This is a misreading of the text, which has been rewritten for clarity.

Comment: Figure 5-4 demonstrates the fact that the distribution of ozone concentrations is not the same throughout the ozone season, which suggests that the process of estimating a design value using a single distributional fit as in, for example, the tail exponential approximation, is inherently contradictory.

EPA Response: It is reasonable to assume that the distribution of ozone concentrations is not the same throughout the ozone season. However, the EPA design value approach, the tail exponential approach, and several of the other preferred design value approaches are based only on the tail of the ozone distribution which is likely to contain values from only a small period within the ozone season. Thus these design methods are essentially based on a single distributional fit to a small portion of the ozone season. The conditional probability approach described in Section 4 is a relatively complex method that might be used to directly treat the nonstationarity issue.

Comment: The procedure for estimating exceedances on days with missing monitoring data suggested by Davison and Hemphill (see reference 15 in Section 5) represents a potential improvement over the current Appendix H method and suggests the need for a review of the Appendix H methodology.

EPA Comment: As noted above, such changes are beyond the scope of this study. However, the treatment of missing values is being addressed in connection with the ozone NAAQS review currently underway.

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12 SUMMARY OF FINDINGS

This report responds to the requirements of Section 183(g) of the Clean Air Act Amendments (CAAA) of 1990, which requires that

> "The Administrator shall conduct a study of whether the methodology in use by the Environmental Protection Agency as of the date of enactment of the Clean Air Act Amendments of 1990 for establishing a design value for ozone provides a reasonable indicator of the ozone air quality of ozone nonattainment areas. The Administrator shall obtain input from States, local subdivisions thereof, and others. The study shall be completed and a report submitted to Congress not later than 3 years after the date of the enactment of the Clean Air Act Amendments of 1990. The results of the study shall be subject to peer and public review before submitting it to Congress."

With passage of the Clean Air Act Amendments (CAAA) of 1990, added emphasis was placed on ozone design values. In addition to designating areas as nonattainment for ozone, the CAAA introduced a classification process to further categorize nonattainment areas according to the extent of their ozone problem. This area classification was based upon the ozone design value. The CAAA stated that the design value "shall be calculated according to the interpretation methodology issued by the Administrator most recently before the date of the enactment." Before the 1990 CAAA, designation of nonattainment areas simply involved a yes/no determination as to whether the area met the standard. The additional classification step introduced by the 1990 CAAA placed greater emphasis on ozone concentration observations and on the methodology used to determine the design value.

Another reference to the use of design values is contained in Section 181(b) of the Act, which states that EPA "shall determine, based on the area's design value (as of the attainment date), whether the area attained the standard by that date." EPA's preliminary interpretation of this Section (EPA, 1992) is that the "average number of exceedances per year shall be used to determine whether the area has attained," which is the attainment test for the ozone NAAQS. Thus, design values are not used to make this determination, although the determinations based on Appendix H and based on the EPA design value are identical in the case of complete monitoring data.

The focus of the Ozone Design Value Study is on EPA's design value methodology as initially developed in the Ozone Guideline and later defined in current EPA guidance "as of the date of enactment of the Clean Air Act Amendments of 1990." Issues concerning the form of the current ozone National Ambient Air Quality Standard (NAAQS) are more properly treated within the existing mechanism for NAAQS review, and the wording of Section 183(g) clearly establishes that Congress was interested in examining EPA's ozone design value methodology, not EPA's ozone NAAQS.

Section 183(g) of the CAAA of 1990 requires the EPA to "obtain input from States, local subdivisions thereof, and others." In conducting the Ozone Design Value Study, EPA has made every effort to have an open process and to ensure full public input and participation. These efforts have focused on information exchange through participation in professional meetings and conferences, involvement of interested parties on the study working group, and holding a public meeting in Arlington, VA on September 10, 1992.

On March 14, 1994, EPA published a *Federal Register* Notice announcing the availability of a draft report on the study for public review and comment. Prior to that announcement, copies of the draft report were mailed to all parties that previously expressed an interest in the study. More than 250 copies of the report were mailed out in response to requests. As of the close of the public comment period on April 14, 1994, comments had been received from only two respondents. Requests were received from several parties to extend the comment period. On April 28, 1994, a second *Federal Notice* was published that extended the public comment period until May 31, 1994. Although many additional requests for copies of the draft report were answered during this period, only eight additional parties submitted comments by the close of the comment period. The report was also sent to the National Institute of Statistical Sciences for peer review.

Comments received during the public meeting and in the draft report can be grouped into two major categories: (1) those relating directly to design value issues and (2) those that would require changes in legislation or a revision to the form of the ozone standard. Those in the first category include issues concerning (1) the statistical robustness of the current design value methodology, (2) the precision and accuracy of ozone monitoring data, and (3) the use of other statistical techniques, such as fitting a tail-exponential model, for determining the design value. The second category includes issues associated with changing the form of the ozone standard to a more robust air quality indicator, or proposing to modify the attainment test to incorporate a statistical test, such as a "t-test" for judging compliance with the standard. Such changes are beyond the scope of this study and are more properly addressed during the next ozone NAAQS review.

Many comments were received that raise issues related to the concept of a "control strategy" design value, not the air quality design value. Recall from earlier discussions, that adjusting for factors such as transported ozone, meteorology, and emissions trends falls within the control strategy design value concept, not the air quality design value methodology used to classify ozone nonattainment areas under the CAAA of 1990.

MAJOR FINDINGS

The Ozone Design Value Study has examined the current EPA method, as well as alternative approaches, for calculating ozone design values. The key findings of the study are as follows:

1. With passage of the Clean Air Act Amendments of 1990, the primary role of the air quality design value is to establish the ozone classification of ozone nonattainment areas.

2. Although the year-to-year differences in ozone concentrations can be large, all of the different methods for estimating air quality design values show similar patterns in the year-to-year variability.

3. Increasing the number of years used to estimate the design value reduces the year-to-year fluctuations. Comparisons made for 3-year periods ending in 1988–90 had less variability in the design value estimates than during previous 3-year periods. This is likely due to the fact that there was a single dominant year (1988) for peak ozone levels during the 1988–90 time period.

4. The past decade has seen large year-to-year variability in ozone concentrations. However, the relative variation in ozone concentrations recorded among monitoring sites throughout large urban areas can be as great as, or greater than, the year-to-year variation in ozone concentrations recorded at a particular monitoring location. Spatial variations in ozone concentrations at smaller, sub-metropolitan length scales are not well defined in many areas due to the sparsity of ozone monitors.

5. The EPA tabular design value method tends to give lower, but more variable, estimates for the ozone design value than some of the statistical modeling methods, such as the Breiman tail exponential approach. Results of the time-series modeling analysis suggest that the tail exponential approach provides the best compromise regarding bias and precision in the estimate of the "true" design value.

6. The EPA design value is highly correlated with some less variable air quality indicators. However, the EPA design value is slightly more variable than lower percentile indicators.

7. Given the database available at the time, generally data through 1989, the use of more robust (less variable) methods such as the tail exponential approach would not have significantly changed the initial ozone nonattainment area designations and classifications. Use of more years of data (i.e., 4 or 5 years) in estimating the design value would have resulted in lower classifications in only a limited number of cases. However, more recent data periods that do not include 1988 yield significantly different results. For the years 1989–91, the first 3-year compliance period that excludes the 1988 data, 42 of the original classified 98 nonattainment have ambient ozone meeting the standard. Seven of these areas have been redesignated to attainment.[1] The most recent compliance period, 1991–93, has 48 of the remaining 91 classified nonattainment areas also meeting the ozone standard.

8. Since the "true" design value is in the tail of the ozone concentration distribution, the EPA tabular design value method and more robust alternatives are perforce subject to greater variability than estimators of the central part of the distribution. Like any statistical

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[1] Areas must apply for and meet certain administrative requirements to be redesignated in addition to meeting the expected exceedance limitation spelled out in the ozone NAAQS.

estimator, errors in these estimated design values can lead to 1990 CAAA misclassification of nonattainment areas, just as errors in the Appendix H estimated expected exceedance rate can lead to misclassification of attainment areas as nonattainment areas and vice versa. Analyses included in this study provide estimates of the theoretical misclassification rates, but for a given site and monitoring period it is impossible to determine whether the estimated classification is the (unknown) true classification.

9. The "air quality" design value differs in concept and application from the "control strategy value." The former is based solely on the actual measured ozone air quality data and relates directly to the form of the ozone NAAQS. Control strategy design values have historically been used to evaluate emission control strategies, and may incorporate adjustments for factors such as transported ozone levels and meteorological variability. Use of the control strategy value concept to judge attainment under the Act would require EPA to revise its preliminary interpretation of Section 181(b)(2) published in the General Preamble to Title I.

10. For thirty-five areas modeled, the transport contribution to design values in areas subject to transport was found to be as large as 0.05 ppm. Increases in the design value of up to 0.04 ppm were estimated when the downwind impact was attributed back to the source area.

11. EPA has initiated a program (Cox and Chu, 1992) to investigate techniques for adjusting ozone trends for meteorological influences. One of the methods being studied is a statistical model in which the frequency distribution of ozone concentrations is described as a function of meteorological parameters. EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS). Preliminary results suggest that the bias and uncertainty associated with long-trend estimates can be significantly reduced by including meteorological covariates as parameters in the statistical modeling process.

12. The use of a simple linear function of the 95th percentile of the distribution of daily maximum ozone concentrations as a surrogate design value is less satisfactory than any of the four more direct estimators of the design value. It fails to significantly reduce the variability of the associated estimated characteristic largest value (CLV) below that achieved with the more direct methods. (From another perspective: controlling the 95th percentile fails to improve control of the underlying CLV.) At the same time it introduces substantial biases which vary with the site. The bias problem would result in uneven treatment of sites relative to what would be achieved with the more direct measures. Nor would the use of the 95th percentile obviate the need to use 3-year data sets.

CONCLUSIONS

The question for the Ozone Design Value Study is "Does the EPA design value methodology provide a 'reasonable indicator of ozone air quality in ozone nonattainment areas'?" The answer depends on the intended application of the design value. Each nonattainment area was classified as a Marginal Area, a Moderate Area, a Serious Area, a Severe Area, or an Extreme Area based on the design value for the area. The area's classification establishes the primary standard attainment date and the requirements for State Implementation Plans.

The ozone design value is a surrogate measure of attainment status, a measure of progress, and an indicator of how much concentrations must be reduced to meet the standard. The EPA design value method yields an estimate for the ozone design value that is consistent with the current ozone NAAQS. Given the findings of this study, the EPA design value yields a "reasonable" estimate of the "true" air quality design value for the area and of peak ozone levels within the nonattainment area for the initial three-year compliance period.

The EPA design value provides a reasonable estimate of peak levels within the urban area, and the degree of nonattainment of the area. However, the design value cannot describe the spatial variability in ozone concentrations across the area. More robust indicators based on specific monitoring sites also have large spatial variability. Due to the spatial variability observed across urban areas, one cannot expect a single numerical value to adequately describe complex concentration gradients.

The current EPA design value method may not provide a reasonable indicator of ozone levels in future years due to the large year-to-year variability in meteorological conditions, or to reductions in emissions from implementation of control measures. Other more robust air quality indicators also exhibit similar year-to-year variability.

The method used to adjust for meteorological influences on long-term ozone trends could be adapted for use in calculating meteorologically adjusted exceedance rates and design values. While such adaptations are technically feasible, and would reduce the year-to-year variability, the use of adjusted exceedance rates in NAAQS attainment and adjusted design values for classification purposes would represent a major departure from current EPA policy and NAAQS implementation guidelines. Also, a meteorologically adjusted design value may not be the best indicator of the air people breathed during a specific calendar year. Such a major change is more appropriately considered within the context of the ozone NAAQS review process as this adjustment could affect the level of health protection intended by the standard.

Concerns about the current ozone standard were raised during the public review process. Although changes to the form of the ozone standard were outside the scope of this study, they are being considered within the context of the current review of the ozone NAAQS. The knowledge gained from the input of all parties to this study during the public review process will be used to address issues concerning the form of the ozone standard and design value methodologies.

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APPENDIX A

Summary of Articles Discussing the Fitting of Statistical Distributions to Air Quality Data

Summary of Articles Discussing the Fitting of Statistical Distributions to Air Quality Data

The articles selected for this literature review are summarized in Table A-1. In the table, the column headed "No." gives the reference number of the cited paper(s) used both in this summary text and in the list of references. The ordering is arbitrary, except that related papers appear consecutively in most cases. The column headed "Distribution fitted" gives the distribution(s) analyzed in the paper, and, in most cases, fitted to an example data set described in the columns headed "Species/Averaging time," "Region," and "Years." In some cases the paper is theoretical only and does not describe applications to real data. Note that "O_x" has been used as an abbreviation for oxidant data, since for many of the earlier papers direct measures of ozone (O_3) were not available. The column headed "Fitting method" describes the statistical method used to fit the distribution to the data (see the next section for descriptions of the terms used.) The column headed "Comments" briefly describes the key issues discussed in the paper and the conclusions reached.

TABLE A-1. Summary of articles discussing the fitting of statistical distributions to air quality data.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
1,2	Log-normal.	SO_2, CO, HC, NO, NO_2, NO_x, O_x. Several averaging times.	Chicago, Cincinnati, Denver, Los Angeles, Philadelphia, St. Louis, San Francisco, Washington.	1962-1968	Fit two quantiles.	Fitted empirically. Median and maximum are proportional to powers of the averaging time.
3	Log-normal.	(see above)	(see above)	(see above)	(see above)	Critiques papers 1,2 re assumptions of independence and the approximation of log expected maximum by expected log maximum.
4	Normal, log-normal, gamma, Weibull, Johnson S_B, beta.	O_3. Hourly.	Wisconsin.	1979	Maximum likelihood.	Computer programs fit statistical distributions and test goodness of fit. Example data best fit log-normal.
5	Log-normal.	Suspended solids; coke oven visible emission times.	--	--	Uses minimum variance unbiased estimate of mean.	Each measurement is replicated so that the multiplicative measurement error can be estimated by analysis of variance.
6	Extremes are Gumbel.	Simulated exponential and normal data.	--	--	--	Reviews the extreme value theory approximation for the distribution of the maximum and other high order statistics.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
7	Extremes are Gumbel.	SO_2, NO_2. Hourly.	South Coast Air Basin.	1956-1974	Least squares fit to extreme value probability plot.	Continuation of paper 6 with applications to real data.
8	Box-Cox transformed normal.	Ground-water chemistry variables.	Michigan.	1986-1987	Maximum likelihood using the EM algorithm to fit non-detected values.	Logarithms or powers of the data are assumed normally distributed. The best (log or power) transformation is selected using the normal probability plot correlations.
9	Log-normal, Weibull. Extremes are approximately Gumbel.	O_x, SO_2. Hourly and daily max hourly.	Pasadena, CA.	1971	Method of moments. Maximum likelihood. Fit two quantiles.	Describes various methods of fitting log-normal and Weibull distributions to concentrations. Includes extreme value approximations to maxima.
10	Log-normal.	Simulated log-normal data.	--	--	Method of moments. Maximum likelihood. Fit two quantiles.	Compares performance of the various fitting methods to estimate the expected annual maximum. Maximum likelihood gave best results.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
11	Daily maxima are Gumbel.	O_3. Daily max hourly.	Stratford and Bridgeport, CT.	1980-1986	Least squares fit to extreme value probability plot.	Gumbel distribution fit well but parameters differed for different groups of years. Also used a bootstrap approach to estimate confidence intervals for the observed percentiles. Used fitted extreme-value distributions to estimate annual exceedance days.
12	Tail exponential.	CO, O_3, SO_2, TSP. Several averaging times.	Los Angeles, and Oakland, CA.	1973-1977	Maximum likelihood.	Only upper tail concentrations and percentiles are used. A weighting scheme adjusts for seasonal effects.
13	Log-normal, Weibull.	NO_2. Hourly.	Essex, MD.	1976	Least squares fit to certain upper percentiles.	The raw data fit the Weibull distribution better than log-normal. Estimated expected annual maxima compared well with asymptotic Gumbel estimates.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
14	Tail exponential.	CO, O_3. Daily max hourly.	EPA National Aerometric Data Bank.	1980-1982	Maximum likelihood.	Observed annual maxima were compared with predictions using the median of the fitted tail exponential distribution. The median error was 0% (1%) for the 5% (10%) tail fit.
15	Gamma, log-normal, t, Weibull, logistic, exponential, beta, normal mixture.	Suspended particulates, O_3, CO, SO_2, NO_2, NO, NO_x. Daily mean.	Melbourne, Australia.	1975-1984	Maximum likelihood.	The best fitting distribution (usually gamma for O_3) was selected according to a Kolmogorov-Smirnov statistic.
16	Gamma, log-normal, Weibull, exponential.	Simulated.	--	--	Maximum likelihood, method of moments, least squares fit to many upper percentiles.	The fitting methods were compared via the simulation estimate of the root mean square error in estimating a given percentile. Maximum likelihood performed best.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
17	Log-normal (2 and 3 parameter), Weibull, gamma.	CO. Hourly.	Chicago, Cincinnati, Denver, Los Angeles, Philadelphia, St. Louis, San Francisco, Washington.	1962-1968	Least squares fit to probability plot.	Best fitting distribution was a 3 parameter log-normal. The average of correlated log-normal distributions is approximately log-normal. Log-normal concentrations are derivable from log-normal wind speeds.
18	Log-normal.	--	--	--	--	Demonstrates that in many cases the average of independent log-normal variables is approximately log-normal rather than normal.
19	Tail exponential.	O_3. Daily max hourly.	California.	1987-1989	Maximum likelihood.	The tail exponential distribution is fitted to the upper k % of the daily maxima and used to estimate the 1 in 7 year return value. The estimates for all possible k from 5 % to 20 % are averaged to give the final return value estimate.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
20	Tail exponential.	O_3. Daily max hourly.	37 California sites, 19 Eastern US sites.	1982-1990	Maximum likelihood.	Similar to paper 19 but modified to use weighted average estimates where the weights are the reciprocals of chi-square goodness-of-fit statistics. A computer program is provided.
21	Tail Generalized Pareto Distribution (GPD).	O_3. Hourly.	Houston, TX.	1973-1986	Maximum likelihood.	The GPD class includes the tail exponential but is more robust. The GPD is fit to the highest hourly values over 72 hour periods that also exceed a given high threshold.
22	Normal, log-normal.	--	--	--	Maximum likelihood.	Demonstrates the bias of the geometric mean from the log-normal distribution when estimating the population mean. Provides formulae for the minimum variance unbiased estimate.

TABLE A-1. Continued.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
23	Maxima of normally distributed data are approximately Gumbel.	--	--	--	--	Proves that the asymptotic Gumbel distribution for maxima applies for autocorrelated stationary normal data provided that the autocorrelations tend to zero sufficiently fast with increasing lags.
24	Log normal, exponential, Weibull.	SO_2, TSP, CO, O_x. Several averaging times.	Philadelphia, Birmingham, Los Angeles, Chicago.	1962-1972.	Plot the logarithm of the tail distribution function against the concentration. Fit two quantiles.	This plot has the advantage of focussing attention on the upper tail. A tail exponential distribution will plot as a straight line. Weibull and log-normal distributions will plot as downward or upward curves.
25	Tail exponential.	Daily maximum hourly ozone.	California.	1982-1990.	Maximum likelihood.	The fitted percentiles were within 2 percent of observed percentiles on average. The theme of the paper is to evaluate the stringency and stability of attainment rules that allow exclusion of very rare (once in seven years) exceedances.

TABLE 1. Concluded.

No.	Distribution Fitted	Species/ Averaging Time	Region	Years	Fitting Method	Comments
26	Linear combinations of exponential distributions (Pseudo-lognormal distributions.)	CO. Hourly.	Washington, DC.	1972.	Method of moments.	The fitted distributions have a similar skewness to the log-normal but gave a better fit to the data according to chi-square and Kolmogorcv-Smirnov tests.

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APPENDIX B

Summary of Articles Discussing Applications of Time Series Models to Ozone Concentrations

TABLE B-1. Summary of articles discussing applications of time series models to ozone concentrations.

No.	Exc./Conc.	Time Series Model	Region	Years	Comments
1	Exc. and conc.	Exceedances follow a first order Markov chain. Concentrations are AR(1).	Los Angeles, San Francisco, Philadelphia, Louisville.	1976-1981	Daily maximum concentrations appear to follow a simple autoregressive order 1 time series. Clustering of exceedance days is significant according to both a runs test and the exceedance autocorrelations.
2	Conc.	Third order autoregressive.	Upland, CA.	1974-1977	Time series forecasts for the daily maximum were worse than predictions assuming persistence of the previous day's maximum. Regression models using meteorological information and numerical modeling gave better forecasts.
3	Conc.	First order autoregressive with additional meteorological and concentration data.	Baton Rouge, LA.	1986-1988	Models with O_3 concentrations only fit poorly. Various models using the previous period concentration, ozone precursor concentrations, and meteorological variables fit well for both the hourly and daily maximum hourly ozone. Monthly effects were significant for the hourly ozone model but not for the daily maxima.
4	Exc. and conc.	--	Azusa, CA.	1969-1978	Runs tests for the exceedance days and autocorrelations for the daily maximum hourly oxidant were statistically significant up to a lag of 2 days.
5	Conc.	First order autoregressive with additional meteorological data.	Los Angeles, CA.	1974-1975	Various models for forecasting the daily maximum hourly oxidant based on the previous day's value and meteorological data were presented. In many cases a term representing the day of the week and/or the month was statistically significant.

TABLE B-1. Continued.

No.	Exc./Conc.	Time Series Model	Region	Years	Comments
6	Exc.	First order Markov chain.	--	--	Letting the exceedance threshold increase with the number of observations gives a limiting Polya-Aeppli distribution for the number of exceedances, a special case of the compound Poisson distribution. This follows because the exceedances occur in clusters with a geometric distribution for the number of exceedances per cluster.
7	Exc.	Exceedances are assumed to follow a first order Markov chain. See paper 8a.	Chicago, IL.	1975-1976	The theoretical results can be applied to all autocorrelated air quality measurements; the example used was for CO. Plots of the reduction in effective sample size for a given autocorrelation are provided.
8	Exc.	Exceedances are assumed to follow a first order Markov chain. See paper 8a.	--	--	Distribution functions for the four highest values are calculated for varying non-negative autocorrelations and sample sizes, including the limiting extreme value distribution for an infinite sample size. The variance increases with autocorrelation and with rank (the maximum has the highest rank). For autocorrelations less than 0.7 the limiting distribution is a good approximation.
8a	--	--	--	--	The assumptions of papers 7 and 8 are discussed. Both these papers calculate probabilities for extremes of an AR(1) normal process by assuming that the exceedances follow a stationary first order Markov chain. Paper 8a comments that the AR(1) dependent model theoretically prohibits the Markov chain assumption for the exceedances. A small simulation study shows that the results of paper 8 are approximately correct for the AR(1) case.

TABLE B-1. Continued.

No.	Exc./Conc.	Time Series Model	Region	Years	Comments
9, 10	Conc.	Daily maximum hourly O_3 is log-normal, autocorrelated, and non-stationary.	St. Louis, MO.	1976	A limiting extreme value approximation for the maximum of n log-normally distributed daily maxima is calculated under fairly general conditions allowing for autocorrelation and non-stationarity. The estimated expected annual maximum is 30 % lower than estimates that assume independent identically distributed daily maxima. The result is incorrect for some trend functions (see Leadbetter et al (1983).)
11	Exc. and conc.	--	Chicago, IL.	1973-1978	Autocorrelations for hourly and daily maximum hourly ozone are calculated. Autocorrelation is high even for lags of 15 days during summer months. Average exceedance durations above 120 ppb varied from 1 to 1.6 days.
12	Conc.	Daily maximum is log-normal, has a cubic time trend, and the errors are autocorrelated.	Azusa, CA.	1969-1978	For each year the cubic trend function was estimated and removed. A Box-Jenkins time series model was fitted to the detrended series. The series were then simulated in order to compute the distributions of the seven highest annual values. The simulation over-estimated these values. An extreme value approximation tended to overestimate even more than the simulation, especially for the higher ranks.
13	Conc.	Stationary normal.	--	--	Proves that the asymptotic Gumbel distribution for maxima applies for autocorrelated stationary normal data provided that the autocorrelations tend to zero sufficiently fast with increasing lags.
14	Exc. and conc.	Stationary with weak long-range dependence.	--	--	Calculates under very general conditions the limiting distributions of the highest values and of the numbers of exceedances over a long sequence. In particular the number of exceedances of a high threshold will have a limiting compound Poisson distribution. (In the independent or near independent case the limit is Poisson).

TABLE 2. Concluded.

No.	Exc./Conc.	Time Series Model	Region	Years	Comments
15	Exc.	Non-homogeneous Poisson process.	S.E. Texas.	1981-1984	The exceedance rate for any day is assumed to have a logarithm that is a linear combination of meteorological variables for that month. The number of exceedances per day has a Poisson distribution. The main purpose of the method is to fill in missing daily exceedances.
16	Conc.	Various autoregressive-type models.	Fraser Valley, BC.	1978-1985	Various forecasting models for daily maximum ozone were fitted. The worst fitting model assumed that the logarithm of the concentration minus a constant had a quadratic time trend plus an autocorrelated error term. Better models were a first order autoregressive model for the day-to-day differences, and persistence. The best model was a regression against the previous day's daily maximum and the forecast daily maximum temperature.
17, 18	Conc.	Integrated auto-regressive moving average process with intervention variables. The general theory is applied to monthly average hourly ozone.	Los Angeles.	1955-1972.	The general method is to add intervention time series to a stationary time series model. For the particular example application, the interventions were a step jump in 1960 due to the opening of the Golden State freeway and changes in VOC limits, and step jumps in 1966 summer/winter for engine design changes. The parameters were estimated by non-linear least squares and the interventions were found to be statistically significant. Seasonality and serial dependence invalidates the usual t-test for the intervention effect.

TABLE 2. Concluded.

No.	Exc./Conc	Time Series Model	Region	Years	Comments
19	Exc. and conc.	Ozone exceedance day counts have Poisson distributions. Daily maximum hourly ozone is first order autoregressive.	Richmond, CA. 274 national sites.	1979-1988	The theme of the paper is a review of the effectiveness of the present standard and a proposal for a new standard that performs better for the criteria evaluated. The criteria used were: the relationship to health, simplicity, sensitivity to air quality changes, stability of attainment status, use of available data, and nominal versus actual stringency. The proposed approach defines violations differently for attainment and non-attainment regions. The approach was tested on real and simulated data.

APPENDIX C

Example Time Series Model Simulation Results

TEST SIMULATION FOR AR(1)/LOWESS FIT WITH LOGNORMAL SHOCK

Simulations: 250

HOUSTON CMSA JAN - DEC Season days: 366

Site: HOU1034 48 201 1034 0 Year: 1988

Yr	AVG	50%	65%	75%	85%	90%	95%	97%	2nd High	1st High	Tail-Expo 5%	Tail-Expo 10%
1	0.052	0.043	0.053	0.067	0.084	0.097	0.124	0.140	0.197	0.207	0.212	0.21
2	0.055	0.045	0.060	0.071	0.085	0.100	0.123	0.151	0.212	0.219	0.230	0.22
3	0.052	0.044	0.057	0.063	0.077	0.091	0.113	0.135	0.219	0.240	0.237	0.22
4	0.054	0.047	0.057	0.068	0.084	0.099	0.119	0.126	0.163	0.209	0.175	0.18
5	0.052	0.047	0.058	0.066	0.079	0.086	0.106	0.121	0.150	0.250	0.180	0.18
6	0.054	0.047	0.056	0.066	0.082	0.097	0.122	0.137	0.201	0.237	0.206	0.20
7	0.049	0.044	0.055	0.062	0.076	0.088	0.112	0.132	0.164	0.180	0.189	0.19
8	0.052	0.044	0.055	0.071	0.085	0.092	0.112	0.114	0.173	0.176	0.163	0.17
9	0.053	0.044	0.056	0.063	0.081	0.097	0.118	0.143	0.189	0.215	0.214	0.20
10	0.051	0.045	0.057	0.067	0.082	0.095	0.108	0.119	0.150	0.152	0.160	0.15
11	0.049	0.042	0.052	0.063	0.082	0.092	0.112	0.135	0.163	0.172	0.191	0.19
12	0.057	0.048	0.062	0.073	0.092	0.108	0.125	0.135	0.204	0.232	0.194	0.19
13	0.052	0.047	0.058	0.066	0.077	0.088	0.110	0.120	0.177	0.205	0.183	0.18
14	0.055	0.047	0.059	0.071	0.085	0.099	0.120	0.140	0.202	0.207	0.219	0.20
15	0.049	0.043	0.055	0.064	0.077	0.086	0.104	0.114	0.148	0.157	0.150	0.16
16	0.050	0.044	0.054	0.063	0.077	0.084	0.094	0.106	0.179	0.209	0.180	0.16
17	0.048	0.042	0.054	0.061	0.075	0.081	0.101	0.112	0.212	0.243	0.194	0.18
18	0.054	0.046	0.055	0.067	0.084	0.104	0.126	0.143	0.230	0.236	0.236	0.22
19	0.053	0.042	0.056	0.068	0.087	0.101	0.128	0.137	0.215	0.242	0.194	0.21
20	0.050	0.046	0.056	0.063	0.077	0.086	0.100	0.113	0.151	0.168	0.172	0.16
21	0.057	0.049	0.059	0.075	0.095	0.108	0.123	0.140	0.223	0.230	0.224	0.20
22	0.054	0.047	0.062	0.070	0.084	0.093	0.115	0.133	0.224	0.252	0.204	0.20
23	0.054	0.046	0.062	0.072	0.085	0.095	0.120	0.128	0.196	0.245	0.182	0.19
24	0.052	0.045	0.056	0.065	0.083	0.097	0.122	0.132	0.162	0.165	0.173	0.19
25	0.051	0.044	0.056	0.066	0.080	0.091	0.111	0.120	0.182	0.262	0.175	0.18
26	0.057	0.050	0.063	0.072	0.089	0.098	0.121	0.129	0.202	0.287	0.221	0.211
27	0.050	0.046	0.055	0.063	0.072	0.090	0.115	0.130	0.168	0.203	0.180	0.192
28	0.050	0.044	0.055	0.062	0.075	0.084	0.105	0.117	0.212	0.234	0.190	0.187
29	0.051	0.045	0.055	0.064	0.078	0.089	0.110	0.124	0.189	0.272	0.195	0.191
30	0.054	0.047	0.058	0.070	0.082	0.091	0.116	0.129	0.185	0.190	0.195	0.203
MU	0.052	0.045	0.057	0.067	0.082	0.093	0.113	0.127	0.183	0.215	0.191	0.190
SD	0.002	0.002	0.003	0.003	0.004	0.005	0.008	0.010	0.025	0.042	0.022	0.019

APPENDIX D

Ozone Design Value Comparisons

TABLE D-1. Ozone design value comparisons for Chicago-Gary-Lake-Wisconsin area.

State	County	Site	Table Look Up (4th)	5% Tail Exp.	10% Tail Exp.	Larsen	3rd Highest	100* 364/365 Percentile	5% Tail Exponential Lower 95% Conf. Bound	5% Tail Exponential Upper 95% Conf. Bound	10% Tail Exponential Lower 95% Conf. Bound	10% Tail Exponential Upper 95% Conf. Bound	Larsen w/o Calibration Factor
IL	031	00011	0.096	0.105	0.104	0.094	0.100	0.096	0.098	0.116	0.098	0.112	0.098
IL	031	00321	0.113	0.117	0.116	0.105	0.116	0.113	0.108	0.130	0.108	0.127	0.109
IL	031	00371	0.087	0.095	0.099	0.089	0.090	0.087	0.089	0.105	0.092	0.108	0.092
IL	031	00501	0.100	0.102	0.108	0.097	0.103	0.100	0.096	0.113	0.100	0.119	0.101
IL	031	10032	0.102	0.109	0.113	0.100	0.103	0.102	0.102	0.120	0.105	0.123	0.104
IL	031	16011	0.104	0.112	0.114	0.104	0.122	0.106	0.104	0.123	0.107	0.124	0.108
IL	031	40021	0.106	0.103	0.106	0.093	0.120	0.107	0.096	0.113	0.098	0.115	0.097
IL	031	40031	0.105	0.107	0.108	0.097	0.108	0.105	0.099	0.118	0.101	0.117	0.101
IL	031	70021	0.109	0.119	0.129	0.116	0.115	0.109	0.111	0.130	0.119	0.142	0.121
IL	043	60011	0.107	0.111	0.110	0.100	0.116	0.107	0.102	0.124	0.102	0.121	0.104
IL	089	00051	0.113	0.112	0.109	0.101	0.115	0.113	0.103	0.125	0.102	0.119	0.105
IL	097	00011	0.112	0.116	0.114	0.104	0.115	0.112	0.107	0.130	0.106	0.124	0.108
IL	097	10021	0.119	0.131	0.131	0.121	0.126	0.119	0.120	0.148	0.121	0.145	0.126
IL	097	30011	0.114	0.111	0.106	0.099	0.115	0.114	0.102	0.131	0.099	0.115	0.103
IL	111	00011	0.106	0.110	0.107	0.099	0.111	0.106	0.102	0.123	0.100	0.116	0.103
IL	197	10081	0.103	0.111	0.111	0.101	0.110	0.104	0.103	0.123	0.104	0.121	0.105
IN	089	20081	0.112	0.113	0.120	0.109	0.113	0.112	0.107	0.122	0.113	0.130	0.114

Continued

TABLE D-1. Concluded.

State	County	Site	Table Look Up (4th)	5% Tail Exp.	10% Tail Exp.	Larsen	3rd Highest	100* 364/365 Percentile	5% Tail Exponential Lower 95% Conf. Bound	5% Tail Exponential Upper 95% Conf. Bound	10% Tail Exponential Lower 95% Conf. Bound	10% Tail Exponential Upper 95% Conf. Bound	Larsen w/o Calibration Factor
IN	127	00201	0.122	0.127	0.129	0.120	0.123	0.122	0.118	0.142	0.120	0.141	0.125
IN	127	00241	0.112	0.117	0.122	0.101	0.113	0.112	0.109	0.128	0.113	0.133	0.105
WI	029	00041	0.132	0.137	0.145	0.129	0.134	0.132	0.126	0.154	0.132	0.161	0.135
WI	059	00021	0.128	0.138	0.144	0.131	0.129	0.128	0.127	0.156	0.132	0.160	0.137
WI	059	00191	0.143	0.159	0.168	0.150	0.146	0.143	0.146	0.179	0.153	0.187	0.157
WI	061	00011	0.120	0.121	0.130	0.115	0.123	0.121	0.112	0.136	0.119	0.144	0.120
WI	071	00021	0.136	0.146	0.152	0.138	0.139	0.136	0.133	0.165	0.139	0.170	0.144
WI	079	00411	0.150	0.151	0.153	0.140	0.151	0.150	0.138	0.164	0.140	0.171	0.147
WI	079	00481	0.125	0.127	0.133	0.118	0.133	0.127	0.117	0.143	0.122	0.147	0.123
WI	079	00851	0.151	0.161	0.165	0.151	0.155	0.152	0.146	0.183	0.151	0.185	0.158
WI	079	10251	0.140	0.148	0.144	0.131	0.141	0.140	0.134	0.171	0.132	0.159	0.137
WI	101	00171	0.136	0.146	0.154	0.139	0.164	0.136	0.134	0.164	0.140	0.172	0.145
WI	127	00051	0.121	0.123	0.124	0.113	0.123	0.121	0.114	0.137	0.116	0.136	0.118
WI	133	00171	0.119	0.121	0.125	0.113	0.125	0.121	0.112	0.136	0.115	0.137	0.118

TABLE D-2. Ozone design value comparisons for New York–New Jersey–Connecticut area.

									5% Tail Exponential		10% Tail Exponential		
State	County	Site	Table Look Up (4th)	5% Tail Exp.	10% Tail Exp.	Larsen	3rd Highest	100* 364/365 Percentile	Lower 95% Conf. Bound	Upper 95% Conf. Bound	Lower 95% Conf. Bound	Upper 95% Conf. Bound	Larsen w/o Calibration Factor
CT	001	00171	0.150	0.167	0.177	0.163	0.161	0.150	0.153	0.188	0.162	0.198	0.171
CT	001	01131	0.149	0.159	0.164	0.148	0.156	0.149	0.143	0.183	0.148	0.185	0.155
CT	001	11231	0.136	0.158	0.159	0.147	0.149	0.136	0.143	0.180	0.146	0.178	0.153
CT	001	30071	0.165	0.175	0.185	0.166	0.175	0.166	0.159	0.199	0.167	0.209	0.175
NJ	003	00011	0.129	0.137	0.153	0.136	0.132	0.129	0.127	0.152	0.139	0.171	0.142
NJ	013	00111	0.122	0.127	0.137	0.123	0.125	0.122	0.117	0.141	0.125	0.152	0.128
NJ	017	00061	0.160	0.152	0.167	0.149	0.167	0.161	0.141	0.168	0.153	0.186	0.156
NJ	019	00011	0.131	0.143	0.152	0.142	0.132	0.131	0.134	0.157	0.141	0.167	0.149
NJ	023	00061	0.142	0.148	0.161	0.145	0.149	0.143	0.137	0.165	0.147	0.179	0.152
NJ	025	00051	0.139	0.165	0.170	0.154	0.151	0.141	0.151	0.187	0.156	0.189	0.161
NJ	027	30011	0.137	0.142	0.154	0.141	0.139	0.137	0.133	0.156	0.143	0.169	0.147
NJ	039	50011	0.120	0.126	0.132	0.119	0.124	0.120	0.117	0.140	0.122	0.145	0.124
NY	061	00101	0.106	0.120	0.132	0.111	0.106	0.106	0.109	0.137	0.119	0.150	0.115
NY	061	00632	0.155	0.165	0.170	0.156	0.175	0.156	0.153	0.182	0.158	0.187	0.164
NY	103	00021	0.152	0.162	0.175	0.158	0.156	0.153	0.149	0.181	0.159	0.195	0.166

TABLE D-3. Ozone design value comparisons for South Coast (Los Angeles) Air Basin.

								5% Tail Exponential		10% Tail Exponential		
State	Site	Table Look Up (4th)	5% Tail Exp.	10% Tail Exp.	Larson	3rd Highest	100* 364/365 Percentile	Lower 95% Conf. Bound	Upper 95% Conf. Bound	Lower 95% Conf. Bound	Upper 95% Conf. Bound	Larson w/o Calibration Factor
CA	0060	0.28	0.32	0.34	0.28	0.30	0.30	0.29	0.37	0.31	0.39	0.30
CA	0069	0.20	0.24	0.25	0.21	0.20	0.21	0.21	0.28	0.22	0.28	0.22
CA	0072	0.12	0.16	0.15	0.12	0.12	0.14	0.14	0.23	0.13	0.18	0.12
CA	0074	0.21	0.24	0.24	0.20	0.22	0.22	0.22	0.28	0.22	0.28	0.21
CA	0075	0.24	0.27	0.28	0.24	0.24	0.24	0.24	0.31	0.25	0.32	0.25
CA	0080	0.20	0.24	0.26	0.21	0.21	0.21	0.21	0.28	0.23	0.31	0.22
CA	0084	0.14	0.17	0.17	0.14	0.14	0.15	0.15	0.22	0.16	0.20	0.15
CA	0085	0.24	0.29	0.30	0.25	0.25	0.25	0.26	0.35	0.27	0.34	0.26
CA	0089	0.24	0.28	0.28	0.24	0.25	0.25	0.25	0.33	0.26	0.32	0.25
CA	3177	0.22	0.25	0.27	0.21	0.22	0.23	0.23	0.30	0.24	0.31	0.22
CA	3186	0.19	0.24	0.25	0.20	0.21	0.22	0.20	0.30	0.21	0.30	0.21
CA	3190	0.16	0.20	0.20	0.16	0.17	0.17	0.17	0.24	0.18	0.23	0.17
CA	4155	0.22	0.25	0.25	0.21	0.22	0.22	0.22	0.30	0.23	0.28	0.22
CA	5181	0.27	0.32	0.32	0.26	0.27	0.28	0.28	0.38	0.29	0.37	0.27
CA	5197	0.27	0.32	0.32	0.26	0.28	0.28	0.29	0.37	0.29	0.36	0.28

APPENDIX E

Ozone Air Quality Update, 1990-92

Tabl . 1. Ozone Nonattainment Areas - Air Quality Update, 1991-93

State	Nonattainment Area Name	Clean Air Act Classification	1991-93 Update A.Q. Value	1991-93 Update Average Est. Exc.	1993 2nd Daily Max 1-hr	1993 Estimated Exceedances
AL	Birmingham NA Area	Marginal	0.124	0.7	0.125	2.0
AZ	Phoenix	Moderate	0.147	4.0 (#4)	0.126	2.0
CA	Los Angeles South Coast Air Basin	Extreme	0.300	104.3	0.250	97.6
CA	Monterey Bay Unified NA Area	Moderate	0.108	0.4	0.104	0.0
CA	Sacramento Metro NA Area	Serious	0.150	9.7	0.150	3.6
CA	San Diego NA Area	Severe 15	0.150	11.8	0.159	4.0
CA	San Francisco-Bay NA Area	Moderate	0.120	0.7	0.130	2.0
CA	San Joaquin Valley NA Area	Serious	0.159	18.9	0.159	27.5
CA	Santa Barbara-Santa Maria-Lompoc	Moderate	0.123	1.0	0.114	0.0
CA	Southeast Desert Modified AQMD	Severe 17	0.200	59.3	0.180	72.6
CA	Ventura Co NA Area	Severe 15	0.150	15.9	0.144	9.0
CT	Greater Connecticut NA Area	Serious	0.158	7.5	0.153	6.0
DC-MD-VA	Washington NA Area	Serious	0.137	1.4	0.132	3.1
DE	Sussex Co NA Area	Marginal	0.118	1.0	0.115	0.0
FL	Miami-Fort Lauderdale-W. Palm Beach	Moderate	0.106	0.0	0.122	1.0
FL	Tampa-St. Petersburg-Clearwater	Marginal	0.110	0.0	0.100	0.0
GA	Atlanta NA Area	Serious	0.149	4.2	0.162	4.3
IL-IN	Chicago-Gary-Lake County NA Area	Severe 17	0.145	4.7 (#5)	0.125	2.4
IL	Jersey Co NA Area	Marginal	0.112	0.7	0.127	2.0
IN	Evansville NA Area	Marginal	0.110	0.0	0.110	0.0
IN	Indianapolis NA Area	Marginal	0.104	0.0	0.104	0.0
IN	South Bend-Elkhart NA Area	Marginal	0.103	0.0	0.096	0.0
KY	Edmonson Co NA Area	Marginal	0.091	0.0	0.092	0.0
KY-WV	Huntington-Ashland NA Area	Moderate	0.122	1.0	0.122	1.0
KY	Lexington-Fayette NA Area	Marginal	0.100	0.0	0.103	0.0
KY-IN	Louisville NA Area	Moderate	0.130	2.2	0.140	2.0
KY	Owensboro NA Area	Marginal	0.104	0.0	0.106	0.0
KY	Paducah NA Area	Marginal	0.106	0.0	0.112	0.0
LA	Baton Rouge NA Area	Serious	0.135	1.8	0.127	3.0
LA	Lake Charles NA Area	Marginal	0.132	1.3 (#6)	0.108	0.0
MA-NH	Boston-Lawrence-Worcester NA Area	Serious	0.137	3.1	0.155	4.0
MA	Springfield (W. Mass) NA Area	Serious	0.141	4.6	0.133	6.2
MD	Baltimore NA Area	Severe 15	0.150	4.8	0.146	6.2
MD	Kent County and Queen Anne's County	Marginal	0.133	2.8	0.128	2.0
ME	Hancock Co and Waldo Co NA Area	Marginal	0.112	1.3 (#7)	0.094	0.0
ME	Knox Co and Lincoln Co NA Area	Moderate	0.134	2.3	0.122	1.2
ME	Lewiston - Auburn NA Area	Moderate	0.106	0.3	0.096	0.0
ME	Portland NA Area	Moderate	0.147	11.8	0.125	3.8
MI	Detroit-Ann Arbor NA Area	Moderate	0.122	1.0	0.122	1.0
MI	Grands Rapids NA Area	Moderate	0.146	3.4 (#8)	0.094	1.0
MI	Muskegon NA Area	Moderate	0.141	2.3	0.104	1.0
MO-KS	Kansas City NA Area	Attainment	0.114	0.3	0.114	1.0
MO-IL	St. Louis NA Area	Moderate	0.132	1.7	0.126	2.1
NC	Charlotte-Gastonia NA Area	Moderate	0.119	0.7	0.137	2.1

Table 1. Ozone Nonattainment Areas - Air Quality Update, 1991-93

State	Nonattainment Area Name	Clean Air Act Classification	1991-93 Update A.Q. Value	1991-93 Update Average Est. Exc.	1993 2nd Daily Max 1-hr	1993 Estimated Exceedances
NC	Greensboro-Winston-Salem-High Point	Attainment	0.113	0.3	0.121	1.0
NC	Raleigh-Durham NA Area	Attainment	0.118	0.7	0.128	2.1
NH	Manchester NA Area	Marginal	0.087	0.0	0.086	0.0
NH	Portsmouth-Dover-Rochester, NH	Serious	0.143	2.2	0.107	1.1
NJ	Atlantic City NA Area	Moderate	0.122	1.0	0.115	0.0
NV	Reno	Marginal	0.089	0.0	0.089	0.0
NY	Albany-Schenectady-Troy NA Area	Marginal	0.104	0.0	0.106	0.0
NY	Buffalo-Niagara Falls NA Area	Marginal	0.106	0.0	0.090	0.0
NY	Essex Co NA Area	Marginal	0.116	0.0	0.100	0.0
NY	Jefferson Co NA Area	Marginal	0.110	0.0	0.092	0.0
NY-NJ-CT	New York-N. New Jersey-Long Island	Severe 17	0.158	6.1	0.165	6.0
NY	Poughkeepsie NA Area	Marginal	0.126	1.4	0.139	2.0
OH	Canton NA Area	Marginal	0.109	0.3	0.109	0.0
OH-KY	Cincinnati-Hamilton NA Area	Moderate	0.125	1.3	0.121	1.0
OH	Cleveland-Akron-Lorain NA Area	Moderate	0.125	1.7 (#9)	0.117	0.0
OH	Columbus NA Area	Marginal	0.118	0.3	0.105	0.0
OH	Dayton-Springfield NA Area	Moderate	0.112	0.0	0.120	1.0
OH	Toledo NA Area	Moderate	0.120	0.3	0.121	1.0
OH-PA	Youngstown-Warren-Sharon NA Area	Marginal	0.113	0.3	0.120	1.0
OR	Portland-Vancouver AQMA NA Area	Marginal	0.108	0.7	0.103	0.0
PA-NJ	Allentown-Bethlehem-Easton NA Area	Marginal	0.115	0.0	0.110	0.0
PA	Altoona NA Area	Marginal	0.105	0.0	0.100	0.0
PA	Erie NA Area	Marginal	0.110	0.0	0.107	0.0
PA	Harrisburg-Lebanon-Carlisle NA	Marginal	0.111	0.0	0.118	0.0
PA	Johnstown NA Area	Marginal	0.107	0.0	0.099	0.0
PA	Lancaster NA Area	Marginal	0.118	0.3	0.118	1.0
PA-NJ-DE-MD	Philadelphia-Wilmington-Trenton	Severe 15	0.156	10.3	0.147	5.2
PA	Pittsburgh-Beaver Valley NA Area	Moderate	0.119	0.7	0.124	0.0
PA	Reading NA Area	Moderate	0.118	0.3	0.110	0.0
PA	Scranton-Wilkes-Barre NA Area	Marginal	0.117	0.4	0.112	0.0
PA	York NA Area	Marginal	0.113	0.0	0.112	0.0
RI	Providence (all of RI) NA Area	Serious	0.152	4.0	0.117	1.4
SC	Cherokee Co NA Area	Attainment	0.105	0.3	0.108	0.0
TN	Knoxville NA Area	Attainment	0.118	0.0	0.120	0.0
TN	Memphis NA Area	Marginal	0.115	0.3	0.119	1.0
TN	Nashville NA Area	Moderate	0.124	1.1	0.126	2.1
TX	Beaumont-Port Arthur NA Area	Serious	0.130	2.7	0.122	0.0
TX	Dallas-Fort Worth NA Area	Moderate	0.141	2.0	0.140	2.3
TX	El Paso NA Area	Serious	0.136	3.7	0.135	4.1
TX	Houston-Galveston-Brazoria NA	Severe 17	0.200	6.3	0.197	10.4
UT	Salt Lake City-Ogden NA Area	Moderate	0.106	0.0	0.104	0.0
VA	Norfolk-Virginia Beach-Newport News	Marginal	0.131	1.7	0.131	3.0
VA	Richmond-Petersburg NA Area	Moderate	0.128	1.4	0.132	3.1

Table 1. Ozone Nonattainment Areas - Air Quality Update, 1991-93

State	Nonattainment Area Name	Clean Air Act Classification	1991-93 Update A.Q. Value	1991-93 Update Average Est. Exc.	1993 2nd Daily Max 1-hr	1993 Estimated Exceedances
VA	Smyth County NA Area	Marginal	ND	ND (#10)	ND	ND
WA	Seattle - Tacoma NA Area	Marginal	0.105	0.0	0.100	0.0
WI	Door Co NA Area	Marginal	0.125	1.6	0.098	0.0
WI	Kewaunee Co NA Area	Moderate	0.107	0.8	0.095	0.0
WI	Manitowoc Co NA Area	Moderate	0.132	2.0	0.095	0.0
WI	Milwaukee-Racine NA Area	Severe 17	0.148	3.9	0.125	2.4
WI	Sheboygan NA Area	Moderate	0.139	2.6 (#11)	0.095	0.0
WI	Walworth Co NA Area	Marginal	0.120	0.3	0.093	0.0
WV	Charleston NA Area	Attainment	0.106	0.3	0.075	0.0
WV	Greenbrier NA Area	Marginal	0.101	0.4	0.090	0.0
WV	Parkersburg NA Area	Attainment	0.118	0.0	0.104	0.0

91 Nonattainment Areas

SOURCE: EPA's air quality data system, the Aerometric Information Retrieval System (AIRS), with supplemental data from EPA Regional Offices.

NOTES:

1. Designations and classifications for ozone nonattainment areas as published in the Federal Register, 40 CFR Part 81. *Unclassified and transitional nonattainment areas are not included in this listing.*

2. The updated air quality value is estimated for the 1991-93 period using EPA guidance for calculating design values (Laxton Memorandum, June 18, 1990). Generally, the fourth highest monitored value with 3 complete years of data is selected as the updated air quality value because the standard allows one exceedance for each year. It is important to note that the 1990 Clean Air Act Amendments required that O_3 nonattainment areas be classified on the basis of the design value at the time the Amendments were passed, generally the 1987-89 period was used.

3. The National Ambient Air Quality standard for ozone is 0.12 parts per million (ppm) daily maximum 1-hour average not to be exceeded more than once per year on average. The average estimated number of exceedances column shows the number of days the 0.12 ppm standard was exceeded on average at the site recording the highest updated air quality value. This is done after adjustment for incomplete, or missing days, during the 3-year period, 1991-93. The last two columns contain data from the site recording the highest second daily maximum 1-hour concentration in 1993. The last column shows the estimated exceedances for 1993 at the site recording the highest second maximum 1-hour concentration listed in the previous column.

4. Special purpose monitoring (SPM) operating during the ozone monitoring season.

5. The nonattainment/updated air quality value site for the Chicago NA Area is in Kenosha County, WI.

6. The Regional Office is reviewing the status of the area based on data through 1994.

7. Incomplete data reported in 1991.

8. Calculation of the updated air quality value and estimated exceedances adjusted to account for start-up of a LMOS Study site with data only in 1991.

9. Data from a monitoring site located at the water treatment plant not used due to localized interference.

10. The site was located atop Whitetop Mountain, VA as part of the Mountain Cloud Study. Site elevation is 5520 feet. No data reported after 1988. This is a rural transport area. The nonattainment area is that portion of Whitetop Mountain above 4500 feet elevation.

11. Calculation of estimated exceedances adjusted for Wisconsin ozone season not yet reflected in AIRS.

APPENDIX F

Ozone Design Values From Time Series Simulations

Time Series Simulation of Chicago Site #17 097 1002 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.137	.121	.128	.128	.089	.077	.128	.128
2	.135	.126	.130	.130	.089	.077	.131	.132
3	.134	.128	.131	.131	.089	.077	.132	.133
4	.134	.130	.131	.131	.089	.077	.133	.133
5	.133	.130	.132	.132	.090	.077	.134	.134
6	.133	.130	.132	.132	.089	.077	.134	.134
10	.132	.130	.131	.131	.089	.077	.133	.133
250	.132	.132	.132	.132	.089	.077	.134	.134

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.029	.020	.021	.020	.010	.008	.021	.020
2	.020	.016	.016	.015	.007	.006	.016	.015
3	.016	.014	.013	.013	.006	.005	.014	.013
4	.015	.013	.012	.011	.005	.004	.013	.012
5	.012	.012	.010	.010	.005	.004	.011	.010
6	.012	.011	.010	.009	.004	.003	.011	.010
10	.009	.009	.008	.008	.004	.003	.008	.008
250	.002	.002	.002	.002	.001	.001	.001	.002

Time Series: Log/LOWESS/AR(1); Shock: Lognormal distribution

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Sites Studied in Time Series Comparisons of Design Values

CMSA	Site Code	Abrev.	Shock	Site-years
Atlanta	13 089 0002	ATL0002	Extreme	11
Charlotte	37 119 0034	CHR0034	Extreme	10
Chicago	55 059 0002	CHI0002	Lognorm	11
Chicago	17 097 1002	CHI1002	Lognorm	11
Chicago	17 031 7002	CHI7002	Lognorm	11
Houston	48 201 1034	HOU1034	Lognorm	10
New York	34 023 0006	NYC0006	Extreme	10
New York	36 085 0067	NYC0067	Extreme	11
New York	09 001 3007	NYC3007	Lognorm	11

Time Series Simulation of Atlanta Site #13 089 0002 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.155	.144	.152	.155	.111	.097	.152	.155
2	.155	.148	.153	.156	.110	.096	.154	.157
3	.157	.152	.155	.158	.110	.097	.157	.159
4	.157	.153	.156	.159	.111	.097	.158	.161
5	.156	.153	.156	.158	.111	.097	.157	.160
6	.156	.153	.156	.158	.111	.097	.157	.160
10	.156	.155	.157	.159	.111	.097	.159	.161
250	.156	.156	.157	.159	.111	.097	.159	.162

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.026	.022	.023	.023	.012	.009	.023	.023
2	.020	.017	.017	.016	.008	.007	.018	.017
3	.017	.015	.014	.014	.007	.005	.015	.015
4	.015	.014	.013	.012	.005	.004	.014	.014
5	.014	.012	.011	.010	.005	.004	.012	.012
6	.013	.012	.011	.010	.005	.004	.012	.012
10	.009	.009	.008	.007	.003	.003	.009	.009
250	.001	.001	.001	.001	.001	.001	.001	.001

Time Series: Log/LOWESS/AR(1); Shock: extreme value distribution

Time Series Simulation of Chicago Site #55 059 0002 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.159	.139	.148	.148	.099	.084	.148	.148
2	.159	.147	.152	.151	.099	.084	.154	.153
3	.157	.149	.152	.151	.098	.084	.155	.154
4	.158	.151	.154	.152	.099	.084	.156	.156
5	.157	.152	.153	.152	.099	.084	.156	.156
6	.157	.153	.155	.153	.099	.084	.158	.157
10	.158	.155	.155	.154	.099	.084	.159	.158
250	.157	.157	.156	.155	.099	.084	.160	.159

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.047	.033	.035	.033	.016	.011	.035	.033
2	.033	.028	.027	.026	.011	.008	.028	.027
3	.028	.025	.023	.022	.009	.006	.025	.024
4	.024	.021	.020	.018	.008	.005	.022	.020
5	.021	.019	.018	.016	.007	.005	.019	.018
6	.020	.019	.017	.016	.007	.005	.018	.018
10	.015	.014	.014	.012	.005	.004	.014	.014
250	.003	.003	.003	.003	.001	.001	.003	.003

Time Series: Log/LOWESS/AR(1); Shock: Lognormal distribution

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Time Series Simulation of Chicago Site #17 031 7002 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.138	.123	.130	.131	.094	.082	.130	.131
2	.137	.129	.133	.134	.094	.082	.134	.134
3	.138	.132	.134	.135	.094	.082	.136	.136
4	.137	.133	.135	.135	.094	.082	.136	.136
5	.137	.134	.135	.135	.094	.082	.137	.137
6	.138	.135	.136	.136	.095	.082	.138	.138
10	.137	.135	.136	.136	.094	.082	.138	.138
250	.137	.137	.137	.137	.095	.082	.139	.139

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.028	.021	.022	.021	.012	.009	.022	.021
2	.021	.018	.018	.017	.009	.007	.018	.017
3	.018	.015	.015	.015	.007	.005	.016	.015
4	.015	.014	.013	.012	.006	.005	.014	.013
5	.013	.012	.011	.010	.005	.004	.012	.011
6	.012	.012	.011	.010	.005	.004	.011	.011
10	.010	.009	.009	.009	.004	.003	.009	.009
250	.002	.002	.002	.002	.001	.001	.002	.002

Time Series: Log/LOWESS/AR(1); Shock: Lognormal distribution

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Time Series Simulation of Charlotte Site #37 119 0034 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.129	.122	.127	.129	.103	.094	.127	.129
2	.130	.126	.129	.131	.103	.094	.129	.131
3	.132	.128	.131	.133	.104	.094	.131	.133
4	.131	.129	.131	.133	.104	.094	.131	.133
5	.131	.129	.131	.133	.104	.094	.132	.134
6	.132	.130	.131	.133	.104	.094	.132	.134
10	.132	.131	.132	.134	.104	.094	.133	.135
250	.133	.133	.133	.135	.104	.095	.134	.136

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.016	.014	.015	.015	.010	.008	.015	.015
2	.013	.012	.012	.012	.007	.005	.012	.012
3	.011	.011	.010	.010	.006	.004	.010	.010
4	.010	.009	.009	.009	.005	.004	.009	.009
5	.009	.008	.008	.008	.004	.004	.008	.008
6	.008	.008	.008	.008	.004	.003	.008	.008
10	.006	.006	.006	.005	.003	.002	.006	.006
250	.001	.001	.001	.001	.000	.000	.001	.001

Time Series: Log/LOWESS/AR(1); Shock: extreme value distribution

Time Series Simulation of New York Site #09 001 3007 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.213	.186	.198	.198	.133	.113	.198	.198
2	.215	.200	.206	.206	.134	.114	.208	.208
3	.217	.206	.210	.210	.136	.114	.213	.213
4	.215	.207	.212	.211	.137	.115	.214	.214
5	.217	.210	.213	.212	.136	.114	.216	.216
6	.217	.211	.213	.212	.136	.114	.216	.216
10	.217	.213	.214	.213	.136	.114	.217	.217
250	.218	.218	.217	.216	.137	.115	.220	.220

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.065	.049	.053	.051	.028	.022	.053	.051
2	.064	.040	.040	.038	.020	.016	.041	.039
3	.035	.032	.032	.031	.017	.013	.033	.032
4	.031	.029	.028	.027	.015	.012	.029	.028
5	.029	.027	.026	.025	.013	.010	.027	.026
6	.023	.022	.021	.020	.011	.009	.022	.021
10	.018	.018	.017	.016	.009	.007	.017	.017
250	.003	.003	.002	.002	.001	.001	.002	.002

Time Series: Log/LOWESS/AR(1); Shock: Lognormal distribution

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Time Series Simulation of Houston Site #48 201 1034 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.239	.200	.212	.210	.115	.093	.212	.210
2	.228	.208	.213	.209	.115	.093	.215	.212
3	.225	.212	.214	.211	.115	.093	.217	.215
4	.223	.213	.214	.211	.115	.093	.217	.215
5	.221	.214	.214	.211	.115	.093	.218	.216
6	.220	.214	.214	.210	.115	.094	.217	.215
10	.220	.216	.215	.211	.115	.093	.219	.217
250	.218	.218	.214	.211	.115	.093	.219	.217

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.066	.040	.039	.034	.013	.010	.039	.034
2	.039	.031	.026	.023	.008	.006	.028	.025
3	.035	.030	.025	.031	.007	.005	.028	.025
4	.027	.023	.019	.017	.006	.004	.021	.019
5	.024	.022	.018	.015	.005	.004	.020	.018
6	.022	.020	.016	.014	.005	.004	.018	.016
10	.018	.016	.013	.011	.004	.003	.015	.013
250	.003	.003	.002	.002	.001	.000	.002	.002

Time Series: Log/LOWESS/AR(1); Shock: Lognormal distribution

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Time Series Simulation of New York Site #34 023 0006 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.172	.157	.166	.169	.121	.105	.166	.169
2	.173	.164	.169	.172	.121	.105	.170	.173
3	.172	.166	.170	.172	.120	.105	.171	.174
4	.173	.169	.172	.174	.122	.105	.173	.176
5	.172	.168	.171	.173	.121	.104	.172	.175
6	.173	.170	.172	.174	.121	.105	.173	.176
10	.173	.171	.172	.174	.121	.105	.174	.177
250	.172	.171	.172	.174	.121	.105	.174	.176

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.033	.027	.029	.029	.016	.012	.029	.029
2	.024	.021	.021	.020	.011	.008	.021	.021
3	.020	.018	.018	.017	.009	.007	.018	.018
4	.017	.016	.016	.015	.008	.006	.016	.016
5	.016	.015	.014	.013	.007	.005	.014	.014
6	.014	.013	.013	.012	.006	.005	.013	.013
10	.011	.011	.010	.009	.005	.004	.010	.010
250	.002	.002	.001	.002	.001	.001	.002	.002

Time Series: Log/LOWESS/AR(1); Shock: Extreme value distribution

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Time Series Simulation of New York Site #36 085 0067 1

Design Values (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.158	.146	.154	.157	.116	.102	.154	.157
2	.160	.153	.157	.160	.117	.103	.158	.161
3	.159	.154	.158	.161	.116	.102	.159	.162
4	.160	.156	.159	.162	.117	.103	.160	.163
5	.160	.157	.160	.162	.117	.103	.161	.163
6	.160	.158	.160	.162	.117	.103	.161	.163
10	.159	.158	.160	.162	.117	.103	.161	.163
250	.160	.160	.161	.163	.118	.103	.163	.165

Standard Deviations (ppm)

	********* N-Year Distribution ********						* Cond. Prob.*	
		Table	Tail-Expo		Percentile		Tail-Ex	
	CLV	Lookup	5%	10%	95%	90%	5%	10%
1	.025	.021	.022	.023	.014	.011	.022	.023
2	.019	.017	.017	.017	.010	.008	.017	.017
3	.015	.014	.014	.014	.008	.007	.014	.014
4	.013	.013	.012	.012	.007	.006	.012	.012
5	.011	.011	.010	.010	.006	.005	.010	.011
6	.011	.011	.010	.010	.006	.005	.010	.010
10	.008	.008	.007	.007	.004	.003	.008	.007
250	.001	.001	.001	.001	.000	.000	.001	.001

Time Series: Log/LOWESS/AR(1); Shock: Extreme value distribution

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APPENDIX G

Summary of Studies on Meteorological Adjustment of Ozone Trends

TABLE G-1. Summary of studies on the meteorological adjustment of ozone trends.

No.	Reference	Location Studied	Annual Ozone Summary Statistic	Variables Used for Adjustment	Adjustment Method
1	Zeldin and Thomas (1975)	Los Angeles Basin	number of hours exceeding 0.20 ppm	inversion strength, 950 mb temperature, inversion height, horizontal pressure gradient	Classification: generated ozone potential score based on tabulated meteorological conditions and regressed cumulative score against number of exceedances - applied regression to climatological mean meteorological conditions
2	Zeldin and Breiman (1979)	Los Angeles Basin	mean daily maximum	850 mb temperature, surface temperature, horizontal pressure gradients, wind speed and direction, inversion base and top heights, inversion strength	(1) Classification: meteorological categories defined from ranges of daily maximum ozone concentration predicted via least squares regression; categories reweighted according to climatological frequency of occurrence; (2) Regression: linear regression of seasonal mean daily maximum ozone vs. meteorological parameter applied to climatology with errors substituted back in
3	Zimmermann et al. (1987)	Houston, TX	number of days with daily maximum 0 - 0.06, 0.06 - 0.12, 0.12 - 0.20, and >0.20 ppm	synoptic typing scheme based on regional surface pressure patterns and local weather	Classification: number of days in each meteorological category re-weighted based on ratio of long-term average category frequency to observed frequency
4	Sweitzer and Kolaz (1984)	Chicago, IL	number of days exceeding 0.12 ppm	daily maximum temperature, dew point, precipitation, wind speed, percent sunshine	Classification: "ozone conducive" days defined on basis of joint meteorological criteria determined by inspection; ratio of number of exceedance days to number of conducive days in each year provides adjusted trend

TABLE G-1. continued

No.	Reference	Location Studied	Annual Ozone Summary Statistic	Variables Used for Adjustment	Adjustment Method
5	Kolaz and Swinford (1990)	Chicago, IL	number of days exceeding 0.12 ppm	daily maximum temperature, average wind speed, insolation, precipitation	Classification: defined daily meteorological index of ozone formation potential; normalized exceedance rate as function of index for each year to 24-year average index values
6	Zeldin et al. (1990)	Los Angeles Basin	mean daily maximum; number of days exceeding 0.20 ppm	24 variables including surface and aloft data and 24-hour trends	Regression: step-wise multivariate linear regression of daily maximum ozone; regression parameters estimated from 3-year base period and applied to all subsequent years; adjustment factor is difference between observed and predicted concentrations in subsequent years
7	Burkhart et al. (1990); Burkhart and Beloin (1991); Burkhart (1992)	New England	second highest daily maximum, fourth highest daily maximum in three years, second highest non-overlapping 8-hour average, number of days exceeding 0.12 ppm	daily maximum temperature	Classification: summary statistics compared for all years with similar numbers of days above 30 and 32 deg. C
8	Savukas (1990)	Allegheny Co., PA	number of days exceeding 0.12 ppm	daily maximum temperature	Deterministic Model: examined variations in annual ratio of exceedance days to days above 85 deg. F

TABLE G-1. continued

No.	Reference	Location Studied	Annual Ozone Summary Statistic	Variables Used for Adjustment	Adjustment Method
9	Sandberg et al. (1978, 1991)	San Francisco Bay Area	number of days exceeding 0.08, 0.09, 0.12 ppm	total precipitation for previous two winters	Regression: simple linear regression for San Francisco Bay Area; correlations with ambient HC, CO, and daily maximum temperature suggest winter rain to summer HC to summer ozone link; no adjusted trend calculated
10	Chock et al. (1982), Kumar and Chock (1984)	Los Angeles Basin	mean daily maximum for selected days; estimated daily maximum under fixed meteorological conditions	temperature, relative humidity, mixing height, wind speed	(1) Classification: examine year-to-year changes on days with similar meteorological conditions (2) Regression: linear multivariate regression equations for each year applied to fixed values of meteorological variables
11	Duckworth et al. (1980)	Los Angeles Basin	mean daily maximum	850 mb temperature, vertical and horizontal temperature gradients	Regression: annual step-wise multiple linear regression applied to climatological mean meteorological conditions
12	Davidson et al. (1985)	Los Angeles Basin	6-station average of annual mean daily maximums; number of days exceeding 0.12 and 0.20 ppm	850 mb temperature	Regression: annual linear regression applied to climatological mean temperature
13	Kuntasal and Chang (1987)	Los Angeles Basin	3-month average of multi-station mean daily maximum	850 mb temperature	Regression: simple linear regression for daily maximum ozone applied with climatological mean temperature with error term added in

TABLE G-1. continued

No.	Reference	Location Studied	Annual Ozone Summary Statistic	Variables Used for Adjustment	Adjustment Method
14	Wackter and Bayly (1988)	Connecticut	number of days exceeding 0.12 ppm; mean daily maximum	daily maximum and minimum temperatures, wind speed and direction	Classification: days conducive to high ozone determined from joint distribution of meteorological variables; annual ozone statistics regressed against number of conducive days and year; year term assumed to represent adjusted trend
15	Pollack and Moezzi (1985)	10 U.S. cities	number of days exceeding 0.10 and 0.12 ppm	daily maximum temperature, wind speed, cloud cover	Classification: ozone conducive and non-conducive days identified on basis of meteorological data; adjusted trend based on frequency of exceedances on ozone conducive days
16	Pollack et al. (1988)	Northeastern U.S.	number of days exceeding 0.12 ppm	daily maximum temperature, wind speed and direction, relative humidity, NO_2 photolysis rate based on time of year and cloud cover, 850 mb height	Regression: elimination of days not conducive to high ozone based on joint distribution of meteorological parameters; multiple log-linear regressions of daily maximum ozone for each year; reference year of meteorological data substituted into each regression model and adjusted expected exceedance rate calculated from regression prediction allowing for random error terms
17	Stoeckenius and Hudischewskyj (1990)	Philadelphia, PA; Bridgeport, CT	number of days exceeding 0.10 ppm; mean daily maximum	daily maximum temperature, relative humidity, cloud cover, insolation, wind speed, wind direction	Decision Tree: classification and regression trees (CART) used to categorize ozone concentration on each day on basis of meteorological variables; reweighting of observations based on climatological frequency of occurrence of each meteorological category; adjusted annual summary statistics calculated from the reweighted observations

TABLE G-1. continued

No.	Reference	Location Studied	Annual Ozone Summary Statistic	Variables Used for Adjustment	Adjustment Method
18	Wakim (1990)	13 U.S. cities	mean of 30 and 60 highest daily maxima; number of days exceeding 0.12 ppm	45 combinations of temperature, wind direction, wind speed, relative humidity, sky cover, dew point, pressure, and precipitation variables	Regression: step-wise multiple linear regression using data from all years; adjusted annual mean summary statistics obtained by applying regression model with climatological mean meteorological conditions and adding errors back in. Logistic regression used to adjust exceedance summary statistics
19	Shively (1990)	Houston, TX	number of days exceeding 12 pphm and 16 pphm	persistence of wind direction by quadrant, cloud cover, wind speed, daily maximum temperature	Statistical Distribution Fit: nonhomogeneous Poisson process with intensity parameter a log-linear function of meteorological variables and annual trend term; parameters fit via maximum likelihood
20	Cox and Chu (1991)	25 Eastern and Midwestern U.S. cities	99th percentile of daily maximum	daily maximum temperature, morning average wind speed, afternoon average wind speed, relative humidity, cloud cover, morning mixing height	Statistical Distribution Fit: Daily maximum ozone modeled by Weibull distribution with invariant shape parameter and scale parameter expressed as a function of meteorological conditions and an annual trend term; parameters fit via maximum likelihood; model applied with normalized meteorological variables
21	Jones (1992a, b)	114 U.S. Cities	number of days exceeding 0.12 ppm	daily maximum temperature	Classification: Ozone conducive days defined as days with temperatures in excess of 90° F. Adjusted trend based on frequency of exceedances on ozone conducive days.

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APPENDIX H

Summary of Articles on Detecting Trends in Ozone Design Values

Table H-1. Summary of articles describing available techniques for detecting trends in ozone design values.

No.	Summary Statistic	Region	Years	Statistical methods	Comments
1	Mean second highest daily maximum.	Nation.	1978-1987	Annual summary statistics for each site are assumed to be the sum of a site term, a year term, plus an independent error term.	This methodology can be used for any national average annual air quality measure. The least squares estimates of model parameters can be used to estimate missing site values and adjust the annual means for those missing values. Trends can be evaluated by comparing annual mean confidence intervals for different years.
2	Mean second highest daily maximum.	Nation.	1978-1987	Annual summary statistics for each site are assumed to be the sum of a site term, a year term depending on the region containing the site, plus an independent error term.	This paper provides an enhancement of paper 1 in which missing annual summary statistics are estimated using trends in local sites rather than the national trends. Regions are defined by an agglomerative algorithm that minimizes the error in the fitted least squares model.
3	Mean eleven highest daily maxima, 90th percentile, annual exceedance days.	SAROAD sites.	1973-1981	Same as 1. An alternative model assumed a straight line trend for the year effect. The models were fitted by least squares.	Only 14 percent of the straight line slopes were statistically significant (those slopes were also all negative). Normal distribution and constant variance assumptions are unlikely to be valid for exceedance statistics.
4,5	Daily maximum.	South Coast Air Basin, CA.	1971-1981	a) Based primarily on the El Monte upper level temperature, days were allocated to high/medium/low oxidant formation potential. b) The logarithms were regressed against meteorological measurements.	In model a, trends were evaluated by plotting annual confidence intervals for the mean daily maximum oxidant for each group of days. In b, the regressions were used to calculate and plot annual confidence intervals based on the midvalues of each range of meteorological parameters used in model a. Trends were essentially flat for each meteorological regime.

Table H-1. Continued.

No.	Summary Statistic	Region	Years	Statistical methods	Comments
6	Cluster maxima. Exceedance hours for a given high threshold within 72 hours of each other are in the same cluster.	Houston, TX.	1973-1986	The tail distribution of the concentration for the cluster maximum is assumed to be the generalized Pareto distribution with a location parameter that is a straight line function of the year (the intercept and slope depend on the month). Cluster maxima occur as a Poisson process.	The statistical model is the asymptotic limit under fairly general conditions. The parameters were estimated by maximum likelihood. At a threshold of 0.08 ppm, the annual (negative) trend was significant for only two out of twelve months. For much higher levels (up to 0.28 ppm) the downward trends were usually significant.
7,8,9	Annual exceedance days.	Chicago, IL.	1977-1987	Trends are adjusted for average meteorological conditions using an ozone formation potential index to define ozone conducive days. The Spearman's rho non-parametric test of trend (correlation between annual values and the integers) was used.	The unadjusted exceedance rates showed a very weak downward trend. The meteorologically adjusted exceedance rates showed a stronger downward trend. Statistical tests of trend in papers 8 and 9 showed a non-significant trend for unadjusted exceedances and a statistically significant trend after adjustment.
10	Highest hourly, highest site second maximum, mean daily maximum, annual exceedance days.	Connect-icut.	1967-1987	Trend lines for the raw data were fitted by simple linear regression. Trend lines were also fitted using multiple linear regression against emissions and "exceedance conducive days."	The trends were shown to be statistically significant at the 1 percent significance level. Normal distribution and constant variance assumptions are unlikely to be valid for some of these statistics.
11	Annual exceedance days, annual exceedance hours, annual mean.	South Coast and South East Desert Area Basin, CA.	1976-1990	For each site, trends were evaluated using simple linear regression to estimate the percentage trend and the statistical significance of the trend.	Observed decreases were found to be statistically significant at the 5 percent level. Constant variance assumptions are unlikely to be valid for the exceedance statistics. Normality assumptions may be reasonable approximations due to the large expected numbers of exceedances.

Table H-1. Continued.

No.	Summary Statistic	Region	Years	Statistical methods	Comments
12	Water quality data.	Rivers in WA, NJ, UT, and AR.	1942-1973	Approximations for the power (trend detection probability) of parametric (linear regression) and non-parametric (Spearman's rho) trend tests are derived mathematically and by simulation. Cases of independent and dependent sequences are considered.	Although the methods were derived in the context of water quality trend analysis they can be applied to trends in ozone design values and summary statistics. The power calculations for linear regression use approximate formulae that are invalid for small samples.
13	Water quality data.	National Stream Quality Account-ing Network (NASQAN) stations. Monte Carlo simulat-ions.	?	The Kendall's tau non-parametric test for annual trends is adjusted to deal with seasonal data by summing 12 monthly Kendall's tau statistics. A related non-parametric slope estimator is also derived.	Trend detection probabilities are derived by simulation for various distributions (including autoregressive - moving average time series) using the seasonal Kendall tau test, simple linear regression, and linear regression applied to normalized monthly values. One advantage of the non-parametric approach is the ease in which censored data can be analyzed.
14	Water quality data.	Monte Carlo simulat-ions.	?	The seasonal Kendall's tau statistic developed in paper 13 is adjusted to include possible correlations between the 12 monthly values.	The enhanced robustness of the test to cases of serial dependence from month to month implies a lowering of the power for the independent case.
15	Mean second highest daily maximum, annual exceedance days.	NAMS sites, all EPA sites.	1975-1982	The mean second highest daily maximum is analyzed by a repeated measures one-way analysis of variance (same as paper 1). The mean exceedance numbers are analyzed by fitting a Poisson distribution.	Simultaneous confidence intervals are developed using the Tukey studentized range for the mean second highest value and using the Bonferroni approach for the mean exceedances. These intervals allow statistical comparisons between any two yearly values to be made.

Table H-1. Continued.

No.	Summary Statistic	Region	Years	Statistical methods	Comments
16	Monthly stratosphe-ric ozone (Dobson total ozone records).	36 Dobson stations.	1964-1979	The methods used assume both spatial and temporal correlations as well as a time trend. The analysis is in the frequency domain.	Trend estimation for autocorrelated annual or monthly ozone values has usually been based on fitting a stationary time series model to the detrended data. The approach developed in this paper is based on separating the significant frequencies in the temporal and spatial series.
17	Monthly stratosphe-ric ozone (Dobson total ozone records).	36 Dobson stations.	1958-1978	Monthly values are assumed to be the sum of a monthly linear trend, a sum of sinusoidal curves representing seasonal (within year) effects, and an autoregressive error term.	The model was fitted by weighted least squares.
18	Annual average TSP.	New Haven, CT, and Tucson, AZ.	1960-1971	Techniques suggested are Spearman's rho, the Pearson correlation coefficient (equivalent to a linear regression trend test), a chi-square test based on exceedance rates at two consecutive time points.	Issues discussed: representativeness and weighting of site statistics, effects of measurement protocol changes, biases due to intermittent sampling, need for meteorological and emissions data in order to extrapolate trends. The chi-square test is simple to perform but has very low trend detection power.
19	k highest daily maxima.	Houston, TX.	1973-1987	Using maximum likelihood estimation, the limiting extreme value joint distribution for the k highest values assuming a linear yearly trend is fitted.	The statistical significance of the trend was evaluated using the bootstrap method (due to the small sample sizes). The trend was statistically significant at only one of the two sites (5 percent level).
20	Daily maxima.	Houston, TX.	1981-1987	Exceedances are assumed to occur as a non-homogeneous Poisson process. Thus the instantaneous exceedance rate does not depend on the past history.	The daily exceedance rate was assumed to depend on meteorological measurements and on the long term linear yearly trend.

Table H-1. Continued.

No.	Summary Statistic	Region	Years	Statistical methods	Comments
21	Annual average.	--	--	The Kendall's tau correlation test and test for test is derived with the corresponding Theil/Sen non-parametric slope estimator.	The discussion includes how to adjust Kendall's tau and the slope estimator to cope with ties.
22	Mean second highest daily average SO_2. Mean daily average SO_2.	Nation.	1977-1982.	Annual summary statistics for each site are assumed to be the sum of a site term, a year term, plus an independent error term.	Simultaneous confidence intervals are developed using the Tukey studentized range. These intervals allow statistical comparisons between any two yearly values to be made. If daily values are randomly missing then the mean of the site daily averages is unbiasedly estimated, but the second highest daily average is not. Thus trend estimates based on annual maxima are less reliable than those based on annual means.
23-40	Annual averages across sites of appropriate design values for TSP, PM_{10}, SO_2, CO, NO_2, O_3, and Pb.	Nation.	1973-1990.	Non-parametric regression. Medians of individual site trend statistics. Two-way analysis of variance with Tukey confidence intervals for annual averages. Poisson distributions and Bonferroni confidence intervals for exceedances.	The non-parametric methods in papers 12, 13, and 21 were often applied in the earlier reports (1970s). Later reports used the parametric methods in papers 1, 15, and 22. One advantage of the ANOVA approaches is that the year to year effects are not always assumed to follow a linear trend.

Note: The heading "Summary Statistic" lists the annual estimated design values or summary statistics used for the trend analysis. Unless otherwise noted in this column, the data used in the article are ozone concentrations. The columns "Region" and "Years" summarize the location and collection period of the data analyzed. The statistical model and/or the statistical methods used in the article are summarized in the "Statistical Methods" column. The "Comments" column includes both a summary of the important and relevant points in each article and an occasional brief critique or caveat.

APPENDIX I

Summary of Oral and Written Comments from the Public Meeting on the Ozone Design Value Study, Arlington, Virginia, September 10, 1992

LIST OF PANEL MEMBERS

William Hunt, Branch Chief
U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Technical Support Division
Monitoring and Reports Branch (MD-14)
Research Triangle Park, NC 27711
919/541-5559

Warren P. Freas, Senior Statistician
U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Technical Support Division
Monitoring and Reports Branch (MD-14)
Research Triangle Park, NC 27711
919/541-5469

Tom Helms, Branch Chief
U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Air Quality Management Division
Ozone/Carbon Monoxide Programs Branch (MD-15)
Research Triangle Park, NC 27711
919/541-5527

Valerie Broadwell, Policy Analyst
U.S. Environmental Protection
Office of Air Quality Planning and Standards
Air Quality Management Division
Ozone/Carbon Monoxide Programs Branch (MD-15)
Research Triangle Park, NC 27711
919/541-3310

LIST OF SPEAKERS

Jon Heuss
Motor Vehicle Manufacturers Association
of the United States, Inc.

David P. Chock
Ford Motor Company
Dearborn, Michigan

LIST OF ATTENDEES

Tim Hogan
American Petroleum Institute
1220 L St., NW
Washington, DC 20025
202/682-8323

Jon Heuss
General Motors/Motor Vehicle
Manufacturers Association
30400 Mound Road
Warren, MI 48090-9015

Hether Macfarlene
Hunter & Williams
2000 Pennsylvania Ave., NW
Washington, DC 20086
202/995-1500

George Lauer
Atlantic Richfield
515 S. Flower
Los Angeles, CA 90071
213/486-0777

Jon Gallinger
American Gas Association
1515 Wilson Blvd.
Arlington, VA 22209
703/787-1735

David P. Chock
Ford Motor Company
Dearborn, MI 48121
313/845-4777

Dirk Herkhof
US Department of Interior
Minerals Management Service
381 Elden Street
Herndon, VA 22071

Susie Brunige
BNA
Washington, DC
202/452-5558

Phyllis Hinterer
Interstate Natural Gas Association
555 13th Street, NW
Washington, DC 20004
202/626-3200

Subroto Mitro
US Navy, Bldg. 212
Washington Naval Yard
Washington, DC 20374
202/433-3777

Victoria Schobel
Clean Air Report
1225 Jefferson Davis Highway
Arlington, VA 22202
703/892-8516

Rob Smith
US Navy, Bldg 212
Washington Naval Yard
Washington, DC 20374
202/433-3777

Amy Steeley
Chemical Manufacturers Association
2501 M Street, NW
Washington, DC 20037
202/887-1357

Kent Avery
US Navy
Naval Air Systems
Command Air-0943G
Washington, DC 20361
703/692-8562, ext. 2313

LIST OF COMMENTERS

92-4 American Petroleum Institute

92-5 Connecticut Department of Environmental Protection

92-6 U.S. Department of the Interior

92-7 Testimony: Motor Vehicle Manufacturer's Association (MVMA) - Jon Heuss, General Motors Corporation (GM)

92-8 MVMA-Ford (Dr. David Chock - JAWMA - 1991)

92-2 MVMA-Ford (J. Heuss and D. Chock - AWMA Tropospheric Ozone Specialty Conference, Atlanta, GA, 1991)

92-10 MVMA-Ford (Dr. David Chock - Atmospheric Environment - 1984)

92-11 MVMA-Ford (Dr. David Chock - JAPCA - 1989)

92-12 MVMA-GM (Jon Heuss - AWMA Annual Meeting, Vancouver, BC, 1991)

92-13 Testimony: Ford Motor Company (Chock, Ford)

92-14 Illinois Environmental Protection Agency

92-15 San Diego County, CA Air Pollution Control Board

92-16 Zephyr Consulting

92-17 General Motors - Jon Heuss (addenda to testimony)

92-18 New York State Department of Environmental Connversation

92-19 California Air Resources Board

SYNOPSIS

AMERICAN PETROLEUM INSTITUTE COMMENTS

"Comments on the Proposed Ambient Air Quality Surveillance Rule, 57 FR 7687 (March 4, 1992)" and resubmitted by API as public input for consideration within the context of the Ozone Design Value Study, August 12, 1992.

API expressed concern about bias and interferences in the ozone measurements. API notes there are interference issues with both of the predominate instrument types comprising the ozone monitoring networks, namely the Federal Reference Method ethylene chemiluminescence (CL) instrument and the equivalent ultraviolet absorption (UV) instrument. API stated that the potential problems relate to specific conditions of high temperature, humidity and ozone precursor concentrations which are especially present in design value situations. Although some of the bias may be in either direction, API feels that most of the factors will result in a positive bias.

API also expressed concern about the robustness of the current design value method. API expressed concern that the current methodology utilizes a small number of high ozone measurements and encourages the development of a more robust technique, which will involve a larger portion of the available ozone data base.

API expressed concerns about the adequacy of the ozone monitoring network.

A region by region review of the current monitoring network size, location, efficiency, and effectiveness is suggested. Flexibility is encouraged in network design to take advantage of local geographical and terrain characteristics, frequencies of wind roses, and current understanding ozone formation mechanisms in the area. API suggested that ozone monitoring might be more efficient and cost-effective if it were more intense in the high season.

SYNOPSIS

CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION COMMENTS

Written comments submitted by Kevin McCarthy, Assistant Director, Radiation and Monitoring Division, Bureau of Air Management, Department of Environmental Protection, State of Connecticut, September 9, 1992.

CT DEP has concern about bias and interferences in the ozone measurements. Connecticut previously submitted a report to EPA describing unstable response for the ultraviolet absorption ozone analyzers, due to presence of water vapor. There was, and still is, concern about potential bias in the ozone data. Also, the State of Virginia has observed similar instability problems causing the invalidation of a significant portion of its 1991 ozone data. Other published reports indicate the ultraviolet ozone analyzers can be biased on the high side due to organic compounds. A summary of the potential interference issue for ozone monitors has been prepared by the American Petroleum Institute for the enhanced ozone monitoring rules and has been resubmitted for the ozone design value study.

CT DEP has concern about the robustness of the current design value method. Connecticut encourages EPA to consider developing a method which relies less heavily on relatively few highest hourly values and which will utilize more data points from other than the extreme tail of the ozone distribution.

SYNOPSIS

U.S. DEPARTMENT OF THE INTERIOR COMMENTS

Written comments submitted by John Goll, Chief, Environmental Policy and Programs Division, Minerals Management Service, U.S. Department of the Interior, Washington, DC, September 9, 1992.

The DOI has concern with small-area resolution of the Regional Oxidant Model (ROM). DOI staff expressed disagreement with the EPA interpretation that ozone isopleths predicted by the ROM Model for the Northeastern United States appear uniform across a broad geographic region. DOI believes the ROM model is not adequate to characterize the more detailed spatial patterns found within individual metropolitan areas.

The DOI also expressed concern about the adequacy of the ozone monitoring network. DOI emphasized the importance of having a monitoring network with sufficient size and density to account for ozone variations which can occur over small distances within metropolitan areas, particularly in areas of complex terrain. Increased consideration of network design issues is encouraged.

DOI stated that there is a need for a method to account for temporal variation in meteorology. Recognition that weather conditions conducive to ozone formation can differ greatly year-to-year, although "high" ozone seasons may recur with an estimateable periodicity, suggests that the design value methodology should be able to adjust in some way for this annual variation. DOI expressed concern that, for a 3-year period of especially good weather for preventing ozone formation, the present form of the design value strategy may not be protective enough.

DOI raised concerns about ozone transport from an adjacent region. DOI points out the issue where ozone or precursors are transported into an air quality control region, such that the region may not be able to demonstrate attainment no matter how rigorous the proposed emission control. DOI stated that some modified approach is necessary, such as consideration of a larger regional effort to design control strategies.

SYNOPSIS

MOTOR VEHICLE MANUFACTURERS ASSOCIATION STATEMENT

"Statement of the Motor Vehicle Manufacturers Association of the United States, Inc. on the Ozone Design Value Study of the Clean Air Act Amendments of 1990," Jon Heuss, Motor Vehicles Manufacturers Association, September 10, 1992.

MVMA expressed general concern about the need for increased robustness in the design value, inconsistency between the nominal and actual stringencies of the standard, requiring a site to average significantly fewer than one exceedance per year to have a reasonably high chance of being designated an attainment site, the need to adjust the current design value method to account for annual fluctuations in meteorology, and the implicit time-lag for providing evidence of emissions improvements for moving toward attainment (i.e., due to the 3-year average criterion, the current procedure begins counting exceedances 3 years before the applicable deadline), which appears inequitable.

The seven criteria proposed by Curran for evaluation of "reasonableness" are discussed by MVMA and endorsed as necessary attributes. Also, the six properties listed by Fairley and Blanchard as desirable are described. MVMA criticized the current design value procedures as being deficient in several of these including stability, sensitivity to changes in air quality, use of available data, and consistent nominal and actual stringency. Heuss suggests several modifications which might improve the method such as using the 95th percentile or a 95th percentile-centered mean, as the mean of the highest 30 daily concentrations instead of the presently used design values in order to increase robustness.

MVMA also expressed concern about the outputs of the deterministic models used to evaluate the effectiveness of control strategies. MVMA stated that there is a need to investigate and understand them in probabilistic form so that informed decisions can be made about the efficacy of selected emissions control scenarios. Heuss notes an inconsistency between the planning tool used to aim at the attainment target, photochemical grid modeling, and the target, the present design value.

These comments are supplemented by the concurrent submission of related reports and technical papers previously prepared by MVMA member company scientists.

SYNOPSIS

FORD MOTOR COMPANY TECHNICAL PAPER

"Issues Regarding the Ozone Air Quality Standards," Dr. David P. Chock, Ford Motor Company, Journal of the Air and Waste Management Association, Vol. 41, No. 2, February, 1991.

The rationale for this report is to develop a statistically-based form of the ozone air quality standard that is based on an order statistic, such as a percentile, and to develop a robust compliance test that reduces the impact of unusual meteorological situations (such as the 1988 heat wave) on the attainment status of a region. A two-component testing procedure is proposed. The first component is a statistical test of an area for attainment such as the t-test with a relatively large α level, which is the probability of misclassifying an area actually in attainment as nonattainment. The second component would be used for those areas which have been previously tested and determined to be in attainment for some time and would consist of the same t-test with a smaller α level. Such areas, to be eligible for this less stringent test, would also have to demonstrate that no significant increases in ozone-precursor emissions had occurred. Chock states that this approach would have the benefit of reducing the impact of unusual weather fluctuations such as the 1988 heat wave on the attainment status of long-time attainment areas while not protecting their ranking category from an upward ozone trend. This approach is similar to that proposed by Fairley and Blanchard. It requires compliance with the current methodology a high percentage of the time (about 95%), rather than the current procedure of 100% compliance for the attainment category.

SYNOPSIS

TECHNICAL PAPER

"The Role of the Design Value in Ozone Compliance" Jon Heuss and David Chock, presented at the Air and Waste Management Association International Specialty Conference, "Tropospheric Ozone and the Environment, II: Effects, Modeling, and Control," Atlanta, GA, November 5-7, 1991.

This report provides a general discussion of the many issues surrounding the application of the Design Value Methodology in Ozone Compliance. It notes the present limitations of the procedure such as lack of stability resulting in frequent changes in attainment status, non-robustness since only 4 hourly concentrations are considered from a 3-year data base, sensitivity to air quality changes, and inconsistency between the nominal and actual stringencies. No single solution is advocated. The several positive suggestions by Chock, Heuss, Fairley and Blanchard, Curran and Freas are cited and should be further evaluated. Several desirable properties of the improved procedures are suggested, however, for example, the use of a more robust statistic such as the 95th percentile, which are consistent with other reports by the authors.

SYNOPSIS

TECHNICAL PAPER

"Statistics of Extreme Values of a First-Order Markov Normal Process: An Exact Result," Dr. David P. Chock, General Motors Research Laboratories, Atmospheric Environment, Vol. 18, No. 11, pp2461-2470, 1984.

This highly mathematical report examines the impact of autocorrelation on extreme values. This paper derives the exact distribution for the maximum, second-highest, third-highest, and fourth-highest values of a first-order Markov normal process. It is found that a high positive autocorrelation ($\geq$ 0.7 at log 1) lowers the values of the extremes and near-extremes while increasing their variability. The means, medians, and modes together with their deviations, for several autocorrelation values and several numbers of observations are presented. As discussed in Section 5, a later paper by Hirtzel and Chock (1985) describes some mathematical errors in these calculations because of inconsistencies in the assumptions made. The relevance of these results to the ozone design value issues is discussed. Concern is expressed that a few high ozone days from a single year or even a single season may dominate the design value procedure for a 3-year period. The author states that the potential efficiency and cost-saving for monitoring more or only in the high ozone season should be further considered. The need to understand and adjust for multiple meteorological variables is noted.

SYNOPSIS

TECHNICAL PAPER

"The Need for a More Robust Ozone Air Quality Standard," Dr. David P. Chock, General Motors Research Laboratories, Journal of the Air Pollution Control Association, Vol. 39, No. 8, pp. 1063-1072, August, 1989.

This report notes limitations in the current ozone air quality standard such as the instability in the annual second-highest value and the fourth highest value in a 3-year period, an implicit compliance test that is not capable of accounting for the fluctuation in ozone concentrations due to severe meteorology conditions, and inconsistencies between the number-of-exceedances criterion and the design value for control implementation. A more robust statistic such as the annual 95th percentile is proposed for this standard. This measure is more stable than the extreme values used at present and yet is still characteristic of repeated high ozone exposures. The author suggests that this statistic can serve both as the compliance criterion and as the design value, eliminating the use of the number of exceedances in the standard. Also, Chock states that the proposed t-test for compliance allows the standard to be enforced simply and without ambiguity. He notes that by determining the mean and standard deviation of the 95th percentile concentrations over 3 or more years in the compliance test, the average concept of the current standard is preserved while accounting for the stochastic nature of ozone concentrations.

SYNOPSIS

TECHNICAL PAPER

"Implications of Attaining and Maintaining an Extreme Value Ozone Air Quality Standard," Jon M. Heuss, presented at the 84th Annual Meeting of the Air and Waste Management Association, June 16-21, 1991, Vancouver, British columbia, Canada.

This report expresses concern about whether the current design value methodology provides a reasonable indicator of air quality in nonattainment areas and hence is an effective target for the development and assessment of local emissions control strategies.

Heuss states that one problem with the procedure to utilize photochemical grid models to demonstrate attainment is that the required detailed input information for emissions, initial conditions, boundary conditions, and meteorology may not be available, particularly for a specific design value day in the past. Heuss notes that guidance has not been fully developed for this situation. He states that this question was not an issue with the Empirical Kinetic Modeling Approach (EKMA) that was previously used to model ozone for SIPs since EKMA is a box model that does not require detailed input data. Updated emission inventories are needed. Heuss suggests that consideration of statistical estimation techniques would be useful to predict future ozone concentrations, even in the case where many data values are missing.

A second issue raised in the paper is a test for maintaining the standard for those areas currently in attainment. The author states that perhaps a less stringent compliance test would avoid the oscillations caused by fluctuations in meteorology and still maintain reasonable detection of increasing ozone precursor emissions. To improve the present situation, a more robust statistic is suggested, which provides greater stability as a design value and, then combined with a compliance test, recognizes that ozone concentrations are probabilistic in nature.

SYNOPSIS

FORD MOTOR COMPANY STATEMENT

Statement of the Ford Motor Company on the Ozone Design Value Study of the Clean Air Act Amendments of 1990, Dr. David Chock, Ford Motor Company, September 10, 1992.

Ford Motor Company has concerns about the current compliance test for the ozone standard. Chock expressed particular concern about the compliance test portion of the design value issue. At present, the compliance test requires complete (100 percent) adherence for all time periods. Chock stated that this feature has resulted in the standard being more stringent than is generally recognized, since an area with a long-term average of one exceedance per year will have a 35 percent chance of having more than three exceedances in 3 years. He also noted that the present method results in instability problems as regional attainment status can oscillate due to the presence of unusual meteorology conditions. Chock suggests developing a statistical compliance test that takes into account the fluctuation of the ozone concentrations. He suggests using the second highest of the three annual second highest values in three consecutive years as the practical design value. Chock stated that this form of design value would increase stability across years and use a more robust procedure that adjusts for a particular year of unusually severe meteorological conditions.

SYNOPSIS

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY COMMENTS

Written comments submitted by Bharat Mathur, Chief, Bureau of Air, Environmental Protection Agency, State of Illinois, September 10, 1992.

Illinois EPA stated that there is a need for a method to account for temporal variation in meteorology. Illinois observes that the design value methodology needs to adjust somehow for the impact of extreme meteorological conditions in a given year. Such an adjustment is needed to provide increased stability so that an air quality region will not fluctuate between attainment and non-attainment. They suggest two possible approaches, which limit the contribution of a single year's data to the 3-year total, as examples of the type of "formalizing" adjustment they believe is needed.

Illinois EPA has concern for the necessary time-lag in demonstrating the impact of emissions control measures on ozone air quality for determining attainment. Illinois observes that the requirement to use the most recent 3-year quality assured ozone data base to determine attainment may be inequitable in some cases because of the time-lag in observing the benefit of newly instituted control measures. They suggest that if a State can justify when a 3-year period is not representative for a metropolitan area, the method allow some flexibility by permitting consideration of some alternative time-table, such as a year-by-year basis, in order to appropriately consider emission controls implemented more recently than 3-4 years previously.

Illinois also expressed concerns about the adequacy of the ozone monitoring network. Illinois observes the importance of having a monitoring network which is sufficiently large to represent the spatial area.

Illinois suggests that the design value protocol be modified to incorporate the results of urban airshed modeling which will be available in 1994 and will indicate whether the SIP revisions will provide attainment by the applicable attainment projected date.

SYNOPSIS

SAN DIEGO COUNTY, CA COMMENTS

Written comments submitted by R. J. Sommerville, Air Pollution Control Officer, Air Pollution Control District, County of San Diego, September 14, 1992.

The San Diego APCD expressed concern about how ozone transport from an adjacent region is treated. San Diego County, being located next to the South Coast Air Basin, an area with the highest U.S. ozone levels, is concerned that the design value methodology be able to determine the correct severity of the ozone problem within San Diego County, so that the area is not unfairly and inequitably required to address the pollution problem in the SCAB. The transport issue has been documented and discussed previously in the San Diego County Air Pollution Control District's 1978 State Implementation Plan, which was approved by EPA. The San Diego APCD feels that it is not clear how the current ozone design value methodology will be modified to take into account ozone transport.

SYNOPSIS

ZEPHYR CONSULTING COMMENTS

Written comments submitted by Dr. Kay H. Jones, President, Zephyr Consulting, September 15, 1992.

Dr. Jones raised the issue of the ozone concentration/frequency relationship. He states that to be technically consistent with the legal attainment target of frequency, i.e., no more than 1 day per year on the average, the primary design value should be defined as a frequency (days/year) rather than as a concentration. He also suggests that if a concentration design value is required for classification reasons, then the frequency/concentration relationship should be determined on a region by region basis, since, in his view, the frequency/concentration correlation varies sufficiently between different locations.

Dr. Jones also stated the need for a method to account for temporal variation in meteorology. He observes that the design value methodology needs to adjust in some manner for the impact of extreme meteorological conditions in a given year. Summary data for the annual frequency of daily maximum temperatures exceeding 90° in Baltimore during 1967-1992 are presented as an illustration of a possible approach for an adjustment procedure.

Additionally, other meteorological factors besides temperatures, such as humidity, rainfall, wind speed, and direction, should also be considered. Dr. Jones recommends that when evaluating data for appropriate meteorological adjustment, the methodology should require identification and use of a single (worst-case) ozone monitoring site location. He states that in the past, some air quality regions have (inappropriately) used different monitor locations for SIPS planning for different years.

Dr. Jones commented on ozone transport from an adjacent region. He states that areas such as rural counties downwind from major urban areas should not be evaluated as unique impacted regions. He suggests that some type of adjustment for transport seems appropriate.

Dr. Jones expressed concerns about the missing data procedures used to calculate estimated exceedances of the ozone standard. He expressed concern that the current missing data procedures do not adequately consider seasonality patterns to equitably estimate missing data for different ozone "seasons." He suggested that improved analysis and understanding of the temperature/ozone relationship is needed for the proper prediction of expected exceedances. Dr. Jones states that this comment is consistent with

recommendations by the National Academy of Sciences report "Rethinking the Ozone Problem in Urban and Regional Air Pollution" and the 1987/88 CEQ Annual Report Chapter on Urban Air Quality.

SYNOPSIS

MVMA / GENERAL MOTORS ADDITIONAL COMMENTS

Written comments submitted by Jon Heuss, General Motors Research and Environmental Staff, September 15, 1992.

In an additional comment submitted following his presentation, Heuss notes an example which he believes illustrates an inconsistency between the current ozone design value methodology and the current modeling guidance that requires all modeled episodes to be below the ozone standard. He feels that EPA guidance may provide an emission control target that is more stringent than the design value resulting in over control. Heuss also notes that the Regional oxidant Model (ROM) may over predict peak ozone concentrations which may also result in an over control situation, without some adjustment.

SYNOPSIS

NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION COMMENTS

Written comments submitted by Edward O. Sullivan, Deputy Commissioner, New York State Department of Environmental Conservation, September 11, 1992.

The NY DEP feels that there is a need for a method to account for temporal variation in meteorology. New York observes that the year-to-year variation in ozone design values for the NJ-NY-CT CMSA during 1988-92 is due more to meteorological annual differences than to precursor emissions changes. New York suggests that the design value methodology should be able to adjust in some way for meteorological annual fluctuations in order to avoid misclassification of areas as to compliance or non-compliance category.

NY DEP also expressed concern about the robustness of the current design value method. New York encourages EPA to explore the development of a more robust statistic, such as a specified quantile of the daily maximum 1-hour ozone concentrations in a 3-year period, as a means of classifying non-attainment areas and specifying their emissions reduction requirements. New York recommends using this new statistic, the Control Strategy Design Value, to identify control requirements.

NY DEP expressed concern about the interpretation 2of non-urban ozone monitoring site data. New York observes that there exist some air quality regions where the only high ozone data contributing to the non-attainment classification are from non-urban sites, such as a mountaintop location, where the contribution of local anthropogenic emissions is negligible.

SYNOPSIS

CALIFORNIA AIR RESOURCES BOARD

Written comments submitted by Terry McGuire, Chief, Technical Support Division, Air Resources Board, State of California, August 25, 1992.

The California Air Resources Board (CARB) stated that there is a need for a method to account for temporal variation in meteorology. CARB observes that the design value methodology could be improved by an adjustment that provides greater stability by accounting for annual meteorological fluctuations. CARB suggests a possible approach, the "recurrence rate" method, which can be set to varying levels of stringency. That is, 0, 1, or more observed high observations could be excluded per year based on the meteorology observed. A 1-in-1 year "recurrence rate" is similar to the stringency in the current EPA design value attainment method. CARB states that in these years with extreme meteorological conditions, a different "recurrence rate" could be used to "normalize" such time periods. In years of favorable meteorology (preventing high ozone formation), it is possible no high values would be excluded.

APPENDIX J

Summary of Written Public and Peer Review Comments on the Draft Ozone Design Value Study

SUMMARY OF COMMENTS

This summary encompasses all substantive comments, excluding those on minor stylistic and editorial matters. For clarity in references to lengthy comments, paragraph numbers are given in brackets after each comment.

AMERICAN PETROLEUM INSTITUTE

API incorporates comments by Chevron of 27 April 1994, by API of 30 September 1986, and by API of 17 March 1989.

1 As the current design value methodology does not characterize ozone air quality temporally or spatially throughout nonattainment areas, it does not answer the 1990 CAAA's requirement in Section 183(g) and should be replaced with a more suitable indicator.

2 The present indicators for ozone—design value and maximum one-hour concentrations—do not represent actual exposures of people, thus a new air quality indicator should be used which incorporates population exposure levels and activity scenarios in addition to other factors that affect exposure levels.

3 Because a very small number of extreme measurements, possibly highly localized or due to natural fluctuations, can result in nonattainment status, the EPA should develop an air quality indicator for the NAAQS review that makes use of the entire body of monitored data throughout an MSA/CMSA and focuses on the influence of anthropogenic emissions.

4 Because the air quality indicators, present and alternative, are unstable and could bounce a region between attainment and nonattainment despite a long-term trend toward attainment, the EPA should establish a "transitional nonattainment" designation for areas that are near attainment.

CALIFORNIA AIR RESOURCES BOARD

1 The CARB recommends use of the Larsen tail exponential method for attainment designations and design value calculations.

2 Clarifications submitted for the discussion of the development of the CARB design value method [Corrections 1,2].

3 Amplification suggested for the treatment of the exponential-tail assumption [Suggestion 1].

4 Suggest combining findings number 2 and 6 on page 1-16 and clarifying [Suggestion 2].

5 While many common air quality indicators are simple to compute, they are complex to interpret and can give misleading results, whereas the CARB method, although more complex to compute, is simple to interpret properly, even for nontechnical people, and thus may serve the public better [Suggestion 3].

CHEVRON

1 The study should review, discuss, and support air quality indicators other than the design value, especially ones that provide information on potential health impacts.

2 The EPA should adopt the Larsen methodology used by the CARB to determine the design value, which removes highly irregular or infrequent meteorological events.

3 The EPA should identify indicators of air quality improvement besides the design value because when used alone, the design value (1) overstates severity of population ozone exposures by applying ozone levels at the design value monitor to an entire region, (2) does not indicate improvement in population exposures due to improvements in peak ozone, and (3) does not show how efficiently (in terms of reducing health risk) progress in air quality is made.

4 Indicators that consider population exposure should be part of the air quality planning process to assess the effectiveness of ways to reach ozone attainment through NO_x and hydrocarbon emission reductions.

5 The EPA should explore methods of determining attainment that avoid weaknesses of the present method based on the design value, which relies on a single monitor that is not weighted according to population and does not take data from other monitors into account.

DU PONT

1 As the draft report points out, the current design value cannot account for spatial and temporal variations in ozone concentration that are necessary for evaluating human exposures, so the section on exposure measures should be expanded and the usefulness of exposure measures emphasized [2-3].

2 Because emissions across the United States have been decreasing, the use of long-term averaging periods is a conservative procedure, and the report should be amended to advocate a design value estimation method that uses averaging periods of six years or longer [4-7].

3 Just as the EPA is studying techniques to adjust ozone trends for meteorological variability, it should look for similar techniques to adjust the design value [8].

4 Contrary to the report's assertion, the Clean Air Act's Section 110(k)(6) provides for adjustments to initial ozone classifications due to transport [9].

5 The report should be amended to include a position on the use of adjusted design values for ozone classification and attainment demonstration, recognizing that because they currently cannot be adjusted they are incompatible with "control strategy design values" used in developing emission control plans, which can be adjusted [10-11].

6 The report should include a more detailed discussion of the EPA's interpretation of CAA Section 181(b), which uses the words "design value" whereas the EPA interprets it to mean "average number of exceedances per year" [12].

Lesser comments [13]:

7 Request background on the basis for the breakpoints in table 1-1.

8 The report should note on page 1-4 that placement of ozone monitors is an additional key concern.

9 Page 3-10 should describe the requirements for density and siting of ozone monitors.

10 Supply a source for the assertion on page 6-30 that the NAAQS is designed to protect against effects of short-term exposure.

11 Explain why design value estimates shown in figure 6-13 rise as averaging time increases.

FORD MOTOR COMPANY

1 The study considers only the reasonableness of the present design value methodology and does not consider alternatives; indeed, alternatives are deferred to the next ozone NAAQS review yet the document on which that NAAQS will be based (the Criteria Document) does not address alternatives [2].

2 The EPA's definition of the design value as the "characteristic largest value" or CLV corresponding to the NAAQS (exceeded once per year on average) is inconsistent with that of the present EPA design value (fourth highest in three years) [3].

3 This inconsistency undermines the quality of the design value methodology and the logic underlying comparisons of different methodologies [4].

4 The CLV is determined with the assumption of infinite sample size, which is inapplicable to the problem of assessing the distribution of a rank order statistic of a finite-size sample [5].

5 The CLV cannot be determined without making assumptions such as those made in Section 6 that cannot be rigorously justified [5].

6 The report should note that 95th percentiles are more robust statistics than the present design value, as supported by Figures 3-3 through 3-14 and Table 6-9 [6].

7 Exceptional years such as 1988 tend to dominate the design value for the three-year periods they belong to under the present methodology, causing large variabilities between non-overlapping three-year periods, whereas alternative design values could avoid this problem [7-8].

8 The comparison of design values and 95th percentiles in the report is not valid due to discrepancies in sample sizes, treating combined instead of individual sites, misinterpretation of correlation diagrams, and misattribution of statistical bias [7-13].

9 The compliance test should take the variability of the test statistic into account [14].

10 The report should discuss the alternative approach of using the three-year mean or median of the annual second highest values [15].

11 Extreme values are unduly affected by the distributions chosen, such as lognormal; a "calibration factor" used by the CARB corrects this to an extent, but the factor is site- and time-specific [16-17].

12 Increasing the multiyear sampling period would increase the design value and the NAAQS stringency [18].

13 Because design values based on multiyear sampling periods become unduly influenced by long-term ozone concentration trends, meteorologically-adjusted ozone trends should be determined by examining ozone concentrations under a fixed set of meteorological conditions for different years, with the ozone-meteorology relation determined separately for each year (in contrast to the Cox and Chu method) [19-20].

14 Adjustment of design values due to transport of ozone and precursors into and out of an area should be done with a photochemical grid model, not the Transported Ozone Design Value model [21].

15 Given the poor correlation between the EPA design value and the expected number of exeedances, the upcoming revision of the NAAQS should use rational, consistent indicators to represent the NAAQS and design value [22].

16 Even though there are more robust alternatives to the EPA design value, compliance flip-flops will remain a problem that is best addressed by a statistical compliance test incorporating design value fluctuations, in order to balance public health needs against inevitable fluctuations in natural conditions [23].

17 As the ideal design value for purposes of public health should take into account human exposures to ozone, indoor as well as outdoor monitors should be part of the NAAQS specifications [24].

GENERAL MOTORS

General Comments

1 The roles of the design value in attainment classification, attainment designations, and the SIP process have changed under the 1990 CAAA Amendments and are a fit subject for review in the Design Value Study even if the EPA wishes to replace design value with number of exceedances as an attainment criterion in section 181(b)(2)(A) of the Act [9-12].

2 The study report should review the method and data used to arrive at the 1990 nonattainment area classifications and technically justifiable modifications should be evaluated [14].

3 The EPA should revisit the CAAA deadlines for attainment after the 1994 SIPs are submitted [15].

4 Since the current EPA design value is a poor measure of health impacts and temporal trends, air quality indicators (such as the 95th percentile or mean of the top ten) that are better correlated with number of exceedances than the current design value should be used [16].

5 The EPA should continue to study more robust indicators of ozone levels that are less sensitive to fluctuations in meteorological conditions and that better reflect changes in emissions [17].

6 The three pages of discussion of the issues raised in public review of Chapter 11 do not represent a sufficient response to the comments received [19].

7 The study acknowledges a discrepancy between the nominal stringency of the present attainment test (one exceedance per year) and its actual stringency (never more than three exceedances per three years, hence significantly less than one exceedance per year), but does not address the full ramifications of this discrepancy [20-22].

8 Given that the EPA is considering the use of statistical attainment tests and the use of a transitional attainment category in its NAAQS review, the study should include analyses of these approaches [23-24].

9 The impact of transport of ozone and its precursors into an area should be discussed in the context of attainment determination as well as classification determination [25-28].

10 Because the design value methodology weights data disproportionately from early in the three-year period of record (when extreme values are more likely),

the study should analyze a methodology that is based on three one-year periods rather than one three-year period for use in determining attainment at CAAA-specified deadlines [29].

11 The study should evaluate ways to adjust the design value and attainment schedule in light of the statistical discrepancy between nominal and actual stringencies of the attainment standard and in light of the change in ozone planning tools from EKMA to photochemical grid modeling [30-34].

12 The study should evaluate the exceedance database with respect to how often the missing data convention is used and how often it affects attainment classifications [35-36].

13 Once having made the additional analyses suggested in these comments, the study will better answer the questions Congress asked regarding uses of design values [37].

14 The Executive Summary and Conclusions should be revised when the rest of the report is modified in accordance with these comments [38].

Specific Comments

15 Chapter 2 should acknowledge the difference between nominal and actual stringencies and should discuss Fairley and Blanchard's six desirable properties in attainment criteria [39].

16 Chapter 3 discussion of background ozone should be changed to be consistent with the latest Criteria Document [40].

17 The discussion of human health effects should be scaled back to what is supported by the data as given in the External Review Criteria Document [41].

18 Discussion of the VOC/NO_x ratio at which NO_x changes from a net ozone former to a net ozone destroyer should include model simulations to account for the complex interactions that affect this ratio [42].

19 Using one of Figures 3-3 to 3-14 in the Executive Summary, rather than Figure 3-15, would better illustrate the extra margin of safety in the present ozone standard resulting from the practice of using the largest design value at any monitoring site to classify an area [43].

20 Chapters 4-6 should give more emphasis to the issues raised by Dr. Chock at the September 10, 1992 public meeting, relating to deriving design values from multiple years of data [44].

21 Chapter 4 should reflect the new recurrence rate (every year, not every seven years) used in CARB's tail exponential method [45].

22 Chapter 7 should investigate analyses that treat each year separately rather than combining ozone and meteorological data for several years, and should recognize secondary influences of meteorological parameters on emissions [46].

23 Chapter 8 should discuss the use of the UAM and coupled urban and regional models to evaluate transport effects [47].

24 Chapter 9 should discuss the recent work of S. T. Rao [48].

25 Chapter 10 should have more discussion of the data in the tables with respect to robust indicators [49].

26 Chapter 11 should address issues related to the form of the standard or the attainment test because these are not treated in the External Review Criteria Document, where the EPA would prefer they be addressed [50].

DR. KAY H. JONES, ZEPHYR CONSULTING

- The report did not properly acknowledge the early work and analyses by Dr. Jones of the adjustment of ozone trends to account for year-to-year variation in in the frequency of ozone conducive days. The adjustment of ozone exceedances for temperature should be shown.

- The report did not properly reference the earlier work of the Council of Environmental Quality on the adjustment of ozone trends to account for temperature that was contained in their annual reports, *Environmental Quality 1984* and *Environmental Quality 1987-88*.

MOBIL OIL CORPORATION

1 The EPA design value does not provide a reasonable estimate of "area-wide nonattainment" since spatial variability in concentrations is not accounted for.

2 Because year-to-year fluctuations cause significant variability in ozone concentrations, the design value calculation should account for meteorological variability and thus minimize the effect of aberrant years like 1988.

3 As the EPA recognizes the value of using multiyear data, which are more stable statistically than one-year values, the design value calculation should use methods like the CARB 7-year method to remove outliers from the database.

4 As the EPA acknowledges that a tail exponential function is a more robust statistic of extreme 1-hour ozone concentrations, it should include a probabilistic (tail exponential) estimation tool or a time-series tool based on a characteristic (extreme value) distribution.

5 The current design value's variability adds cost and uncertainty to the task of planning air quality policy and control technology.

NATIONAL INSTITUTE OF STATISTICAL SCIENCES

General Comments (numbers are paragraph numbers)

- The current procedure is reasonable but improved robustness should be sought by considering alternatives such as those based on exponential tail assumptions [1-2].

- A distinction needs to be made between the true design value, expected to be exceeded once per year, and estimated design values [3-4].

- The design value is not used as the ozone NAAQS compliance test but rather as a classifying statistic that indicates air quality in nonattainment areas [3].

- The study focuses on the fundamental issue of comparing methods of estimating the design value but inadequately treats the important issue of how to take spatial variation into account when using design values at different sites to assess area air quality [5-9].

- Desirable properties of a design value that are shared by the EPA estimator are that it is easy to understand, the definition is the same at every site, and that the general form of the distribution of the (estimated) design value is statistically well determined (i.e. the general shape is approximately known, and the parameters that define the specific shape at a given site can be well estimated) [10-12].

- A desirable property of a design value that may not be properly shared by the EPA estimator is low variability, which is needed to reduce misclassification probabilities [10, 12-15].

- Example calculations of misclassification probabilities for attainment/-nonattainment designations (based on estimated expected exceedances) and for nonattainment classifications (based on estimated design values) suggest the need to consider wider ranges for the nonattainment classification definitions and the use of "too close to call" categories for attainment/nonattainment designations [13-15].

- Design value estimators based on fitting a parametric distribution to the entire data set are less desirable because they may tend to be site specific and to give a relatively poor fit in the tail of the distribution [16].

- The fitting of the tail exponential (or more general tails) should be considered an important alternative to the EPA procedure, although it is more complex and may not apply at all sites [17-18].

- Exclusion or downweighting of exceedances based on meteorological adjustment needs careful scientific justification, which may be obtained with improved knowledge of the dependence of ozone on meteorology and ozone precursors [19].

- The study is generally an extremely well considered document [19-20].

Detailed Comments (numbers are referenced pages from the draft document)

- Attainment determinations are based on estimated rather than true design values [1-2].

- The advantages of reproducibility and uniformity can also apply to other methods [1-3].

- The advantage that the EPA design value only uses summary statistics is not important with the use of modern computers [1-3].

- Mention of any disadvantages of the EPA design values should be made here [1-3].

- Different evaluations of the ability of EPA design values to indicate nonattainment area ozone air quality are based on the site-specific misclassification probabilities or on measures of spatial uniformity [1-4, 2-9].

- Using three years of data for design values is more stable than using one year [1-6].

- The statistical modeling approach design value may correctly indicate nonattainment when the attainment test wrongly indicates attainment [1-9].

- Comments on alternative forms of the ozone NAAQS may be relevant to the design value study since a revised ozone NAAQS might better correspond to a different design value [1-11].

- Finding 4 of high spatial variability suggests the problem that nonattainment is more likely for areas with more monitoring sites, which may result in inequities between different areas [1-16, 2-1, 2-10, 2-11, 11-4].

- An explanation is needed for the fact that 38 sites met the standard in 1989–1991 but were not redesignated to attainment [1-17].

- The conclusion section should discuss the crucial issues of the performance of the design value estimates and their ability to accurately classify nonattainment areas [1-18].

- The design value definition should be kept consistent and explicit throughout the report as "the concentration with an expected exceedance rate of one per year," rather than "the value that should be reduced to the standard level thereby ensuring that the site will meet the standard," which defines the design value for nonattainment areas only [2-1, 4-1, 6-1, 9-1, etc.].

- Based on a Poisson approximation, an area just in attainment will have two or more exceedances 26 percent of the time and three or more exceedances 8 percent of the time [2-3].

- If the three-year EPA design value is used it can be less than the NAAQS for a nonattainment area only if the monitoring record is incomplete [2-3].

- NAAQS attainment/nonattainment criteria are equivalent to comparing the fourth highest in three years with the standard [2-4].

- The same percentage emission reduction on different days can lead to different estimated changes in ozone concentrations according to the EKMA [2-4].

- Computer modeling should be adaptable to treat estimated design values that did not actually occur [2-4].

- The single $(n+1)$th highest value is likely to be more variable than estimates based on more values or based on fitted distributions, as illustrated in McCurdy and Atherton (1990) [2-4, 2-10].

- For an area just in attainment, reasonable Poisson approximations lead to a probability of only 0.23 for having different designations in two consecutive years [3-19].

- The same Poisson approximation shows that it is much more likely (probability 0.61) that a borderline nonattainment area is misclassified compared to the 0.35 probability of misclassifying a borderline attainment area [3-19].

- The 95th percentile has less variability, but it may not be statistically similar to the EPA design value in all locations [3-19].

- It is not clear why using alternative design values for nonattainment area designations and classifications would require revision to the NAAQS and the CAAA [3-19].

- The text wrongly implies that a deterministic relationship to the current NAAQS design value, rather than just a statistical relationship, is required to justify the use of the 95th percentile [3-20].

- Use of the 100 × 364/65th percentile as the design value assumes the same distribution throughout the year [4-3].

- A reference to the "comprehensive" book by Leadbetter et al. (p. 5-22) is appropriate here [4-3, 4-7].

- The extreme value approximation is often improved using fitted rather than theoretical constants or by fitting the three-parameter extreme value distribution rather than the limiting two-parameter distribution [4-4].

- The reviewer agrees with the "growing concensus" in favor of the tail exponential approach because it requires fewer assumptions than a total parametric fit, probably gives a less variable design variable, and may be more universally applicable than other candidate distributions [4-4].

- In some cases even strong serial dependence can still lead to the same form of the limiting extreme value distribution [4-6, 5-9].

- Use of a lognormal distribution requires that the log transformed concentrations are regarded as the fundamental measurement, and/or that the geometric mean is regarded as the fundamental average [4-6, 4-7].

- Clusters of more than one exceedance rarely occur in practice but have been analyzed in a cited paper [4-8].

- More discussion of the conditional probability approach is suggested [4-1, 4-9].

- Robustness seems to be defined inconsistently as either (a) the property of not being overly dependent on distributional assumptions, (b) the use of a less variable statistic, or (c) the property that the distribution does not vary significantly across sites [4-11, 6-22, 11-1, etc.].

- Warnings should be given that some of the cited references (e.g., references [7] and [8]) erroneously assume that if the daily maximum concentrations are Markov (have a conditional distribution that depends only on the most recently

observed concentration), then the binary exceedances form a Markov chain [5-8, I-11].

- The missing value procedures used in Davison and Hemphill's paper (15) might be more generally applicable, and suggest the need for a review of the missing value procedures in the NAAQS [5-8].

- Figure 5-4 demonstrates the fact that the distribution of ozone concentrations is not the same throughout the ozone season, which suggests that the process of estimating a design value using a single distributional fit is inherently contradictory [5-15].

- Section 6.0 appears to have the same objective as Table 5-1 [6-1].

- The fitting of a single tail exponential distribution to a year of daily maximum concentrations is inappropriate because of nonstationarity (trends within the year) unless either nonstationarity is regarded as negligible, or the tail only contains data from a single "high season," or the procedure seems "sensible though ad hoc" [6-1].

- It would be interesting to know how many of the areas given in Table 6-4 were correctly classified [6-17].

- The term CLV is not widely used and is easily confused with the design value; a better approach would be to refer to the CLV as the (true) design value and the design value as the estimated design value [6-25, 6-29].

- The referenced 3-year 95th percentile does not appear in Table 6-11 and "estimated average CLV" is not clearly defined [6-30].

- The arguments made that a poor regression fit implies the 95th percentile gives a poor design value estimate are not convincing [6-30, 6-31].

- The regression line CLV = $1.896S - 0.046$ closely approximates the exponential case result CLV = $2S$ [6-41].

- The role of meteorology in ozone formation is of interest because future control requirements may take it into account, and also because it should be an important part of any stochastic models for exceedances [7].

- Some discussion about the purposes of meteorological modeling should be included here [7-1].

- Scalar and vector average wind speed should be defined [7-4].

- Complex models such as those of Cox and Chu (1991) and Shively (1990) may tend too much to be tailored to fit the specific local data [7-15].

- Those complex models usefully take into account the variation of the concentration distribution by assuming that the parameters of the distribution on consecutive days depend on meteorological variables [7-15].

- The purpose of Cox and Chu's linear transformation of meteorological variables is unclear [7-15].

- As noted, the Bonferroni approach can lead to wide, and then perhaps not very useful, confidence intervals [9-4].

- The absence of trend does not imply exactly equal annual exceedance rates [9-7].

- Independence between sites may not be too realistic an assumption; if there is dependence then the total number of exceedances summed across sites could be modeled as compound Poisson rather than simple Poisson [9-8].

- The assumption made by Shively (ref 19) of identical daily distributions within a year seems tenuous [9-9].

- Several papers by the reviewer and others give a more formal theoretical treatment than Smith's of the clustering of exceedances [9-9, 9-10].

- Sufficiency of the 75 percent completeness criterion used for the EPA table lookup procedure could perhaps be easily evaluated [10-1].

- The "expected exceedance rate" should be the "estimated expected exceedance rate" [10-1, 10-4, etc.].

- The percentiles of the daily maximum concentrations are presumably from a mixture of distributions applying to different parts of the ozone year [10-15].

- The 95th percentile should intuitively be somewhat less variable than the fourth highest, but this is not supported by the evidence presented [11-2].

- The mean of the highest 30 values is a close relative of Hill's estimator for the exponential tail parameter and therefore may be worth consideration [11-2].

- Less variable statistics may behave equivalently to exceedances at one site but not at another [11-2].

- Meteorological adjustment has a role in assessing the effects of controls, but the EPA correctly points out that health is affected by actual rather than meterologically adjusted ozone [11-2].

- Consistency between the design value and the compliance test is natural, aesthetic, and traditional but modest departures from consistency would be justified if good statistical properties were then achieved [11-3].

- It does not appear that the 95th percentile has compelling statistical advantages [11-3].

- The oscillation between attainment and nonattainment, and the suggested "too close to call" procedures both deserve study [11-3, I-13].

- Design value estimates could be used to determine compliance if matched to the NAAQS; e.g., if the fourth highest value in three years is used [12-1].

- Regarding Finding 8, the control strategy value is likely to be more uncertain than the design value because of imprecise knowledge about ozone transport and the use of models; a corresponding control strategy based attainment test would thus have further uncertainty problems [12-3].

- A search for simple but more "robust" procedures or modifications to the NAAQS is valuable [12-4].

- An important test of the reasonableness of the EPA design value methodology is the degree of correct classification [12-4].

- Data from years of small variability may also not provide reasonable estimates of ozone levels in future years since the time period for the design value needs to include both large and small fluctuations [12-4].

- Although the study authors' work has been exceptionally thorough, a reader should realize that inclusion of a paper in the summaries is not an endorsement and does not guarantee correctness [Appendix].

- Spatial variability is an important issue that fortunately can to an extent be treated separately from the problem of single-site design value estimation; ORD and AREAL work on monitoring network design using techniques of geostatistics may be relevant to ozone [I-7].

- This summary may need further clarification [I-8].

- Chock's papers represent impressive scientific inquiry; Chock's t-test proposal may lack simplicity and may not be uniform across sites [I-9, I-12].

- The cited paper has a fundamental mathematical error [I-11].

- Since there is a 65 percent probability of misclassifying a borderline, noncompliant site as compliant using the current NAAQS (the converse case has a 35 percent probability), the argument should lead to more stringent, rather than less stringent, alternatives to the NAAQS [I-13, I-14].

- Ozone transport is an important concern and current adjustment procedures are somewhat ad hoc [I-16, I-17].

- Meteorological effects on ozone variability should be studied but the actual ozone levels are crucial to the standard [I-16, I-17, I-20, I-21].

- More explanation about "modeling guidance" is needed to make this summary more generally understandable [I-19].

NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION

1 Conclusions stated in the report regarding the comparison of "alternative" design value methodologies are vague.

2 The issues of meteorological variability and transport are considered only in connection with what the report refers to as the "control strategy design value" and consideration of them is relegated to the NAAQS review process rather than the study, despite the fact that the current design value methodology is used to classify nonattainment areas and hence determine control requirements [7-8].

3 The report should clarify the relation between determination of attainment and determination of a design value, particularly the treatment of "expectations" in the two procedures, since some relevant factors in these expectations (such as temperature) would be categorized as "control strategy design values" and hence could not be considered in nonattainment classification [9-11].

4 While the CAA explicitly mentions use of design values in connection with attainment determinations, the report reiterates the EPA's position that attainment is based strictly on exceedances [9].

5 While the use of longer periods of data to determine design values would reduce the effects of meteorological variability, it would also mask indications of progress toward attainment and could lengthen a nonattainment region's wait for reclassification [12].

STATE OF OHIO ENVIRONMENTAL PROTECTION AGENCY

1 The report holds that adjustments to the design value, to allow for transported ozone for example, should be called "control strategy adjustments" as diffrentiated from the "air quality design values" estimated from monitoring data [1-2].

2 Although the report shows that use of a fitted statistical distribution instead of the look-up table procedure for determining the design value does not produce significantly different design values, the use of a fitted distribution can result in areas being reclassified nonattainment that are presently designated attainment on the basis of the look-up table [3-4].

3 Use of longer averaging periods would have little effect on reducing the impact of an unusual year such as 1988 [5].

4 Methods that adjust for transport and meteorological variability cannot be used under the CAA in judging attainment, and hence must be considered under the NAAQS review to correct design values for Ohio that are extremely high [6-8].

5 Control requirements should be reviewed on a rolling three-year basis, which would avoid the effect of the extreme 1988 air quality measurements on setting control requirements (that are inappropriate given the last five years of near-attainment ozone levels) and would be more consistent with the methods used to evaluate redesignation requests [9].

6 If Section 181(b)(2) of the CAA does not allow for adjustment of the design value to account for transport and meteorological variability, then a "control strategy design value" that permits such adjustment should be adopted [10].

APPENDIX K

Misclassification Probabilities for Design Value Classes

$$P = Pr\{N_1 \geq 4, N_2 < 4\} = P\{N_1 \geq 4\} - P\{N_2 \geq 4\}$$

where N_1 and N_2 are the numbers of exceedances in three years of the levels .121, .138. These are Poisson random variables with respective means $3\lambda_1 = 9.0$, $3\lambda_2 = 5.4$, so that $P\{N_1 \geq 4\} = .979$, $P\{N_2 \geq 4\} = .787$ and hence $P = .192$. Thus there is a 19% probability that the area – actually borderline between moderate and serious – will be misclassified as marginal (and corresponding probabilities for other misclassifications).

Example 2: Suppose the area is in the middle of the serious region, with D.V. $u = 1.7$. Then $\alpha = 27$ and the expected numbers of exceedances per year of $u_1 = .16$, $u_2 = .18$ are respectively $\lambda_1 = 1.3$, $\lambda_2 = .78$. Hence the numbers N_1 and N_2 of exceedances of u_1 and u_2 in 3 years are Poisson with respective means. 3.9, 2.34 giving the probability of correctly classifying the area (as serious) as

$$P\{N_1 \geq 4\} - P\{N_2 \geq 4\} = .547 - .209 = .338.$$

Example 1 shows a significant probability that a D.V. will be estimated in a class which is not contiguous with the true 1. Example 2 shows substantial probability (66%) of a wrong classification.

Assuming arithmetic correctness these examples suggest that misclassification probabilities by the D.V. estimate may be rather high. If this is the case two options are

(i) to use less groups in the classification;

or (ii) to investigate other D.V. definitions, of the type considered in the study, based on more observations than just the fourth largest.

Finally, these examples assume a distribution of totally exponential form (not just in the tail). Certainly other cases should be considered, with tail behavior approximating some found in practice, before regarding the above calculations as at all conclusive. It may be noted incidentally that the exponential tail form with $\alpha = 29$ is close to that actually observed in Philadelphia data, as shown on Attachment D.

Attachment A

Misclassification probabilities
for given true annual expected exceedance rates,
under the expected exceedance criterion

	True annual expected exceedance rate m	Misclassification probability
Actually compliant cases ($m \leq 1$)	1	.35
	0.9	.29
	0.8	.22
	0.5	.07
Actually non-compliant cases ($m > 1$)	marginally > 1	.65
	1.1	.58
	1.2	.52
	1.5	.34
	2.0	.15

Attachment B

Misclassification Probabilities for Design Value Classes
(EPA estimator)

The ozone classification quoted in the study define classes as follows:

Class	Design value (ppm)
Marginal	.121 to .138
Moderate	.138 to .160
Serious	.160 to .180
Severe	.180 to .280
Extreme	.280 and above

A nonattainment area is classified in a given class if the estimated D.V. – the fourth highest daily maximum in 3 years – falls in the indicated range. These calculations given two examples of the probability that the D.V. estimate will give an incorrect classification.

For calculation it is assumed for simplicity that the distribution is exponential with tail $e^{-\alpha x}$ so that the expected number of exceedances of the D.V. u in an assumed 100 day ozone season is $100\ e^{-\alpha u}$. Since this is 1 by definition of the D.V. it follows that the

$$\alpha = -u^{-1}\ \ln .01 = 4.6\ u^{-1}.$$

Example 1: Area on the border between moderate and serious.

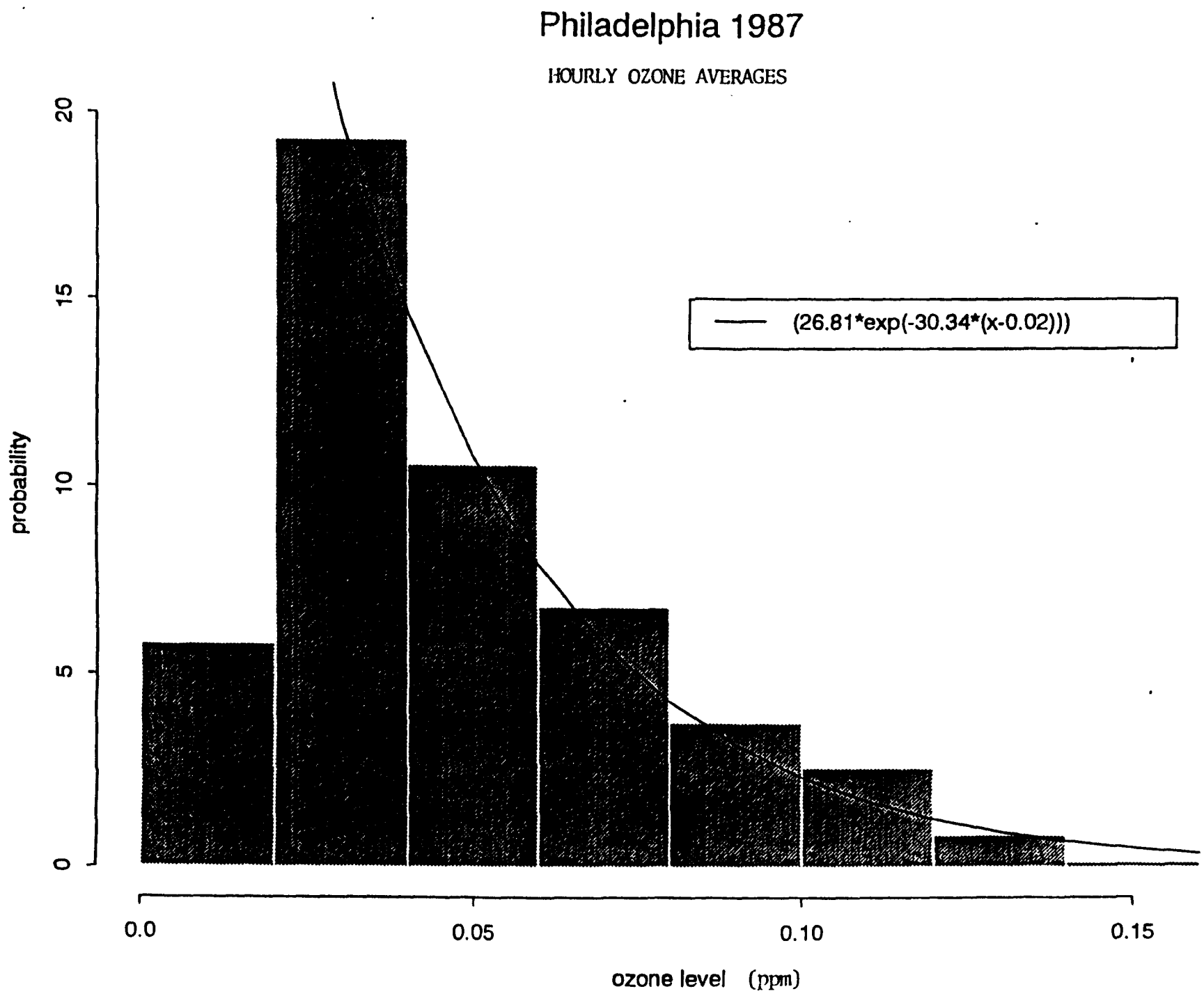
Here the D.V. u = .16 so that $\alpha = 4.6/.16 = 29$.

The expected number of exceedances per year of a level v is $100\ e^{-\alpha u}$. This is

$$\lambda_1 = 3.0 \quad \text{if} \quad v = .121$$

$$\lambda_2 = 1.8 \quad \text{if} \quad v = .138.$$

The probability P that the area will be declared marginal is the probability that the fourth largest daily maximum in 3 years will lie between .121 and .138, i.e.


Philadelphia 1987
HOURLY OZONE AVERAGES
(26.81*exp(-30.34*(x-0.02)))
probability
0
5
10
15
20
0.0
0.05
0.10
0.15
ozone level (ppm)

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES
Mr. T. Stoeckenius and Dr. J. Cohen, Systems Applications International, provided support for the statistical and meteorological analysis. Dr. W. Biller performed the time series analysis.

16. ABSTRACT

Under Section 183 of the Clean Air Act, EPA was directed to conduct a study of the methodology currently in use for calculating design values to determine if the calculated design value "provides a reasonable indicator of the ozone air quality of ozone nonattainment areas." The focus of the study was on technical and statistical issues relating to the methodology contained in existing rules and guidance. Issues concerning the current form of the National Ambient Air Quality Standard (NAAQS) for ozone were not dealt with in the study.

The study found that the EPA ozone design value method does indeed provide a reasonable estimate of the "true" air quality design value for ozone nonattainment areas and of peak ozone levels within those nonattainment areas for the initial 3-year compliance period. However, the design value cannot describe the spatial variability in ozone concentrations across the area. More robust indicators based on specific monitoring sites also have large spatial variability. Ozone design values calculated with the EPA design value method are highly correlated with other more robust indicators. However, due to the spatial variability observed across urban areas, one cannot expect a single numerical value to adequately describe complex concentration gradients across large metropolitan areas.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Design values Ozone Clean Air Act Nonattainment	Air Pollution Regulation	

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