LOCAL BACKGROUND LEVELS OF CARBON MONOXIDE IN URBAN AREAS

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16. ABSTRACT

The objective of this study was to obtain a better understanding of CO concentrations immediately upwind of urban roadways, the "local background" values, and how these concentrations depend upon the surrounding traffic and the general meteorology. Measurements were made at seven sites during the winter of 1993. Local background CO concentrations were characterized by an absence of short term fluctuations, a steady buildup during the period between 3:00 PM and 11:00 PM, and a lack of spatial gradients in the eight-hour average values. Distinctly different log-normal distributions of the eight-hour averages were observed for "trafficked" sites versus "urban park" sites, with mean values of 1.6 and 1.0 ppm respectively. A simple regression model was developed to predict the local background CO. This regression model included distance from the roadway, average daily traffic on nearby roadways, and the frequency of low wind speeds ($R^2 = 0.74$; $F = 170$). A new CO sampler was also developed as a part of this project.

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Research Project T9233, Task 37
Urban Carbon Monoxide

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DISCLAIMER

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Carbon monoxide levels (CO in ambient air) have dramatically decreased in the last 15 years because of reduced emissions from motor vehicles. However, engineers must be able to assess the environmental impacts of new roadway projects, including the resulting increase in CO concentration. This increase must then be added to the area's "local background" concentration. Little is actually known about background CO levels in Washington state; however, several approaches have been used to estimate them. Among these approaches are direct measurement of CO at an appropriate location near the roadway site, estimation of levels using meteorological models, and the use of default values as provided by regulatory agencies.

The broad objective of this study was to obtain a better understanding of "background" CO concentrations in urban areas and their dependence upon location, traffic, and meteorology. "Background" concentration refers to a local reference concentration that is not directly attributable to the emissions from any one source, roadway, or intersection. None of the current monitoring sites in the state of Washington are specifically designated as "background" sites, and various computer models are limited in their ability to predict "background" concentrations. Moreover, "default background" values have been based on information obtained at a time when emissions were higher and prior to the use of oxygenated fuels.

Specific study objectives included the following: (1) to develop and test a low-cost system for measuring CO concentrations; (2) to establish a "background" monitoring network in the Seattle urban area; and (3) to investigate and identify the relationships among traffic, location, and meteorology that best predict "local background" CO concentrations.

A low-cost sampler was developed to reliably collect CO samples over a prescribed averaging time. The resulting sampler uses much less power than

conventional pump/bag units and can operate at much lower flow rates. The reliability of the CO analyzer used in this study was verified by comparisons with independent calibration gases provided by the Washington State Department of Ecology (DOE). In these tests, an accuracy value of 4.6 percent and precision value of 0.4 percent were observed, both of which are well within acceptable limits.

Seven sites were established in the Seattle urban area. The most meteorologically stable period of winter was chosen for analysis. Samples were collected between 3:00 PM and 11:00 PM to provide "worst case" conditions (characterized by high traffic volumes and stable conditions after sunset). The wind speeds and atmospheric stability during our winter sampling period were not obviously different from those of the previous two years. Sampling locations were chosen on the basis of combined distance/traffic criteria, with no site less than 30 m from any roadway and no site less than 70 m from any major intersection.

Local background sites, unlike curbside sites, were characterized by CO concentrations that displayed relatively small short-term fluctuations, a steady buildup during the period between 3:00 PM and 11:00 PM, and a lack of spatial gradients. Distinctly different log-normal distributions of the eight-hour averages were observed for "trafficked" sites as opposed to "urban park" sites. The grand average of all the eight-hour average CO concentrations for all background sites was 1.3 ppm, with an estimated uncertainty of 0.4 ppm. Given the number of sites and the number of days sampled in this study, reduction of this uncertainty from 0.4 to 0.2 ppm would have required an additional 140 winter days of sampling, which clearly would have been an impractical task with diminishing returns.

Our background sites, all of which were located a minimum of 70 m from major intersections, can be grouped into at least two distinct categories: 1) "trafficked" sites (30 m to 100 m from arterials and at least 200 m from major freeways); and 2) "Urban Park" sites (400 m to 700 m from arterials and at least 5 000 m from major freeways).

The mean level observed at the trafficked sites during the period between January 25 and March 11, 1993, was 1.6 ppm. The corresponding mean of the Urban Park sites was 1.0 ppm. The maximum eight-hour average CO concentrations measured during the study was 4.2 ppm; it was observed at a trafficked background site. An "Isolated Park" site, located in a very low traffic area, had consistently lower CO levels (mean = 0.7 ppm) than all of the other sites and appeared to belong to a third site category.

The daily mean of the eight-hour average CO concentrations at the trafficked background sites was compared with simultaneous measurements taken at several street sites to assess the magnitude of the background levels relative to street levels. The ratio of the daily mean value at all trafficked background sites relative to the value at a given street site was computed for each day during the study period. In general, the CO concentrations at the trafficked background sites were about one-half the corresponding values observed at the street sites, even at high street site concentrations.

A simple regression model was developed to predict local background CO; the model included distance from the roadway, average daily traffic of nearby roadways, and the frequency of low wind speeds ($R^2 = 0.74$; $F = 170$). The wind parameter that best described these stagnant conditions was the number of hours during the eight-hour sampling period during which the average wind speed was less than 0.2 meters per second, the wind instrument's detection threshold.

The following procedure for estimating background CO is recommended for use in project level analyses.

<u>For trafficked urban areas</u>

1. Roadways with between 5 000 and 100 000 vehicles per day located at or less than 30 meters from the receptor of interest should be specifically included as a part of the project impact analyses.

2. Roadways with greater than 100 000 vehicles per day located at or less than 200 meters from the receptor of interest should be specifically included as a part of the project impact analyses.

3. The "worst case" 8-hour average background CO concentration from all other surrounding sources (in ppm) = $1.85\ (V_{traf})^{0.048}$, where V_{traf} = the highest average weekday traffic volume within 200 meters of the receptor site (vehicles per day). For example, if V_{traf} = 50 000 vpd, then "worst case" 8-hour average background CO = $1.85\ (50\ 000)^{0.048} = 3.1$ ppm.

For urban parks

4. For roadways with greater than 5 000 vehicles per day located at least 400 meters from the receptor of interest, the "worst case" background CO concentration from all other surrounding sources is 2.0 ppm.

Additional background carbon monoxide may also be present in low-lying areas that are heavily impacted by wood smoke. An upper bound estimate of the contribution of wood burning to background CO at these locations is 0.5 ppm. This estimate is based upon the fine particle concentrations in these areas and the relative emissions of CO and particles from conventional wood stoves and fireplaces. However, this estimate is qualified by the fact that we did not make measurements of CO in these wood smoke impacted areas.

These measurements were made in an urban area that is slightly elevated with respect to the surrounding water. In contrast, some urban areas are located at the bottom of a valley, surrounded by elevated terrain. Therefore, under stable nighttime conditions, the wind flow patterns in our study area may be different from those of a valley location. Valley drainage winds would be expected to "pool" over the urban area, possibly creating different background CO concentrations with different spatial patterns. For these reasons, the results of this study should not be extrapolated to urban areas located in a valley.

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

Carbon monoxide (CO) concentrations in ambient air have decreased dramatically in the last 15 years as a result of reduced emissions from motor vehicles. Nevertheless, when a new roadway project is proposed, engineers must accurately assess its environmental impacts, including the incremental changes in CO concentrations that will result from the proposed project. Such incremental impacts are assessed with computer models. This is done by adding the estimated incremental changes to the area's "local background" concentrations. To ensure that the CO levels in the project area do not exceed air quality standards, the absolute CO concentrations must also be estimated. Unfortunately, little is known about local background levels in the state of Washington.

A number of approaches for estimating these "local background" levels have been reported in the literature. Cooper (1) has written a good general discussion on this subject. One approach is to measure the CO levels directly at an appropriate location near the site in question. Another approach to estimating background CO concentrations is to use a meteorological dispersion model. Yet another is to examine the relationships between traffic volume and measured CO levels at a curbside monitoring site, and then, to estimate the CO level that would have existed in the absence of any local traffic. One more approach is to simply adopt one of several default values suggested by regulatory agencies in the absence of any of the above information. Each of these approaches is discussed below.

Monitoring background CO concentrations at one or more selected sites over a given period poses several potential problems. Not only are the criteria for choosing an "appropriate" location unclear, but so is the choice of representative meteorological conditions. Ott and Eliassen (2) and Ott (3) published several criteria for location of "background exposure stations." Specifically, the sites should be located no fewer than

100 meters from streets that have average daily traffic volumes of under 500 vehicles per day. Typical locations would include parks, malls, or landscaped areas that have no traffic. Perardi et al. (4) also measured CO levels at sites located within 1000 meters of major roadways (>10 000 vehicles per day) in San Jose, California. Other investigators have reported highly variable background values immediately upwind of intersections (5,6). or totally removed from the city center. (7) Although these studies were done in the late 1970s and early 1980s, when CO emissions were much greater than they are today, the results of these investigations generally support the notion that local background levels can be measured directly. However, there is no consensus as to the distance from which a background monitor should be placed from the roadway or the acceptable maximum traffic volume on the roadway closest to the background site. Moreover, there are no criteria that can be applied to the measurements at a given location to confirm whether that location is indeed a local background site. Finally, there is no specific guidance as to the number of samples that are needed per site or the meteorological conditions that are most appropriate for sampling.

Computer models that describe the emission and dispersion of CO over the area surrounding an intersection have been used to assess the magnitude of background concentrations as opposed to curbside CO concentrations. An important and unresolved question is the size of the surrounding area that should be included in such models. Some investigators have adopted models that include a multi-block area within 300 to 1000 m of the intersection (8,9,10), while others have included the entire urban area. (11) Uncertainties associated with these models include the spatial distribution of emissions, the effects of complex terrain (hills, valleys, and surrounding buildings), the importance of very low wind speeds that cannot be measured with standard wind sensors, and the magnitude of vertical mixing under stable conditions. For these reasons, the predictions from any such models should be compared with local CO measurements at background sites in the region of interest before this general approach can be used with confidence.

Another general approach is to use statistical models to correlate CO concentrations from existing curbside monitors with coincident traffic volumes. The concentration predicted via extrapolation to minimum traffic volume is sometimes assumed to be the local background value. However, this residual background value may not reflect actual conditions because the time periods with low traffic volume are not necessarily the time periods of interest. The local background values needed are those that exist during peak traffic periods and during unfavorable meteorological dispersion conditions. To address this problem, time series analysis has been used to determine the local background at high impact sites. (12) This approach involves detrending the CO time series to remove impacts that occur during periods of high traffic volume. When this traffic "signature" is removed from the measured CO values, the remaining residual concentrations are defined as the local background values. However, this approach cannot specifically assess the magnitude of local background levels that exist off the roadway. It cannot distinguish between the average CO concentrations that exist within the roadway "mixing zone" and the concentrations that exist immediately upwind of the roadway. Both of these concentrations may be lower than the levels measured at curbside.

In the past, regulatory agencies adopted "default" background values based on unofficial recommendations. (13,14) Primarily because of the research of Ott and Eliassen (2,3), a distinction has been made between sites located in central business districts and those located in suburban or rural areas. Typical default values for 8-hour background CO concentrations are 3.5 ppm for central business districts, 2.1 ppm for suburban locations, and 0.7 ppm for rural locations. (13) These values are usually adjusted for the future through the use of locally derived emission factors. However, this approach does not reflect recent changes in CO emissions due to oxygenated fuels; as such, it is problematic.

PROBLEM STATEMENT

The broad objective of this study is to obtain a better understanding of "background" CO concentrations in urban areas and their dependence upon location, traffic and meteorology. This "background" concentration is not the lowest background level upwind of the urban area but, rather, a local area reference concentration that is not directly attributable to the emissions from any one source, roadway, or intersection.

Information on local background levels in the state of Washington is scarce. None of the current monitoring sites in the state are specifically designated as "local background" sites. Moreover, no measurements intended to specifically characterize "local background" CO concentrations have ever been taken in this region. Statistical models used to estimate background levels at existing Environmental Protection Agency (EPA) curbside sites are limited by their inability to distinguish on-road from off-road levels. To date, urban scale computer models have not been used to estimate background levels in this area. Finally, the use of default values is problematic because they have been based upon information gathered when emissions were higher and before oxygenated fuels were in use. Because of these problems, new information on local background levels in this region is needed.

Estimation of this background will require an understanding of the inter-relationships among traffic patterns, emissions, and dispersion processes; however, this information is not yet available. Therefore, this study was designed to meet the following objectives:

- to develop and test a relatively low-cost system for measuring background CO concentrations and to establish an appropriate monitoring network in the Seattle urban area;
- to investigate the relationships between the measured background CO concentrations and site location, surrounding traffic, and meteorology; and
- to identify those traffic and location characteristics that best predict the "local background" CO concentrations.

RESEARCH APPROACH

Our approach was to select background sampling locations, to collect and measure CO concentrations, and to summarize the results in a form that should be useful to those who assess the environmental impacts of proposed roadway projects. We chose to sample during the most meteorologically stable period of the winter to capture "worst case" meteorological conditions accurately. Samples were collected between 3 PM and 11 PM because this period is characterized by high traffic volumes and stable conditions after sunset. Site selection criteria were based on previous research. In addition, we established a meteorological monitoring site within the study area to measure wind speeds typical of urban intersections rather than to measure meso-scale winds. Finally, the information on CO and meteorology was combined into a statistical model that describes background CO concentrations.

Sampling Locations

Sampling locations were chosen on the basis of combined distance/traffic criteria that were based on the field work of Ott (2) and Perardi (4) and the theoretical results of Matzoros and Van Vliet. (8) We chose "trafficked" sites that were at least 30 m from any roadway, 30 to 100 m from roads with at least 8 000 to 10 000 vehicles per day, and at least 200 m from major freeways (>200 000 vehicles per day). In addition, "less trafficked" sites were located within urban parks at a distance of 400 to 700 m from similarly trafficked roads. All sites were at least 70 m from major intersections. The sites are listed in Table 1, and their locations are illustrated in Figure 1. The University of Washington carbon monoxide sampler described in the next section was utilized at all sites except those operated by the Washington State Department of Ecology (DOE). Detailed site maps are included in Appendix A.

Carbon Monoxide Measurement Methodology

The University of Washington (UW) carbon monoxide air sampler was developed as a part of this project to provide a low-cost, reliable method of obtaining ambient

Table 1. Local Traffic at Background Sites

Site	Site Code	Distance to Roads (m)	Roadway Traffic*
Roosevelt	ROS	30	19 000
		75	10 000
Green Lake	GRL	100	10 000
		210	250 000
Maple Leaf	MLF	90	8 000
		160	12 000
		180	9 000
Univ. of Wash.	UW	50	46 000
		230	15 000
Magnuson Park	MAG	730	14 000
Richmond Beach Pk.	RBH	320	1 500**
		460	10 000**
Discovery Park	DIS	625	5 000
		650	7 000
Zanadu***	ZA	2	8 000
		30	25 000
Northgate Mall***	NG	2	30 000
		300	250 000

* 1991 average weekday values from the City of Seattle Traffic Engineering Division
** 1992 average weekday values from King County Transportation Planning Section
*** Air monitoring sites operated by Washington State Dept. of Ecology for regulatory purposes

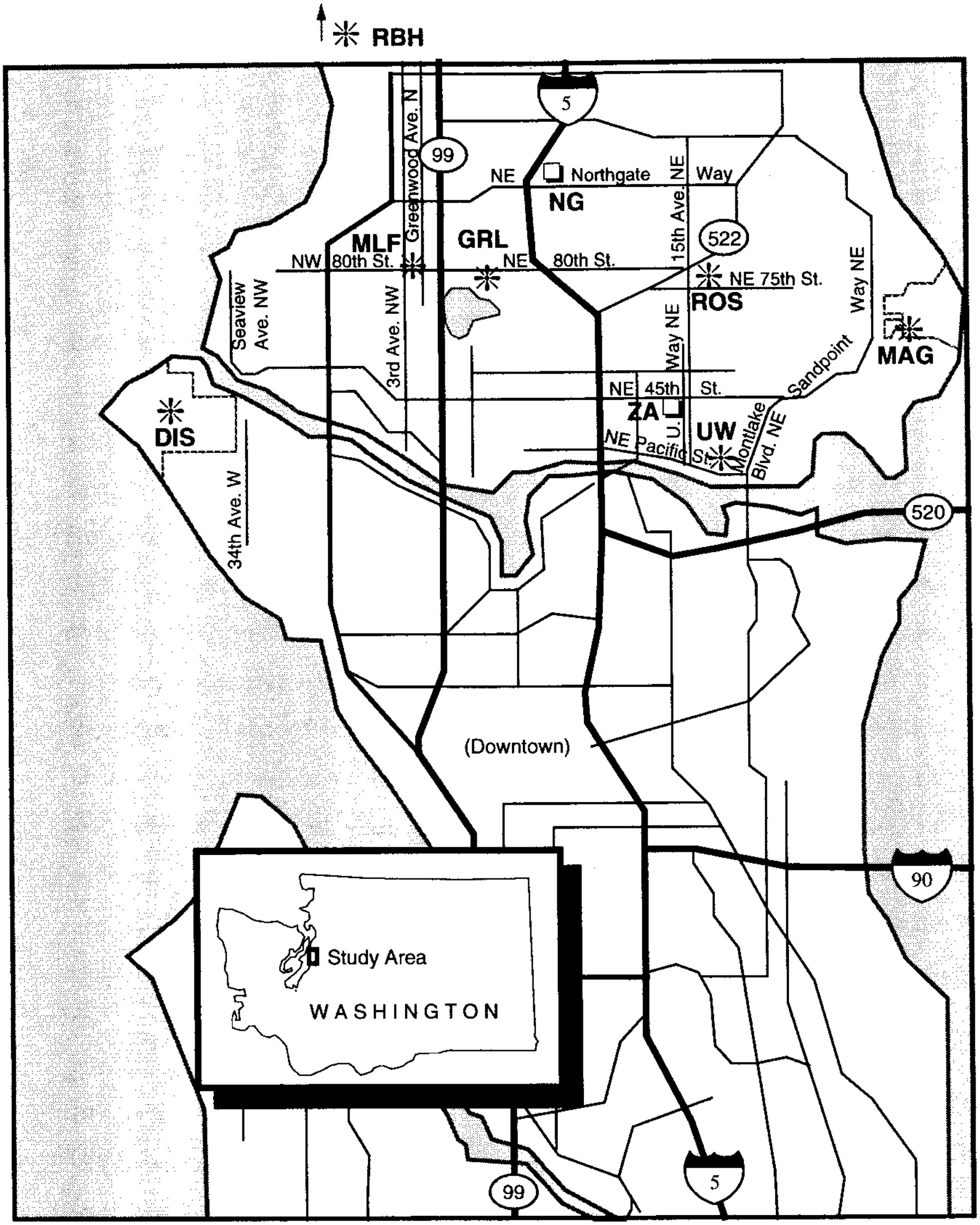


Figure 1. 1993 Urban "Background" Carbon Monoxide Sampling Sites (✳) and Two Department of Ecology Air Pollution Monitoring Sites (❑)

carbon monoxide measurements over a wide urban area. It is capable of obtaining a batch sample of ambient air drawn at a constant flow rate over an extended period for the purpose of determining a time-averaged carbon monoxide concentration value. A detailed description and evaluation of our sampling and analysis system are given in Appendices B and C. The averaging period used for this study was 8 hours; however, a simple adjustment to the sampler allows for other averaging periods.

Collected samples were analyzed at the UW with a Lear-Siegler model ML9830 non-dispersive infrared photometer. This instrument is designated as a reference method by the EPA. Zero and span gases were used for daily calibration of the instrument, along with a third, intermediate-value gas used as a precision check. The accuracy and precision of this instrument were examined in cooperation with the DOE. Access to a certified, continuous carbon monoxide monitor and calibration gases was obtained. This monitor is located in Seattle's University District at the Zanadu Comic Book Store on 45th Street N.E. Repeated analysis ($n = 8$) of the DOE calibration gases was employed to evaluate the accuracy of the calibrated Lear-Siegler analyzer. The results of these tests indicated an instrument accuracy of 4.6 percent and an instrument precision of 0.4 percent. Accuracy is defined as the ability of the instrument to give a reading that matches the true value of a standard gas, expressed as the average percentage of deviation from the true value. Precision is defined as the ability of the instrument to give reproducible results with repeated analysis of the same gas, expressed as the coefficient of variation multiplied by 100.

The performance of the UW carbon monoxide air sampler was compared with DOE pump samplers. Eighteen paired, 8-hour air samples were collected, and the CO concentrations were measured in the laboratory on the Lear-Siegler continuous CO analyzer. All of the paired data are shown in Figure 2. The DOE and UW samplers were highly correlated ($R^2 = 0.99$). During the project sampling period (January 25 to March 11, 1993), several UW air samplers were also co-located near the inlet of the continuous

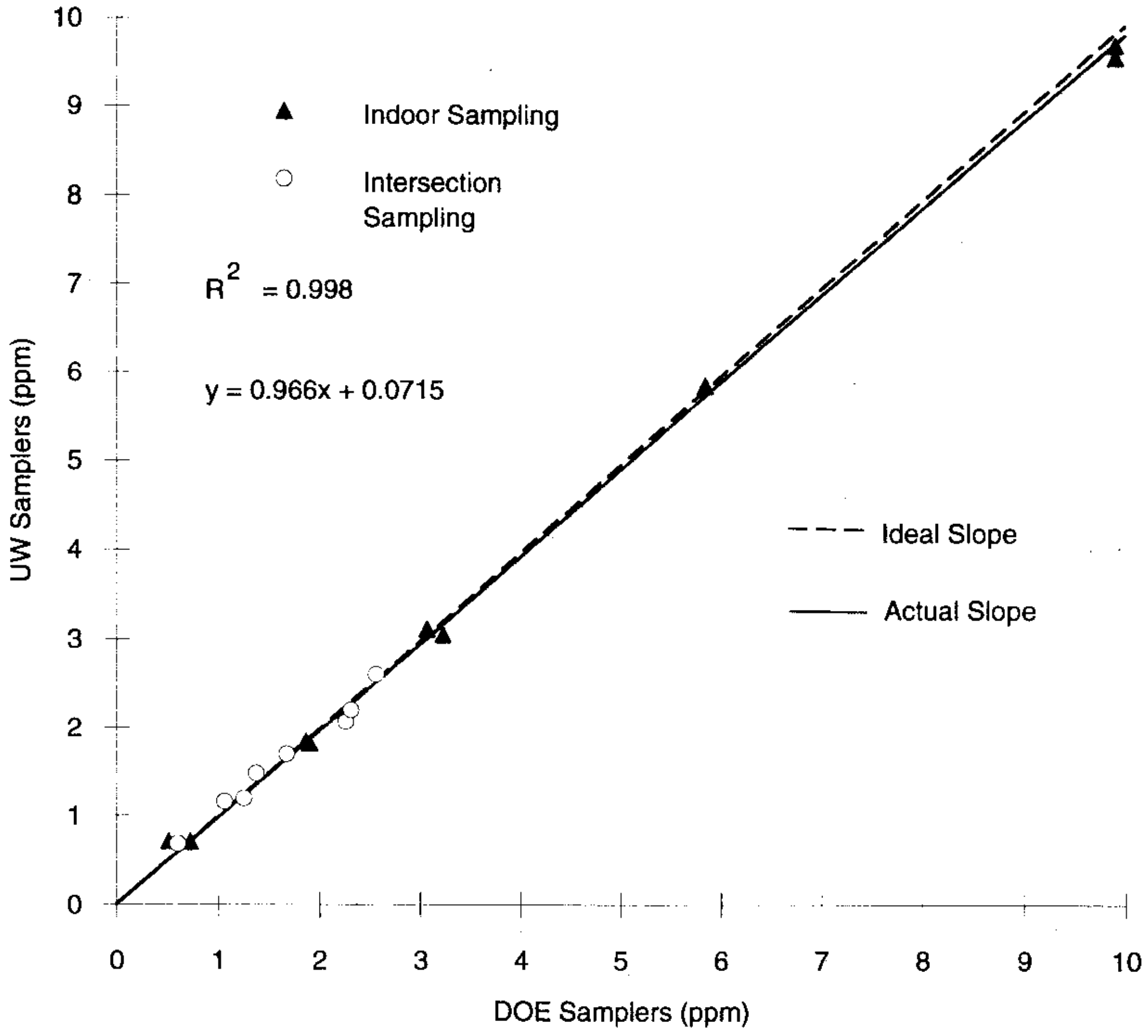


Figure 2. Comparison of UW and DOE Bag Samplers,
8-hr CO Concentration, June - July 1993

CO monitor at the UW site. The distance between the UW air sampler inlet and the inlet to the continuous monitor was approximately 6 to 7 m. This location allowed for comparison, on a regular basis over the study period, of 8-hour average readings from the continuous monitor with the 8-hour average values obtained with the UW air samplers. Because the inlets were located a few meters apart, some deviation between the two measurements was expected. The data are shown in Figure 3. Regression analysis showed that the 8-hour CO concentration values produced by the UW air samplers were highly correlated (R^2 = 0.985) to the 8-hour values produced by the continuous monitor. From these results, we concluded that the accuracy and precision of the UW monitor is reasonable and that the UW air sampler gives consistent, reliable results.

Measurement of Wind Speed

A wind sensor (Weatherpak-100™ Automatic Weather Station, Coastal Climate Company, Seattle, Wash.) was placed 3 m above the roof of Wilcox Hall on the UW main campus. The Weatherpak was programmed to store 15-minute averages, on the hour, of air temperature, wind speed, wind direction, and standard deviation of the wind direction. Data collection began in December 1992 and continued through March 1993. Data were stored weekly on a computer.

The Weatherpak was calibrated at the National Oceanic and Atmospheric Administration (NOAA) wind tunnel facility, located at Sand Point in Seattle, Wash. The range of wind speed calibration was 1.48 to 8.22 meters per second (m/s). The Weatherpak indicated approximately 4 percent lower wind speeds than the "true" wind speeds of the wind tunnel. The Weatherpak wind speeds were highly correlated (R^2 = 0.9996) to the NOAA "true" wind speeds (complete calibration data are given in Tables 2 and 3). This calibration procedure is more rigorous than the standard EPA field method (15) in that it tests not only the tachometer but also the propeller calibration. The stated instantaneous threshold of 0.2 m/s could not be validated because the wind tunnel did not generate accurate wind speeds in this low range.

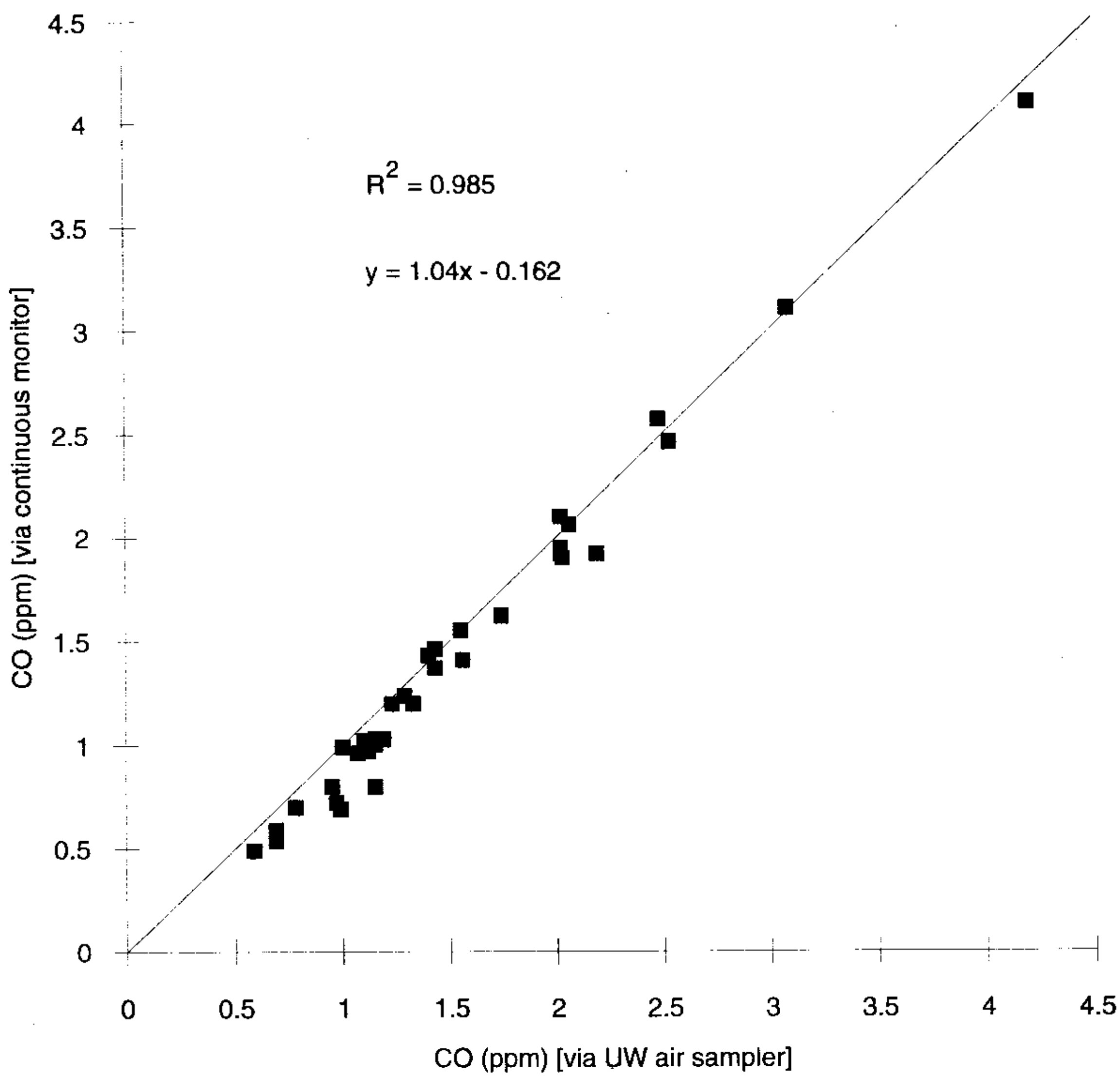


Figure 3. Comparison of 8-hr Average CO Concentration Obtained with UW Air Sampler (abscissa) to Concentration Obtained from Continuous Sampling with Lear-Siegler Analyzer (ordinate)

Table 2. Wind Tunnel Parameters

Wind Tunnel		Standard Cup Anemometer			
Fan Motor Current (amps)	Nominal Wind Sped* (m/sec)	Total Revolutions# (cycles)	Time Period (sec)	Rotation Frequency (Hz)	Measured Wind Speed** (m/sec)
10.5	1.5	371	10	37	1.48
26	3.5	830	10	83	3.44
38.5	6.5	1666	10	167	6.58
46.5	7.8	2102	10	210	8.22

*Value taken from look-up table provided by PMEL
** Value computed from the following formula provided by PMEL:
wind speed (m/sec) = 0.03782 * [Rotation Frequency (Hz)] + 0.281635
The arithmetic average of ≥ 5 replicate measurements at a given motor setting

Table 3. Wind Speed Calibration Data

Reference* (m/sec)	Weatherpak (m/sec)
1.48	1.15
3.44	3.15
6.58	6.09
8.22	7.64

* "True" value taken as PMEL standard cup anemometer value

FINDINGS

DISTINGUISHING CHARACTERISTICS OF BACKGROUND SITES

Short-Term Fluctuations

How does one know whether measurements have been made at a "background" site? One important phenomenon that distinguishes background sites from street (EPA micro-scale) sites is short-term fluctuations in the CO concentration due to passing mobile sources. At a street site, these rapid fluctuations account for a significant fraction of the longer term average value and vary not only with traffic flow but also with wind direction. Fluctuations of the 1-minute average CO concentration can be quite pronounced at street locations. By contrast, the 1-minute average fluctuations at background sites, i.e., sites located some distance from roadways, are much less pronounced. There is also a noticeable absence of spatial concentration gradients in the longer term (e.g. 8-hour) average CO concentrations at these background sites, and therefore, there is a correspondingly high degree of spatial correlation of longer term concentrations among background sites.

This phenomenon was examined at several of our background sites. One-minute average CO concentrations were recorded over a 4- to 8-hour period on different days at the UW, GRL and ROS, sites as well as at the ZA street site using our continuous Lear-Siegler monitor. To characterize the fluctuations in these short-term concentrations, we computed the geometric standard deviation (s_g) of CO concentration for each non-overlapping, 5-minute period within the overall sampling period. This resulted in 12 values each hour. The results are summarized in Table 4. As shown, s_g was larger at the street sites than at the background sites, reflecting the fact that short-term fluctuations at the street sites were more pronounced.

Table 4. Observed Short-Term Fluctuations at Background and Street Sites

Site	Number of Measurements (n)	Geometric Standard Deviation
Background Sites		
GRL	480	1045 (0004)*
ROS	480	1044 (0005)
UW	330	1109 (0008)
Street Sites		
ROS**	480	1243 (0010)
ZA	240	1353 (0016)

*mean of (n/5) measurements; parentheses indicate standard error of the mean; see text for details
** temporary site located 2 m from nearby roadway (19 000 vehicles per day; see Table 1)

Time of Occurrence of Peak Hourly Value

In a separate experiment, the continuous CO analyzer also recorded 1-hour averages at the UW background site for 36 days during the study period. We compared the time of occurrence of the maximum hourly CO concentration during the 3 PM to 11 PM period on a given day at the UW site with the corresponding values at the ZA and NG street sites. A distinguishing feature of the UW background site was the delayed buildup of the hourly CO concentration over this 8-hour period. At the street sites, the maximum hourly value usually occurred early in the 8-hour period, coincident with peak traffic. At the UW background site, the maximum hourly value usually occurred later in the 8-hour sampling period. This phenomenon reflects the importance of mobile source contributions near the roadway, as well as the transport of CO from the street to areas between major roadways. The hourly values at each site are listed in Appendix D, and the times the peak hour occurred are summarized in Figure 4. Pair-wise, Kolmogorov-Smirnov (K-S) two-sample tests were performed to determine whether the distributions of peak hours with respect to time of occurrence, shown in Figure 4, were the same at these different sites. The procedure calculates the maximum distance between the cumulative distribution functions. The tests revealed that the distribution of peak times at

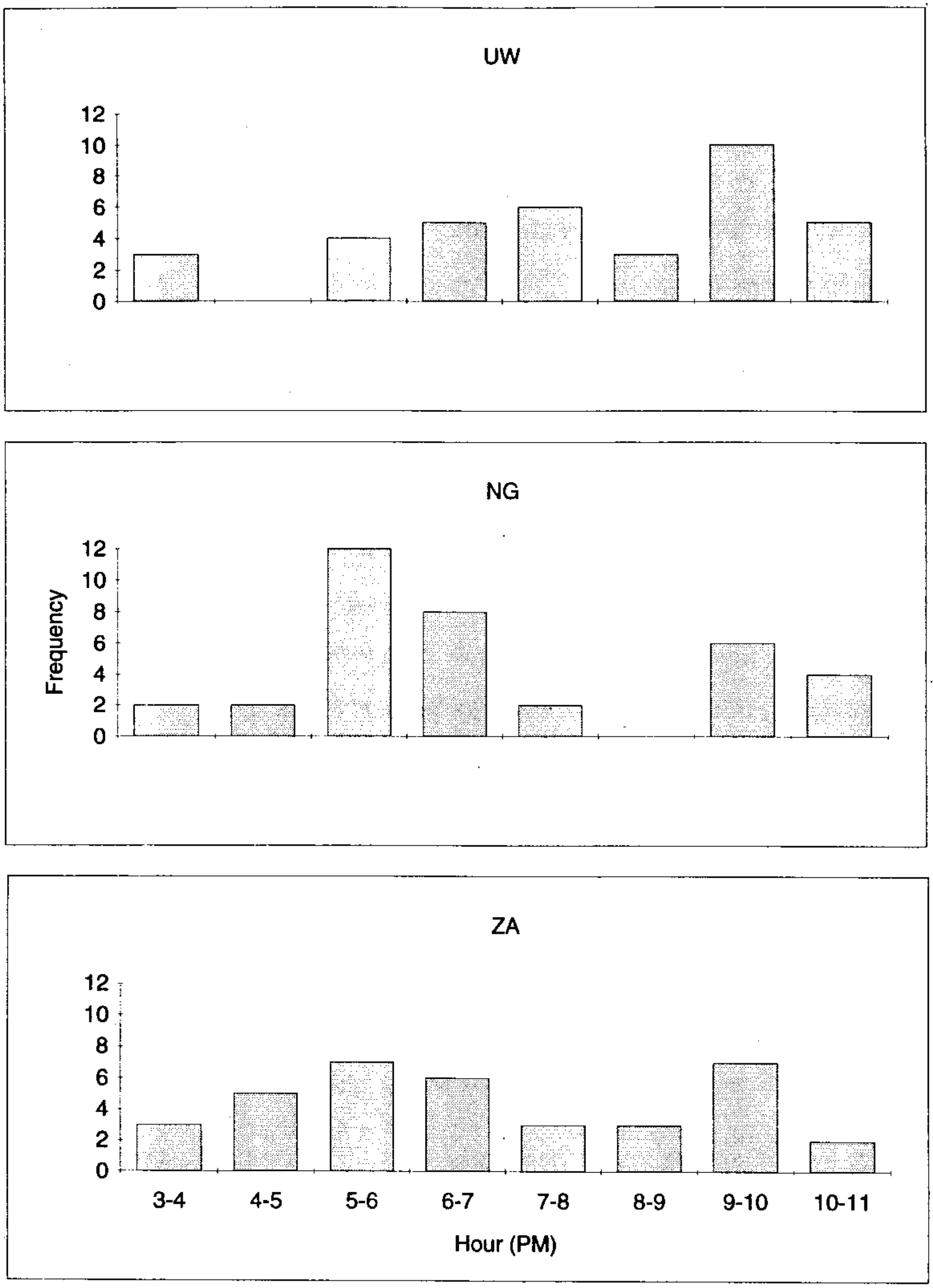


Figure 4. Time of Occurence of Peak One Hour Average CO Concentration in the 8-hr Sampling Period (The UW site is a background site whereas the other two are EPA micro-scale sites. Data were obtained with continuous analyzers.)

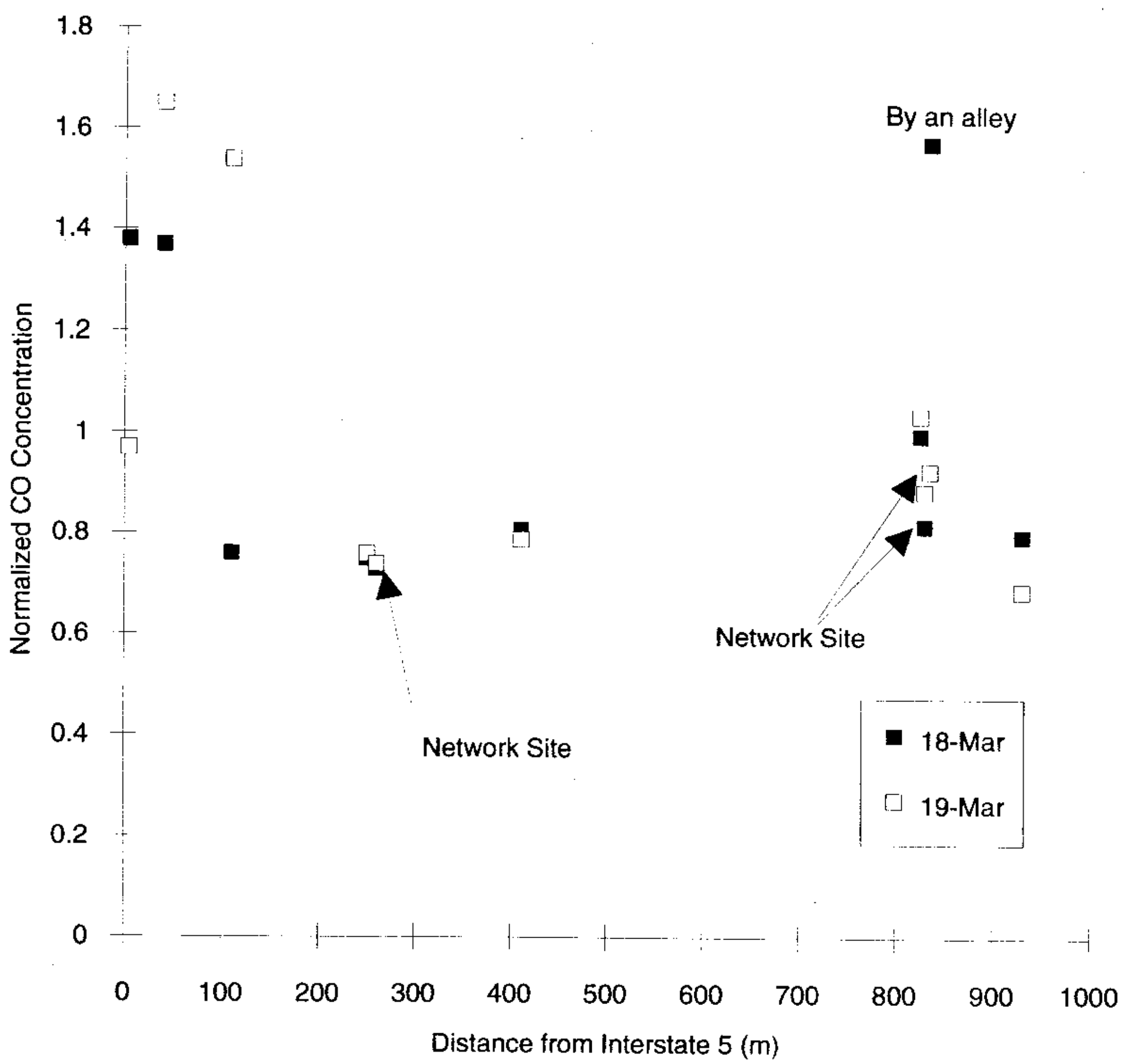


Figure 6. Normalized 8-hr Average CO Concentration vs. Distance from Interstate 5 (See Figure 1 for location of I-5. The normalized concentration is the observed concentration divided by the daily mean of all samples.)

a given site. In the absence of any other information, the EPA is considering recommending a value of 0.7 to be used in project analysis. (16) Figure 7 shows the measured persistence factor as a function of time for the UW background site, as well as for the ZA and NG street sites. The average values for this period are shown in Table 5.

Table 5. Persistence Factors* (January 25 to March 11, 1993)

Site	Number of Sampling Periods	Persistence Factor
Background:		
UW	39	0.66 (0.015)**
Street:		
ZA	39	0.71 (0.015)
NG		0.76 (0.015)

* defined as the ratio of the 8-hour mean to the maximum hourly value (3 PM to 11 PM)
** arithmetic mean value; standard error of the mean is in parentheses

OBSERVED 8-HOUR AVERAGE BACKGROUND CONCENTRATIONS

CO Concentrations by Site

Eight-hour average concentrations were simultaneously measured at our sites during the daily period from 3 PM to 11 PM with the UW air sampler. Sampling was performed on a regular basis from January 25 to March 11, 1993. During this sampling period, 20 percent of the data collected were missing; this problem was randomly distributed among sites. A list of the 8-hour average values by site is given in Appendix F.

Figure 8 shows the CO levels by site on a logarithmic concentration scale, which was chosen because the measured CO concentrations were approximately log-normally distributed. Shown are the median (50 percent fractile), upper and lower quartiles (25 percent and 75 percent fractiles), and minimum and maximum values for each site. The lowest measured 8-hour concentration was 0.4 ppm observed at the DIS site; the highest was 4.2 ppm observed at the UW site. The overall average was 1.32 ppm CO for all background sites.

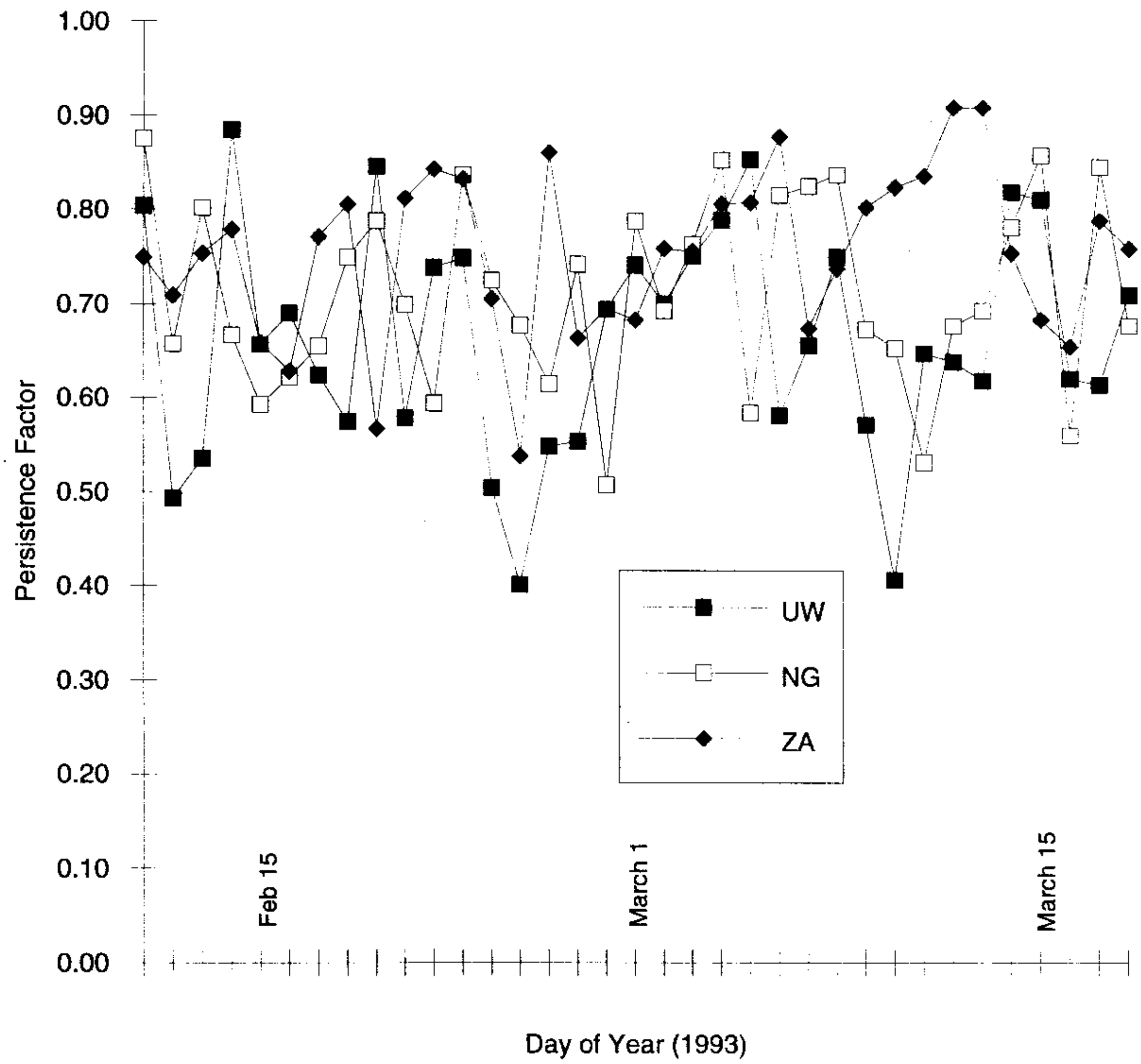


Figure 7. Persistence Factors (8-hr CO Average/1-hr CO Maximum)
for UW, NG, and ZA (3 PM - 11 PM)

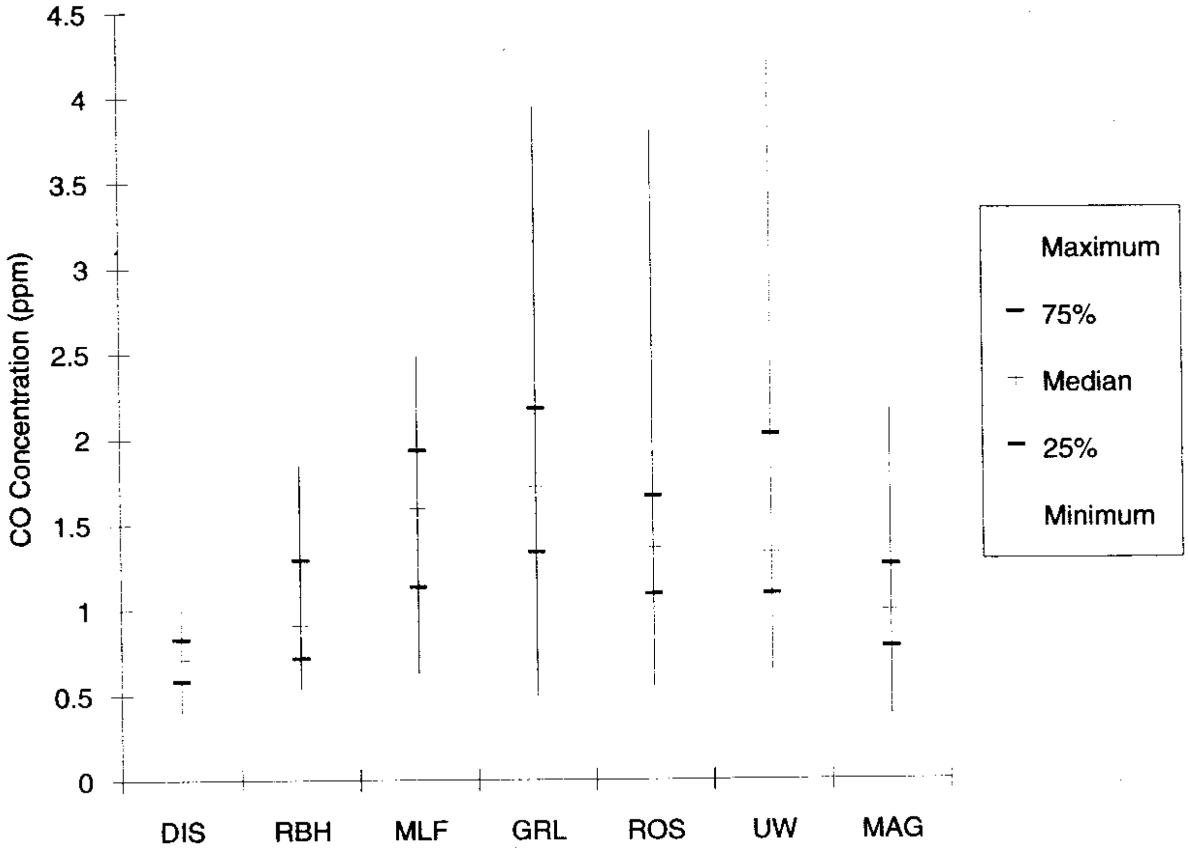


Figure 8. 8-hr Average CO Concentrations at Seven Sites in North Seattle during Jan. - March, 1993

Classification of Sites

The background sites can be grouped into three concentration levels (I, II, III), as summarized in Table 6. For comparison, we have included the corresponding 8-hour average CO concentrations at the ZA and NG street sites operated by the DOE.

Table 6. Grouping of Sites

Site Grouping*		8-hour mean CO concentration (ppm)**
I	(DIS)	0.70 (0.03)
II	(RBH, MAG)	1.04 (0.07)
III	(MLF, GRL, ROS, UW)	1.62 (0.11)
IV	(ZA, NG)	2.73 (0.16)

* see Table 1 and Figure 1 for site descriptions
** 3 PM to 11 PM PST; standard errors of the mean are in parentheses

This grouping of background sites (I,II,III) was tested with a one-way ANOVA analysis on the log-transformed CO concentration values. The F-ratio for testing the hypothesis that the site groups' means were significantly different was 22.8 (degrees of freedom (d.f.) = 6; 244). Figure 9 shows the estimated 95 percent confidence limits of the site mean values. The CO levels at the two street sites (group IV) were significantly higher than those of the group III sites ($p < 0.0001$)

This grouping of sites, although based solely on CO concentrations, was nevertheless consistent with local traffic patterns near each site. Group I contained the site most isolated not only from local traffic but also from the rest of the city, whereas Group III contained sites located relatively near trafficked roadways. Group II sites were relatively isolated from local traffic but were nonetheless nearer to more densely trafficked areas than the Group I site. All three groups of sites could be distinguished from the Group IV sites, which were typical EPA microscale sites located a few meters from roadways and/or intersections. We will subsequently refer to these site groups as

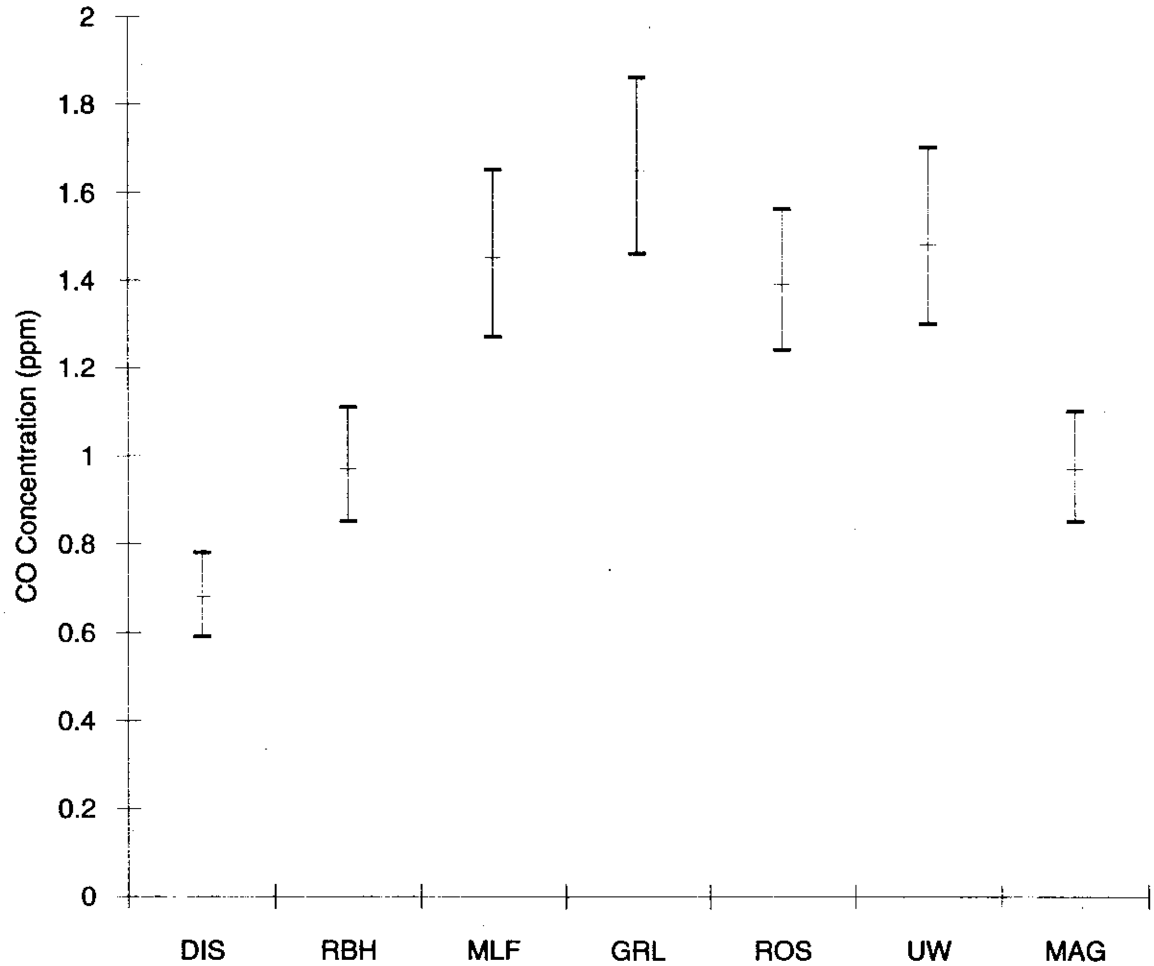


Figure 9. 8-hr Means (and 95% confidence limits) for CO at Seven Sites Across North Seattle During Jan. - March, 1993

follows: Group I = "Isolated Park," Group II = "Urban Park," Group III = "Trafficked," and Group IV = "Street" sites.

Site Specific Frequency Distributions

The CO 8-hour average cumulative density functions for all four groups of sites are shown in Figure 10. Pair-wise, K-S two-sample tests were performed to determine whether the distributions were the same. The tests revealed that all frequency distributions were highly significantly different from each other ($p < 0.0001$).

Also tested was the hypothesis that the cumulative frequency distributions of CO concentrations at a given site for 8-hour average wind speeds below 1.4 m/s were different from the cumulative frequency distributions for all wind speeds at that site (see Figure 11). The wind speed was that measured at the UW site. The criterion of 1.4 m/s was used to select the most stable meteorological periods (see Appendix G for details). Although the measured CO values appeared higher at low wind speeds, as seen in Figure 11, the K-S test found that the frequency distributions were not different ($p > 0.9$).

Figure 12 shows the log-normal probability plot for wind speeds below 1.4 m/s for the four groups of sites. This subset of days represents the most stable meteorological conditions during the study period. From the number of samples in a given site group, we could compute the cumulative percentage corresponding to a given day's CO value. For example, the second highest value out of 30 values for our Trafficked background sites was 3.11 ppm. This corresponds to the 95th percentile ($100\ [1\ -0.5\{(1/30) + (2/30)\}] = 95$). The log-normal distributions depicted by the solid lines in Figure 12 can be mathematically described by the following relationship:

$$C = m_g (s_g)^z \qquad \text{(Equation 1)}$$

where

C = site group mean 8-hour average CO concentration at a given percentile (ppm)

m_g = geometric mean of a given site group (ppm)

s_g = geometric standard deviation of a given site group

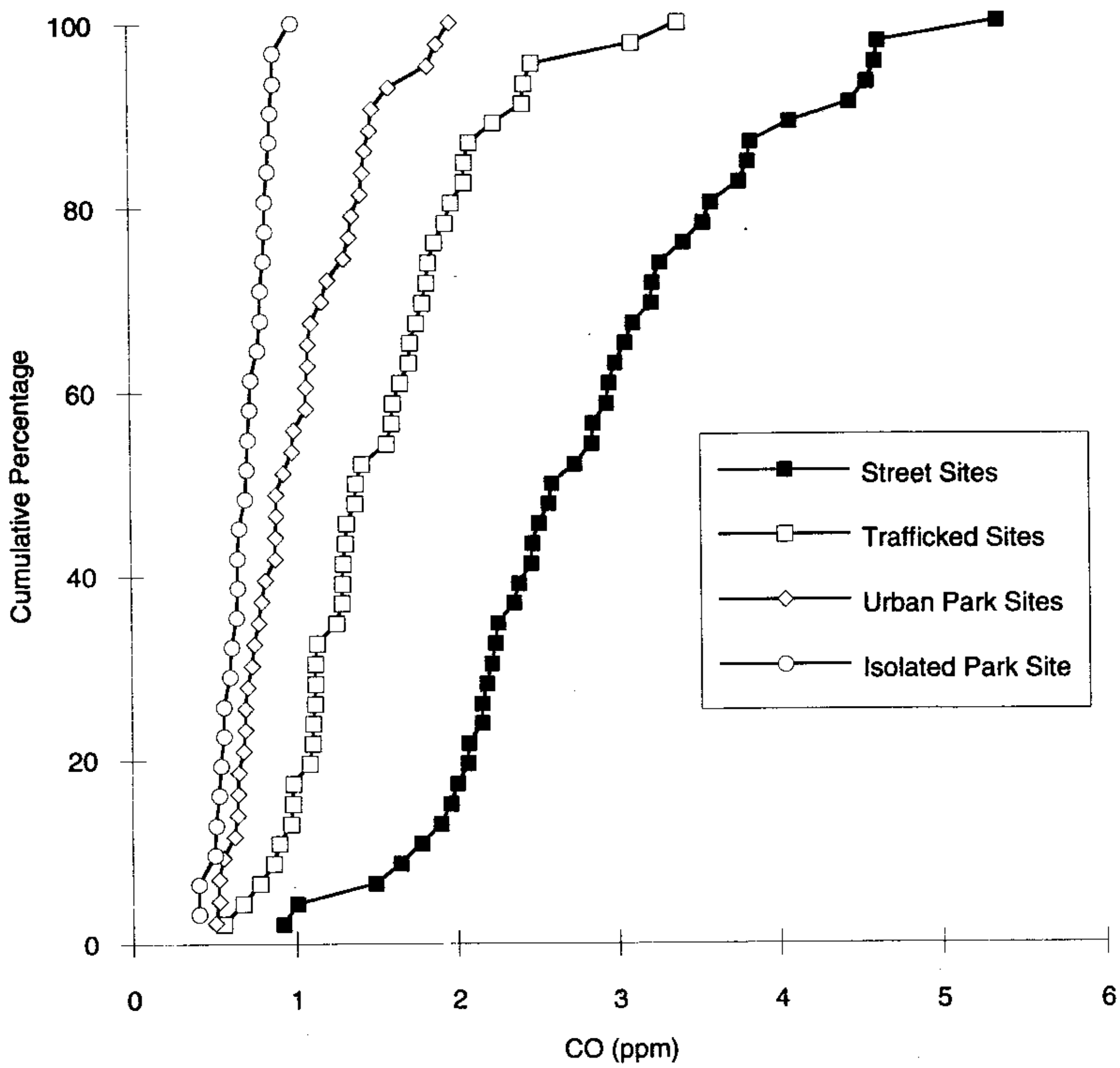


Figure 10. Cumulative Percentage of Samples Less Than Stated 8-hr Average CO Concentration (Distributions are shown for the daily mean of all samples within a site group.)

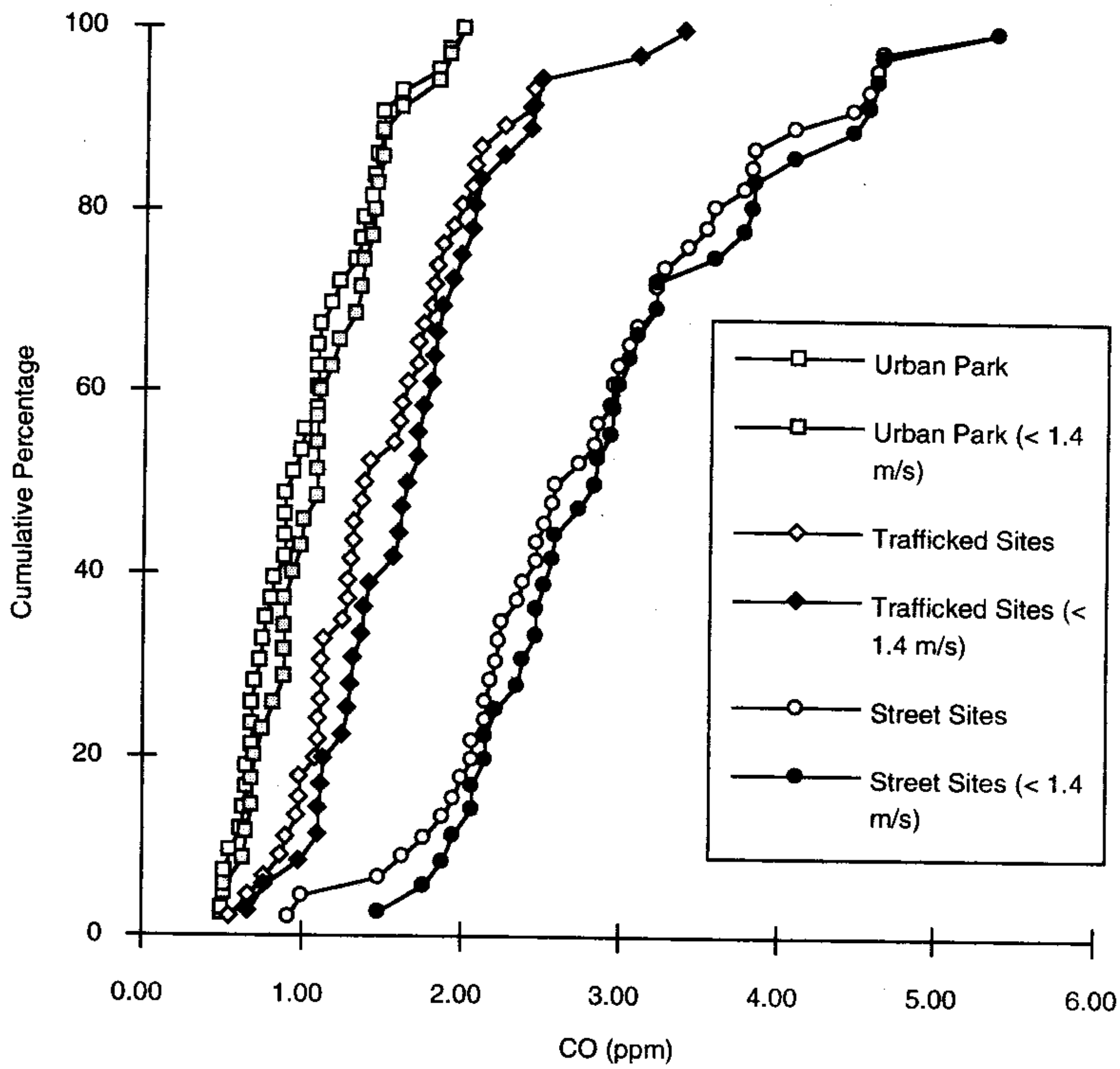


Figure 11. Cumulative Percentage of Samples Less than Stated 8-hr Average Concentration (Distributions are shown for the daily mean of all samples within a site group over all sampling days (open symbols) and over those days with 8-hr average wind speeds below 1.4 m/s (filled symbols). Winds were measured at the UW site.)

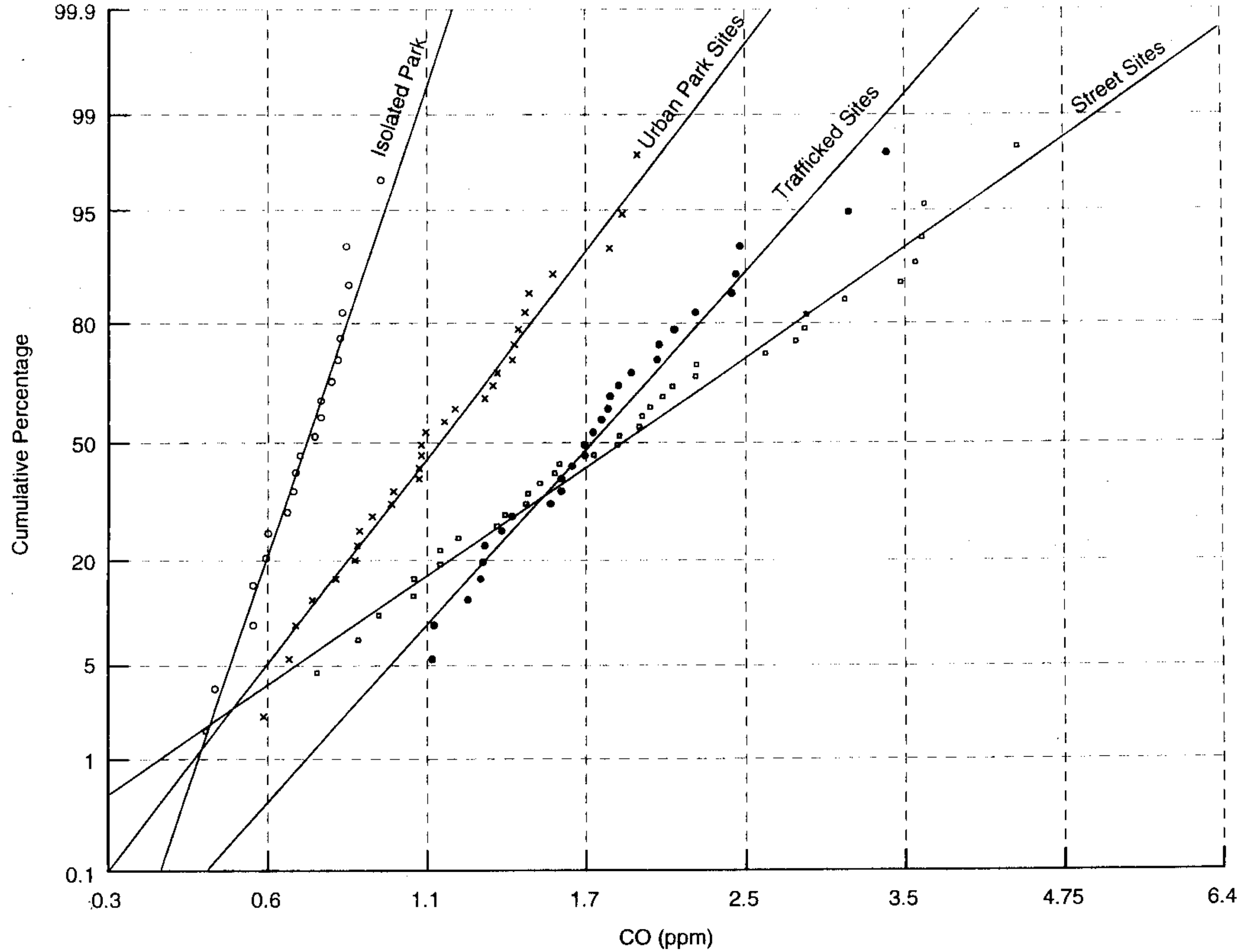


Figure 12. Log-normal Probability Plot of Daily Group Mean 8-hr Average CO Concentrations for Days with Low Wind Speeds (<1.4 m/s)

z = number of standard deviations in the cumulative normal distribution corresponding to the given percentile (e.g., z = 0 for 50th percentile; z = 1.645 for 95th percentile).

Table 7 lists the estimated parameter values for the log-normal distribution corresponding to each site group. The values for the two Street sites are listed individually.

Table 7. Estimated Parameters of the Two-Parameter Log-Normal Distributions of the Daily Group Mean of 8-Hour Average CO Concentrations (wind speed* < 1.4 m/s).

Parameter	m_g	s_g
Background Sites		
Trafficked	1.69	1.33
Urban Park	1.08	1.37
Isolated Park	0.74	1.18
Street sites		
Zanadu	2.84	1.68
Northgate	2.62	1.35

* 8-hour average wind speed measured at UW site

CO concentrations as a function of percentile and site group can be predicted with equation 1 and the parameter values in Table 5. For example, the 95 percent value of CO at the Trafficked background sites is estimated as $C = (1.69)(1.33)^{1.645} = 2.70$ ppm. This predicted value is lower than the observed 95 percent value of 3.11 because equation 1 does not perfectly describe the observed values (see Figure 12).

SPATIAL AND TEMPORAL VARIABILITY OF BACKGROUND CO

Temporal Correlations

Today's 8-hour average background CO concentration at a given site is expected to be positively correlated with yesterday's concentration because of weather and traffic patterns. The weather strongly affects local build-up of CO concentrations, and today's weather is related much of the time to yesterday's weather. In addition, yesterday's traffic during the 8-hour period is similar to today's traffic, especially on weekdays. Figure 13 shows the time sequence plot for the four site groups.

The temporal correlation at a given site can be described by a so-called first order auto-regressive process, AR(1). This process can be quantified by a simple linear regression model for CO concentrations with random error terms that are correlated in time:

$$C_t = k_0 + k_1(C_{t-1}) + e_t \qquad \text{(Equation 2)}$$

$$e_t = r_a (e_{t-1}) + u_t \qquad \text{(Equation 3)}$$

where:

C_t = site group mean 8-hour average CO concentration on day t

r_a = auto-regression parameter ($|r_a| < 1$)

e_t = noise signal at day t

u_t = true random noise ($N[0,(\sigma_{ut})^2]$)

k_0, k_1 = regression constants

For our measurements, $r_a = 0.56$ (s.e.= 0.05) with $s_{ut}^2 = (0.566)^2$ (d.f. = 249) for $k_0 = 1.31$, and $k_1 = 0.56$. From these results, about 25 percent of the variation in daily 8-hour CO averages can be explained by yesterday's value. The auto-correlation varied from site to site, being lowest for DIS ($r_a = 0.21$ (s.e.=0.21)) and highest for MAG ($r_a = 0.65$ (s.e.=0.14)).

Knowledge about correlations over time is necessary for formulating appropriate predictive models and for determining the number of measurements needed at a given site to estimate the true mean (or any other percentile value) over a group of sites with specified accuracy and confidence. If temporal correlation exists, results on consecutive days are not independent measurements. Therefore, more days are needed for a specified level of uncertainty than if the measurements are independent of each other. The adequacy of our sampling network will be discussed later.

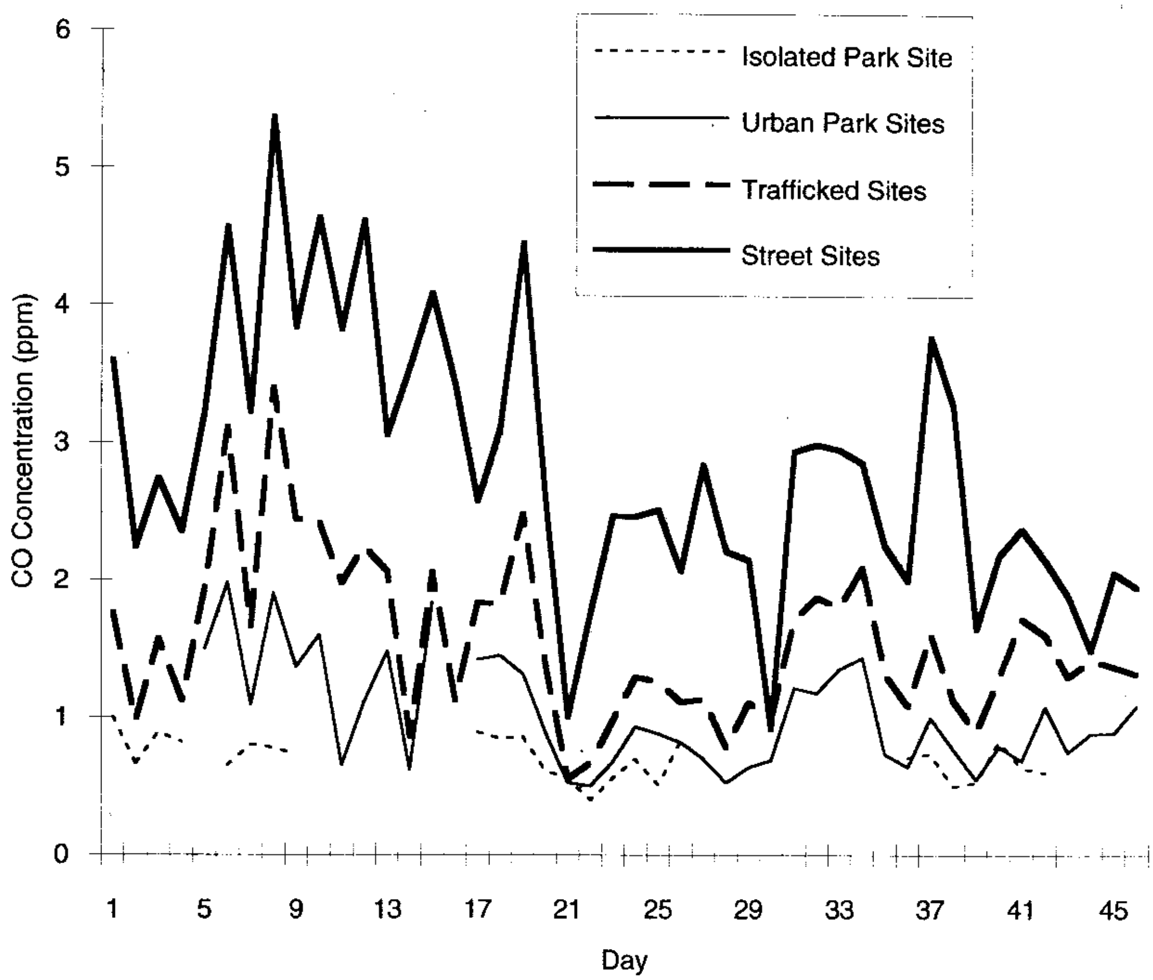


Figure 13. 8-hr Average CO Concentration vs. Time
(Daily mean values for each site group are shown.
See text for explanation of site groupings.)

Spatial Correlations

Our sites were chosen so that they were away from local roadway sources. To the extent that they reflected a general background level that was determined by spatially correlated traffic and weather patterns, the 8-hour average CO concentrations at these sites should also be spatially correlated. Therefore, despite the variability from day to day in CO concentrations, as shown in Figure 13, three groups of background sites (Street, Trafficked, and Urban Park) seemed to have similar concentrations on any given day. The Isolated Park site showed the lowest daily variation in 8-hour CO concentrations and also the lowest spatial correlation with any of the other sites.

Scatter plots showing the relationships between 8-hour average site group means are shown in Figure 14, together with the spatial correlation coefficient for each pair of site groups. These data were obtained with the UW air sampler. The Isolated Park site had the poorest correlation with any other site group (R^2 was between 0.10 and 0.30). Best correlated among the background sites were the Urban Park sites and the Trafficked sites ($R^2 = 0.72$). Street sites were also correlated with Trafficked sites ($R^2 = 0.64$)

Ratio of Background Concentrations to Street Concentrations

The estimated ratios of 8-hour average background concentrations to street concentrations are given in Table 8. On average, the CO concentrations at the Trafficked background sites were about one-half the corresponding values observed at the Street sites.

Table 8. Ratio of Background CO Concentrations To Those At Street Sites.*

Background Site Group	Ratio relative to Zanadu site	Ratio relative to Northgate site
Isolated Park	0.20 (0.01)**	0.25 (0.02)
Urban Park	0.30 (0.02)	0.39 (0.02)
Trafficked	0.48 (0.02)	0.59 (0.03)

* 8-hour average background values from UW air sampler; street site values from continuous monitors
**value in parenthesis is standard error of the mean.

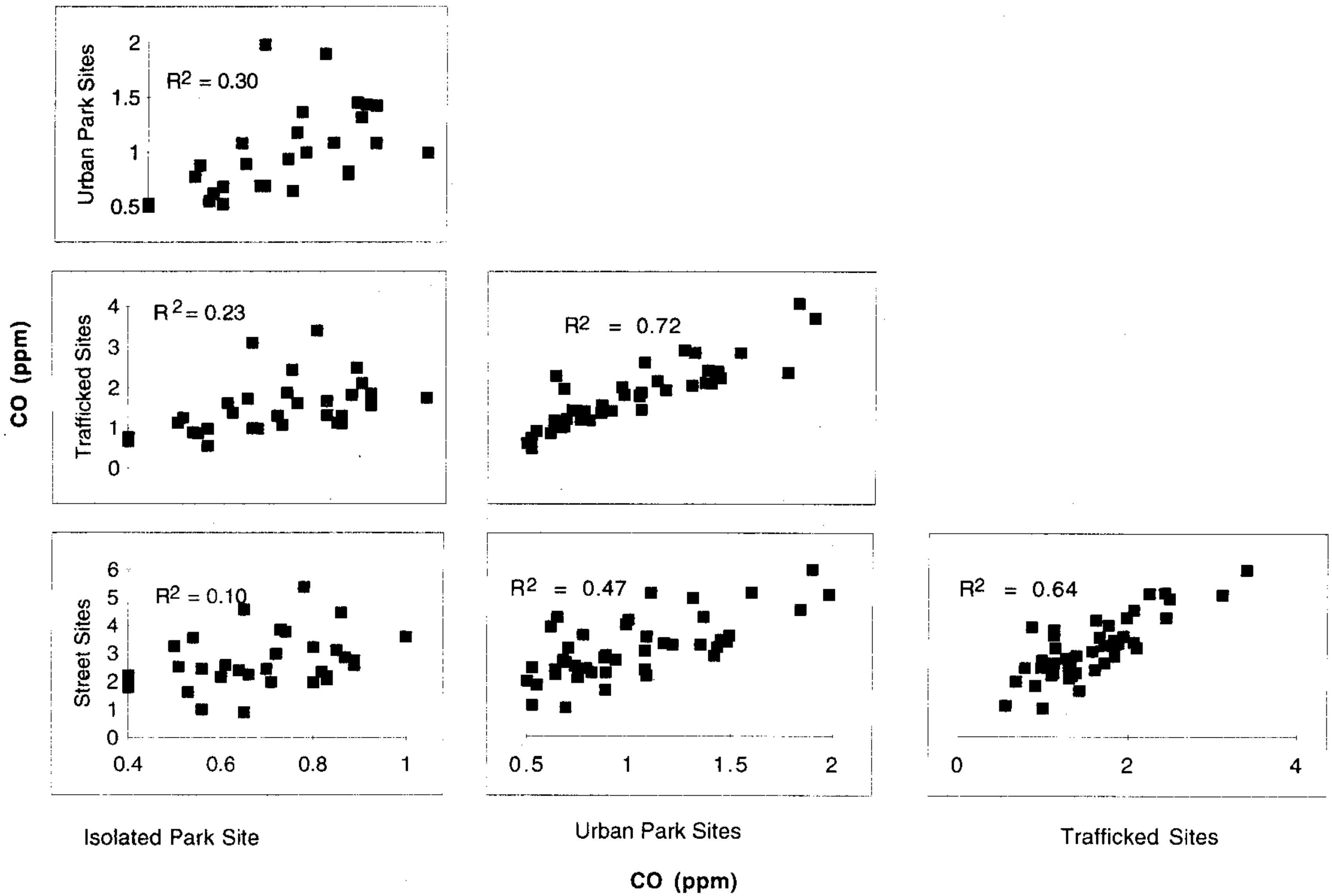


Figure 14. Scatter Plots of Daily Mean 8-hr Average CO Concentrations by Site Group

The ratios reported in Table 6 are the mean values over all sampling days. The ratios associated with high CO levels at the Street sites were also examined. During our 46-day study period, the ratio of the daily mean CO level at all Trafficked sites relative to the concentration at the Zanadu site was 0.49 (s.e. = 0.08) for the two days with the highest 8-hour average CO levels at the Zanadu site. The corresponding value for the highest two days at the Northgate site was 0.44 (s.e. = 0.28).

Adequacy of Monitoring Network

To determine the adequacy of our network to estimate the site group mean values over time and space, the spatial and temporal correlations characteristic of CO background concentrations had to be taken into account. To achieve a given accuracy when estimating the regional mean, Gilbert (17) developed an expression for the relationship between the required number, n, of samples taken at each site, as well as the required number of sites, n_s, for a pre-specified level of accuracy:

$$n = (2\sigma/d)^2 [1+2r_a][1+r_c(n_s-1)] \qquad \text{(Equation 4)}$$

where

σ^2	=	the residual variance, i.e., the variance that is not associated with between-day and between-site variability (= [0.325 ppm]^2, as estimated in Appendix H)
d	=	the uncertainty of the sample mean (absolute error) in ppm units at the 95 percent confidence level
r_a	=	the auto-regression parameter from equation 3 (= 0.56 as an average for our data)
r_c	=	the average spatial correlation coefficient between sites (= 0.8 as an average for our data).

The residual variance in our network, (0.325 ppm)^2 consisted of the variability associated with our sampling and analysis of CO, as well as variability due to unexplained factors. On the basis of an analysis of co-located samplers run simultaneously, we estimated that the variability due to sampling and analysis was

$(0.054\ ppm)^2$ (see Appendix H). Therefore, most of the residual variance was not associated with experimental variability.

Given the values of r_a and r_c from our network, equation 4 becomes

$$n \approx (1/d^2)[1+0.8(n_s-1)] \qquad \text{(Equation 5)}$$

Figure 15 shows values of n for given values of d and n_s. To estimate the CO 8-hour mean with an absolute error of d = 0.5 ppm, one would need to sample for 15 days at three sites, or 30 days at six sites. Because more sites introduce more variability, more sampling days are needed. However, more sites also give a better representation of an area, or regional mean. In this study, we estimated the means of three site groups containing from one to four sites per group using 30 days of samples representing stable atmospheric conditions. For the four trafficked background sites, 30 days of sampling corresponded to an estimated uncertainty (from Figure 15) of 0.4 ppm. This is consistent with the uncertainties shown in Figure 9 that include an additional random effect due to daily variability. If we wanted to reduce our uncertainty in the sample means of any site group by a factor of two, we would have to sample for an additional 90 days under these winter conditions, clearly an impractical task with diminishing returns.

MODELING BACKGROUND CO CONCENTRATIONS

Winds and Stability During Winter Sampling Period

We examined the hourly wind speed distributions, as well as the stability distributions, for three years at two meteorological monitoring sites in the study area. Details of this analysis are described in Appendix I. Hourly wind measurements at the UW site are given in Appendix J. As seen in Figure 16, the frequency distribution of 8-hour average wind speeds during the sample period at both sites did not vary appreciably from year to year. A K-S two-sample test was used to determine whether a statistically significant difference in wind speed distributions existed between 1993 and 1991 or 1992. Test results indicated no significant differences between years (see Appendix I).

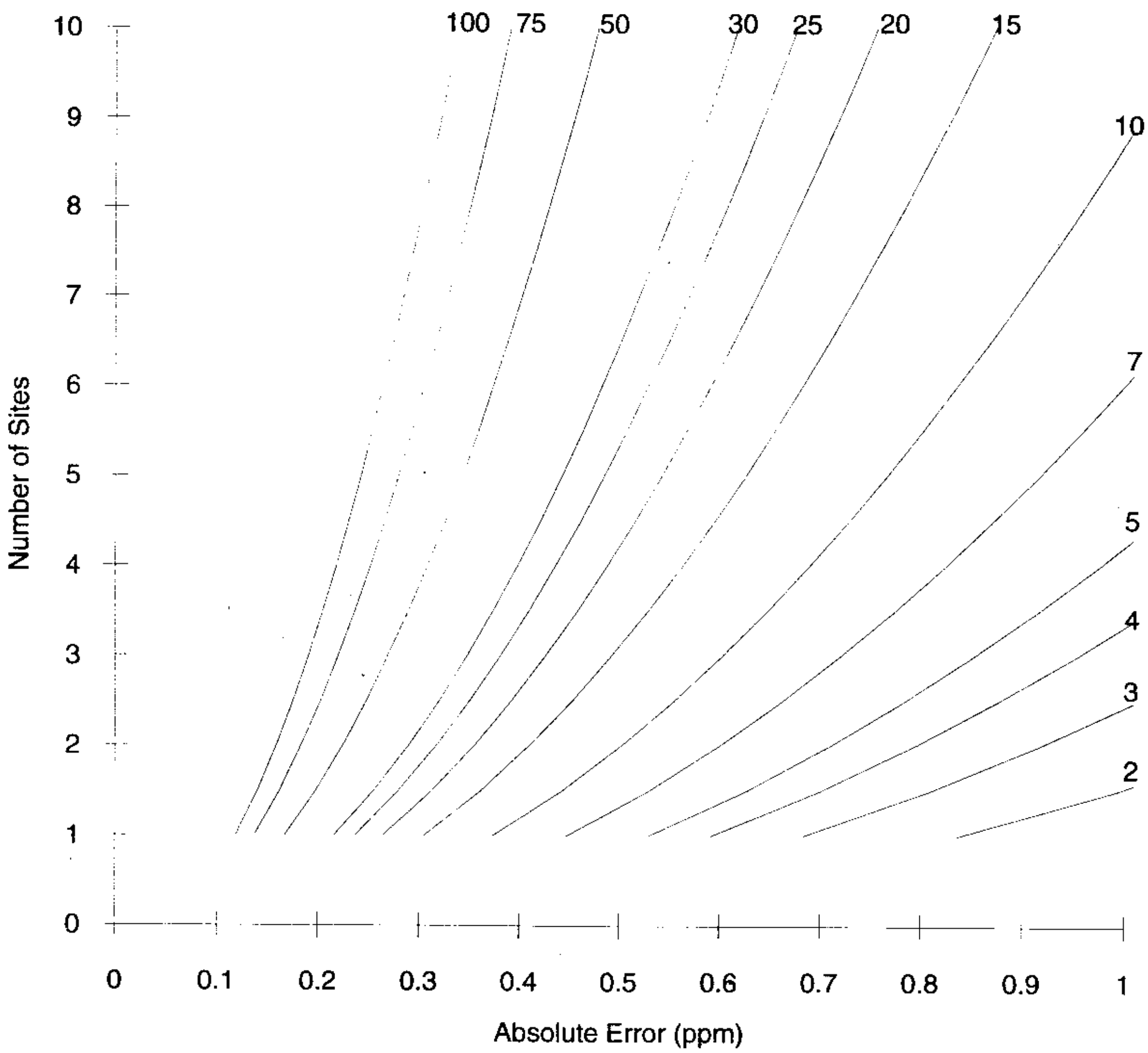


Figure 15. Number of Sampling Days as a Function of Absolute Error of CO Mean Concentrations and Number of Sites During Stable Atmospheric Conditions

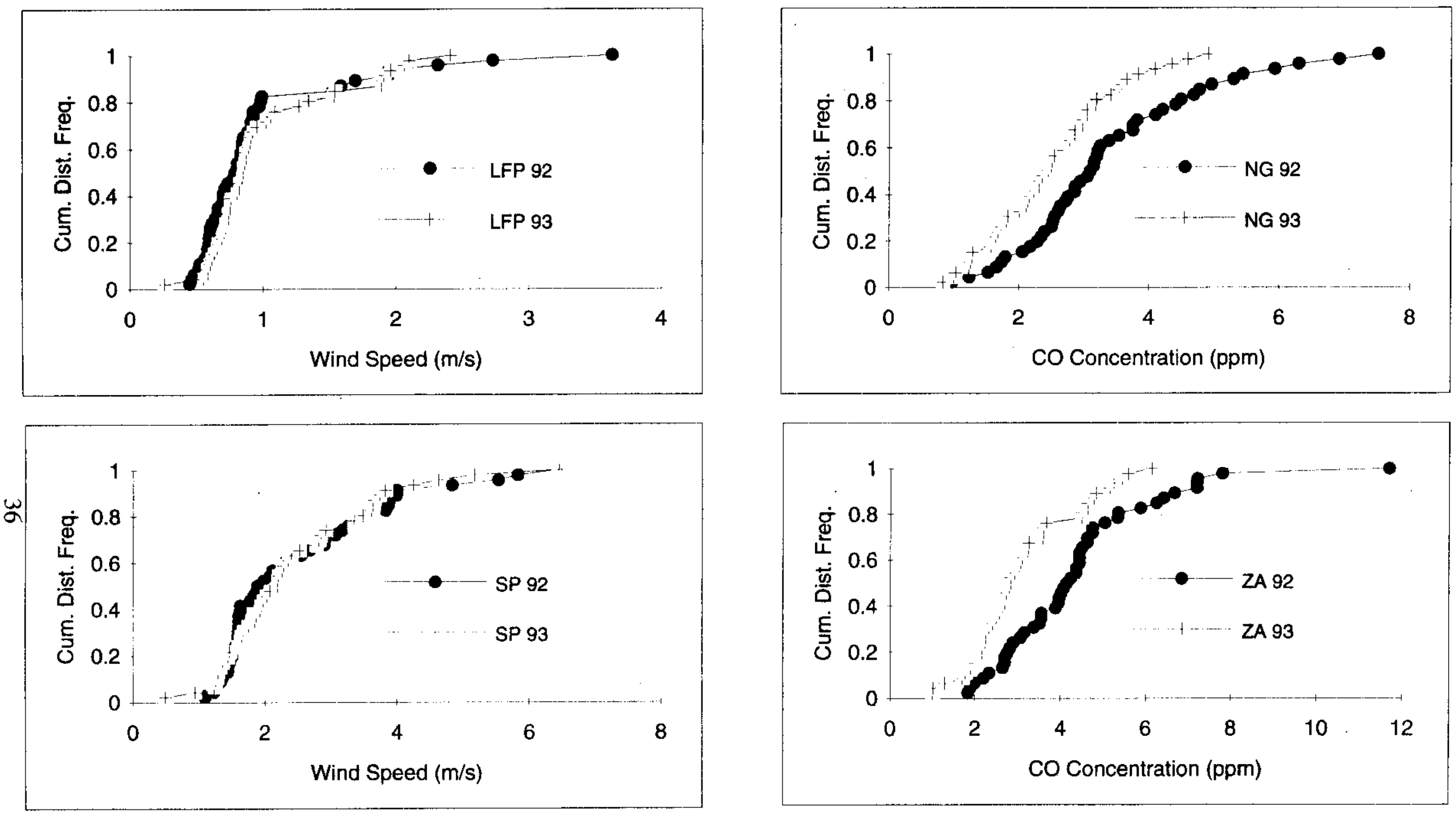


Figure 16. Frequency Distributions of Wind Speed and CO Concentration at Sandpoint (SP) and Lake Forest Park (LFP) During the Period Jan. 25 - March 11 (The 1993 period is compared with a similar period in 1992.

Atmospheric stability was classified via the "sigma theta" method (18) with hourly wind data from Sandpoint from January 25 to March 11, 1991 to 1993. A value of 0.05 m was used as an estimate of the roughness length at the Sandpoint site. The number of hours of D, E, and F stability classes during the sample period from 3 PM to 11 PM were computed. The results are summarized in Table 9.

Table 9. Number of Hours with Indicated Stability (3 PM to 11 PM)*

Year	Stability Class			
	D	E	F	Other
1991	145	43	126	54
1992	132	54	123	59
1993	99	77	133	59

*January 25th to March 11th in each of three years at the Sandpoint site; 368 hours were analyzed each year

The proportion of hours of "F" stability remained fairly constant from year to year. A chi-square test was used to determine whether the proportion of "F" hours in 1993 was significantly different from the corresponding numbers in 1992 and 1993. The test showed no statistically significant difference between 1993 and the two previous years.

Measured CO Concentrations Versus Wind Speed and Traffic

Decreased wind speed and increased traffic increases CO background concentrations. Figure 17 shows the general relationship between wind speed measured at the UW site and the daily site group mean of 8-hour CO concentrations at the Trafficked background sites. The effect of wind speed, as well as other meteorological parameters, on CO concentrations is explored in more detail in the next subsection.

Figure 18 shows average CO background concentrations plotted against distance to the major trafficked roadway (within 300 m) at a given site. Also included is the annual mean traffic volume on that roadway.

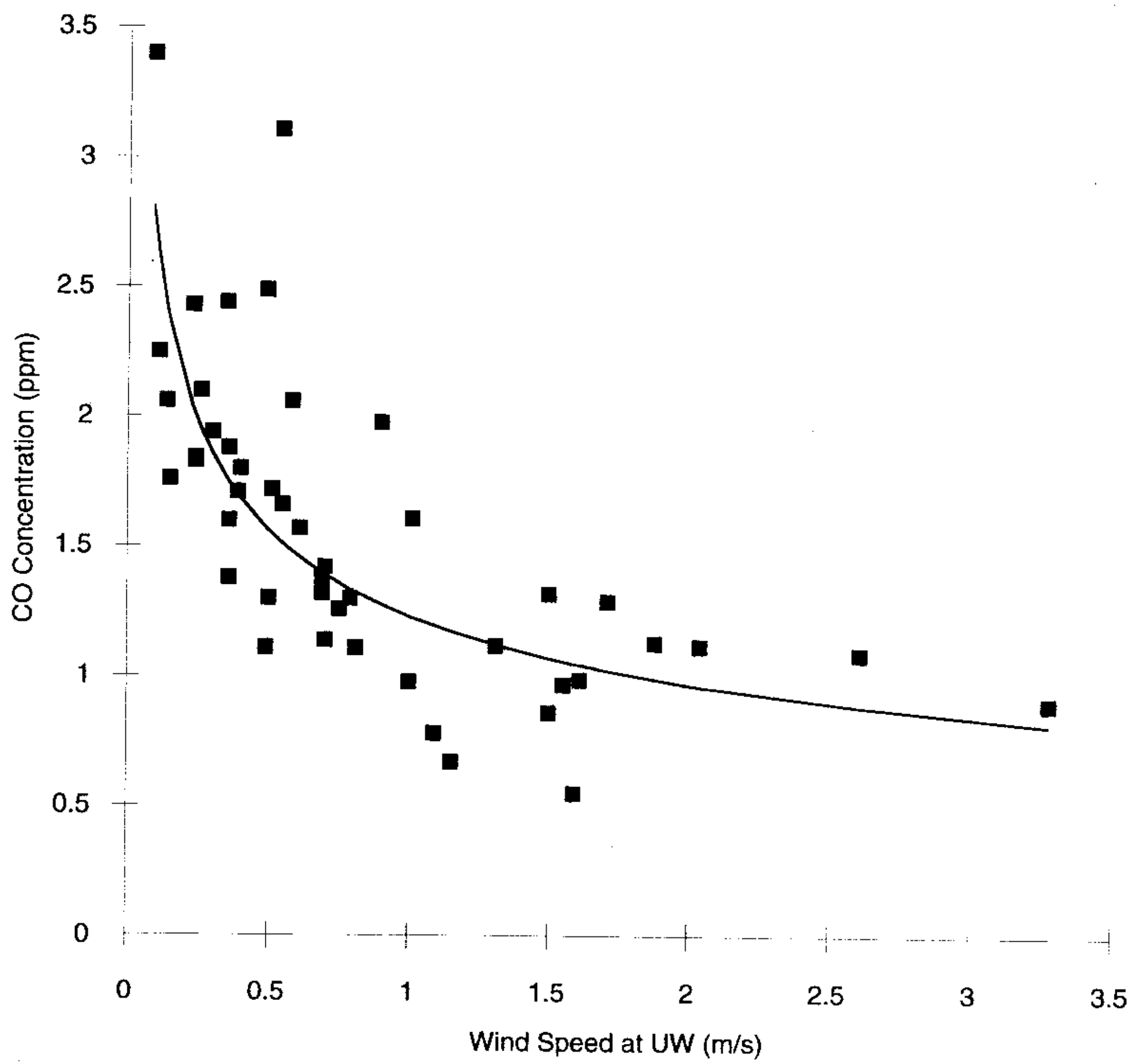


Figure 17. Daily Mean of 8-hr Average CO Concentrations for Trafficked Sites vs. 8-hr Average Wind Speed

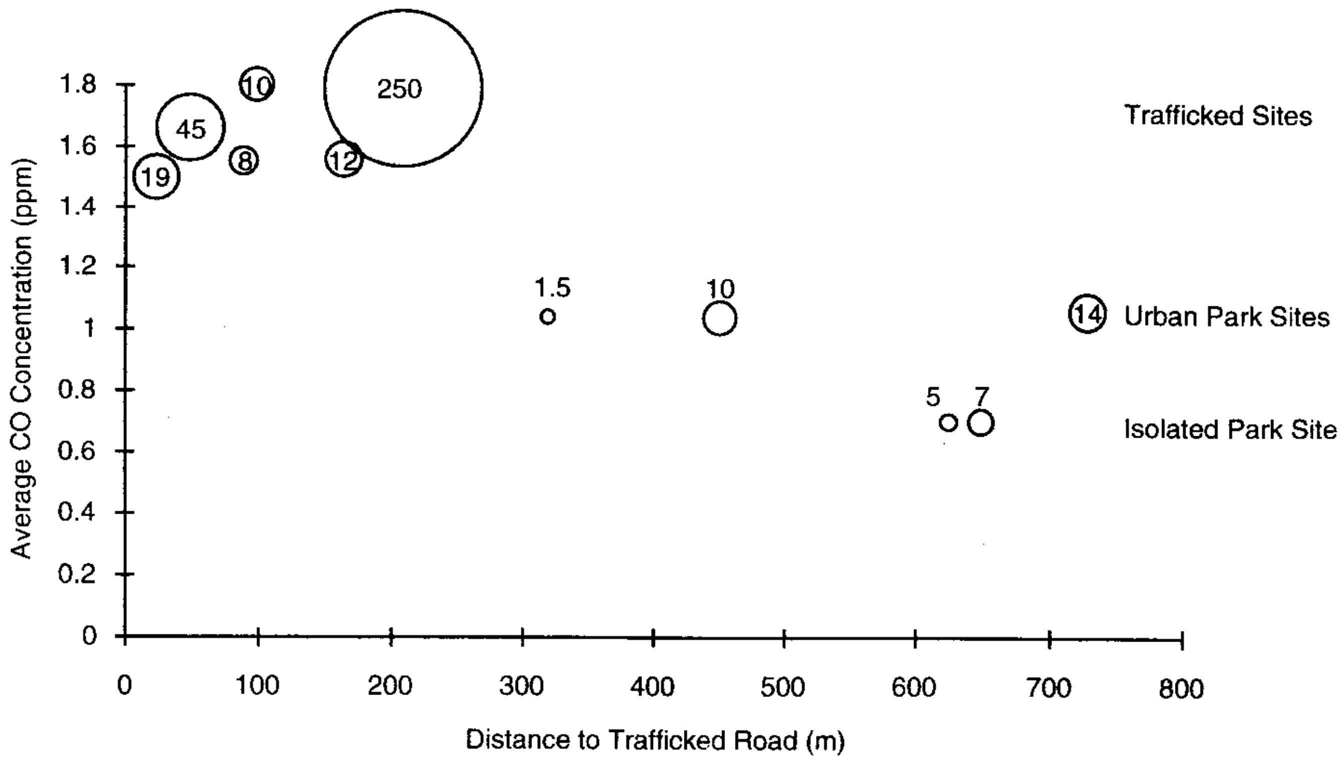


Figure 18. Overall 8-hr Average CO Concentration at a Given Site vs. Site Location, Distance to Roadways, Traffic Volume, and Site Category (Values in circles are average daily traffic (ADT) in thousands of vehicles/day. Circle area is proportional to ADT.)

Meteorological Dispersion of CO Emissions

We have examined the theoretical relationships between measured meteorological parameters, CO emissions, and observed 8-hour average CO background concentrations. The goal was to formulate appropriate meteorological co-variates for inclusion in subsequent regression analyses. The conceptual models that were developed from this examination are outlined below.

Box Model

The concept behind this model is that the nighttime CO concentration is the major determinant of 8-hour (3 PM to 11 PM) average values at background sites, and the major determinants of this concentration are wind speed and effective vertical mixing depth, as estimated from atmospheric turbulence measurements.

Assuming a well mixed box or set of boxes of uniform height, we have

$$C = Q\, x_{box}/(u_{box}\, h_{mix}) \qquad \text{(Equation 6)}$$

where

Q = emission rate (g/s)

x_{box} = length of box in downwind direction

u_{box} = vertically averaged wind speed through box

h_{mix} = mixing depth = vertical extent of box

If we assume that emissions do not vary with meteorology and that x_{box} is proportional to wind speed and time, then variations in the time-averaged value of C as a function of meteorology would be described by a model in which C was inversely proportional to h_{mix}. Unfortunately, the relationship between turbulence parameters and mixing depth under stable conditions is not well known. The 'conventional' model of the stable mixing depth (i.e., the boundary layer height) is

$$h_{mix} = 0.4\{u^*L/f\}^{0.5} \qquad \text{(Equation 7)}$$

where

f = Coriolis parameter, taken as constant ($\approx 1 \times 10^{-4}$ sec^{-1} at mid-latitudes)

u* = friction velocity, a turbulence scaling parameter (m/s)

L = Obukhov length, a turbulence scaling parameter (m)

The friction velocity and Obukhov length can be estimated with the methods described in Appendix H. Combining equations 6 and 7, we find that if x_{box} is proportional to u_{box},

$$C \text{ is proportional to } (u^*)^{-1.5} \qquad \text{(Equation 8)}$$

If x_{box} is independent of u_{box},

$$C \text{ is proportional to } (u^*)^{-1.5} (u_{box})^{-1} \qquad \text{(Equation 9)}$$

Line Source Model

The concept behind this model is that the nighttime CO concentration is the major determinant of 8-hour (3 PM to 11 PM) average values at background sites, and the major determinant of this concentration is an array of ground level line sources whose impacts at a fixed location can be described as a function of atmospheric turbulence parameters. Venkatram (19) proposed the following empirical equation to estimate the concentration of a nonreactive air pollutant released from a line source at ground level under stable atmospheric conditions (e.g., at night):

$$C(x,0) = Q/(u^* \, x^{0.67} \, L^{0.33}) \quad \text{for } x/L > 1.4 \qquad \text{(Equation 10)}$$

where

C(x,0) = cross-wind integrated pollutant concentration (g/m^2)

x = downwind distance from the source (m)

In this conceptual model, the emission rate and horizontal distance variables can be assumed to be constant. Only the values of u* and L will vary because of meteorology. This is somewhat oversimplified, in that changes in wind direction can alter the effective value of "x". However, we can assume that over a large enough urban area, these changes will not be important. Assuming L is proportional to $(u^*)^2$, then

$C(x,0)$ is proportional to $(u^*)^{-1.67}$ (Equation 11)

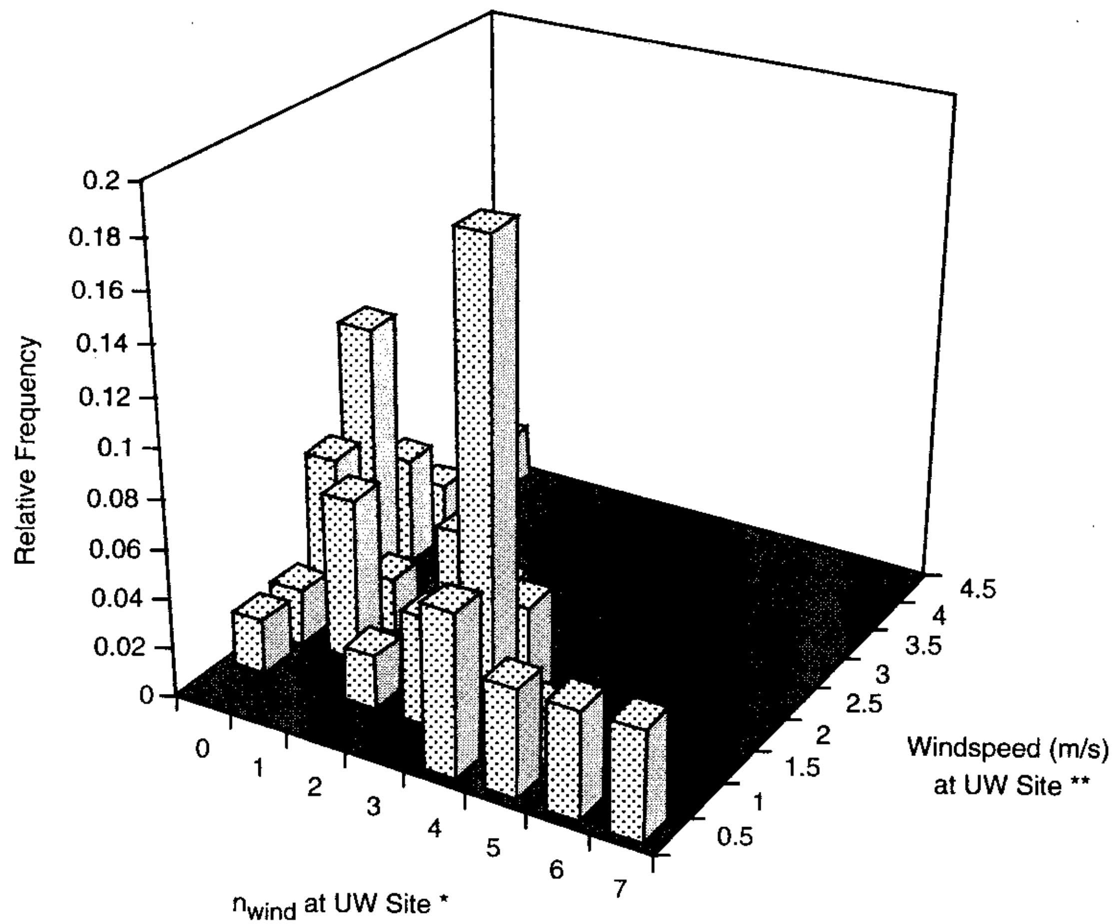
Stagnation Model

The concept behind this model is that background CO concentrations increase only during periods of very calm winds, when existing atmospheric turbulence theory does not apply. In our analysis, turbulence theory cannot be used to describe vertical wind speed and temperature profiles when the 15-minute average wind speed is less than or equal to 0.2 m/s (see Appendix I). A simple index of this phenomena is n_{wind}, the number of hours when wind speed is less than or equal to 0.2 m/s during 3:00 PM to 11:00 PM. In the absence of any physical theory, and given that the concentration distributions are log-normal, we hypothesize that

$\ln(C)$ is proportional to n_{wind} (Equation 12)

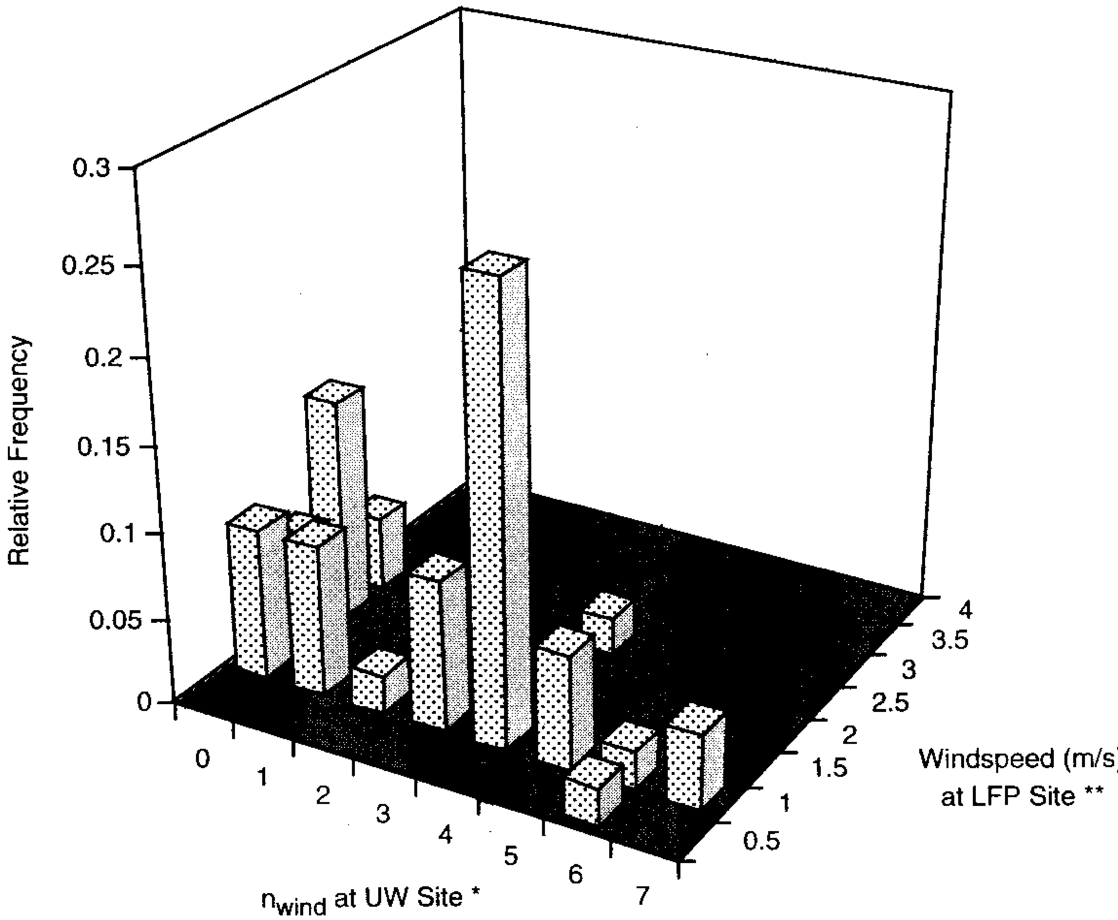
Figures 19 to 21 show the relationship between n_{wind} and the reciprocal 8-hour average wind speed for all study days at three wind measurement sites in the study area: the UW, LFP, and Sandpoint (SP) sites. The latter two sites are operated by the Puget Sound Air Pollution Control Agency and DOE, respectively. During the study period, an 8-hour average wind speed of 1 m/s at the UW site was most frequently associated with a value of $n_{wind} = 4$ at the same site. At the LFP site, an 8-hour average wind speed of approximately 1 m/sec was most frequently associated with a value of $n_{wind} = 4$ recorded at the UW site. The value for the SP site was $n_{wind} = 5$. The SP site is an official EPA site that is exposed to the wind in all directions. It rarely records winds of less than 1 m/s and, in general, records winds that are higher than either of the two more sheltered LFP or UW sites. However, these latter sites may best represent the winds at or near trafficked intersections within the urban area. These relationships are of interest because a wind speed of 1 m/s is the value recommended by the EPA to model the local traffic impacts on air quality for project analysis.

The above analysis shows that we can choose several meteorological co-variates to test via regression. The regression analysis, discussed in the next section, uses as its



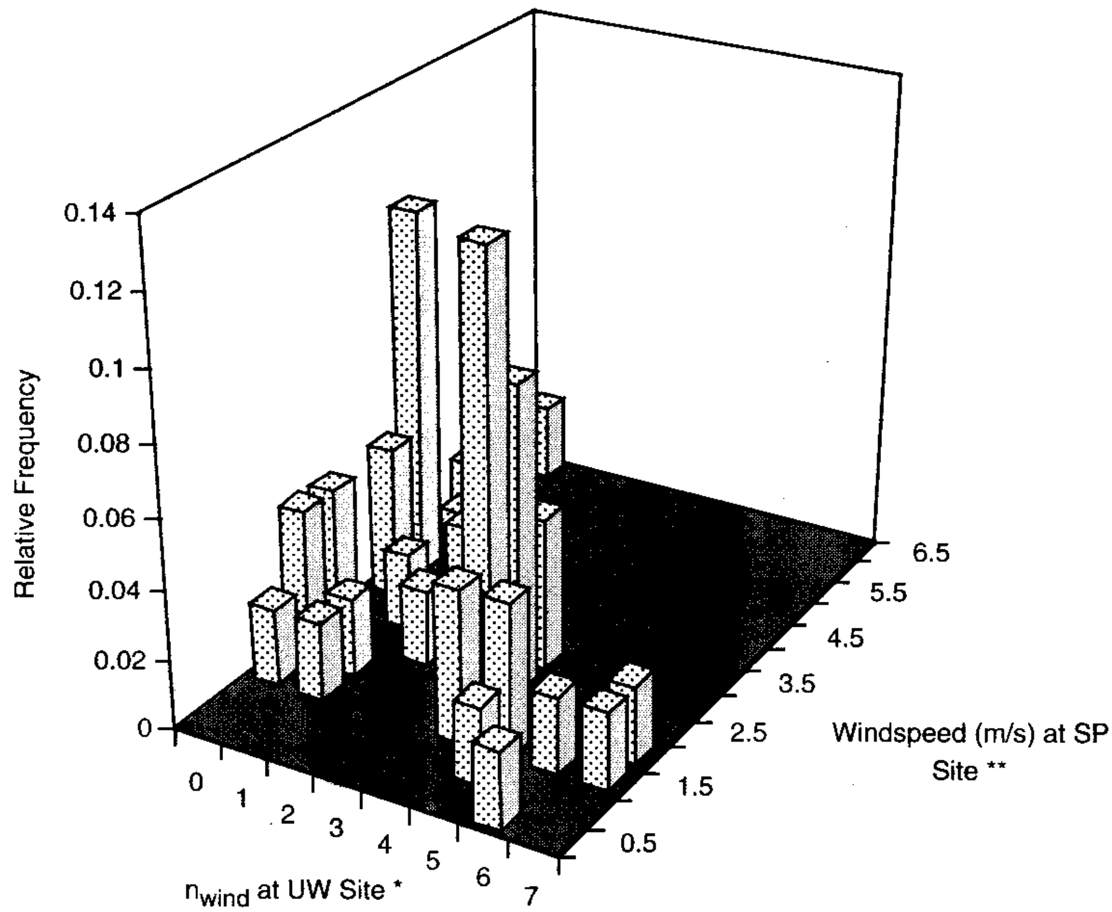
* see text for definition
** 8-hr average (3 PM - 11 PM)

Figure 19. 8-hr Average Wind Speed vs. n_{wind} (All measurements taken at UW site.)



* see text for definition
** 8-hr average (3 PM - 11 PM)

Figure 20. 8-hr Average Wind Speed Measured at Lake Forest Park vs. n_{wind} Measured at UW Site



* see text for definition

** 8-hr average (3 PM - 11 PM)

Figure 21. 8-hr Average Wind Speed Measured at Sandpoint vs. n_{wind} Measured at UW Site

dependent variable the ln(C). Equations 8 and 11 imply that ln(C) is proportional to $\ln(u^*)$; equation 9 implies that ln(C) is proportional to $\ln[(u^*)^{-1.5}(u)^{-1}]$; and, equation 12 implies that ln(C) is proportional to n_{wind}.

Predicting CO Levels From Wind and Traffic

The model we tested for estimating background CO levels (weekdays only) was an ANOVA model based on our site classification scheme. Different versions of the model corresponded to different combinations of meteorological parameters (n_{wind} , u^*, u), as well as different traffic parameters. The models we tested applied to weekdays only and are given below.

$$\ln(C)_i = s_i + \alpha_1[\ln(V_{traf}) - \mu_1] + \alpha_2[n_{wind} - \mu_2] + \varepsilon \quad \text{(Equation 13)}$$

$$\ln(C)_i = s_i + \alpha_2[n_{wind} - \mu_2] + \varepsilon \quad \text{(Equation 14)}$$

$$\ln(C)_i = s_i + \alpha_1[\ln(V_{traf}) - \mu_1] + \alpha_2[\ln\{(u^*)^{-1.5}(u)^{-1}\} - \mu_3] + \varepsilon \quad \text{(Equation 15)}$$

$$\ln(C)_i = s_i + \alpha_1[\ln(V_{traf}) - \mu_1] + \alpha_2[\ln(u^*) - \mu_4] + \varepsilon \quad \text{(Equation 16)}$$

where

$\ln(C)_i$ = the expected log-transformed value of the daily mean 8-hour average CO concentration (in ppm) for site class i, [i= 1 to 3 for Isolated Park, Urban Park, and Trafficked sites, respectively]

s_i = the effect of site group

α_i = co-variate constants

V_{traf} = the highest average weekday traffic volume within 200 m of the site (vehicles per day, see Table 1)

μ_1 = the mean value of V_{traf} for all sites (vehicles per day)

μ_2 = the mean value of n_{wind} for all sites

μ_3 = the mean value of $\ln\{(u^*)^{-1.5}(u)^{-1}\}$ for all sites

μ_4 = the mean value of $\ln(u^*)$ for all sites

ε = the random error $(N[0,(\sigma)^2])$

The performance of each model is summarized in Table 10. As shown, the "best" model in terms of prediction ability was equation 13. This was only a slightly better model than equation 14, a similar but simpler model in which traffic volume was not directly included as a co-variate and site category was the only parameter that depended upon traffic. Equations 15 and 16 included the alternative meteorological covariates discussed above. These latter two models did not perform as well as those that used n_{wind} as the meteorological descriptor. The poorer performance of the line source model is not surprising, given the relatively simplistic assumption of constant downwind distance.

Table 10. Model Predictions Versus Observed Values (Weekdays Only)

Model	Statistics*		
	R^2	σ^2	F-value
Equation 13	0.75	$(0.226)^2$	135
Equation 14	0.74	$(0.230)^2$	170
Equation 15	0.63	$(0.276)^2$	75
Equation 16	0.52	$(0.315)^2$	48

* R is the correlation coefficient; σ^2 is the residual variance; F-value is based upon the ANOVA model

The model constants for equation 13 are shown in Table 11. Figure 22 shows a plot of the predicted versus observed values of the 8-hour average CO concentration (3 PM to 11 PM on weekdays) at each site during the study period. The predictions were made with equation 13. The model residuals were log-normally distributed, as shown in Figure 23, and therefore, increased with increasing CO concentration on a linear scale, as shown in Figure 22.

The models described above were modified to include the previous day's CO concentration. This was done because of the temporal correlations we had observed in the data. However, the previous day's concentration was not a significant predictor of the CO concentration; therefore, this term was not included in the final models.

Table 11. Constants For ANOVA Model (Equation 13)

Model Constants	Value
S_1	-0.344
S_2	.0069
S_3	0.4218
α_1	0.0480
μ_1	9.9794
α_2	0.1298
μ_2	2.8297

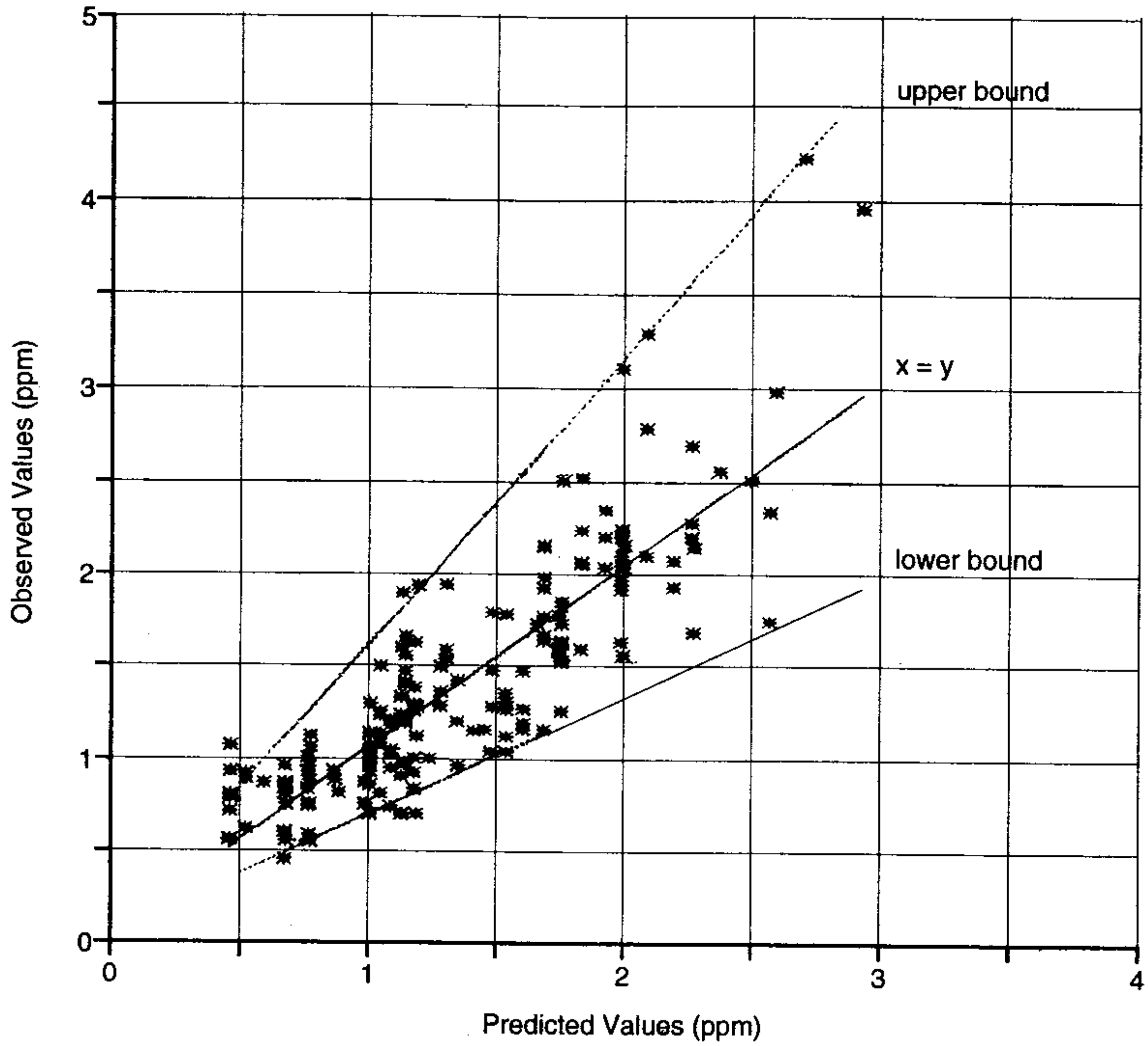


Figure 22. Predicted vs. Observed 8-hr Average CO Concentrations for All Sites and Weekdays (Model is given by Equation 13 in text.)

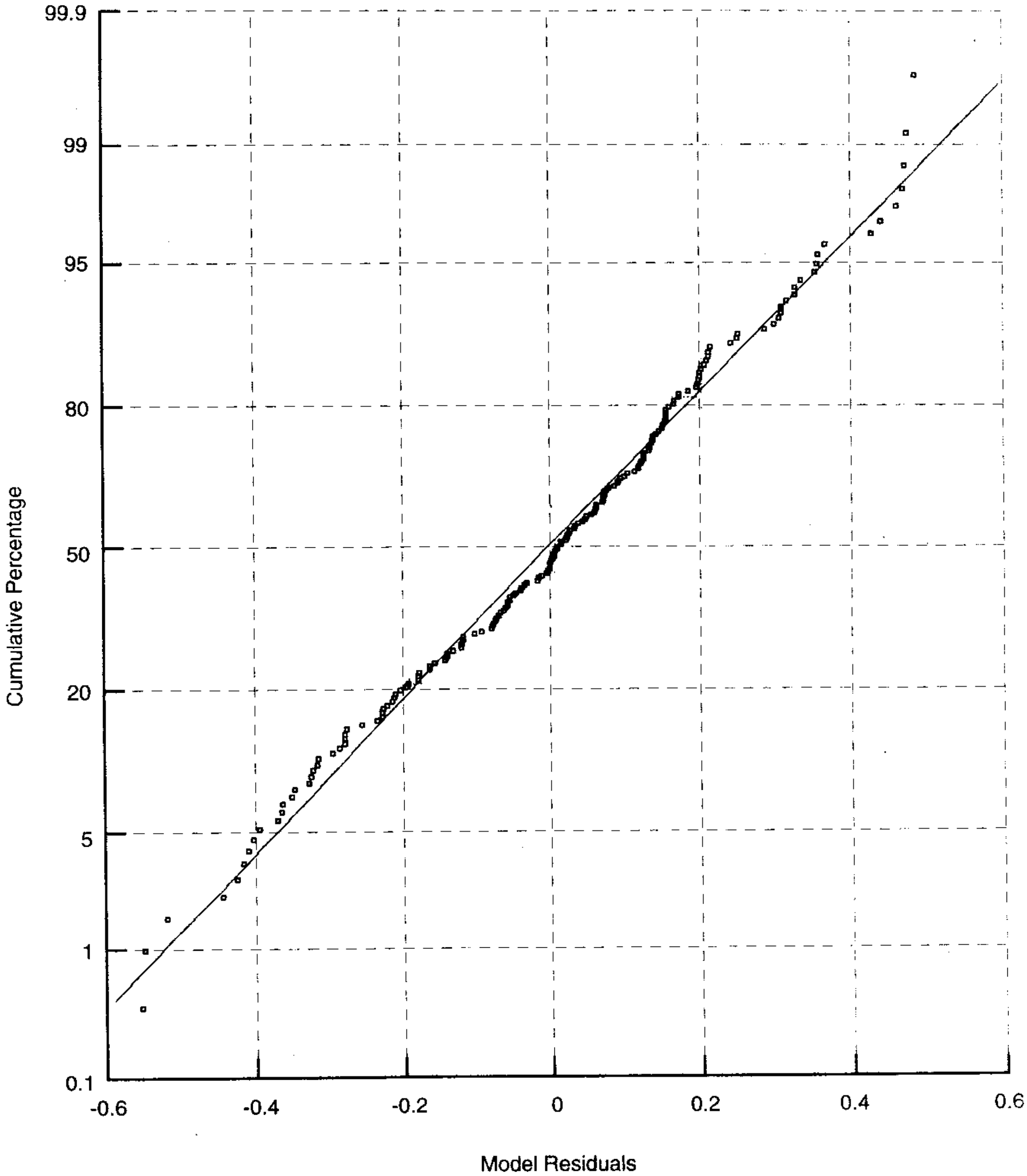


Figure 23. Log-normal Probability Plot of Model Residuals
(Model predictions are shown in Figure 22.)

INTERPRETATION, APPRAISAL, AND APPLICATION

Background concentrations are an important part of any project level analysis; therefore they must be accurately assessed. To what extent can our results aid in this assessment? First, if one wishes to directly measure the background level, we have provided objective criteria not only for siting a background monitor, but also for assessing whether it is properly sited on the basis of its measurements. Second, we have provided a site classification framework and corresponding log-normal distribution parameters that allow direct use of our observations. Finally, we have proposed a model that describes the influence of meteorology on the background levels in an urban area. This model can be used to assess the relative importance of local, as opposed to regional background levels, which makes our observations more generalizable. We discuss each of these results in more detail below.

SITING CRITERIA

The siting criteria developed in this study can be used to site a background monitor in an urban area. These criteria are somewhat different than those first proposed by Ott. (3) He concluded that all background sites should be located in urban parks, at least 100 m from lightly traveled roadways. We have found that placement inside a park is not as important as is the distance from the site to significant roadways. Moreover, distance from the road is more important than traffic volume variation on that road. Our "Isolated Park" sites happened to be located farther from trafficked roads than our "Trafficked" sites.

Although highly trafficked background sites can be located relatively close to major roadways (30 to 200 m), once a site has been established, it should not experience the large fluctuations in short-term (1-minute average) CO concentrations that are found at near-roadway, EPA microscale sites. The average geometric standard deviation of the 1-minute CO concentrations about the mean of non-overlapping 5-minute periods is a simple and useful criterion for assessing the magnitude of these fluctuations and, therefore, the magnitude of local source contributions. The values shown in Table 2 should be applicable to any location in an urban area. We would further expect that the peak hour within the afternoon 8-hour sampling period will occur later in the period than it does at sites next to the road. Again, this simply reflects the relative importance of mobile source emission patterns and the relative unimportance of atmospheric transport phenomena at street sites in comparison to local background sites. The persistence factors at our background sites are in good agreement with those observed at curbside sites. (20)

SITE CLASSIFICATION FRAMEWORK

Our site classification was based upon observed concentrations measured simultaneously at a number of background locations. What was most striking about these observations was the high degree of spatial correlation within site groups, even though sites within a given group were spaced relatively far apart. This result does not imply that there was a single background level over the entire north end of Seattle. The fact that the Isolated Park sites were located on both the east and the west sides of the study area demonstrated that this was not the case. Nor does this result imply that the general background level over the north end of Seattle was slightly higher in the center of the study area (near the freeway) and lower at the edges (near the water). The fact that the UW site had some of the highest background values but was also near the eastern edge of the study area counters this idea. The only explanation consistent with our results is that each site must be classified according to its proximity to nearby traffic. The magnitude of nearby traffic is also a factor, but to a lesser degree. This traffic "density" index places the Isolated Park sites on the edges of our study area because, in general, traffic was more densely spaced in the center of our study area than on the edges. Ott and Eliassen (2) recognized the importance of local traffic effects in their pioneering work in this area. Our site classification criteria are consistent with this notion.

Our literature review in this area did not uncover any previous reports of the frequency distribution parameters at background sites. The log-normal distribution model, coupled with our site classification, provides a very good description of our measured background CO concentrations. Our analysis of the network's ability to accurately sample these distributions indicated that the 46-day sampling period was reasonable. Had we sampled for twice as long under the same meteorological conditions, we think that the uncertainty associated with our estimate of the site group means would have been reduced by only 30 percent. Note that our measurements were made in the middle of winter during the most meteorologically stable period of the year. To use the log-normal model, one must understand that the percentiles chosen were for the winter period, during which the highest CO concentrations occur. Therefore, the worst case day in 20 winter days (95th percentile) may actually have represented the worst case day of that year (99.7th percentile). The winter period that we sampled appeared to be similar to the previous two winters in terms of both the frequency of stable days and the wind speed distribution at nearby monitoring sites.

BACKGROUND VERSUS CURBSIDE LEVELS

In this study, we selected sampling sites to avoid contributions from local sources, specifically individual mobile sources on nearby roadways. Therefore, the concentrations we observed were consistently lower than simultaneous measurements taken by the DOE at sites located for regulatory purposes within a few meters of the roadway edge. These latter sites are heavily influenced by local sources. Our best estimate is that the local source contributions at the Zanadu and Northgate sites during "worst case" conditions are between 50 and 60 percent of the total observed 8-hour average CO concentration (see, for example, Table 6). The remaining CO comes from "background." This observation implies that a 20 percent emission reduction on a localized scale, because of improved traffic flow at a given intersection, for example, would only result in a 10 percent reduction in the CO concentration at that intersection. Further reductions would only be achieved if the emissions from all sources in the area were reduced.

These results are consistent with the earlier findings of Perardi et al. (4), who compared street measurements in San Jose, California, with simultaneous measurements at nearby sites located several blocks away from major roads. They found that 75 percent of the observed CO was due to background sources. However, their observations were made in the late 1970s and early 1980s, when CO concentrations were generally higher than they are now in most urban areas. Nevertheless, the fact that we observed a significant contribution from background is not surprising in light of these earlier observations.

PREDICTING CO BACKGROUND LEVELS

Background CO levels for given sites and characteristic meteorology can be estimated by using our measurements directly, by using the log-normal parameterization of our measurements, or by using our ANOVA model that includes meteorological co-variates. We recommend the latter approach in order to include "worst case" meteorology into the background estimate and therefore to generalize our results to other locations within the urban area independent of meteorological variability from site to site. Specifically, one can specify $n_{wind} = 8$ for use in "worst case" EIS project analyses. This corresponds to 8 out of a possible 8 hours with stagnant conditions. For "trafficked" sites, we can write equation 13, with $n_{wind} = 8$, as: $\ln(C)_3 = s_3 + \alpha_1[\ln(V_{traf}) - \mu_1] + \alpha_2[8 - \mu_2]$. Using the values listed in Table 9 for s_3, α_1, μ_1, α_2 and μ_2, we obtain the following simplified expression for "trafficked" sites:

$$\text{background CO (ppm)} = 1.85\,(V_{traf})^{0.048} \qquad \text{(Equation 13a)}$$

where V_{traf} = the highest average weekday traffic volume within 200 meters of the receptor site (vehicles per day).

For "urban park" sites, with $n_{wind} = 8$, we ignore the small effect of traffic and use equation 14: $\ln(C)2 = s_2 + \alpha_2[8 - \mu_2]$. Using the values listed in Table 9, we obtain the following simplified expression for "urban park" sites:

background CO (ppm) = exp[.0069 + .671] = 2.0 ppm (Equation 14a)

Equally important, the model also gives us error bounds on these estimates. The model (equation 13) standard error is 0.226 ppm, and so the estimated background CO value, C, for "trafficked" sites is within the following bounds:

lower bound: $\exp[\ln C - (z_{1-p/2})(0.226)]$

upper bound: $\exp[\ln C + (z_{1-p/2})(0.226)]$

The model (equation 14) standard error is 0.230 ppm, and so the estimated background CO value, C, for "urban park" sites is within the following bounds:

lower bound: $\exp[\ln C - (z_{1-p/2})(0.230)]$

upper bound: $\exp[\ln C + (z_{1-p/2})(0.230)]$

If one chooses the 95 percent confidence limits, for example, then from the standard normal distribution, $z_{1-p/2} = 1.95$. The uncertainty quantified here reflects the variability not accounted for in the model estimate of background CO.

The site locations in this study were chosen to avoid significant impacts from stationary sources, most notably residential wood heating devices. The USEPA emission factors for conventional wood stoves and fireplaces include a ratio of carbon monoxide to fine particle emissions of between 6.1 to 1 and 6.2 to 1. Measurements of PM_{10} at the Lake Forest Park monitor operated by the Puget Sound Air Pollution Control Agency have shown that maximum fine-particle wood smoke levels in the North Seattle area do not exceed 100 micrograms per cubic meter on a 24-hour basis. This implies a maximum CO concentration from wood burning of about 600 micrograms per cubic meter, or 0.5 ppm on a 24-hour basis. However, the wood burning peak impacts occur between 7 PM and 7 AM, whereas the peak evening traffic hours are between 3 PM and 11 PM. In addition, the maximum wood smoke impacts occur at the bottom of creek valleys, which occupy a relatively small fraction of the urban area. Therefore, this 0.5-ppm level is an upper bound estimate of the background CO contribution from wood burning in these valleys.

COMPONENTS OF THE BACKGROUND CONCENTRATION

It is instructive to consider the various components of the 8-hour average CO concentration in an urban area. The measured concentration consists of 1) a local source contribution, 2) a local background contribution, 3) a "regional" background contribution, and 4) a global background contribution. We have already discussed the relative magnitude of the local source contribution relative to "background," i.e., the total of the latter three components. A reasonable estimate of the magnitude of the "regional" background contribution is the mean value at the Isolated Park site. This site is, on average, about one-half of the observed level at Trafficked background sites (see Table 6). This is also true under conditions of high wind and low traffic. From equation 13 with $n_{wind} = 0$ and $V_{traf} = 0$, we have

$$\ln(C)i = si - \alpha 1 (\mu traf) - \alpha 2 (\mu wind) \qquad \text{(Equation 17)}$$

For the Trafficked sites, i = 3, $\ln(C) = \{0.4218 - 0.048(9.9794) - 0.1298(2.8297)\} = -0.42$, and therefore $C = \exp(-0.42) = 0.65$ ppm. For the Isolated Park and Urban Park sites, i = 1 and 2, respectively, with the result that C = 0.30 and 0.43 ppm, respectively. The predicted value from the Isolated Park site is again about one-half of the value for the Trafficked sites. The predicted value of 0.30 ppm at the Isolated Park site can also be compared with the lowest value measured in this study, 0.4 ppm, and with the previously reported values of the northern hemispheric background CO level of 0.13 ppm (21, 22) in the winter. The estimated value at the Isolated Park site under conditions of high wind and no local traffic is about twice that of the northern hemispheric background level in the winter. The mean value at the Isolated Park site during this study was about five times the northern hemispheric background level.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A new, low volume, self contained, vacuum-based air sampler was developed to reliably collect CO samples over a prespecified averaging time (e.g., eight hours). The resulting UW air sampler uses much less power than conventional pump/bag units and can operate at much lower flow rates. Sampler reliability was demonstrated in field experiments in which a high correlation ($R^2 = 0.999$) was observed between the UW air sampler and a co-located DOE sampler. Over the duration of the study period, readings from the UW air sampler also correlated highly with readings from a continuous monitor whose inlet was nearby ($R^2 = 0.985$).

The reliability of the CO analyzer used in this study was verified by comparisons with independent calibration gases provided by the DOE. In these tests, an accuracy of 4.6 percent and precision of 0.4 percent were observed. These values are well within acceptable limits. Our wind speed sensor was also deemed acceptable on the basis of comparisons with a reference sensor located at the NOAA wind tunnel facility ($R^2 = 0.9996$).

The wind speeds and atmospheric stability during our winter sampling period were not obviously different from the previous two years. For the entire sampling period, both the frequency distribution of 8-hour average wind speeds and the proportion of hours of "F" stability were no different in 1993 than they had been during the same 46-day period in either of the previous two winters.

Our measurements indicated that a background site has the characteristics listed below. In contrast, street (source impacted) sites have the opposite features.

- The site has an absence of large fluctuations in 1-minute average CO concentrations. These short-term fluctuations in CO concentrations can be quantified by the geometric standard deviation of CO concentration for each non-overlapping 5-minute period within the overall sampling period. This parameter differs significantly between street sites and background sites. Values above 1.2 are indicative of direct street influences.

- The buildup of CO levels at the site occurs over the entire 8-hour sampling period (3 PM to 11 PM), with peak hourly CO concentrations occurring late in the period.
- The site lacks obvious spatial gradients in the 8-hour (3 to 11 PM) average concentrations in areas at least 20 m from urban arterials and 100 m from freeways. Sites similarly located with respect to traffic also have a high degree of spatial correlation.

The grand average of all the 8-hour average CO concentrations at all background sites was 1.32 ppm. Given the number of sites and the number of days sampled in this study, and accounting for temporal and spatial correlations within the sampling network, the estimated 95 percent confidence limits of the true population mean was 0.4 ppm. To reduce this uncertainty from 0.4 to 0.2 ppm would require an additional 140 winter days of sampling, clearly an impractical task with diminishing returns.

Our background sites, all of which were located a minimum of 70 m from major intersections, can be grouped into at least two distinct categories: 1) "Trafficked" sites (30 to 100 m from arterials and at least 200 m from major freeways); 2) "Urban Park" sites (400 to 700 m from arterials and at least 5 000 m from major freeways). The mean level observed at the Trafficked sites during the period from January 25 to March 11, 1993, was 1.6 ppm. The corresponding mean of the Urban Park sites was 1.0 ppm. The maximum 8-hour average CO concentration measured during the study was 4.2 ppm and was observed at a Trafficked background site. An "Isolated Park" site, located in a very low traffic area, had consistently lower CO levels (mean = 0.7 ppm) than all other sites and appeared to belong to a third site category. Traffic volume variations with time were not accounted for in this study, although the 8-hour averaging time diminishes the importance of traffic variations during peak periods.

The persistence factor was measured at one of our background sites. The value was 0.66 (standard error of the mean = 0.015), very close to the default value of 0.7 recommended by EPA for project level analysis.

The daily mean of the 8-hour average CO concentrations at the Trafficked background sites was compared with simultaneous measurements taken at several street sites to assess the magnitude of the background levels relative to street levels. The ratio of the daily mean value at all Trafficked background sites relative to the value at a given street site was computed for each day during the study period. The average ratio for our Trafficked background sites relative to the Zanadu street site was 0.48 (s.e. = 0.02); the corresponding ratio for Trafficked sites relative to the Northgate street site was 0.59 (s.e. = 0.03). The ratios associated with highest CO levels at the street sites were also examined. For the two days with the highest 8-hour average CO levels at the Zanadu and Northgate sites, the ratios were 0.49 (s.e. = 0.08) and 0.44 (s.e. = 0.28), respectively. In general, the CO concentrations at the trafficked background sites were about one-half the corresponding values observed at the street sites, even at high street site concentrations.

Thirty out of the 46 days sampled in the winter had low winds and stable night-time conditions. The overall study period was the most stagnant time during the entire fall and winter, and included the most stagnant days during these seasons. The 8-hour average CO concentrations during these stable periods were log-normally distributed, and these distributions differed between site categories. These log-normal distribution parameters may be used to estimate the daily mean value by site category of the 8-hour average background concentration that is not exceeded a given percentage of the time during meteorologically stable winter evenings. For Trafficked background sites, our best estimate of this value in ppm units = $1.69\ (1.33)^{z}$, where z = the number of standard deviations in the cumulative normal distribution that corresponds to the percentile of interest.

The log-normal distribution model of background levels accounts for the effects of traffic by specifying different values of the geometric mean and geometric standard deviation for each background site category. It indirectly accounts for meteorology in that it is limited to stable winter periods. To examine these factors in greater detail, an ANOVA model was developed. This model predicts background levels at a given site by including specific traffic and meteorological variables. Several meteorological co-variates were examined within this framework. The best model of the observed background levels (R^2=0.75) used a meteorological parameter derived from a wind sensor located in a sheltered urban area. This parameter was the number of hours during the 8-hour sampling period when the average wind speed at the sheltered sensor was less than 0.2 meters per second, the instrument's detection threshold. In our final recommendations, we assumed "worst case" meteorology. This was done to minimize the uncertainties associated with site-to-site variability of wind speeds over the study area.

RECOMMENDATIONS

Recommended Procedure for Project Level Analysis

The following procedure for estimating background CO is recommended for use in project level analyses.

For trafficked urban areas

1. Roadways with between 5 000 and 100 000 vehicles per day located at or less than 30 meters from the receptor of interest should be specifically included as a part of the project impact analyses.
2. Roadways with greater than 100 000 vehicles per day located at or less than 200 meters from the receptor of interest should be specifically included as a part of the project impact analyses.

3. The "worst case" 8-hour average background CO concentration from all other surrounding sources (in ppm) = $1.85(V_{traf})^{0.048}$, where V_{traf} = the highest average weekday traffic volume within 200 meters of the receptor site (vehicles per day). For example, if V_{traf} = 50 000 vpd, then "worst case" 8-hr average background CO = $1.85\ (50\ 000)^{0.048} = 3.1$ ppm.

For urban parks

4. For roadways with greater than 5 000 vehicles per day located at least 400 meters from the receptor of interest, the "worst case" background CO concentration from all other surrounding sources is 2.0 ppm.

The procedures outlined above describe the results of measurements taken in Seattle, Washington. They should not be used in urban areas with significantly different topography, such as urban areas located in a valley that is completely surrounded by elevated terrain.

Additional background carbon monoxide may also be present in low-lying areas that are heavily impacted by wood smoke. An upper bound estimate of the contribution of wood burning to background CO at these locations is 0.5 ppm. This estimate is based upon the fine particle concentrations in these areas and the relative emissions of CO and particles from conventional wood stoves and fireplaces. However, this estimate is qualified by the fact that we did not make measurements of CO in these wood smoke impacted areas.

Extrapolation of Results to Other Urban Areas

Our measurements were made in an urban area that is elevated with respect to the surrounding water (see Figure 1). However, some urban areas are located at the bottom of a valley, surrounded by elevated terrain. Under stable nighttime conditions, the wind flow patterns in our study area may be very different from those in such valleys. Valley drainage winds would be expected to "pool" over the urban area, possibly creating very different background CO concentrations and different spatial patterns of the background concentrations. It is unclear whether the siting criteria we used in this study would apply to the valley case. Experiments should be carried out to test this variation.

Establishment of a Background CO Monitoring Site

Currently, all CO monitoring sites in the state are located near roadways. A background site should be established at one location within the Seattle area. Proper placement of the site can be checked by using the distinguishing features of a background site as discussed previously. Such a site would provide two functions. First, it would allow a check of the results of this particular study. Second, it would provide a useful monitor of long-term trends in urban CO concentrations that would be relatively unaffected by any one roadway or intersection.

Model Testing

Estimating background levels with the EPA's Urban Airshed Model (UAM) for assessment of conformity with the state implementation plan for CO requires knowledge of relevant meteorological conditions. The fact that background CO levels are most strongly associated with very low wind speeds below conventional detection limits makes it difficult to define the relevant wind speeds for use in the UAM. In contrast, the ANOVA model described here provides a flexible framework for such "worst case" analyses. For these reasons, the ANOVA model should be compared with the UAM. To perform this comparison, background monitoring sites need to be established because the UAM predicts the CO levels at these "well mixed" sites rather than at source impacted locations (e.g., existing DOE sites). The upper air meteorology needed for running the UAM in this area will be available after December, 1993, when a vertical wind profiler is installed at NOAA's Sand Point facility.

Distinguishing Features of Background Sites

Our measurements indicate that careful analysis of the magnitude of the short-term fluctuations in CO levels can provide an independent check on proper location of a background monitor. These short-term fluctuations in CO concentrations can be quantified by the geometric standard deviation of CO concentration for each non-overlapping 5-minute period within the overall sampling period. Although we performed this analysis at three background locations, this analysis needs to be extended to more sites throughout the study area. Our combined distance/traffic criteria, which were used to located our background sites, can be tested within the framework of this short-term fluctuation criterion.

Sampling in Cold Climates

Because the samplers developed for this study do not rely on a battery operated air pump, they are less susceptible to failure at low temperatures. Therefore we recommend consideration of this sampling technology when sampling for CO in cold climates.

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APPENDIX A

DETAILED MAPS OF SAMPLING SITES

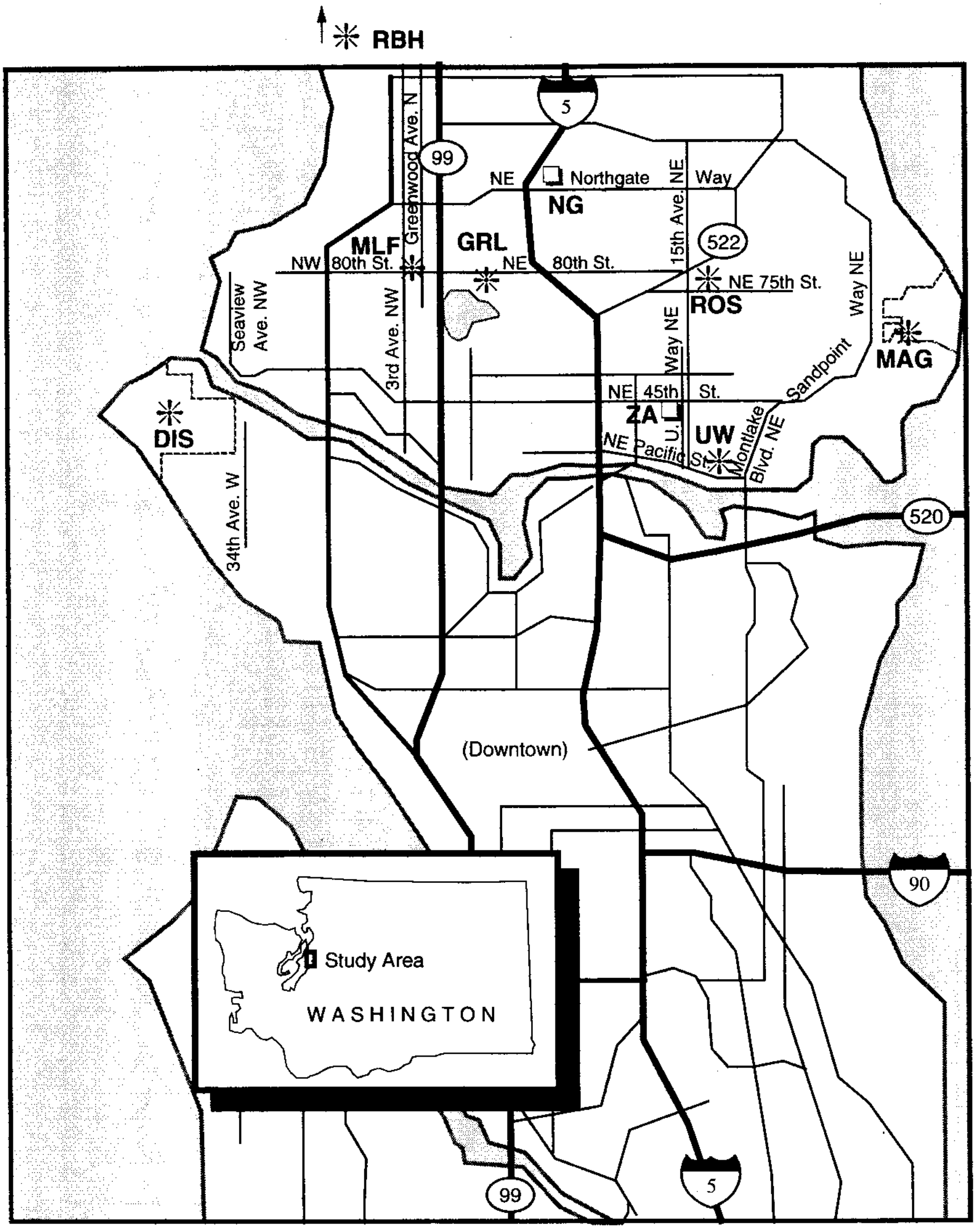


Figure A-1. 1993 Urban "Background" Carbon Monoxide Sampling Sites (✳) and Two Department of Ecology Air Pollution Monitoring Sites (❑)

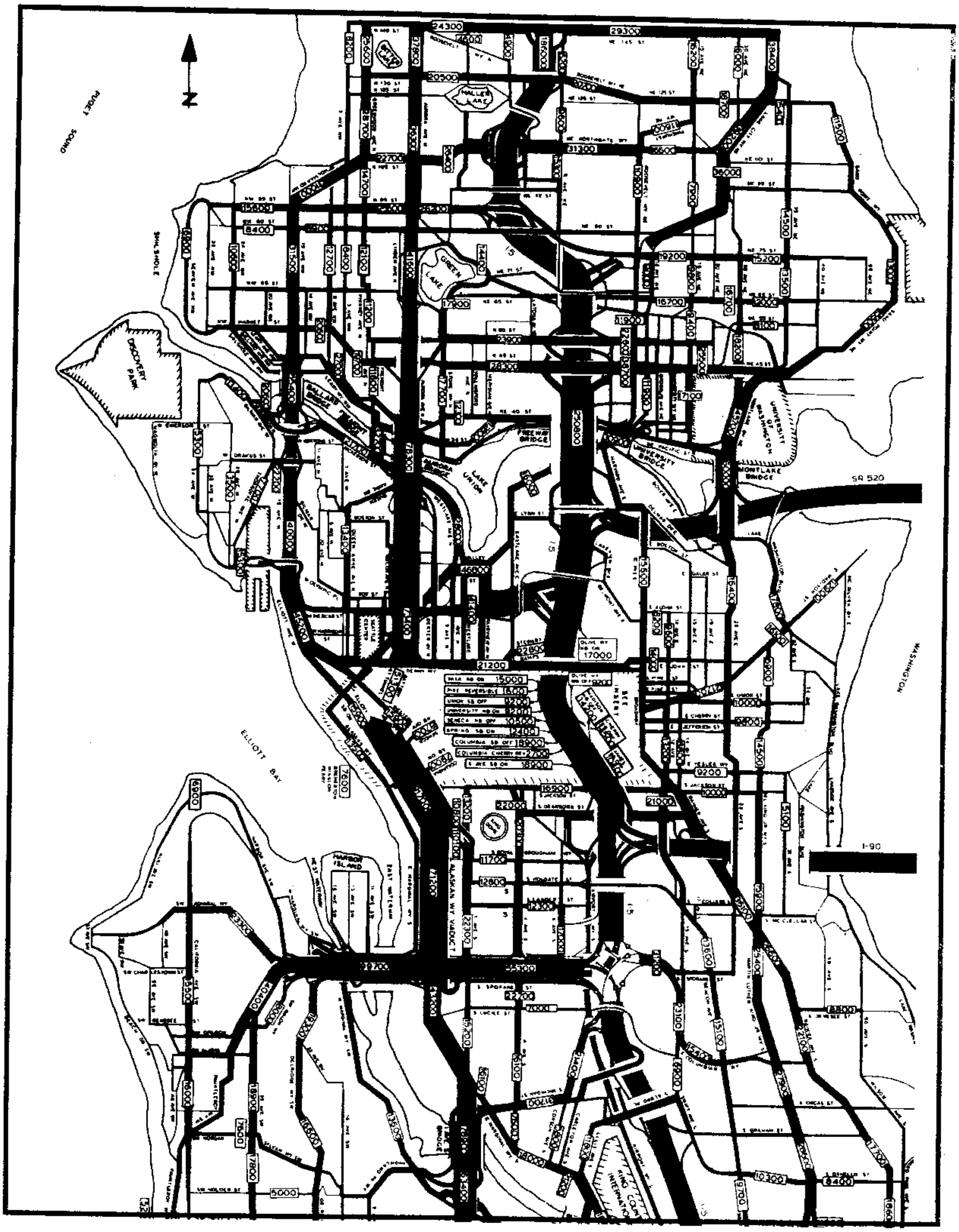
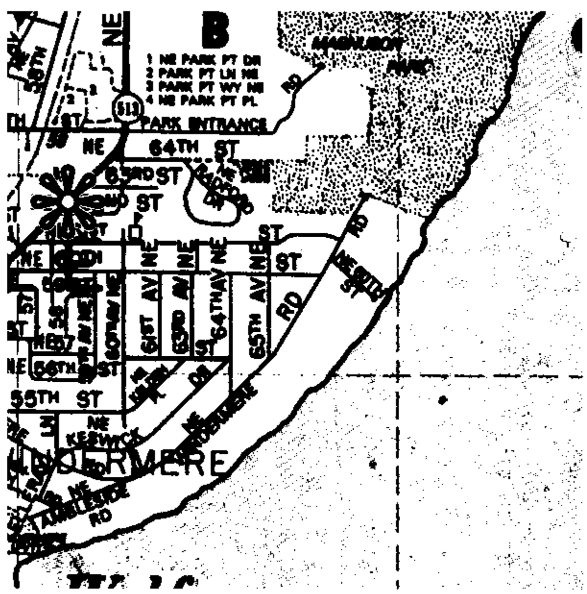


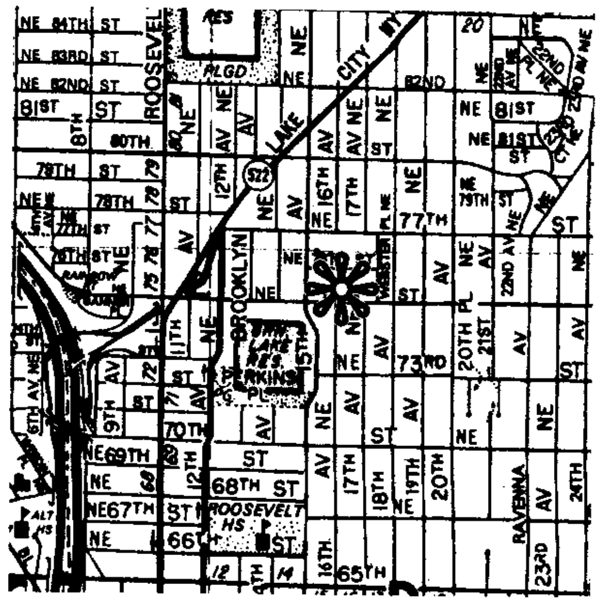
Figure A-2. Seattle Traffic Flow Map (1991)

UW



MAG

Figure A-3. Carbon Monoxide Sampling Sites



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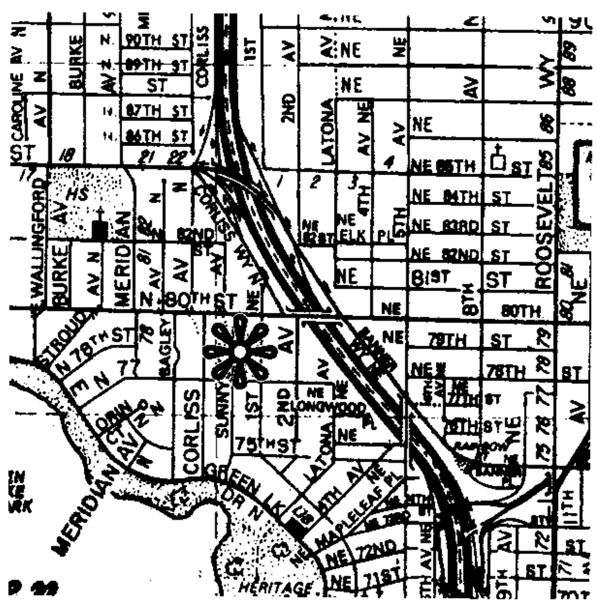
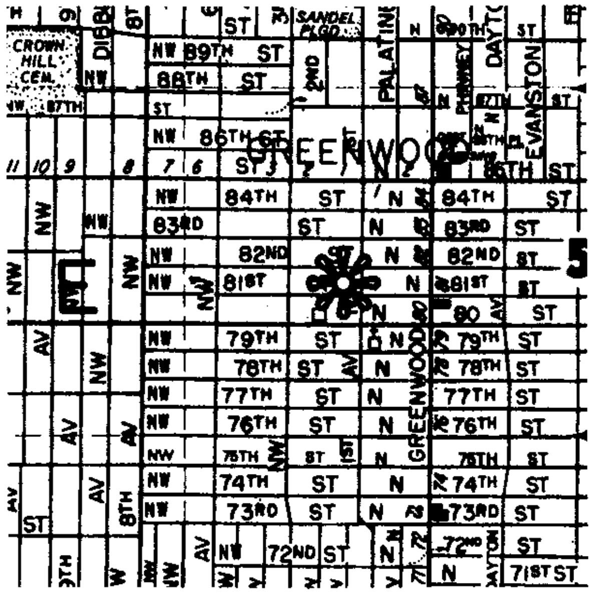


GRL

Figure A-4. Carbon Monoxide Sampling Sites



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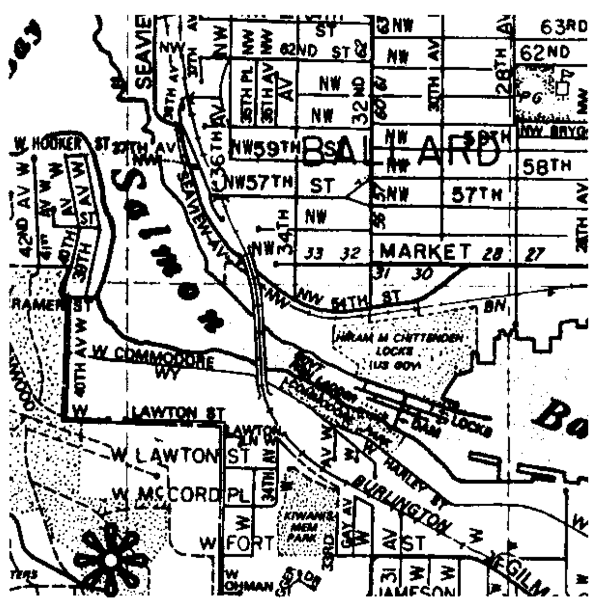
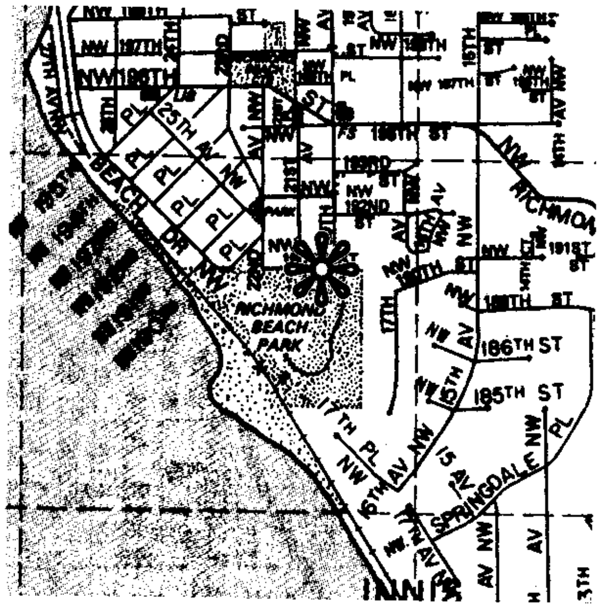


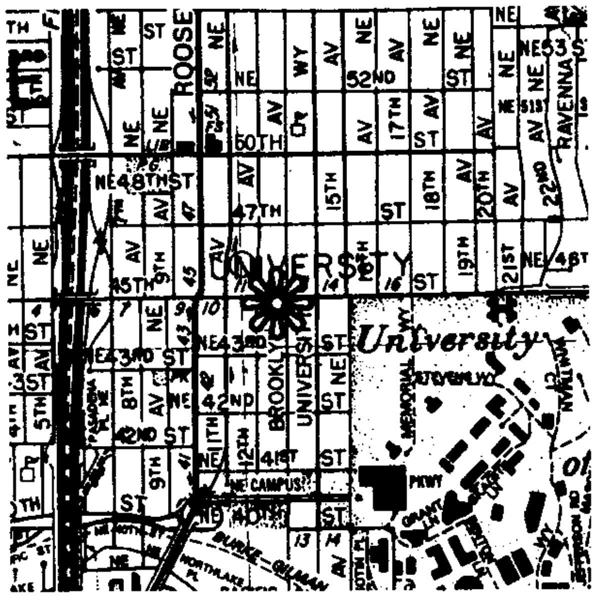
DIS

Figure A-5. Carbon Monoxide Sampling Sites



RBH

Figure A-6. Carbon Monoxide Sampling Sites



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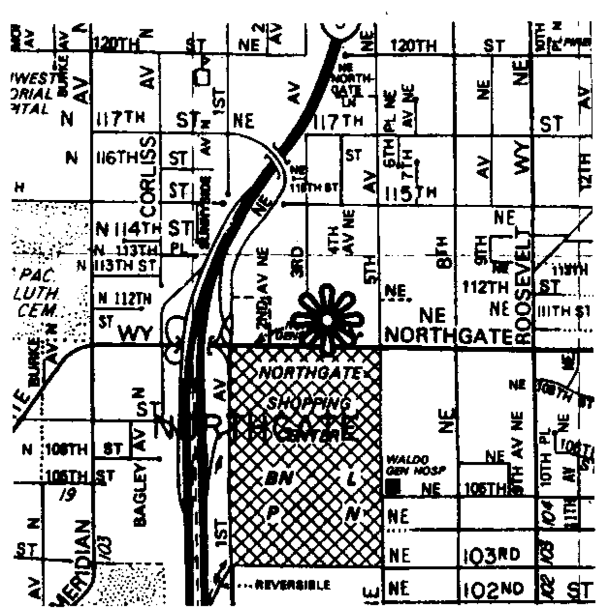


NG

Figure A-7. Department of Ecology Air Pollution Monitoring Sites

APPENDIX B

DESCRIPTION AND EVALUATION OF UW AIR SAMPLER

DESCRIPTION OF AIR SAMPLER

A schematic of the sampler is shown in Figure B-1. Ambient air is drawn through a micro-bore Teflon tube to a low-density polyethylene (LDPE) bag by means of an internal vacuum of approximately 25 cm of water. Reserve vacuum is provided by a 5-liter reservoir evacuated to 550 mm of mercury. Precise control of the sampler internal vacuum and the length of the sampling period are provided by digital circuitry and a pair of solenoid valves. A rechargeable, 12-volt battery provides power for the electronics.

The entire assembly consists of the following four sub-units.

A) Sampler housing—A 20-liter, high-density polyethylene container houses the sample bag. The container is held at atmospheric pressure during non-sampling periods and at 25 cm nominal water vacuum during sampling periods.

B) Vacuum supply—A 50 cm length of 10 cm diameter ABS pipe, capped at both ends, holds the reserve vacuum. This container is evacuated to 550 mm of mercury and is recharged before each sampling period.

C) Manometer—A straight-tube manometer is connected directly to the internal chamber of the sampler housing and is used to control the sampler internal vacuum. The exterior shell of the manometer is constructed from 45 cm of 5 cm diameter ABS tubing that is capped at one end. A 1.3 cm clear plastic tube, containing a free-moving glass float, is positioned within the ABS shell, which is filled to an approximate depth of 10 cm with an ethylene glycol/water mixture.

As the pressure within the sampler housing is lowered at the start of the sampling period, the glass float is drawn up into the central clear plastic tube until the float blocks a photodiode emitter/receiver pair. This photodiode level detector controls the sampler internal vacuum to 25 cm of water with a deadband of approximately 0.5 cm of water.

D) Control circuitry—An electronic control circuit switches the sampler into and out of sampling periods by receiving timing signals from two digital alarm clocks. The circuit opens and closes two solenoid valves that are connected between the sampler housing and either the reserve vacuum container or the atmosphere.

During sampling periods, the vacuum solenoid is controlled by feedback from the photodiode level detector in the manometer. At the conclusion of a sampling period, the atmospheric solenoid valve is opened in order to equalize the pressure within the sampler housing and thus stop sample air uptake. During non-sampling periods, the atmospheric solenoid valve is pulsed for about 5 seconds at regular intervals of approximately 2 minutes so that the internal/external pressure is balanced, power consumption is minimized, and air sampling does not occur.

SAMPLER FLOW RATE

The temporal variation of carbon monoxide in ambient air makes a consistent sampling flow rate over the sample period crucial in determining accurate, time-averaged carbon monoxide concentration values. The flow rate, over an 8-hour period, of the UW carbon monoxide air sampler was determined. For comparison, portable pump and bag samplers were borrowed from the Department of Ecology; these samplers were also analyzed for flow rate variations.

The experimental procedure consisted of measuring the total sample volume accumulated over each hour of an 8-hour period for both the UW and DOE samplers. Results of these tests are shown in Figure B-2. The sampling flow rate, and thus total sample volume, was approximately five times higher for the DOE samplers than for the UW samplers because of the different modes of operation used by each sampler. Both the UW and DOE samplers showed consistent sample flow rates over the 8-hour period.

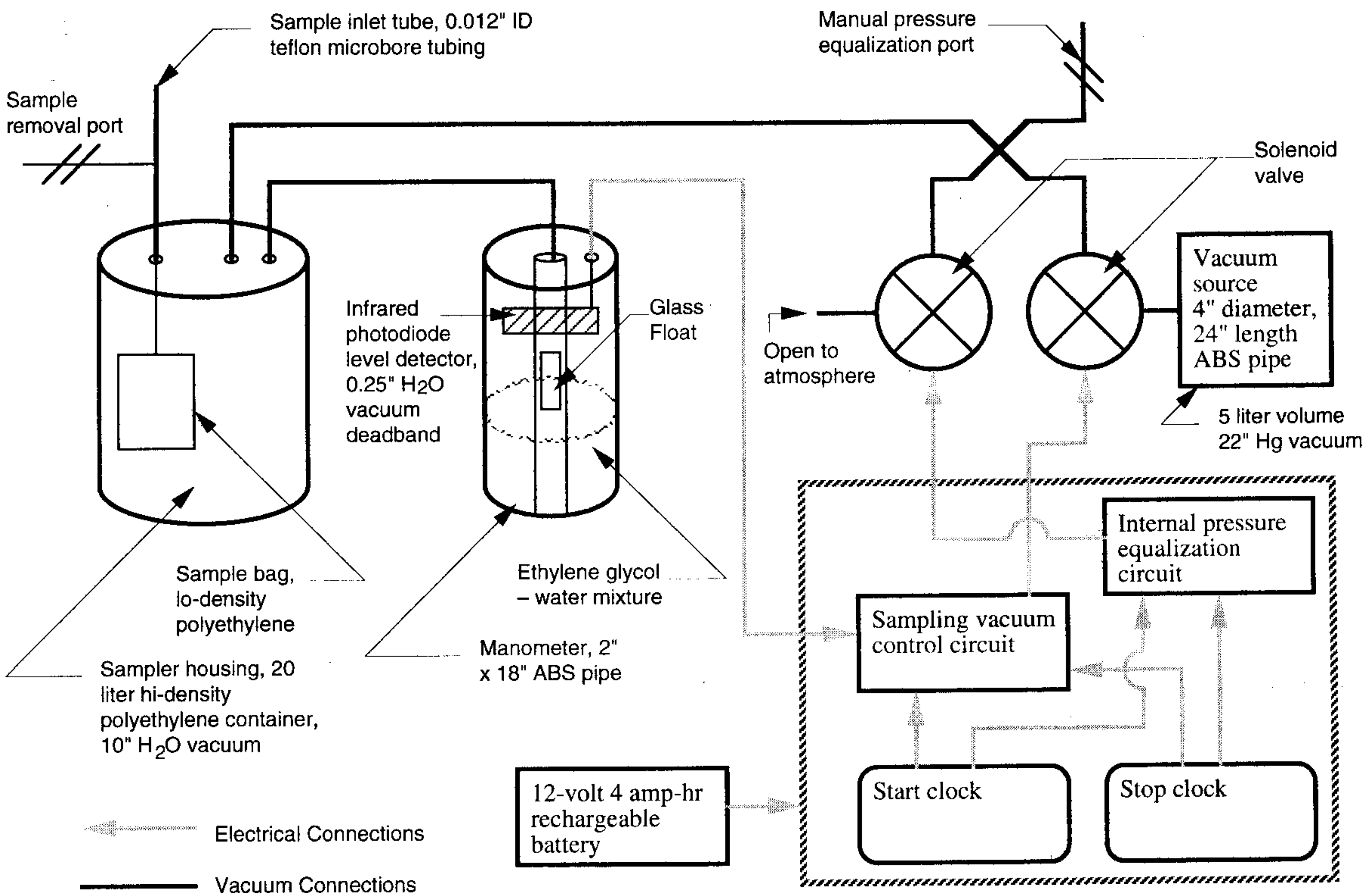
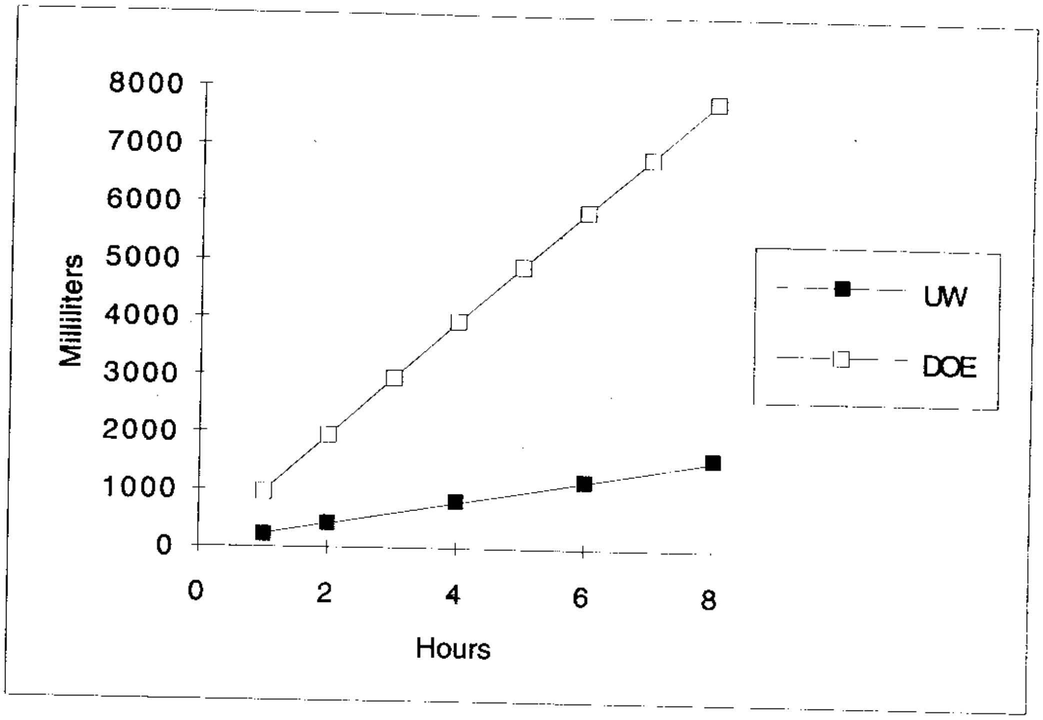


Figure B-1. University of Washington Carbon Monoxide Air Sampler



Regression Data

DOE

$r^2 = 0.099$

y = 975x + 10 milliliters = 975 (hours) + 10

UW

$r^2 = 0.99$

y = 196.4x + 15.9 milliliters = 196.4 (hours) + 15.9

Figure B-2. Flow Rate Comparison of UW and DOE CO Air Samplers (May 1993)

APPENDIX C

ACCURACY AND PRECISION OF UW CO ANALYZER

The UW CO analyzer is a Lear-Siegler model ML9830. It is a non-dispersive, infrared photometer instrument and is designated as a reference method by the United States Environmental Protection Agency. The analyzer produces infrared radiation that is absorbed by CO along the path length of the instrument. The lower detectable limit is below 0.05 parts per million when the internal Kalman filter is active.

The accuracy and precision of the instrument used to analyze air samples were examined to validate the experimental data obtained by the UW carbon monoxide air samplers. A Lear-Siegler Model 9300 Continuous Carbon Monoxide Analyzer was used for all measurements in this investigation. Zero and span gases were used for daily calibration of the instrument, along with a third, intermediate-value gas used to calibrate a slope value. Nominal values for the carbon monoxide concentration in these gases are as follows

Zero gas:	0 ppm
Span gas:	15 ppm
Slope gas:	4.71 ppm

Access to a certified continuous carbon monoxide monitor and calibration gases was obtained thanks to the Washington State Department of Ecology (DOE). This monitor is located in the University District of Seattle at the Zanadu Comic Book Store on 45th Street NE. Repeated analysis (n = 8) of the DOE calibration gases was used to evaluate the accuracy of the calibrated UW carbon monoxide analyzer. The DOE uses two gases for calibration: a span gas and a slope-check gas. Zero gas is provided by an internal carbon monoxide scrubber. The carbon monoxide concentration values of these gases (at the time of this validation procedure) were as follow:

Span gas:	29.71 ppm	(certified) 2 percent
Slope gas:	10.00 ppm	(certified) 2 percent

Repeated readings (n = 46) obtained for the UW slope gas during the daily calibration procedure were used to calculate the precision of the UW instrument. The calculated values for the precision and accuracy of the UW carbon monoxide analyzer were found to be satisfactory and within expected ranges:

Accuracy: 4.60 percent

Precision: 0.43 percent

Accuracy is defined as the instrument's ability to give a reading that matches the true value of a standard gas. Precision is defined as the instrument's ability to give consistent repeated readings of the same gas.

COMPARISON OF THE PERFORMANCE OF THE UW AND DOE SAMPLES

The performance of the UW carbon monoxide air sampler was compared with the DOE samplers. Both indoor and outdoor sampling was done with the air inlets of each sampler in close proximity. Altogether, 18 paired, 8-hour air samples were taken, and the carbon monoxide concentrations were measured in the laboratory on the UW analyzer.

Ten paired indoor air samples were taken in a home kitchen with a natural gas stove as the carbon monoxide source. Burners on the stove were lit, and fresh air was introduced at various intervals to create a varying level of carbon monoxide in the kitchen. Instantaneous values ranging from 1 to 15 parts per million were observed. Outdoor concentrations at this site, at the time of testing, were approximately one-half part per million.

Eight paired outdoor air samples were also taken. The samplers were placed in a car that was then parked near traffic intersections for the duration of the sampling period. Sampler air inlets were positioned so that they extended out of an opening in the car window. A total of three sites with moderate amounts of traffic were selected.

All of the paired data were plotted; they are shown in Figure C-1. Eight-hour average carbon monoxide concentrations varied from approximately 1.5 to 10 parts per million for the indoor data. Outdoor 8-hour average concentrations varied from 0.6 to 2.6 parts per million.

As shown in the plot, all of the paired data lie very close to the line representing equal concentration values from each sampler. This indicates that the air samples obtained by the UW air samplers closely matched the air samples obtained by the DOE samplers under similar conditions.

A curve was fitted to the 18 data points of the plot in Figure C-1. As shown by the regression data, this curve is a very good fit with the sample data and shows that the samplers were performing very similarly. The regression data were

R^2 = 0.999

y = 0.966x + 0.0715

where y = DOE sampler reading

x = UW sampler reading

During the project sampling period (January 25 to March 11, 1993), several UW samplers were co-located near the inlet of the UW continuous CO monitor located at the UW. The distance between the UW sampler inlet and the inlet to the continuous monitor was approximately 6 to 7 m. This allowed for comparison of 8-hour averaged readings from the monitor to the 8-hour values obtained with the samplers. Because the inlets were somewhat separated, some deviation between the two data sets was expected.

The data were plotted and are depicted in Figure C-2. Regression analysis showed that the 8-hour CO concentration values produced by the UW samplers were very similar to 8-hour values produced by the continuous monitor. The regression data were

R^2 = 0.985

y = 1.04x - 0.162

where y = UW monitor reading

x = UW sampler reading

The accuracy and precision of the UW monitor were reasonable, and the UW samplers produced consistent, reliable results.

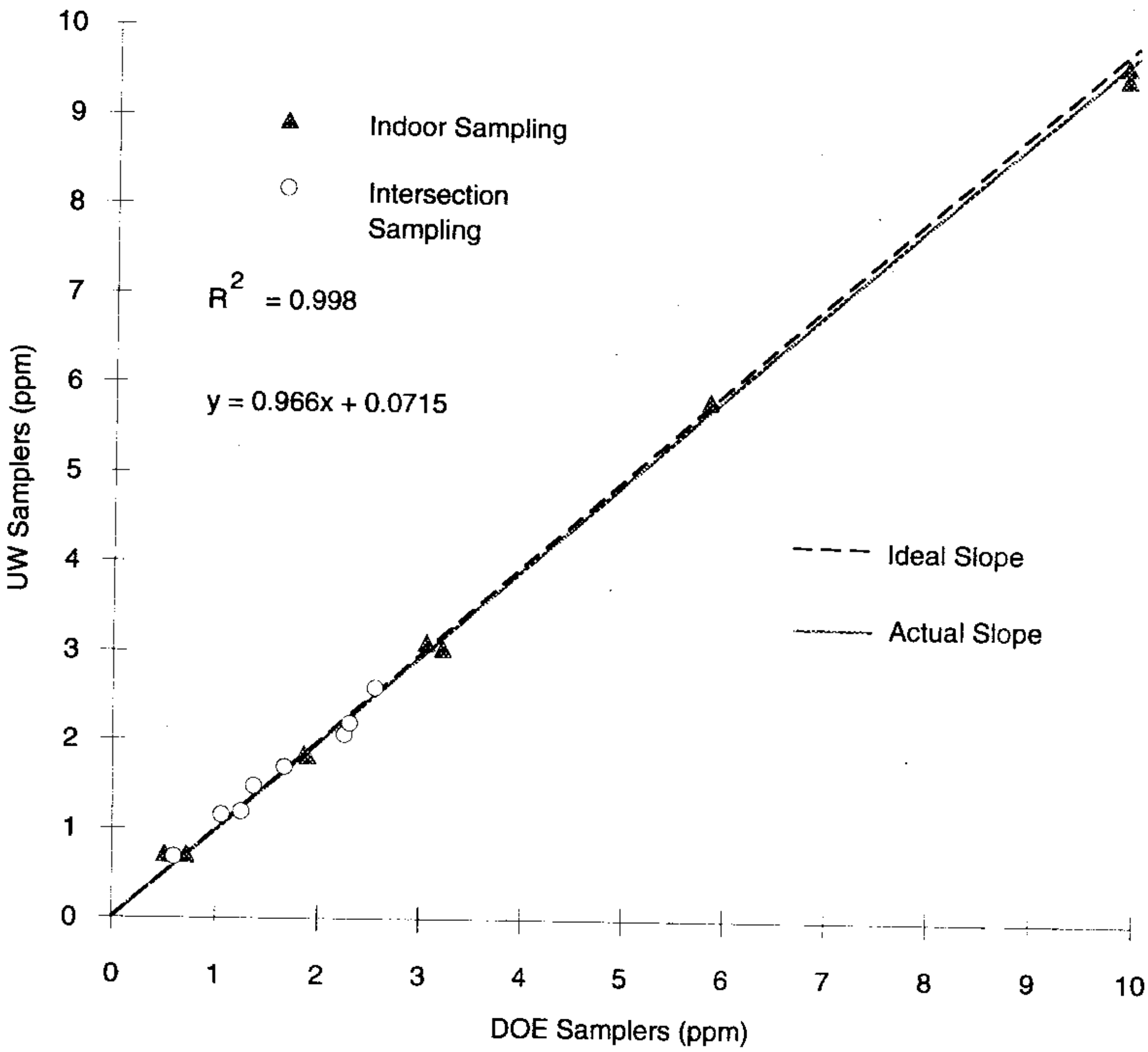


Figure C-1. Comparison of UW and DOE Bag Samplers,
8-hr CO Concentration, June - July 1993

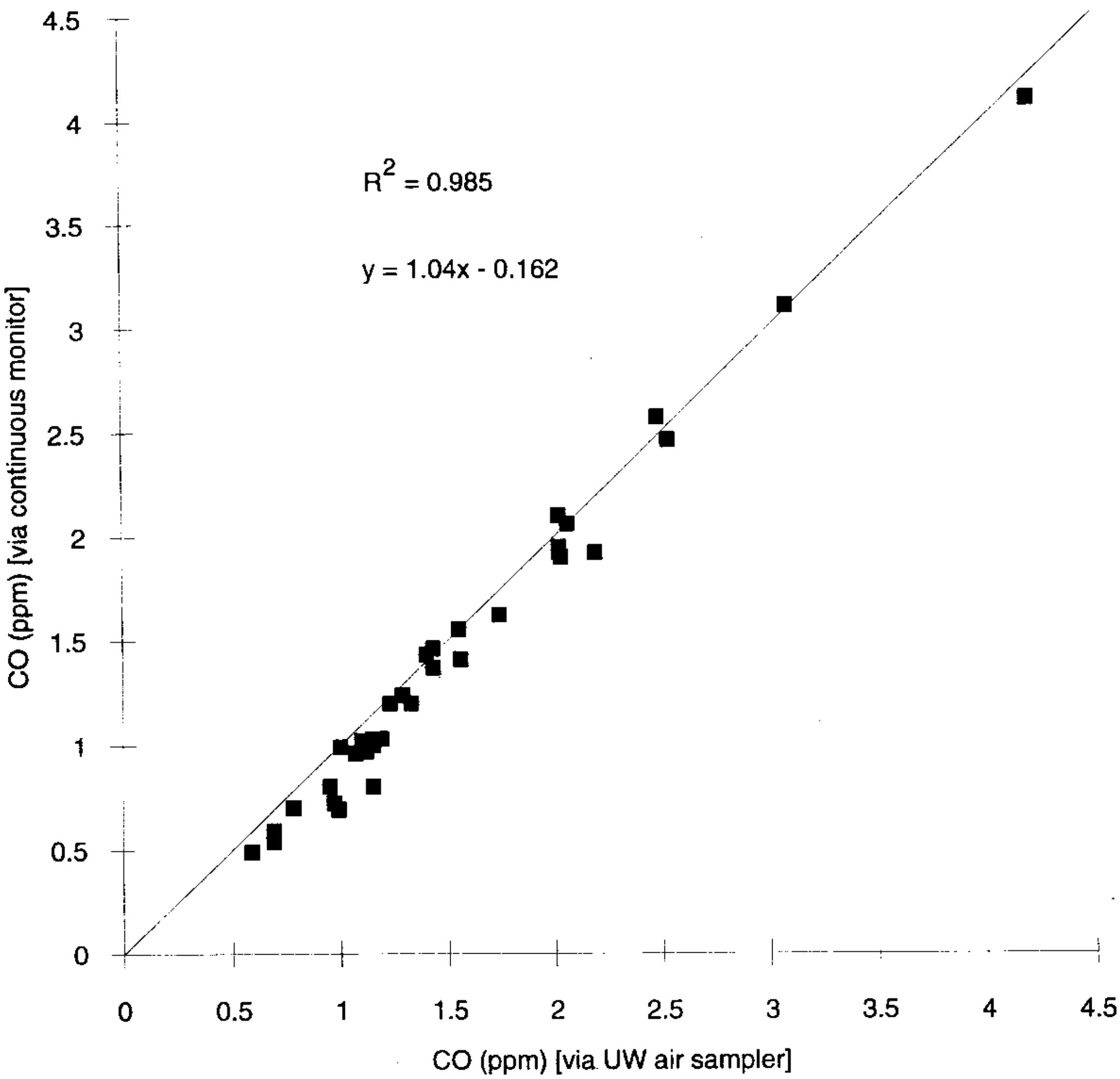


Figure C-2. Comparison of 8-hr Average CO Concentration Obtained with UW Air Sampler (abscissa) to Concentration Obtained from Continuous Sampling with Lear-Siegler Analyzer (ordinate)

APPENDIX D

HOURLY CO CONCENTRATIONS AND PERSISTENCE FACTORS AT THREE SITES

Table D-1. 1993 Zanadu Hourly CO and Persistence Data

Date	Hourly Carbon Monoxide Data								
	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	8-hr Mean
12/14/92	4.2	5.4	6.2	4.8	3.4	3.3	3.7	2.4	4.18
12/15/92	4.4	5.5	5.8	5.9	5.2	4.1	3.9	3.1	4.74
2/11/93	4.3	4.3	3.7	3.4	2.2	2.2	3.0	2.7	3.23
2/12/93	4.7	5.0	4.5	4.4	6.8	4.4	4.3	4.5	4.83
2/13/93	1.4	1.7	2.3	3.2	2.5	2.6	2.8	2.8	2.41
2/14/93	1.0	1.1	1.1	1.3	1.1	0.7	0.8	1.0	1.01
2/15/93	1.0	1.0	1.2	1.3	1.7	2.5	2.6	2.4	1.71
2/16/93	1.2	1.4	2.0	3.4	3.3	2.6	4.1	2.6	2.58
2/17/93	1.7	1.8	2.2	2.5	2.3	2.1	2.9	2.4	2.24
2/18/93	1.7	1.7	2.2	2.3	2.1	2.4	2.7	2.3	2.18
2/19/93	1.4	2.0	1.8	1.8	2.3	2.0	4.1	3.2	2.33
2/20/93	4.4	4.3	3.5	3.4	2.9	2.8	3.9	3.4	3.58
2/21/93	3.1	3.0	2.4	3.1	2.6	3.2	2.5	1.7	2.70
2/23/93	0.9	1.1	1.2	1.1	0.9	0.9	1.0	0.9	1.00
2/24/93	1.9	2.2	2.7	2.5	2.6	2.9	4.0	3.8	2.83
2/25/93	2.4	2.0	2.3	3.1	2.0	1.8	3.6	5.2	2.80
2/26/93	2.3	1.8	2.3	2.5	2.9	2.9	2.7	2.6	2.50
2/27/93	2.8	2.4	2.3	2.1	1.9	3.0	3.2	4.1	2.73
2/28/93	3.1	3.3	3.2	4.2	3.1	2.9	1.9	1.7	2.93
3/1/93	2.5	4.0	3.2	3.3	2.9	2.1	2.0	1.9	2.74
3/2/93	4.6	5.9	5.2	4.7	4.7	3.8	4.1	2.9	4.49
3/3/93	2.6	2.9	3.3	3.5	2.8	2.4	2.2	1.5	2.65
3/4/93	2.2	2.2	2.8	2.7	2.4	2.2	2.1	1.5	2.26
3/5/93	2.5	3.4	3.8	3.1	2.8	3.8	2.9	2.3	3.08
3/6/93	2.5	2.0	2.9	2.7	3.0	2.9	2.8	2.3	2.64
3/7/93	1.4	1.5	2.1	2.7	2.2	2.0	3.2	2.2	2.16
3/8/93	2.1	2.1	1.4	1.8	1.4	1.4	2.4	1.6	1.78
3/9/93	1.2	1.1	1.0	1.6	12	1.4	1.6	1.2	1.29
3/10/93	1.2	1.5	1.9	2.1	2.0	2.3	2.1	2.1	1.90
3/11/93	1.7	1.8	1.9	2.2	2.7	2.7	2.5	2.6	2.26
3/12/93	4.6	5.1	4.6	3.7	4.7	4.9	4.6	5.0	4.65
3/13/93	4.3	4.9	4.1	5.9	5.3	4.2	4.8	3.6	4.64
3/14/93	3.4	2.8	2.7	2.5	2.7	2.2	2.3	2.0	2.58
3/15/93	4.0	4.1	2.6	2.2	2.3	2.6	2.4	2.3	2.81
3/17/93	6.1	5.9	6.6	4.2	3.2	3.0	3.4	2.3	4.34
3/18/93	3.4	4.8	3.9	4.5	3.1	3.4	4.2	3.1	3.80
3/19/93	2.6	2.8	4.4	5.0	4.2	3.2	3.5	4.8	3.81
3/31/93	4.6	3.7	3.3	3.3	1.2	1.3	1.9	1.1	2.55
4/1/93	2.2	1.8	2.3	2.3	2.0	1.7	2.0	2.3	2.08

Table D-2. 1993 Northgate Hourly CO and Persistence Data

Date	Hourly Carbon Monoxide Data								
	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	8-hr Mean
12/14/92	2.5	3.1	4.9	3.9	3.4	2.3	3.4	2.5	3.25
12/15/92	2.7	2.4	4.8	4.0	3.6	3.6	4.0	3.9	3.63
2/11/93	3.0	3.4	3.3	3.4	2.8	2.4	3.1	2.4	2.98
2/12/93	2.7	3.2	4.1	4.7	6.2	6.0	3.1	2.6	4.08
2/13/93	2.2	2.3	3.4	3.1	2.5	2.5	3.2	2.6	2.73
2/14/93	0.9	1.3	1.3	1.5	0.7	0.7	0.8	0.8	1.00
2/15/93	1.0	1.0	1.1	1.3	2.0	2.4	3.1	2.8	1.84
2/16/93	2.0	2.0	3.8	2.4	2.4	2.0	2.6	1.7	2.36
2/17/93	2.0	1.9	4.1	3.4	2.7	2.7	2.6	2.1	2.69
2/18/93	1.9	2.1	2.7	3.4	3.0	2.2	3.7	3.8	2.85
2/19/93	1.1	1.3	1.8	2.3	2.0	1.9	2.2	1.9	1.81
2/20/93	2.5	2.0	3.0	2.7	1.6	1.5	1.5	2.0	2.10
2/21/93	1.5	1.5	2.3	2.9	2.4	1.2	1.2	0.8	1.73
2/23/93	0.8	1.0	1.0	0.8	0.9	0.7	0.9	0.6	0.84
2/24/93	2.2	2.0	2.7	3.5	2.8	3.3	4.2	3.7	3.05
2/25/93	2.3	2.2	3.0	3.7	2.5	2.8	4.7	4.3	3.19
2/26/93	1.9	1.9	3.2	3.7	2.9	3.1	5.2	3.7	3.20
2/27/93	2.1	3.0	3.8	2.8	2.0	2.5	3.6	4.0	2.98
2/28/93	1.3	1.5	1.8	3.1	1.8	1.3	1.0	0.8	1.58
3/1/93	1.3	1.3	1.6	1.3	1.1	1.1	1.4	1.0	1.26
3/2/93	2.7	2.6	2.3	3.1	4.5	4.5	3.7	1.6	3.13
3/3/93	1.0	1.1	1.4	1.2	1.4	1.3	1.7	1.3	1.30
3/4/93	0.8	1.1	1.2	1.2	1.1	1.0	1.2	0.6	1.03
3/5/93	0.9	1.0	1.1	1.4	1.3	1.3	2.2	1.1	1.29
3/6/93	1.6	1.7	2.1	2.6	2.4	1.9	2.5	2.2	2.13
3/7/93	1.3	1.7	2.6	2.4	2.5	2.1	2.2	2.4	2.15
3/8/93	2.3	1.6	1.8	2.4	1.7	1.6	2.0	2.7	2.01
3/9/93	1.5	1.5	2.0.	2.5	1.9	1.3	1.5	1.3	1.69
3/10/93	1.4	1.6	3.4	2.8	2.0	1.4	2.1	3.1	2.23
3/11/93	1.5	1.6	3.1	2.1	1.4	1.2	1.4	0.9	1.65
3/12/93	1.8	1.3	1.5	1.8	1.8	2.2	2.9	3.0	2.04
3/13/93	1.9	3.2	3.9	2.9	3.4	2.4	2.4	1.6	2.71
3/14/93	1.1	1.1	1.1	1.1	0.6'	0.5	0.5	0.9	0.86
3/15/93	1.8	1.8	1.5	1.7	1.5	1.4	1.6	1.1	1.55
3/17/93	3.0	2.3	1.7	1.3	1.2	1.2	1.8	1.0	1.69
3/18/93	2.7	2.3	2.1	2.3	2.4	2.2	2.8	2.9	2.46
3/19/93	2.7	3.2	3.5	3.6	2.1	1.5	1.2	1.8	2.45
3/31/93	1.9	3.1	1.8	1.3	1.1	1.7	2.9	1.8	1.95
4/1/93	1.9	1.6	2.1	2.6	1.9	2.2	2.3	1.2	1.98

Table D-3. 1993 University of Washington Hourly CO and Persistence Data

Date	Hourly Carbon Monoxide Data								
	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	8-hr Mean
12/14/92	1.017	1.654	2.015	2.582	3.376	2.314	2.384	2.165	2.188
12/15/92	1.288	1.570	2.051	2.485	2.654	2.431	1.792	2.162	2.054
2/11/93	1.830	2.310	2.630	2.740	1.480	1.960	2.400	2.260	2.201
2/12/93	1.100	1.370	1.700	3.090	5.220	3.250	2.510	2.330	2.571
2/13/93	0.640	0.650	1.050	1.110	1.780	1.240	1.930	2.560	1.370
2/14/93	0.400	0.410	0.470	0.500	0.480	0.380	0.430	0.470	0.443
2/15/93	0.290	0.330	0.380	0.420	0.680	0.820	0.710	0.680	0.539
2/16/93	0.470	0.670	1.060	1.120	1.160	0.550	0.560	0.820	0.801
2/17/93	0.720	0.700	0.860	2.230	1.240	1.880	2.080	1.420	1.391
2/18/93	0.550	0.590	0.930	1.710	2.130	1.970	2.540	1.250	1.459
2/19/93	0.960	0.870	1.210	0.800	1.160	1.190	1.070	0.930	1.024
2/20/93	0.760	0.930	1.700	0.890	0.730	0.690	1.100	1.080	0.985
2/21/93	0.630	0.810	0.520	0.720	0.700	0.710	0.950	0.580	0.703
2/23/93	0.250	0.280	0.370	0.380	0.350	0.360	0.480	0.410	0.360
2/24/93	0.470	0.530	0.920	1.140	1.590	3.120	3.720	3.780	1.909
2/25/93	0.630	0.660	0.930	1.550	2.400	3.090	3.160	5.610	2.254
2/26/93	0.760	0.750	1.110	1.500	2.810	2.450	3.560	3.820	2.095
2/27/93	1.280	1.240	1.330	1.220	1.340	1.330	2.320	2.930	1.624
2/28/93	0.690	0.740	0.880	1.150	1.150	0.660	0.530	0.600	0.800
3/1/93	0.820	0.740	0.930	0.770	0.630	0.560	0.550	0.530	0.691
3/2/93	1.350	1.740	2.250	2.600	2.420	1.840	1.420	0.980	1.825
3/3/93	0.770	0.760	0.730	0.780	1.000	0.780	0.640	0.560	0.753
3/4/93	0.920	0.970	1.120	1.070	1.270	0.970	1.070	0.640	1.004
3/5/93	0.750	0.820	0.880	1.150	1.130	1.120	1.170	0.980	1.000
3/6/93	0.470	0.700	1.370	1.780	2.180	2.870	3.340	2.860	1.946
3/7/93	0.530	0.640	0.790	1.050	2.170	2.170	2.140	1.920	1.426
3/8/93	0.650	0.840	0.880	1.120	1.570	1.590	1.460	1.250	1.195
3/9/93	0.560	0.570	0.630	0.750	1.000	1.200	1.730	1.800	1.030
3/10/93	0.380	0.410	0.570	0.890	1.280	1.280	3.450	2.980	1.405
3/11/93	0.700	0.610	0.650	1.490	1.190	1.110	1.320	0.670	0.968
3/12/93	0.800	0.690	0.970	0.730	0.780	1.130	1.600	1.500	1.025
3/13/93	0.510	0.530	0.630	1.680	1.630	1.780	2.000	1.160	1.240
3/14/93	0.590	0.580	0.530	0.500	0.430	0.370	0.450	0.430	0.465
3/15/93	0.690	0.450	0.970	1.140	1.050	1.180	1.080	1.120	0.960
3/17/93	1.430	1.010	0.630	0.730	0.900	0.620	0.790	0.820	0.891
3/18/93	0.550	1.710	2.510	1.710	1.410	1.650	1.660	1.190	1.549
3/19/93	0.690	0.780	1.160	1.680	1.420	1.190	1.130	1.540	1.199
3/31/93	1.360	2.330	1.020	0.810	0.510	0.950	1.580	0.720	1.160
4/1/93	1.140	0.760	0.960	0.910	0.550	0.590	0.560	0.700	0.771

Table D-4. 1993 Zanadu Persistence Data

Date	Peak Hour	Persistence Factor
12/14/92	3	0.67
12/15/92	3	0.82
2/11/93	1,2	0.75
2/12/93	5	0.71
2/13/93	4	0.75
2/14/93	4	0.78
2/15/93	7	0.66
2/16/93	7	0.63
2/17/93	7	0.77
2/18/93	7	0.81
2/19/93	7	0.57
2/20/93	1	0.81
2/21/93	6	0.84
2/23/93	3	0.83
2/24/93	7	0.71
2/25/93	8	0.54
2/26/93	5,6	0.86
2/27/93	8	0.66
2/28/93	4	0.70
3/1/93	2	0.68
3/2/93	2	0.76
3/3/93	4	0.76
3/4/93	3	0.81
3/5/93	3	0.81
3/6/93	5	0.88
3/7/93	7	0.68
3/8/93	7	0.74
3/9/93	4	0.80
3/10/93	6	0.83
3/11/93	6	0.84
3/12/93	2	0.91
3/13/93	4	0.91
3/14/93	1	0.76
3/15/93	2	0.69
3/17/93	3	0.66
3/18/93	2	0.79
3/19/93	4	0.76
3/31/93	1	0.55
4/1/93	3	0.90
	Mean	0.754
	Std. Dev.	0.095

Table D-5. 1993 Northgate Persistence Data

Date	Peak Hour	Persistence Factor
12/14/92	3	0.66
12/15/92	3	0.76
2/11/93	2,4	0.88
2/12/93	5	0.66
2/13/93	3	0.80
2/14/93	4	0.67
2/15/93	7	0.59
2/16/93	3	0.62
2/17/93	3	0.66
2/18/93	8	0.75
2/19/93	4	0.79
2/20/93	3	0.70
2/21/93	4	0.59
2/23/93	2,3	0.84
2/24/93	7	0.73
2/25/93	7	0.68
2/26/93	7	0.62
2/27/93	8	0.74
2/28/93	4	0.51
3/1/93	3	0.79
3/2/93	5,6	0.69
3/3/93	7	0.76
3/4/93	3,4,7	0.85
3/5/93	7	0.59
3/6/93	4	0.82
3/7/93	3	0.83
3/8/93	4	0.84
3/9/93	4	0.68
3/10/93	3	0.65
3/11/93	3	0.53
3/12/93	8	0.68
3/13/93	3	0.70
3/14/93	1,2,3,4	0.78
3/15/93	1,2	0.86
3/17/93	1	0.56
3/18/93	8	0.85
3/19/93	4	0.68
3/31/93	2	0.63
4/1/93	4	0.76
	Mean	0.712
	Std. Dev.	0.098

Table D-6. 1993 University of Washington Persistence Data

Date	Peak Hour	Persistence Factor
12/14/92	5	0.65
12/15/92	5	0.77
2/11/93	4	0.80
2/12/93	5	0.49
2/13/93	8	0.54
2/14/93	4	0.89
2/15/93	6	0.66
2/16/93	5	0.69
2/17/93	4	0.62
2/18/93	7	0.57
2/19/93	3	0.85
2/20/93	3	0.58
2/21/93	7	0.74
2/23/93	7	0.75
2/24/93	8	0.50
2/25/93	8	0.40
2/26/93	8	0.55
2/27/93	8	0.55
2/28/93	4	0.70
3/1/93	3	0.74
3/2/93	4	0.70
3/3/93	5	0.75
3/4/93	5	0.79
3/5/93	7	0.85
3/6/93	7	0.58
3/7/93	5	0.66
3/8/93	6	0.75
3/9/93	8	0.57
3/10/93	7	0.41
3/11/93	4	0.65
3/12/93	7	0.64
3/13/93	7	0.62
3/14/93	1	0.82
3/15/93	6	0.81
3/17/93	1	0.62
3/18/93	3	0.62
3/19/93	4	0.71
3/31/93	2	0.50
4/1/93	1	0.68
	Mean	0.661
	Std. Dev.	0.120

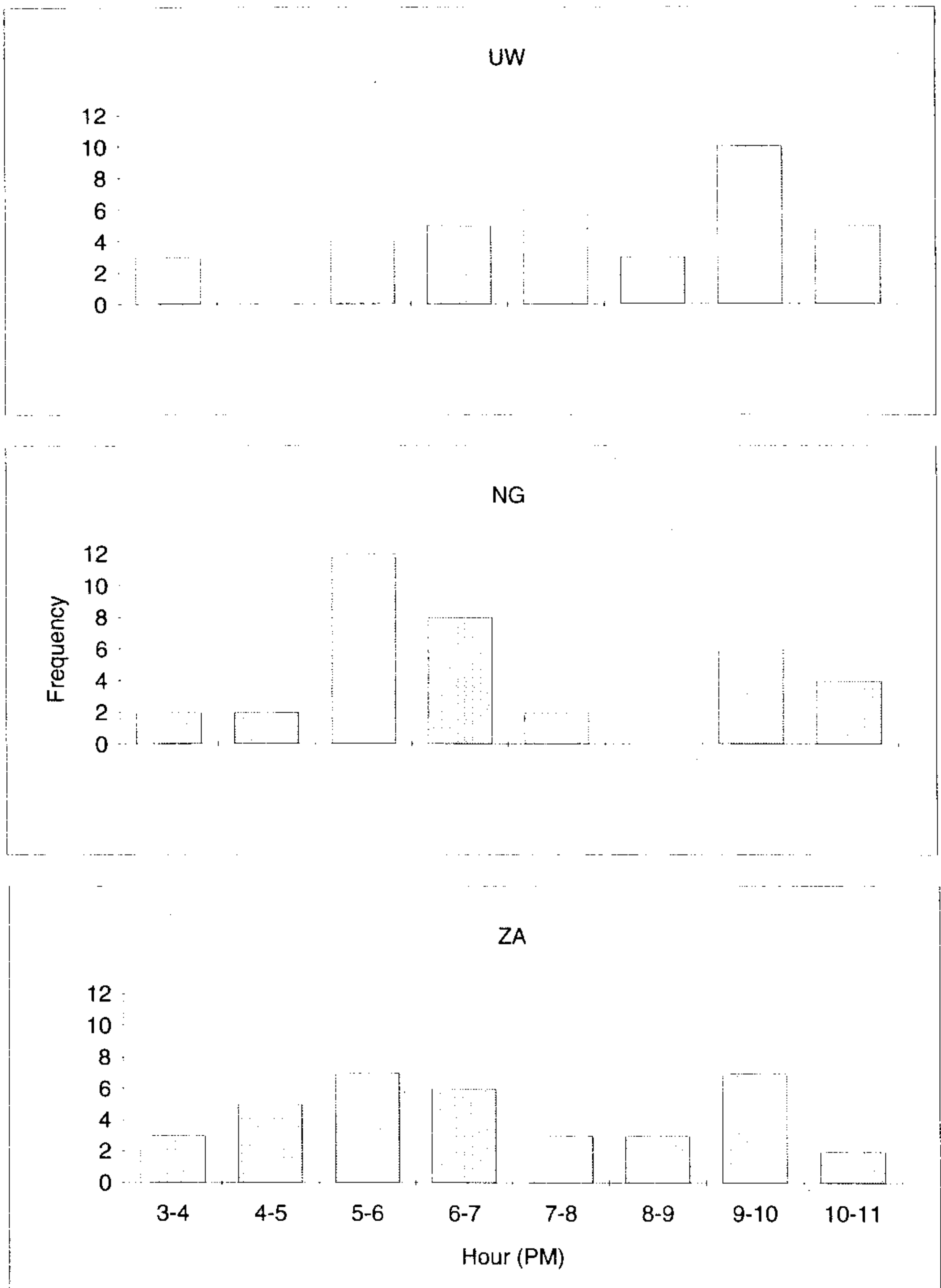


Figure D-1. Time of Occurrence of Peak 1-Hour Average CO Concentration in the 8-Hour Sampling Period (The UW site is a background site, whereas the other two are EPA micro-scale sites. Data were obtained with continuous analyzers.)

APPENDIX E

GRADIENT STUDY RESULTS

Table E-1. Measured Carbon Monoxide Concentrations

Date	Mean CO (ppm)	Distance to Roadway (meters)				
		1.5	3.0	23	52	358
3/16/93	1.352	1.89	1.60	1.21	1.03	1.03
3/17/93	1.686	2.46	2.23	1.42	1.21	1.11
3/31/93	1.542	2.30	1.89	1.22	1.16	1.14
4/1/93	1.443	2.16	1.93	1.18	1.03	0.92
5/12/93	2.430	4.76	2.10	1.91	1.47	1.91

Table E-2. Normalized Carbon Monoxide Concentrations

Date		Distance to Roadway (meters)				
		1.5	3.0	23	52	358
3/16/93		1.40	1.18	0.89	0.76	0.76
3/17/93		1.46	1.32	0.84	0.72	0.66
3/31/93		1.49	1.23	0.79	0.75	0.74
4/1/93		1.50	1.34	0.82	0.71	0.64
5/12/93		1.96	0.86	0.79	0.60	0.79

Table E-3. Measured Carbon Monoxide Concentrations

		Distance to Highway (meters)									
Date	Mean CO (ppm)	6	40	115	255	260	415	830	830	830	930
3/18/93	1.336	1.84	1.83	1.02	1.00	0.98	1.08	1.33	1.10	2.11	1.07
3/19/93	1.477	1.43	2.44	2.27	1.12	1.10	1.16	1.53	1.32	1.38	1.02

Table E-4. Normal Distance To Highway (meters)

		Distance to Highway (meters)									
		6	40	115	255	260	445	830	830	830	930
3/18/93		1.38	1.37	0.76	0.75	0.73	0.81	1.00	0.82	1.58	0.80
3/19/93		0.97	1.65	1.54	0.76	0.74	0.79	1.04	0.89	0.93	0.69

APPENDIX F

SUMMARY OF MEASUREMENTS AT BACKGROUND SITES

Table F-1. 1993 Urban "Backgrond" Carbon Monoxide Daily Summary
(8-hr averages, 3:00 - 11:00 PM)

Date	DIS	MLF	GRL	ROS	MAG	RBH	UW rep 1	UW rep 2	UW rep 3	UW rep 4	UW rep 5	UW Avg.
1/25/93	1.00	1.90	1.72	1.66	0.99							
1/26/93	0.66	0.99	0.95									
1/27/93	0.89	1.24	1.74	1.74	1.08							
1/28/93	0.82	0.92	1.25	1.20								
1/29/93		2.00	2.17	1.53	1.54	1.45	2.06					2.06
1/30/93	0.65	2.14	3.41	3.81	2.16	1.80	3.08	3.20				3.14
1/31/93	0.8		1.73	1.90	1.10	1.08	1.35					1.35
2/1/93	0.78	2.48	3.94	2.96	2.11	1.69	4.20					4.20
2/2/93	0.73	2.16	2.24	2.12	1.49	1.24	3.25	3.37				3.31
2/3/93		2.30	2.66	2.00	1.89	1.31	2.75					2.75
2/4/93		1.88	2.19	1.82		0.65	2.03					2.03
2/5/93		2.04	2.31	2.11		1.11	2.53					2.53
2/6/93		2.17	2.57	1.45		1.48						
2/7/93	0.54	0.94	1.10	0.72		0.62	0.69					0.69
2/8/93			2.20	1.79		1.84	2.19					2.19
2/9/93			1.21	1.18			0.97					0.97
2/10/93	0.89	1.73	2.01	1.59	1.42		2.02					2.02
2/11/93	0.85	1.63	2.16	1.69	1.61	1.29						
2/12/93	0.86	1.94	3.06	2.46	1.35	1.28	2.48					2.48
2/13/93	0.61		1.57	1.14	0.89		1.43					1.43
2/14/93	0.56	0.62	0.49	0.55	0.45	0.60						
2/15/93	0.40	0.65			0.50		0.69					0.69
2/16/93	0.56	0.92		1.07		0.68	0.95					0.95
2/17/93	0.70	1.36		1.23	1.00	0.87						
2/18/93	0.51			1.08	0.88		1.43					1.43
2/19/93	0.83		1.31	0.92	0.76	0.88	1.10	1.16				1.13
2/20/93		1.16		1.25	0.57	0.84	1.00					1.00
2/21/93	0.40		0.64	0.91	0.37	0.68	0.78					0.78
2/22/93		1.51	1.15	0.66	0.50	0.78						
2/23/93	0.65		0.88	1.09	0.69							
2/24/93		1.60	2.06	1.48	1.14	1.29						
2/25/93	0.72	2.10	1.93	1.60	1.16	1.19						
2/26/93			1.88	1.50	1.15	1.55	2.02					2.02
2/27/93	0.87	1.86	2.54	2.25	1.54	1.33	1.74					1.74
2/28/93		1.16	1.57	1.38	0.79	0.68	1.15	1.02				1.09
3/1/93	0.71			1.18	0.75	0.54	0.99	0.93				0.96
3/2/93	0.74	1.58	1.38	1.88	1.06	0.94						
3/3/93	0.50	1.01	1.57	1.03	0.80	0.75	0.89	0.78				0.84
3/4/93	0.53	0.88	0.79	0.76		0.55	1.15	1.02	0.92	1.07		1.04
3/5/93	0.83	1.25	1.34	1.45	0.79	0.80	1.13	1.08	1.04	1.11	1.02	1.08
3/6/93	0.64	1.80	1.72	1.34	0.69		2.02	1.95	2.00			1.99
3/7/93	0.60		2.01	1.40		1.08	1.40	1.47	1.42			1.43
3/8/93		1.43	1.55	0.99	0.80	0.70	1.23	1.27	1.28			1.26
3/9/93		1.75	1.56	1.22	0.95	0.82	1.15	1.17	1.19			1.17
3/10/93		1.12	1.60	1.22	0.93	0.85	1.56	1.59	1.60			1.58
3/11/93	0.80		1.59	1.26	1.09		1.12	1.08				1.10
Avg.	0.698	1.536	1.794	1.490	1.057	1.036	1.652	1.506	1.350	1.090	1.020	1.649
StdDev	0.152	0.508	0.717	0.608	0.445	0.373	0.826	0.810	0.365	0.028	n/a	0.838

APPENDIX G

ESTIMATION OF TURBULENCE PARAMETERS

To characterize surface layer turbulence in terms of standard variables, we require information on wind speed at given measurement height, as well as on air temperature and surrounding surface roughness. These parameters allow estimation of both the Monin-Obukhov length and the friction velocity, properties of the atmospheric turbulence near the surface.

We employed Venkatram's (1) method for estimating u* and L during stable atmospheric conditions that occur only during the nighttime. This method requires knowledge of wind speed, cloud cover, temperature, and surface roughness for each hour. For simplicity, the data analyses were applied to the five hours from 6:00 PM to 11:00 PM during the period from January 25, 1993, to March 11, 1993. Neutral conditions can develop during completely overcast nighttime skies with wind speeds of less than 2.0 m/s. Cloud cover fractions were obtained from Boeing King County International Field, a local commercial airport, approximately 13 kilometers south of the university weather station. A professional observer recorded the cloud cover according to four classes of sky cover fractions: clear (0/8), scattered (3/8), broken (6/8), and overcast (8/8). March 2nd was the only date on which all five hours were overcast, and observations were not made between March 6 and March 8, 1993. Sixteen additional hours with overcast skies were distributed over the collection period (Table G-1).

The surface roughness length, z_0, was also estimated for the UW site. The surrounding terrain of the Wilcox roof was nonhomogeneous; therefore, the effective roughness length was computed using a standard Environmental Protection Agency (EPA) estimation method (2):

$$\sigma_U/u_S = \{\ln(z/z_0)\}^{-1} \qquad \text{(Equation 1)}$$

where

σ_U	=	horizontal wind speed standard deviation
u_S	=	scaler mean horizontal wind speed (m/s)
z	=	wind speed measurement height (= 3.0 m at our site)

For this method to be valid, the wind speeds must be greater than 5 m/s, and the sampling duration should be at least 3 minutes. It was estimated that the surface roughness length for the site was 0.5 meters. Once the surface roughness length had been obtained, the friction velocity was estimated for stable atmospheric conditions using an iterative method outlined by Venkatram. (1) The temperature scale, q*, is estimated by means of an empirical equation that is based on fractional cloud cover and then incorporated into an intermediate variable, A, that represents an estimation of the temperature heat flux:

$$A = (T_a)/(g\, q^*\, k) \quad \text{(Equation 2)}$$

$$q^* = 0.09(1 - 0.5\{C_f\}^2) \quad \text{(Equation 3)}$$

where

C_f = fractional cloud cover.

T_a = ambient temperature (degrees K)

g = gravitational constant = 9.81 m/s

k = Von Karman's constant = 0.4

Initial estimates of the Obukhov length and friction velocity are made with equations (4) and (5):

$$u^* = (u_z\, k)/\ln(z/z_0) \quad \text{(Equation 4)}$$

$$L = A\{u^*\}^2 \quad \text{(Equation 5)}$$

where

u^* = friction velocity (m/s)

L = Obukhov length (m)

u_z = wind speed @ measurement height z

An improved estimate of the friction velocity is then given by the similarity equation:

$$u^* = (k\, u_{zo})/[\ln(z/z_0) - y(z/L) - y(z_0/L)] \quad \text{(Equation 6)}$$

where

$$y(z/L) = -17\,[1-\exp\{-0.29z/L\}] \quad \text{(Equation 7)}$$

$$y(z_0/L) = -17\,[1-\exp(-0.29 z_0/L)]$$ (Equation 8)

Equations (5) and (6) are sequentially solved until the Obukhov length, L, converges to a final value.

Before the Boeing Field cloud cover data were available, a constant cloud cover fraction was assumed for all hours and placed into the calculation matrix. For the period between January 25 and March 11, 1993, the estimated friction velocity was plotted against its corresponding wind speed (see Figure G-1). A break in the curve occurred around 1.4 m/s wind speed. Those hours with an average wind speed of less than 1.4 m/s had a systematically lower value of friction velocity and were considered "stable" in the context of this study.

The Venkatram iterative method for estimating u* and L does not converge at very low wind speeds, specifically wind speeds of 0.2 m/s and less. The turbulences associated with these low winds under very stable conditions are not described by existing theory (similarity equations 7 and 8). Therefore, we have no estimates of u* and L under these low wind speed conditions.

REFERENCES

1. Venkatram, Akula and John C. Wyngaard, eds., Lectures on Air Pollution Modeling, American Meteorological Society, Boston, 1988, pp. 390.

2. On-Site Meteorological Program Guidance for Regulatory Modeling Applications," United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Park, North Carolina, EPA 450/4-87-013, 1987.

Table G-1. 1993 Boeing King County International Field Cloud Cover Data

Date	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM
1/25/93	0.375	0.375	1.000	0.375	0.750
1/26/93	0.375	0.750	0.750	0.750	0.750
1/27/93	0.375	0.375	0.375	0.375	0.375
1/28/93	1.000	1.000	1.000	0.750	1.000
1/29/93	0.000	0.000	0.000	0.000	0.000
1/30/93	0.000	0.000	0.000	0.000	0.000
1/31/93	0.000	0.000	0.000	0.000	0.000
2/1/93	0.750	0.750	0.750	0.000	0.000
2/2/93	0.000	0.000	0.000	0.000	0.000
2/3/93	0.375	0.750	0.000	0.000	0.000
2/4/93	0.750	0.750	0.750	0.750	0.375
2/5/93	0.750	0.750	0.375	0.750	0.750
2/6/93	0.375	0.375	0.375	0.750	0.750
2/7/93	0.000	0.000	0.000	0.000	0.000
2/8/93	0.750	1.000	0.750	0.750	1.000
2/9/93	0.750	0.750	0.375	0.750	0.375
2/10/93	0.750	0.750	0.375	0.375	0.375
2/11/93	0.750	0.750	0.750	0.375	0.375
2/12/93	0.750	0.750	0.750	0.375	0.375
2/13/93	0.000	0.000	0.000	0.000	0.000
2/14/93	0.375	0.000	0.000	0.000	0.000
2/15/93	0.375	0.000	0.000	0.000	0.000
2/16/93	0.000	0.000	0.000	0.000	0.000
2/17/93	0.000	0.000	0.000	0.000	0.000
2/18/93	0.375	0.375	0.375	0.750	0.750
2/19/93	1.000	1.000	0.750	1.000	1.000
2/20/93	0.750	0.375	0.375	0.375	0.375
2/21/93	0.375	0.375	0.375	0.375	0.375
2/22/93	0.375	0.375	0.000	0.000	0.000
2/23/93	0.000	0.000	0.000	0.000	0.000
2/24/93	0.000	0.000	0.000	0.000	0.000

Table G-1. 1993 Boeing King County International Field Cloud Cover Data (continued)

Date	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM
2/25/93	0.000	0.000	0.000	0.000	0.000
2/26/93	0.750	0.750	0.750	0.750	0.750
2/27/93	0.375	0.000	0.000	0.000	0.000
2/28/93	0.750	0.750	0.750	1.000	1.000
3/1/93	0.750	0.750	0.375	0.375	0.750
3/2/93	1.000	1.000	1.000	1.000	1.000
3/3/93	0.375	0.375	0.375	0.375	1.000
3/4/93	0.375	0.375	0.375	0.375	0.375
3/5/93	0.375	0.750	1.000	1.000	0.375
3/6/93	N/A	N/A	N/A	N/A	N/A
3/7/93	N/A	N/A	N/A	N/A	N/A
3/8/93	N/A	N/A	N/A	N/A	N/A
3/9/93	0.375	0.000	0.000	0.000	0.000
3/10/93	0.000	0.000	0.000	0.000	0.000
3/11/93	0.375	0.000	0.000	0.000	0.000

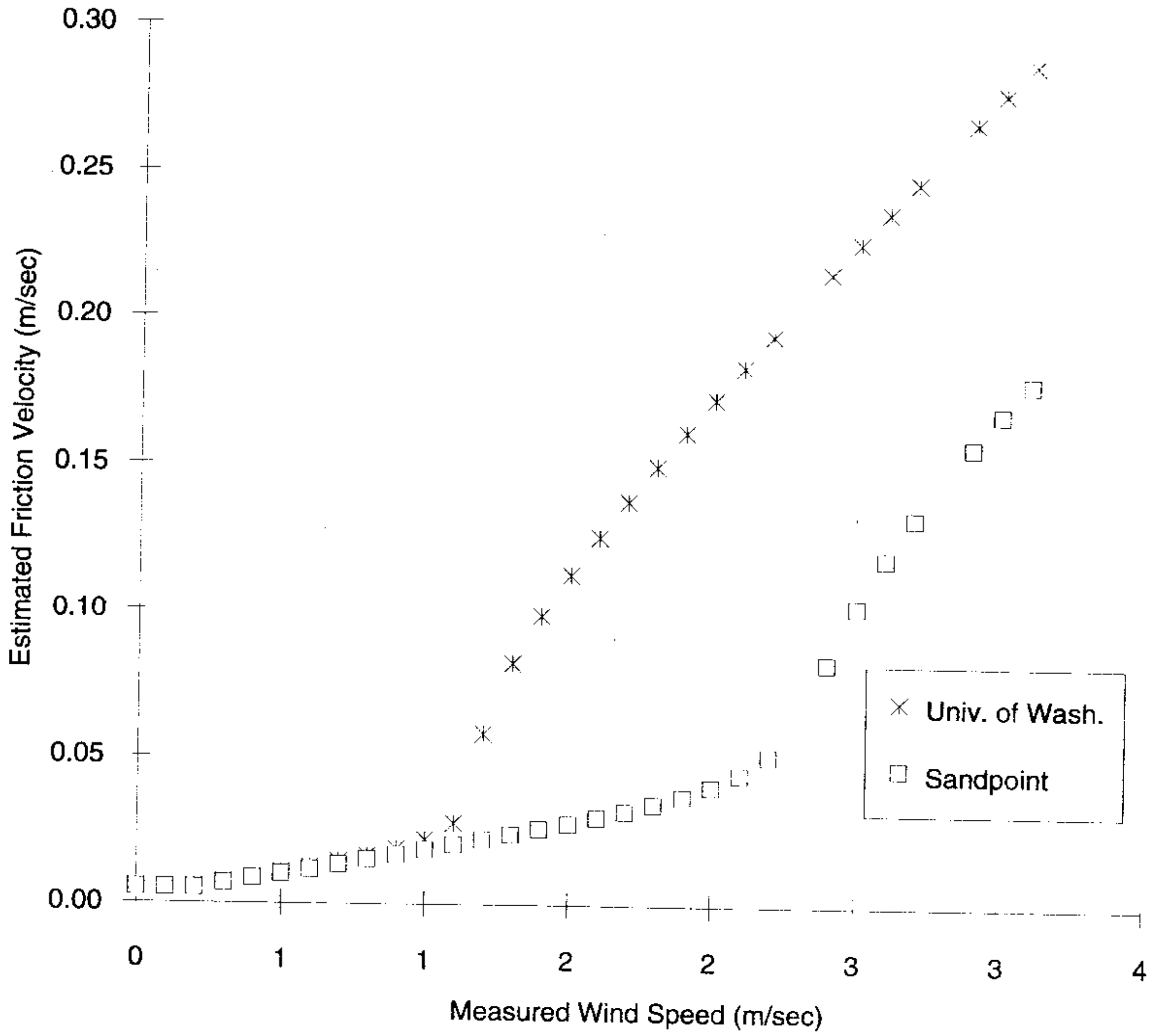


Figure G-1. Generalized Relationship between Friction Velocity and 5-hr (6 p.m. - 11 p.m.) Average Wind Speed

(Calculations were done assuming constant cloud cover)

APPENDIX H

ESTIMATION OF VARIABILITY BETWEEN SITES, DAYS, AND SAMPLERS

The 8-hour CO background concentrations were collected at seven sites at equal time intervals (46 days), and they were both correlated spatially and serially. If we assume sites and days to be random effects, a simple analysis of the variance model for the CO concentrations becomes

$$X_{ij} = \text{mean} + S_i + D_j + \varepsilon \qquad \text{(Equation 1)}$$

where Si is a random site effect distributed $N(0,\sigma_s^2)$, Dj a random day effect distributed $N(0,\sigma_d^2)$, and e the usual random (residual) error distributed $N(0,\sigma^2)$.

Although we assumed the error to be independent and normally distributed for the sake of simplicity, this is not the case. The 8-hour concentration values would be normalized by a log-transformation, and the data would be mildly autocorrelated, as shown above. However, for planning purposes, an analysis on untransformed and unfiltered data was sufficient. From our data, we obtained the variance estimates shown in Table H-1.

The between-sampler variability was determined by a one-way ANOVA analysis of the results of 18 days of parallel sampling using two samplers chosen randomly. This was done at several sites. The between-sampler variance was found to be $(0.054)^2$ ppm^2. This value included analyzer variability; however, this source of variability was about a factor 10 lower than the variability due to the samplers.

Table H-1. Analysis of Variance for Network CO 8-Hour Values (units in ppm)

Source of variation	Sum of squares	d.f.	Mean square	Expected mean square
Sites	28.073	6	4.678	$\sigma^2 + 46(\sigma_s)^2$
Days	57.262	45	1.272	$\sigma^2 + 7(\sigma_d)^2$
Residual	21.058	199	0.1058	σ^2

The following estimates were obtained:

- Between-site variance $(\sigma_s)^2 = (0.315)^2$
- Between-day variance $(\sigma_d)^2 = (0.408)^2$
- Residual variance $(\sigma)^2 = (0.325)^2$

APPENDIX I

COMPARISON OF WINDS AND CO WITH PREVIOUS WINTER'S VALUES

This is an analysis of the similarity of wind patterns and carbon monoxide (CO) concentrations between the 1993 sampling period and the same period during the previous two winters in the study region. We examined CO and wind data collected by the DOE because we did not have measurements of our own for the previous time periods. Hourly-averaged meteorological data and CO concentration values for the period of January 25 to March 11, 1991 to 1993, were downloaded from the Washington State Department of Ecology (DOE) Air Monitoring Data Network for sites at Sandpoint Naval Station, Lake Forest Park City Hall, Zanadu Comics Store (University District), and Northgate Apartments in Seattle, Washington.

These data consisted of wind speed and direction, standard deviation of the wind direction, incoming solar radiation, temperature difference between the base and top of a 10-meter tower located at Sandpoint, and wind speed and direction at Lake Forest Park. Hourly CO concentration values were obtained from continuous monitors at Zanadu and Northgate. This data set was then analyzed for yearly meteorological trends and CO "episode" patterns. A CO "episode" was defined as a period of time with relatively high hourly CO concentrations and simultaneous low wind speeds.

DATA SUMMARY

The first task was to reduce the very large number of data (over 10 000 hourly-averaged measurements) to a form that could be more easily handled. This was accomplished by calculating 8-hour means and standard deviations for wind speed from 3 PM to 11 PM daily. This period was chosen to coincide with our CO sampling time period.

Summaries of the wind speed and 8-hour averaged CO concentration values are shown in Tables I-1 through I-4. The following points are important:

- Overall 8-hour mean wind speeds at Sandpoint were highest in 1991 and lowest in 1993 (approximately 15 percent lower in 1993 than in 1991).

Table I-1. Sandpoint 8-hr Average Mean Wind Speed in Meters/second (3 PM to 11 PM)

Date	Wind Speed		
	1991	1992	1993
1/25/93	2.49	3.07	0.49
1/26/93	1.69	1.44	3.61
1/27/93	2.96	3.48	2.2
1/28/93	2.30	3.98	2.20
1/29/93	0.94	1.88	1.43
1/30/93	3.11	2.89	1.35
1/31/93	1.73	5.53	1.27
2/1/93	1.99	3.34	1.46
2/2/93	5.16	1.57	0.93
2/3/93	3.39	1.35	1.23
2/4/93	4.34	1.58	2.84
2/5/93	1.44	1.87	1.31
2/6/93	1.26	1.44	1.86
2/7/93	1.39	1.77	3.82
2/8/93	2.62	1.59	1.75
2/9/93	1.30	4.83	3.63
2/10/93	1.59	2.68	1.66
2/11/93	5.26	1.62	1.59
2/12/93	1.49	2.90	1.64
2/13/93	1.43	1.46	2.08
2/14/93	1.29	4.00	5.17
2/15/93	1.55	1.60	3.48
2/16/93	2.53	1.08	4.25
2/17/93	2.44	3.88	2.52
2/18/93	4.39	5.83	3.35
2/19/93	6.35	3.86	2.29
2/20/93	2.01	3.17	1.84
2/21/93	2.37	6.45	1.93
2/22/93	1.44	1.82	1.94
2/23/93	2.21	1.22	6.45

Table I1. Sandpoint 8-hr Average Mean Wind Speed in Meters/second (3 PM to 11 PM) (continued)

Date	Wind Speed		
	1991	1992	1993
2/24/93	2.82	1.54	2.21
2/25/93	3.09	3.25	1.62
2/26/93	3.46	1.60	2.27
2/27/93	2.49	1.49	2.41
2/28/93	6.26	2.11	2.36
3/1/93	1.97	2.33	3.73
3/2/93	6.36	3.82	1.28
3/3/93	6.37	1.60	3.63
3/4/93	2.53	1.25	4.63
3/5/93	4.38	1.62	3.35
3/6/93	1.75	1.33	1.25
3/7/93	2.67	2.07	1.97
3/8/93	1.29	2.28	2.03
3/9/93	4.33	1.98	2.77
3/10/93	3.78	1.50	2.92
3/11/93	3.85	2.55	2.81
Mean	2.87	2.51	2.45
Std. Dev.	1.53	1.31	1.19

Table I-2. Lake Forest Park 8-hr Average Mean Wind Speed in Meters/second (3 PM to 11 PM)

Date	Wind Speed		
	1991	1992	1993
1/25/93	0.89	1.58	0.26
1/26/93	0.78	0.48	1.89
1/27/93	1.13	1.69	0.74
1/28/93	0.87	1.94	0.89
1/29/93	0.55	0.80	0.66
1/30/93	1.62	0.60	0.86
1/31/93	1.00	2.73	0.87
2/1/93	2.61	0.59	0.71
2/2/93	1.96	0.84	0.58
2/3/93	1.96	0.84	0.58
2/4/93	1.84	0.70	2.10
2/5/93	0.81	0.60	0.55
2/6/93	0.73	0.69	0.91
2/7/93	0.43	0.46	1.27
2/8/93	0.79	0.59	0.72
2/9/93	0.73	0.78	2.06
2/10/93	0.85	0.97	0.61
2/11/93	2.69	0.61	0.69
2/12/93	0.71	0.71	0.9
2/13/93	0.88	0.58	0.72
2/14/93	0.71	1.52	1.54
2/15/93	0.49	0.91	1.34
2/16/93	1.02	0.73	0.85
2/17/93	0.63	1.94	0.84
2/18/93	2.80	2.31	0.85
2/19/93	2.61	0.66	0.60
2/20/93	0.59	0.70	0.75
2/21/93	0.89	3.63	0.76
2/22/93	0.66	0.66	0.63
2/23/93	0.96	0.58	1.89

Table I-2. Lake Forest Park 8-hr Average Mean Wind Speed in Meters/second (3 PM to 11 PM) (continued)

Date	Wind Speed		
	1991	1992	1993
2/24/93	0.79	0.52	0.75
2/25/93	0.96	0.85	0.82
2/26/93	1.06	0.99	0.92
2/27/93	0.99	0.83	0.8
2/28/93	2.28	0.92	1.02
3/1/93	0.64	0.98	1.91
3/2/93	3.35	0.92	0.65
3/3/93	2.43	0.64	1.96
3/4/93	0.76	0.44	2.41
3/5/93	1.81	0.56	1.53
3/6/93	0.7	0.51	0.82
3/7/93	1.26	0.77	0.74
3/8/93	1.05	0.91	0.87
3/9/93	2.88	0.8	0.95
3/10/93	1.33	0.83	1.06
3/11/93	1.76	0.88	1.09
Mean	1.26	0.99	1.02
Std. Dev.	0.76	0.64	0.50

Table I-3. Northgate CO Concentration (ppm) 8-hr average (3 pm to 11 pm)

Date	CO Concentration (ppm)					
	1991 8-hr avg.	1991 8-hr max	1992 8-hr avg.	1992 8-hr max	1993 8-hr avg.	1993 8-hr max
01/25	4.46	5.80	2.29	3.30	2.35	3.90
01/26	5.80	7.40	3.36	6.80	1.15	1.50
01/27	2.78	4.60	1.41	2.60	2.39	3.50
01/28	4.91	6.40	1.69	3.10	1.53	2.20
01/29	6.28	8.40	2.23	6.60	3.09	4.40
01/30	3.23	4.40	2.04	4.40	4.58	6.00
01/31	3.28	4.30	0.96	1.30	2.73	5.80
02/01	4.51	7.20	1.73	2.60	4.75	5.90
02/02	1.38	2.20	3.05	5.10	2.93	4.50
02/03	0.91	1.40	7.36	9.80	3.64	5.90
02/04	1.03	1.80	6.20	8.90	2.68	4.60
02/05	4.53	6.90	4.61	6.20	3.75	4.60
02/06	5.66	8.30	3.70	5.00	2.38	4.00
02/07	4.91	6.20	4.56	6.80	n/a	n/a
02/08	3.53	5.00	4.69	7.10	n/a	n/a
02/09	3.58	4.40	2.29	3.30	n/a	n/a
02/10	3.73	5.60	5.29	6.60	2.06	4.10
02/11	1.70	4.90	6.93	8.90	2.96	3.40
02/12	2.83	5.50	4.98	8.20	4.13	6.20
02/13	2.78	4.30	n/a	n/a	2.75	3.40
02/14	3.80	6.20	2.30	4.60	1.04	1.50
02/15	2.14	3.90	3.68	5.60	1.99	3.10
02/16	2.83	4.80	4.43	6.20	2.26	3.80
02/17	1.65	2.40	1.88	2.40	2.68	4.10
02/18	1.38	3.30	1.58	2.00	3.13	4.10
02/19	0.98	1.60	3.60	4.40	1.90	2.30
02/20	1.55	3.10	2.66	4.40	2.00	3.00
02/21	2.98	3.70	1.15	1.40	1.63	2.90
02/22	3.69	4.60	2.79	3.90	2.18	3.10
02/23	3.90	5.00	2.76	3.80	0.80	1.00
02/24	2.74	4.10	3.30	4.30	3.16	4.20
02/25	3.45	4.00	2.76	3.70	3.34	4.70
02/26	3.41	4.20	n/a	n/a	3.20	5.20
02/27	4.19	6.30	5.38	7.30	3.30	4.70
02/28	1.38	2.10	2.93	4.40	1.51	3.10
03/01	3.28	5.40	2.14	3.60	1.19	1.60
03/02	1.33	2.10	2.00	2.80	2.88	3.70

Table I-3. Northgate CO Concentration (ppm) 8-hr average (3 prn to 11 pm) (continued)

Date	CO Concentration (ppm)					
	1991 8-hr avg.	1991 8-hr max	1992 8-hr avg.	1992 8-hr max	1993 8-hr avg.	1993 8-hr max
03/03	0.85	2.20	2.76	4.50	1.29	1.70
03/04	2.88	4.30	6.29	7.40	0.98	1.20
03/05	1.20	1.90	3.00	4.80	1.36	2.20
03/06	2.96	3.70	2.76	4.20	2.34	3.30
03/07	3.16	3.70	2.68	3.80	2.21	2.60
03/08	4.59	6.60	2.96	3.70	1.85	2.70
03/09	2.34	3.10	3.39	4.10	1.65	2.50
03/10	1.85	3.70	4.25	5.40	2.41	3.40
03/11	2.49	5.60	3.26	4.20	1.54	3.10
Mean	3.02	4.49	3.32	4.85	2.41	3.55
Std. Dev.	1.39	1.78	1.53	2.02	0.95	1.36

Table I-4. Zanadu CO Concentration (ppm) 8-hr average (3 pm to 11 pm)

Date	CO Concentration (ppm)					
	1991 8-hr avg.	1991 8-hr max	1992 8-hr avg.	1992 8-hr max	1993 8-hr avg.	1993 8-hr max
01/25	3.24	5.00	4.50	5.30	4.30	5.80
01/26	6.30	11.50	4.25	5.60	3.09	3.90
01/27	3.89	4.50	3.23	5.00	3.06	3.90
01/28	3.34	4.60	3.19	4.40	2.96	4.10
01/29	6.60	9.20	4.03	7.80	3.55	4.20
01/30	4.58	6.40	4.71	8.80	5.60	9.00
01/31	5.49	7.20	3.36	4.10	3.53	6.30
02/01	5.84	9.70	4.09	4.90	6.21	7.50
02/02	2.99	4.60	4.61	5.60	4.26	7.50
02/03	2.71	3.70	12.35	17.50	5.11	8.80
02/04	2.74	4.60	5.60	6.90	5.36	9.30
02/05	4.95	6.20	5.25	9.10	5.41	6.40
02/06	7.86	11.20	3.70	6.40	3.86	6.30
02/07	6.48	8.20	6.45	8.40	2.06	2.80
02/08	3.41	4.40	6.38	8.10	4.09	6.20
02/09	5.00	6.00	1.80	2.60	2.98	5.20
02/10	3.94	4.40	4.35	6.50	2.63	4.50
02/11	2.83	4.70	7.84	10.70	2.98	4.30
02/12	4.04	6.30	5.59	8.50	4.84	6.80
02/13	4.69	7.50	6.65	10.20	2.59	3.20
02/14	6.20	11.20	3.90	7.60	1.01	1.30
02/15	3.01	4.70	3.84	5.40	1.80	2.60
02/16	3.96	5.00	5.34	9.80	2.65	4.10
02/17	2.80	4.60	2.78	4.60	2.21	2.90
02/18	2.15	3.30	2.58	4.50	2.19	2.70
02/19	2.14	3.10	1.66	2.30	2.53	4.10
02/20	2.24	4.40	3.91	5.20	3.41	4.30
02/21	2.71	3.30	2.50	3.80	2.45	3.20
02/22	3.73	5.10	3.10	5.30	1.79	2.40
02/23	3.39	4.70	4.18	5.50	1.00	1.20
02/24	1.81	2.30	3.94	7.20	2.90	4.00
02/25	2.29	2.90	2.23	3.40	2.99	5.20
02/26	2.78	4.50	3.83	5.80	2.53	2.90
02/27	4.84	7.80	7.13	12.30	2.75	4.10
02/28	1.09	1.20	6.60	10.50	2.73	4.20
03/01	6.11	8.30	3.91	5.30	2.65	4.00
03/02	2.66	3.80	1.91	2.20	4.30	5.90

Table I-4. Zanadu CO Concentration (ppm) 8-hr average (3 prn to 11 pm) (continued)

Date	CO Concentration (ppm)					
	1991 8-hr avg.	1991 8-hr max	1992 8-hr avg.	1992 8-hr max	1993 8-hr avg.	1993 8-hr max
03/03	n/a	n/a	5.25	7.10	2.51	3.50
03/04	2.20	3.00	6.64	8.00	2.13	2.80
03/05	2.78	4.90	3.29	4.40	3.09	3.80
03/06	2.78	3.90	3.89	5.80	2.59	3.00
03/07	4.13	5.30	2.94	6.20	2.25	3.20
03/08	4.68	6.50	2.88	3.80	1.63	2.40
03/09	4.33	5.30	3.26	5.20	1.24	1.60
03/10	2.34	3.40	4.76	6.70	1.99	2.30
03/11	3.68	7.50	2.86	3.30	2.54	3.90
Mean	3.82	5.55	4.37	6.47	3.05	4.38
Std. Dev.	1.51	2.38	1.90	2.85	1.21	1.97

- Overall 8-hour mean wind speeds at Lake Forest Park were highest in 1991 and roughly the same in 1992 and 1993 (approximately 21 percent lower in 1992 and 1993 than in 1991).
- Mean CO concentrations are consistently higher at Zanadu than at Northgate.
- CO concentrations at both Zanadu and Northgate were lowest in 1993 and highest in 1992 (approximately 30 percent lower in 1993 than in 1992).

FREQUENCY DISTRIBUTIONS OF WIND SPEED AND CO CONCENTRATION

As seen in Figures I-1 and I-2, the frequency of distribution of overall 8-hour wind speeds over the sample period did not vary appreciably from year to year. Generally, the mean values were lowest in 1993 and highest in 1991 (at Lake Forest Park, 1992 and 1993 were equivalent). The standard deviations for wind speed categories also varied similarly. These results seem to indicate that although wind speeds on average were lower in 1993, it was not an unusual year for observed wind speeds.

The frequency of occurrence of CO concentration values (Figures I-3 and I-4) for the 8-hour average from 3 PM to 11 PM at Northgate and Zanadu showed a trend toward lower values in 1993 than in 1991 and 1992. Unlike wind speed, the overall mean value for the 8-hour average CO concentration fell dramatically in 1993 from a peak in 1992. The frequency distribution also showed much less spread in the values for 1993, with a shift toward lower CO concentrations at both Zanadu and Northgate. The highest CO levels for all years were observed at the Zanadu site.

Using wind speed and CO concentration data for all four sites, cumulative density function plots were drawn to compare the 1993 sampling period to similar time periods in 1991 and 1992. These plots are shown in Figures I-5 and I-6. Visually, the greatest differences between years is evident in the CO concentrations at Northgate and Zanadu.

Sampling Period: January 25 to March 11

Sampling Duration: 8 hours (3 p.m. to 11 p.m.)

Wind Speed m/sec	SANDPOINT 1991	1992	1993
0.5	0	0	1
1	1	0	1
1.5	9	10	8
2	7	14	10
2.5	7	4	9
3	6	4	5
3.5	3	5	3
4	3	5	5
4.5	4	0	1
5	0	1	1
5.5	2	0	1
6	0	2	0
6.5	4	1	1
7	0	0	0
Total days	46	46	46

	Wind Speed, m/sec 1991	1992	1993
Mean	2.87	2.51	2.45
Std. Deviation	1.53	1.31	1.19

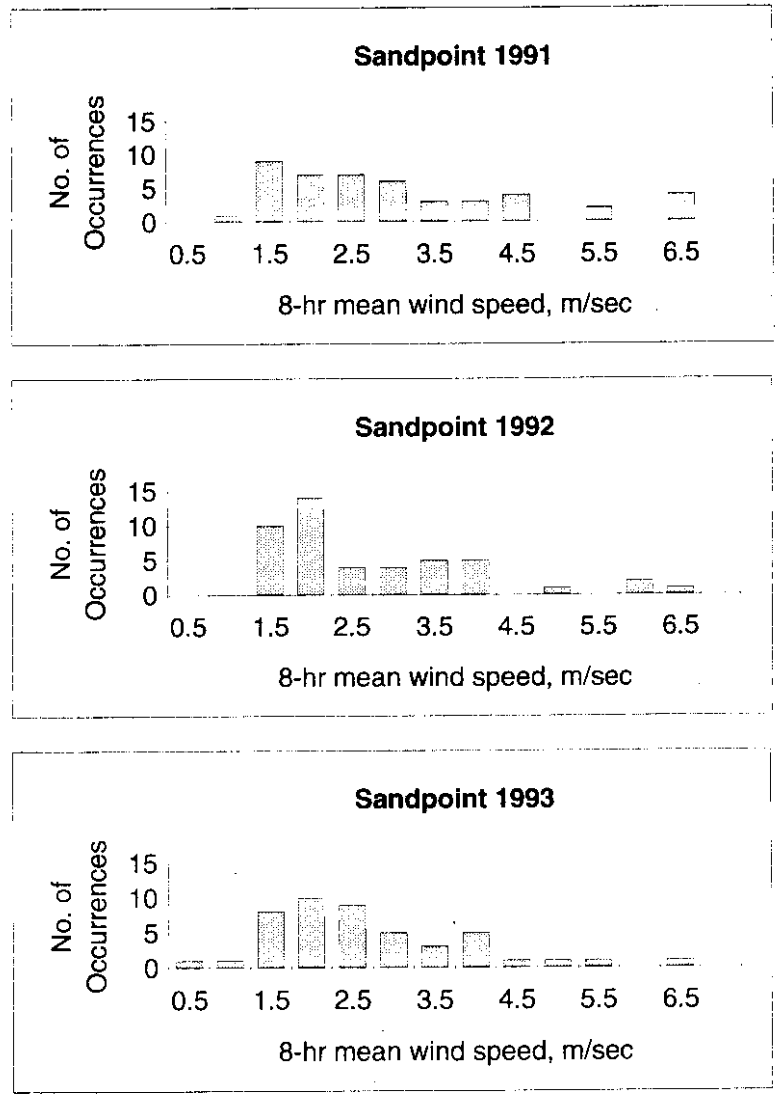
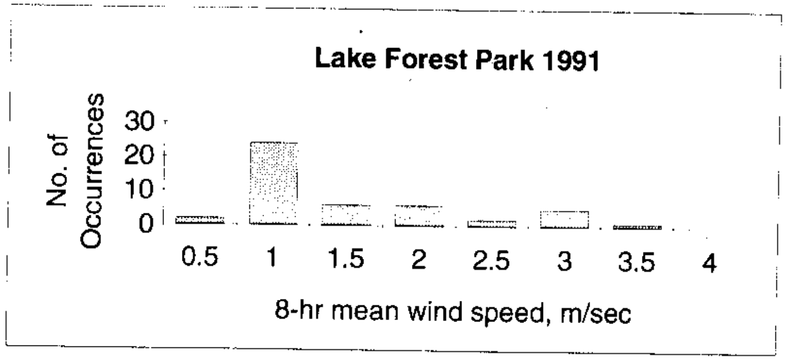


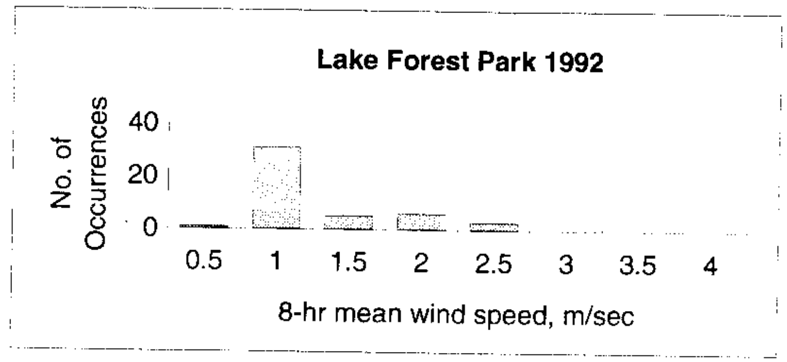
Figure I-1. Frequency of Occurrence of 8-hr Mean Sandpoint Winds

Sampling Period: January 25 to March 11
Sampling Duration: 8 hours (3 p.m. to 11 p.m.)

Wind Speed m/sec	Lake Forest Park 1991	1992	1993
0.5	2	1	3
1	24	31	35
1.5	6	5	0
2	6	6	5
2.5	2	3	1
3	5	0	1
3.5	1	0	0
4	0	0	1
Total days	46	46	46

	Wind Speed, m/sec 1991	1992	1993
Mean	1.26	0.99	1.02
Std. Deviation	0.76	0.64	0.5





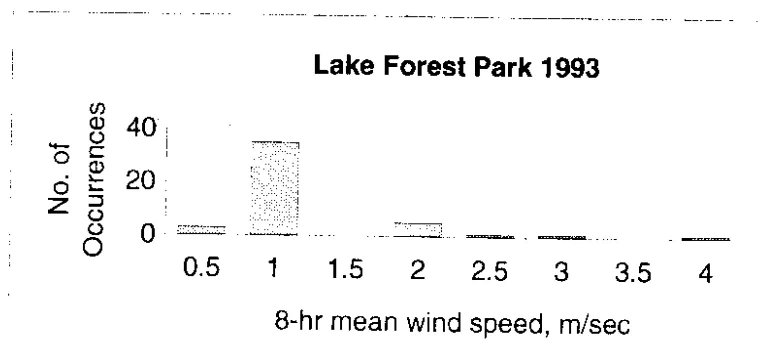


Figure I-2. Frequency of Occurence of 8-hr Mean Lake Forest Park Winds

Sampling Period: January 25 to March 11
Sampling Duration: 8 hours (3 p.m. to 11 p.m.)

CO ppm	NORTHGATE 1991	1992	1993
0.5	0	0	0
1	1	1	2
1.5	7	1	4
2	4	4	8
2.5	3	6	10
3	5	8	9
3.5	7	7	5
4	9	4	2
4.5	2	4	2
5	5	3	1
5.5	1	2	0
6	1	1	0
6.5	1	1	0
7	0	1	0
7.5	0	1	0
Total days	46	44	43

	CO Concentration, ppm 1991	1992	1993
Mean	3.12	3.42	2.41
Std. Deviation	1.33	1.49	0.91

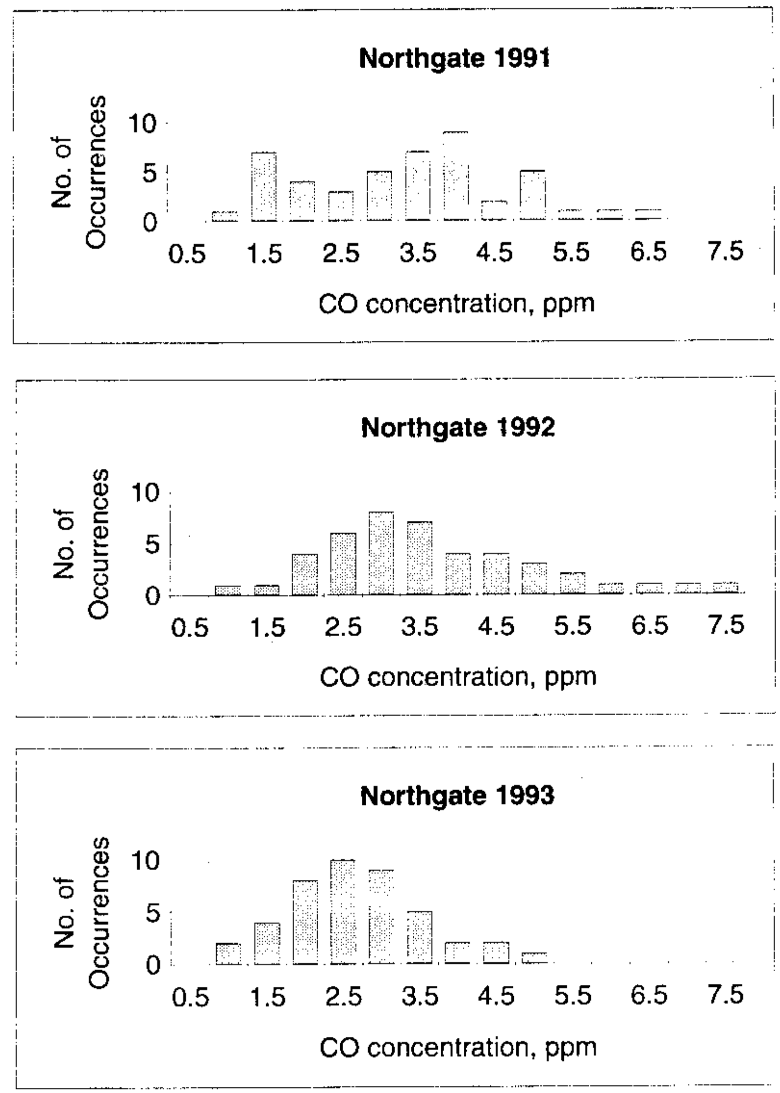


Figure I-3. Frequency of Occurrence of 8-hr Mean Northgate CO Concentration

Sampling Period: January 25 to March 11
Sampling Duration: 8 hours (3 p.m. to 11 p.m.)

CO ppm	ZANADU 1991	1992	1993
0.5	0	0	0
1	0	0	1
1.5	1	0	2
2	1	3	4
2.5	5	2	9
3	8	5	10
3.5	8	3	6
4	3	6	4
4.5	7	9	2
5	3	5	4
5.5	1	4	2
6	2	1	1
6.5	1	2	1
7	4	1	0
7.5	0	3	0
8	1	1	0
Total days	45	45	46

CO Concentration, ppm	1991	1992	1993
Mean	3.9	4.47	3.09
Std. Deviation	1.51	1.86	1.21

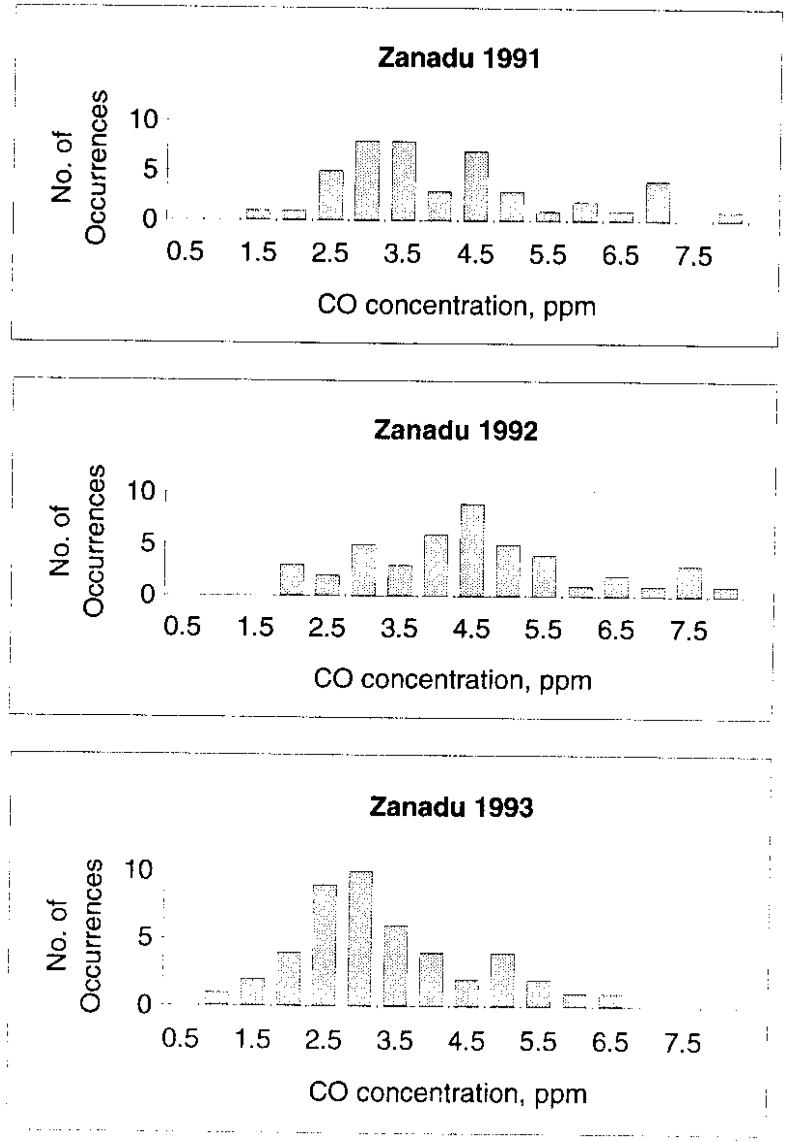


Figure I-4. Frequency of Occurrence of 8-hr Mean Zanadu CO Concentration

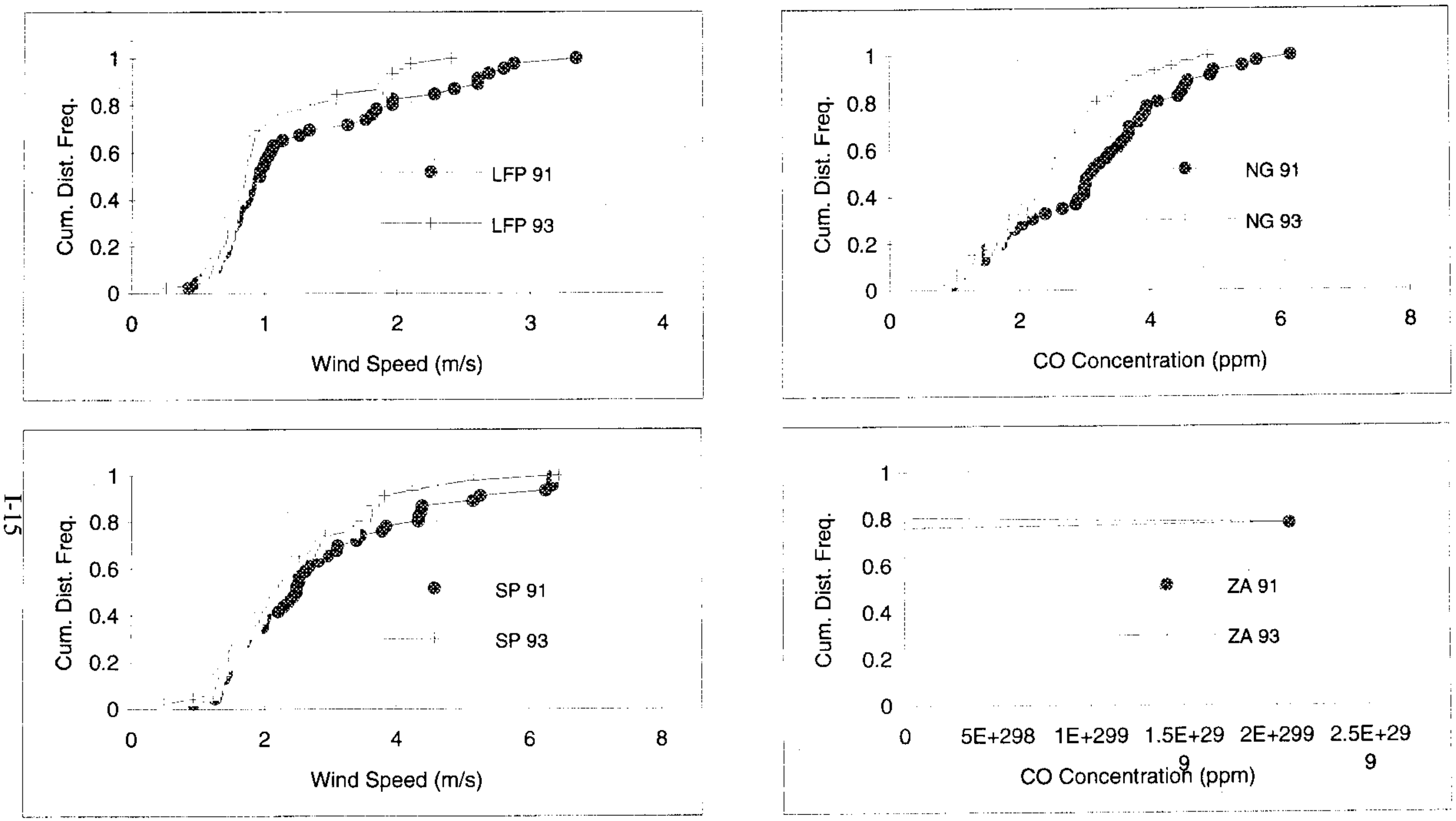


Figure I-5. Frequency Distributions of Wind Speed and CO Concentration at Sandpoint (SP) and Lake Forest Park (LFP) during the Period Jan. 25 - March 11 (The 1993 period is compared with a similar period in 1991.)

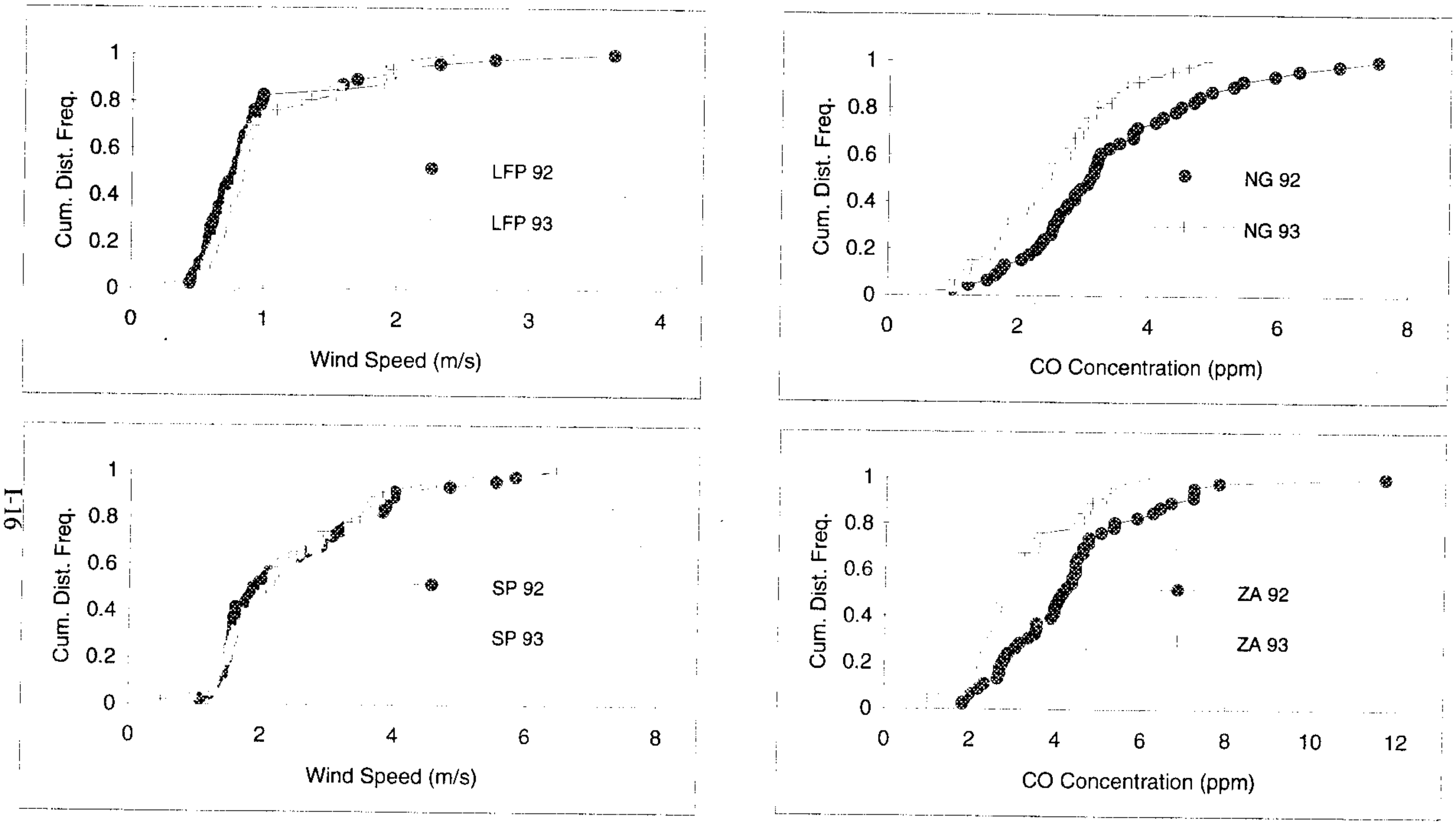


Figure I-6. Frequency Distributions of Wind Speed and CO Concentration at Sandpoint (SP) and Lake Forest Park (LFP) During the Period Jan. 25 - March 11 (The 1993 period is compared with a similar period in 1992.

Generally, CO concentration values for 1993 were lower than values for 1991 and 1992. Wind comparisons did not show substantial differences between the three years.

STATISTICAL COMPARISONS

A Kolmogorov-Smirnov two-sample test was used to determine whether the difference between 1993 and 1991 or between 1993 and 1992 was statistically significant. CO concentration values in 1993 decreased significantly from both 1991 and 1992. The two-sample test results are summarized in Tables I-5 and I-6.

Table I-5. Comparison of CO and Wind Speed Distributions (1991 vs. 1993)*

Variable	Site	DN	Probability**
Wind Speed	Lake Forest Park	0.22	0.23
	Sandpoint	0.17	0.49
CO	Northgate	0.33	0.02
	Zanadu	0.28	0.05

* Hourly values for the period January 25th - March 11th
** A probability of 0.05 means there is a 5 percent chance that the difference between distributions is due to chance

Table I-6. Comparison of CO and Wind Speed Distributions (1992 vs. 1993)*

Variable	Site	DN	Probability**
Wind Speed	Lake Forest Park	0.22	0.23
	Sandpoint	0.17	0.49
CO	Northgate	0.28	0.05
	Zanadu	0.39	0.002

* Hourly values for the period January 25th - March 11th
** A probability of 0.05 means there is a 5 percent chance that the difference between distributions is due to chance

PASQUILL STABILITY ESTIMATES

Hourly Pasquill stability estimates were made with the Sandpoint wind speed and wind direction data from January 25 to March 11, 1991 to 1993. A value of 0.05 meters was used as an estimate of the roughness length, zo, at Sandpoint. From this, the number of hourly D, E, and F classes in the sample period from 3 PM to 11 PM were summed for each year. These numbers are summarized below in Table I-7.

Table I-7. Number of Hours with Indicated Stability

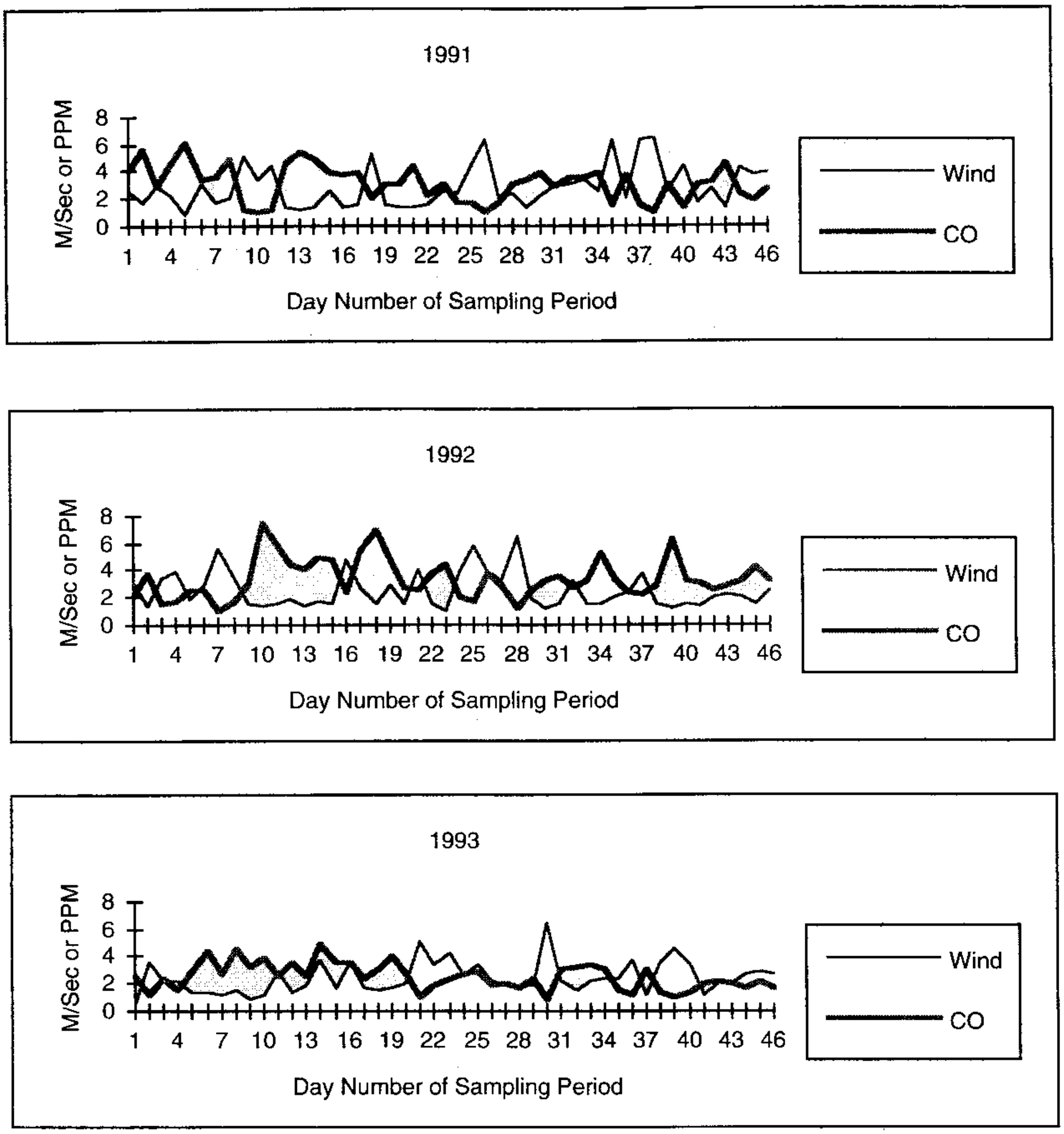
Year	Stability Class			
	D	E	F	Other
1991	145	43	126	54
1992	132	54	123	59
1993	99	77	133	59

The number of F class hours remained fairly constant over the three-year period. From 1991 to 1993, the number of E class hours increased while the number of D class hours decreased; this suggests that the sample period in 1993 was somewhat more stable than that of the two previous winters. This is probably due to the incidence of slightly lower wind speeds in 1993, as discussed earlier.

A chi-square test was used to determine whether the proportion of F stability class hours relative to all other class hours for 1993 was significantly different from the corresponding values in 1992 and 1993. This test showed no statistically significant difference between either 1991 and 1993 ($p<0.45$) or 1992 and 1993 ($p<0.28$).

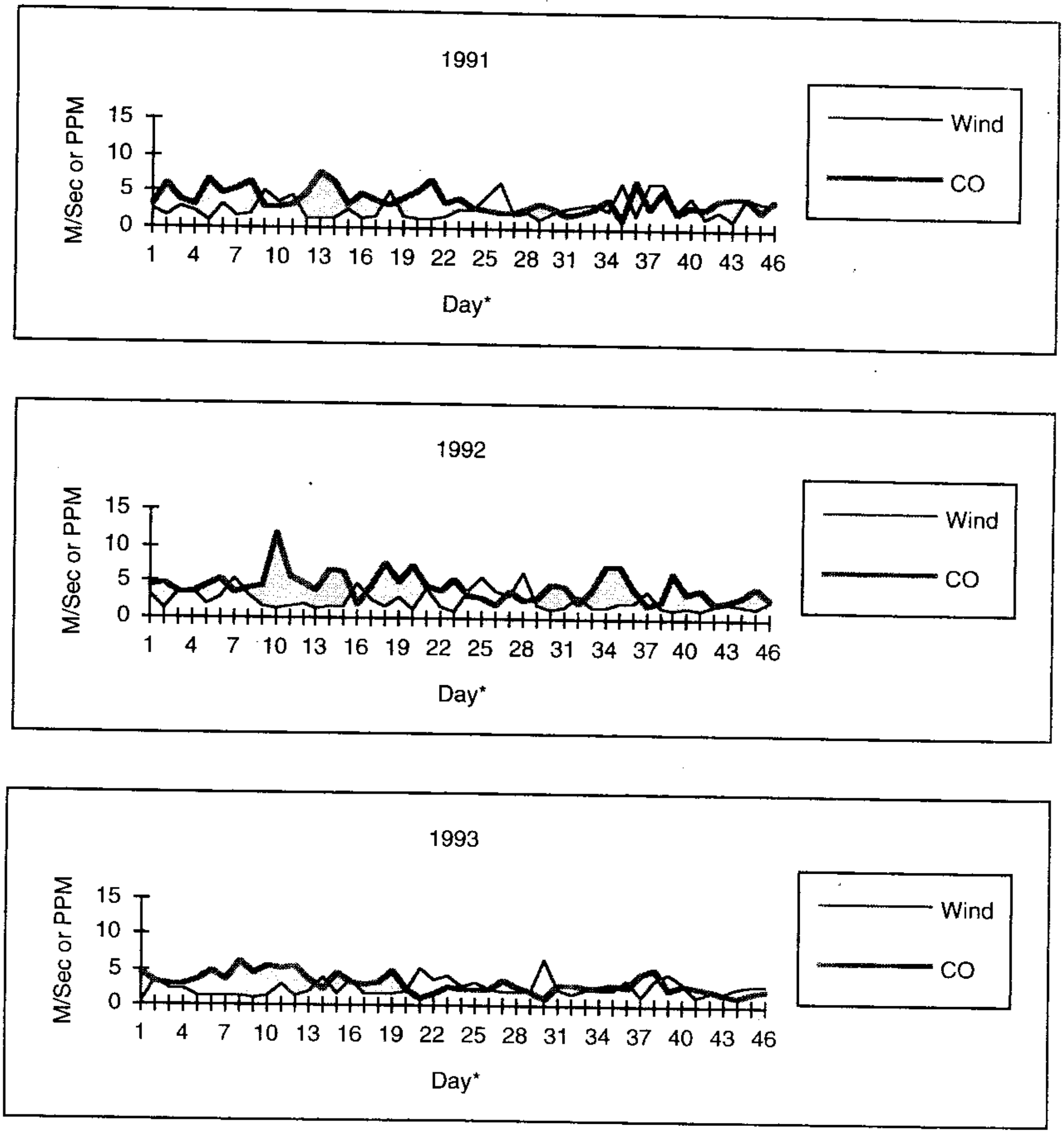
CO "EPISODES"

By looking at periods of relatively low winds and high CO concentration values, one can compare the incidence of CO "episodes" from one year to the next. A CO "episode" is defined as a time period characterized by time-averaged CO concentration ppm values that are greater than the wind speed values in meters per second. Figures I-7 and I-8 show plots of the 8-hour average CO concentration values for January 25 to March 11, 1992, at Northgate and Zanadu versus the 8-hour average wind speeds at Sandpoint for the years 1991 to 1993. CO episodes are shown in red. Although the frequency distribution



* ith day of sampling period (1/25/93 - 3/11/93)

Figure I-7. Time Series of Sandpoint 8-hr Mean Wind and Northgate 8-hr Mean CO (3 p.m. - 11 p.m.)



* i^{th} day of sampling period (1/25/93 - 3/11/93)

Figure I-8. Time Series of Sandpoint 8-hr Mean Wind and Zanadu 8-hr Mean CO (3 p.m. - 11 p.m.)

of wind speeds does not appear to differ greatly from 1991 to 1993, the time sequence of wind speed variation does seem to show differences. As seen in Figures I-7 and I-8, there was a direct and rapid increase in the CO concentration value as 8-hour averaged wind speeds shifted from high to low intensities and a decrease in that value as the wind speeds shifted from low to high.

The number of CO episodes was roughly the same (approximately seven to eight) from 1991 to 1993 at both Zanadu and Northgate. This reflects the timing and magnitude of wind sequences. The intensity of individual episodes, however, was less severe during 1993 than during either 1991 or 1992. This difference could be due to several factors, including shorter duration low-wind periods and lower source strength.

Low-wind periods did appear to be shorter in duration in 1993. In 1991, three periods of lower-than-average winds lasting six days or longer were observed. In 1992, the number was two, and in 1993, only one period of longer than six days occurred. Further, at least half of the CO episodes in 1993 lasted only two days or less, while 1991 and 1992 contained only one or two episodes this short.

Lower source strength is more difficult to quantify. Several possibilities seem plausible, such as improved traffic signal timing, fewer high-CO-emitting vehicles, and the introduction of oxygenated gasoline in 1993.

SUMMARY

The following is a summary of the findings from the DOE wind speed and CO concentration data for the time periods of January 25 to March 11, 1991-93.

- 1993 wind speeds were slightly lower, on average, than 1991 and 1992 windspeeds at the same locations in our study area.
- There was no statistical difference in wind speed distribution between the 1993 sampling period and similar periods in 1991 and 1992.

- Using Sandpoint wind data, the absolute numbers of "F" stability hours between 3 PM and 11 PM during the period January 25th to March 11th were similar for 1991, 1992, and 1993.
- A statistically significant decrease in CO concentration values was evident between the 1993 sampling period and similar periods in 1991 and 1992.
- There was a direct and rapid observed inverse correlation between CO concentration and wind speed at the Zanadu and Northgate sites.
- The hours between 3 PM and 11 PM in 1993 showed fewer sustained, severe periods of high CO with simultaneously low wind speeds than the same time periods in 1991 and 1992.

APPENDIX J

HOURLY WEATHERPAK MEASUREMENTS AT THE UW SITE

Table J-1. Hourly Weatherpak Meteorological Data

YEAR	MONTH	DAY	TIME (hour)	TEMP deg C	WIND (m/s)	sigma
93	1	25	19	9.70	0.0	21.6
93	1	25	20	9.40	0.1	19.9
93	1	25	21	9.10	0.2	20.8
93	1	25	22	9.40	0.0	43.9
93	1	25	23	9.30	0.1	27.3
93	1	26	19	11.50	1.4	24.2
93	1	26	20	11.00	0.7	39.8
93	1	26	21	10.40	0.5	42.6
93	1	26	22	10.40	1.1	25.6
93	1	26	23	10.80	1.3	34.6
93	1	27	19	10.50	0.2	59.0
93	1	27	20	9.70	1.3	22.0
93	1	27	21	9.30	0.5	65.5
93	1	27	22	9.00	0.6	50.7
93	1	27	23	9.30	1.5	45.1
93	1	28	19	9.20	1.1	30.7
93	1	28	20	9.20	1.0	25.8
93	1	28	21	9.30	0.8	28.9
93	1	28	22	9.40	1.3	26.8
93	1	28	23	9.30	1.9	21.0
93	1	29	19	9.70	0.3	32.5
93	1	29	20	8.30	0.0	42.1
93	1	29	21	7.10	0.0	23.8
93	1	29	22	7.30	0.1	54.5
93	1	29	23	7.10	0.0	48.9
93	1	30	19	8.40	0.0	38.4
93	1	30	20	7.60	0.6	19.7
93	1	30	21	6.60	0.1	66.6
93	1	30	22	5.90	0.1	39.2
93	1	30	23	4.50	0.1	53.0
93	1	31	19	9.90	1.0	38.6
93	1	31	20	8.60	0.5	33.6
93	1	31	21	7.30	0.6	23.6
93	1	31	22	6.50	0.6	26.2
93	1	31	23	6.20	0.5	22.8
93	2	1	19	10.30	0.1	65.9
93	2	1	20	9.60	0.3	50.4
93	2	1	21	8.40	0.2	57.8
93	2	1	22	6.80	0.0	29.7
93	2	1	23	6.20	0.0	19.9
93	2	2	19	9.60	0.0	82.4
93	2	2	20	8.40	0.1	49.7
93	2	2	21	8.10	0.5	56.0
93	2	2	22	8.60	1.0	54.0
93	2	2	23	7.80	1.1	41.2

Table J-1. Hourly Weatherpak Meteorological Data (continued)

YEAR	MONTH	DAY	TIME (hour)	TEMP deg C	WIND (m/s)	sigma
93	2	3	19	8.10	0.0	60.7
93	2	3	20	8.30	0.6	49.9
93	2	3	21	8.50	0.6	27.2
93	2	3	22	7.30	0.1	34.6
93	2	3	23	6.30	0.2	58.3
93	2	4	19	14.10	0.2	23.1
93	2	4	20	13.70	0.2	31.9
93	2	4	21	12.50	1.5	10.3
93	2	4	22	11.30	2.1	10.0
93	2	4	23	10.70	0.2	69.2
93	2	5	19	12.10	0.1	56.3
93	2	5	20	10.80	0.3	35.3
93	2	5	21	10.70	0.0	48.4
93	2	5	22	10.70	0.1	68.1
93	2	5	23	10.50	0.0	48.3
93	2	6	19	12.90	0.0	56.2
93	2	6	20	11.90	0.1	26.7
93	2	6	21	11.50	0.0	20.3
93	2	6	22	11.20	0.2	40.9
93	2	6	23	10.40	0.2	38.9
93	2	7	19	13.50	1.1	26.3
93	2	7	20	12.60	0.5	37.0
93	2	7	21	12.30	1.3	20.6
93	2	7	22	12.10	1.2	21.0
93	2	7	23	11.70	0.3	31.5
93	2	8	19	14.20	0.2	52.7
93	2	8	20	13.70	0.1	42.1
93	2	8	21	13.40	0.1	52.7
93	2	8	22	13.30	0.6	47.5
93	2	8	23	13.80	1.8	22.6
93	2	9	19	11.00	2.1	26.2
93	2	9	20	10.20	1.7	31.2
93	2	9	21	10.30	2.4	23.4
93	2	9	22	9.80	2.7	17.9
93	2	9	23	9.50	1.9	23.8
93	2	10	19	10.10	0.1	40.0
93	2	10	20	9.40	0.3	25.8
93	2	10	21	8.70	0.4	20.7
93	2	10	22	8.20	0.6	20.8
93	2	10	23	8.10	0.5	23.4
93	2	11	19	8.80	0.7	39.6
93	2	11	20	8.10	0.3	74.2
93	2	11	21	6.60	0.1	41.5
93	2	11	22	6.10	0.0	23.8
93	2	11	23	6.50	0.0	24.3
93	2	12	19	8.30	0.0	27.0
93	2	12	20	7.80	0.1	13.9
93	2	12	21	7.50	0.5	18.1
93	2	12	22	6.90	0.2	17.4

Table J-1. Hourly Weatherpak Meteorological Data (continued)

YEAR	MONTH	DAY	TIME (hour)	TEMP deg C	WIND (m/s)	sigma
93	2	12	23	6.40	0.2	23.9
93	2	13	19	7.40	0.3	59.6
93	2	13	20	6.60	0.2	51.5
93	2	13	21	6.30	0.1	65.5
93	2	13	22	5.50	0.1	52.7
93	2	13	23	4.60	0.1	47.9
93	2	14	19	6.80	1.0	45.1
93	2	14	20	6.70	2.1	37.1
93	2	14	21	6.90	2.5	28.6
93	2	14	22	6.60	1.7	32.8
93	2	14	23	5.80	0.8	39.3
93	2	15	19	4.50	1.6	38.5
93	2	15	20	3.60	0.5	47.0
93	2	15	21	2.80	0.5	55.4
93	2	15	22	1.80	0.5	51.6
93	2	15	23	1.00	0.3	46.2
93	2	16	19	1.30	0.7	44.7
93	2	16	20	0.60	0.5	39.5
93	2	16	21	0.60	1.6	33.7
93	2	16	22	0.00	1.0	29.2
93	2	16	23	-0.90	0.2	34.6
93	2	17	19	2.80	0.5	32.7
93	2	17	20	2.40	0.7	31.9
93	2	17	21	1.00	0.5	24.1
93	2	17	22	0.60	0.2	20.2
93	2	17	23	0.40	0.3	23.1
93	2	18	19	3.50	0.3	43.5
93	2	18	20	2.40	0.2	36.6
93	2	18	21	1.90	0.4	29.2
93	2	18	22	1.90	0.2	48.8
93	2	18	23	1.90	0.2	32.6
93	2	19	19	4.60	0.8	38.4
93	2	19	20	4.50	0.3	44.7
93	2	19	21	4.50	0.2	54.3
93	2	19	22	3.70	0.5	21.3
93	2	19	23	3.40	0.1	45.1
93	2	20	19	3.00	1.3	26.3
93	2	20	20	3.00	1.4	22.6
93	2	20	21	2.80	0.5	27.1
93	2	20	22	2.90	0.6	21.0
93	2	20	23	2.90	0.4	28.2
93	2	21	19	3.60	0.5	27.5
93	2	21	20	3.50	1.5	24.8
93	2	21	21	2.90	0.4	46.2
93	2	21	22	2.70	1.4	38.7
93	2	21	23	3.20	1.1	27.9
93	2	22	19	6.00	0.8	30.1
93	2	22	20	5.20	1.4	25.3
93	2	22	21	4.60	1.1	32.7

Table J-1. Hourly Weatherpak Meteorological Data (continued)

YEAR	MONTH	DAY	TIME (hour)	TEMP deg C	WIND (m/s)	sigma
93	2	22	22	4.10	0.7	31.2
93	2	22	23	2.90	0.1	39.1
93	2	23	19	3.60	1.9	37.5
93	2	23	20	3.60	1.7	35.2
93	2	23	21	3.20	0.9	53.6
93	2	23	22	2.80	0.5	56.8
93	2	23	23	2.40	0.4	57.5
93	2	24	19	4.20	0.8	29.7
93	2	24	20	3.10	0.2	40.4
93	2	24	21	1.60	0.0	17.2
93	2	24	22	1.40	0.1	27.0
93	2	24	23	0.70	0.0	31.5
93	2	25	19	5.30	0.3	44.3
93	2	25	20	3.60	0.1	33.9
93	2	25	21	2.60	0.0	27.6
93	2	25	22	2.20	0.1	13.6
93	2	25	23	1.40	0.0	56.9
93	2	26	19	6.70	0.5	62.5
93	2	26	20	5.00	0.1	33.2
93	2	26	21	4.40	0.1	29.6
93	2	26	22	3.60	0.0	34.8
93	2	26	23	2.80	0.1	20.9
93	2	27	19	8.60	0.3	45.1
93	2	27	20	6.90	0.2	38.6
93	2	27	21	6.20	0.1	55.7
93	2	27	22	5.00	0.1	34.6
93	2	27	23	4.40	0.0	69.7
93	2	28	19	13.00	1.1	34.2
93	2	28	20	11.90	1.5	28.7
93	2	28	21	10.60	1.3	34.4
93	2	28	22	10.20	1.8	26.2
93	2	28	23	9.70	1.2	27.0
93	3	1	19	8.40	2.0	27.3
93	3	1	20	8.20	1.8	30.0
93	3	1	21	8.00	2.9	17.4
93	3	1	22	8.00	2.6	21.1
93	3	1	23	7.90	1.9	25.1
93	3	2	19	12.10	0.1	60.1
93	3	2	20	11.80	0.8	28.2
93	3	2	21	11.10	1.3	13.4
93	3	2	22	9.70	1.1	36.6
93	3	2	23	8.40	1.2	46.5
93	3	3	19	11.30	1.8	29.9
93	3	3	20	10.50	0.9	40.9
93	3	3	21	10.00	1.0	44.7
93	3	3	22	9.60	1.1	34.6
93	3	3	23	9.60	1.0	30.9
93	3	4	19	11.50	3.1	16.8
93	3	4	20	11.40	3.0	16.7

Table J-1. Hourly Weatherpak Meteorological Data (continued)

YEAR	MONTH	DAY	TIME (hour)	TEMP deg C	WIND (m/s)	sigma
93	3	4	21	11.40	2.1	19.1
93	3	4	22	11.30	2.9	17.7
93	3	4	23	11.20	2.7	17.6
93	3	5	19	13.50	2.2	16.9
93	3	5	20	13.00	1.2	24.2
93	3	5	21	12.50	0.4	62.2
93	3	5	22	12.80	0.4	45.3
93	3	5	23	12.60	0.4	51.6
93	3	6	19	13.30	0.7	13.9
93	3	6	20	12.30	0.0	53.2
93	3	6	21	11.30	0.0	69.6
93	3	6	22	11.70	0.1	46.4
93	3	6	23	11.60	0.1	44.2
93	3	7	19	12.10	0.3	51.8
93	3	7	20	11.00	0.1	54.5
93	3	7	21	10.20	0.1	29.5
93	3	7	22	9.80	0.0	27.3
93	3	7	23	9.50	0.0	46.8
93	3	8	19	11.10	0.6	30.6
93	3	8	20	9.20	0.2	39.4
93	3	8	21	7.90	0.3	33.8
93	3	8	22	7.60	0.2	49.0
93	3	8	23	7.30	0.2	58.4
93	3	9	19	10.10	0.5	40.8
93	3	9	20	9.00	0.3	38.5
93	3	9	21	8.30	0.2	37.2
93	3	9	22	7.60	0.0	26.8
93	3	9	23	6.90	0.0	38.7
93	3	10	19	10.90	0.4	56.8
93	3	10	20	9.30	0.1	40.7
93	3	10	21	8.40	0.0	35.1
93	3	10	22	7.40	0.0	27.0
93	3	10	23	6.70	0.0	58.0
93	3	11	19	11.90	0.4	39.1
93	3	11	20	10.90	0.3	27.7
93	3	11	21	10.10	0.4	25.1
93	3	11	22	9.40	0.2	33.3
93	3	11	23	9.30	0.1	54.9

Table J-2. Eight-Hour Average Wind Speed at UW Site

DATE	UW WIND 8-HR AVE m/s
1/25/93	0.16
1/26/93	1.68
1/27/93	0.53
1/28/93	1.33
1/29/93	0.39
1/30/93	0.68
1/31/93	0.59
2/1/93	0.13
2/2/93	0.23
2/3/93	0.21
2/4/93	1.06
2/5/93	0.20
2/6/93	0.16
2/7/93	1.80
2/8/93	0.40
2/9/93	1.98
2/10/93	0.24
2/11/93	0.30
2/12/93	0.61
2/13/93	0.46
2/14/93	1.70
2/15/93	1.38
2/16/93	1.16
2/17/93	0.93
2/18/93	0.91
2/19/93	0.61
2/20/93	0.74
2/21/93	1.16
2/22/93	0.88
2/23/93	1.91
2/24/93	0.48
2/25/93	0.51
2/26/93	0.53
2/27/93	0.33
2/28/93	1.53
3/1/93	2.70
3/2/93	0.93
3/3/93	2.09
3/4/93	3.39
3/5/93	2.09
3/6/93	0.58
3/7/93	0.50
3/8/93	0.54
3/9/93	0.89
3/10/93	0.93
3/11/93	0.84