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The NAAQS Exposure Model (NEM) Applied to Carbon Monoxide

Ted Johnson and Roy A. Paul
PEDCo Environmental, Inc.
505 South Duke Street, Suite 503
Durham, North Carolina 27701

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Thomas McCurdy, Task Manager

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This draft report is being circulated for review and comment. Anyone interested in commenting or providing information concerning the material should address their communications to Thomas Feagans, Ambient Standards Branch, MD-12, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711. If you would like to discuss the report, please call him at (919)541-5655 (FTS 629-5655).

CONTENTS

CONTENTS (continued)

FIGURES

TABLES

TABLES (continued)

TABLES (continued)

TABLES (continued)

TABLES (continued)

TABLES (continued)

TABLES (continued)

TABLES (continued)

TABLES (continued)

ACKNOWLEDGMENTS

The development of a general model for assessing population exposures associated with possible National Ambient Air Quality Standards (NAAQS's) and the application of that model to carbon monoxide (CO) reported in this document have involved the efforts of many people. The following persons associated with PEDCo Environmental, Inc., played important roles in conducting this study. Coauthor Roy Paul developed the population movement algorithms and created the population data files. Coauthor Ted Johnson developed the statistical models used to process air quality data and managed the development of air quality and population data bases. Irene Griffin assisted in the compilation of population and air quality data. James Capel created and debugged the computer programs which processed air quality data. Barbara Blagun developed estimates of background pollutant concentrations. Dianne Gupton and Dian Dixon typed the report.

George M. Duggan, Strategies and Air Standards Division (SASD), U.S. Environmental Protection Agency (EPA), designed and implemented the computer programs used to calculate exposure estimates. Thomas McCurdy, SASD, EPA, facilitated conduct of the study and co-managed the SASD exposure assessment program with Henry Thomas. Much of the cohort data used in the model is based upon work done by SRI International.[1]

Dr. William F. Biller, EPA contractor, and Thomas B. Feagans, SASD, developed the general exposure model and the method used to extrapolate exposure estimates for individual study areas to the nation. The general model makes use of ideas developed by EPA's Office of Research and Development and others.[2] The model was first applied to carbon monoxide at an early stage of its development.[3] A later version of the model was applied to nitrogen dioxide and particulate matter.[4,5] An exposition of the general model is available from EPA.[6]

REFERENCES

1. Marc F. Roddin, Hazel T. Ellis, and Waheed M. Siddiqee, Background Data for Human Activity Patterns, Vols. 1 and 2, Draft final report prepared for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, August 1979.

2. James L. Repace, Wayne R. Ott, and Lance A. Wallace, "Total human exposure to air pollution," paper 80-61.6, presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, June 1980.

3. William F. Biller, Thomas B. Feagans, Ted R. Johnson, George M. Duggan, and James E. Capel, Estimated Exposure to Ambient Carbon Monoxide Concentrations Under Alternative Air Quality Standards, Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, January 1981.

4. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Nitrogen Dioxide, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, Environmental Protection Agency, Research Triangle Park, N.C. 27711, August 1981.

5. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Particulate Matter, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, August 1981.

6. William F. Biller, Thomas B. Feagans, Ted R. Johnson, George M. Duggan, Roy A. Paul, Thomas McCurdy, and Henry C. Thomas, "A general model for estimating exposure associated with alternative NAAQS," paper 81-18.4, presented at the 74th Annual Meeting of the Air Pollution Control Association, Philadelphia, June 1981.

SECTION 1

INTRODUCTION

Under the Clean Air Act, the Environmental Protection Agency (EPA) is responsible for establishing National Ambient Air Quality Standards (NAAQS's) and for reviewing them periodically to determine their adequacies on the basis of recent experience and research. In view of these responsibilities, the Strategies and Air Standards Division (SASD) of the Office of Air Quality Planning and Standards (OAQPS) is exploring the use of quantitative methods for assessing health risks associated with proposed air quality standards.

An important aspect of health risk assessment is the estimation of population exposure. For the past few years, SASD has been engaged in the development of an exposure model suitable for evaluating alternative ambient air standards. The model is known as NEM, an acronym for NAAQS Exposure Model.

Two versions of NEM have been developed. The exposure district version of NEM simulates the pollutant concentration expected to occur in selected exposure districts within a study area under user-specified regulatory scenarios. It then adjusts these estimates to account for an exhaustive set of microenvironments and simulates typical movements of population subgroups, called cohorts, through the districts and microenvironments. Outputs of the simulation program are population exposure estimates at specified pollutant levels. Three indices of exposure are used currently, and more are being investigated.

The other version of NEM substitutes "neighborhood types" for exposure districts. This report describes this alternative model and its application to four U.S. urban areas (Chicago, IL, St. Louis, MO-IL, Philadelphia, PA, and Los Angeles, CA) to estimate population exposures associated with alternative NAAQS's proposed for carbon monoxide (CO). Results of these analyses are included in this report. The contribution of indoor CO sources to total population exposure is also evaluated.

SECTION 2

OVERVIEW OF THE EXPOSURE MODEL

Analysis of population exposure under present and proposed National Ambient Air Quality Standards (NAAQS's) requires that the significant factors contributing to total human exposure be taken into account. Consequently, these factors have been incorporated into the NAAQS Exposure Model (NEM), a simulation model capable of estimating human exposure in selected urbanized areas under user-specified regulatory scenarios. The general model has been designed so that pollutants as diverse as ozone and CO can be accommodated without making changes to the basic NEM program. Instead, input data files are developed to reflect the assumed spatial characteristics of the specific pollutant being analyzed. In one version of the model, air quality data are selected to represent a small number of discrete exposure districts. This version has been applied to NO_2 and particulate matter. Another version incorporating the concept of "neighborhood types" is the basis of the CO exposure analysis described in this report. This section briefly discusses the differences between these two versions of NEM.

2.1 THE EXPOSURE DISTRICT VERSION OF NEM

In the exposure district version of NEM, land areas within a selected study area are represented by large, bounded "exposure districts." The population within each exposure district is assigned to a single discrete point, the population centroid. The air quality level within each exposure district is represented by the air quality level at the population centroid, which is estimated for each hour of the year by using monitoring data from adjacent monitoring sites. Because pollutants in the air can be modified considerably when entering a building or vehicle, these ambient air quality estimates are adjusted to account for five different microenvironments: indoors at work or school, indoors at home or other locations, inside a transportation vehicle, outdoors near a roadway, and other outdoor locations. NEM simulates hour-by-hour movements of representative population groups through different districts of the city and through different microenvironments, accumulating the resulting exposure over a period of one year.

Because degree of exposure and susceptibility to effects of pollution vary with age, occupation, and intensity of exercise; the total population of each study area is divided into age-occupation (A-O) groups, and each A-O group is further subdivided into three or more subgroups. For each subgroup, a typical pattern of activity through the five microenvironments is established, and an exercise level (high, medium, or low) within each is specified.

Units of population analyzed by NEM are called cohorts. Each cohort is identified by exposure district of residence, by exposure district of employment, by A-O group, and by activity-pattern subgroup. During each hour of the year, each cohort is assigned to a particular exposure district and a particular microenvironment. Since NEM simulates hour-by-hour air quality in each district and each microenvironment, the hourly exposures of each cohort may be summed over a one year period. Annual cohort exposures are summed to provide exposure estimates for each A-O group, which, in turn, are summed for all groups to provide an estimate of total population exposure for a particular study area. Output of NEM is a series of tables showing frequency distributions of total exposure at different averaging times (e.g., 1 hour, 8 hours, 1 year) using different measures of exposure (e.g., number of persons with exposures above selected pollutant levels).

In developing data bases for this version of NEM, PEDCo had to establish exposure districts within each study area that would accommodate the available breakdowns of transportation and census data; establish air quality data sets for exposure districts; and set up files listing hourly assignments to an exposure district, a microenvironment, and an exercise level for each cohort. In addition, files had to be established which contained air quality adjustment factors appropriate to each microenvironment and rollback factors for adjusting air quality data according to each air quality standard under consideration. The methods used in carrying out these tasks are described in previous reports.[1,2] Figure 2-1 shows a flow diagram for the exposure district version of NEM.

2.2 THE NEIGHBORHOOD VERSION OF NEM

Under the exposure district version of NEM, air quality within each microenvironment is a linear function of hourly air quality values derived from data reported by one or more monitors near the district centroid. This representation works best when air quality within a microenvironment varies slowly with distance and the sources of pollution are widely distributed. A good example of this type of pollutant is ozone (O_3), which is formed relatively slowly in the atmosphere from nitrogen dioxide (NO_2) and hydrocarbon (HC) precursors. Ozone is transported long distances with only small changes in concentration, and the primary sources of pollution (automobiles) are widely distributed. Under these conditions the use of large exposure districts works well.

Large exposure districts are not always appropriate for determining exposure. For some pollutants, air quality within a microenvironment is often more dependent on land use than geographic location. In this case, it is more appropriate to divide a study area into zones which can be classified according to the types and intensities of emission sources within them. In the neighborhood version of NEM, a small number of neighborhood types (NT's) are established for this purpose.

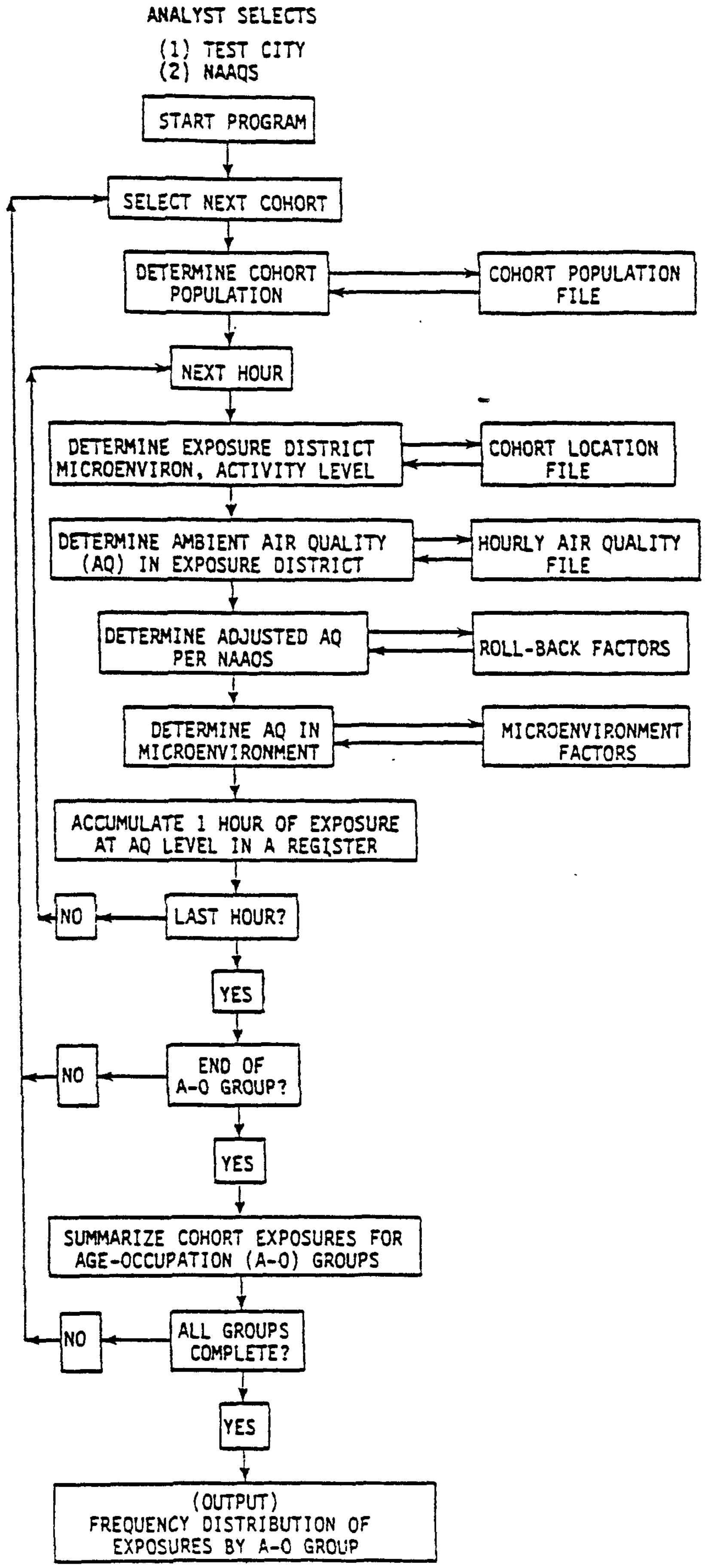


Figure 2-1. Flow diagram of exposure district version of NEM.

The neighborhood version of NEM is particularly appropriate for analyzing CO exposure. Since suburban neighborhoods generally have lower population densities and lower traffic densities than center-city neighborhoods, they generally have lower CO levels. Likewise, commercial and industrial neighborhoods generally have CO source patterns different from residential neighborhoods.

Figure 2-2 shows the flow diagram for the neighborhood version of NEM. The principal differences between the two versions lie in the concept of people-movement and in the structure of data files used as inputs. The concept of neighborhood-type and methods of creating population data bases are described in the next section.

2.3 REFERENCES

1. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Nitrogen Dioxide, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C. 27711, May 1981.

2. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Particulate Matter, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C. 27711, August 1981.

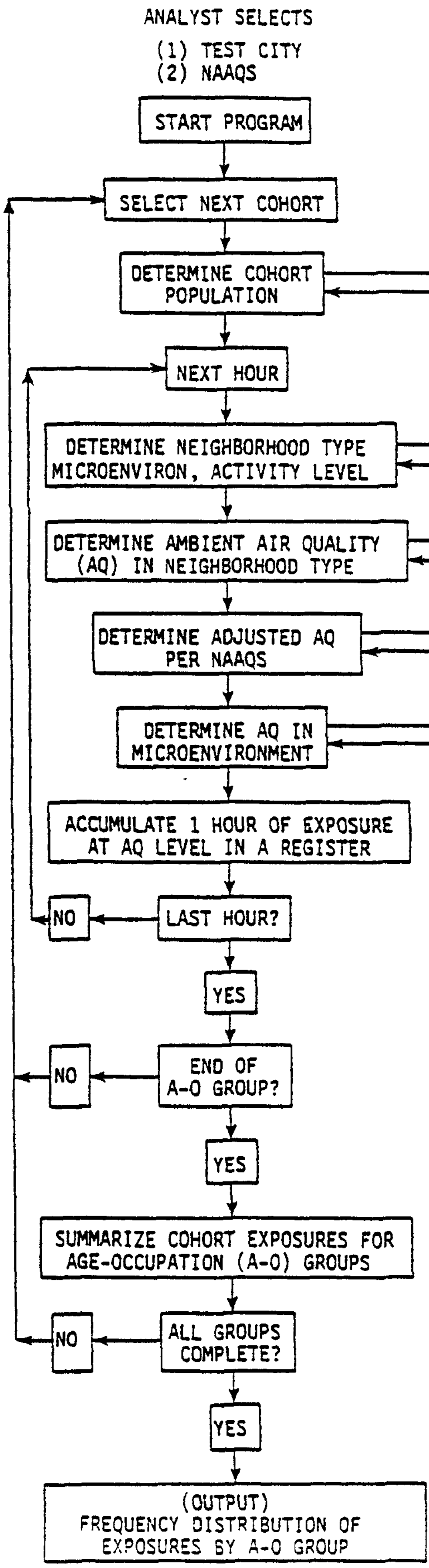


Figure 2-2. Flow diagram of neighborhood version of NEM.

SECTION 3

SIMULATION OF POPULATION MOVEMENT

NEM simulates movement of small, homogeneous groups called cohorts through zones of varying air quality. This section describes the development of computer files delineating cohort movements and the allocation of study area population among the cohorts.

3.1 COMPOSITION OF COHORT FILES

A cohort is defined as a group of individuals having a statistical factor in common in a demographic study. In the neighborhood version of NEM, all members of a particular cohort

(1) live in the same neighborhood type (NT),
(2) work in the same NT,
(3) are members of the same age-occupation group, and
(4) are members of a subgroup with a specified daily activity pattern.

Consequently, a computer file describing a cohort is labeled as to home NT, work NT, age-occupation group, and activity pattern.

In the exposure district version of NEM, the activity pattern for a cohort contains hourly assignments to predetermined exposure districts. Cohort movement can be visualized as transfers between geographically connected districts. For example, Figure 3-1 illustrates movement between various districts of the Los Angeles-San Bernardino study area. By contrast, the activity pattern for a cohort in the neighborhood version of NEM contains hourly assignments to predetermined NT's. A particular NT may be scattered over an entire study area and mixed with other NT's, as shown in Figure 3-2. Movement from one NT to another may represent a significant change in air quality level, without involving a significant change in geographic location.

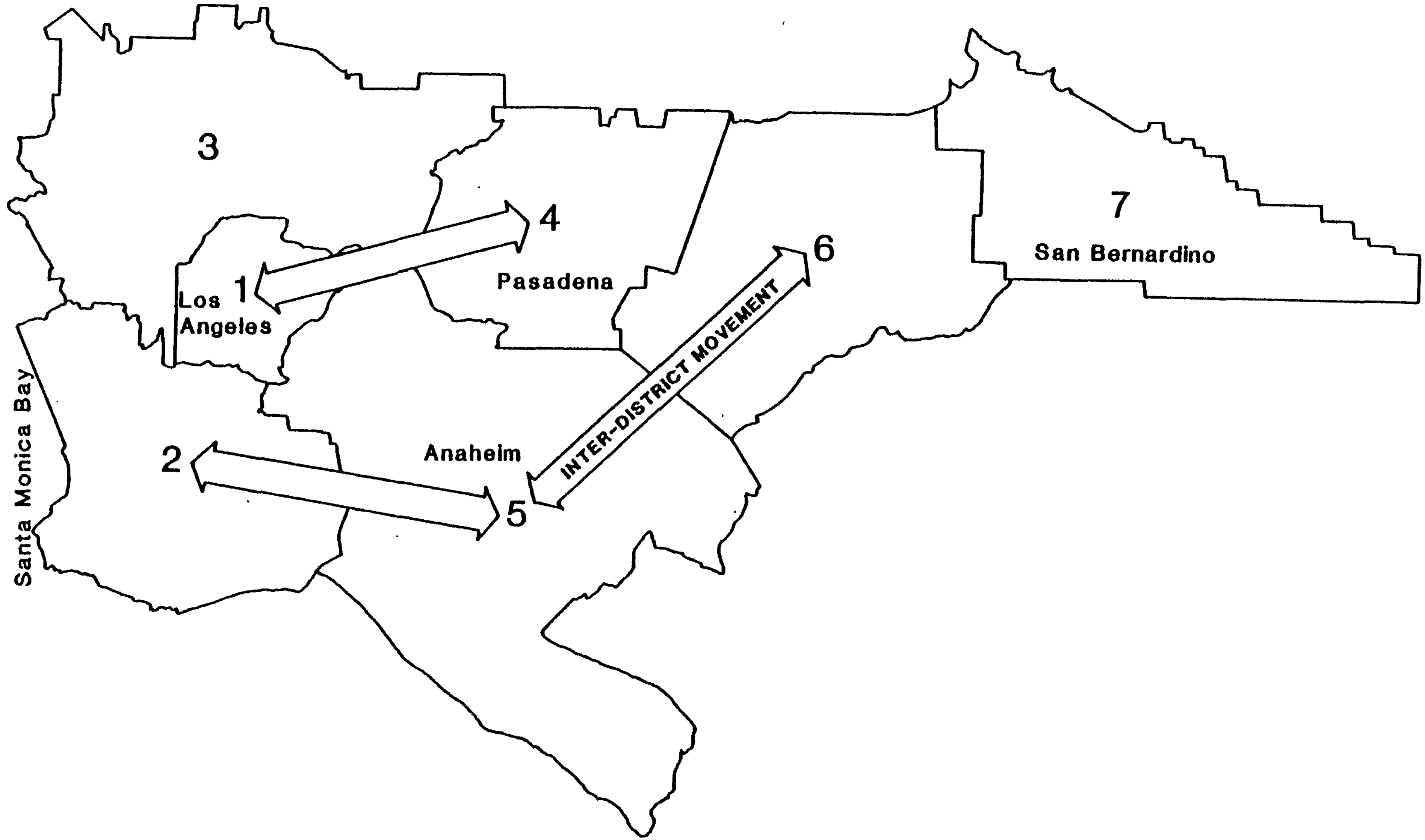


Figure 3-1. Simulated movements between exposure districts in the Los Angeles-San Bernardino study area.

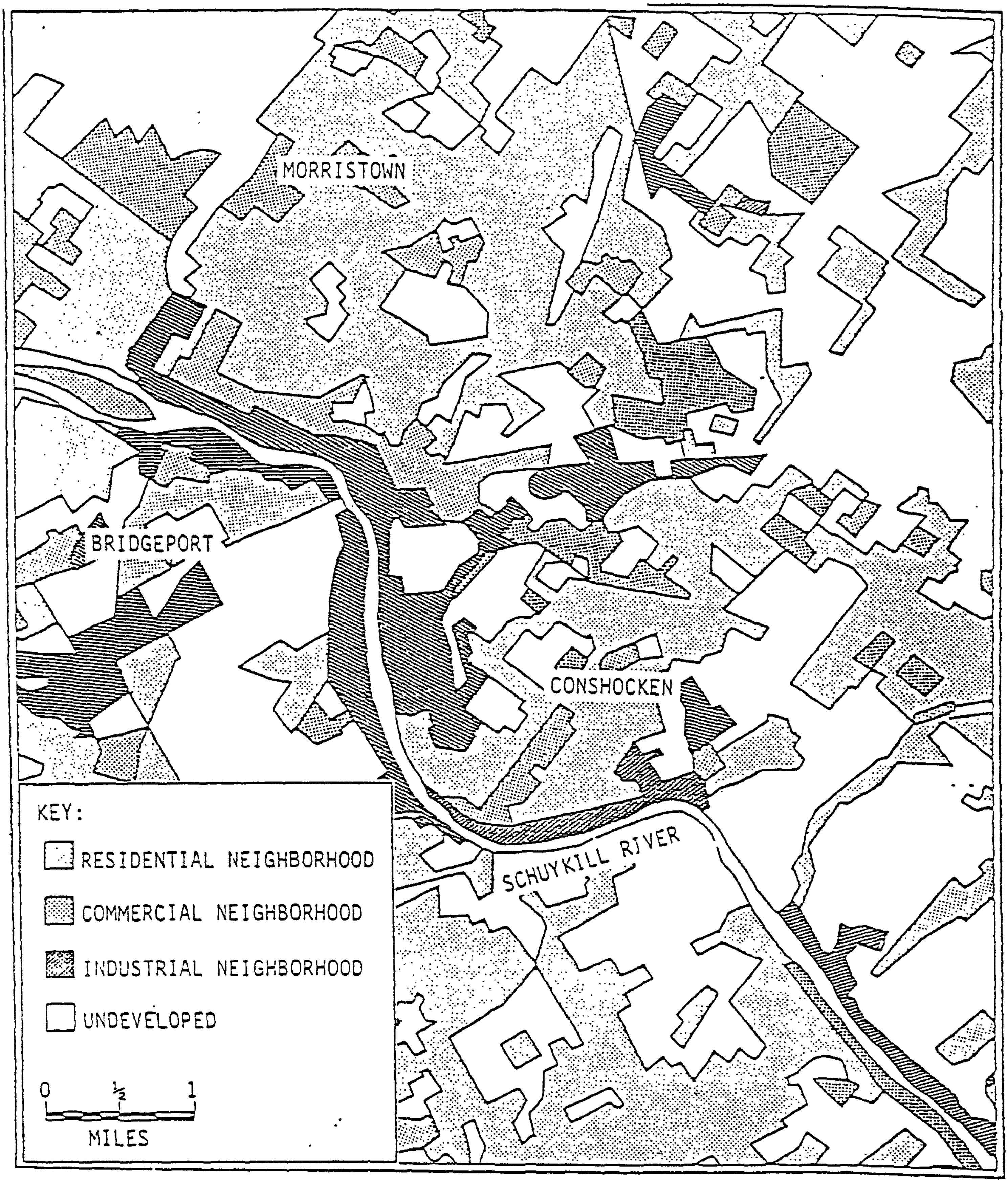


Figure 3-2. Pattern of neighborhood types in a portion of the Philadelphia study area.

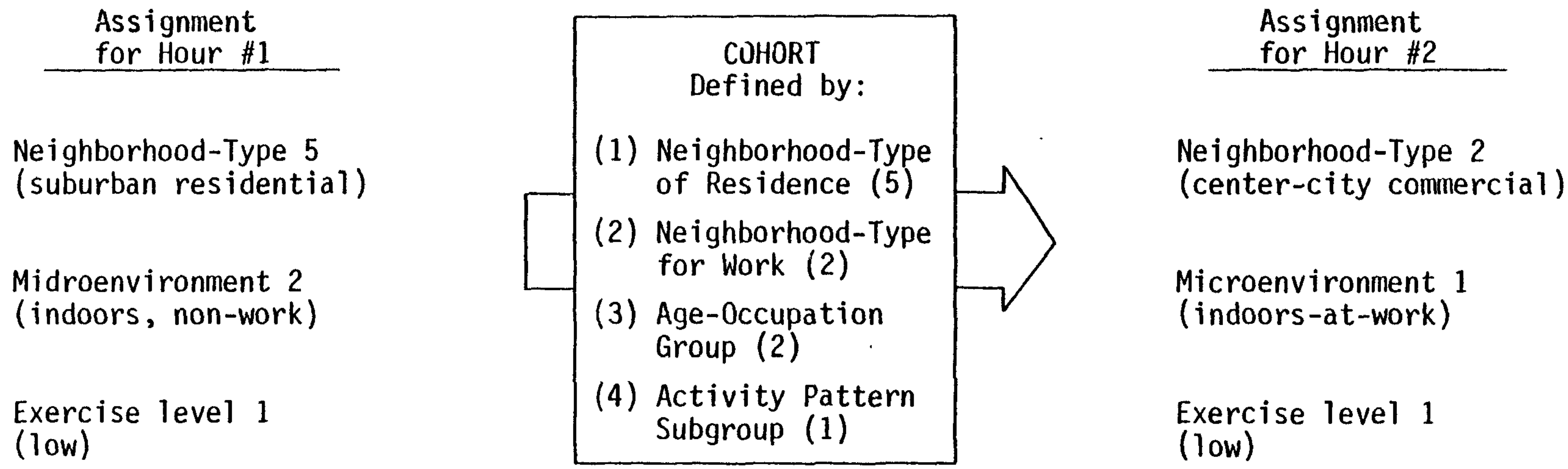


Figure 3-3. Representation of people-movement in the neighborhood version of NEM.

In addition to NT assignments, the activity pattern file contains hourly assignments of each cohort to a microenvironment and an exercise level for typical weekdays, Saturdays, and Sundays. Exposure to CO during a particular hour is determined by adjusting ambient CO for the assigned NT according to the assigned microenvironment. Because high exercise levels may induce a higher uptake of airborne chemicals into the body, NEM keeps track of exercise levels so that exposure distributions can be calculated for each exercise level separately.

In developing activity patterns appropriate for analyzing CO exposure, we divided each A-O group into three to six subgroups which could be described by one or more demographic variables affecting exposure (see Table 3-1). These variables include commuting time, work shift, work location (e.g., inside, outside, in motor vehicle), age, and degree of mobility. The population of each age-occupation group was apportioned among its constituent subgroups according to demographic statistics obtained from the Bureau of Census and other sources.[1] Whenever possible, the activity patterns developed for the subgroups were based on actual human activity data. Because such data are limited to a small number of studies initiated for other purposes, many simplifying assumptions were made in constructing the activity patterns. For example, retired persons with limited mobility were assigned to the outdoor microenvironment for fewer hours than retired persons with full mobility. Housewives with school-age children at home were assigned to the transportation vehicle microenvironment more often than housewives with no children at home. In each case, an attempt was made to construct an activity pattern which was consistent with our intuitive expections of what members of that subgroup would do on a typical weekday, Saturday, or Sunday. The resulting activity patterns are contained in a separate document.[2] Sample activity patterns are presented in Appendix A.

TABLE 3-1. DESCRIPTION AND APPORTIONMENT OF ACTIVITY PATTERN SUBGROUPS

Age-occupation group	Subgroup		
	Code[a]	Description	Percent
Students 18 and over	011	<30 min commute, 8 a.m. class	23
	012	<30 min commute, 9 a.m. class	45
	013	>30 min commute, 8 a.m. class	11
	014	>30 min commute, 9 a.m. class	21
Managers and professionals	021	<30 min commute, single family house	47
	022	<30 min commute, others	21
	023	>30 min commute, single family house	22
	024	>30 min commute, others	10
Sales workers	031	Indoor work, <30 min commute	43
	032	Indoor work, >30 min commute	21
	033	Outdoor work	5
	034	Indoor and outdoor work	9
	035	Traveling	22
Clerical and kindred workers	041	Indoor work, 1st shift, <30 min commute	56
	042	Indoor work, 1st shift, >30 min commute	26
	043	Indoor work, 2nd shift, <30 min commute	9
	044	Indoor work, 2nd shift, >30 min commute	4
	045	Outdoor work	1
	046	Indoor and outdoor work	4
Craftsmen and kindred workers	051	Indoor work, 1st shift, <30 min commute	50
	052	Indoor work, 1st shift, >30 min commute	24
	053	Indoor work, 2nd shift	10
	054	Indoor work, 3rd shift	2
	055	Outdoor work	4
	056	Indoor and outdoor work	10
Operatives and laborers	061	Indoor work, 1st shift, <30 min commute	39
	062	Indoor work, 1st shift, >30 min commute	18
	063	Indoor work, 2nd shift	6
	064	Indoor work, 3rd shift	3
	065	Outdoor work	18
	066	Work in motor vehicle	16

(continued)

TABLE 3-1 (continued)

Age-occupation group	Subgroup		
	Code[a]	Description	Percent
Service, military, and private household workers	081	Service, day time work, <30 min commute	36
	082	Service, day time work, >30 min commute	17
	083	Service, night time	22
	084	Service, in motor vehicle	3
	085	Military	14
	086	Private household	8
Housewives	091	No children at home	42
	092	Some children <13	49
	093	No children <13, some 13 to 18	9
Unemployed and retired	101	Unemployed, job hunting	20
	102	Unemployed, not job hunting	24
	103	Disabled	20
	104	Retired, full mobility	30
	105	Retired, limited mobility	4
	106	Retired, confined indoors	2
Children less than 5	111	0 to 12 months	21
	112	13 to 24 months	20
	113	25 to 36 months	20
	114	37 to 60 months	39
Children 5 to 17	121	Elementary school, <30 min commute	56
	122	Elementary school, >30 min commute, walk or bike	4
	123	Elementary school, >30 min commute, vehicle	7
	124	High school, <30 min commute	26
	125	High school, >30 min commute, walk or bike	2
	126	High school, >30 min commute, vehicle	5

[a]First two digits indicate age-occupation group, third digit indicates subgroup.

3.2 TYPES OF NEIGHBORHOODS

Like the exposure district version of NEM, estimation of human exposure to CO using the neighborhood version involves a simple two-way trip model. This model assumes that each cohort is located either in its home NT or its work NT during each hour of the year. To use this model, it is necessary to determine hourly ambient CO concentration in home NT's and work NT's.

In reviewing air quality data available from CO monitors, PEDCo found that information about neighborhood settings of monitors is very limited, except for two National Air Monitoring Systems (NAMS) monitors in each city where sites have been surveyed in detail. For most monitors, neighborhood data are limited to the station-type (ST) identifiers listed in the Storage and Retrieval of Aerometric Data (SAROAD) system. The ST identifiers classify monitors according to geographic location and land use. Geographic location categories include

1. Center City - core area of the city, not its incorporated limits
2. Suburban
3. Rural
4. Remote - far enough from any activity to measure background levels.

Land use categories vary with geographic location as follows:

1. Center City and Suburban

   a. Industrial - product-oriented establishments such as manufacturing concerns, utilities, mining, and graineries.

   b. Commercial - service-oriented establishments such as retail establishments, shopping centers, gas stations, and laundromats.

   c. Residential - because other areas are also used residentially, this category is used only in the absence of a dominating industrial or commercial influence.

   d. Mobile - sites located in airports, truck or bus terminals, or an expressway cloverleaf. Sites placed near parking lots would probably be better categorized as industrial or commercial.

2. Rural

   a. Industrial - same as center city and suburban industrial.

   b. Commercial - same as center city and suburban industrial.

   c. Near urban - sites located in a rural area, yet close enough to a major urban center to be affected by the urban area.

   d. Agricultural - sites located near orchards, crop raising, cattle, and sheep grazing.

3. Remote

To simplify the selection of monitors to represent NT's, we established NT's to conform to the SAROAD ST's. Since all study areas were urbanized, ST's with rural and remote categories were dropped from consideration. The remaining eight ST's provide the basis for eight NT's used for classifying cohorts in a population exposure analysis (see Table 3-2). These NT's are coded with numbers 1 through 9 to facilitate their use in computer files.

TABLE 3-2. NEIGHBORHOOD TYPES (NT's) AND CODES

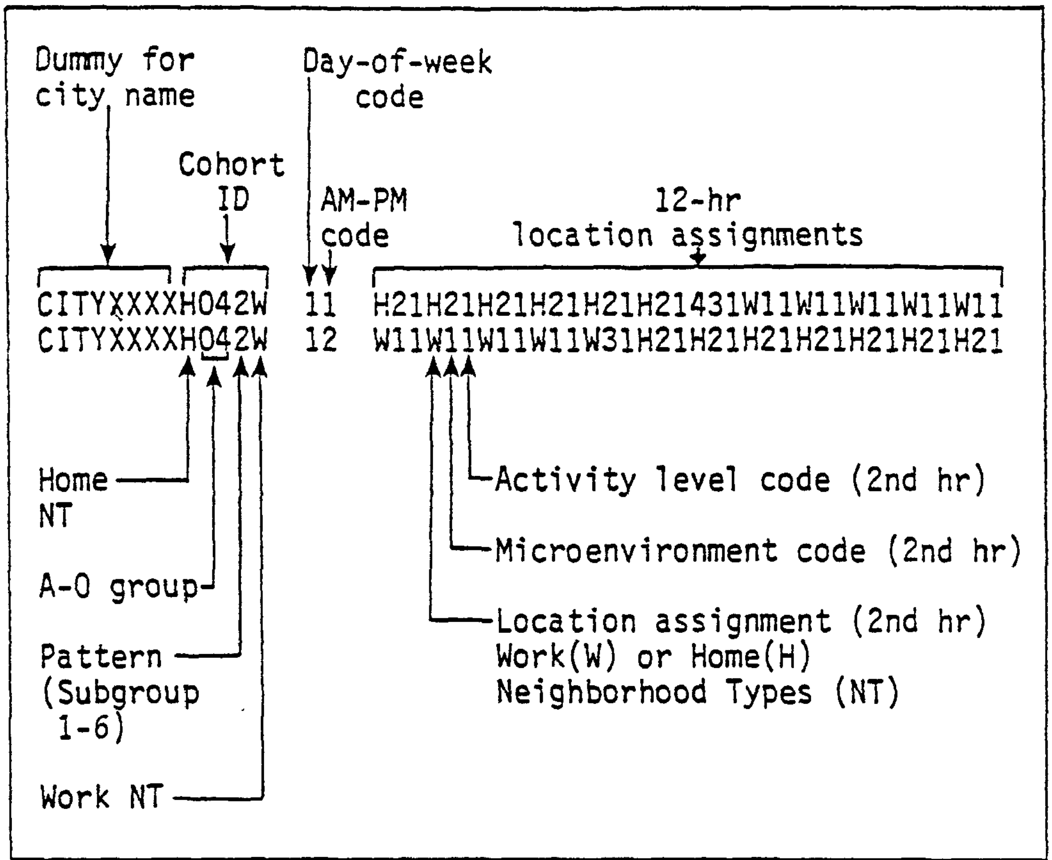
NT	Computer code
Center-city residential	1
Center-city commercial	2
Center-city industrial	3
Center-city mobile	4
Suburban residential	5
Suburban commercial	6
Suburban industrial	7
Suburban mobile	8
Not used or "other"	9

Once NT's are established, they can be used like exposure districts within an activity pattern computer file. District codes 1 to 9 can be replaced with NT codes 1 to 9 in both the definition of cohorts and in hour-by-hour assignments, as shown in Figure 3-4. The concept of "home" now refers to home NT rather than home district, and "work" refers to work NT rather than work district. The 2-way trip model is retained; commuters move from a home NT to a work NT in the morning and return in the evening. Consequently, activity patterns developed for the neighborhood version of NEM use the same format as activity patterns developed for the exposure district version.

3.3 ESTIMATION OF COHORT POPULATIONS

There were several problems associated with establishing cohorts and determining cohort populations in the neighborhood version of NEM. First, NT's did not provide a convenient unit for assembling population data. As shown on a previous map (Figure 3-2) neighborhoods occur in irregular patterns scattered throughout a city. Boundaries of neighborhoods do not correspond to the boundaries of census tracts or any other unit used by the Bureau of Census to organize population data. Second, even if it were theoretically possible to collect population data for each NT, such an effort would require a significant expenditure of resources which were not available for this purpose. Consequently, we made certain simplifying assumptions so that population data that had already been assembled for the exposure district version of NEM could be used in CO exposure analysis.

Population data assembled for previous NEM analyses consisted of the numbers of people in 12 A-O groups who resided in each of the exposure districts comprising each of four study areas. The first step in using this data was to determine the number of people in each A-O group residing in center-city neighborhoods and the number of people residing in suburban neighborhoods.



Day-of-week codes:

1 = weekday
2 = Saturday
3 = Sunday

AM-PM codes:

1 = AM, hrs 1-12
2 = PM, hrs 1-12

Activity codes:

1 = low activity level
2 = medium activity level
3 = high activity level

Microenvironment codes:

1 = indoors at work
2 = indoors, other
3 = transportation vehicle
4 = transportation, other
5 = outdoors

Figure 3-4. Contents of cohort activity file.

This was possible because each exposure district could be classified center-city or suburban by its geographic location and predominant land use pattern. Classifications of exposure districts were established in study areas used for previous NEM analyses, as shown in Table 3-3.

TABLE 3-3. GEOGRAPHIC CLASSIFICATION OF EXPOSURE DISTRICTS

Study area	Exposure districts	
	Center-city	Suburban
Chicago	1,2,3,4,5	6,7,8
Philadelphia	1	2,3,4,5,6
St. Louis	1,2,3,4	5,6,7
Los Angeles	1	2,3,4,5,6,7

Using this breakdown, the A-O group residence data could be classified into suburban or center-city, as listed in Table 3-4. The next step was to further subdivide these general neighborhood classifications into specific NT's. For this breakdown, it was necessary to use transportation data and certain assumptions about movements of A-O groups and their place of residence.

To simplify the problem of NT assignments, we assumed that all people live in a residential neighborhood. This might be considered obvious by definition, but some neighborhoods are better characterized by predominant land uses. For example, some people live in a predominantly industrial neighborhood. However, it is not important to use pure definitions of neighborhoods, but to differentiate high pollution residential neighborhoods from presumably low pollution residential neighborhoods. Using the NT's listed in Table 3-2, this dichotomy can be approximated by center-city residential (high pollution) and suburban residential (low pollution). In St. Louis, for example, we approximated the population living in center-city residential NT's by the persons living within neighborhoods classified center-city in Table 3-3, and the population living within suburban-residential NT's

TABLE 3-4. A-O GROUP POPULATION BY RESIDENTIAL NEIGHBORHOOD CLASSIFICATIONS IN FOUR STUDY AREAS

Age-occupation group	Chicago		Philadelphia		St. Louis		Los Angeles	
	Center-City	Suburban	Center-City	Suburban	Center-City	Suburban	Center-City	Suburban
1. Students 18+	83,982	25,639	18,429	75,594	16,319	23,191	75,047	266,634
2. Professionals/Managers	387,741	119,336	43,002	214,878	35,848	70,853	155,876	645,758
3. Sales workers	82,701	25,482	14,398	74,567	11,729	23,063	46,364	198,847
4. Clerical and kindred workers	269,599	66,877	64,792	199,801	50,088	48,284	151,100	490,555
5. Craftsmen, foremen, kindred	174,648	60,795	39,052	116,303	24,115	27,664	66,589	333,381
6. Operatives and laborers	206,363	55,626	98,768	161,890	63,188	40,018	134,679	478,973
7. Farm workers	-	-	862	1,891	685	843	978	12,847
8. Military, service household	137,201	30,803	57,695	103,172	46,636	26,155	71,972	321,552
9. Married housewives	170,209	92,439	93,110	290,814	65,402	81,385	166,345	810,286
10. Unemployed or retired	57,399	16,385	96,979	212,055	87,668	54,180	202,601	563,154
11. Children under 5	50,295	38,455	75,481	166,766	49,973	50,029	115,731	538,814
12. Children 5-17	120,703	92,292	209,444	508,243	147,659	163,026	267,644	1,617,642
TOTALS	1,704,843	624,115	812,009	2,125,970	599,320	608,690	1,454,924	6,278,412

by the number of people living in all areas classified suburban. This allocation procedure allowed the population of each study area to be divided into residential neighborhood categories which are also geographic areas. The resulting breakdown of population is shown in Table 3-4.

We next determined work NT's by making simple, intuitive assumptions about the work environment of A-O groups. For example, we assumed that children under 5 years did not go to work, but stayed at home. We assumed that children 5-17 years of age went to "work" at a school, but that the school was located in the same NT as their residence. We assumed that operatives and laborers worked primarily in industries located within an industrial NT. The full roster of assumptions is listed in Table 3-5; these statements allowed the work NT of each A-O group to be classified residential, commercial, or industrial, but they did not determine whether NT's are center-city or suburban. For this purpose, transportation data were used in the form of home-to-work trip tables.

As documented in other reports,[3,4] home-to-work trip tables were previously developed for each study area based on data provided by regional transportation planning agencies. These trip tables may be visualized as an n x n array which lists the number of trips taken during a typical day from each transportation zone of a city to every other zone. In previous NEM analyses, arrays were reduced in size by aggregating transportation zones into exposure districts. The resulting smaller arrays showed the number of trips from each exposure district to every other exposure district.

In the CO analysis, each study area trip table was further condensed into a 2 x 2 array, because the only geographic elements used were suburban and center city NT classifications. In other words, all exposure districts were aggregated into either a suburban super-district or a center-city super-district. The resulting collapsed trip tables are listed in Table 3-6. As in previous NEM analyses, we assumed that the fraction of all trips

TABLE 3-5. ASSUMPTIONS CONCERNING WORK NT'S OF A-O GROUPS

A-O Group	Assumptions
1. Students 18+	Work NT is same as home NT.
2. Professional and administrative	All work in a commercial neighborhood; some work in suburban areas, others in center-city.
3. Sales workers	Work neighborhood is suburban-commercial or center-city commercial.
4. Clerical workers	Work neighborhood is suburban-commercial or center-city commercial.
5. Craftsmen	Work neighborhood is suburban-industrial or center-city industrial.
6. Operatives and laborers	Work neighborhood is suburban-industrial or center-city industrial.
7. Farmers	There are no farmers in urbanized area.
8. Service, military and household	Work neighborhood is same as home.
9. Housewives	Work neighborhood is same as home.
10. Unemployed and retired	Work neighborhood is same as home.
11. Children under 5	Work neighborhood is same as home.
12. Children 5 to 17	Work neighborhood is same as home.

TABLE 3-6. COLLAPSED HOME-TO-WORK TRIP TABLES, EXPRESSED AS NUMBER OF TRIPS AND FRACTION OF TRIPS

Study area	From home	To work	
		Center city	Suburban
Chicago	Center-city	3,182,820(0.935)[a]	221,720(0.065)
	Suburban	524,260(0.843)	97,300(0.157)
Philadelphia	Center-city	270,517(0.718)	106,507(0.283)
	Suburban	405,867(0.353)	743,723(0.647)
St. Louis	Center-city	114,627(0.793)	29,920(0.207)
	Suburban	76,977(0.435)	99,957(0.565)
Los Angeles	Center-city	246,970(0.570)	1,861,400(0.430)
	Suburban	581,480(0.133)	3,800,720(0.867)

[a]Number in parenthesis is fraction of trips.

taken from one super-district to another could be used to represent trip distributions for all A-O groups. These fractions were used in a modified 2-way trip model to calculate number of persons in each cohort, as follows:

$$P_{H,A,S,W} = \left(P_{H,A}\right)\left(F_S\right)\left(\frac{t_{H-W}}{T_H}\right) \qquad (3\text{-}1)$$

where H = home NT

A = age-occupation category

S = subgroup specified by activity pattern

W = work NT

$P_{H,A,S,W}$ = population of a cohort which is defined by the subscripts

$P_{H,A}$ = population of an age-occupation category in a home NT (center-city residential or suburban residential)

F_S = fraction of persons in A-O group allocated to subgroup

t_{H-W} = number of trips from a home super-district to a work super-district

T_H = total number of trips by all A-O groups from a home super-district to both super-districts (suburban or center-city).

Calculation of cohort populations may be illustrated by an example. Using the modified trip model, one cohort may be defined as those persons residing in suburban-residential NT in St. Louis who are managers or professionals (A-O Group 2), who follow typical activity patterns of subgroup 2, and who are located in center-city commercial NT during working hours. This definition is consistent with the list of assumptions in Table 3-5. This table shows that 70,853 people live in suburban residential NT's in St. Louis and belong to A-O Group 2. From Table 3-1 we find that the fraction of A-O Group 2 belonging to subgroup 2 is 21 percent. From the collapsed trip table, Table 3-6, we find that 110,046 people out of a total of 397,200 people from suburban residential NT's go to a center-city NT for work. Thus, we may calculate the cohort population as follows:

$$P_{5,2,2,2} = (70,853)(0.21)\ \frac{(110,046)}{(397,200)} = 4,122 \text{ persons.}$$

Populations of all cohorts were calculated similarly; a complete list of cohorts and estimated cohort populations is provided in Appendix B.

Once methods for representing people movement were established, and methods were devised for calculating numbers of people following various movement patterns, there remained the task of estimating air quality levels to which cohorts were exposed. Development of air quality data is the subject of subsequent sections.

3.4 REFERENCES

1. Memorandum from Ted Johnson, PEDCo Environmental, to Thomas McCurdy, Strategies and Air Standards Division, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711, April 6, 1982.

2. Ted Johnson, Activity Patterns for NEM Analysis of Carbon Monoxide Exposure, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C., October 1982.

3. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Nitrogen Dioxide, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C., May 1981.

4. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Particulate Matter, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C., August 1981.

SECTION 4

PREPARATION OF AIR QUALITY DATA

NEM requires representative outside air quality data for each neighborhood type in the form of a complete year of hourly average values. This section describes the procedures used for selecting appropriate data sets, for validating these data, and for filling in missing values.

4.1 SELECTION OF REPRESENTATIVE DATA SETS

To simplify the computer simulation, air quality in all neighborhoods classified as belonging to a specific NT was assumed to be a linear function of air quality monitored at a single representative monitoring site. Consequently, for each study area we had to select one monitoring site per NT. We originally considered using the 8 NT's listed in Table 3-1; however, evaluation of data availability indicated that there was an insufficient number of center-city mobile and suburban mobile sites to include these NT's in the exposure analysis. The remaining NT's were:

- o center-city residential (CR),
- o center-city commercial (CC),
- o center-city industrial (CI),
- o suburban residential (SR),
- o suburban commercial (SC), and
- o suburban industrial (SI).

Table 4-1 lists data sets selected to represent these NT's. These data sets were selected according to the following procedure.

(1) Data for the same year were used for all sites in a study area. The year was selected to maximize the number of NT's that could be represented by acceptable

TABLE 4-1. DATA SETS (mg/m^3) SELECTED FOR ANALYSIS OF POPULATION EXPOSURE TO CARBON MONOXIDE IN FOUR CITIES

Study area and year	NT	ST	SAROAD code	Probe height (ft)	1-hour obs.	Geo. mean	99th percentile	Notes
Chicago (1979)	CR	CC	141220039F01	11	6172	1.8	7.0	b
	CC	CC	141220040F01	11	8392	2.9	15.8	a
	CI	CI	141220026H01	26	7615	2.6	9.8	
	SR	SR	140780002G01	15	8664	1.3	6.7	
	SC	SC	145680001G01	15	7662	1.4	7.0	
	SI	SC	147160005G01	39	8425	1.4	6.4	b
Los Angeles (1977)	CR	CR	056400003F01	32	7921	1.8	9.2	
	CC	CC	053900001I01	20	7940	2.6	18.4	a
	CI	SI	050900002I01	15	7775	3.9	17.3	b
	SR	SR	058720001I01	15	7777	3.4	13.8	a
	SC	SC	050230001I01	15	7888	3.0	13.8	a
	SI	SI	050900002I01	15	7775	3.9	17.3	
Philadelphia (1978)	CR	CC	397140026H01	13	7773	2.2	10.4	a,b
	CC	CC	397140026H01	13	7773	2.2	10.4	a
	CI	SI	397140022H01	13	8088	1.3	5.8	a,b
	SR	SR	397140004H01	17	8193	0.8	5.8	a
	SC	SR	397140004H01	17	8193	0.8	5.8	a,c
	SI	SI	397140021H01	13	8485	1.9	8.1	
St. Louis (1978)	CR	CR	264280007H01	35	5944	?	6.4	a,d
	CC	CC	264280064H01	?	7466	5.4	10.7	a
	CI	CI	264280061H01	12	7539	2.5	11.8	
	SR	SR	260200002G01	13	6817	2.6	9.3	
	SC	SC	261040001G01	14	7010	2.6	9.8	
	SI	CI	264280061H01	12	7539	2.5	11.9	b

a: detailed site location description available at MDAD.

b: site with matching ST not available.

c: site with matching ST not appropriate.

d: geometric mean not calculated because data completeness <75 percent.

data sets. A data set was considered acceptable if it contained at least 5839 observations (66% completeness).

(2) When possible, an NT was represented by a data set with a corresponding ST (e.g., the center-city commercial NT for St. Louis was represented by site 264280064H01, which has a center-city commercial ST).

(3) If two or more sites with the required ST were available, the site judged most representative of the NT was selected. In 11 cases, degree of representation was determined from photographs of site surroundings and detailed local land use descriptions on file in the Monitoring and Data Analysis Division (MDAD), EPA. Summary statistics, probe location, and data completeness were also considered in selecting sites.

(4) If no site with the required ST was available, the site with the most similar ST was selected. Whenever possible, the MDAD photographs and land use descriptions were used in selecting alternate sites.

In six cases, NT's and ST's do not match because a site with the appropriate ST was not available. For the Chicago center-city residential NT, we selected a center-city commercial site with low geometric mean and 99th percentile values. For the Chicago suburban industrial NT, we selected a suburban commercial site located in Skokie, a town near Chicago generally characterized as industrial. In Los Angeles, we used a suburban industrial site (the only industrial site in the study area) to represent the center-city industrial NT. A suburban commercial site in Afton was used for the St. Louis suburban industrial NT because Afton is located near an industrial area. The center-city residential NT in Philadelphia was represented by a center-city commercial site which photographs revealed to be surrounded by apartments. Similarly, the center-city industrial NT in Philadelphia was represented by a suburban industrial site because photographs suggested that the site is actually located in a heavily urbanized area.

In one case, a site with the correct ST was not used because photographs revealed a site with a different ST was more appropriate. The only suburban commercial site in Philadelphia (397140024H01) is surrounded on all sides by Philadelphia International Airport. Site 397140004H01, although labeled suburban residential, was used instead because it had commercial establishments nearby.

4.2 VALIDATION OF AIR QUALITY DATA

Air quality data sets containing erroneous values can bias the results of exposure studies, especially if the errors occur as extreme values. To ensure good data quality, the data sets listed in Table 4-1 were screened for anomalous values using three methods: (1) the gap test, (2) the patterns test, and (3) visual inspection.

4.2.1 The Gap Test

The Monitoring and Reports Branch (MRB) of MDAD has developed a standardized data review program called the MRB Validation Report.[1] This program uses two different concepts to identify anomalies (unexpected data patterns) in hourly data sets. The first approach, called the Gap Test, is a statistical analysis of data over a 1-month period. This analysis assumes that the data can be modeled reasonably well by a smooth probability distribution curve. Two exponential curves are fit to the data using the 50th and 95th percentiles of the data for one fit and the 50th and 99.9th percentiles for the other fit. Both fits emphasize the upper tail of the distribution. All data values are arranged in order of magnitude and the program examines "gaps" in the data, i.e., large differences between succeeding ordered values. Using the fitted distribution functions, the program calculates the probability that a gap of magnitude "x" could be obtained by chance. A gap that is greater than would be expected from the underlying assumptions is flagged as a data anomaly. The strength of the Gap Test is that the criteria for identifying anomalies are based on an analysis of the data set itself.

Its weakness is that the assumed distribution is not always appropriate; consequently some false failures may occur.

In this study, the output from the gap test was evaluated to determine whether or not the flagged data were plausible from other points of view. It was desired that data not be rejected unless a strong case for error could be established. Flagged data were usually retained if the tested data set contained a large number of missing values, only one of the two fitted curves indicated an anomaly, or there were more than five observations above the gap. Data flagged by the gap test were more likely to be rejected if they were flagged by other tests.

4.2.2 The Pattern Test

The second test in the MRB Validation Program is called the Pattern Test. It is composed of 5 subtests carried out for each 24-hour period, as follows:

(1) High-value test - the test flags an hourly value that exceeds a predetermined limit. For carbon monoxide, the criterion depends on whether or not the measurement was taken during rush hours (7-11 a.m. or 4-9 p.m.). During rush hours the limit is 66 ppm and at other times it is 44 ppm.

(2) Adjacent-hour difference test - this test assumes that data take the form of an auto-correlated time series, i.e., a large jump or drop in the values within 1 hour is not expected. If there is a jump or drop greater than 22 ppm, the suspect value is flagged.

(3) Dixon-ratio test - this is a statistical analysis of the highest and lowest value found during the day. If A is the difference between the two highest values and B is the range of values for the day, then the Dixon Ratio is A/B. If this ratio is statistically significant, the suspect values are flagged.

(4) Spike-test - the differences between a suspect hourly value and the preceding and following hourly value is measured. If either of these two differences is greater than 20 ppm, or if

the suspect value is 500 percent greater than either of the adjacent values, the suspect value is flagged.

(5) Consecutive high values - it is unusual for a series of hourly measurements to remain at a high level. If four consecutive hourly values are greater than 40 ppm, the data are flagged.

PEDCo evaluated the results of applying MRB Validation Program to SO_2 data in four cities.[2] This analysis led to the development by PEDCo of a revised validation program. This new program (denoted here as MRB-2) contains improvements in the pattern tests and an option for graphical output of flagged data. The Dixon Ratio Test was enhanced for all pollutants in order to incorporate the recommendations of a recent EPA report.[3] In the new version, the formulas for testing the high and low hourly values from each 24-hour period vary according to the number of hourly measurements recorded during the period. The spike test was enhanced so that an individual hourly value is compared to the two (rather than one) preceeding values and the two succeeding values. In addition, MRB-2 incorporates a preliminary screening test, so that if all the values in a 24-hour period are low, the pattern tests are skipped. By passing over data that do not require testing, the computer program runs more quickly.

The strength of the pattern test program is that it uses more than one test to identify possible anomalies. Its weakness is that the criteria for identifying anomalies is predetermined for all tests except the Dixon Ratio Test. The pattern test program could be improved by adjusting test criteria according to the data reported by each individual monitoring site.

4.2.3 Visual Inspection

George Duggan of SASD has developed a computer program which will plot all hourly values in a year of data on a single graph. Such data plots are useful in identifying unusually high values and long strings of identical values. All data sets used in the

CO exposure analysis were plotted using this program and reviewed by PEDCo. Values which appeared anomalous were flagged for further investigation.

4.2.4 Results of Data Screening

CO levels recorded at monitoring sites can be drastically altered by short-term changes in local emissions. Exhaust from a delivery truck idling near a monitor may result in a high reading which appears totally inconsistent with other CO values recorded that day. However, this reading should not be excluded from the exposure analysis since it represents an exposure situation which may occur frequently throughout the study area. Consequently, we decided to retain flagged data unless they appeared to be the obvious result of instrument malfunction or transcription error. As discussed below, few of the flagged data fell into these categories.

Table 4-2 lists data anomalies flagged by one or more of the screening methods. Of the anomalies detected, most were flagged by the gap test or visual inspection. No values were flagged by the high value test, the spike test, or the consecutive hour test.

Eight data anomalies were identified by visual inspection. In two cases, Chicago site 145680001G01 and St. Louis site 261040001G01, long strings of values equal to 0.1 ppm or zero were found. We assumed in both cases that these values were incorrectly entered in place of missing values and removed them from the data. The other six anomalies involved unusually high values. Analysis showed that the flagged high values occurred simultaneously at the two Chicago sites and at the two Philadelphia sites. We considered this sufficient corroboration to retain these values.

We also retained the values flagged by visual inspection at sites 260200002G01 and 264280064H01 in St. Louis. In the first case, four large values (20.8, 26.3, 26.1, and 26.6 ppm) were preceded and followed by values of 3.1 ppm. This episode was unusual

TABLE 4-2. ANOMALIES FLAGGED BY DATA SCREENING

Study area	SAROAD code	NT	Date	Anomaly	Screening procedure: Gap	Adjacent hour	Dixon ratio	Visual inspect.
Chicago	140780002G01	SR	12-29-79	9 values ≥ 10 ppm				X
	145680001G01	SC	12-29-79	9 values ≥ 10 ppm				X
			2-79	long string of values near zero	X			X
Los Angeles	053900001I01	CC	2-07-77	large value			X	
			2-17-77	large value			X	
Philadelphia	397140021H01	SI	6-78	large gap	X			
	397140022H01	CI	1-25-78	6 values ≥ 10 ppm				X
	397140026H01	CR,CC	1-25-78	12 values ≥ 10 ppm	X		X	X
St. Louis	260200002G01	SR	6-78	large gap	X			
			7-24-78	4 values > 20 ppm	X	X		X
	261040001G01	SC	12-78	long string of values near zero				X
	264280064H01	CC	4-09-78	2 values > 15 ppm	X			X

enough to cause the day to be also flagged by the gap test using 50th and 95th percentiles and the adjacent hour test. However, the day was not flagged when the gap test was repeated using the 50th and 99.9 percentiles. In the other case, two large values (15.2 and 16.5 ppm) were preceded and followed by smaller values. These data were also flagged by the 50/95 gap test but not by the 50/99.9 gap test.

The 50/95 gap test also flagged data at site 397140021H01 in Philadelphia and at site 260200002G01 in St. Louis. Since these data were not flagged by any other test, including the 50/99.9 gap test, they were accepted.

Three days of data were flagged by the Dixon Ratio test. Because analysis of these data indicated that the assumption of normality was not valid, we repeated the Dixon Ratio test using the logarithms of the recorded values as recommended by Nelson, et al.[3] This time no values were flagged by the test. We concluded there was no probable cause under an assumption of lognormality for rejecting the data.

In summary, we investigated 12 cases of data flagged by various screening procedures. We retained the anomalies in all but the two cases where visual inspection had identified long strings of values equal to 0.1 ppm or zero. These values were removed from the data sets. The next section describes the methodology used to fill in these and other missing values.

4.3 SIMULATION OF MISSING VALUES IN HOURLY AVERAGE CO DATA SETS

NEM requires air quality data sets with values for every hour of the year. Since absolutely complete data sets were not available, gaps were filled in using a time series model developed by Johnson and Wijnberg.[4]

4.3.1 The Time Series Model

A complete year of hourly average data takes the form of a time series $x_1, x_2, \ldots, x_t, \ldots, x_n$ where n = 8760. We can fit this series exactly by the model

$$x_t = \bar{x} + \sum_{j=1}^{4380} R_j \cos(\omega_j t + \theta_j) \tag{4-1}$$

where $\bar{x}$ is the arithmetic mean of the series, R_j and θ_j are amplitude and phase angle values determined by Fourier analysis, and $\omega_j = 2\pi j/8760$. Omission of one or more of the 4380 Fourier cosine terms will yield an approximate fit. Because Fourier cosine functions are orthogonal and because the contribution of each cosine function to the representation of the original time series is proportional to its amplitude R_j, we can provide a least squares fit to the original time series with m cosine terms by using the cosine terms with the m largest amplitudes. We denote each term of this estimated time series as $\hat{x}_t$ where

$$\hat{x}_t = \bar{x} + \sum_{i=1}^{m} R_i \cos(\omega_i t + \theta_i) \tag{4-2}$$

and R_i, ω_i, and θ_i are the parameters of the Fourier term having the i<u>th</u> largest amplitude. For convenience, we will refer to the m Fourier terms in Equation 4-2 as the essential cyclical component (ECC).

The differences between the x_t series and the $\hat{x}_t$ series comprise the d_t series, i.e.,

$$d_t = x_t - \hat{x}_t \,. \tag{4-3}$$

We can define how well the $\hat{x}_t$ series represents the x_t series by the goodness of fit statistic

$$r^2 = 1 - \sum_{t=1}^{8760} d_t^2 \Big/ \sum_{t=1}^{8760} (x_t - \bar{x})^2 \equiv \sum_{i=1}^{m} R_i^2 \Big/ \sum_{j=1}^{4380} R_j^2 \qquad (4\text{-}4)$$

As m increases, r^2 increases and the goodness of fit improves. Note that $r^2 = 1$ when $m = 4380$.

If the x_t series exhibits autocorrelation, the d_t series is likely to exhibit autocorrelation. One means of characterizing a series which exhibits autocorrelation is to use an AR(p) process (i.e., an autoregressive process of order p). In this case, each d_t term can be expressed as

$$d_t = a_t + \phi_1 d_{t-1} + \phi_2 d_{t-2} + \cdot \cdot \cdot + \phi_p d_{t-p} \qquad (4\text{-}5)$$

where a_t is a normally distributed random variate with mean 0 and variance σ_a^2.

Estimates of $\phi_1, \phi_2, \ldots, \phi_p$ can be obtained by first estimating each autocorrelation ρ_k, using the relationship $\hat{\rho}_k = r_k$ where

$$r_k = \frac{c_k}{c_0} \qquad k = 1, 2, \ldots, p \qquad (4\text{-}6)$$

and

$$c_k = (1/8760) \sum_{k+1}^{8760} (d_t - \bar{d})(d_{t-k} - \bar{d}). \qquad (4\text{-}7)$$

From these estimates, the Yule-Walker estimates of the autoregressive parameters can be obtained.[5]

Autocorrelation of the d_t series will decrease as m increases since an increasing portion of the x_t series autocorrelation is explained by the cosine functions. We assumed that most of the autocorrelation in the data corresponding to $k \geq 3$ would be contained in the ECC we selected and that an AR(2) process would suffice to characterize the d_t series. In this case,

$$\hat{\phi}_1 = \frac{r_1(1 - r_2)}{1 - r_1^2}, \qquad (4\text{-}8)$$

$$\hat{\phi}_2 = \frac{r_2 - r_1^2}{1 - r_1^2}, \tag{4-9}$$

and

$$\hat{\sigma}_a^2 = c_0(1 - \hat{\phi}_1 r_1 - \hat{\phi}_2 r_2). \tag{4-10}$$

This AR(2) process represents a stationary time series if it meets certain conditions described by Box and Jenkins.[6]

A theoretical AR(2) process will have non-zero values of ρ_k for k > 2 that decrease gradually according to the relationship

$$\rho_k = \phi_1 \rho_{k-1} + \phi_2 \rho_{k-2} \qquad k > 0 \tag{4-11}$$

until a point is reached where the distribution of r_k is approximately normal with mean zero and standard error

$$\sigma(r_k) \doteq \sqrt{\frac{1}{n}(1 + 2\rho_1^2 + 2\rho_2^2)}. \tag{4-12}$$

The values of ρ_1 and ρ_2 are estimated by r_1 and r_2. No more than 5% of the values of r_k for large values of k should deviate from zero by more than two standard errors.[7]

If we can select an ECC such that the autocorrelations in the d_t series corresponding to k > 2 are consistent with Equations 4-11 and 4-12, then an AR(2) process should suffice to characterize the d_t series. To select this ECC, we can start by determining the d_t series that corresponds to m = 1. We then calculate r_k for values of k that are likely to be significant. These include k = 3, 4, 6, 8, 12, 24, and 168 for typical air quality data. If the r_k values are not consistent with Equations 4-11 and 4-12, we determine the d_t for m = 2 and repeat the analysis. We continue increasing m until the r_k values for k > 2 meet our criteria. At this stage, we should have a combination of ECC and AR(2) process that will adequately characterize the data.

4.3.2 Initial Treatment of Missing Values

Fourier analysis cannot be applied to a time series if one or more values are missing. If air quality data to be analyzed are incomplete, some method of estimating missing values must be used prior to analysis. Bloomfield[8] recommends replacing each missing observation by a linear combination of its neighbors if most of the missing values tend to occur in small, isolated groups. If a gap containing b-1 missing values occurs between values x_a and x_{a+b}, each missing value x_t can be estimated by linear interpolation as

$$\hat{x}_t = x_a + \frac{1}{b}(t - a)(x_{a+b} - x_a). \qquad (4\text{-}13)$$

However, linear interpolation may not yield reasonable estimates of missing one-hour values for large gaps, especially if they are bounded by extreme values. In these cases, the arithmetic mean ($\bar{x}$) may be a better estimate of each missing value. Inspection of data sets to be used in the CO population exposure analysis suggested that the arithmetic mean should be used to fill in gaps whenever gap length exceeded 72 hours and/or one of the boundary values exceeded the arithmetic mean by more than two standard deviations. In other cases, linear interpolation produced reasonable results.

4.3.3 Procedure for Simulating Missing Values

The time series model described above was the basis for the following procedure for simulating missing values.

(1) The mean and standard deviation of each data set were calculated.

(2) Gaps with lengths exceeding 72 hours and/or with boundary values exceeding the arithmetic mean by more than two standard deviations were identified. These gaps were filled in with the arithmetic mean.

(3) Linear interpolation was used to fill in the remaining gaps.

(4) Fourier analysis was applied to the augmented time series created in steps (2) and (3).

(5) An ECC was constructed which contained the smallest number of cosine terms required to produce a d_t series consistent with Equations 4-11 and 4-12.

(6) The d_t series was represented by an AR(2) process by using Equations 4-8, 4-9, and 4-10 to determine $\hat{\phi}_1$, $\hat{\phi}_2$, and $\hat{\sigma}_a$.

(7) An a_t series was formed by dividing each term in a N(0,1) random series by $\hat{\sigma}_a$. For consistency, the same random series was used in each case.

(8) Missing d_t values were simulated using the relationship

$$\hat{d}_t = \hat{\phi}_1 \hat{d}_{t-1} + \hat{\phi}_2 \hat{d}_{t-2} + a_t. \tag{4-14}$$

(9) Missing x_t values were filled in using the model

$$\hat{x}_t = \bar{x} + \sum_{i=1}^{m} R_i \cos(\omega_i t + \theta_i) + \hat{d}_t \tag{4-15}$$

to create the final augmented data set.

Note that the final simulation (Equation 4-15) uses information concerning the cyclical, autoregressive, and stochastic properties of the time series which are omitted in the initial estimates made in steps (2) and (3).

Figure 4-1 shows a data set which is missing 1750 values. Figure 4-2 shows the augmented data set after the initial simulation of missing values [steps (1) through (3)]. Figure 4-3 shows the final augmented data set with missing terms filled in by adding an appropriate AR(2) process to the most significant Fourier cosine functions [steps (4) through (9)]. This two-step process simulates missing terms which are consistent with both the cyclical and the random character of the known values.

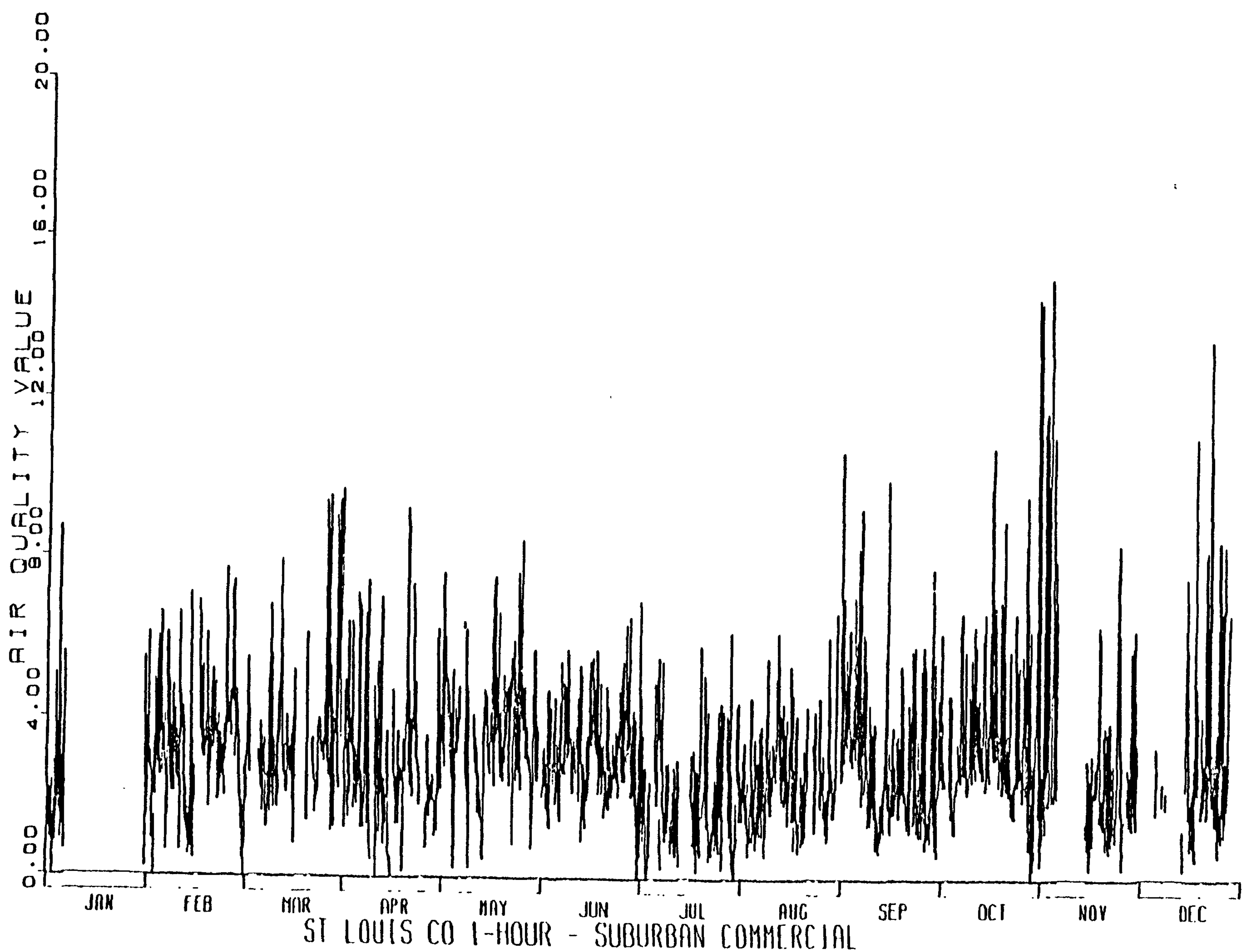


Figure 4-1. Hourly average 1978 carbon monoxide data reported by monitoring site 261040001G01 in St. Louis.

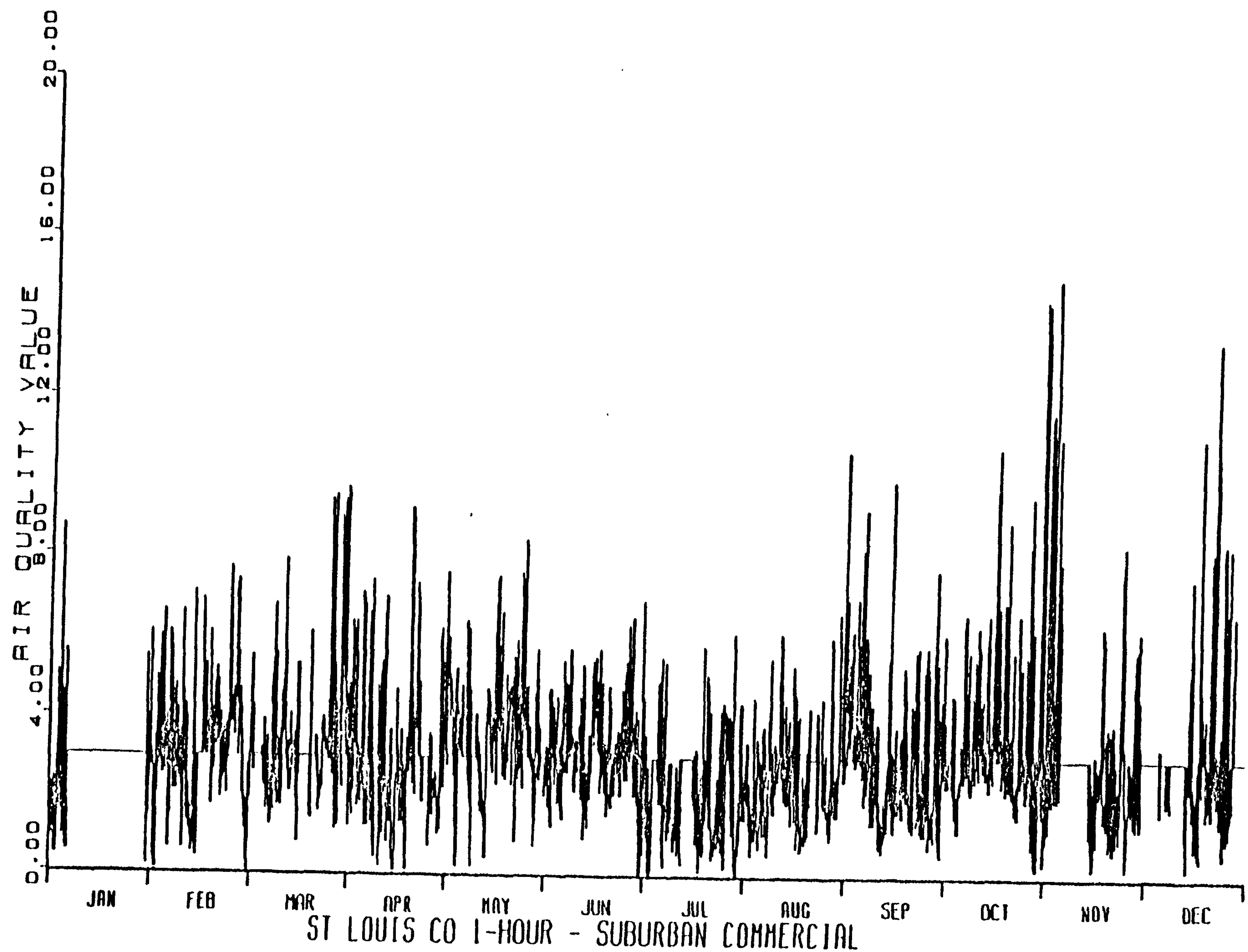


Figure 4-2. Hourly average 1978 carbon monoxide data for monitoring site 261040001G01 in St. Louis after initial simulation of missing values.

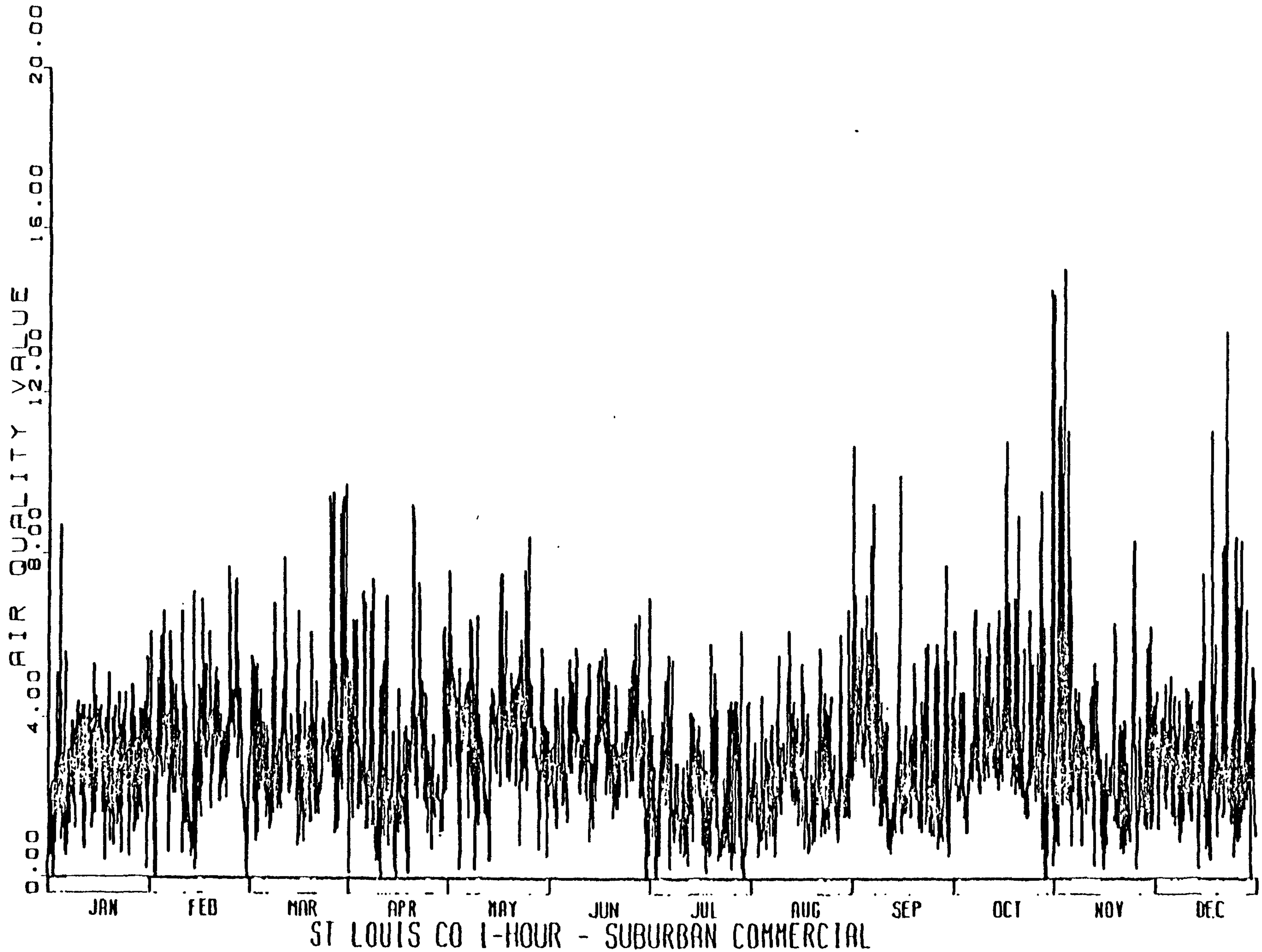


Figure 4-3. Hourly average 1978 carbon monoxide data for monitoring site 261040001G01 in St. Louis after final simulation of missing values.

4.4 REFERENCES

1. Screening Procedures for Ambient Air Quality Data, publication no. EPA-450/2-78-037, U.S. Environmental Protection Agency, Research Triangle Park, N.C., July 1978.

2. Roy A. Paul, R. B. Faoro, W. F. Hunt, "Screening SO_2 data anomalies from four test cities," Technical Conference Transactions, American Society for Quality Control, Milwaukee, Wisconsin, 1981.

3. A. C. Nelson, D. W. Armentrout, and T. R. Johnson, Validation of Air Monitoring Data, publication no. EPA-600/4-80-030, U.S. Environmental Protection Agency, Research Triangle Park, N.C., June 1980.

4. Ted Johnson and Luke Wijnberg, "Time series analysis of hourly average air quality data," paper no. 81-33.5, presented at the 74th Annual Meeting of the Air Pollution Control Association, Philadelphia, Pennsylvania, June 21-26, 1981.

5. G.E.P. Box and G.M. Jenkins, Time Series Analysis: Forecasting and Control, Holden-Day, San Francisco, 1976, p. 55.

6. Box and Jenkins, p. 58.

7. Box and Jenkins, pp. 35 and 59.

8. Peter Bloomfield, Fourier Analysis of Time Series: An Introduction, John Wiley and Sons, New York, 1976, p. 245.

SECTION 5

SIMULATION OF AIR QUALITY EXPECTED AT FIXED MONITORING SITE UNDER ALTERNATIVE CARBON MONOXIDE STANDARDS

The augmented data sets described in Section 4.3 were assumed to represent the current status of air quality at a representative monitor in each neighborhood type (NT). To represent air quality expected under the current NAAQS for CO and under proposed CO standards, these data sets were adjusted using a modified form of the EPA rollback model.

5.1 THE ROLLBACK MODEL

Each augmented data set is a time series containing 8760 hourly values, i.e.,

$$x_1, x_2, \ldots, x_t, \ldots, x_{8760}.$$

We assumed that y_t, the difference between each x_t and an assumed constant background level x_b, would increase or decrease in proportion to the changes in emissions dictated by a given air quality standard, as long as $x_t > x_b$. If $x_t < x_b$, we assumed x_t would not be affected by changes in emissions. We further assumed that all emissions would change in proportion to the change in emissions required to bring the most polluted NT in the study area into compliance.

Air quality in each NT was characterized by air quality indicators (AQI's) which varied according to the form of the air quality standard. We assumed the most polluted NT to be the one with the largest AQI with respect to the standard being considered.

To simulate the air quality expected in each NT under a standard, we created an adjusted data set

$$x_1', x_2', \ldots, x_t', \ldots, x_{8760}'$$

where

$$x_t' = \rho y_t + x_b \tag{5-1}$$

and ρ is a rollback factor. Consistent with the assumptions above, values of ρ were calculated according to the formulas

$$\rho = \frac{x_s - x_b}{x_{max} - x_b} \quad \text{if } y_t > 0 \tag{5-2}$$

and

$$\rho = 1 \qquad \text{if } y_t \leq 0 \ , \tag{5-3}$$

where x_s is the highest concentration permitted by the standard for the stated averaging time and x_{max} is the corresponding AQI for the most polluted NT. The rollback model assumes reasonable estimates of x_{max} and x_b are available; Sections 5.2 and 5.3 describe how these estimates were developed.

5.2 AIR QUALITY INDICATORS

Use of the rollback model to adjust air quality data requires parameters for characterizing data which are related to the form of each standard under consideration. At the time of the CO population exposure analyses, four types of parameters were considered for proposed standards: the daily maximum 1-hour value expected to be exceeded once per year, the daily maximum 1-hour value expected to be exceeded five times, the daily maximum 8-hour running average expected to be exceeded once, and the daily maximum 8-hour running average expected to be exceeded five times. Reasonable estimates of the 1-hour parameters can be made by fitting a cumulative distribution [F(x)] to the daily maximum values of an augmented data set and then calculating the values $\hat{b}_{1,365}$ and $\hat{b}_{5,365}$ such that

$$F(\hat{b}_{v,n}) = 1 - \frac{v}{n} \tag{5-4}$$

where v is the number of permitted exceedances and n is the number of possible daily maximum values. Similarly, reasonable estimates of the 8-hour parameters can be made by fitting a cumulative distribution to the daily maximum 8-hour running averages of an augmented data set and again calculating $\hat{b}_{1,365}$ and $\hat{b}_{5,365}$. In statistical theory, $b_{1,n}$ is known as the characteristic largest value and $b_{5,n}$ is known as the characteristic fifth largest value.[1]

Selection of an appropriate cumulative distribution to fit the data is important in determining a reasonable characteristic largest value. Two distributions which often provide close fits to ambient air quality data are the Weibull and the lognormal.[2] The Weibull distribution is defined as

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\delta}\right)^{k}\right] \tag{5-5}$$

where δ is the scale parameter and k is the shape parameter. The lognormal distribution is defined as

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{w} \exp\left(-t^2/2\right)\, dt \tag{5-6}$$

where

$$w = \frac{\ln x - \mu}{\sigma} \tag{5-7}$$

and ln x is distributed normally with mean μ and variance σ^2. From Equations 5-4 and 5-5, the characteristic v<u>th</u> largest value of the Weibull distribution can be estimated as

$$\hat{b}_{v,n} = \hat{\delta}\left(\ln \frac{n}{v}\right)^{1/\hat{k}} \tag{5-8}$$

if good estimates of δ and k are available. Similarly, the characteristic v<u>th</u> largest value of the lognormal distribution can be estimated as

$$\hat{b}_{v,n} = \exp\left(\hat{\mu} + \hat{\sigma} z_{v,n}\right) \tag{5-9}$$

if good estimates of μ and σ are available. The value of $z_{v,n}$ is determined from the normal distribution such that the area under the standard normal curve from $z_{v,n}$ to ∞ is v/n. Approximate values for $z_{1,365}$ and $z_{5,365}$ are 2.7774 and 2.2058.

The results of fitting distributions to a large number of ambient air quality data sets suggest that the characteristic vth largest value can be better estimated if the upper tail of the data is emphasized in the fit. PEDCo Environmental has used two methods to fit distributions to data censored on the left (i.e., data from which low values have been excluded): the method of least squares and the method of maximum likelihood.

5.2.1 Fitting Distributions by the Method of Least Squares

The least squares method requires that the equation defining the distribution under consideration be expressed as a linear relationship of the form y = az + b. Equations 5-5 and 5-6 can be rewritten in linear form using the following identities where x_m is the mth ranked value in ascending order.

Distribution	y	a	z	b
lognormal	$\ln x_m$	σ	$z_{m,n}$	μ
Weibull	$\ln x_m$	$\frac{1}{k}$	$\ln[\ln(\frac{n+1}{n+1-m})]$	$\ln \delta$

These identities follow Gumbel's recommendation[3] that $F(x_m) = \frac{m}{n+1}$ when fitting distributions to empirical data. Values of $z_{m,n}$ for the lognormal distribution are determined such that the area under the standard normal curve from $-\infty$ to $z_{m,n}$ is $m/(n+1)$.

A linear regression analysis of data transformed by these identities yields a regression line with an equation in the form of $y = \hat{a}z + \hat{b}$. Parameters of the corresponding distribution can be determined from the values of $\hat{a}$ and $\hat{b}$ using the following equations:

Weibull distribution

$$\hat{\delta} = \exp \hat{b} \tag{5-10}$$

$$\hat{k} = \frac{1}{\hat{a}} \tag{5-11}$$

Lognormal distribution

$$\hat{\mu} = \hat{b} \tag{5-12}$$

$$\hat{\sigma} = \hat{a} \tag{5-13}$$

5.2.2 Fitting Distributions by the Method of Maximum Likelihood

In an earlier analysis[4] of population exposure to NO_2, the least squares method described in Section 5.2.1 was the sole method used to fit distributions to air quality data. The method of maximum likelihood was not used because no procedure was then available for applying it to the upper tail of a data set. During the PM exposure analysis,[5] Louis Wijnberg of PEDCo Environmental (extending the work of Cohen[6,7]) developed the following maximum likelihood procedure which can fit Weibull and lognormal distributions to any portion of the upper tail of a data set.

The n values in an augmented data set are ranked from smallest to largest to yield an ordered series

$$x_1, x_2, \ldots, x_m, \ldots, x_n$$

where x_m indicates the mth ranked value. We are interested in obtaining maximum likelihood estimates (MLE's) of the parameters θ_1 and θ_2 of a two-parameter distribution $F(x;\theta_1,\theta_2)$ fitting the $n_f = n-c+1$ values that equal or exceed x_c. Letting $f(x;\theta_1,\theta_2)$ denote the density function of a two-parameter distribution and $F(x_c)$ be the value of the cumulative distribution at x_c,

$$L = \frac{n!}{(n-n_f)!} \left[\prod_{m=c}^{n} f(x_m;\theta_1,\theta_2) \right] \left[F(x_c) \right]^{n-n_f} \qquad (5\text{-}14)$$

is the likelihood function of interest. MLE's of θ_1 and θ_2 are determined by simultaneously solving the likelihood equations

$$\frac{\partial}{\partial \theta_1}(\log L) = 0 \qquad (5\text{-}15)$$

and

$$\frac{\partial}{\partial \theta_2}(\log L) = 0. \qquad (5\text{-}16)$$

In the case of the Weibull distribution, the likelihood equations are

$$\frac{1}{k} + \frac{1}{n_f} \sum_{m=c}^{n} \ln(\frac{x_m}{x_c}) - \frac{\zeta}{n_f} \sum_{m=c}^{n} (\frac{x_m}{x_c})^k \ln(\frac{x_m}{x_c}) = 0 \qquad (5-17)$$

and

$$\frac{1}{\zeta} + \frac{1}{n_f} \sum_{m=c}^{n} (\frac{x_m}{x_c})^k + \frac{n-n_f}{n_f(\exp\zeta - 1)} = 0, \qquad (5-18)$$

where

$$\zeta = (\frac{x_c}{\delta})^k . \qquad (5-19)$$

When fitting the lognormal distribution, the likelihood equations are:

$$(\bar{y} - \mu) - \left[\frac{(n-n_f)\sigma\phi(z_c)}{n_f\Phi(z_c)}\right] = 0 \qquad (5-20)$$

and

$$s^2 + (\bar{y} - \mu)^2 - \sigma^2 \left[1 + \frac{(n-n_f)\sigma^2\phi(z_c)}{n_f\Phi(z_c)}\right] = 0 \qquad (5-21)$$

where

$$\bar{y} = \frac{1}{n_f} \sum_{m=c}^{n} y_m, \qquad (5-22)$$

$$s^2 = \frac{1}{n_f} \sum_{m=c}^{n} (y_m - \bar{y})^2, \qquad (5-23)$$

$$y_m = \ln x_m, \qquad (5-24)$$

$$z_c = \frac{y_c - \mu}{\sigma}, \qquad (5-25)$$

Φ denotes the standard normal distribution, and ϕ is the standard normal density function.

The likelihood equations were solved by using the least square procedure described in Section 5.2.1 to make initial estimates of the parameters and then improving these estimates using an iterative process (the Secant method) until an optimal solution was reached.

The method of maximum likelihood has several advantages over the method of least squares. In particular, maximum likelihood estimates (MLE's) of parameter values have minimum variance and they asymptotically approach a normal distribution about the "true" parameter value as the number of observations increases. It is also possible to construct confidence intervals for MLE's. Parameter estimates developed by the least squares method have none of these properties. Consequently, we decided to use maximum likelihood to fit Weibull and lognormal distributions to the CO data.

5.2.3 Determining Goodness-of-Fit

Following the recommendations of Stephens[8], and Green and Hegazy,[9] we investigated the use of the Cramér-von Mises (W^2) and Anderson-Darling (A^2) statistics to determine goodness of fit. These statistics are defined by the expressions

$$W^2 = 1/12n + \frac{1}{n} \sum_{m=1}^{n} [F(x_m)-(2m-1)/2n]^2 \qquad (5\text{-}26)$$

and

$$A^2 = -\frac{1}{n} \sum_{m=1}^{n} (2m-1) \left\{ \ln F(x_m) + \ln [1-F(x_{n+1-m})] \right\} - n. \qquad (5\text{-}27)$$

The null hypothesis (H_0) is that the sample comes from a population with distribution function F(x). H_0 is rejected at a given significance level if a goodness-of-fit statistic exceeds a critical value corresponding to that significance level.

In our analysis, we were interested in which of two distributions (Weibull and lognormal) better fits a specified portion of a sample data set. Unfortunately, the W^2 and A^2 statistics of a Weibull distribution fit to data cannot be directly compared with the W^2 and A^2 of a lognormal fit to the same data. The corresponding significance levels can be compared, but tables which list significance levels for censored data or for Weibull distributions are not currently available. Consequently, W^2 and A^2 can only be used to characterize the fit of a lognormal distribution to an uncensored data set.

We also investigated various statistics based on the absolute differences between the sample data set and the fitted distribution. The <u>mth</u> absolute difference is

$$\varepsilon_m = |x_m - \hat{x}_m| \qquad m = c, c+1, \ldots, n \qquad (5\text{-}28)$$

where x_m is the <u>mth</u> ranked value, $\hat{x}_m$ is the estimate of x_m determined by the parameters of the fitted distribution, and c is the rank of the smallest data value used in the fit. In the case of a fitted Weibull distribution with parameters $\hat{\delta}$ and $\hat{k}$,

$$\hat{x}_m = \hat{\delta} \left[\ln\left(\frac{n+1}{n+1-m}\right)\right]^{1/\hat{k}}. \qquad (5\text{-}29)$$

Similarly,

$$\hat{x}_m = \exp\left(\hat{\mu} + \hat{\sigma}\, z_{m,n}\right) \qquad (5\text{-}30)$$

for a fitted lognormal distribution with parameters $\hat{\mu}$ and $\hat{\sigma}$.

The statistics considered were:

$$\text{max diff} = \max \varepsilon_m, \qquad (5\text{-}31)$$

$$\text{mean diff} = \frac{1}{n-c+1} \sum_{m=c}^{n} \varepsilon_m, \qquad (5\text{-}32)$$

$$\text{mean diff**2} = \frac{1}{n-c+1} \sum_{m=c}^{n} \varepsilon_m^{\,2}, \qquad (5\text{-}33)$$

$$\text{max reldiff} = \max \left[2\varepsilon_m/(x_m + \hat{x}_m)\right], \text{ and} \qquad (5\text{-}34)$$

$$\text{mean reldiff} = \frac{1}{m-c+1} \sum_{m=c}^{n} \left[2\varepsilon_m/(x_m + \hat{x}_m)\right]. \qquad (5\text{-}35)$$

The closer any one of these statistics is to zero, the better the distribution fits the data. The bracketed term in Equations 5-34 and 5-35 is termed the relative difference; it is the absolute difference divided by the mean of the observed and estimated values.

We initially evaluated these statistics as alternatives to the R^2 statistic used for characterizing goodness-of-fit for the least squares method. Table 5-1 summarizes the results of fitting Weibull and lognormal distributions to 1978 CO data from St. Louis site 261040001G01. Fits were made to the upper 50%, 20%, 5%, and 1% of the data by the least squares method. In each of the four cases, all six statistics indicate the same distribution as the best fit. The Weibull distribution provides a better fit in the 5% case; the lognormal distribution is superior in the other three cases. According to most of the statistics, the two best fits are lognormal/50% and Weibull/5%. The estimated characteristic high, $\hat{b}_n$, is close to the recorded maximum value of 14.9 ppm for both fits. The two worst fits are Weibull/50% and Weibull/20%; in both instances, $\hat{b}_n$ is significantly different from the recorded maximum value.

We ultimately selected mean reldiff as our goodness-of-fit statistic. This statistic is particularly robust (i.e., not significantly affected by outliers) and weights each value used in the fit equally. Max diff, mean diff**2, and max reldiff can be significantly affected by outliers. Max diff, mean diff, and mean diff**2 weight higher values more heavily than lower values.

Weibull and lognormal distributions were first fit to the upper 50 percent of the daily maximum values in each augmented data set (Tables 5-2 and 5-3). Evaluation of the results indicated that the closer fitting distribution did not always yield a close fit to the five largest values. Repeating the analysis using the upper 20 percent of the daily maximum values in each augmented data set produced similar reldiff statistics and superior fits to the five largest values (Tables 5-4 and 5-5). Consequently, we decided to use the upper 20 percent of the augmented data set for all fits. The general procedure used for determining characteristic largest and fifth largest values is described below.

(1) Maximum daily 1-hour and 8-hour running average values in each augmented data set were ranked from lowest to highest.

TABLE 5-1. RESULTS OF FITTING WEIBULL AND LOGNORMAL DISTRIBUTIONS TO 1978 CO DATA (ppm) FROM ST. LOUIS, MO[a] BY LEAST SQUARES METHOD.

Statistic	Data fit by distribution							
	Upper 50%		Upper 20%		Upper 5%		Upper 1%	
	Weibull	lognormal	Weibull	lognormal	Weibull	lognormal	Weibull	lognormal
R^2	0.979	0.998	0.980	0.995	0.997	0.995	0.987	0.990
Max diff	4.608	1.574	2.818	0.955	1.026	1.415	1.090	0.946
Mean diff	0.138	0.043	0.150	0.074	0.063	0.084	0.109	0.096
Mean diff**2	0.091	0.009	0.055	0.010	0.009	0.020	0.034	0.026
Max reldiff	0.38	0.12	0.22	0.07	0.07	0.09	0.08	0.07
Mean reldiff	0.029	0.008	0.026	0.013	0.008	0.010	0.010	0.009
$\hat{\delta}$	3.115	-	2.692	-	2.089	-	2.160	-
$\hat{k}$	1.829	-	1.432	-	1.123	-	1.147	-
$\hat{\mu}$	-	0.982	-	0.939	-	0.875	-	1.055
$\hat{\sigma}$	-	0.460	-	0.486	-	0.520	-	0.453
$\hat{b}_n$	10.401	14.540	12.565	15.366	14.890	16.315	14.783	15.226

[a] Recorded maximum value: 14.9 ppm.

TABLE 5-2. RESULTS OF FITTING WEIBULL AND LOGNORMAL DISTRIBUTIONS BY MAXIMUM LIKELIHOOD PROCEDURE TO UPPER 50 PERCENT OF DAILY MAXIMUM 1-HOUR CO DATA

		Weibull			Lognormal		
			Characteristic values, ppm			Characteristic values, ppm	
Study area	NT	Mean reldiff	$\hat{b}_{1,365}$	$\hat{b}_{5,365}$	Mean reldiff	$\hat{b}_{1,365}$	$\hat{b}_{5,365}$
Chicago	CR	0.0347	10.0	8.4	0.0186	11.2	8.7
	CC	0.0241	23.5	20.0	0.0121	26.4	20.9
	CI	0.0197	15.7	13.5	0.0112	17.4	14.1
	SR	0.0331	11.6	9.2	0.0153	13.5	9.6
	SC	0.0406	11.7	9.5	0.0153	13.1	9.8
	SI	0.0179	10.0	8.3	0.0254	11.6	8.7
Los Angeles	CR	0.0425	14.6	12.1	0.0535	17.0	12.8
	CC	0.0321	29.0	23.1	0.0351	35.0	24.9
	CI	0.0315	26.3	21.2	0.0485	31.6	22.8
	SR	0.0282	20.0	16.3	0.0388	23.6	17.4
	SC	0.0305	21.8	17.2	0.0435	26.9	18.7
	SI	0.0315	26.3	21.2	0.0485	31.6	22.8
Philadelphia	CR	0.0897	16.6	13.4	0.0598	17.3	13.0
	CC	0.0897	16.6	13.4	0.0598	17.3	13.0
	CI	0.0932	8.9	7.4	0.0678	9.0	7.1
	SR	0.0850	11.5	8.6	0.0777	13.3	8.9
	SC	0.0850	11.5	8.6	0.0777	13.3	8.9
	SI	0.0505	12.2	10.2	0.0472	13.9	10.7
St. Louis	CR	0.0519	8.8	7.3	0.0338	10.0	7.6
	CC	0.0185	12.7	11.4	0.0118	13.4	11.5
	CI	0.0331	17.6	14.7	0.0147	19.9	15.2
	SR	0.1214	16.4	12.9	0.0758	17.4	12.6
	SC	0.0433	13.0	11.0	0.0214	14.3	11.3
	SI	0.0331	17.6	14.7	0.0147	19.9	15.2

TABLE 5-3. RESULTS OF FITTING WEIBULL AND LOGNORMAL DISTRIBUTIONS BY MAXIMUM LIKELIHOOD PROCEDURE TO UPPER 50 PERCENT OF DAILY MAXIMUM 8-HOUR RUNNING AVERAGE CO DATA

Study area	NT	Weibull			Lognormal		
		Mean reldiff	Characteristic values, ppm		Mean reldiff	Characteristic values, ppm	
			$\hat{b}_{1,365}$	$\hat{b}_{5,365}$		$\hat{b}_{1,365}$	$\hat{b}_{5,365}$
Chicago	CR	0.0383	6.2	5.4	0.0178	6.8	5.5
	CC	0.0110	14.6	12.7	0.0156	16.3	13.3
	CI	0.0211	10.4	9.1	0.0112	11.4	9.4
	SR	0.0588	7.8	6.2	0.0247	8.8	6.3
	SC	0.0702	8.0	6.4	0.0362	8.7	6.4
	SI	0.0609	6.8	5.5	0.0310	7.5	5.6
Los Angeles	CR	0.0208	9.2	7.8	0.0393	10.8	8.3
	CC	0.0290	21.5	16.7	0.0518	27.0	18.4
	CI	0.0251	19.5	15.8	0.0383	23.0	16.9
	SR	0.0278	15.1	12.3	0.0219	17.8	13.1
	SC	0.0231	16.3	12.9	0.0248	19.8	14.0
	SI	0.0251	19.5	15.8	0.0383	23.0	16.9
Philadelphia	CR	0.0954	11.4	9.3	0.0521	11.9	9.0
	CC	0.0954	11.4	9.3	0.0521	11.9	9.0
	CI	0.0684	6.4	5.3	0.0340	6.6	5.1
	SR	0.0509	6.8	5.2	0.0310	8.1	5.5
	SC	0.0509	6.8	5.2	0.0310	8.1	5.5
	SI	0.0359	9.1	7.6	0.0172	10.2	7.8
St. Louis	CR	0.0512	5.3	4.5	0.0271	5.8	4.6
	CC	0.0082	10.4	9.5	0.0138	11.2	9.8
	CI	0.0570	12.0	10.1	0.0314	13.1	10.2
	SR	0.0901	10.1	8.4	0.0519	10.5	8.2
	SC	0.0394	9.9	8.5	0.0218	10.9	8.8
	SI	0.0570	12.0	10.1	0.0314	13.1	10.2

TABLE 5-4. RESULTS OF FITTING WEIBULL AND LOGNORMAL DISTRIBUTIONS BY MAXIMUM LIKELIHOOD PROCEDURE TO UPPER 20 PERCENT OF DAILY MAXIMUM 1-HOUR CO DATA

Study area	NT	Weibull			Lognormal		
		Mean reldiff	Characteristic values, ppm		Mean reldiff	Characteristic values, ppm	
			$\hat{b}_{1,365}$	$\hat{b}_{5,365}$		$\hat{b}_{1,365}$	$\hat{b}_{5,365}$
Chicago	CR	0.0165	10.7	8.7	0.0196	11.4	8.8
	CC	0.0116	24.9	20.7	0.0164	26.4	20.9
	CI	0.0139	16.3	13.9	0.0126	17.2	13.9
	SR	0.0317	12.5	9.6	0.0210	13.3	9.6
	SC	0.0386	12.9	10.1	0.0250	13.6	10.0
	SI	0.0231	10.2	8.3	0.0177	10.8	8.4
Los Angeles	CR	0.0360	14.1	11.8	0.0432	14.9	12.0
	CC	0.0289	29.3	23.3	0.0288	31.4	23.5
	CI	0.0252	25.0	20.6	0.0230	26.2	20.6
	SR	0.0278	19.6	16.1	0.0300	20.8	16.2
	SC	0.0282	21.0	16.8	0.0316	22.3	16.9
	SI	0.0252	25.0	20.6	0.0230	26.2	20.6
Philadelphia	CR	0.0782	19.0	14.3	0.0607	19.2	13.8
	CC	0.0782	19.0	14.3	0.0607	19.2	13.8
	CI	0.0843	9.9	7.8	0.0672	9.7	7.4
	SR	0.0688	12.2	8.9	0.0718	13.2	8.9
	SC	0.0688	12.2	8.9	0.0718	13.2	8.9
	SI	0.0439	12.8	10.5	0.0390	13.4	10.5
St. Louis	CR	0.0234	9.8	7.8	0.0327	10.6	7.9
	CC	0.0249	13.2	11.6	0.0169	13.4	11.5
	CI	0.0353	19.0	15.3	0.0263	20.1	15.3
	SR	0.0802	21.1	14.6	0.0608	22.8	14.6
	SC	0.0225	14.5	11.7	0.0189	15.4	11.8
	SI	0.0353	19.0	15.3	0.0263	20.1	15.3

TABLE 5-5. RESULTS OF FITTING WEIBULL AND LOGNORMAL DISTRIBUTIONS BY MAXIMUM LIKELIHOOD PROCEDURE TO UPPER 20 PERCENT OF DAILY MAXIMUM 8-HOUR RUNNING AVERAGE CO DATA

		Weibull			Lognormal		
Study area	NT	Mean reldiff	Characteristic values, ppm $\hat{b}_{1,365}$	Characteristic values, ppm $\hat{b}_{5,365}$	Mean reldiff	Characteristic values, ppm $\hat{b}_{1,365}$	Characteristic values, ppm $\hat{b}_{5,365}$
Chicago	CR	0.0165	6.8	5.7	0.0111	7.2	5.7
	CC	0.0168	15.0	12.9	0.0117	15.6	12.9
	CI	0.0135	10.8	9.3	0.0178	11.4	9.4
	SR	0.0467	9.0	6.7	0.0345	9.5	6.6
	SC	0.0510	9.4	6.9	0.0407	10.0	6.9
	SI	0.0362	7.8	5.9	0.0280	8.3	6.0
Los Angeles	CR	0.0170	8.8	7.6	0.0222	9.3	7.6
	CC	0.0296	20.1	16.1	0.0399	21.6	16.3
	CI	0.0391	19.4	15.8	0.0275	20.3	15.7
	SR	0.0253	15.5	12.5	0.0330	16.6	12.7
	SC	0.0247	16.6	13.1	0.0364	18.0	13.3
	SI	0.0391	19.4	15.8	0.0275	20.3	15.7
Philadelphia	CR	0.0944	13.7	10.2	0.0757	14.3	9.9
	CC	0.0944	13.7	10.2	0.0757	14.3	9.9
	CI	0.0836	7.2	5.6	0.0623	7.2	5.3
	SR	0.0467	7.4	5.5	0.0437	7.9	5.5
	SC	0.0467	7.4	5.5	0.0437	7.9	5.5
	SI	0.0400	9.9	7.9	0.0301	10.4	7.9
St. Louis	CR	0.0406	5.9	4.8	0.0297	6.1	4.8
	CC	0.0106	10.5	9.5	0.0075	10.7	9.5
	CI	0.0327	13.8	10.9	0.0240	14.7	10.9
	SR	0.0821	12.0	9.2	0.0665	12.5	9.0
	SC	0.0224	10.8	9.0	0.0219	11.5	9.0
	SI	0.0327	13.8	10.9	0.0240	14.7	10.9

(2) The upper 20 percent of the daily maximum values were fit by Weibull and lognormal distributions using the maximum likelihood method described above.

(3) The reldiff statistics of the two fits were compared and the parameters of the better fitting distribution (i.e., the one with the smaller reldiff value) were used to determine the characteristic largest and fifth largest values.

Table 5-6 lists characteristic values developed using this procedure. Appendix B discusses the relationship between these values and the expected concentration (EC) values developed by EPA for the four study areas.

5.3 BACKGROUND CONCENTRATIONS

NEM requires a city-specific average background level in order to calculate the rollback factor applied to ambient pollutant concentrations in each study area. This background value should represent the average hourly concentration of a given pollutant being transported into the urban area, a value unaffected by any control strategies imposed upon the urban area. The monitoring sites selected to determine CO background should ideally be located sufficiently upwind from the urban area in a nonlow-lying location, within no less than five degrees of alignment with extended straight highway segments. Also, each site should be in an area with sufficient ventilation so that air is not likely to stagnate. Sites established to monitor regional concentrations are preferred to those established to monitor local concentrations. PEDCo identified monitoring sites which satisfied these criteria through an evaluation of (1) regional office and local agency recommendations, (2) local wind profiles, and (3) local land use. It should be noted that the CO background concentration being transported into an urbanized area may in fact be higher on occasion than some of the reported values within the area. This phenomenon is due to dispersion and dilution and is dependent upon the siting objectives and spatial distribution of CO monitors across the study area.

TABLE 5-6. AIR QUALITY INDICATORS FOR CO DATA

Study area	NT	Daily maximum 1-hour averages (ppm)		Daily maximum 8-hour running averages (ppm)	
		Char. largest	Char. 5th largest	Char. largest	Char. 5th largest
Chicago	CR	10.7	8.7	7.2	5.7
	CC	24.9	20.7	15.6	12.9
	CI	17.2	13.9	10.8	9.3
	SR	13.3	9.6	9.5	6.6
	SC	13.6	10.0	10.0	6.9
	SI	10.8	8.4	8.3	6.0
Los Angeles	CR	14.1	11.8	8.8	7.6
	CC	31.4	23.5	20.1	16.1
	CI	26.2	20.6	20.3	15.7
	SR	19.6	16.1	15.5	12.5
	SC	21.0	16.8	16.6	13.1
	SI	26.2	20.6	20.3	15.7
Philadelphia	CR	19.2	13.8	14.3	9.9
	CC	19.2	13.8	14.3	9.9
	CI	9.7	7.4	7.2	5.3
	SR	12.2	8.9	7.9	5.5
	SC	12.2	8.9	7.9	5.5
	SI	13.4	10.5	10.4	7.9
St. Louis	CR	9.8	7.8	6.1	4.8
	CC	13.4	11.5	10.7	9.5
	CI	20.1	15.3	14.7	10.9
	SR	22.8	14.6	12.5	9.0
	SC	15.4	11.8	11.5	9.0
	SI	20.1	15.3	14.7	10.9

Contact with the local EPA Regional Office resulted in identification of the Chicago Heights site (SAROAD code: 141240001G01) as an appropriate background site for the Chicago study area. The site is located at a high school sufficiently far from areas with high traffic concentrations.

A rural site near the urban area of St. Louis (SAROAD code: 264300006G01) was selected as the indicator for background CO levels for that study area. CO levels measured at this site are similar to those reported by a site predominantly upwind of the metropolitan area.

As a result of diurnal wind cycling caused by land-sea breezes, each station in the South Coast Air Basin is occasionally upwind and downwind of the center city core. Consequently, predominant wind direction was not considered a valid criterion for identifying a background site for the Los Angeles area. A rural-agricultural site fairly removed from urban influence (SAROAD code: 055160001I01) was selected.

The Philadelphia local agency recommended a site in Northwest Philadelphia (SAROAD code: 397140014H01) as the most appropriate indicator for average background concentrations.

The average hourly concentration was calculated for a recent year at each site to estimate annual average background for the corresponding study area. These values are listed in Table 5-7.

TABLE 5-7. ESTIMATED ANNUAL AVERAGE BACKGROUND LEVELS

Study area	Year	CO background concentration	
		mg/m^3	ppm[1]
Chicago	1979	1.5	1.31
Los Angeles	1977	2.0	1.75
Philadelphia	1978	1.1	0.96
St. Louis	1978	2.6	2.27

[1]Converted at STP using 1 ppm = 1145 $\mu g/m^3$.

5.4 REFERENCES

1. E. J. Gumbel, Statistics of Extremes, Columbia University Press, New York, 1958, p. 82.

2. T. Johnson, "A comparison of the two-parameter Weibull and lognormal distributions fitted to ambient ozone data," Proc. of Specialty Conference on Quality Assurance in Air Pollution Measurement, Air Pollution Control Association, 1979.

3. Op. cit., Gumbel, p. 34.

4. T. Johnson and R. Paul, The NAAQS Exposure Model (NEM) and Its Application to Nitrogen Dioxide, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, August 1981.

5. Ted Johnson and Roy Paul, The NAAQS Exposure Model (NEM) and Its Application to Particulate Matter, prepared by PEDCo Environmental, Inc., for Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N. C. 27711, August 1981.

6. A. C. Cohen, Jr., "Simplified estimators for the normal distribution when samples are singly censored or truncated," Technometrics, Vol. 1, No. 3, August 1959.

7. A. C. Cohen, Jr., "Maximum likelihood estimation in the Weibull distribution based on complete and on censored samples," Technometrics, Vol. 7, No. 4, November 1965.

8. M. A. Stephens, "EDF statistics for goodness of fit and some comparisons," Journal of the American Statistical Association, Vol. 69, No. 347, September 1974.

9. J. R. Green and Y. A. S. Hegazy, "Powerful modified-EDF goodness-of-fit-tests," Journal of the American Statistical Association, Vol. 71, No. 353, March 1976.

SECTION 6

SIMULATION OF CARBON MONOXIDE LEVELS IN THE MICROENVIRONMENT

A basic assumption of NEM is that each member of the study area population can be assigned during each hour of the day to one of five microenvironments: indoors (work or school), indoors (home or other), inside a transportation vehicle, outdoors near a roadway, or other outdoor locations. In applying NEM to CO, we initially assumed that air quality in each microenvironment ($x_{m,t}$) of a given neighborhood type could be estimated by the expression

$$x_{m,t} = a_{m,t} + b_m x_t' \qquad (6\text{-}1)$$

where $a_{m,t}$ is the pollutant concentration generated by a particular source in the microenvironment, x_t' is the monitor-derived air quality estimated for the neighborhood type, and b_m is a multiplicative factor. Consequently, estimates of $a_{m,t}$ and b_m (denoted $\hat{a}_{m,t}$ and $\hat{b}_m$) appropriate for CO were needed for each microenvironment. We assumed that $a_{m,t}$ will vary with microenvironment, CO source, and time of day; and that b_m will vary only with microenvironment. Equation 6-1 was later revised to account for observed lags between indoor and outdoor CO.

PEDCo reviewed 75 reports with key words or abstracts suggesting they contained information useful in estimating $a_{m,t}$ and b_m--jointly referred to as microenvironment factors (MF's). The review indicated that 26 of these reports contained data applicable to our analysis. These reports are categorized by microenvironment in Table 6-1. In the following discussion, results of these studies are used to estimate MF's and, in some cases, to develop alternatives to Equation 6-1.

TABLE 6-1. STUDIES CONSIDERED IN DEVELOPING CO MICROENVIRONMENT FACTORS

Microenvironment	Study
Indoors: work or school	Harke[1] Penkala and Oliveira[2] Moschandreas, et al.[3] Yocum, et al.[4] General Electric[5] Derham, et al.[6] Godin, et al.[7] Thompson, et al.[8]
Indoors: home or other	Yocum, et al.[4] Moschandreas, et al.[9] Cote, et al.[11] Bridge and Corn[12] Sterling and Kobayashi[13] Penkala and Oliveira[2] Repace and Lowrey[16] Spengler, et al.[17] Sterling and Sterling[18] Spengler, et al.[20] Godin, et al.[7] Elliot and Rowe[21] Thompson, et al.[8]
Transportation vehicle	Ott and Willits[22] Ziskind, et al.[23] Colwill and Hickman[24] Wallace[25] Cortese[26] Brice and Roesler[27] Petersen and Sabersky[28] Harke, et al.[1]
Roadside	Wilson and Schweiss[29] Wilson and Schweiss[30] Jabara, et al.[31]

6.1 WORK-SCHOOL MICROENVIRONMENT

Smoking has been identified by several studies as affecting CO levels in enclosed working areas. The contribution of smoking does not appear to be very significant, however. CO was monitored for 18 days by Harke[1] in two office buildings, one air-conditioned, the other not. Harke found that no significant increase in CO occurred after employees started to smoke. In another experiment, Harke found that CO did not exceed 10 ppm in an unventilated office room (30 m^3) when an occupant smoked at a rate of 2 cigarettes per hour. Background and outdoor CO levels are not mentioned in either study. Using test chamber data, Penkala and Oliveira[2] estimate that CO in a 400 ft^3 room occupied by one smoker consuming 1.25 cigarettes per hour will average 18.6 mg/m^3 per hour at 0 air changes per hour. At recommended ventilation rates (2.1 to 7.5 air changes per hour), CO should average 1.2 to 3.6 mg/m^3. Moschandreas, et al.,[3] studied CO in two office buildings in Boston. They hypothesized that indoor sources of CO are largely damped by the diffusive effect of the air handling systems. Elevated CO concentrations related to smoking were not observed. Yocum, et al.,[4] suggest that daytime indoor-outdoor ratios above 1.00 observed in two office buildings in Hartford, CT, are the result of smoking by occupants and visitors but do not provide useful data for estimating $a_{m,t}$.

The report by Penkala and Oliveira is the most useful of these four studies. The following excerpt describes their model and discusses their assumptions.

> Assume a smoker and a nonsmoker occupy the same office with a total volume of 400 ft^3. Ventilation rates in forced ventilations systems are usually between 7 and 25 ft^3 of fresh air per minute per room occupant. These ventilation rates are equivalent to 2.1-7.5 air changes per hour, and can be attained by normal leakage around windows and doors.
>
> A typical smoker consumes one pack of 20 cigarettes per day (16 waking hours). Each cigarette is smoked in

about 10 minutes, creating a high concentration of CO and SPM in the room, and then the ventilation system and other removal mechanisms (as measured in this study) lower those concentrations somewhat during a rest period (40 minutes) before the next cigarette is lit. The concentrations can be time-averaged by considering the room to be in a cycle consisting of a rapid concentration rise and a slower exponential decay. The decay rate depends upon the ventilation rate and the measured gas removal rate. Both can be represented by the equivalent air changes per hour, and converted to a time constant, τ, representing the minutes per equivalent air change.

Then $C_2 = C_1[-1/\tau]$

C_2 is concentration at time t

C_1 is an initial concentration

τ is the number of minutes per equivalent air change

t is the average time of one cigarette smoke plus following rest period

Note that $(C_1 - C_2)$ is the concentration added by smoking a cigarette.

A cycle ends with the room at concentration C_2 and is raised to a new concentration C_1 through smoking a cigarette. Combining the equations allows computing C_1 and C_2 for any equivalent air change rate. The average concentration $\overline{C}$, can be found by integration over a smoking period plus rest period.[2]

The 400 ft^3 room volume is based on a ASHRAE recommendation of 200 ft^3 per office building occupant. Repace and Lowrey[15] estimate that one-third of adults smoke. They also state that the recommended occupancy density for general office space is 10 persons per 1000 square feet. Assuming an 8-foot ceiling, we can estimate that there is one smoker per 2400 ft^3. Since Penkala and Oliveira assume there is one smoker per 400 ft^3, their estimates can be multiplied by 400/2400 to yield the CO levels expected in an office with one smoker per 2400 ft^3. Both sets of estimates are listed in Table 6-2.

TABLE 6-2. ESTIMATES OF CO CONCENTRATIONS IN AN OFFICE WITH SMOKERS

air changes/hour	mean CO (mg/m^3) 400 ft^3 per smoker	2400 ft^3 per smoker
0	18.6	3.10
1	6.2	1.03
2.1	3.6	0.60
7.5	1.2	0.20

Based on these results, reasonable bounds for $a_{m,t}$ during working hours would be 0.20 mg/m^3 (0.17 ppm) and 0.6 mg/m^3 (0.52 ppm); a reasonable best estimate for $a_{m,t}$ would be 0.35 mg/m^3 (0.30 ppm), the geometric mean of the bounds.

The relationship

$$\hat{b}_m = (x_{m,t} - \hat{a}_{m,t})/x_{a,t} \qquad (6\text{-}2)$$

where $x_{a,t}$ represents ambient CO levels reported by a fixed monitor, can be used to estimate b_m if good data for determining $x_{m,t}$, $x_{a,t}$ and $\hat{a}_{m,t}$ are available. Two studies--Moschandreas, et al.,[3] and General Electric[5]--provide $x_{m,t}$ and $x_{a,t}$ data. Yocum, et al.,[4] provide $x_{m,t}/x_{a,t}$ values. None of these studies list values directly relating to $a_{m,t}$. General Electric measured CO inside and outside of two buildings in New York. One building was an air rights building above the Trans Manhattan Expressway; the other was a more conventional high rise structure on one side of a street canyon in midtown Manhattan. The following excerpt is taken from their conclusions.

> Concentrations indoors at the building base vary with outdoor concentrations. Indoor concentrations lag changes in outdoor CO levels. It is suspected that this time delay is a variable that is a function of both wind conditions as seen at the building and the direction of change in outdoor concentrations.

Average concentrations inside and outside the buildings reduce exponentially with height above ground level. The rate of change with height is essentially constant outdoors for both heating and non-heating seasons. However, indoors the decay in average concentrations with height is greater during the non-heating season than during the heating season. This variation is the result of changes in the roof wind angle from the non-heating to the heating season.

Indoor concentrations normally are lower than outdoor concentrations at all heights above the roadway when outdoor concentrations are high. Conversely, indoor concentrations are higher than outdoor concentrations when outdoor concentrations are low.[5]

Because the air-rights building is atypical of urban work places, data for the street canyon building should receive primary attention. This building was not air-conditioned; ventilation, especially during the summer months, was achieved by opening windows. Table 6-3 lists average weekday CO concentrations at 9 feet above street level, third floor, fifth floor, 11th floor, and 19th floor.

TABLE 6-3. WEEKDAY CO MEASUREMENTS AT STREET CANYON SITE[5]

season	location	average CO (ppm) outside	average CO (ppm) inside
heating	9 feet	11.2	-
	3rd floor	9.9	9.5
	5th floor	7.7	7.8
	11th floor	6.6	6.9
	19th floor	5.4	6.8
non-heating	9 feet	11.2	-
	3rd floor	10.3	8.2
	5th floor	8.1	7.1
	11th floor	4.8	4.7
	19th floor	4.2	3.8

Inside CO concentrations are generally the same as outside CO concentrations at the same building height. CO decreases with height so that the ratio of inside CO to CO 9 feet above street-level varies from 0.85 at the third floor to 0.61 at the 19th floor during the heating season. In the non-heating season, the ratio ranges from 0.73 at the third floor to 0.34 at the 19th floor. The contribution of indoor sources to indoor CO is unknown but is probably small in proportion to the ambient CO levels.

Moschandreas, et al.,[3] measured CO inside and outside of two office buildings in Boston. Their results are listed in Table 6-4.

TABLE 6-4. CO CONCENTRATIONS (ppm) AT TWO OFFICE SITES RECORDED BY MOSCHANDREAS, ET AL.[3]

building	mean indoor	max indoor	mean outdoor/indoor
new	3.18	11.35	1.02
old	2.16	14.36	0.88

Note they reported outdoor/indoor ratios rather than indoor/outdoor ratios. Figure 3 in Moschandreas, et al., shows indoor CO tracking outdoor CO at the new building.

Table 6-5 lists indoor-outdoor ratios for two air-conditioned office buildings in Hartford, CT, determined by Yocum, et al.[4]

TABLE 6-5. INDOOR-OUTDOOR CO RATIOS DETERMINED FOR TWO OFFICE BUILDINGS BY YOCUM, ET AL.[4]

Building	Season	Daytime ratio	Nightime ratio
100 CP	Summer	1.31	1.00
	Fall	1.32	1.25
	Winter	1.13	1.21
250 CP	Summer	1.05	1.02
	Fall	0.96	1.04
	Winter	0.76	0.96

CP: Constitution Plaza

Inside CO was measured on the second floor at 100 CP and the third floor at 250 CP. The authors suggest that the start-up of building ventilation during rush hour is the primary cause of summer and fall daytime ratios greater than 1.00 at 100 CP. They further suggest smoking may have elevated ratios in the winter.

Derham, et al.,[6] monitored CO inside and outside a building in Los Angeles. They found that indoor levels of CO reflect directly the levels outdoors but with a phase lag that can be explained by means of a simple analytical model which accounts for ventilation rates but neglects any chemical reactions. They do not provide simultaneous indoor/outdoor readings and smoking is not discussed as a possible CO source.

Godin, et al., measured CO levels inside and outside a downtown office in Toronto with the windows closed. They summarize their findings as follows:

> At 150 College St., about a mile from the city center, outdoor values were 2.7 ± 1.8 ppm, while the corresponding values for the first and third floors were, respectively, 2.2 ± 1.3 ppm and 2.8 ± 1.5 ppm. Values in taller downtown buildings apparently depended on the level of air intake for the floor in question; at the Toronto Dominion Centre, the sidewalk concentration was 6.4 ppm, figures for the first and third floors were 4.6 and 4.0 ppm, respectively, but the 54th floor (with a much higher air intake) has a level of only 2.4 ppm.[7]

Godin, et al., conclude that indoor CO concentrations mirror outdoor concentrations, with a lag of one to two hours.

These studies suggest that a reasonable model for hourly average CO in the workplace is

$$x_m(t) = a_{m,t} + \frac{bm}{2} [x_c(t) + x_c(t-1)] \quad . \qquad (6\text{-}3)$$

The indoor CO at time t is equal to the indoor generated CO at time t plus b_m times the average of the outdoor CO at time t and at time t-1. This model assumes that building ventilation dampens variations in indoor CO and causes a slight lag between indoor and outdoor concentrations. A reasonable "best" estimate of b_m for buildings of 3 stories or less is 0.85, the ratio of third floor CO to outside ground floor CO in the General Electric study. A reasonable range for b_m is 0.60 (unairconditioned highrise) to 1.05 (ventilation system of 250 CP).

The microenvironment under consideration includes schools as well as work places. Only one study--Thompson, et al.[8]--measured indoor and outdoor CO levels at a school. Accuracy of their CO analyzer, ± 1.0 ppm, prevents a critical comparison of the low values which were measured. Since NEM treats indoors work and indoors school as the same microenvironment, we used the model already developed for indoors at work for the combined work-school microenvironment.

6.2 HOME-OTHER MICROENVIRONMENT

The value of b_m for homes can be estimated by comparing indoor and outdoor CO levels of homes with no indoor CO sources. Yocum, et al.,[4] measured indoor and outdoor CO at two residences in Hartford, CT. Neither home had a gas stove or habitual smoker. Average indoor/outdoor ratios are listed in Table 6-6.

TABLE 6-6. AVERAGE INDOOR/OUTDOOR CO RATIOS RECORDED BY YOCUM, ET AL.[4]

Residence	Season	Time of day	Ratio
Blinn St.	Summer	Day	1.02
		Night	1.07
	Fall	Day	1.03
		Night	1.08
	Winter	Day	1.07
		Night	1.08
Caroll St.	Summer	Day	1.04
		Night	1.02
	Fall	Day	1.03
		Night	1.08
	Winter	Day	0.96
		Night	1.08

Note that all ratios are close to unity. Yocum, et al., do not provide data useful in determining if indoor CO lags outdoor CO. Figure 4 from Moschandreas, et al.,[9] suggests a lag of one hour in a conventional residence in Baltimore. The following is an excerpt from their study.

> Indoor concentration peaks of CO tend to lag behind outdoor CO peaks. Due to the CO emissions, this behavior may be shortened in houses with indoor sources. The observed large fluctuations of the hourly CO concentrations display a local structure without a general pattern. However, examination of the CO data base from several weekdays leads to identification of a typical pattern with respect to 3-h averages. Typically, the time periods 0800-1000 and 1900-2100 exhibit the highest observed CO levels. These 3-h indoor peaks correspond to outdoor peaks caused by automobile traffic during the typical urban rush hours (0600-0800 and 1700-1900). The association of rush-hour traffic and typical indoor high level periods reflect the time lag monitored earlier. Figure 4 illustrates the indoor and outdoor variation of CO concentrations for a typical day, in a dwelling with indoor CO sources. The indoor peak at hours 1400 to 1600 is not a typically observed elevation of the indoor concentrations.[9]

These results suggest that Equation 6-3 is applicable to the home microenvironment as well as the work microenvironment. Based solely on the results of Yocum et al., a preliminary estimate of b_m would be 1.00. However, analysis by Feagans[10] indicates that 1.00 is probably too high. Feagans suggests 0.85 as a more appropriate best estimate of b_m and 0.70 to 1.10 as a reasonable range for $\hat{b}_m$. Appropriate values of $\hat{a}_{m,t}$ for different indoor sources are developed below.

CO sources in the home include smoking, gas stoves, gas furnaces, coal furnaces, and attached garages. CO from these sources combined with CO from outside have resulted in indoor levels exceeding the CO NAAQS.

Three studies--Cote, et al.,[11] Moschandreas, et al.,[9] and Bridge and Corn[12]--mention smoking as an indoor CO source in the home. Cote, et al., monitored indoor and outdoor CO in four homes in Hartford, CT. Unfortunately, the homes with smokers also had gas appliances so that the contribution of smoking to indoor CO cannot be determined separately. Moschandreas, et al., monitored CO levels in 15 homes. Persons living in these houses were polled as to smoking habits. Unfortunately, the report by Moschandreas, et al., provides only a few sample days of CO data and no smoking data. Bridge and Corn measured CO at two experimental "parties." Sterling and Kobayashi provide the following summary of this study.

> In one 5120 ft^3 room containing 50 people, 25 people consumed 50 cigarettes and seven cigars in 1½ hours. With a room air exchange rate of seven times per hour, CO averaged 7 ppm during the course of the party. During the second experiment in a 3750 ft^3 room containing 73 people, 36 smokers consumed 63 cigarettes and 10 cigars in 1½ hours and the average CO content was 9 ppm.[13]

These results suggest that 7 ppm is a worst case a_m value for smoking that would not be exceeded in the typical home except during occasional social functions.

The three studies described above are not useful in determining a typical $a_{m,t}$ for smoking. However, with suitable assumptions we can use the model developed by Penkala and Oliveira to estimate $a_{m,t}$ if we have good estimates of air exchange rates. Table 6-7 lists air exchange rates determined by Moschandreas, et al., for residences of various kinds.

TABLE 6-7. AIR EXCHANGE RATES DETERMINED BY MOSCHANDREAS, ET AL.[9]

location	residence type	exchanges/h
Washington	experimental	0.5 - 1.0
	conventional	0.2 - 0.8
Baltimore	experimental	0.5 - 1.2
	conventional	0.6 - 2.0
Denver	conventional	0.8 - 1.0
Chicago	conventional	0.6 - 1.0
	experimental	0.1 - 0.3
Pittsburg	mobile 1	0.4 - 1.0
	mobile 2	0.3 - 1.1
	low-rise 1	0.3 - 0.8
	low-rise 2	0.7 - 1.4
	low-rise 3	1.6 - 1.7
	high-rise 1	0.9 - 1.4
	high-rise 2	0.9 - 1.4
	high-rise 3	0.9 - 1.2

Air exchange rates range from 0.1 to 2.0. The mean of the midpoints of the 15 ranges listed in Table 6-7 is 0.9. The mean of the midpoints of the particular residence types are listed below.

residence type	exchanges/h
experimental	0.6
conventional	0.9
mobile	0.7
low-rise	1.1
high-rise	1.1

These results suggest a typical ventilation rate for a nonexperimental home of one exchange per hour. Penkala and Oliveira estimate that one smoker per 400 ft^3 in an enclosed space will add 6.2 mg/m^3 (5.4 ppm) to indoor CO if there is one air exchange per hour. According to U.S. Census data,[14] the average number of rooms in a living unit is 5.1. Assuming the typical five room house has a floor area of 1300 square feet and a ceiling 8 feet high, we can estimate that the typical living unit has a volume of 10,400 ft^3.

Housing data indicate that the average living unit has 2.1 adults.[15] Repace and Lowrey[16] estimate that one third of adults smoke. Since some teenagers smoke, the average living unit has at least 0.7 smokers per 10,400 ft^3 or 0.027 smokers per 400 ft^3. Smoker-generated CO would be at least (0.027)(5.4 ppm) = 0.15 ppm. A house with 10,400 ft^3 and two smokers would have a smoker-generated CO concentration of 0.42 ppm. These levels are negligible. In fact, the number of smokers must be increased to five per 10,400 ft^3 for the smoker-generated CO concentration to exceed 1.00 ppm.

In a sample of 69 homes, Spengler, et al.,[17] found 32 percent had one smoker and 13 percent had two or more smokers. From these data we can estimate the average house with smokers has about 1.3 smokers per 10,400 ft^3 or 0.05 smoker per 400 ft^3. Smoker-generated CO concentration in such a house would be about 0.3 ppm. Consequently, we used 0.3 ppm as our best estimate of $\hat{a}_{m,t}$ for smoking households from 7 a.m. to 9 a.m. and from 5 p.m. to 11 p.m. A smaller $\hat{a}_{m,t}$, 0.2 ppm, was considered appropriate from 9 a.m. to 5 p.m. We assumed $\hat{a}_{m,t}$ = 0 from 11 p.m. to 7 a.m.

In the CO exposure analysis we are particularly interested in kitchen and living room CO levels generated by gas stoves. Peak home CO exposure is expected to occur in the kitchen during and immediately after meal preparation. We assume that typical home CO exposure is better represented by CO levels in the living room. Data useful in estimating $a_{m,t}$ for gas stoves are provided by several studies performed by Research Corporation of New England. Yocum, et al.,[4] measured CO in two houses with gas stoves and gas furnaces. They found that "the heating system had no measurable effect on the indoor or outdoor CO levels; however, the gas fired stoves in each house had a significant influence on indoor CO levels." Figure 4 in Yocum, et al., shows kitchen levels in house G-1 exceeding outside levels by 3 ppm during meal preparation; living room levels exceeded outside levels by about 1.5 ppm. In house G-2, kitchen and family room levels during meal preparation exceeded outdoor levels by 3.0 to 4.5 ppm and 1.0 to 1.5 ppm, respectively. In a later study by Cote, et al.,[11] indoor and outdoor CO levels were measured at four homes in Hartford, CT. House 1 is a 2,000 ft^2 split-level with well-ventilated kitchen occupied by a married couple and two children. The wife smokes a pack a day. Yocum, et al., found that an attached garage made a significant contribution to indoor CO at this house. House 2 is a 1500 ft^2 two-story home with well-ventilated kitchen. A single adult lives there who seldom uses the stove. House 3 is a 1,000 ft^2 apartment with a small, unventilated kitchen. A nonsmoking couple and their 2 children live there. House 4 also has two adults and two children. It is a 1500 ft^2 ranch-style house with kitchen open to other areas of the house. Table 6-8 lists the seasonal means of daily average CO concentrations measured in various areas of the four houses. Average kitchen and living room CO values in house 1 exceed outside CO by 1010 $\mu g/m^3$ (0.88 ppm) and 590 $\mu g/m^3$ (0.52 ppm), respectively. The contribution of the attached garage is difficult to quantify. Data from house 2 are probably atypical because of the infrequent stove use. Houses 3 and 4 are not as well ventilated as house 1 and may be more appropriate for determining typical a_m values. Average kitchen CO exceeds average outside CO by 3040 $\mu g/m^3$ (2.66 ppm) and by 4120 $\mu g/m^3$ (3.60 ppm) in house 3 and by 6590 $\mu g/m^3$ (5.76 ppm) in house 4. Average living room CO exceeds average outside CO by 980 $\mu g/m^3$ (0.86 ppm) and 1690 $\mu g/m^3$ (1.48 ppm) in house 3 and by 5780 $\mu g/m^3$ (5.05 ppm) in house 4. Closer examination of 2-hour CO values included in the report reveals that the difference between inside (kitchen and living room) and outside CO levels is usually greatest from 1600 to 1800 (4 p.m. to 6 p.m.) and is usually smallest from 400 to 600 (4 a.m. to 6 a.m.). Typical mealtime CO levels seem to occur between the hours 1200 and 1400 (noon and 2 p.m.). Table 6-9 lists average differences between inside and outside CO levels during these 2-hour periods for houses 1, 3, and 4.

TABLE 6-8. INDOOR/OUTDOOR CO DATA RECORDED BY COTE, ET AL.[11]

House	Season	Mean daily average CO concentration, $\mu g/m^3$					Avg. stove usage (min)
		Stove	Kitchen	Living Room	Bedroom	Outside	
1	Spring-summer	-	4490	4070	4170	3480	198
	Fall-winter	4190	3520	3230	-	1670	106
	Fall-winter	4790	4210	-	3830	2310	?
2	Spring-summer	3000	-	3080	2900	2940	43
3	Spring-summer	4310	-	3210	2680	2230	37
	Fall-winter	7820	6420	5070	-	3380	66
	Fall-winter	7130	6620	-	5500	2500	115
4	Fall-winter	9070	9000	8190	-	2410	201

Sterling and Sterling[18] studied the rate of CO buildup and dissipation in kitchens, dining rooms, and living rooms of nine homes in Burnaby, British Columbia. Kitchen levels of CO in house 1 increased from 6 ppm to 36 ppm in 30 minutes, depending on the number of burners on.

Burners on	CO increase, ppm per minute
1	0.2
2	0.63
3	0.73
4	1.20

Rates of increase for the other eight homes varied from 0.7 to 3.3 (number of burners on was not specified). The average rate of CO increase for the nine homes was about 2 ppm. Operating a stove at this rate for 30 minutes would yield an hourly average of 30 ppm if CO decayed immediately. Sterling and Sterling found that CO decayed very slowly in the test homes and that it diffused rapidly throughout the houses.

An increase in kitchen CO of 30 ppm during meal preparation is probably atypical since it is based on the use of three to four burners continually for 30 minutes. None of the studies by Research Corporation of New England suggest meal-time CO levels

TABLE 6-9. AVERAGE DIFFERENCES BETWEEN KITCHEN, LIVING ROOM, AND OUTSIDE CO CONCENTRATIONS

House	Season	Time of day	Difference in CO concentration, $\mu g/m^3$	
			Kitchen-outside	Living room-outside
1	Spring/summer	4-6	624 (11)[a]	385 (11)
		12-14	1109 (12)	743 (12)
		16-18	1742 (12)	832 (13)
	Fall/winter	4-6	1941 (11)	1236 (5)
		12-14	2247 (12)	1154 (6)
		16-18	3380 (14)	2105 (8)
3	Spring/summer	4-6	-	844 (16)
		12-14	-	1062 (16)
		16-18	-	915 (16)
	Fall/winter	4-6	3284 (21)	1757 (9)
		12-14	3372 (23)	2189 (12)
		16-18	3622 (22)	1045 (10)
4	Fall/winter	4-6	2704 (9)	2256 (9)
		12-14	7123 (7)	6177 (7)
		16-18	12,424 (9)	11,328 (9)

[a]Numbers in parentheses indicate number of days with data.

this high. If the data provided by Yocum and Cote are assumed to be more typical, a reasonable model for kitchen $a_{m,t}$ in gas stove homes would be $\hat{a}_{m,t} = 4.0$ ppm during meal-time hours, and $\hat{a}_{m,t} = 2.5$ ppm other times. Reasonable living room estimates would be $\hat{a}_{m,t} = 2.0$ ppm during meal-time hours and $\hat{a}_{m,t} = 1.0$ ppm other times. Meal-time hours would be defined as the 2-hour periods 600 to 800, 1100 to 1300, and 1700 to 1900.

Although the home-other microenvironment includes nonresidential locations such as shopping malls, a single set of $a_{m,t}$ and b_m values is used for the combined microenvironment. Spengler[19] cites work by Chapin which suggests that 92 percent of people's time characterized as spent in home-other microenvironments is spent in the home. Consequently, using the indoor home values for the combined microenvironment should not significantly bias exposure estimates. We can assume that a cohort is at home whenever its activity pattern places them in the home-other microenvironment during a meal-time hour. Using the gas stove estimates for $a_{m,t}$ in these situations is reasonable. At other times of the day, home-other could indicate visits to a library, courthouse, shopping center, sports arena, or doctor's office. The principal CO source in these enclosed areas is probably cigarette smoke, although Spengler, et al.,[20] have found that ice cleaning machines at hockey rinks can produce one-hour CO levels exceeding 35 ppm. Godin, et al.,[7] reported that CO in a theater foyer where smoking was permitted exceeded CO in the auditorium by 2 ppm. Elliot and Rowe[20] found an average CO concentration of 25 ppm in a sports arena (not air conditioned) where smoking was permitted. CO levels of 9 ppm were recorded in two other arenas with posted "No Smoking" signs. Average CO during periods of nonactivity was 3 ppm in all three arenas. Thompson, et al.,[8] recorded average daytime CO levels in a hospital, YMCA pool, department store, and shopping mall (see Table 6-10).

TABLE 6-10. AVERAGE CO LEVELS IN VARIOUS STRUCTURES[8]

Kind of structure	CO, ppm	
	Out	In
community hospital	2.1	1.7
YMCA pool	0.5	1.0
department store	6.4	3.3
shopping mall	2.7	3.1

Thompson, et al., state that the inaccuracy of their analyzer, ± 1.0 ppm, prevented critical comparison of most of the rather low values obtained with the possible exception of the CO levels measured at the department store. Thompson, et al., suggest the following explanation for the relatively low indoor/outdoor ratio. Because auto exhaust emissions near the building would be minimal at night, a mass of air with a minimal level of CO would accumulate during the night. If daytime ventilation rates are low, the inside air would fail to come to equilibrium with outside CO.

None of these studies provide dependable data on typical CO levels in the "other" microenvironment. Consequently, we used the factors determined for "home" as the factors for the combined home-other microenvironment.

6.3 TRANSPORTATION VEHICLE MICROENVIRONMENT

The most commonly used transportation vehicle in the four study areas is the automobile. The principal internal sources of CO in automobiles are probably cigarette smoking and leaky exhausts. In the absence of these sources, available data indicate that average interior CO is equal to or less than average exterior CO, although exterior CO shows greater fluctuations. Ott and Willits[22] concluded that the average value of the interior CO concentration is approximately equal to the average value of the exterior CO concentration if the averaging time, T, was much greater than the time constant τ. They estimate τ = 4.5 minutes for a test vehicle moving on residential side streets at 20 mph with windows closed. Since τ decreases as speed increases or windows are open, we can assume $T >> \tau$ for most moving vehicles.

Ziskind, et al.,[23] studied buses, cabs, and police cars in Denver and Boston. They found that interior concentrations "rise and fall with exterior concentrations, yet are almost always lower." They hypothesize that the relatively small difference between interior and exterior levels provides too small a driving force for diffusion of CO into the vehicle. Furthermore, there is insufficient time for the two concentrations to equilibriate, since the external source is constantly changing as long as the vehicle keeps moving. Ziskind, et al., found that all vehicles in their study having interior concentrations in excess of exterior concentrations had both exhaust system leaks and pathways through to the passenger area. Since most of the vehicles which were monitored continuously in their study were selected because of high interior CO levels, their results cannot be applied to the general vehicle population.

Colwill and Hickman[24] measured interior and exterior CO levels of 11 new cars driven around a 35 km route in London. They report inside/outside ratios of 0.35 to 0.75 with a mean ratio of 0.55. Although they did not relate inside CO levels to stationary monitor readings, Colwill and Hickman state that occupants of vehicles moving in heavy traffic are exposed to CO levels higher than those recorded at curbside.

Several studies provide data which relate interior CO levels to fixed monitoring data directly. When Ziskind, et al., compared personal sampler data with fixed site data, they found that total exposures exceeded fixed site concentrations by an average of 13.9 ppm. An average ratio was not determined. Ziskind, et al., also list average interior CO as measured by continuous monitors in 9 vehicles (8 buses and 1 cab) and the average CO levels at corresponding fixed sites. Interior/fixed site ratios vary from 1.0 to above 7.0 with a median of 2.7. Ziskind, et al., are uncertain how much of the difference between interior and fixed site CO "was due to vehicle self-contamination and how much was due to the inherent lack of representativeness of the fixed site monitoring station readings." However, they make the following inconsistent statement in their section listing overall study conclusions:

> Typically the CO level measured inside or immediately outside the vehicle significantly exceeded the value recorded by the nearest fixed site monitoring station. Vehicle self-contamination does not appear to be the cause of this disparity. Rather, it is postulated that the proximity of the vehicle to the emission sources accounts for the difference between vehicle and fixed site monitor concentrations.[23]

Wallace[25] measured CO levels in cars and buses on 37 runs (27 by bus, 10 by car) around Washington, D.C. Mean bus CO was 11.7 ppm, excluding one outlier; mean car CO was 13.8 ppm. These values are three to four times higher than mean CO measured simutaneously at a stationary monitor at 427 New Jersey Avenue, N.W. However, Wallace found no significant relationship between ambient concentrations and interior vehicular concentrations. His results suggest that factors associated with particular vehicles--power source, design, and maintenance--may effect interior CO levels more than exterior CO levels.

A doctoral thesis by Cortese[26] provides more definitive results. In this study, population exposure to CO was measured by equipping volunteers living and working in the metropolitan Boston area with portable CO monitors. The monitored cohort consisted of 66 nonsmoking volunteers who carried a portable monitor for 3 to 5 days during commuting and working activities. Participants' commuting mode and route, residential and occupational location, exposure to cigarette smoke, and daily activities were documented. Volunteers were chosen from populations without significant occupational exposures to CO so that measured exposures resulted from ambient air contamination. Population exposure data, as measured by personal monitoring, were compared to CO concentrations measured at 6 fixed location monitoring stations operated by the Massachusetts Bureau of Air Quality Control. Two of the fixed location monitoring stations are located in downtown Boston. These urban stations approach Federal siting criteria for monitoring maximum 1-hour exposure to CO. The other four stations are located in suburban areas. These stations approach federal siting criteria for monitoring 8-hour average CO exposure but are not located close enough to heavily traveled roadways to monitor maximum 1-hour exposure. The following conclusions were drawn by Cortese.

- o Measurements at 6 fixed locations in metropolitan Boston underestimated mean 1-hour CO exposure during commuting by a factor of 1.8 to 2.0.
- o Measurements at the two urban monitoring stations, whose characteristics approach Federal criteria for monitoring maximum 1-hour exposures, underestimated the mean 1-hour CO exposure during commuting by a factor of 1.4. Because Boston pedestrians can be closer to automobile traffic than the two urban stations, measurements from the stations would also underestimate pedestrian exposure to CO.
- o Measurements at the four suburban monitoring stations underestimated mean 1-hour CO exposure during commuting by a factor of 2.1. This result is significant because a large portion of the average commuting trip in this study occurred in suburban areas.
- o Analysis of the highest 5-7% of the personal exposure and fixed location measurements, which are of greatest public health importance, indicated that fixed location measurements were better estimates of the higher commuting exposures than of the entire range of commuting exposures. Nevertheless, the mean 1-hour personal

exposure concentration was 1.6 times the mean concentration at all fixed stations and 1.3 times the mean concentration at urban stations.

- 10 to 15% of the difference between commuting exposures and the concentrations measured by fixed location monitors was attributed to an observed reduction in CO concentrations with increased sampling height between personal monitors at or near breathing zone (5.5 feet) and fixed location monitors at a height of 15 feet. The remainder of the difference was attributed to commuters being closer to CO emission sources than fixed location monitors.
- No consistent relationship was observed between personal exposure during commuting and fixed location measurements over the entire range of values encountered. This result made it impossible to develop a predictive relationship between personal exposure and fixed location measurements.
- Mode of travel (automobile, mass transit, split mode, i.e., part auto, part transit) and route of travel were the significant factors influencing personal exposure to CO during commuting. Cigarette smoke is the only other significant source of CO to which a commuter may be exposed.
- Total travel by automobile resulted in a mean CO exposure nearly twice that of rail mass transit commuting and approximately 1.6 times that of split mode commuting.
- Automobile commuting on 4-lane, heavily traveled arterial roads resulted in a mean CO exposure approximately 1.4 times the mean exposure during automobile commuting on other types of roads.
- Wind speed, wind direction, season, and automobile age did not influence commuter population exposure to CO.[26]

Pertinent data from the Cortese study are summarized in Table 6-11. These results suggest $1.4 \leq b_m \leq 2.1$ for unspecified Boston transportation vehicles during commuting hours. Ziskind's median ratio of 2.7 may be the result of using some vehicles known to have leaky exhausts and not using any rail transit.

TABLE 6-11. RATIOS OF MEAN PERSONAL CO EXPOSURES TO MEAN CO CONCENTRATIONS AT FIXED MONITORS[26]

mode of travel	fixed monitors	mean personal exposure / mean monitor CO
all vehicles	6 urban sites	1.8 to 2.0
all vehicles	2 urban sites meeting EPA criteria	1.4
all vehicles	4 suburban sites	2.1

An earlier study by Brice and Roesler[27] compared CO in motor vehicles moving in moderate to heavy traffic with concurrent concentrations measured at CAMP sites in six cities. Table 6-12 lists results of the study. The mean of the five ratios is 3.5; the median is 2.4. Ratios of vehicles moving in light to moderate traffic would probably be lower. Most CAMP sites were located in downtown areas; probes were usually positioned 15 feet off the street. Brice and Roesler state that the low ratio in Chicago corresponds to a high average concentration of CO at the CAMP site, which is attributed to the close proximity of that site to high-density traffic routes. In-vehicle data for Cincinnati is heavily weighted toward downtown street canyons. The average ratio for major arteries in Cincinnati is 4.8.

Petersen and Sabersky[28] measured CO inside a car driving a route in Los Angeles that included a business district, a residential district, a part of a generally uncrowded freeway, and a part of a congested freeway. During a 50-minute drive from 1:52 p.m. to 2:42 during the summer, average CO varied from 15 to 20 ppm. The maximum reading reported by APCD for the day was 8 ppm and may not have occurred concurrently. Consequently, the ratio of interior CO to fixed site CO is at least 1.9. These data are too limited to make any firm estimates of b_m for Los Angeles, however.

TABLE 6-12. RATIOS OF CO IN MOTOR VEHICLES CONCURRENT TO CO AT CAMP STATIONS[27]

City	Interior CO/ CAMP CO
Chicago	1.3
Cincinnati	6.8
Denver	2.4
St. Louis	2.1
Washington, D.C.	4.7

The above studies suggest that b_m for the transportation microenvironment should fall between 1.3 and 4.7. In the NEM analysis, we used 2.1, the upper range of Cortese's estimates, since it incorporates movement by motor vehicles and trains. We assumed reasonable bounds for b_m would be 1.4, the smallest ratio in Table 6-11, and 3.5, the mean of the ratios in Table 6-12.

There are few data on typical levels of CO from cigarette smoke in transportation vehicles. Ziskind, et al.,[23] report that chi-square analysis of taxicab data showed that CO levels were not significantly higher when drivers and/or passengers smoked. However, Harke, et al.,[1] measured CO levels of 30 ppm in an unventilated car with an outside windspeed of 50 km/hour when 9 cigarettes were smoked intermittently. CO levels averaged 5 to 6 ppm in a well-ventilated car with three people smoking continuously. Unfortunately, Harke does not give outside CO levels.

Information on the percentage of automobiles that contain smokers and the average cigarette-generated CO levels on buses and trains is unavailable. Consequently, we let $a_{m,t} = 0$ for smoking and assumed that our estimate $b_m = 2.1$ incorporates some of the smoker-generated CO to which commuters in Cortese's study were exposed. We made the same assumption concerning CO from leaky exhausts, since some of Cortese's subjects probably commuted in cars with leaking exhaust systems.

6.4 ROADSIDE MICROENVIRONMENT

Persons walking near roadways are usually closer to the automobiles that produce CO than the nearest fixed CO monitor. Consequently, fixed monitors usually underestimate roadside CO levels. If we assume $a_{m,t} = 0$, then b_m must exceed unity for reasonable estimates of roadside levels.

Two studies by Wilson and Schweiss[29,30] provide data useful in estimating b_m. In 1977, Wilson and Schweiss measured 8-hour (10 am - 6 pm) CO values at 33 sites in the central business district and 7 sites in nearby areas of Boise, Idaho, during November and December, the season when high CO levels frequently occur. These values were compared to 8-hour values recorded at the only continuous CO monitor in Boise. The fixed site was located in the center of the downtown business district. Most of the 40 study sites were near roadways (but not "hotspot" locations). Sample probes were mounted 3.5 meters above the ground. Roadside/fixed monitor ratios ranged from 0.3 to 1.5. The mean ratio was 0.92; the median ratio was 0.90. These results suggest that the fixed station may have been purposely sited in an area of Boise with particularly high CO levels.

Wilson and Schweiss conducted a similar study in Seattle, collecting data from 36 outside samplers and 4 fixed-site monitors. Table 6-13 summarizes their results. In this case, roadside/fixed monitor ratios range from 0.69 to 2.22 and average about 1.15.

Jabara, et al.,[31] measured the occupational exposure of Denver traffic officers to CO during eight hour work shifts and compared the results to ambient levels at fixed site monitors. The ratio of mean dosimeter reading to mean fixed site reading was 21.7/6.4 = 3.39. Since traffic officers work in areas of

TABLE 6-13. RATIOS OF MEAN CO CONCENTRATIONS AT EXPERIMENTAL SITES AND AT FIXED SITES[30]

Fixed site	Study site CO/fixed site CO	
	Nearest study site	2nd nearest study site
Pike St.	0.69	1.03
University St.	1.07	1.10
James St.	0.89	1.25
Fire station	2.22	1.26
Smejcor St.	0.98	1.09
mean	1.16	1.15

congested traffic, this ratio is probably high for the typical pedestrian. A more reasonable estimate of b_m would be 1.2, as suggested by the Seattle data of Wilson and Schweiss. We assumed that b_m should fall between 0.7 and 2.3, and used $\hat{b}_m = 1.2$ as our best estimate.

6.5 OTHER OUTDOOR LOCATIONS

We assumed that CO levels at outdoor locations away from roads could be approximately represented by x_t', the monitor-derived CO concentration, with no lag time or additive factor. Consequently, we used Equation 6-1 to estimate CO levels in this microenvironment. Following the recommendations of Feagans,[10] we assumed $a_{m,t} = 0$ and that a reasonable range for b_m would be 0.90 to 1.00. Feagans' best estimate for b_m was 0.95.

6.6 SUMMARY

Tables 6-14 and 6-15 summarize the estimates of $a_{m,t}$ and b_m for CO according to microenvironment, room, CO source, and time of day. Equation 6-3 was used to estimate CO levels in the work-school and home-other microenvironments. Equation 6-1 was used to estimate CO levels in the other three microenvironments.

TABLE 6-14. ESTIMATES OF ADDITIVE MICROENVIRONMENTAL FACTORS ($a_{m,t}$)

Microenvironment	Pollutant source	Room	Hours ending	Estimated value (ppm) low	best	high
Indoors: work or school	none	all	all	0	0	0
	smoking		all	0.2	0.3	0.5
Indoors: home or other	none	all	all	0	0	0
	smoking		8,9,18-23	0.1	0.3	0.5
			10-17	0.1	0.2	0.5
	gas stove	kitchen	7,8,12,13,18, 19	1.0	4.0	11.0
			1-6,9-11, 14-17,20-24	0.5	2.0	3.0
		living room	7,8,12,13,18, 19	0.7	2.5	10.0
			1-6,9-11, 14-17,20-24	0.3	1.0	2.0
Transportation vehicle	none	NA	all	0	0	0
Roadside	none	NA	all	0	0	0
Other outdoor locations	none	NA	all	0	0	0

TABLE 6-15. ESTIMATES OF MULTIPLICATIVE MICROENVIRONMENTAL FACTOR (b_m)

Microenvironment	Estimated value		
	low	best	high
Indoors: work or school	0.60	0.85	1.05
Indoors: home or other	0.70	0.85	1.10
Transportation vehicle	1.40	2.10	3.50
Roadside	0.70	1.20	2.30
Other outdoor locations	0.90	0.95	1.00

6.7 REFERENCES

1. H. P. Harke, "The problem of passive smoking. I. The influence of smoking on the CO concentration of office rooms," International Archives Arbeitsmedizin, Vol. 33, 1974, pp. 199-204.

2. S. J. Penkala and G. De Oliviera, "The simultaneous analysis of carbon monoxide and suspended particulate matter produced by cigarette smoking," Environmental Research, Vol. 9, 1975, pp. 99-114.

3. D. J. Moschandreas, J. Zabransky, Jr., and D. J. Pelton, "Indoor air quality characteristics of the office environment," Paper no. 80-61.2, presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 22-27, 1980.

4. J. Yocom, et al., A Study of Indoor-Outdoor Air Pollutant Relationships. Volume I and II, Publication number APTD-0592, Research Corporation of New England, Hartford, Connecticut, May 1970.

5. General Electric Company, Indoor-Outdoor Carbon Monoxide Pollution Study, Publication number EPA-R4-73-020, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 1972.

6. R. L. Derham, G. Peterson, R. H. Sabersky, and F. H. Shair, "On the relation between the indoor and outdoor concentrations of nitrogen oxides," Journal of the Air Pollution Control Association, Vol. 24, No. 2 (February 1974), pp. 158-161.

7. G. Godin, G. Wright, and R. J. Shepard, "Urban exposure to carbon monoxide," Archives of Environmental Health, Vol. 25, 1972, pp. 305-313.

8. C. R. Thompson, E. G. Hensel, and G. Kats, "Outdoor-indoor levels of six air pollutants," Journal of the Air Pollution Control Association, Vol. 23, No. 10 (October 1973). pp. 881-886.

9. D. J. Moschandreas, J. Stark, J. E. McFadden, and S. S. Morse, Indoor Air Pollution in the Residential Environment, Vol. I. Data Collection, Analysis, and Interpretation, Publication number EPA-600/7-78-229a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 1978.

10. Personal communication to Ted Johnson, PEDCo Environmental, from Thomas B. Feagans, Strategies and Air Standards Division, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711, December 1981.

11. W. A. Cote, W. A. Wade III, and J. E. Yocum, A Study of Indoor Air Quality, Publication No. EPA-650/4-74-042, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, September 1974.

12. D. P. Bridge and M. Corn, "Contributions to the assessment of non-smokers to air pollution from cigarette and cigar smoke in occupied spaces," Environmental Research, Vol. 5, 1972, pp. 215-220.

13. T. D. Sterling and D. M. Kobayashi, "Exposure to Pollutants in Enclosed Living Spaces," Environmental Research, Vol. 13, pp. 1-35.

14. U.S. Census data.

15. U.S. Housing data.

16. J. S. Repace and A. H. Lowrey, "Indoor air pollution, tobacco smoke, and public health," Science, Vol. 208, May 2, 1980.

17. John D. Spengler, et al., Summary of Air Pollution Measurements, Air Quality Assessment Group, Harvard School of Public Health, Boston, Massachusetts.

18. T. D. Sterling and E. Sterling, "Carbon monoxide levels in kitchens and homes with gas cookers," Journal of the Air Pollution Control Association, Vol. 29, No. 3 (March 1979), pp. 238-241.

19. J. D. Spengler, B. G. Ferris, Jr., and D. W. Dockery, "Sulfur dioxide and nitrogen dioxide levels inside and outside homes and implications on health effects research," Environmental Science and Technology, Vol. 13, No. 10 (October 1979), pp. 1276-1280.

20. J. D. Spengler, K. R. Stone, and F. W. Lilley, "High carbon monoxide levels measured in enclosed skating rinks," Journal of the Air Pollution Control Association, Vol. 28, No. 8 (August 1978), pp. 776-779.

21. L. P. Elliot and D. R. Rowe, "Air quality during public gatherings," Journal of the Air Pollution Control Association, Vol. 25, No. 6 (June 1975), pp. 635-636.

22. W. Ott and N. Willits, "Modeling the dynamic response of an automobile for air pollution exposure studies," Environmetrics 81, Summaries of Conference Presentations, 1981, pp. 104-105.

23. R. A. Ziskind, M. B. Rogozen, I. Rosner, and T. Carlin, Carbon Monoxide Intrusion in Sustained-Use Vehicles, Publication number SAI-068-80-535, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, November 15, 1979.

24. D. M. Colwill and A. J. Hickman, "Exposure of drivers to carbon monoxide," paper no. 79-59.3, 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

25. Lance Wallace, "Use of personal monitor to measure commuter exposure to carbon monoxide in vehicle passenger compartments," paper no. 79-59.2, 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

26. A. D. Cortese, Ability of Fixed Monitoring Stations to Represent Personal Carbon Monoxide Exposure, thesis submitted to the Faculty of the Harvard School of Public Health, Boston, Massachusetts, April 1976.

27. R. M. Brice and J. F. Roesler, "The exposure to carbon monoxide of occupants of vehicles moving in heavy traffic," Journal of the Air Pollution Control Association, Vol. 16, No. 11 (November 1966), pp. 597-600.

28. G. A. Peterson and R. H. Sabersky, "Measurements of pollutants inside an automobile," Journal of the Air Pollution Control Association, Vol. 25, No. 10 (October 1975), pp. 1028-1032.

29. C. B. Wilson and J. W. Schweiss, Part 1. Carbon Monoxide Study - Boise, Idaho, November 25 - December 22, 1977, Publication number EPA-910/9-78-055a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, September 1975.

30. C. B. Wilson and J. W. Schweiss, Carbon Monoxide Study, Seattle, Washington, October 6 - November 2, 1977, publication no. EPA 910/9-78-054, U.S. Environmental Protection Agency, Region X, Seattle, Washington, December 1978.

31. J. W. Jabara, T. J. Keefe, H. J. Beaulieu, and R. M. Buchon, "Carbon monoxide: dosimetry in occupational exposures in Denver, Colorado," Archives of Environmental Health, Vol. 35, No. 4 (July/August 1980).

SECTION 7

EXPOSURE ESTIMATES FOR ADULTS WITH CARDIOVASCULAR DISEASE IN FOUR URBAN AREAS

The computer output of NEM provides estimates of population exposure for various measures of exposure and averaging times. In the case of CO, NEM also estimates carboxyhemoglobin (COHb) levels, an important indicator of the physiological effects of CO on the exposed population. In this section the results of NEM analyses of CO exposure in the four study areas under various air quality assumptions are summarized. Extrapolations of these results to the nation are presented in Section 8.

The exposure estimates presented in this report are for adults with cardiovascular disease. Adults are defined to be those at least 18 years old. Adults with peripheral vascular disease are included in the subpopulation considered to have cardiovascular disease. Based on the currently available evidence, this subpopulation is judged to be the most sensitive group of persons with respect to CO-induced adverse health effects.

Estimates for three alternative standards are presented in Section 7.1. A comparison of male and female estimates is made in Section 7.2. The impact on the exposure estimates of omitting indoor sources from the analyses is discussed in Section 7.3. A brief discussion concerning the uncertainty about the accuracy of the estimates is provided in Section 7.4.

7.1 "BEST ESTIMATE" RESULTS

Tables 7-1 through 7-27 contain selected printouts of a NEM analysis of exposure of adults with cardiovascular disease to CO in the four study areas under various air quality assumptions. Each table is identified as to CO/COHb indicator and air quality standard being simulated. CO exposure estimates are provided for both 1- and 8-hour average CO concentrations. In each case, the

TABLE 7-1. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0			1,280	
30.0			1,280	709
25.0	1,250		3,800	6,910
20.0	25,300	5,790	22,900	13,500
15.0	223,000	145,000	141,000	39,200
12.0	828,000	1,310,000	389,000	216,000
9.0	3,080,000	4,930,000	1,140,000	878,000
7.0	10,600,000	22,100,000	4,120,000	2,880,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	25.6	21.6	36.0	32.0
ENCOUNTERS AT MAX.	523	5,790	1,270	707

TABLE 7-2. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0			1,270	
30.0			1,270	707
25.0	1,250		3,800	6,200
20.0	11,400	5,790	21,600	7,270
15.0	22,300	62,200	36,800	19,500
12.0	54,900	188,000	69,300	28,800
9.0	109,000	256,000	85,400	36,600
7.0	121,000	304,000	110,000	44,800
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	25.6	21.6	36.0	32.0
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-3. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 1-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0				
55.0 < C <= 60.0				
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0				
35.0 < C <= 40.0			1,280	
30.0 < C <= 35.0				709
25.0 < C <= 30.0	1,250		2,520	5,490
20.0 < C <= 25.0	10,100	5,790	17,900	1,070
15.0 < C <= 20.0	10,900	56,400	15,100	12,200
12.0 < C <= 15.0	32,600	126,000	32,500	9,240
9.0 < C <= 12.0	54,500	68,000	16,000	7,860
7.0 < C <= 9.0	11,700	47,600	25,100	8,160
0.0 < C <= 7.0	494	1,360	5,910	2,730
MAX. CONCENTRATION	25.6	21.6	36.0	32.0
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-4. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0				
15.0				
12.0	122		24,600	
9.0	107,000	153,000	322,000	66,500
7.0	2,070,000	2,170,000	1,030,000	429,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	12.0	10.6	14.0	11.5
ENCOUNTERS AT MAX.	54	4,460	29	11

TABLE 7-5. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0				
15.0				
12.0	120		11,900	
9.0	5,260	5,790	34,300	13,300
7.0	67,200	147,000	48,300	24,200
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	12.0	10.6	14.0	11.5
PEOPLE AT MAXIMUM	54	4,460	29	11

TABLE 7-6. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 8-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0				
55.0 < C <= 60.0				
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0				
35.0 < C <= 40.0				
30.0 < C <= 35.0				
25.0 < C <= 30.0				
20.0 < C <= 25.0				
15.0 < C <= 20.0				
12.0 < C <= 15.0	122		11,900	
9.0 < C <= 12.0	5,140	5,790	22,400	13,300
7.0 < C <= 9.0	61,900	141,000	14,000	10,900
0.0 < C <= 7.0	54,400	158,000	68,000	23,300
MAX. CONCENTRATION	12.0	10.6	14.0	11.5
PEOPLE AT MAXIMUM	54	4,460	29	11

TABLE 7-7. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30			71	
2.10			1,490	
2.00			5,150	21
1.50	78,300	115,000	236,000	53,400
1.00	8,600,000	19,800,000	2,540,000	2,000,000
0.00	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. COHB CONC.	1.92	1.87	2.31	2.02
ENCOUNTERS AT MAX.	54	701	15	5

TABLE 7-8. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30			35	
2.10			685	
2.00			2,730	21
1.50	9,680	5,790	34,300	15,700
1.00	99,000	253,000	86,200	34,000
0.00	122,000	305,000	116,000	47,500
MAX. COHB CONC.	1.92	1.87	2.31	2.02
PEOPLE AT MAXIMUM	54	701	15	5

TABLE 7-9. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED RANGES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL RANGE (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70 < C <= 10.00				
3.50 < C <= 3.70				
3.30 < C <= 3.50				
3.10 < C <= 3.30				
3.00 < C <= 3.10				
2.90 < C <= 3.00				
2.70 < C <= 2.90				
2.50 < C <= 2.70				
2.30 < C <= 2.50			36	
2.10 < C <= 2.30			651	
2.00 < C <= 2.10			2,040	21
1.50 < C <= 2.00	9,680	5,790	31,600	15,700
1.00 < C <= 1.50	89,300	248,000	51,900	18,300
0.00 < C <= 1.00	22,600	52,000	30,200	13,500
MAX. COHB CONC.	1.92	1.87	2.31	2.02
PEOPLE AT MAXIMUM	54	701	15	5

TABLE 7-10. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0			1,280	
40.0			1,280	709
35.0			1,280	6,910
30.0	11,200		3,800	6,910
25.0	50,500	17,400	33,100	24,000
20.0	223,000	145,000	141,000	36,100
15.0	987,000	1,310,000	397,000	248,000
12.0	2,640,000	4,840,000	1,070,000	628,000
9.0	9,320,000	13,900,000	3,700,000	2,000,000
7.0	25,700,000	55,800,000	8,990,000	5,430,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	34.6	29.1	49.0	44.0
ENCOUNTERS AT MAX.	523	5,790	1,270	707

TABLE 7-11. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0			1,270	
40.0			1,270	707
35.0			1,270	6,200
30.0	11,200		3,800	6,200
25.0	11,400	5,790	23,000	16,100
20.0	22,300	62,200	36,800	19,900
15.0	59,200	188,000	69,300	28,800
12.0	108,000	256,000	85,400	32,400
9.0	119,000	296,000	109,000	43,700
7.0	122,000	305,000	116,000	47,500
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	34.6	29.1	49.0	44.0
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-12. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 1-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0				
55.0 < C <= 60.0				
50.0 < C <= 55.0				
45.0 < C <= 50.0			1,280	
40.0 < C <= 45.0				709
35.0 < C <= 40.0				5,490
30.0 < C <= 35.0	11,200		2,520	
25.0 < C <= 30.0	182	5,790	19,200	9,900
20.0 < C <= 25.0	10,900	56,400	13,800	3,840
15.0 < C <= 20.0	36,900	126,000	32,500	8,830
12.0 < C <= 15.0	48,700	68,000	16,000	3,590
9.0 < C <= 12.0	11,000	39,500	23,200	11,300
7.0 < C <= 9.0	2,670	8,790	7,850	3,770
0.0 < C <= 7.0	68	714		38
MAX. CONCENTRATION	34.6	29.1	49.0	44.0
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-13. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0				
15.0	4,470		42,700	58
12.0	61,300	72,800	267,000	41,700
9.0	1,880,000	1,480,000	1,020,000	302,000
7.0	10,900,000	16,400,000	2,640,000	1,680,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	16.0	13.6	18.5	15.0
ENCOUNTERS AT MAX.	54	4,460	29	11

TABLE 7-14. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0				
15.0	1,900		17,300	27
12.0	5,260	5,790	33,500	8,800
9.0	67,300	95,600	44,300	23,700
7.0	93,300	252,000	104,000	29,000
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	16.0	13.6	18.5	15.0
PEOPLE AT MAXIMUM	54	4,460	29	11

TABLE 7-15. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 8-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0				
55.0 < C <= 60.0				
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0				
35.0 < C <= 40.0				
30.0 < C <= 35.0				
25.0 < C <= 30.0				
20.0 < C <= 25.0				
15.0 < C <= 20.0	1,910		17,300	29
12.0 < C <= 15.0	3,360	5,790	16,200	8,770
9.0 < C <= 12.0	62,000	89,800	10,800	14,900
7.0 < C <= 9.0	26,100	156,000	59,600	5,310
0.0 < C <= 7.0	28,300	53,500	12,400	18,500
MAX. CONCENTRATION	16.0	13.6	18.5	15.0
PEOPLE AT MAXIMUM	54	4,460	29	11

TABLE 7-16. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00			71	
2.90			329	
2.70			1,840	
2.50	134		8,850	187
2.30	2,460	5,190	42,300	3,980
2.10	16,600	18,200	114,000	16,400
2.00	39,700	35,900	163,000	31,500
1.50	1,240,000	927,000	861,000	243,000
1.00	32,700,000	75,600,000	7,140,000	5,490,000
0.00	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. COHB CONC.	2.52	2.38	3.03	2.59
ENCOUNTERS AT MAX.	24	1,560	15	5

TABLE 7-17. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00			35	
2.90			156	
2.70			776	
2.50	78		4,670	186
2.30	1,250	2,470	17,100	2,780
2.10	3,770	5,090	29,400	7,500
2.00	8,910	5,790	32,100	12,600
1.50	60,000	65,400	36,800	24,300
1.00	120,000	300,000	114,000	43,100
0.00	122,000	305,000	116,000	47,500
MAX. COHB CONC.	2.52	2.38	3.03	2.59
PEOPLE AT MAXIMUM	24	1,560	15	5

TABLE 7-18. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED RANGES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL RANGE (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70 < C <= 10.00				
3.50 < C <= 3.70				
3.30 < C <= 3.50				
3.10 < C <= 3.30				
3.00 < C <= 3.10			36	
2.90 < C <= 3.00			121	
2.70 < C <= 2.90			621	
2.50 < C <= 2.70	79		3,890	187
2.30 < C <= 2.50	1,180	2,470	12,400	2,590
2.10 < C <= 2.30	2,510	2,620	12,300	4,720
2.00 < C <= 2.10	5,150	700	2,730	5,130
1.50 < C <= 2.00	51,100	59,600	4,680	11,700
1.00 < C <= 1.50	59,600	234,000	77,500	18,800
0.00 < C <= 1.00	1,930	5,660	2,050	4,460
MAX. COHB CONC.	2.52	2.38	3.03	2.59
PEOPLE AT MAXIMUM	24	1,560	15	5

TABLE 7-19. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0			1,280	
55.0			1,280	709
50.0			1,280	709
45.0			1,280	1,420
40.0	11,200		3,800	6,910
35.0	21,900	5,790	22,900	13,500
30.0	63,300	23,200	55,000	24,100
25.0	212,000	145,000	141,000	32,800
20.0	667,000	849,000	277,000	181,000
15.0	2,520,000	3,440,000	1,050,000	513,000
12.0	6,190,000	8,030,000	2,090,000	1,130,000
9.0	19,800,000	31,500,000	5,750,000	3,270,000
7.0	49,800,000	109,000,000	13,300,000	9,220,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	43.6	37.0	61.5	56.1
ENCOUNTERS AT MAX.	523	5,790	1,270	707

TABLE 7-20. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 1-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0			1,270	
55.0			1,270	707
50.0			1,270	707
45.0			1,270	707
40.0	11,200		3,800	6,200
35.0	11,200	5,790	21,600	7,270
30.0	19,200	5,790	26,500	16,300
25.0	22,300	62,200	36,800	18,600
20.0	53,200	167,000	50,400	26,300
15.0	108,000	256,000	85,400	32,300
12.0	118,000	287,000	93,600	40,000
9.0	122,000	305,000	116,000	46,600
7.0	122,000	305,000	116,000	47,500
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	43.6	37.0	61.5	56.1
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-21. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 1-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0			1,280	
55.0 < C <= 60.0				709
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0	11,200		2,520	5,490
35.0 < C <= 40.0		5,790	17,900	1,070
30.0 < C <= 35.0	8,020		4,880	8,990
25.0 < C <= 30.0	3,050	56,400	10,300	2,380
20.0 < C <= 25.0	30,900	105,000	13,600	7,670
15.0 < C <= 20.0	54,600	89,100	35,000	6,010
12.0 < C <= 15.0	10,400	30,500	8,270	7,640
9.0 < C <= 12.0	3,350	17,700	22,700	6,660
7.0 < C <= 9.0	68	714		880
0.0 < C <= 7.0				
MAX. CONCENTRATION	43.6	37.0	61.5	56.1
PEOPLE AT MAXIMUM	523	5,790	1,270	707

TABLE 7-22. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0	122		12,600	
15.0	53,500	55,900	243,000	38,900
12.0	939,000	647,000	704,000	186,000
9.0	7,390,000	8,150,000	2,000,000	1,020,000
7.0	29,100,000	43,200,000	5,940,000	3,670,000
0.0	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. CONCENTRATION	20.0	17.0	23.0	18.5
ENCOUNTERS AT MAX.	120	4,460	29	11

TABLE 7-23. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 8-HOUR CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0	120		5,870	
15.0	5,260	5,790	33,500	8,300
12.0	54,500	12,200	36,600	23,100
9.0	84,200	234,000	81,800	28,800
7.0	118,000	298,000	116,000	36,100
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	20.0	17.0	23.0	18.5
PEOPLE AT MAXIMUM	120	4,460	29	11

TABLE 7-24. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM 8-HOUR CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION RANGE (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0 < C <= 100.0				
55.0 < C <= 60.0				
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0				
35.0 < C <= 40.0				
30.0 < C <= 35.0				
25.0 < C <= 30.0				
20.0 < C <= 25.0	122		5,870	
15.0 < C <= 20.0	5,140	5,790	27,600	8,300
12.0 < C <= 15.0	49,300	6,440	3,050	14,800
9.0 < C <= 12.0	29,700	222,000	45,300	5,730
7.0 < C <= 9.0	33,500	64,400	34,500	7,260
0.0 < C <= 7.0	3,890	7,130		11,500
MAX. CONCENTRATION	20.0	17.0	23.0	18.5
PEOPLE AT MAXIMUM	120	4,460	29	11

TABLE 7-25. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70			79	
3.50			833	
3.30			1,910	
3.10	67		6,040	120
3.00	240		11,900	332
2.90	1,130	1,560	24,300	1,640
2.70	6,330	8,650	65,400	7,900
2.50	21,300	21,400	131,000	20,400
2.30	71,200	61,000	216,000	46,300
2.10	180,000	193,000	371,000	84,800
2.00	361,000	319,000	493,000	108,000
1.50	5,120,000	6,320,000	1,850,000	789,000
1.00	67,400,000	166,000,000	15,100,000	12,500,000
0.00	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. COHB CONC.	3.10	2.89	3.75	3.16
ENCOUNTERS AT MAX.	54	701	15	5

TABLE 7-26. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70			43	
3.50			398	
3.30			822	
3.10	66		2,810	119
3.00	81		6,380	331
2.90	800	1,560	11,300	1,240
2.70	2,390	2,600	22,800	4,160
2.50	4,200	5,630	30,700	9,510
2.30	9,170	5,790	34,300	15,700
2.10	20,100	8,900	35,300	21,600
2.00	32,500	16,300	35,400	23,000
1.50	85,300	230,000	58,400	28,700
1.00	122,000	305,000	116,000	43,900
0.00	122,000	305,000	116,000	47,500
MAX. COHB CONC.	3.10	2.89	3.75	3.16
PEOPLE AT MAXIMUM	54	701	15	5

TABLE 7-27. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED RANGES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL RANGE (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70 < C <= 10.00			44	
3.50 < C <= 3.70			356	
3.30 < C <= 3.50			423	
3.10 < C <= 3.30	67		1,980	120
3.00 < C <= 3.10	15		3,570	212
2.90 < C <= 3.00	720	1,560	4,880	909
2.70 < C <= 2.90	1,590	1,040	11,500	2,920
2.50 < C <= 2.70	1,810	3,030	7,870	5,350
2.30 < C <= 2.50	4,970	161	3,640	6,160
2.10 < C <= 2.30	10,900	3,110	981	5,930
2.00 < C <= 2.10	12,400	7,360	132	1,400
1.50 < C <= 2.00	52,800	214,000	23,000	5,730
1.00 < C <= 1.50	36,200	74,700	57,900	15,200
0.00 < C <= 1.00	70	639		3,590
MAX. COHB CONC.	3.10	2.89	3.75	3.16
PEOPLE AT MAXIMUM	54	701	15	5

"best-estimate" microenvironment factors developed in Section 6 were used to simulate the contribution of gas stoves and smoking to total CO exposure.

7.1.1 Attainment of 9 ppm/1 ExEx Standard

NEM estimates in Tables 7-1 through 7-9 were developed by adjusting the air quality data for each study area using the roll-back formula described in Section 5.1 so that the most polluted neighborhood type just meets a "9 ppm/1 ExEx" standard, i.e., one specifying that the expected number of 8-hour CO values exceeding 9 ppm shall not be greater than one per year. Table 7-1 provides estimates of the number of occurrences for adults with cardiovascular disease of 1-hour exposures to CO concentrations exceeding selected values. (Exposures exactly equal to zero are counted as exceeding zero.) Thus, each column in Table 7-1 presents a cumulative frequency distribution in which the number of 1-hour exposures increases as CO concentration decreases; the distribution reaches a maximum at a CO concentration of zero. This maximum is the number of adults with cardiovascular disease used in the simulation times the number of possible occurrences in a year (8760). Although NEM yields individual frequency distributions for cohorts who are at low, medium, and high activity levels when a given CO concentration is encountered, only the total frequency distribution for all activity levels is presented in Table 7-1. According to these estimates, none of the four study areas would have more than 6,910 occurrences of 1-hour CO exposures above 25 ppm if a 9 ppm/1 ExEx standard were just attained.

Table 7-2 uses an alternative exposure indicator, adults with cardiovascular disease with 1-hour exposures. This is the number of adults with cardiovascular disease in the study area that experience one or more 1-hour exposures per year to CO concentrations that exceed a specified value. This exposure indicator is also expressed as a cumulative frequency distribution. The number of adults with cardiovascular disease exposed at zero concentration (or above) is the total population of the study area.

Table 7-3 provides estimates of the number of adults with cardiovascular disease who experience their peak exposure of the year within selected intervals of 1-hour CO concentrations. These estimates are not cumulative; each peak exposure falls within a single interval.

Tables 7-4 through 7-6 are similar to Tables 7-1 through 7-3 except that exposures are estimated in terms of 8-hour running average CO concentrations. Because the average of any 8 successive hourly concentrations is less than or equal to the highest value in the series, pollutant exposures usually occur at lower concentrations for 8-hour running averages than for 1-hour averages. For example, the maximum 8-hour running average concentration experienced in Chicago is 12.0 ppm (Table 7-4), while the maximum 1-hour concentration is 25.6 ppm (Table 7-1). Similarly, the number of 8-hour running average exposures above 9 ppm is 107,000 in Table 7-4, compared with 3,080,000 1-hour average exposures in Table 7-1.

Table 7-28 lists the general algorithm used by NEM to estimate COHb levels in the exposed populations. Specific values assigned to the variables in the algorithm are listed in Table 7-29. Full documentation of the rationale for the choice of these values is provided in an EPA memorandum.[1] A brief summary of the reasons for these choices is given below. Sensitivity analysis runs exploring the impact on exposure estimates of using alternative values for some of these variables are discussed in Section 7.4.

The value used for the Haldane constant is 218. This value comes from the study by Rodkey, et al.[2] Values ranging from 210 to 250 have been reported in the literature. The Clean Air Scientific Advisory Committee (CASAC) CO Subcommittee has recommended 218 as a best estimate.

The value used for the hemoglobin level in the blood is 13.8 g/100 ml for adult females and 15.7 g/100 ml for adult males. These are the mean values found in HEW's National Health and Nutrition Examination Survey (NHANES) for adult males and females aged 18-74 years.[3] Since the exposure estimates are for adults with

TABLE 7-28. ALGORITHM USED TO CALCULATE CARBOXYHEMOGLOBIN IN BLOOD OF COHORTS

1. Given the altitude, calculate average barometric pressure (P_B):

   $$P_B = 760*\exp(-0.0000386*Alt)$$

2. Calculate capillary oxygen pressure (P_cO_2):

   $$p_cO_2 = 0.209*(P_B-47) - 46.9$$

3. Calculate quantity B:

   $$B = (1/D_L) + (P_B -47)/\dot{V}_A$$

4. Let $(\%O_2Hb) = 100$

5. Calculate quantity A:

   $$A = p_cO_2/(M*(\%O_2Hb))$$

6. Calculate quantity F:

   $$F = \exp(-t*A*60*10^4/(1.38*Hb*Vb*B))$$

7. Calculate trial (%COHb) value:

   $$(\%COHb) = (\%COHb)_o*F + (B*V_{CO} + (P_B-47)*10^{-6}*(CO))*(1-F)/A$$

8. Calculate $(\%O_2Hb)$ value for next iteration:

   $$\text{New } (\%O_2Hb) = 100*(\%O_2Hb)/((\%O_2Hb) + (\%COHb))$$

9. Starting with the new value of $(\%O_2Hb)$ repeat Steps 5 through 8. Compare the (%COHb) calculated with that from the previous iteration. Repeat cycle until two successive COHb values agree within the desired accuracy.

TABLE 7-29. VALUES ASSIGNED TO VARIABLES IN ALGORITHM USED TO ESTIMATE CARBOXYHEMOGLOBIN

Variable	Category	Value
Haldane constant	All	218.0
Hemoglobin concentration	Females	13.8 grams/100 ml
	Males	15.7 grams/100 ml
Endogenous CO production rate	Females	0.0062 ml/min
	Males	0.0081 ml/min
Altitude	All	0
CO diffusion rate	Females	31 ml/min/torr
	Males	34 ml/min/torr
Blood volume	Females	4,800 ml
	Males	5,800 ml
Ventilation rate	Low exercise	8,000 ml/min
	Medium exercise	20,000 ml/min
	High exercise	35,000 ml/min

cardiovascular disease, values were not developed for the two age/ occupation groups consisting of children.

The value used for the endogenous CO production rate (V_{CO}) is 0.0081 ml/min for adult males and 0.0062 ml/min for adult females. These values are simple weighted (by the number of subjects) averages of the results of six studies for males[4-9] and four studies for females[5-8] reported in the literature.

The value used for the CO diffusion rate in the lung is 34 ml (min·mm Hg) for adult males and 31 ml (min·mm Hg) for adult females. These values are taken from Joumard, et al.[10]

The values used for blood volume are 5,800 ml for adult males and 4,800 ml for adult females. Each of these values was calculated by multiplying two other values: the 74 ml/kg body weight for average males and 73 ml/kg body weight for average females reported by Sjostrand[11] multiplied by 78 kg average weight for adult males and 65 kg average weight for females, respectively. The latter two values are based on data provided by a publication of the U.S. National Center for Health Statistics.[12]

Ventilation rates used for both adult males and adult females are 8 liters/min for a low exercise level, 20 liters/min for a medium exercise level, and 35 liters/min for a high exercise level. The basis for these values is a study by Niinimaa, et al.[13] The low exercise level value represents sleeping and sitting, the medium exercise level value represents walking and other light forms of exercise, and the high exercise level value represents forms of exercise more strenuous than walking. Obviously these three categories represent a partitioning of a continuum of exercise levels (see Table A-1 of the Office of Air Quality Planning and Standards Staff Paper on Sulfur Oxides[14]).

In essence, the algorithm presented in Table 7-28 estimates the COHb levels of an individual at the end of every hour of the year. Although COHb levels are, strictly speaking, the result of CO exposure, they can be described using concepts similar to those used for CO exposure. For example, Table 7-7 lists the number of occurrences of COHb levels that exceed selected values. Table 7-8 lists the number of adults with cardiovascular disease that experience COHb levels which exceed selected values. Table 7-9 lists the number of adults with cardiovascular disease who experience their highest COHb level within selected ranges of COHb values. As would be expected, Tables 7-7 and 7-8 present cumulative distributions, while Table 7-9 lists results in discrete intervals.

The relative frequencies of high COHb levels among the four study areas can be compared by normalization, i.e., by converting the estimates of adults with cardiovascular disease experiencing different COHb levels to the corresponding percentage of total adults with cardiovascular disease in the study area population. Table 7-30 shows that none of the study areas have adults with cardiovascular disease with COHb levels exceeding 3.0 percent under the 9 ppm/1 ExEx standard. Approximately 2.4 percent of the Philadelphia adults with cardiovascular disease experience COHb levels exceeding 2.00 percent. Maximum COHb levels are 1.92 percent for Chicago, 1.87 percent for Los Angeles, 2.31 percent for Philadelphia, and 2.02 percent for St. Louis.

As previously noted, the estimates presented in the tables are for cardiovascular adults. The values used for the percentage of adult females with cardiovascular disease was 4.2% and for adult males 5.8%. These values are based on U.S. Department of Health, Education, and Welfare data.[15] In this application of NEM, estimates for the whole population were ratioed down to the estimates for cardiovascular adults by using these two values in conjunction with estimates of the percentages of adults who are male and female in each of the four cities (52% female and 48% male). The fact that married women are all female was accounted for in the calculation, but the fact that the male/female percentage breakdown varies in general from one age/occupation group to another was not.

The estimates use 1970 census data for the four cities but are projected to 1987 by using the multiplicative factor 1.195.

TABLE 7-30. PERCENTAGE OF ADULTS WITH CARDIOVASCULAR DISEASE EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHb level exceeded (percent)	Chicago	Los Angeles	Philadelphia	St. Louis
3.00				
2.90				
2.80				
2.70				
2.60				
2.50				
2.40				
2.30			0.03	
2.10			0.59	
2.00			2.35	0.04
1.50	7.93	1.90	29.57	33.05
1.00	81.15	82.95	74.31	71.58
0.00	100.00	100.00	100.00	100.00
Max. COHb conc.	1.92	1.87	2.31	2.02
Percent at maximum	0.04	0.23	0.01	0.01

The 1.195 multiplicative factor is the product of 1.115, the ratio of 1980 total U.S. population to 1970 total U.S. population, and 1.072, a growth factor corresponding to a projected 1 percent growth each year from 1980 to 1987. That is, 1.072 is approximately equal to $(1.01)^7$ and 1.195 is approximately equal to 1.114 x 1.072.

7.1.2 Attainment of 12 ppm/l ExEx Standard

Tables 7-10 through 7-18 provide NEM estimates based on the assumption that the most polluted neighborhood type in each study area just meets a standard specifying that the expected number of 8-hour CO values exceeding 12 ppm shall not exceed one per year. This "12 ppm/l ExEx" standard is less stringent than the 9 ppm/l ExEx standard. Tables 7-10 through 7-12 provide 1-hour exposure estimates; Tables 7-13 through 7-15 provide 8-hour exposure estimates; and Tables 7-16 through 7-18 provide COHb estimates. Table 7-31 provides normalized COHb estimates for the 12 ppm/l ExEx standard. Note that all study areas have maximum COHb levels which equal or exceed 2.38 percent under this assumption; the maximum COHb level in Philadelphia is 3.03 percent.

7.1.3 Attainment of 15 ppm/l ExEx Standard

NEM estimates in Tables 7-19 through 7-27 are based on the assumption that the most polluted neighborhood type will just meet a standard specifying that the expected number of 8-hour CO values exceeding 15 ppm shall not exceed one per year. The "15 ppm/l ExEx" standard is the least stringent of the three standards analyzed. Normalized COHb estimates for this standard are listed in Table 7-32. As expected, COHb levels are higher under the 15 ppm/l ExEx standard than under the 12 ppm/l ExEx and 9 ppm/l ExEx standards. All four study areas have COHb levels which equal or exceed 2.89 percent. Philadelphia has a maximum COHb level of 3.75 percent, compared with a maximum of 2.31 percent estimated for the 9 ppm/l ExEx case.

TABLE 7-31. PERCENTAGE OF ADULTS WITH CARDIOVASCULAR DISEASE EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 12 PPM/1 EXEX STANDARD IS ATTAINED

COHb level exceeded (percent)	Chicago	Los Angeles	Philadelphia	St. Louis
3.00			0.03	
2.90			0.13	
2.70			0.67	
2.50	0.06		4.03	0.39
2.30	1.02	0.81	14.74	5.85
2.10	3.09	1.67	25.34	15.79
2.00	7.30	1.90	27.67	26.53
1.50	49.18	21.44	31.72	51.16
1.00	98.36	98.36	98.28	90.74
0.00	100.00	100.00	100.00	100.00
Max. COHb conc.	2.52	2.38	3.03	2.59
Percent at maximum	0.02	0.51	0.01	0.01

TABLE 7-32. PERCENTAGE OF ADULTS WITH CARDIOVASCULAR DISEASE EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 15 PPM/1 EXEX STANDARD IS ATTAINED

COHb level exceeded (percent)	Chicago	Los Angeles	Philadelphia	St. Louis
3.70			0.04	
3.50			0.34	
3.30			0.71	
3.10	0.05		2.42	0.25
3.00	0.07		5.50	0.70
2.90	0.66	0.51	9.74	2.61
2.70	1.96	0.85	19.66	8.76
2.50	3.44	1.85	26.47	20.02
2.30	7.52	1.90	29.57	33.05
2.10	16.48	2.92	30.43	45.47
2.00	26.64	5.34	30.52	48.42
1.50	69.92	75.41	50.34	60.42
1.00	100.00	100.00	100.00	92.42
0.00	100.00	100.00	100.00	100.00
Max. COHb conc.	3.10	2.89	3.75	3.16
Percent at maximum	0.04	0.23	0.01	0.01

7.2 MALE/FEMALE COMPARISONS

In this section, a brief comparison is made between selected COHb estimates for males and for females. The estimates for females are in Table 7-33, and the estimates for males are in Table 7-34. The estimates are based on the assumption that a 9 ppm/1 ExEx 8-hour average standard is met in each of the four study areas.

The difference in the number of males and females estimated to exceed selected COHb levels under the same standard is a result of three factors. First, different values were assigned to various physiological variables for males and females (see Section 7.1.1). The differences in these values result in higher estimated COHb levels in the blood of females, assuming the same pattern of CO exposure. Second, a slightly greater percentage of the adult population is female. Third, the exposure estimates are for males and females with cardiovascular disease and reflect the fact that only 4.2 percent of adult females are estimated to have cardiovascular disease, whereas 5.8 percent of adult males are estimated to have cardiovascular disease.

Combining the last two factors, there are approximately 27 percent more adult males with cardiovascular disease in each study area than adult females. The fact that there is a slightly greater percentage of females in the population is outweighed by the more significant difference between the percentage of adult males and females who have cardiovascular disease.

Comparing the estimates in Table 7-33 with the estimates in Table 7-34, it is apparent that the male/female differences in physiology have a significant impact on the COHb levels which result from a given pattern of CO exposure. More cardiovascular females reach the highest COHb levels despite there being more cardiovascular males. The difference in physiology gives this result within the model since all cohorts include some females. The greater number of cardiovascular males begins to dominate as comparisons between the two move down in COHb level.

TABLE 7-33. ESTIMATES OF ADULT FEMALES WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30			66	
2.10			1,040	
2.00			4,480	39
1.50	11,800	4,910	29,700	15,300
1.00	85,500	219,000	74,500	29,300
0.00	103,000	259,000	98,800	40,400
MAX. COHB CONC.	1.93	1.88	2.32	2.03
PEOPLE AT MAXIMUM	103	1,330	30	11

TABLE 7-34. ESTIMATES OF ADULT MALES WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30				
2.10			289	
2.00			746	
1.50	7,250	6,770	39,500	16,100
1.00	114,000	292,000	99,400	39,500
0.00	142,000	357,000	136,000	55,800
MAX. COHB CONC.	1.83	1.75	2.19	1.86
PEOPLE AT MAXIMUM	142	4,070	41	15

7.3 THE SIGNIFICANCE OF INDOOR SOURCES

The exposure estimates discussed in Section 7.1 assume gas stoves and smoking contribute to total CO exposure. To evaluate the significance of these CO sources, we can repeat the analysis with the all additive microenvironment factors set equal to zero (i.e., $a_{m,t} = 0$ for all microenvironments). Tables 7-35 and 7-36 are sample output of such an analysis. They provide estimates of the number of people exposed to 1-hour and 8-hour CO concentrations under the 9 ppm/1 ExEx standard in the absence of indoor sources. Comparison with Tables 7-2 and 7-5 reveals that indoor sources have a minor effect on 1-hour and 8-hour exposures. Maximum 1-hour CO exposures are less than 1.0 percent higher when indoor sources are included. Maximum 8-hour CO exposures are 1.0 to 7.7 percent higher when indoor sources are included.

Tables 7-37 through 7-39 provide three indicators of COHb levels in exposed populations in the absence of indoor sources. These tables can be compared to Tables 7-7 through 7-9 to determine the significance of indoor sources on COHb levels. For the four study areas analyzed, maximum COHb levels are only 1.0 percent (St. Louis) to 4.1 percent (Philadelphia) higher when indoor sources are included.

These results are not unexpected. In the NEM model, peak CO levels are generally experienced in transportation vehicles or along roadways--microenvironments with "best-estimate" multiplicative factors of 2.10 and 1.20, respectively, and additive factors equal to zero. As discussed in section 6.3, the additive factor corresponding to smoking in transportation vehicles was set equal to zero because the multiplicative factor was assumed to already incorporate this CO source.

7.4 UNCERTAINTY IN NEM EXPOSURE ESTIMATES

Any method used to estimate exposure of large, diverse groups of people must deal with a myriad of complexities. The exposure model can only represent major structural features. Because the

TABLE 7-35. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 1-HOUR CO EXPOSURES ABOVE SELECTED VALUES UNDER 9 PPM/1 EXEX STANDARD WITH INDOOR SOURCES OMITTED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0			1,270	
30.0			1,270	708
25.0	1,250		3,800	6,200
20.0	11,400	5,790	21,600	7,280
15.0	22,300	62,200	36,800	19,500
12.0	53,200	188,000	69,300	28,800
9.0	108,000	256,000	85,400	36,600
7.0	119,000	299,000	99,000	43,400
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	25.7	21.7	36.0	32.0
PEOPLE AT MAXIMUM	523	5,790	1,270	708

TABLE 7-36. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO HAVE 8-HOUR CO EXPOSURES ABOVE SELECTED VALUES UNDER 9 PPM/1 EXEX STANDARD WITH INDOOR SOURCES OMITTED

CONCENTRATION EXCEEDED (PPM)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0				
15.0				
12.0			2,160	
9.0	5,260	5,790	32,300	7,220
7.0	54,200	13,400	36,300	22,500
0.0	122,000	305,000	116,000	47,500
MAX. CONCENTRATION	11.6	10.5	13.0	10.7
PEOPLE AT MAXIMUM	147	5,790	100	45

TABLE 7-37. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE OF COHb LEVELS EXCEEDING SELECTED VALUES UNDER 9 PPM/1 EXEX STANDARD WITH INDOOR SOURCES OMITTED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30				
2.10			367	
2.00			1,870	21
1.50	45,200	60,100	140,000	22,100
1.00	3,720,000	3,540,000	1,340,000	775,000
0.00	1,070,000,000	2,670,000,000	1,020,000,000	416,000,000
MAX. COHB CONC.	1.89	1.82	2.22	2.00
ENCOUNTERS AT MAX.	66	2,030	53	21

TABLE 7-38. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHO EXPERIENCE COHb LEVELS EXCEEDING SELECTED VALUES UNDER 9 PPM/1 EXEX STANDARD WITH INDOOR SOURCES OMITTED

COHB LEVEL EXCEEDED (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30				
2.10			156	
2.00			864	21
1.50	9,170	5,790	33,000	9,110
1.00	75,800	175,000	47,100	26,000
0.00	122,000	305,000	116,000	47,500
MAX. COHB CONC.	1.89	1.82	2.22	2.00
PEOPLE AT MAXIMUM	66	2,030	53	21

TABLE 7-39. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED RANGES UNDER 9 PPM/1 EXEX STANDARD WITH INDOOR SOURCES OMITTED

COHB LEVEL RANGE (PERCENT)	CHICAGO	LOS ANGELES	PHILADELPHIA	ST LOUIS
3.70 < C <= 10.00				
3.50 < C <= 3.70				
3.30 < C <= 3.50				
3.10 < C <= 3.30				
3.00 < C <= 3.10				
2.90 < C <= 3.00				
2.70 < C <= 2.90				
2.50 < C <= 2.70				
2.30 < C <= 2.50				
2.10 < C <= 2.30			157	
2.00 < C <= 2.10			709	21
1.50 < C <= 2.00	9,170	5,790	32,200	9,090
1.00 < C <= 1.50	66,600	169,000	14,100	16,900
0.00 < C <= 1.00	45,800	130,000	69,300	21,500
MAX. COHB CONC.	1.89	1.82	2.22	2.00
PEOPLE AT MAXIMUM	66	2,030	53	21

relevant data bases often are incomplete and/or inaccurate, professional judgment plays a significant role in selecting monitors to represent neighborhood types, in validating air quality data, in estimating cohort populations, and in determining cohort movements.

Ideally, the uncertainty in each significant factor affecting exposure would be addressed formally within the exposure model so that a formal representation of the uncertainty in each exposure estimate would be part of the output of the model. Formal techniques for characterizing the uncertainty in estimates generated by applying the NEM model are under development. Due to limitations of time and resources, these techniques were not available for this application. Instead, several sources of uncertainty were investigated via a limited sensitivity analysis. Several values were used for some of the input quantities to see how sensitive selected exposure estimates are to this variation. The inputs chosen are the microenvironment factors, the largest source of uncertainty in estimating exposure, and the physiological variables used in determining blood COHb levels from exposure patterns.

Lower, best, and upper estimates of microenvironmental factors are presented in Section 6.0. These differing estimates of microenvironmental factors were used to calculate exposure estimates for adults with cardiovascular disease in Chicago, assuming a 9 ppm/1 ExEx standard is just met. Exposure estimates for 1-hour average and 8-hour average CO concentrations are presented in Tables 7-40 and 7-41. The results indicate that the difference between the lower estimates and the upper estimates is appreciable. This large variation primarily results from the large differences between lower and upper estimates of multiplicative microenvironment factors, particularly those for transportation vehicles and roadsides.

Tables 7-42 through 7-44 provide COHb level estimates corresponding to the same lower, best, and upper estimates of microenvironment factors. The resulting variation in COHb levels is

TABLE 7-40. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE IN CHICAGO WITH 1-HOUR CARBON MONOXIDE EXPOSURES ABOVE SELECTED VALUES UNDER 12 PPM/1 EXEX STANDARD USING BEST, LOWER, AND UPPER MICROENVIRONMENT FACTORS

CONCENTRATION EXCEEDED (PPM)	BEST ESTIMATE		LOWER ESTIMATE	UPPER ESTIMATE
60.0				
55.0				1,250
50.0				11,200
45.0				11,400
40.0				19,500
35.0				22,300
30.0	11,200			51,100
25.0	11,400			59,200
20.0	22,300		11,200	99,600
15.0	59,200		22,000	121,000
12.0	108,000		51,100	122,000
9.0	119,000		99,900	122,000
7.0	122,000		120,000	122,000
0.0	122,000		122,000	122,000
MAX. CONCENTRATION	34.6		23.0	58.0
PEOPLE AT MAXIMUM	523		523	523

TABLE 7-41. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE IN CHICAGO WITH 8-HOUR CARBON MONOXIDE EXPOSURES ABOVE SELECTED VALUES UNDER 12 PPM/1 EXEX STANDARD USING BEST, LOWER, AND UPPER MICROENVIRONMENT FACTORS

CONCENTRATION EXCEEDED (PPM)	BEST ESTIMATE		LOWER ESTIMATE	UPPER ESTIMATE
60.0				
55.0				
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				776
20.0				5,260
15.0	1,900			31,000
12.0	5,260			86,400
9.0	67,300		4,670	115,000
7.0	93,300		61,600	121,000
0.0	122,000		122,000	122,000
MAX. CONCENTRATION	16.0		10.6	29.0
PEOPLE AT MAXIMUM	54		335	54

TABLE 7-42. ESTIMATES OF OCCURRENCES FOR ADULTS WITH CARDIOVASCULAR DISEASE IN CHICAGO OF COHb LEVELS EXCEEDING SELECTED VALUES UNDER 12 PPM/1 EXEX STANDARD USING BEST, LOWER, AND UPPER MICROENVIRONMENT FACTORS

COHB LEVEL EXCEEDED (PERCENT)	BEST ESTIMATE		LOWER ESTIMATE	UPPER ESTIMATE
3.70				3,980
3.50				9,390
3.30				24,100
3.10				53,000
3.00				83,300
2.90				120,000
2.70				257,000
2.50	134			562,000
2.30	2,460			1,210,000
2.10	16,600			2,480,000
2.00	39,700			3,580,000
1.50	1,240,000		14,700	31,500,000
1.00	32,700,000		2,890,000	409,000,000
0.00	1,070,000,000		1,070,000,000	1,070,000,000
MAX. COHB CONC. ENCOUNTERS AT MAX.	2.52 24		1.78 67	4.55 24

TABLE 7-43. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE IN CHICAGO EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES UNDER 12 PPM/1 EXEX STANDARD USING BEST, LOWER, AND UPPER MICROENVIRONMENT FACTORS

COHB LEVEL EXCEEDED (PERCENT)	BEST ESTIMATE		LOWER ESTIMATE	UPPER ESTIMATE
3.70				1,310
3.50				2,670
3.30				3,550
3.10				5,090
3.00				7,380
2.90				8,550
2.70				12,100
2.50	78			24,300
2.30	1,250			55,600
2.10	3,770			75,100
2.00	8,910			85,800
1.50	60,000		3,760	117,000
1.00	120,000		78,300	122,000
0.00	122,000		122,000	122,000
MAX. COHB CONC.	2.52		1.78	4.55
PEOPLE AT MAXIMUM	24		67	24

TABLE 7-44. ESTIMATES OF ADULTS WITH CARDIOVASCULAR DISEASE IN CHICAGO WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED RANGES UNDER 12 PPM/1 EXEX STANDARD USING BEST, LOWER, AND UPPER MICROENVIRONMENT FACTORS

COHB LEVEL RANGE (PERCENT)	BEST ESTIMATE		LOWER ESTIMATE	UPPER ESTIMATE
3.70 < C <= 10.00				1,310
3.50 < C <= 3.70				1,360
3.30 < C <= 3.50				881
3.10 < C <= 3.30				1,540
3.00 < C <= 3.10				2,290
2.90 < C <= 3.00				1,170
2.70 < C <= 2.90				3,550
2.50 < C <= 2.70	79			12,200
2.30 < C <= 2.50	1,180			31,300
2.10 < C <= 2.30	2,510			19,600
2.00 < C <= 2.10	5,150			10,600
1.50 < C <= 2.00	51,100		3,760	30,900
1.00 < C <= 1.50	59,600		74,600	4,940
0.00 < C <= 1.00	1,930		43,300	
MAX. COHB CONC.	2.52		1.78	4.55
PEOPLE AT MAXIMUM	24		67	24

consistent with the large variations in 1-hour and 8-hour CO exposures discussed above.

The results of a limited sensitivity analysis on two of the physiological variables which determine COHb levels in the blood resulting from given patterns of CO exposure are presented in Table 7-45. Three different values are used for the Haldane constant and two different values are used for the ventilation rate at low exercise level. Five different combinations of values for these two variables are used for a 12 ppm/1 ExEx standard. One combination, the highest value for each variable, is used for a 9 ppm/1 ExEx standard. It is clear that these variations have a significant effect, but not as large an effect as the variation in estimated microenvironment factors.

TABLE 7-45. SENSITIVITY OF COHb ESTIMATES FOR CHICAGO TO VARIATIONS IN TWO PHYSIOLOGICAL VARIABLES

Case				Estimates of the percentage of adults with cardiovascular disease who would experience COHb levels exceeding the selected values		
Run	Stand.	Haldane constant	Venti-lation rate, ml/min	2.0% COHb	2.5% COHb	2.7% COHb
1	(12,1)	246	10,000	11.5	2.9	0.8
2	(12,1)	246	8,000	8.8	1.3	0.1
3	(12,1)	218	10,000	8.1	0.6	-
4	(12,1)	230	8,000	8.1	0.8	-
5	(12,1)	218	8,000	8.1	0.1	-
6	(9,1)	246	10,000	1.3	-	-

No sensitivity analysis runs were made in which microenvironment factors and physiological values were varied together. Obviously, doing so would result in even more widely divergent estimates. Also, there are other uncertainties which have not been subjected to analysis in this application.

7.5 REFERENCES

1. Memorandum from Harvey Richmond, Ambient Standards Branch, to Mike Jones, Chief of the Ambient Standards Branch, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711. September 8, 1982.

2. F. L. Rodkey, J. D. O'Neal, and H. A. Collison, "Oxygen and carbon monoxide equilibria of human adult hemoglobin at atmospheric and elevated pressure," Blood, Vol. 33, No. 1, 1960, pp. 57-65.

3. U.S. Department of Health, Education, and Welfare, Public Health Service, Hemoglobin and Selected Iron-Related Findings of Persons 1-74 Years of Age: United States, 1971-1974. Advance data number 46, January 26, 1979.

4. R. F. Coburn, et al, "Endogenous carbon monoxide production in man," J. of Clin. Invest., Vol. 42, 1963, pp. 1172-1178.

5. S. R. Lynch and A. L. Moede, "Variation in the rate of endogenous carbon monoxide production in normal human beings," J. Lab. Clin. Med., Vol. 79, 1972, pp. 85-95.

6. P. D. Berk, et al, "Comparison of plasma bilirubia turnover and carbon monoxide production in man," J. Lab. Clin. Med., Vol. 83, 1974, pp. 29-37.

7. M. Delivoria-Papadopoulos, R. F. Coburn, and R. E. Forster, "Cyclic variation of rate of carbon monoxide production in normal women," J. Appl. Physiol., Vol. 36, 1974, pp. 49-51.

8. R. P. Brouillard, M. E. Conrad, and T. A. Bensinger, "Effect of blood in the gut on measurements of endogenous carbon monoxide production," Blood, Vol. 45, 1975, pp. 67-69.

9. C. A. Coltman and G. M. Dudley, "The relationship between endogenous carbon monoxide production and total heme mass in normal and abnormal subjects," Am. J. Med. Sci., Vol. 258, 1969, pp. 374-385.

10. R. Joumard, et al, "Mathematical models of the uptake of carbon monoxide on hemoglobin at low carbon monoxide levels," Env. Health Persp., Vol. 41, 1981, pp. 277-289.

11. T. Sjöstrand, "Blood volume," Handbook of Physiology, Vol. 1, Section 2, Chap. 4, 1962, pp. 51-62.

12. U. S. National Center for Health Statistics, Advance Data. No. 3, November 19, 1976, and No. 14, November 30, 1977.

13. V. Niinimaa, P. Cole, S. Mintz, and R. J. Shephard, "Oral nasal distribution of respiratory airflow," Resp. Physiol, Vol. 43, 1981, pp. 69-75.

14. Review of the National Ambient Air Quality Standards for Sulfur Oxides: Assessment of Scientific and Technical Information, Strategies and Air Standards Division, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, November 1982.

15. U. S. Department of Health, Education, and Welfare, Public Health Service, Coronary Heart Disease in Adults. United States: 1960-1962, Vital and Health Statistics Series 11, No. 10, December 1975.

SECTION 8

NATIONWIDE EXTRAPOLATIONS

The exposure model described in the preceding sections is applied directly to individual urbanized areas. To obtain CO exposure and COHb distributions for all urbanized areas directly from the model would require that the model be applied to each urbanized area separately and the distributions obtained be summed according to the expression

$$E(C) = \sum_{i=1}^{n} e_i(C) \quad , \qquad (8\text{-}1)$$

where E(C) is the total number of exposures to a concentration above C for all urbanized areas and $e_i(C)$ is the exposure distribution for the i^{th} area of n urbanized areas. Analogous expressions can be written for the number of people with exposures above selected concentrations and the number of people whose maximum exposure occurs in selected ranges. To carry out these computations would require the development of pollutant concentration and human activity data bases for each urbanized area in the U.S. Such an analysis is not feasible at the present time. Accordingly, rough estimates of national exposure for adults with cardiovascular disease were made by extrapolating the exposure and COHb estimates obtained from modelling the four study areas discussed in previous sections, namely, Chicago, Los Angeles, Philadelphia, and St. Louis.

The extrapolation procedure used is described in Section 8.1. Results of the extrapolation are presented in Section 8.2. A discussion of the uncertainty about the accuracy of these estimates is given in Section 8.3.

8.1 EXTRAPOLATION PROCEDURE

Equation 8-1 can be rewritten, in terms of exposures per person in the population, as

$$E(C) = \sum_{i=1}^{n} P_i e_i^o(C) \tag{8-2}$$

where $e_i^o(C)$ is the exposure distribution per person in the population and P_i is the population of the i^{th} urbanized area. As with Equation 8-1, analogous equations can be written for each of the exposure and COHb distributions provided by the model. The effect of factoring out the population is to bring the $e_i^o(C)$ values for different areas just meeting a given alternative standard into closer agreement. There will continue to be significant differences, however, and the basic assumption of the extrapolation is that the $e_i^o(C)$ for the four base study areas are sufficient to represent these differences exhaustively. Therefore, the first step in applying the method was to assign each urbanized area to one of the four base areas. The value of n in Equation 8-2 was set equal to four, and P_i became the total population of urbanized areas assigned to the i^{th} base area.

The ultimate goal of the extrapolation is to estimate what the exposure of the sensitive population (i.e., adults with cardiovascular disease) would be in 1987 under each of three air quality assumptions. These assumptions are that the three air quality standards discussed in Section 7 are just met in all urban areas. Since some urban areas are expected to have cleaner air in 1987 than required by the given standards, NEM estimates which are based on just meeting the standards are higher than they would be if they had been based on estimated 1987 quality.

The CO exposure and COHb distributions for each of the four base areas are divided by their respective adult population values to obtain the $e_i^o(C)$ distributions. To obtain the urban population estimates to associate with each of the base areas, each of the urbanized areas with populations greater than 200,000 is assigned to one of the four base areas based on such considerations as proximity to the base area, average wind speed, observed peak CO concentration, climate, and general character of the area. The total population for urban areas with population greater than 200,000 associated with each base area (which included that of the base area) was obtained by summing the associated populations for each base area. The population data used at this stage were based on 1970 census data.

The total and sensitive populations assigned to each base area are listed in Table 8-1. Review of these data reveals that the 105 urbanized areas with populations greater than 200,000 in 1970 are distributed relatively evenly among the four base areas. However, although only 22 areas were assigned to Chicago, over 35 percent of the total urban population is associated with this base area. This situation occurs because several of the largest urbanized areas, including the New York urbanized area (pop. 16,200,000), are assigned to Chicago.

An adjustment is required because the total sensitive population of associated urbanized areas with population greater than 200,000 is less than the total population of urbanized areas. This adjustment is made by using the ratio of the total urbanized area population in 1970 to the total 1970 population in urban areas with populations greater than 200,000. Substitution in Equation 8-2 of the adjusted population values and the appropriate $e_i^o(C)$ values for each exposure and COHb distribution yields the desired extrapolated distributions.

Note that although the $e_i^o(C)$ values are based on 1970 urban area population data they are extrapolated to 1987 (see Section 7.1.1). The 1970 urban data are not only used to estimate base populations, but also are used in conjunction with 1980 total U.S. population data and an estimated growth rate to determine the factor used for the extrapolation. The 1970 data were the best urban population data available for this purpose and for making the adjustment described in the last paragraph.

TABLE 8-1. URBANIZED AREA POPULATION DATA USED TO EXTRAPOLATE MODEL RESULTS

Area	1970 Associated urbanized areas	1970 Pop. of associated urbanized areas with pop. >200,000	1987 Sensitive pop. of associated urbanized areas
Chicago	22	38,894,365	1,886,000
Los Angeles	26	26,339,249	1,277,000
Philadelphia	25	20,553,523	997,000
St. Louis	32	17,350,712	841,000
Totals	105	103,137,849	5,001,000

By using an expression, which is mathematically equivalent to the per person approach described above, the desired extrapolated distributions can be calculated directly from the exposure distributions which are calculated for the four study areas. That is, E(C) can be calculated from the $e_i(C)$ for the four study areas by using the expression,

$$E(C) = \frac{\text{Total Population (1970)}}{\text{Total Population} > 200{,}000 \text{ (1970)}} \cdot \sum_{i=1}^{4} f_i \, e_i(C) \qquad (8\text{-}3)$$

where $f_i = \frac{\text{Total Pop. of i-type urban areas}}{\text{Total Pop. of ith urban area}}$.

8.2 EXTRAPOLATION RESULTS

The results of the nationwide extrapolation are presented in Tables 8-2 through 8-12. The first nine tables can be divided into three sets of three tables. Tables 8-2, 8-3, and 8-4 present exposure estimates for a one-hour averaging time. Estimates of occurrences during 1987 among adults with cardiovascular disease of 1-hour average CO exposures above selected concentration values during 1987 under four alternative air quality assumptions are presented in Table 8-2. Estimates of the number of adults with cardiovascular disease in the urban U.S. who would incur 1-hour average CO exposures above the same set of selected

TABLE 8-2. ESTIMATES OF OCCURRENCES IN THE CARDIOVASCULAR ADULT URBAN U.S. POPULATION OF 1-HOUR AVERAGE CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION EXCEEDED (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0			21,900	
45.0		10,200	33,600	
40.0		21,900	359,000	
35.0	10,200	124,000	849,000	
30.0	21,900	359,000	2,140,000	
25.0	168,000	1,700,000	6,310,000	
20.0	915,000	6,570,000	21,300,000	
15.0	6,620,000	31,300,000	78,700,000	
12.0	27,700,000	88,500,000	185,000,000	
9.0	102,000,000	296,000,000	602,000,000	
7.0	370,000,000	873,000,000	1,640,000,000	
0.0	45,900,000,000	45,900,000,000	45,900,000,000	
MAX. CONCENTRATION ENCOUNTERS AT MAX.	36.0 10,200	49.0 10,200	61.5 10,200	

TABLE 8-3. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. WITH 1-HOUR AVERAGE CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION EXCEEDED (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0			21,900	
45.0		10,200	21,900	
40.0		21,900	348,000	
35.0	10,200	113,000	531,000	
30.0	21,900	348,000	872,000	
25.0	157,000	691,000	1,270,000	
20.0	535,000	1,290,000	2,510,000	
15.0	1,290,000	2,900,000	4,290,000	
12.0	2,820,000	4,290,000	4,800,000	
9.0	4,390,000	5,030,000	5,220,000	
7.0	5,140,000	5,240,000	5,240,000	
0.0	5,240,000	5,240,000	5,240,000	
MAX. CONCENTRATION	36.0	49.0	61.5	
PEOPLE AT MAXIMUM	10,200	10,200	10,200	

TABLE 8-4. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. WHOSE MAXIMUM 1-HOUR AVERAGE CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION RANGE (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0 < C <= 55.0				
45.0 < C <= 50.0		10,200		
40.0 < C <= 45.0		11,700	326,000	
35.0 < C <= 40.0	10,200	90,600	184,000	
30.0 < C <= 35.0	11,700	235,000	341,000	
25.0 < C <= 30.0	135,000	344,000	401,000	
20.0 < C <= 25.0	378,000	603,000	1,240,000	
15.0 < C <= 20.0	753,000	1,610,000	1,770,000	
12.0 < C <= 15.0	1,530,000	1,390,000	510,000	
9.0 < C <= 12.0	1,570,000	738,000	426,000	
7.0 < C <= 9.0	747,000	211,000	18,600	
0.0 < C <= 7.0	107,000	4,730		
MAX. CONCENTRATION	36.0	49.0	61.5	
PEOPLE AT MAXIMUM	10,200	10,200	10,200	

TABLE 8-5. ESTIMATES OF OCCURRENCES IN THE CARDIOVASCULAR ADULT URBAN U.S. POPULATION OF 8-HOUR AVERAGE CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION EXCEEDED (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0			104,000	
15.0		429,000	3,830,000	
12.0	200,000	4,290,000	29,200,000	
9.0	6,340,000	54,900,000	206,000,000	
7.0	63,500,000	322,000,000	835,000,000	
0.0	45,900,000,000	45,900,000,000	45,900,000,000	
MAX. CONCENTRATION	14.0	18.5	23.0	
ENCOUNTERS AT MAX.	232	232	232	

TABLE 8-6. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. WITH 8-HOUR AVERAGE CO EXPOSURES ABOVE SELECTED CONCENTRATION VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION EXCEEDED (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0				
45.0				
40.0				
35.0				
30.0				
25.0				
20.0			49,400	
15.0		176,000	529,000	
12.0	98,000	538,000	1,770,000	
9.0	618,000	2,410,000	3,660,000	
7.0	2,650,000	4,090,000	4,950,000	
0.0	5,240,000	5,240,000	5,240,000	
MAX. CONCENTRATION	14.0	18.5	23.0	
PEOPLE AT MAXIMUM	232	232	232	

TABLE 8-7. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. WHOSE MAXIMUM 8-HOUR AVERAGE CO EXPOSURE OCCURS IN SELECTED CONCENTRATION RANGES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

CONCENTRATION RANGE (PPM)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
50.0 < C <= 55.0				
45.0 < C <= 50.0				
40.0 < C <= 45.0				
35.0 < C <= 40.0				
30.0 < C <= 35.0				
25.0 < C <= 30.0				
20.0 < C <= 25.0			49,400	
15.0 < C <= 20.0		176,000	480,000	
12.0 < C <= 15.0	98,100	362,000	1,240,000	
9.0 < C <= 12.0	520,000	1,870,000	1,890,000	
7.0 < C <= 9.0	2,030,000	1,680,000	1,290,000	
0.0 < C <= 7.0	2,590,000	1,160,000	291,000	
MAX. CONCENTRATION	14.0	18.5	23.0	
PEOPLE AT MAXIMUM	232	232	232	

TABLE 8-8. ESTIMATES OF OCCURRENCES AMONG CARDIOVASCULAR ADULTS IN URBAN U.S. OF COHb LEVELS EXCEEDING SELECTED VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

COHB LEVEL EXCEEDED (PERCENT)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
3.70			637	
3.50			6,690	
3.30			15,300	
3.10			51,800	
3.00		570	106,000	
2.90		2,650	250,000	
2.70		14,800	810,000	
2.50		76,700	1,880,000	
2.30	570	473,000	4,100,000	
2.10	12,000	1,580,000	8,580,000	
2.00	41,700	2,730,000	13,900,000	
1.50	4,730,000	38,300,000	151,000,000	
1.00	296,000,000	1,070,000,000	2,270,000,000	
0.00	45,900,000,000	45,900,000,000	45,900,000,000	
MAX. COHB CONC.	2.30	3.02	3.75	
ENCOUNTERS AT MAX.	120	120	120	

TABLE 8-9. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

COHB LEVEL EXCEEDED (PERCENT)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
3.70			345	
3.50			3,200	
3.30			6,600	
3.10			25,800	
3.00		281	58,200	
2.90		1,250	132,000	
2.70		6,230	308,000	
2.50		42,000	506,000	
2.30	281	217,000	732,000	
2.10	5,500	452,000	1,060,000	
2.00	22,200	660,000	1,350,000	
1.50	742,000	2,100,000	3,480,000	
1.00	4,140,000	5,090,000	5,180,000	
0.00	5,240,000	5,240,000	5,240,000	
MAX. COHB CONC.	2.30	3.02	3.75	
PEOPLE AT MAXIMUM	120	120	120	

TABLE 8-10. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. WHOSE MAXIMUM COHb LEVEL OCCURS IN SELECTED CONCENTRATION RANGES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

COHB LEVEL RANGE (PERCENT)	9 PPM 8HR 1EXEX	12 PPM 8HR 1EXEX	15 PPM 8HR 1EXEX	
3.70 < C <= 10.00			351	
3.50 < C <= 3.70			2,860	
3.30 < C <= 3.50			3,400	
3.10 < C <= 3.30			19,200	
3.00 < C <= 3.10		285	32,400	
2.90 < C <= 3.00		972	74,100	
2.70 < C <= 2.90		4,990	175,000	
2.50 < C <= 2.70		35,900	198,000	
2.30 < C <= 2.50	285	175,000	227,000	
2.10 < C <= 2.30	5,230	235,000	327,000	
2.00 < C <= 2.10	16,700	208,000	291,000	
1.50 < C <= 2.00	720,000	1,440,000	2,130,000	
1.00 < C <= 1.50	3,400,000	2,990,000	1,700,000	
0.00 < C <= 1.00	1,100,000	149,000	63,000	
MAX. COHB CONC.	2.30	3.02	3.75	
PEOPLE AT MAXIMUM	120	120	120	

TABLE 8-11. PERCENTAGE OF CARDIOVASCULAR ADULT URBAN U.S. POPULATION EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES UNDER ALTERNATIVE AIR QUALITY ASSUMPTIONS

COHb level exceeded (percent)	9 ppm 8 hr 1 ExEx	12 ppm 8 hr 1 ExEx	15 ppm 8 hr 1 ExEx
3.70			0.01
3.50			0.06
3.30			0.13
3.10			0.49
3.00		0.01	1.11
2.90		0.02	2.52
2.70		0.12	5.88
2.50		0.80	9.66
2.30	0.01	4.14	13.97
2.10	0.10	8.63	20.23
2.00	0.42	12.60	25.76
1.50	14.16	40.08	66.41
1.00	79.01	97.14	98.85
0.00	100.00	100.00	100.00

TABLE 8-12. ESTIMATES OF CARDIOVASCULAR ADULTS IN URBAN U.S. EXPERIENCING COHb LEVELS EXCEEDING SELECTED VALUES A GIVEN NUMBER OF DAYS ASSUMING 9 PPM/1 EXEX STANDARD IS ATTAINED

CONCENTRATION EXCEEDED (PERCENT)	NUMBER OF TIMES			
	1 DAY	2 - 4 DAYS	5 - 25 DAYS	> 25 DAYS
3.70				
3.50				
3.30				
3.10				
3.00				
2.90				
2.70				
2.50				
2.30	281			
2.10	5,500			
2.00	21,800	1,120		
1.50	372,000	656,000	909,000	
1.00	673,000	2,570,000	25,300,000	39,200,000
0.00				1,910,000,000

concentrations under the same assumptions are presented in Table 8-3. Estimates of the number of urban U.S. adults whose maximum 1-hour average CO exposure would occur in various concentration ranges are presented in Table 8-4.

Analogous estimates for 8-hour average CO exposures are presented in Tables 8-5, 8-6, and 8-7 respectively. Similar estimates for COHb levels resulting from CO exposure are presented in Tables 8-8, 8-9, and 8-10. The absolute numbers presented in Table 8-9 are presented in percentage form in Table 8-11.

Estimates of the number of adults with cardiovascular disease who would have their blood COHb levels elevated above selected concentrations for various numbers of days if an 8-hour average 9 ppm/1 ExEx standard were just met in all urban areas are presented in Table 8-12. The table indicates the frequency of repeated peak COHb levels. The table indicates, for example, that of the 5,500 adults with cardiovascular disease who are estimated to have their blood COHb level exceed 2.1 percent under the 9 ppm/1 ExEx standard, none would have it occur more than one day.

8.3 UNCERTAINTY OF THE NATIONWIDE ESTIMATES

The uncertainty of the CO exposure and COHb estimates made for the four base cities was discussed in Section 7.4. The nationwide estimates are even more uncertain because of the additional uncertainty introduced by the extrapolation of exposure estimates for these four cities to all urban areas in the U.S.

Formal means of dealing with the uncertainty of nationwide estimates are under development, but were not available for this analysis. Hence, no attempt was made to formally represent the uncertainty of the estimates presented in Section 8.2. The analyses discussed in Section 7.4 indicate that uncertainty is already great at the city level. That even greater uncertainty exists in the nationwide estimates should be recognized when considering the estimates presented in Tables 8-2 through 8-12.

APPENDIX A

Section 3.1 describes the development of activity patterns for the 56 population subgroups used in the NEM analysis. Reference 2 of Section 3.4 contains these 56 activity patterns. This appendix contains three examples of these activity patterns. At the top of each table is a label indicating the age-occupation group, the subgroup, and the percentage of the age-occupation group falling into the subgroup. In the body of the table are hourly assignments to locations, microenvironments, and activity levels for weekdays, Saturdays, and Sundays. Note that the hour designated "1 AM" is the hour which ends at 1 AM.

ACTIVITY PATTERNS BY AGE-OCCUPATION SUBGROUP

A-O GROUP: 4--Clerical workers   SUBGROUP:2   PCT IN SUBGROUP:26

DAY OF WEEK	TIME OF DAY	1	2	3	4	5	6	7	8	9	10	11	12
		LOCATION/MICROENVIRONMENT/ACTIVITY-LEVEL BY HOUR											
WEEKDAYS	AM	H	H	H	H	H	H	H	H	W	W	W	W
		2	2	2	2	2	2	2	3	1	1	1	1
		1	1	1	1	1	1	1	1	1	1	1	1
	PM	W	W	W	W	W	W	H	H	H	H	H	H
		2	1	1	1	1	3	2	2	2	2	2	2
		1	1	1	1	1	1	1	1	1	1	1	1
SATURDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	2	2	2	5	2
		1	1	1	1	1	1	1	1	1	2	2	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	2	3	2	2	2
		1	1	1	2	1	1	1	1	1	1	1	1
SUNDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	2	2	2	3	2
		1	1	1	1	1	1	1	1	1	1	1	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	5	4	2	2	2	2	2	2
		1	1	1	1	3	2	1	1	1	1	1	1

LOCATION CODES: H=home   W=work

MICROENVIRONMENT CODES:
1 = work or school   2 = home or other   3 = transport vehicle
4 = roadside   5 = outdoors   6 = kitchen

ACTIVITY LEVELS: 1=low   2=medium   3=high

ACTIVITY PATTERNS BY AGE-OCCUPATION SUBGROUP

A-O GROUP: 6--Operatives &Laborers SUBGROUP:6   PCT IN SUBGROUP:16

DAY OF WEEK	TIME OF DAY	1	2	3	4	5	6	7	8	9	10	11	12
		LOCATION/MICROENVIRONMENT/ACTIVITY-LEVEL BY HOUR											
WEEKDAYS	AM	H	H	H	H	H	H	W	W	W	W	W	W
		2	2	2	2	2	2	3	3	3	3	4	2
		1	1	1	1	1	1	1	1	1	1	2	1
	PM	W	W	W	W	W	H	H	H	H	H	H	H
		3	3	2	3	3	2	2	2	2	2	2	2
		1	1	1	1	1	1	1	1	1	1	1	1
SATURDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	2	2	2	2	2
		1	1	1	1	1	1	1	1	1	1	2	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	5	2	2	2	2	4	2	2	2	2
		1	1	2	1	1	1	1	2	1	1	1	1
SUNDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	2	2	2	3	2
		1	1	1	1	1	1	1	1	1	1	1	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	5	2	2	2	2	2	2	2
		1	1	1	1	2	1	1	1	1	2	1	1

LOCATION CODES: H=home   W=work

MICROENVIRONMENT CODES:
1 = work or school   2 = home or other   3 = transport vehicle
4 = roadside   5 = outdoors   6 = kitchen

ACTIVITY LEVELS: 1=low   2=medium   3=high

ACTIVITY PATTERNS BY AGE-OCCUPATION SUBGROUP

A-O GROUP: 9--Housewives SUBGROUP:1 PCT IN SUBGROUP:42

DAY OF WEEK	TIME OF DAY	LOCATION/MICROENVIRONMENT/ACTIVITY-LEVEL BY HOUR 1	2	3	4	5	6	7	8	9	10	11	12
WEEKDAYS	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	6	2	2	2	2	5
		1	1	1	1	1	1	1	2	1	1	2	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	3	2	2	6	2	2	2	2	2	2
		1	1	1	1	1	1	1	1	1	1	1	1
SATURDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	6	2	2	2	2
		1	1	1	1	1	1	1	1	2	1	1	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		6	2	5	2	2	2	2	4	3	2	2	2
		1	1	2	1	1	1	1	2	1	1	1	1
SUNDAY	AM	H	H	H	H	H	H	H	H	H	H	H	H
		2	2	2	2	2	2	2	6	2	2	2	3
		1	1	1	1	1	1	1	1	1	1	1	1
	PM	H	H	H	H	H	H	H	H	H	H	H	H
		6	2	2	2	5	2	6	2	2	2	2	2
		1	1	1	2	2	1	1	1	1	1	1	1

LOCATION CODES: H=home W=work

MICROENVIRONMENT CODES:
1 = work or school 2 = home or other 3 = transport vehicle
4 = roadside 5 = outdoors 6 = kitchen

ACTIVITY LEVELS: 1=low 2=medium 3=high

APPENDIX B

COHORT POPULATIONS BY STUDY AREA

Cohort description				Cohort population			
A-O group	Home NT[a]	Work NT[a]	Sub-group	Chicago	Phila-delphia	St. Louis	Los Angeles
Students 18+ 01	CR 1	CR 1	1	19,316	4,239	3,753	17,261
			2	37,792	8,293	7,344	33,771
			3	9,238	2,027	1,794	8,255
			4	17,636	3,870	3,427	15,760
	SR 5	SR 5	1	5,897	17,387	5,334	61,326
			2	11,538	34,017	10,436	119,985
			3	2,820	8,315	2,551	29,330
			4	5,384	15,875	4,870	55,993
Professionals 02	CR 1	CC 2	1	170,393	14,501	13,364	41,759
			2	76,133	6,479	5,971	18,658
			3	79,758	6,788	6,256	19,547
			4	36,254	3,085	2,834	8,885
	CR 1	SC 6	1	11,845	5,710	3,489	31,503
			2	5,293	2,551	1,559	14,076
			3	5,545	2,673	1,633	14,746
			4	2,520	1,215	742	6,702
	SR 5	CC 2	1	47,282	35,661	14,490	40,366
			2	21,126	15,933	6,474	18,036
			3	22,132	16,692	6,782	18,895
			4	10,060	7,587	3,083	8,589
	SR 5	SC 6	1	8,806	65,332	18,812	263,140
			2	3,934	29,191	8,405	117,573
			3	4,122	30,581	8,805	123,172
			4	1,874	13,901	4,002	55,987
Sales workers 03	CR 1	CC 2	1	33,250	4,442	4,000	11,364
			2	16,238	2,169	1,953	5,550
			3	3,866	517	465	1,321
			4	6,959	930	837	2,378
			5	17,011	2,273	2,046	5,814
	CR 1	SC 6	1	2,312	1,749	1,044	8,573
			2	1,129	854	510	4,187
			3	269	203	121	997
			4	484	366	219	1,794
			5	1,183	895	534	4,386

(continued)

Cohort description				Cohort population			
A-O group	Home NT[a]	Work NT[a]	Sub-group	Chicago	Phila-delphia	St. Louis	Los Angeles
Sales workers 03 (cont.)	SR 5	CC 2	1	9,244	11,322	4,315	11,372
			2	4,514	5,529	2,107	5,554
			3	1,073	1,317	502	1,322
			4	1,932	2,370	903	2,380
			5	4,722	5,792	2,208	5,818
	SR 5	SC 6	1	1,719	20,742	5,602	74,133
			2	839	10,130	2,736	36,204
			3	200	2,412	651	8,620
			4	360	4,341	1,173	15,516
			5	879	10,612	2,866	37,928
Clerical workers 04	CR 1	CC 2	1	141,163	26,033	22,242	48,231
			2	65,540	12,087	10,327	22,393
			3	22,687	4,184	3,575	7,751
			4	10,083	1,860	1,589	3,445
			5	2,520	465	397	861
			6	10,083	1,860	1,589	3,445
	CR 1	SC 6	1	9,813	10,250	5,806	36,385
			2	4,556	4,759	2,696	16,893
			3	1,577	1,647	933	5,848
			4	701	732	415	2,599
			5	175	183	104	650
			6	701	732	415	2,599
	SR 5	CC 2	1	31,571	39,508	11,765	36,537
			2	14,658	18,343	5,462	16,963
			3	5,074	6,349	1,891	5,872
			4	2,255	2,822	840	2,609
			5	564	706	210	652
			6	2,255	2,822	840	2,609
	SR 5	SC 6	1	5,880	72,380	15,274	238,175
			2	2,730	33,605	7,092	110,175
			3	945	11,633	2,455	38,278
			4	420	5,170	1,091	17,013
			5	105	1,293	273	4,253
			6	420	5,170	1,091	17,013

(continued)

Cohort description				Cohort population			
A-O group	Home NT[a]	Work NT[a]	Sub-group	Chicago	Phila-delphia	St. Louis	Los Angeles
Craftsmen 05	CR 1	CI 3	1	81,648	14,010	9,562	18,978
			2	39,191	6,725	4,590	9,109
			3	16,330	2,802	1,912	3,796
			4	3,266	560	382	759
			5	6,532	1,121	765	1,518
			6	16,329	2,802	1,912	3,796
	CR 1	SI 7	1	5,676	5,516	2,496	14,317
			2	2,725	2,648	1,198	6,872
			3	1,135	1,103	499	2,863
			4	227	221	100	573
			5	454	441	200	1,145
			6	1,135	1,103	499	2,863
	SR 5	CI 3	1	25,626	20,533	6,018	22,170
			2	12,300	9,856	2,889	10,641
			3	5,125	4,107	1,204	4,434
			4	1,025	821	241	887
			5	2,050	1,643	481	1,774
			6	5,125	4,107	1,204	4,434
	SR 5	SI 7	1	4,772	37,618	7,813	144,520
			2	2,291	18,056	3,750	69,370
			3	954	7,524	1,563	28,904
			4	191	1,505	313	5,781
			5	382	3,009	625	11,562
			6	954	7,524	1,563	28,904
Laborers 06	CR 1	CI 3	1	75,251	27,638	19,542	29,939
			2	34,731	12,756	9,020	13,818
			3	11,577	4,252	3,007	4,606
			4	5,789	2,126	150	2,303
			5	34,731	12,756	9,020	13,818
			6	30,872	11,339	8,017	12,283
	CR 1	SI 7	1	5,231	10,882	19,542	22,586
			2	2,414	5,022	2,354	10,424
			3	805	1,674	785	3,475
			4	402	837	392	1,737
			5	2,414	5,022	2,354	10,424
			6	2,146	4,464	2,093	9,266

(continued)

Cohort description				Cohort population			
A-O group	Home NT[a]	Work NT[a]	Sub-group	Chicago	Phila-delphia	St. Louis	Los Angeles
Laborers 06 (cont.)	SR 5	CI 3	1	18,289	22,294	6,791	24,843
			2	8,441	10,289	3,134	11,466
			3	2,813	3,430	1.045	3,822
			4	1,406	1,715	522	1,911
			5	8,441	10,289	3,134	11,466
			6	7,503	9,146	2,786	10,192
	SR 5	SI 7	1	3,406	40,843	8,817	161,945
			2	1,572	18,851	4,069	74,744
			3	524	6,284	1,356	24,914
			4	262	3,142	678	12,457
			5	1,572	18,851	4,069	74,744
			6	1,397	16,756	3,617	66,439
Service workers 08	CR 1	CR 1	1	49,393	20,770	16,789	25,910
			2	23,324	9,808	7,928	12,235
			3	30,184	12,693	10,260	15,834
			4	4,116	1,731	1,399	2,159
			5	19,208	8,077	6,529	10,076
			6	10,976	4,616	3,731	5,758
	SR 5	SR 5	1	11,090	37,142	9,416	115,759
			2	5,236	17,539	4,446	54,664
			3	6,777	22,698	5,754	70,741
			4	924	3,095	785	9,647
			5	4,312	14,444	3,662	45,017
			6	2,464	8,254	2,092	25,724
Housewives 09	CR 1	CR 1	1	71,488	39,106	27,469	69,865
			2	83,402	45,624	32,047	81,509
			3	15,319	8,380	5,886	14,971
	SR 5	SR 5	1	38,824	122,142	34,182	340,320
			2	45,295	142,499	39,879	397,040
			3	8,320	26,173	7,325	72,926
Retired 10	CR 1	CR 1	1	11,480	19,396	17,534	40,520
			2	13,776	23,275	21,040	48,624
			3	11,480	19,396	17,534	40,520
			4	17,219	29,093	26,300	60,781
			5	2,296	3,879	3,507	8,104
			6	1,148	1,940	1,753	4,052

(continued)

Cohort description				Cohort population			
A-0 group	Home NT[a]	Work NT[a]	Sub-group	Chicago	Phila-delphia	St. Louis	Los Angeles
Retired 10 (cont.)	SR 5	SR 5	1	3,277	42,411	10,836	112,631
			2	3,933	50,893	13,003	135,157
			3	3,277	42,411	10,836	112,631
			4	4,916	63,617	16,254	168,946
			5	655	8,482	2,167	22,526
			6	327	4,241	1,084	11,263
Children <5 11	CR 1	CR 1	1	10,562	15,851	10,494	24,304
			2	10,059	15,096	9,995	23,146
			3	10,059	15,096	9,995	23,146
			4	19,615	29,438	19,489	45,135
	SR 5	SR 5	1	8,076	35,021	10,506	113,151
			2	7,691	33,353	10,006	107,763
			3	7,691	33,353	10,006	107,763
			4	14,997	65,039	19,511	210,137
Children 5-17 12	CR 1	CR 1	1	67,594	117,289	82,690	149,881
			2	4,828	8,378	5,906	10,706
			3	8,449	14,661	10,336	18,735
			4	31,383	54,455	38,391	69,587
			5	2,414	4,189	2,953	5,353
			6	6,035	10,472	7,383	13,382
	SR 5	SR 5	1	51,683	284,616	91,294	905,879
			2	3,692	20,330	6,521	64,706
			3	6,460	35,577	11,412	113,235
			4	23,996	132,143	42,387	420,587
			5	1,846	10,165	3,261	32,353
			6	4,615	25,412	8,151	80,882

APPENDIX C

DISCUSSION OF AIR QUALITY INDICATORS
USED IN THE NEM ANALYSIS AND ESTIMATED
CONCENTRATIONS USED IN THE REGULATORY ANALYSIS

A number of reviewers of early drafts of this report have asked how air quality indicators (AQI's) used in the NEM analyses of CO compare with estimated concentrations (EC's) used in the regulatory impact analysis of alternative CO NAAQS's. This appendix discusses how EC's are determined and why they differ from AQI's.

For regulatory impact analysis purposes, EPA characterizes air quality levels in urbanized areas by a single value. This value, the EC, is determined from existing air quality data according to the same criteria that states would use to determine whether or not an area attains a proposed NAAQS. These criteria vary according to the "form" of the standard being analyzed and the allowed violation rate. In the case of CO, forms under consideration include one-hour and eight-hour daily maximum standards with allowed violation rates of one and five expected exceedances per year over a three year period.

The EC for a given urbanized area is usually based on air quality data from the monitor which reported the highest air quality values over a two or three year period. According to current EPA guidance, the EC may be determined by applying the simple formula

$$\text{descending rank of EC value} = \begin{pmatrix}\text{number}\\ \text{of years}\\ \text{analyzed}\end{pmatrix}\begin{pmatrix}\text{allowed}\\ \text{exceedance}\\ \text{rate}\end{pmatrix} + 1 \qquad \text{(B-1)}$$

to a multi-year data set from this monitor. Thus if the permitted exceedance rate is five and three years of data are considered, the EC value would be the 16th highest concentration in the data set. For two years of data and one allowed exceedance, the third highest concentration would be used. Note that each EC corresponds to an actual observed value.

AQI values used in the NEM analysis are determined by fitting distributions to single-year data sets which have had missing values filled in by time series analysis (see Section 5). Values with expected exceedance rates of one and five are represented by the characteristic largest and fifth largest values, respectively. These values correspond to quantiles in the fitted distributions rather than particular observed values.

Table C-1 lists the EC's for the four study areas which have been developed for alternative CO NAAQS's which consider (1) the daily maximum one-hour concentration with one expected exceedance, (2) the daily maximum eight-hour running average concentration with one expected exceedance, and (3) the daily maximum eight-hour running average concentration with five expected exceedances. Also, listed is the value of the largest corresponding AQI from Table 5-6. In over half the cases, EC and AQI values differ by more than 10 percent.

There are a number of reasons for such large differences. EC's are based on observed values from incomplete data sets. AQI's are quantiles on curves fit to the upper tails of filled-in data. In addition, EC and AQI values are determined from data representing different time periods. EC's represent average air quality over three years (1977-79), while AQI's represent air quality for a single year (1977, 1978, or 1979). Air quality during a single year may differ significantly from the three year average. A third reason is that an EC and the corresponding AQI may represent different monitors. The monitor used to determine the EC for a city is determined by analyzing data from all monitors in an urbanized area and identifying the monitor which recorded the highest CO levels. The selection of monitors for determining the corresponding AQI is limited to the sites used in the NEM analysis. Because no more than six sites (one per neighborhood type) are used to represent CO levels across a NEM study area and because the boundary of the study area is smaller than the corresponding urbanized area, the monitor used for determining the AQI is often different from that used to determine the EC.

TABLE C-1. ESTIMATED CONCENTRATIONS (EC'S) DEVELOPED BY EPA AND CORRESPONDING AIR QUALITY INDICATORS (AQI'S) FROM TABLE 5-6 (concentrations in parts per million)

Study area	1-h average value, 1 expected exceed.		8-h running average value			
			1 expected exceed.		5 expected exceed.	
	EC	AQI	EC	AQI	EC	AQI
Chicago	30.9	24.9	18.0	15.6	14.0	12.9
Los Angeles	37.8	31.4	24.4	20.3	17.0	16.1
Philadelphia	32.9	19.2	14.7	14.3	11.0	9.9
St. Louis	27.9	22.8	17.0	14.7	10.0	10.9

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16. ABSTRACT

This report presents a version of the National Ambient Air Quality Standard (NAAQS) Exposure Model (NEM) suitable for assessing carbon monoxide (CO) exposure and presents the results of applying it to CO. NEM is a simulation model that simulates the intersection of a population with pollutant concentrations over space and time to estimate exposures that would obtain if various alternative NAAQS were just met. Estimates are presented for adults with cardiovascular disease in four urban study areas and for a nationwide extrapolation.

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