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Risk and Exposure Assessment to Support the Review of the Carbon Monoxide Primary National Ambient Air Quality Standards:

First External Review Draft

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U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
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This document has been reviewed by the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA), and approved for publication. This draft document has been prepared by staff from the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Any opinions, findings, conclusions, or recommendations are those of the authors and do not necessarily reflect the views of the EPA Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use. This document is being provided to the Clean Air Scientific Advisory Committee for their review, and made available to the public for comment. Any questions or comments concerning this document should be addressed to Souad Benromdhane, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, C504-06, Research Triangle Park, North Carolina 27711 (email: benromdhane.souad@epa.gov). Elements of this report have been provided to the U.S. Environmental Protection Agency (EPA) by Abt Associates, Inc. in partial fulfillment of Contract No. EP-D-08-100, Work Assignment 0-08.

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1. INTRODUCTION

1.1 BACKGROUND

The U. S. Environmental Protection Agency (EPA) is presently conducting a review of the national ambient air quality standards (NAAQS) for carbon monoxide (CO). Sections 108 and 109 of the Clean Air Act (Act) govern the establishment and periodic review of the NAAQS. These standards are established for pollutants that may reasonably be anticipated to endanger public health and welfare, and whose presence in the ambient air results from numerous or diverse mobile or stationary sources. The NAAQS are to be based on air quality criteria, which are to accurately reflect the latest scientific knowledge useful in indicating the kind and extent of identifiable effects on public health or welfare that may be expected from the presence of the pollutant in ambient air. The EPA Administrator is to promulgate and periodically review, at five-year intervals, "primary" (health-based) and "secondary" (welfare-based) NAAQS for such pollutants. Based on periodic reviews of the air quality criteria and standards, the Administrator is to make revisions in the criteria and standards, and promulgate any new standards, as may be appropriate. The Act also requires that an independent scientific review committee advise the Administrator as part of this NAAQS review process, a function performed by the Clean Air Scientific Advisory Committee (CASAC).

The current NAAQS for CO includes two primary standards to provide protection for exposures to carbon monoxide. In 1994, EPA retained the primary standards at 9 parts per million (ppm), 8-hour average and 35 ppm, 1-hour average, neither to be exceeded more than once per year (59 FR 38906). These standards were based primarily on the clinical evidence relating carboxyhemoglobin (COHb) levels to various adverse health endpoints and exposure modeling relating CO exposures to COHb levels. The review completed in 1994 also reaffirmed an earlier decision that the evidence did not support the need for a secondary standard for CO (59 FR 38906).

A subsequent review of the CO NAAQS was initiated in 1997, which led to the completion of the 2000 Air Quality Criteria Document for Carbon Monoxide (US EPA, 2000) and a draft exposure analysis methodology document (US EPA, 1999). EPA put on hold the NAAQS review when Congress requested that the National Research Council (NRC) review the impact of meteorology and topography on ambient CO concentrations in high altitude and extreme cold regions of the U.S. In response, the NRC convened the Committee on Carbon Monoxide Episodes in Meteorological and Topographical Problem Areas, which focused on Fairbanks, Alaska as a case-study. A final report, "Managing Carbon Monoxide Pollution in Meteorological and Topographical Problem Areas" (NRC, 2003), offered a wide range of recommendations regarding management of CO air pollution, cold start emissions standards, oxygenated fuels, and CO monitoring. Following completion of this NRC report, EPA did not conduct rulemaking to complete the review.

EPA initiated the current review of the NAAQS for CO on September 13, 2007, with a call for information from the public (72 FR 52369) requesting the submission of recent scientific information on specified topics. A workshop was held on January 28–29, 2008 (73 FR 2490) to discuss policy-relevant scientific and technical information to inform EPA's planning for the CO NAAQS review. Following the workshop, EPA outlined the science-policy questions that would frame this review, outlined the process and schedule that the review would follow, and provided more complete descriptions of the purpose, contents, and approach for developing the key documents that would be developed in the review in a draft Integrated Review Plan for the National Ambient Air Quality Standards for Carbon Monoxide (US EPA, 2008a). After CASAC and public input on the draft plan, EPA made the final plan available in August 2008 (US EPA, 2008b). EPA is currently completing the process of assessing the latest available policy-relevant scientific information to inform the review of the CO standards. The latest draft of this assessment is contained in the second external review draft of the Integrated Science Assessment for Carbon Monoxide (hereafter, "draft ISA") (US EPA, 2009c) which was released in September 2009 for review by the CASAC and for public comments. The draft ISA includes an evaluation of the scientific evidence on the health effects of CO, including information on exposure, physiological mechanisms by which CO might adversely impact human health, an evaluation of the clinical evidence for CO-related morbidity, and an evaluation of the epidemiological evidence for CO-related morbidity and mortality associations.[1]

Building upon the health effects evidence presented in the draft ISA as well as CASAC advice (Brain and Samet, 2009) and public comments on a scope and methods planning document for the exposure/risk assessment (hereafter, "Scope and Methods Plan") (US EPA,

[1] The draft ISA also evaluates scientific evidence for the effects of CO on public welfare which EPA will consider in its review of the need for a secondary standard. EPA is not intending to do a quantitative risk assessment for the secondary standard review.

2009a), EPA's Office of Air Quality Planning and Standards (OAQPS) has developed this first draft Risk/Exposure Assessment describing the initial quantitative assessments being conducted by the Agency to support the review of the primary CO standards. This draft document is a concise presentation of the methods, key results, observations, and related uncertainties associated with the quantitative analyses performed. The final REA will draw upon the final ISA and will reflect consideration of CASAC and public comments on this draft REA.

The schedule for completion of this review is governed by a court order that specifies that EPA sign for publication notices of proposed and final rulemaking concerning its review of the CO NAAQS no later than October 28, 2010 and May 13, 2011, respectively. The order also sets dates for the following interim milestones: release of a first draft ISA by March 14, 2009 (completed), a first draft risk/exposure assessment by October 29, 2009, a final ISA by January 29, 2010, and a final risk/exposure assessment by May 28, 2010.

The final ISA and final REA will inform the policy assessment and rulemaking steps that will lead to final decisions on the CO NAAQS. The policy assessment will be described in a Policy Assessment (hereafter, "PA") document, which will include staff analysis of the scientific basis for alternative policy options for consideration by senior EPA management prior to rulemaking. The PA will integrate and interpret information from the ISA and the REA to frame policy options for consideration by the Administrator. The PA is intended to help "bridge the gap" between the Agency's scientific and technical assessments, presented in the ISA and REA and the judgments required of the Administrator in determining whether it is appropriate to retain or revise the standards. The PA is also intended to facilitate CASAC's advice to the Administrator on the adequacy of existing standards, and any new standards or revisions to existing standards as may be appropriate. OAQPS currently plans to release a draft PA in late February 2010 for review by CASAC, as well as for public comment, in conjunction with CASAC review and public comment of the second draft REA (US EPA, 2009c).

1.2 ASSESSMENTS FROM PREVIOUS REVIEWS

Reviews of the CO NAAQS completed in 1985 and 1994 included analysis of exposure to ambient CO and associated internal dose in terms of COHb levels which were used to characterize risks for at-risk populations (50 FR 37484; 59 FR 38906). These prior risk characterizations compared the numbers of at-risk individuals and percent of the at-risk population exceeding several potential health effect benchmarks, expressed in terms of COHb levels. This characterization was based on COHb levels observed in several controlled human exposure studies reporting aggravation of angina associated with short-term (< 8-hr) CO exposures and described in EPA's Air Quality Criteria Document (AQCD) (US EPA, 1979; US EPA, 1984; US EPA, 1991).

In the review completed in 1994, this characterization was performed for the at-risk population in the city of Denver, Colorado (US EPA, 1992). That analysis indicated that if the current 8-hr standard were just met, the proportion of the nonsmoking population with cardiovascular disease experiencing exposures at or above 9 ppm for 8 hrs decreased by an order of magnitude or more as compared to the proportion under then-existing CO levels, down to less than 1 percent of the total person-days in that population. Likewise, meeting the current 8-hr standard reduced the proportion of the nonsmoking cardiovascular-disease population person days at or above COHb levels of concern by an order of magnitude or more relative to then-existing CO levels. More specifically, upon meeting the 8-hr standard, EPA estimated that less than 0.1% of the nonsmoking cardiovascular-disease population would experience a COHb level of about 2.1%. A smaller percentage of the at-risk population was estimated to exceed higher COHb percentages. The analysis also took into account that certain indoor sources (e.g., passive smoking, gas stove usage) contributed to total CO exposure but could not be effectively mitigated by setting more stringent ambient air quality standards.

In the subsequent review, initiated in 1997, EPA consulted with CASAC on a draft exposure analysis methodology document, Estimation of Carbon Monoxide Exposures and Associated Carboxyhemoglobin Levels in Denver Residents using pNEM/CO (Version 2.0) (Johnson, 1999). Although the EPA did not complete the review initiated in 1997, OAQPS continued work on the CO exposure assessment to further develop the exposure assessment modeling component of the Total Risk Integrated Methodology (TRIM) system. A subsequent draft technical report (Johnson et al., 2000) was produced documenting the application of the CO exposure and dose modeling methodology (and version 2.1 of pNEM/CO) for two study areas (Denver and Los Angeles). This report was subjected to an external peer review by three exposure modeling experts convened by Science Applications International Corporation (SAIC, 2001).

1.3 CURRENT ASSESSMENT

In preparing the Scope and Methods Plan for the current health risk/exposure assessment, we considered the scientific evidence presented in the first draft ISA (US EPA, 2009b) and the key science policy issues raised in the IRP (US EPA, 2008b). EPA held a consultation with CASAC to solicit comments on the Scope and Methods Plan during a May 2009 CASAC meeting at which CASAC also provided comments on the first draft of the ISA. Public comments were also requested (74 FR 15265). CASAC and public comments were considered in advance of the conduct of the analyses and results presented in this draft REA. The design of the current risk assessment builds upon information presented in the second draft ISA (US EPA, 2009c) with particular attention to conclusions regarding the adequacy of the air quality data for the purposes of exposure assessment.

In this draft assessment we are relying on generally similar methodology and focusing on the same two urban areas (Denver and Los Angeles) as that used in the assessment for the previous review. Although improvements have been made to the exposure model since the time of the last review, we recognize significant data limitations in the current review. In CASAC's comments on the first draft ISA, the Committee stated that the "current ambient monitoring network is not well designed to characterize spatial and temporal variability in ambient concentrations" and that "it does not adequately support detailed assessments of human exposure" (Brain and Samet, 2009). As a result, the draft assessment that we describe in this document has implemented a much-simplified, screening-level approach focused on a single monitor and an exposure situation of particular interest for ambient CO (as described in detail in chapters 5 and 6). Based on the concerns raised by CASAC regarding the adequacy of the current monitoring data for this purpose, staff decided not to perform a detailed analysis involving multiple monitors and comprehensive estimation of exposure concentrations in multiple microenvironments, as has been done in the past. In presenting this draft, screening-level assessment, however, we recognize that the simplifications in this approach contribute to limitations and uncertainties in the interpretation of the results. One purpose of this draft document is to seek CASAC views, and public comment, regarding our characterization of the results in light of uncertainties associated with the assessment design and inputs, and CASAC's advice on the role of this assessment in informing the current review of the CO NAAQS.

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2. OVERVIEW OF EXPOSURE AND DOSE ASSESSMENT CONCEPTUAL MODEL

In order to help inform the discussion of the CO assessment presented in chapters 5 and 6, staff has briefly summarized the conceptual model for the consideration of exposure to ambient CO and associated health risk, from key sources through the identification of at-risk population groups, dose metric, and the risk characterization approach.

2.1. SOURCES OF CARBON MONOXIDE

Carbon monoxide in ambient air is formed primarily by the incomplete combustion of carbon-containing fuels and photochemical reactions in the atmosphere. The amount of CO emitted from these reactions, relative to carbon dioxide (CO_2), is sensitive to conditions in the combustion zone. CO production relative to CO_2 generally decreases with any increase in fuel oxygen (O_2) content, burn temperature, or mixing time in the combustion zone (draft ISA, section 3.2). As a result, CO emissions from large fossil-fueled power plants are typically very low because of the boilers highly efficient combustion and optimized fuel consumption. In contrast, internal combustion engines used in many mobile sources have widely varying operating conditions. Therefore, higher and more varying CO formation results from the operation of these mobile sources (draft ISA, section 3.2). In 2002, CO emissions from on-road vehicles accounted for 63% of total emissions by individual source sectors in the U.S. (draft ISA, Figure 3-1).[1] As with previous reviews, mobile sources continue to be a significant source sector for CO in ambient air.

Sources of indoor CO include infiltration of ambient air indoors, as well as, where present, indoor (nonambient) sources such as gas stoves and environmental tobacco smoke. (draft ISA, section 3.6.5.2).

2.2. EXPOSURE PATHWAYS AND RELEVANT MICROENVIRONMENTS

Human exposure to CO involves the contact (via inhalation) between a person and the pollutant in the various locations (or microenvironments) in which people spend their time. Studies of personal exposure to ambient CO have shown that the largest percentage of the time in

[1] This was the most recent publicly available data tracking CO emissions in the National Emissions Inventory (US EPA, 2006), which included data from various sources such as industries and state, tribal, and local air agencies (draft ISA, p. 3-2).

which an individual is exposed to ambient CO occurs indoors (draft ISA, section 2.3). As a result of people spending a significant amount of their time indoors (whether at home, school, workplace or elsewhere), CO concentrations in indoor microenvironments are an important determinant of an individual's CO exposures. Microenvironments that may influence CO exposures typically include residential indoor environments and other indoor locations, near-traffic outdoor environments and other outdoor locations, and inside vehicles. As is summarized further in section 5.4, the highest exposure concentrations to ambient CO are experienced by individuals in transit on or near roadways (draft ISA, section 2.3). Ambient concentrations near roadways are generally influenced by vehicle traffic densities (draft ISA, section 3.5.2.2). As a consequence, near-road and in-vehicle exposure to CO will be much higher during commuting times. Thus, exposure to CO near roadway and in vehicle microenvironments are of concern in this review and are a focus of this draft assessment.

Although not the focus of this review, indoor sources such as gas stoves and environmental tobacco smoke can, where present, also be important contributors to total exposure. For example, some assessments performed for previous reviews have included modeling simulations both without and with indoor sources (gas stoves and environmental tobacco smoke) to provide context for the assessment of ambient CO exposure and dose (e.g., USEPA, 1994; Johnson et al., 2000).[2] As noted in section 5.5, this draft assessment does not include a simulation with indoor sources on.

2.3. AT-RISK-POPULATIONS

In considering populations for inclusion in this exposure/risk assessment, we considered the evidence regarding those with increased susceptibility or vulnerability. The term 'susceptibility' has been used to characterize populations that have a greater likelihood of experiencing effects related to ambient CO exposure, and the term 'vulnerability' has been used to identify those periods during an individual's life when they are more susceptible to environmental exposures (draft ISA, section 5.7). In reviewing and setting NAAQS, EPA is required to establish a primary standard that provides protection for population groups that may be at greater risk due to increased susceptibility and/or increased vulnerability.

[2] As has been recognized in previous CO NAAQS reviews, such sources cannot be effectively mitigated by setting more stringent ambient air quality standards and are therefore not a focus of this assessment of ambient CO exposure and dose.

The draft ISA states that the strongest evidence regarding CO induced health effects relates to cardiovascular morbidity indicating that a causal relationship is likely to exist between relevant short-term CO exposures and cardiovascular morbidity, particularly in individuals with coronary artery disease (CAD), also referred to as coronary heart disease (CHD) (draft ISA, section 5.8). This evidence comes from human exposure studies of individuals with CAD, along with coherent results from recent epidemiologic studies reporting associations between short-term CO exposure and increased risk of emergency department visits and hospital admissions for individuals affected with ischemic heart disease (IHD) and related outcomes (draft ISA, section 5.7). Other subpopulations potentially at risk include individuals with diseases such as chronic obstructive pulmonary disease (COPD), anemia, or diabetes, and individuals in very early or late life stages, such as older adults or the developing young (draft ISA, section 2.6.1). There is limited evidence available from controlled human exposure, epidemiologic, or toxicological studies characterizing the nature of specific health effects of CO in these subpopulations.

The ISA notes that the most compelling evidence of a CO-induced effect on the cardiovascular system at COHb levels relevant to the current NAAQS comes from a series of controlled human exposure studies among individuals with CHD (draft ISA, section 2.5.1). The draft ISA indicates that these studies demonstrate consistent decreases in the time to onset of exercise induced angina and ST-segment changes (as indicators of myocardial ischemia) following CO exposures resulting in COHb levels of 3-6%, with one multicenter study reporting similar effects at COHb levels as low as 2.0-2.4%. It also recognizes that no human clinical studies have evaluated the effect of controlled exposures to CO resulting in COHb levels lower than 2% (draft ISA, section 5.2.6). Furthermore, human clinical studies of individuals without diagnosed heart disease that were conducted since the 2000 CO AQCD did not report an association between CO and ST-segment changes or arrhythmia (draft ISA, section 2.5.1)

Therefore, the primary target population for the assessment described in this document will be adults with CHD (also known as ischemic heart disease (IHD) or CAD). This is the same population group that was the focus of the exposure/dose assessments conducted for previous CO NAAQS reviews. Coronary heart disease includes those who have angina pectoris (cardiac chest pain), as well as those who have experienced a heart attack. Approximately 13.7 million people were diagnosed with CHD in 2007, which represent a large population that may be more susceptible to ambient CO exposure when compared to the general population (draft ISA, section 5.7).

2.4. EXPOSURE AND DOSE METRICS

Upon inhalation, CO diffuses through the respiratory zone (alveoli) to the blood where it binds to a number of heme-containing molecules, mainly hemoglobin (Hb), forming carboxyhemoglobin (COHb). Inhaled ambient CO elicits various health effects through this binding and associated alteration of the function of a number of heme-containing molecules, mainly Hb (draft ISA, section 4.1). The dosimetry and pharmacokinetics of CO are discussed in detail in chapter 4 of the draft ISA (US EPA, 2009). The best characterized health effect associated with CO levels of concern is hypoxia (reduced O_2 availability) induced by increased COHb levels in blood (draft ISA, section 5.1.2). Thus, the dose metric used to characterize health risks associated with exposure to ambient CO in this assessment is the level of COHb in the blood. The Coburn-Forster-Kane (CFK) model (draft ISA, section 4.2.1) has been used to estimate dose (blood levels of COHb) for the exposure/dose modeling in this assessment (see section 5.3.7 of this document).

2.5. RISK CHARACTERIZATION METRIC

The category of health endpoints on which we focused in the risk and exposure assessment are those associated with coronary heart disease (see chapter 4). Similar to the approach used in prior CO NAAQS reviews, we have estimated CO exposures and resulting doses (i.e., COHb levels) for the defined at-risk population (people with CHD) and characterized the risk for this population in urban study areas associated with CO levels representing recent air quality and air quality adjusted to simulate just meeting the current CO NAAQS. In previous reviews, the COHb estimates were compared to potential health benchmarks (see section 1.2 above). Although the draft ISA has described epidemiologic findings from a group of studies, many of which were conducted since the 2000 CO AQCD, that observe associations between short term ambient CO exposures and increases in emergency department visits and hospital admissions for cardiovascular effects (draft ISA, section 5.2.1.9), a number of issues complicate the use of these studies in a quantitative risk assessment (draft ISA, section 5.2.3). In consideration of these issues and CASAC views on the Scope and Methods Plan (Brain and

Samet, 2009; US EPA, 2009), risk has been characterized in this assessment using the potential health effect benchmark level approach.[3] More specifically, we have estimated the number of persons and percent of the at-risk population (i.e., individuals with CHD) that exceed potential health effect benchmark levels, derived from the evaluation of the controlled human exposure studies mentioned above and specified in terms of COHb levels, associated with various CO air quality scenarios.

The range of potential health effects benchmarks that we have used extends to lower levels than the range where controlled human exposure studies reported CO-related health effects (i.e., 3-6% COHb with one multicenter study reporting effects at 2.0 to 2.4% COHb using gas chromatography (GC)) to take into consideration both the uncertainty about the actual COHb levels experienced in the controlled human exposure studies due to the use of different measurement methods and that these studies did not include individuals with more severe CHD who may respond at lower COHb levels relative to the subjects tested. In addition, there were no studies evaluating effects of CO below 2.0-2.4% COHb levels. Based on these considerations, staff has included 1.5-, 2.0-, 2.5-, and 3.0 % COHb as potential health effect benchmark levels in the current CO risk characterization.

Two metrics in this CO exposure/dose assessment are considered: (1) estimates of the number of people, percentage of the at risk population, and total number of person days for CO at-risk populations exposed to CO at concentrations that exceed selected benchmarks (1.5, 2.0, 2.5, and 3.0 % COHb) for various CO air quality scenarios; (2) estimates of the number of people and the total number of occurrences for which potential health effect COHb benchmark levels are exceeded for the various CO air quality scenarios.

[3] While not used for the purposes of this quantitative assessment, EPA will fully consider the health evidence, including the epidemiological studies, in the Policy Assessment Document, along with considerations based on the risk and exposure assessment findings.

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3. AIR QUALITY CONSIDERATIONS

Ambient air quality data can be used as an indicator of exposure or used in conjunction with other information to estimate exposure concentrations. How well the ambient air quality is represented in a particular location is dependent on the ambient monitoring network design relative to the spatial and temporal characteristics of the pollutant as well understanding the concentration contribution from important local source emissions. This chapter summarizes findings about the current air quality conditions and their spatial distribution, with particular focus on aspects informative to the design and conduct of this assessment and including descriptions of CO measurement methods, monitor siting requirements, and monitor locations (section 3.1).[1] Section 3.2 then draws upon the information presented in sections 3.1, among other data, to select ambient air quality/study locations most useful in meeting the objectives of the REA. Finally, key observations of the chapter are presented in section 3.3.

3.1 AMBIENT CO MONITORING

In this section, a broad overview of the monitoring network is provided (section 3.1.1) and is followed by a summary of analytical detection issues (section 3.1.2). Ambient CO concentrations and their spatial and temporal variability are characterized in section 3.1.3. Lastly, estimates of policy-relevant background (PRB) concentrations which are defined as those ambient concentrations that would occur in the U.S. in the absence of anthropogenic emissions in continental North America are presented in section 3.1.4 of this document.

3.1.1 Monitoring Network

Ambient CO concentrations are measured by monitoring networks that are operated by state and local monitoring agencies in the U.S., and are funded in part by the EPA. The main network providing ambient data for use in comparison to the NAAQS is the State and Local Air Monitoring Stations (SLAMS) network. The subsections below provide specific information regarding the methods used for obtaining ambient CO measurements and the requirements that apply to states in the design of the CO network.

Minimum monitoring requirements for CO were revoked in the 2006 revisions to ambient monitoring requirements (see 71 FR 61236, October 17, 2006). This action was made to allow for reductions in measurements of some pollutants (CO, SO_2, NO_2, and Pb) where measured levels were well below the applicable NAAQS and air quality problems were not expected. CO

[1] A complete description of spatial scales is listed in 40 CFR Part 58 Appendix D, section 1.2. Ambient monitoring of other NAAQS pollutants such as NO_2 and SO_2 follow the same general spatial scales.

monitoring activities have been maintained at some SLAMS and these measurements of CO are required to continue until discontinuation is approved by the EPA Regional Administrator.

CO monitors are typically sited to reflect one of the following spatial scales[2]:

- **Microscale**: Data represents concentrations within a 100 m radius of the monitor. For CO, microscale monitors are sited 2 – 10 m from a roadway. Measurements are intended to represent the near-road or street canyon environment.
- **Middle scale**: Data represents concentrations averaged over areas defined by 100 – 500 m radii. Measurements are intended to represent several city blocks.
- **Neighborhood scale**: Data represents concentrations averaged over areas defined by 0.5 – 4.0 km radii. Measurements are intended to represent extended portions of a city.

In addition to monitoring required for determining compliance with the NAAQS, the EPA is currently in the process of implementing plans for a new network of multi-pollutant stations called NCore that is intended to meet multiple monitoring objectives. A subset of the SLAMS network, NCore stations are intended to address integrated air quality management needs to support long-term trends analysis, model evaluation, health and ecosystem studies, as well as the more traditional objectives of NAAQS compliance and Air Quality Index reporting.[3] States were required to submit to EPA Annual Monitoring Network Plans (AMNP) describing their candidate NCore stations by July 1, 2009. EPA is reviewing these plans and intends to provide station approvals later in 2009. The complete NCore network, required to be fully implemented by January 1, 2011, will consist of approximately 63 urban and 20 rural stations and will include some existing SLAMS sites that have been modified to include additional measurements. Each state will contain at least one NCore station, and 46 of the states plus Washington, D.C. will have at least one urban station. CO will be measured using trace-level monitors, as will SO_2, NO, and NO_Y.[4] The majority of NCore stations will be sited to represent neighborhood, urban, and regional scales, consistent with the NCore network design objective of representing exposure expected across urban and rural areas in locations that are not dominated by local sources.

3.1.2 Analytical Sensitivity

To promote uniform enforcement of the air quality standards set forth under the CAA, EPA has established provisions in the Code of Federal Regulations (CFR) under which analytical

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[3] (http://www.epa.gov/ttn/amtic/ncore/index.html).

[4] NCore sites must measure, at a minimum, $PM_{2.5}$ particle mass using continuous and integrated/filter-based samplers, speciated $PM_{2.5}$, $PM_{10\text{-}2.5}$ particle mass, speciated $PM_{10\text{–}2.5}$, O_3, SO_2, CO, NO/NO_Y, wind speed, wind direction, relative humidity, and ambient temperature (http://www.epa.gov/ttn/amtic/ncore/index.html).

methods can be designated as federal reference methods (FRMs) or federal equivalent methods (FEMs). Measurements for determinations of NAAQS compliance must be made with FRMs or FEMs.[5] Specifications for CO monitoring are designed to help states utilize equipment that has met performance criteria utilized in the FRM or FEM approval process; operational parameters are documented in 40 CFR Part 53, Table B-1. Given the levels of the CO NAAQS (35 ppm, 1-hour; 9 ppm, 8-hour), a 1.0 ppm lower detectable limit (LDL) is well below the NAAQS levels and is therefore sufficient for demonstration of compliance. However, with ambient CO levels now routinely near 1 ppm, there is greater uncertainty in a larger portion of the distribution of monitoring data because a large percentage of these measurements are below the LDL of conventional monitors. For this reason, a new generation of ambient CO monitors has been designed that provides trace-level measurements with improved sensitivity at or below the typical ambient CO levels measured in most urban and all rural locations. Additionally, trace-level CO measurements are needed to support additional objectives such as validating the inputs to chemical transport models and assessing the role of transport between urban and rural areas because background CO concentrations on the order of 0.1 ppm are well below the LDL of conventional monitors. Newer GFC instruments have been designed for automatic zeroing to minimize drift (US EPA, 2000).

Currently, a total of 13 approved FRMs are in use in the SLAMS network, based on a retrieval of data reported between 2005 and 2009. Among these methods, nine are "legacy" monitors with a federal method detection limit (MDL) listed as 0.5 ppm according to records in EPA's Air Quality System (AQS).[6] As discussed in the draft ISA, many of the reported concentrations in recent years are near or below these MDLs (draft ISA, p. 3-43). Four of these methods are newer trace-level methods with a federal MDL of 0.02 ppm and a growing body of ambient data from trace-level CO instruments is becoming available. Among newer GFC trace-level instruments, manufacturer-declared LDLs range from 0.02 – 0.04 ppm, with 24-hour zero drift varying between 0.5% within 1 ppm and 0.1 ppm, and precision varying from 0.5% to 0.1 ppm. EPA performed MDL testing on several trace-level CO monitors in 2005 and 2006 following the 40 CFR Part 136 procedures. Those tests demonstrated MDLs of approximately 0.017 – 0.018 ppm (17 – 18 ppb), slightly below the stated LDL of 0.02 – 0.04 ppm.

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[5] As of August 2009, twenty automated FRMs had been approved for CO measurement. All EPA FRMs for CO operate on the principle of non-dispersive infrared (NDIR) detection and can include the gas filter correlation (GFC) methodology. An extensive and comprehensive review of NDIR, GFC, and alternative, non-FRM techniques for CO detection was included in the 2000 CO AQCD (US EPA, 2000).

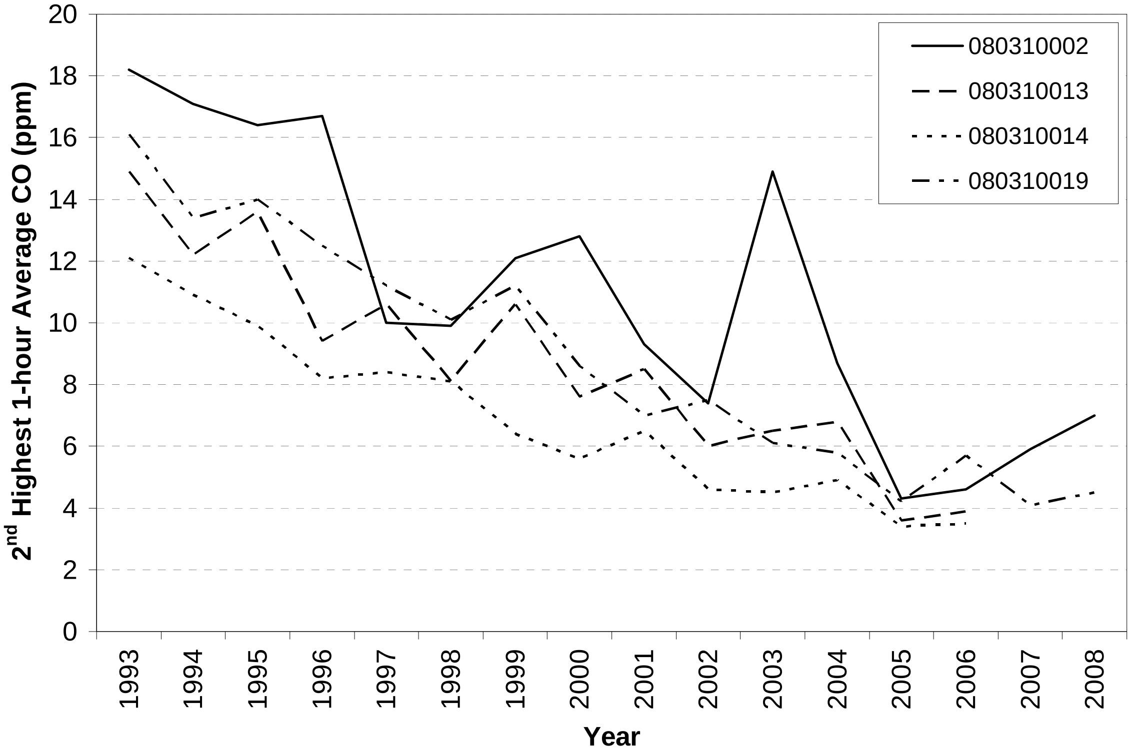
[6] Among several of the older instruments (Federal Reference Method codes 008, 012, 018, 033, 041, 050, 051, and 054), performance testing has shown LDLs of 0.62 – 1.05 ppm, with 24-hour drift ranging from 0.044 – 0.25 ppm and precision ranging from 0.022 – 0.067 ppm at 20% of the upper range limit of the instrument (Mitchie et al., 1983).

Based on a retrieval of data reported between 2005 and 2009 to AQS, a total of 36 trace-level CO monitors have reported data with the majority of these monitors currently active. The majority of these active monitors are associated with the implementation of the NCore network. The extent to which trace-level monitors become integrated into non-NCore SLAMS stations, however, will depend on the availability of funding for states to replace well-operating legacy CO monitors as well as the possibility that monitoring requirements for CO might either encourage or require such technological improvements.

3.1.3 Patterns of CO Concentrations

As discussed in the draft ISA, the spatial and temporal patterns of ambient CO concentrations are heavily influenced by the patterns associated with mobile source emissions (draft ISA, chapter 3). Based on the 2002 National Emissions Inventory (NEI), on-road mobile sources comprise about half of the total anthropogenic CO emissions, though in metropolitan areas of the U.S. the contribution can be as high a 75% of all CO emissions due to greater motor vehicle density. For example, emissions in Denver county originating from on-road mobile sources is about 71% of total CO emissions (draft ISA, section 3.2). When considering all mobile sources (non-road and on-road combined), the contribution to total CO emissions can be over 80%. Again using Denver County as an example, all mobile sources contribute to about 98% of total CO emissions. Temporally, the national-scale anthropogenic CO emissions have decreased 35% between 1990 and 2002. Nearly all the national-level CO reductions since 1990 are the result of emission reductions in on-road vehicles (draft ISA, Figure 3.-2).

Nearly 400 ambient monitoring stations report continuous hourly averages of CO concentrations across the U.S. Over the period 2005-2007, 291 out of 376 monitors met a 75% completeness requirement, spread among 243 counties, cities, or municipalities (draft ISA, section 3.4.2.2). All CO concentrations measured at these monitoring sites are well below the current NAAQS. For example, in 2007, none of the monitors reported a second-highest 1-hour CO concentration above 35 ppm, the level of the current 1-hour NAAQS, while only two sites reported a 2^{nd} highest 1-hour CO concentrations between 15.1 and 35.0 ppm. Only five counties reported 2^{nd} highest 8-hour CO concentration 5.0 ppm or higher.



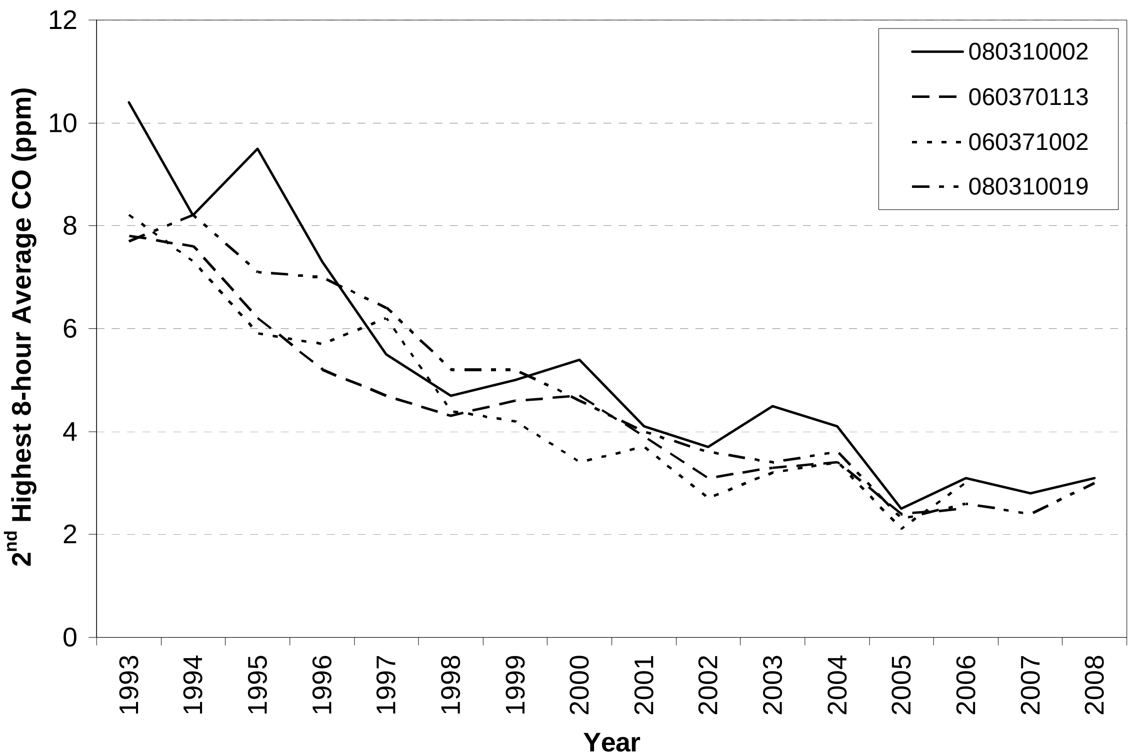
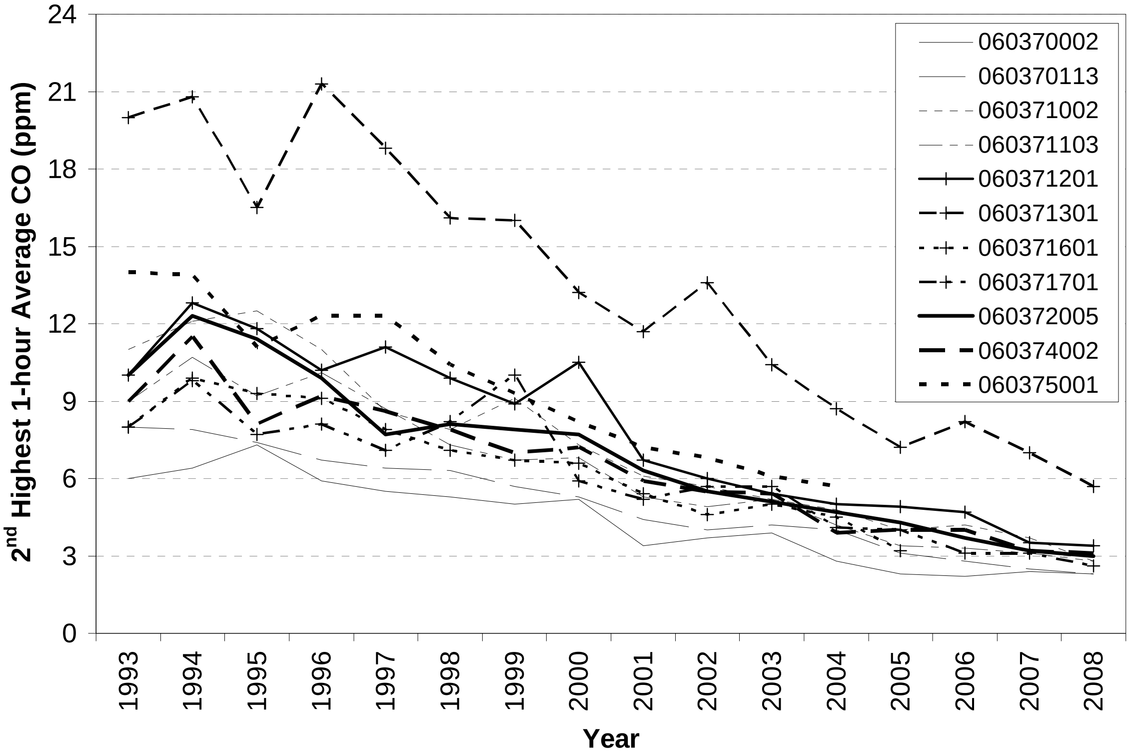


Figure 3-1. Spatial and Temporal Trends in the 2nd Highest 1-hour (top) and 8-hour Average (bottom) CO Ambient Monitoring Concentrations in Denver, Colorado, Years 1993 – 2008.



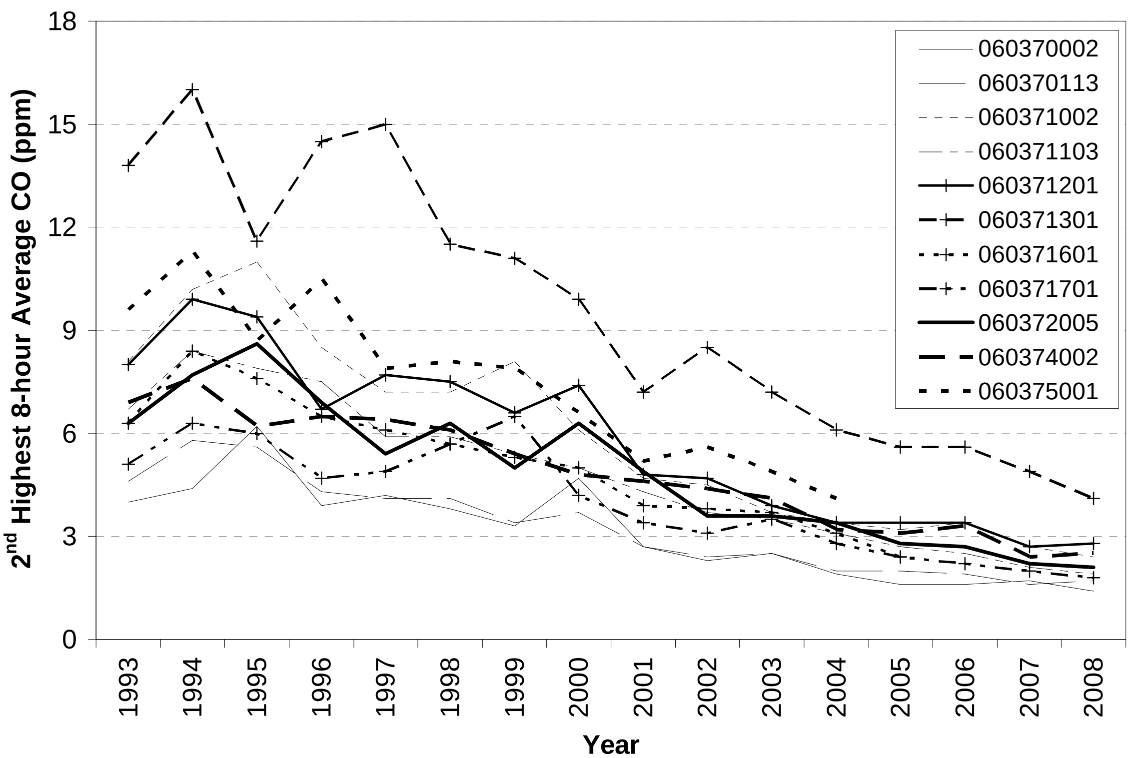


Figure 3-2. Spatial and Temporal Trends in the 2nd Highest 1-hour (top) and 8-hour Average (bottom) CO Ambient Monitoring Concentrations in Los Angeles, California, Years 1993 – 2008.

The current levels of ambient CO across the U.S. reflect the steady declines in ambient concentrations that have occurred over the past several years. On average across the U.S. the decline has been on the order of 50% since the early 1990s (draft ISA, Figure 3-31). As an example, Figures 3-1 and 3-2 illustrate the trends observed in Denver and Los Angeles, respectively, for the period from 1993 through 2008. Both the 2nd highest 1-hour and 8-hour concentrations are plotted for each year from all existing monitors in those metropolitan areas respectively. Note, these figures indicate both a significant decrease in the 2nd highest 1-hour and 8-hour average CO concentrations and a relative decrease in spatial variability in ambient CO concentrations since the last review.

Carbon monoxide also exhibits hourly variability within a day, with two distinct temporal patterns noted for weekdays and weekends (draft ISA, section 3.5.2.2). The diel variation is inherently linked to the typical commute times-of-day that occurs within urban locations. In general, in recent years observed mean and median concentrations for all hours of the day and across all monitors within urban areas demonstrated limited variability, however 90th and 95th percentile hourly concentrations generally exhibit early-morning and late afternoon peak CO concentrations during weekdays (draft ISA, Figure 3-33). The weekend diel variation in ambient CO concentrations was much lower than that occurring during weekdays as expected due to the relative absence of commuter vehicle traffic during the morning and evening hours of the day. Most urban areas have relatively stable concentrations throughout weekend days at each of the selected percentiles, though a few locations (e.g., Phoenix, Los Angeles, Seattle) did have a more pronounced late afternoon peak (draft ISA, Figure 3-34).

Staff investigated local hourly variation at two separate CO monitors located in Denver and Los Angeles to illustrate similar trends. Figure 3-3 indicates that on average, peak ambient CO concentrations that occur during typical commute times in Denver ranged from about 1 to 5 ppm during weekdays in 1995, while, currently, ambient CO concentrations during morning and afternoon commutes range from about 1 to 2 ppm. Weekends tend to exhibit less variability throughout the day. On average, CO ambient concentrations generally ranged from 1 to 3 ppm throughout the day in 1995, while current weekend concentrations are less than 1 ppm for most hours of the day. In Los Angeles, both the concentration levels and variability are greater than when compared with similar years and times of day in Denver (Figure 3-4). Peak ambient CO concentrations are more prominent during morning commutes and generally ranged from 2 to 10 ppm in 1995, while currently (year 2006) most commuting times are associated with concentrations ranging from between 1 and 5 ppm. The weekend profile exhibits some variation when considering either year, with maximum concentration levels and variability exhibited during the overnight hours.

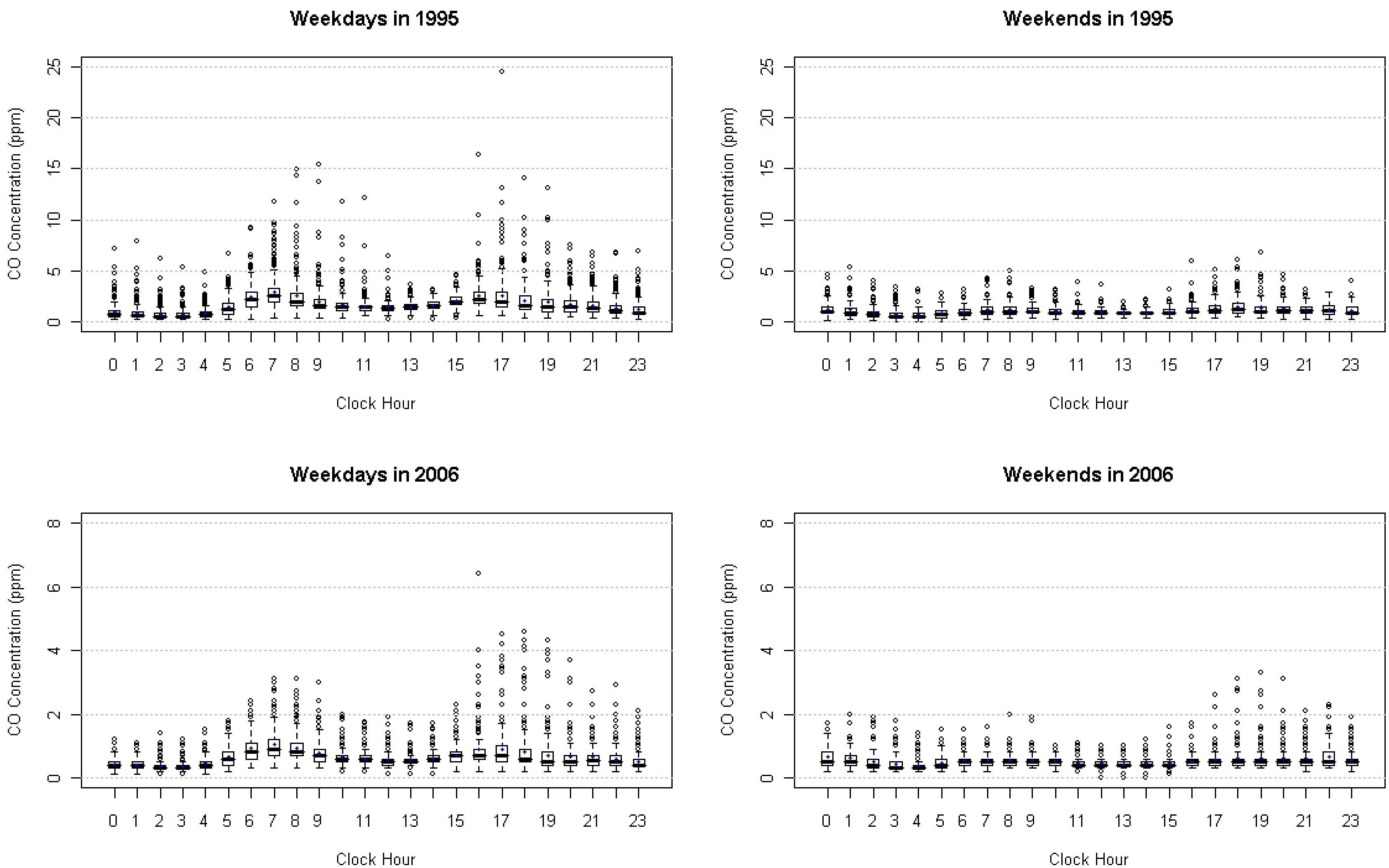


Figure 3-3. Diurnal Distribution of 1-hour CO Concentrations in Denver (Monitor 08-031-0002) by Day-type (weekdays-left; weekends-right), Years 1995 (top) and 2006 (bottom). The box encompasses concentrations from the 25th to 75th percentiles or Interquartile range (IQR), the line bisecting the box is the median, the solid dot within the box is the mean, the whiskers represent 1.5 times the IQR, and concentrations outside the whiskers are indicated by open circles.

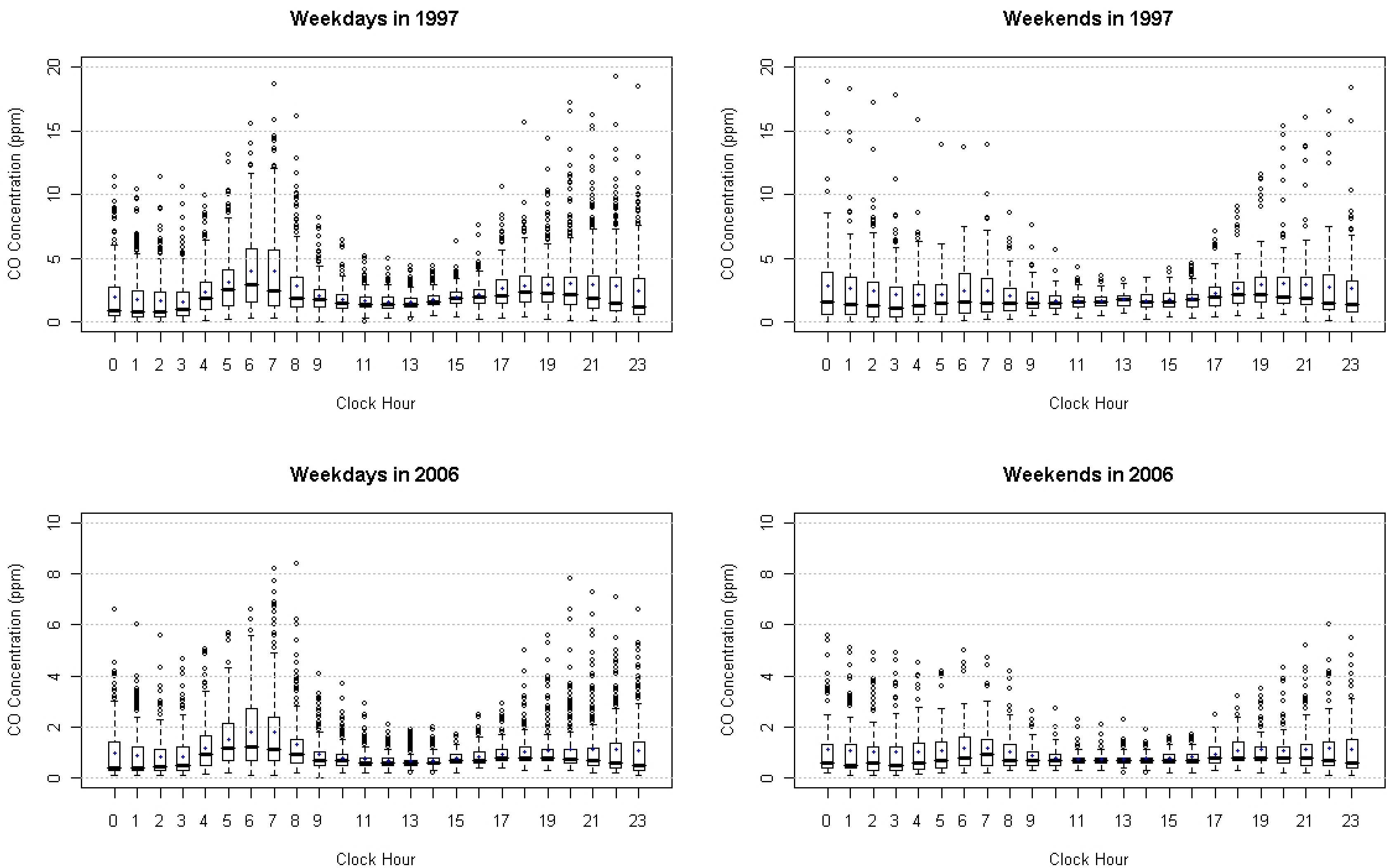


Figure 3-4. Diurnal distribution of 1-hour CO concentrations in Los Angeles (Monitor 06-037-1301) by day-type (weekdays-left; weekends-right), years 1997 (top) and 2006 (bottom). The box encompasses concentrations from the 25th to 75th percentiles or IQR, the line bisecting the box is the median, the solid dot within the box is the mean, the whiskers represent 1.5 times the IQR, and concentrations outside the whiskers are indicated by open circles.

Ambient monitor siting characteristics can also influence ambient CO concentration observations. Microscale and middle scale monitors are commonly used to measure significant source impacts, while neighborhood and urban scale monitors are designated for population-oriented monitoring (40 CFR Part 58 Appendix D). As CO concentrations primarily originate from vehicle emissions, the microscale and middle scale data can be a useful indicator of near-road air quality. Such data analyzed in the draft ISA were concluded to be consistent with hourly concentrations reported in the literature for the near road environment in the U.S. (draft ISA, p. 3-63). Further, when considering monitoring scale across ambient monitors in the U.S., the median hourly CO concentration measured at microscale monitors was about 25% higher than at middle scale monitors and 67% higher than at neighborhood scale monitors (draft ISA, Table 3-12). In general, similar patterns were present in the 1-hour daily max, 1-hour daily average, and 8-hour daily max distributions (draft ISA, Table 3-12). These patterns are also consistent with findings presented by other researchers regarding the relative decrease in concentration with increasing distance from roadways, though the magnitude of the relationship can vary. Two studies summarized in the draft ISA (Zhu et. al., 2002; Baldauf et. al., 2008) indicate that near-road CO concentrations (i.e., measured within 20 m of an interstate highway) can range from 2 – 10 times greater than CO concentrations measured as far as 300 m from a major road (draft ISA, Figures 3-26 and 3-27).

While recognizing that monitoring site attributes are not available for all monitors in the current network and that data for some attributes may not reflect current conditions, [7] the draft ISA also analyzed the information available for network monitors on average annual daily traffic (AADT). The ISA noted that only two microscale monitors and two middle scale monitors in the existing network are sited at roads with ≥100,000 AADT, although it is not uncommon for roadways within CSAs to have several roads with AADT > 100,000. The AADT ranged from 160,000-178,000 for the near-road monitors used in the aforementioned study by Zhu et al. (2002) where CO concentrations were up to 10 times greater than monitors sited at 300 m from a major road. Existing microscale sites near roads having only moderate traffic count data (<100,000AADT) may record concentrations that are not substantially different from those obtained from neighborhood scale measurements (draft ISA, section 3.5.1.3).

Within a specific urban area however, consideration of only monitor scale or other attributes reported in AQS, such as AADT estimates may be of limited use in efforts to characterize the monitoring data as to its representation of local near-road CO concentrations. For example, of the five monitors meeting a 75% completeness criterion in the Denver

[7] Note that recorded AQS monitoring site attributes are not always available for each monitor or may not always reflect potential source influences. For example, of 24 CO monitors in the Los Angeles CSA, AQS had no information regarding monitoring scale for 16 (draft ISA, Figure 3-20).

Consolidated Statistical Area (CSA), three were microscale and two were neighborhood scale (draft ISA, section 3.5.1.2). While one of the microscale monitors sited within downtown Denver measured the highest hourly ambient CO concentrations (ID 080310002), another microscale monitor located outside the urban core measured the lowest hourly ambient CO concentrations (draft ISA, Figure 3-18). Further, the AADT estimate for a major road near the microscale monitor within the urban core (ID 080310002, AADT=17,200) was lower than that listed for the microscale monitor outside the urban core (ID 080130009, AADT=20,000) (draft ISA, Table A-2). And, a third microscale monitor located 1.3 km from monitor ID 080310002, within the urban core, and measuring somewhat lower CO concentrations (but not lower than the monitor outside the urban core) had only 500 AADT listed for the nearest major road. It is likely that the higher CO concentrations measured at the downtown monitor reflect influences of the denser roadway network surrounding that monitor in the downtown Denver area (Figure 3-17).[8]

Thus, to better characterize the representation of near-road CO concentrations for many of the existing ambient monitors, additional analyses, beyond consideration of AQS attributes such as monitoring scale and traffic count, would likely need to be performed (e.g., using GIS to determine monitor distance from roads, the number and type of roads within close proximity of the monitor, and obtaining current traffic count data for all roads).

3.1.4 Policy-Relevant Background Concentrations

EPA has generally conducted NAAQS risk assessments that focus on the risks associated with ambient levels of a pollutant that are in excess of policy-relevant background (PRB). Policy-relevant background levels are defined, for purposes of this document, as concentrations of a pollutant that would occur in the U.S. in the absence of anthropogenic emissions in the U.S., Canada, and Mexico. Over the continental U.S. (CONUS), the 3-year (2005- 2007) average CO PRB concentration is estimated to range from 118 to 146 ppb (draft ISA, section 3.5.4). Outside the CONUS, the 3-year average CO PRB in three Alaskan sites is estimated to range from 127 to 135 ppb, and from 95 to 103 ppb in two Hawaiian monitoring locations. The estimated PRB concentrations exhibit significant within-location seasonal variation, with minimum concentrations observed in the summer and fall and maximum concentrations occurring in the winter and spring. For example, PRB in two California sites is estimated to range from about 85 to 170 ppb, and one site in Colorado, ranged from about 80 to 140 ppb (Figure 3-40 of the draft ISA).

Given that ambient concentrations of interest in this REA are well above the estimated PRB levels discussed above and, thus the contribution of PRB to overall ambient CO

[8] Staff also recognizes some uncertainty in how well the AQS AADT estimates reflect current conditions at this monitor site.

concentrations is very small, EPA is characterizing risks associated with ambient CO levels without regard to estimated PRB levels.

3.2 STUDY AREAS FOR CURRENT ASSESSMENT

Staff identified several criteria to select the exposure assessment study areas drawing from information discussed in the earlier sections of this Chapter and additional scientific evidence in the draft ISA. We selected Denver and Los Angeles as areas to focus the current assessment because (1) both cities have been included in prior CO NAAQS exposure assessments and thus serve as an important connection with past assessments, (2) they have historically had the highest CO ambient concentrations among urban areas in the U.S., and (3) Denver is at high altitude and represents an important risk scenario due to the increased susceptibility of individuals at high altitude from exposure to CO. In addition, of 10 urban areas across the U.S. having monitors meeting a 75% completeness criteria, the two locations were ranked 1st (Los Angeles) and 2nd (Denver) regarding percent of elderly population within 5, 10, and 15 km of monitor locations, and ranked 1st (Los Angeles) and 5th (Denver) regarding number of 1- and 8-hour daily maximum CO concentration measurements (draft ISA, section 3.5.1.1).

Maximum and 2nd highest 1-hour and 8-hour average CO concentrations are provided in Table 3-1 for all monitors located within four Denver-area counties (i.e., Adams, Boulder, Jefferson, and Denver) having at least one year of ambient monitoring data for years 2005 through 2007.[9] Table 3-2 provides a similar concentration summary for the Los Angeles monitors in four counties (i.e., Los Angeles, Orange, Riverside, and San Bernardino) that reported CO concentrations for at least one year between 2005 and 2007. Additional discussion regarding specific sites and monitoring data used in the exposure modeling is provided in sections 5.5 and 6.1.2.

In order to investigate ambient CO concentrations in each study area, EPA initially considered the sites listed in Tables 3-1 and 3-2 that reported data for at least one year between 2005 and 2007 with 75% completeness. As shown in these tables, maximum concentrations as well as 2nd highest 1-hour and 8-hour average CO concentrations generally are quite homogeneous and do not exhibit great variability. Focusing on Denver and Los Angeles Counties, however, the sites show higher concentrations for the year 2006 in specific sites within each county.

Considering the spatial scale and location of monitoring sites in these two areas, staff recognizes limitations related to the coverage provided by the available sites, particularly in the Denver area, to support development of a comprehensive population exposure assessment for these urban areas in this time period. This issue is discussed further in chapter 5.

[9] There were no CO monitoring data reported for Arapahoe and Douglas Counties.

Table 3-1. Descriptive Statistics for CO Concentrations Measured at Selected Fixed-Site Monitors in the Denver Metropolitan Area for the Years 2005 - 2007.

County	Site ID (location)	Year	Number of 1-hour values	CO concentration (ppm) 1-hour Maximum	1-hour 2nd Highest	8-hour average Maximum	8-hour average 2nd Highest
Adams	080013001 (Welby)	2005	8693	3.4	3.3	2.5	2.2
		2006	8633	3.8	3.8	2.6	2.5
		2007	8663	3.1	3	2.3	2.1
Boulder	080130009 (440 Main St)	2005	8509	5	4.8	2.5	2.4
		2006	8531	3.9	2.8	2.2	1.8
		2007	8588	3.8	3.4	2.3	1.9
	080130010 (2150 28th St.)	2005	2978	3.6	3.2	2	1.9
Denver	080310002 (CAMP)	2005	8680	4.6	4.3	2.9	2.5
		2006	8672	6.4	4.6	3.4	3.1
		2007	8676	6	5.9	3.2	2.8
	080310013 (NJE-E)	2005	8674	5.3	3.6	2.5	2.4
		2006	8635	4.4	3.9	2.9	2.5
	080310014 (Carriage)	2005	8121	3.9	3.4	2.3	2.1
		2006	8557	3.9	3.5	3	3
	080310019 (Firehouse #6)	2005	8640	5.6	4.2	2.4	2.3
		2006	8569	9.3	5.7	3.1	2.6
		2007	8412	4.2	4.1	2.5	2.4
Jefferson	080590002	2005	8461	4.1	3.6	2.1	2
		2006	8603	3.6	3.5	2	2

Table 3-2. Descriptive Statistics for CO Concentrations Measured at Selected Fixed-Site Monitors in the Los Angeles Metropolitan Area for the Years 2005 - 2007.

County	Site ID (location)	Year	Number of 1-hour values	CO concentration (ppm)			
				1-hour		8-hour average	
				Maximum	2nd Highest	Maximum	2nd Highest
Los Angeles	060370002 (Azusa)	2005	8355	2.5	2.3	1.7	1.6
		2006	8368	2.2	2.2	1.7	1.6
		2007	8344	2.6	2.4	1.8	1.7
	060370113 (West Los Angeles)	2005	8350	3.4	3.1	2.1	2.0
		2006	8365	2.9	2.8	2.0	1.9
		2007	8267	2.7	2.5	2.0	1.6
	060371002 (Burbank)	2005	8279	4.4	4.0	3.4	3.2
		2006	8345	4.3	4.2	3.4	3.4
		2007	8334	3.7	3.7	2.8	2.7
	060371103 (Los Angeles)	2005	8298	3.9	3.4	3.1	2.7
		2006	8265	3.5	3.3	2.7	2.5
		2007	8148	3.2	3.1	2.2	2.1
	060371201 (Reseda)	2005	8018	5.1	4.9	3.5	3.4
		2006	8375	4.8	4.7	3.5	3.4
		2007	7954	3.7	3.5	2.8	2.7
	060371301 (Lynwood)	2005	8331	7.4	7.2	5.9	5.6
		2006	8275	8.4	8.2	6.2	5.6
		2007	8284	7.8	7.0	5.3	4.9
	060371601 (Pico Rivera)	2005	2538	3.3	3.2	2.4	2.4
		2006	4698	3.1	3.1	2.7	2.7
		2007	8318	4.8	3.7	2.9	2.8
	060371701 (Pomona)	2005	8350	4.2	4.0	2.5	2.4
		2006	8335	3.3	3.1	2.2	2.2
		2007	8293	3.3	3.1	2.0	2.0
	060372005 (Pasadena)	2005	8274	4.3	4.3	2.8	2.8
		2006	8258	4.1	3.7	2.8	2.7
		2007	8338	3.3	3.2	2.3	2.2
	060374002 (Long Beach)	2005	8340	4.2	4.0	3.5	3.1
		2006	8216	4.2	4.0	3.4	3.3
		2007	7769	3.3	3.2	2.6	2.4
	060375005 (Los Angeles)	2005	8364	2.8	2.7	2.1	2.1
		2006	8356	2.8	2.7	2.3	2.1
		2007	8311	3.3	3.2	2.4	2.1
	060376012 (Santa Clara)	2005	8248	2.2	2.0	1.3	1.2
		2006	8339	2.0	2.0	1.3	1.1
		2007	8339	1.9	1.9	1.2	1.2
	060379033 (Lancaster)	2005	8265	2.9	2.5	1.5	1.5
		2006	7710	3.2	2.8	1.6	1.6
		2007	8226	2.5	2.3	1.3	1.2
Orange	060590007	2005	8307	4.1	4	3.3	3.1

County	Site ID (location)	Year	Number of 1-hour values	CO concentration (ppm)			
				1-hour		8-hour average	
				Maximum	2nd Highest	Maximum	2nd Highest
	(Anaheim)	2006	8342	4.5	4.3	2.9	2.9
		2007	7681	3.6	3.6	2.9	2.3
	060591003 (Costa Mesa)	2005	8308	4.7	4.1	3.2	3.1
		2006	8358	3.5	3.3	3.0	2.5
		2007	8160	4.5	4.4	3.1	2.6
	060592022 (Mission Viejo)	2005	8265	2.2	2.2	1.6	1.6
		2006	8336	1.9	1.9	1.6	1.3
		2007	8296	2.9	2.7	2.2	2.0
	060595001 (La Habra)	2005	8333	6.8	6.7	3.1	3.0
		2006	8227	6.0	6.0	2.9	2.9
		2007	8211	6.3	6.3	2.9	2.7
Riverside	060651003 (Riverside)	2005	8190	4.0	3.7	2.4	2.2
		2006	8385	3.8	3.8	2.4	2.1
		2007	8376	3.7	3.4	2.2	2.0
	060655001 (Palm Springs)	2005	8296	2.1	2.0	0.8	0.7
		2006	8357	2.3	1.8	0.9	0.8
		2007	8351	1.5	1.5	0.8	0.7
	060658001 (Rubidoux)	2005	8216	3.4	3.3	2.5	2.3
		2006	8348	2.7	2.7	2.3	2.1
		2007	8280	3.8	3.6	2.9	2.5
	060659001 (Lake Elsinore)	2005	8312	1.7	1.5	1.0	1.0
		2006	8256	1.4	1.4	1.0	1.0
		2007	8290	1.6	1.5	1.4	1.3
San Bernardino	060710001 (Barstow)	2005	8106	3.3	2.2	1.3	1.2
		2006	7847	3.5	2.6	1.2	1.1
		2007	8217	1.4	1.3	0.7	0.6
	060710306 (Victorville)	2005	8289	2.5	2.1	1.6	1.4
		2006	8225	2.2	2.2	1.6	1.5
		2007	8348	2.1	2.0	1.6	1.5
	060711004 (Upland)	2005	8314	2.5	2.4	1.9	1.7
		2006	8210	2.7	2.6	1.9	1.8
		2007	8309	2.4	2.2	1.7	1.6
	060719004 (San Bernardino)	2005	8240	3.8	3.3	2.5	2.2
		2006	8340	2.8	2.8	2.2	2.0
		2007	8330	3.7	3.1	2.3	2.1

3.3 KEY OBSERVATIONS

Presented below are key observations resulting from the air quality considerations.

- Automobiles are the primary contributor to CO emissions, particularly in urban areas due to greater vehicle and roadway densities.
- Recent (2005-2007) ambient CO concentrations across the U.S. are lower than those reported in the previous CO NAAQS review and are also well below the current CO NAAQS levels. Further, a large proportion of the reported concentrations are below the conventional instrument detection limit of 1 ppm.
- Ambient CO concentrations are highest at monitors sited closest to roadways (i.e., microscale and middle scale monitors) and exhibit a diel variation linked to the typical commute times of day, with peaks generally observed during early morning and late afternoon during weekdays.
- The currently available information for CO monitors indicates that siting of microscale and middle scale monitors in the current network is primarily limited to roads where traffic density described for them is moderate (<100,000 AADT), however, factors other than reported AADT (e.g., orientation with regard to dense urban roadway networks) can contribute to sites reporting higher CO concentrations.
- Due to the limited number of existing ambient monitors and the monitor site characteristics, it is difficult to fully characterize the current spatial and temporal variability in CO ambient concentrations across the two urban areas that are the focus for this assessment, Denver and Los Angeles.

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4. APPROACH TO RISK CHARACTERIZATION FOR CURRENT REVIEW

This section describes the health effects evidence, dose metric of interest and approach to characterization of risk in support of the current review of the CO primary NAAQS. Similar to the approach used in prior CO NAAQS reviews, the approach to risk characterization presented in this section is based on the estimation of CO exposures and resulting doses (an internal biomarker) for a defined at-risk population within urban study areas associated with CO levels representing recent air quality and air quality adjusted to simulate just meeting the current CO NAAQS.

Carbon monoxide can elicit a broad range of effects in multiple tissues and organ systems that are dependent upon concentration and duration of exposure, and that may involve multiple mechanisms including hypoxic stress and others such as free radical production and the initiation of cell signaling. However, binding of CO to reduced iron in heme proteins with subsequent alteration of heme protein function is the common mechanism underlying the biological responses to CO (draft ISA, section 5.1). Similarly, based on the health effects evidence summarized in the draft ISA, the best characterized dose metric for estimating exposure to CO associated with adverse health effects is blood carboxyhemoglobin (COHb) levels. As described in the draft ISA, the most compelling evidence of a CO-induced effect on the cardiovascular system at COHb levels relevant to the current NAAQS comes from a series of controlled human exposure studies among individuals with coronary heart disease (CHD) (draft ISA, section 5.2). Specifically for the current analysis, we characterize risk for the population of interest (CHD population) by using a potential health effects benchmark level approach, in combination with short-term CO exposure and dose modeling, to estimate the number and percent of the population with CHD that would potentially exceed COHb levels of concern, upon just meeting various CO air quality scenarios. Section 4.1 presents a brief summary of the health effects evidence from controlled human exposure studies (draft ISA, section 5.2.4) and section 4.2 describes the rationale for the selection of potential health effects benchmarks and their use in the characterization of risk for adults with CHD. Section 4.3 presents key observations relevant to the approach for the risk characterization.

4.1. CARDIOVASCULAR DISEASE RELATED EFFECTS

Controlled human studies provide strong evidence for an association between short-term exposure to CO and exacerbation of preexisting coronary heart disease. Several controlled human exposure studies discussed in the 2000 CO AQCD (section

6.2.2, US EPA, 2000) showed that short-term exposure to CO and subsequent elevation of COHb levels enhance exercise-induced myocardial ischemia.

Among those studies the draft ISA places emphasis on the work of Allred et al., a large multi-laboratory study designed to evaluate myocardial ischemia, as documented by electrocardiogram ST-segment changes and time to onset of angina, during a standard treadmill test, at CO exposures targeted to result in COHb levels of 2% and 4%. As described in the draft ISA (draft ISA, section 5.2.4), other controlled human exposure studies (Adams et al. 1988, Anderson et al. 1973, Kleinman et al 1989, Kleinman et al., 1998) involving individuals with stable angina have also demonstrated the capacity of CO to decrease the time to onset of angina, as well as to reduce the duration of exercise at COHb concentrations between 3 and 6% (as measured by CO-oximeter). A single study by Sheps et al. (1987) observed no change in time to onset of angina or maximal exercise time following a 1 h exposure to 100 ppm CO (targeted COHb of 4%) among a group of 30 patients with CHD. In a subsequent study conducted by the same laboratory, a significant increase in number of ventricular arrhythmias during exercise was observed relative to room air among individuals with CHD following a 1-hr exposure to 200 ppm CO (targeted COHb of 6%), but not following a 1-hr exposure to 100 ppm CO (targeted COHb of 4%) (Sheps et al., 1990). The draft ISA notes that although the subjects evaluated in the studies described above are not necessarily representative of the most sensitive population, the level of disease in these individuals was relatively severe, with the majority either having a history of myocardial infarction or having ≥ 70% occlusion of one or more of the coronary arteries.

The draft ISA (draft ISA, section 5.2.4) states that no new human clinical studies involving controlled short-term CO exposures among subjects with coronary artery disease have been published since the 2000 CO AQCD. However, a number of new studies have investigated the effects of CO in healthy adults. Adir et. al., (1999) showed that short-term exposure to CO at concentrations targeted to produce 4-6% COHb, followed by a treadmill test (at maximal exercise capacity), caused a decrease in the duration of exercise and in the metabolic equivalent units (indicative of the oxygen consumed by the body during exercise). The draft ISA notes that these results are in agreement with the findings of several studies cited in the 2000 CO AQCD which observed decreases in exercise duration and maximal aerobic capacity among healthy adults at COHb levels ≥ 3% (draft ISA, section 5.2.4), which provides coherence with the observed effects of short-term exposure to CO on exercise-induced myocardial ischemia among patients with CHD.

4.2. HEALTH EFFECT BENCHMARKS

As in the review completed in 1994 and in the CO exposure/dose assessment completed in 2000 (section 6.3.2), a health effect benchmark level approach is used in the current analysis to estimate the number and percent of the population with CHD that would potentially exceed COHb levels of concern for specific CO air quality scenarios. Since the ISA has not identified new studies that demonstrate CO effects at COHb levels lower than those described in the 2000 AQCD, we are relying in the same studies as we did on the review completed in 1994. As mentioned above, a number of studies, described in detail in the 2000 CO AQCD (section 6.2.2, US EPA, 2000), showed statistically significant group mean responses, measured in terms of reduced time to onset of exercise-induced angina, in the range of 3 to 6 %COHb (measured by CO-oximeter) in subjects with coronary heart disease. We note that the lowest COHb level at which reduced time to onset of angina was observed was in the range of 2.0 to 2.4% COHb (measured by gas chromatography), in a multi-center CO exposure study (Allred et al., 1989a,b, 1991; draft ISA, section 5.2.6). This range (2.0-2.4%) is representative of the two individual COHb level averages obtained post-exposure (2.4%) and post-exercise test (2.0%). However, there was no clear pattern across the different studies with respect to the magnitude of the decreased time to onset of angina versus dose level. In addition, these studies do not address the fraction of the population experiencing a specified health effect at various dose levels. Thus, based on information in the draft ISA, staff concluded that at this time there is insufficient controlled human exposure data to support the development of quantitative dose-response relationships which would be required in order to conduct a quantitative risk assessment for this health endpoint.

Potential health effect benchmark values used in the risk characterization linked to the exposure/dose analyses were derived solely based on the controlled human exposure literature. This is primarily because CO concentrations reported in controlled human exposure studies represent actual personal exposures rather than concentrations measured at fixed site ambient monitors. In addition, controlled human exposure studies can examine the health effects of short-term exposure to CO in the absence of co-pollutants that can confound results in epidemiologic analyses; thus, health effects observed in controlled human exposure studies can confidently be attributed to a defined COHb dose level associated with ambient short-term CO exposures.

In identifying the potential health effect benchmark levels for the risk characterization, staff considered a number of factors in drawing on the results of controlled human exposure studies. As noted above, the lowest group mean COHb level at which reduced time to onset of angina was observed was in the range of 2.0 to 2.4% COHb (measured by gas chromatography(GC)) in a multi-center CO exposure study (Allred et al., 1989a,b, 1991; draft ISA, section 5.2.6 and 2.5.1). Similar effects have not been evaluated below this range.

Staff identified potential health effects benchmarks of 1.5%, 2.0%, 2.5% and 3% COHb levels based on the consideration of the studies reporting adverse effects at COHb levels as low as 2 to 2.4% (using GC) discussed above. These levels reflect comments from the CASAC CO panel on the draft Analysis Plan (Brain and Samet, 2009) and include the range of levels considered in the review completed in 1994 (US EPA, 1992). The potential health effects benchmarks extend lower than the range where controlled human exposure studies reported CO-related health effects to take into consideration both the uncertainty about the actual COHb levels experienced in the controlled human exposure studies due to the use of different measurement methods and that these studies did not include individuals with more severe cardiovascular disease who may respond at lower COHb levels relative to the subjects tested.

4.3. KEY OBSERVATIONS

Presented below are key observations relevant to the risk characterization approach in support of the current CO NAAQS review.

- An important at-risk population for short-term exposure to is the adult CHD population.
- The data from controlled human studies do not support the development of a quantitative risk assessment due to lack of sufficient information to characterize the dose-response relationship within the range of interest. Instead, risk will be characterized in the current assessment using a potential health effect benchmark levels approach (as in previous assessments).
- Evaluation of health effects evidence reported in controlled human exposure studies of short-term CO exposure in the adult CHD population is the basis for the selection of potential health effects benchmarks of 1.5, 2.0, 2.5, and 3.0% COHb on the consideration of studies reporting adverse effects at COHb levels in the range of 2 to 2.4%.

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5. APPROACH TO EXPOSURE AND DOSE ASSESSMENT FOR CURRENT REVIEW

This chapter presents an overview and description of the overall approach to estimating human exposure and dose for past and recent assessments and presents a strategy for the current exposure and dose assessments for the CO NAAQS review. Section 5.1 provides a brief overview of the exposure model, followed by a short history that explains the evolution of the exposure and dose models used in NAAQS reviews in section 5.2. Section 5.3 provides a description of the exposure and dose models that have been used by OAQPS to conduct prior exposure and dose assessments for CO NAAQS and which serve as the basic modeling tools to be used for the current assessment. Section 5.4 briefly summarizes information about personal exposure and key microenvironments for CO. Section 5.5 discusses the current monitoring network in the two study areas selected for the current assessment and the limitations of the existing monitoring network for purposes of conducting an exposure and dose assessment in these areas. This final section also presents the strategy for the current exposure and dose analysis.

5.1 MODEL OVERVIEW

The Air Pollutants Exposure model (APEX) is a personal computer (PC)-based program designed to estimate human exposure to criteria and air toxic pollutants at the local, urban, and consolidated metropolitan levels. APEX, also known as TRIM.Expo, is the human inhalation exposure module of EPA's Total Risk Integrated Methodology (TRIM) model framework (US EPA, 1999), a modeling system with multimedia capabilities for assessing human health and ecological risks from hazardous and criteria air pollutants.[1]

> A **microenvironment** is a three-dimensional space in which human contact with an environmental pollutant takes place and which can be treated as a well characterized, relatively homogeneous location with respect to pollutant concentrations for a specified time period.

APEX estimates human exposure to criteria and toxic air pollutants at the local, urban, or consolidated metropolitan area levels using a stochastic, "microenvironmental" approach. The model randomly selects data for a sample of hypothetical individuals from an actual population database and simulates each hypothetical individual's movements through time and space (e.g., indoors at home, inside vehicles) to estimate

[1] Additional information on the TRIM modeling system, as well as downloads of the APEX Model, user guides (U.S. EPA 2008a, 2008b), and other supporting documentation, can be found at http://www.epa.gov/ttn/fera.

his or her exposure to a pollutant. APEX can account for travel to and from work locations (i.e., commuting) and provide estimates of exposures at both home and work locations for individuals who work away from home.

5.2 MODEL HISTORY AND EVOLUTION

APEX was derived from the National Ambient Air Quality Standards (NAAQS) Exposure Model (NEM) series of models. The NEM series was developed to estimate population exposures to the criteria pollutants (e.g., CO, ozone). In 1988, OAQPS first incorporated probabilistic elements into the NEM methodology and used activity pattern data based on available human activity diary studies to create an early version of probabilistic NEM for ozone (i.e., pNEM/O_3). In 1991, a probabilistic version of NEM was developed for CO (pNEM/CO) that included a one-compartment mass-balance model to estimate CO concentrations in indoor microenvironments. The application of this model to Denver, Colorado is summarized in Johnson et al. (1992). Between 1999 and 2001, updated versions of pNEM/CO (versions 2.0 and 2.1) were developed that rely on detailed activity diary data compiled in EPA's Consolidated Human Activities Database (CHAD) (McCurdy et al., 2000; US EPA, 2002) and enhanced algorithms for simulating gas stove usage, estimating alveolar ventilation rate (a measure of human respiration), and modeling home-to-work commuting patterns. A draft report by Johnson et al. (2000) describes the application of Version 2.1 of pNEM/CO to Denver and Los Angeles.

The first version of APEX was essentially identical to pNEM/CO (version 2.0) except that it ran on a PC instead of a mainframe. The next version, APEX2, was substantially different, particularly in the use of a personal profile approach rather than a cohort simulation approach. APEX3 introduced a number of new features including automatic site selection from national databases, a series of new output tables providing summary exposure and dose statistics, and a thoroughly reorganized method of describing microenvironments and their parameters. Johnson and Capel (2003) describe a case study in which Version 3.1 of APEX was used to estimate population exposure to CO in Denver and Los Angeles.

The current version of APEX (Version 4.3) (US EPA, 2008a; 2008b) was used to estimate CO exposure and dose as described in chapter 6 of this document. This version was also recently used to estimate ozone (O3) exposures in 12 urban areas for the O3 NAAQS review (US EPA, 2007), in estimating population exposures to nitrogen dioxide (NO2) in Atlanta as part of the NO2 NAAQS review (EPA, 2008c), and in estimating sulfur dioxide (SO2) exposures for asthmatics and asthmatic children in two study areas in Missouri as part of the SO2 NAAQS review (US EPA, 2009a). There have been several recent enhancements to APEX since the prior 1994 CO NAAQS review, including:

- Algorithms for the assembly of multi-day (longitudinal) activity diaries that model intra-individual variance, inter-individual variance, and day-to-day autocorrelation in diary properties;
- Methods for adjusting diary-based energy expenditures for fatigue and excess post-exercise oxygen (EPOC) consumption;
- New equations for estimation of ventilation (i.e., breathing rate);
- The ability to model commuters leaving the study area;
- The ability to model air quality and exposure for flexible time scales;
- New output files containing diary event-level, time-step level, and hourly-level exposure, dose, and ventilation data, and hourly-level microenvironmental data;
- The ability to model the prevalence of disease states such as asthma or coronary heart disease (CHD);
- New output exposure tables that report exposure statistics for population groups and lifestages such as children and active people under different ventilation levels;
- The inclusion of commuting data from the 2000 census; and
- Expanded options for modeling microenvironments.

As discussed below in section 5.3, due to limitations in the CO ambient monitoring data, the current exposure/dose assessment does not take advantage of a number of the recent advances listed above.

5.3 MODEL SIMULATION PROCESS

APEX is designed to simulate population exposure to criteria and air toxic pollutants at local, urban, and regional scales. The user specifies the geographic area to be modeled and the number of individuals to be simulated to represent this population. APEX then generates a personal profile for each simulated person that specifies various parameter values required by the model. The model next uses diary-derived time/activity data matched to each personal profile to generate an exposure event sequence (also referred to as "activity pattern" or "composite diary") for the modeled individual that spans a specified time period, such as a calendar year. Each event in the sequence specifies a start time, exposure duration, a geographic location, a microenvironment, and an activity. Probabilistic algorithms are used to estimate the pollutant concentration and ventilation (respiration) rate associated with each exposure event. The estimated pollutant concentrations account for the effects of ambient (outdoor) pollutant concentration, penetration factor, air exchange rate, decay/deposition rate, and proximity to emission sources, depending on the microenvironment, available data, and the estimation method selected by the user. The ventilation rate is derived from an energy expenditure rate estimated for each individual and specified activity performed. Because the modeled individuals represent a random sample of the population of interest, the distribution of modeled individual exposures can then be extrapolated to the larger population of interest.

The model simulation generally includes up to seven steps.

1. **Characterize the study area:** APEX selects sectors (e.g., census tracts) within a study area—and thus identifies the potentially exposed population — usually based on the user-defined center and radius of the study area and availability of air quality and weather input data for the area (section 5.3.1).
2. **Generate simulated individuals**: APEX stochastically generates a sample of simulated individuals based on the census data for the study area and human profile distribution data (such as age-specific employment probabilities). (section 5.3.2)
3. **Construct activity sequences:** APEX constructs an exposure event sequence (activity pattern) spanning the simulation period for each of the simulated persons based on the CHAD activity pattern data (section 5.3.3).
4. **Calculate microenvironmental concentrations:** APEX enables the user to define microenvironments that people in a study area would visit (e.g., by grouping location codes included in the activity pattern database). The model then calculates time-averaged concentrations (e.g., hourly) of each pollutant in each of the microenvironments for each simulated person for the period of simulation, based on the user-provided ambient air quality data (section 5.3.4).
5. **Estimate energy expenditure and ventilation rates:** APEX constructs a time-series of energy expenditures for each profile based on the activity event sequence. These expenditures are adjusted to ensure that they are physiologically realistic, and then used to estimate a number of ventilation metrics that are later used in estimating dose (section 5.3.5).
6. **Calculate exposure**: APEX assigns a concentration to each exposure event based on the microenvironment occupied during the event and the person's activity. These values are time-averaged (e.g., hourly) to produce a sequence of exposures spanning the specified exposure period (typically one year). The hourly values may be further aggregated to produce 8-hour, daily, monthly, and annual average exposure values (section 5.3.6).
7. **Calculate dose:** APEX optionally calculates hourly, daily, monthly, and annual average dose values for each of the simulated individuals. For the application of APEX to CO, a module within the model estimates the percent COHb level in the blood at the end of each hour based on the time-series of CO concentrations and alveolar ventilation rates experienced by the simulated person (section 5.3.7).

The model simulation continues until exposures (and associated COHb levels) are calculated for the user-specified number of simulated individuals. Figure A-1 in Appendix A presents a conceptual model and simplified data flow of APEX used in this assessment. The following sections provide additional details on the general procedures and algorithms used in each of the simulation steps listed above. The specific inputs and algorithms used in applying APEX to CO for the current assessment are further described in section 6.1

5.3.1 Characterize the Study Area

An initial study area in an APEX analysis consists of a set of basic geographic units called sectors, typically defined as census tracts. The user may provide the geographic center (latitude/longitude) and radius of the study area and then APEX calculates the distances to the center of the study area of all the sectors included in the sector location database, and finally selects the sectors within the radius of the study area. APEX then maps the user-provided air quality and meteorological data for specified monitoring districts to the selected sectors. The sectors identified as having acceptable air quality and meteorological data within the radius of the study area are selected to comprise a final study area for the APEX simulation analysis. This final study area determines the population make-up of the simulated persons (profiles) to be modeled.

5.3.2 Generate Simulated Individuals

APEX stochastically generates a user-specified number of simulated (hypothetical) persons to represent the population in the study area. Each simulated person is represented by a "personal profile." APEX generates the simulated person or profile by probabilistically selecting values for a set of profile variables. The profile variables include:

- Demographic variables (e.g., age, gender, home sector, work sector) that are generated based on the census data;
- Residential variables (e.g., air conditioning prevalence) which are generated based on sets of distribution data;
- Physiological variables (e.g., blood volume, body mass, resting metabolic rate) that are generated based on age- and gender-specific distribution data; and
- Daily varying variables (e.g., daily work status) which are generated based on distribution data that change daily during the simulation period.

APEX first selects and calculates demographic, residential, and physiological variables (except for daily values) for each of the specified number of simulated individuals. APEX then follows each simulated individual over time and calculates exposures (and optionally doses) for the individual over the specified time period. The profile variables are listed and described in detail in section 5 of US EPA (2008b).

5.3.3 Construct Activity Sequences

APEX probabilistically creates a composite diary for each of the simulated persons by selecting a 24-hour diary record – or diary day – from an activity database for each day of the simulation period. (CHAD data are supplied with APEX for this purpose.) A composite diary is a sequence of events that simulates the movement of a modeled person through geographical locations and microenvironments during the simulation period. Each event is defined by geographic location, start time, duration, microenvironment visited, and an activity performed.

The activity database input to APEX contains the following information for each diary day: age, gender, employment status, occupation, day-of-week (day-type), and maximum hourly average temperature. This information enables APEX to select data from the activity database that tend to match the characteristics of the simulated person, the study area, and the specified time period. APEX develops a composite diary for each of the simulated individuals according to the following steps.

1. Divide diary days in the CHAD database into user-defined activity pools, based on day-type and temperature.
2. Assign an activity pool number to each day of the simulation period, based on the user-provided daily maximum/average temperature data.
3. Calculate a selection probability for each of the diary days in each of the activity pools, based on age/gender/employment similarity of a simulated person to a diary day.
4. Probabilistically select a diary day from available diary days in the activity pool assigned to each day of the simulation period.
5. Estimate a metabolic value for each activity performed while in a CHAD location, based on the activity-specific metabolic distribution data. This value is used to calculate a ventilation rate for the simulated person performing the activity.
6. Map the CHAD locations in the selected diary to the user-defined modeled microenvironments.
7. Concatenate the selected diary days into a sequential longitudinal diary for a simulated individual covering all days in the simulated period.

APEX provides an optional longitudinal diary assembly algorithm that enables the user to create composite diaries that reflect the tendency of individuals to repeat activities on a day-to-day basis. The user specifies values for two statistical variables (i.e., D and A) that relate to a key daily variable, typically the time spent per day in a particular microenvironment (e.g., in a motor vehicle). The D statistic reflects the relative importance of within person variance and between person variance in the key variable. The A statistic quantifies the lag-one (day-to-day) variable autocorrelation. APEX then constructs composite diaries that exhibit the statistical properties defined by the specified values of D and A. The longitudinal diary assembly algorithm is described in greater detail in section 6.3 of US EPA (2008b).

5.3.4 Calculate Microenvironmental Concentrations

Probabilistic algorithms are used to estimate the pollutant concentration associated with each exposure event. The estimated pollutant concentrations account for the effects of ambient (outdoor) pollutant concentration, penetration factor, air exchange rate, decay/deposition rate, and proximity to emission sources, depending on the microenvironment, available data, and the estimation method selected by the user.

APEX calculates air concentrations in the various microenvironments visited by the simulated person by using the ambient air data for the relevant census tracts and the user-specified method and parameters that are specific to each microenvironment. In typical applications, APEX calculates hourly concentrations in all the microenvironments at each hour of the simulation for each of the simulated individuals, based on the hourly ambient air quality data specific to the geographic locations visited by the individual. APEX provides two methods for calculating microenvironmental concentrations: the mass balance method and the transfer factors method (described briefly below). The user is required to specify a calculation method for each of the microenvironments; there are no restrictions on the method specified for each microenvironment (e.g., some microenvironments can use the transfer factors method while the others can use the mass balance method). As discussed in section 5.4, the current draft assessment employed a simplified approach relying on the factors model approach with particular focus on the in-vehicle microenvironment.

Mass Balance Model

The mass balance method models an enclosed microenvironment as a well-mixed volume in which the air concentration is assumed to be spatially uniform at any specific time. The concentration of an air pollutant in such a microenvironment is estimated using the following four processes:

- Inflow of air into the microenvironment;
- Outflow of air from the microenvironment;
- Removal of a pollutant from the microenvironment due to deposition, filtration, and/or chemical degradation; and
- Emissions from sources of a pollutant inside the microenvironment (if indoor sources are modeled).

The mass balance model feature of APEX (see Appendix B) has not been used in the APEX application for CO described in this draft REA.

Factors Model

The factors model approach is conceptually simpler than the mass balance method and has fewer user-specified parameters. It estimates the concentration in a microenvironment as a linear function of ambient concentration of that hour, regardless of the concentration in the microenvironment during the preceding hour. Table 5-1 lists the parameters required by the factors model approach to calculate concentrations in a microenvironment without emissions sources.

Table 5-1. Parameters of the Factors Model

Variable	Definition	Units	Value Range
$f_{proximity}$	Proximity factor	N/A	$f_{proximity} > 0$
$f_{penetration}$	Penetration factor	N/A	$0 \leq f_{penetration} \leq 1$

The factors model approach uses the following equation to calculate hourly mean concentration in a microenvironment from the user-provided hourly air quality data:

$$C_{ME}^{hourlymean} = C_{ambient} \times f_{proximity} \times f_{penetration} \qquad (5\text{-}1)$$

where:

$C_{ME}^{hourlymean}$ = Hourly concentration in a microenvironment (ppm)
$C_{ambient}$ = Hourly concentration in ambient environment (ppm)
$f_{proximity}$ = Proximity factor (unitless)
$f_{penetration}$ = Penetration factor (unitless)

The proximity factor ($f_{proximity}$) is used to account for differences in ambient concentrations between the geographic location represented by the ambient air quality data (e.g., a regional fixed-site monitor) and the geographic location of the particular microenvironment. For example, a residence might be located near a heavily-trafficked roadway, whereby the ambient air outside the house would likely have elevated levels of mobile source pollutants such as carbon monoxide. In this case, a value greater than one for the proximity factor would be appropriate to represent the increase in concentrations outside the home relative to the ambient monitor. Additionally, for some pollutants the process of infiltration may remove a fraction of the pollutant from the air. The fraction that is retained in the indoor air is given by the penetration factor ($f_{penetration}$) and is dependent on the particular pollutant's physical and chemical removal rates. Typically, the value of the penetration factor ranges from 0 to 1.

5.3.5 Estimate Energy Expenditure and Ventilation Rates

APEX includes a module that estimates COHb levels in the blood as a function of alveolar ventilation rate, the CO concentration of the respired air, endogenous CO production rate, and various physiological variables such as blood volume and pulmonary CO diffusion rate. Alveolar ventilation rate is estimated as a function of oxygen uptake rate, which in turn is estimated as a function of energy expenditure rate. This section provides a brief summary of the algorithm used to estimate alveolar ventilation rate. A detailed description of the algorithm, together with the distributions and estimating equations used in determining the value of each parameter in the algorithm, can be found in Appendix C.

Energy Expenditure

McCurdy (2000) has recommended that measures of human ventilation (respiration) rate be estimated as functions of energy expenditure rate. The energy expended by an individual during a particular activity can be expressed as

$$EE = (METS) \times (RMR) \qquad (5\text{-}2)$$

in which EE is the average energy expenditure rate (kcal min^{-1}) during the activity and RMR is the resting metabolic rate of the individual expressed in terms of number of energy units expended per unit of time (kcal min^{-1}). METS (i.e., metabolic equivalent of work) is a ratio specific to the activity and is dimensionless.

The METS concept provides a means for estimating the alveolar ventilation rate associated with each activity. For convenience, let EE(i,j,k) indicate the energy expenditure rate associated with the i^{th} activity on day j for person k. Equation 5-2 can now be expressed as

$$EE(i,j,k) = [METS(i,j,k)] \times [RMR(k)] \qquad (5\ 3)$$

in which RMR(k) is the average value for resting metabolic rate specific to person k. Note that METS(i,j,k) is specific to a particular activity performed by person k.

Oxygen Requirements for Energy Expenditure

Energy expenditure requires oxygen which is supplied by ventilation (respiration). ECF(k) represents an energy conversion factor defined as the volume of oxygen required to produce one kilocalorie of energy in person k. The oxygen uptake rate (VO_2) associated with a particular activity can be expressed as

$$VO_2(i,j,k) = [ECF(k)] \times [EE(i,j,k)], \qquad (5\ 4)$$

in which $VO_2(i,j,k)$ has units of liters oxygen min^{-1}, ECF(k) has units of liters oxygen kcal^{-1}, and EE(i,j,k) has units of kcal min^{-1}. The value of $VO_2(i,j,k)$ can now be determined from MET(i,j,k) by substituting Equation 5-3 into Equation 5-4 to produce the relationship

$$VO_2(i,j,k) = [ECF(k)] \times [METS(i,j,k)] \times [RMR(k)]. \quad (5\text{-}5)$$

Excess Post-Exercise Oxygen Consumption

At the beginning of exercise, there is a lag between work expended and oxygen consumption. During this work/ventilation mismatch, an individual's energy needs are met by anaerobic processes. The magnitude of the mismatch between expenditure and consumption is termed the oxygen deficit. During heavy exercise, further oxygen deficit (in addition to that associated with the start of exercise) may be accumulated. At some point, oxygen deficit reaches a maximum value, and performance and energy expenditure deteriorate. After exercise ceases, ventilation and oxygen consumption will remain elevated above baseline levels. This increased oxygen consumption was historically labeled the "oxygen debt" or "recovery oxygen consumption." However, the term "excess post-exercise oxygen consumption" (EPOC) has been adopted for this phenomenon. APEX has an algorithm for adjusting the MET values to account for EPOC. This algorithm is described in detail in section 7.2 of US EPA (2008b).

Alveolar Ventilation Rate

Alveolar ventilation (V_A) represents the portion of the minute ventilation that is involved in gaseous exchange with the blood. VO_2 is the oxygen uptake that occurs during this exchange. The absolute value of V_A is known to be affected by total lung volume, lung dead space, and respiration frequency -- parameters which vary according to person and/or exercise rate. However, it is reasonable to assume that the ratio of V_A to VO_2 is relatively constant regardless of a person's physiological characteristics or energy expenditure rate. Consistent with this assumption, APEX converts each estimate of $VO_2(i,j,k)$ to an estimate of $V_A(i,j,k)$ by the proportional relationship

$$V_A(i,j,k) = (19.63) \times [VO_2(i,j,k)] \quad (5\text{-}6)$$

in which both V_A and VO_2 are expressed in units of liters min^{-1}. This relationship was obtained from Joumard et al. (1981), who based it on research by Galetti (1959). Equation 5-6 can also be expressed by the equivalent equation

$$V_A(i,j,k) = (19.63) \times [METS(i,j,k)] \times [ECF(k)] \times [RMR(k)]. \quad (5\text{-}7)$$

If ECF and RMR are specified for an individual, then Equation 5-7 requires only an activity-specific estimate of METS to produce an estimate of the energy expenditure rate for a given activity. APEX processes time/activity data obtained from the CHAD to create a sequence of activity-specific METS values for each simulated individual. APEX estimates RMR as a function of body mass based on probabilistic equations specific to age and gender using equations reported by Schofield (1985). A value of ECF is selected for each individual from a uniform distribution (minimum = 0.20, maximum = 0.21) based on data provided by Esmail et al. (1995). Using Equation 5-7 and these inputs, APEX calculates a sequence of V_A values for each simulated individual. These values are provided to the algorithm that estimates the percent COHb in the blood resulting from the simulated exposure (see section 5.3.7 and Appendix C).

5.3.6 Calculate Exposure

APEX calculates exposure as a time series of exposure concentrations that a simulated individual experiences during the simulation period. APEX determines the exposure using hourly ambient air concentrations, calculated concentrations in each microenvironment based on these ambient air concentrations, and the minutes spent in a sequence of microenvironments visited according to the composite diary. The hourly exposure concentration at any clock hour during the simulation period is determined using the following equation:

$$C_i = \frac{\sum_{j=1}^{N} C_{ME(j)}^{hourlymean} \quad t_{(j)}}{T} \qquad (5\text{-}8)$$

where:

C_i	=	Hourly exposure concentration at clock hour *i* of the simulation period (ppm)
N	=	Number of events (i.e., varied microenvironments visited/activities performed) in clock hour *i* of the simulation period.
$C_{ME(j)}^{hourlymean}$	=	Hourly mean concentration in microenvironment *j* (ppm)
$t_{(j)}$	=	Time spent in microenvironment *j* (minutes)
T	=	60 minutes

From the hourly exposures, APEX calculates time series of 8-hour and daily average exposure concentrations that a simulated individual would experience during the simulation period. APEX then statistically summarizes and tabulates the hourly, 8-hour, and daily exposures in a series of output tables.

5.3.7 Calculate Dose

Using time/activity data obtained from several diary studies, APEX constructs a composite diary for each simulated person in the specified at-risk population. The composite diary consists of a sequence of events spanning the specified period of the exposure assessment (typically one calendar year). Each event is defined by a start time, duration, a geographic location, a microenvironment, and an activity. Using the algorithms described above in sections 5.3.5 and 5.3.6, APEX provides estimates of CO concentration and alveolar ventilation rate for each event in the composite diary, for each simulated individual. APEX then uses these data, together with estimates of various physiological parameters specific to the simulated individual, to estimate the percent COHb in the blood at the end of each event. The percent COHb calculation is based on the solution to the non-linear Coburn, Forster, Kane (CFK) equation, as detailed in Appendix C.

Briefly, the CFK model describes the rate of change in COHb blood levels as a function of the following quantities:

- Inspired CO pressure;
- COHb level;
- Oxyhemoglobin (O2Hb) level;
- Hemoglobin (Hb) content of blood;
- Blood volume;
- Alveolar ventilation rate;
- Endogenous CO production rate;
- Mean pulmonary capillary oxygen pressure;
- Pulmonary diffusion rate of CO;
- Haldane coefficient (M);
- Barometric pressure; and
- Vapor pressure of water at body temperature (47 torr).

If all of the listed quantities except COHb level are constant over some time interval, the CFK equation has a linear form over the interval and is readily integrated. The solution to the linear form gives reasonably accurate results for lower levels of COHb. However, CO and oxygen compete for the available hemoglobin and are, therefore, not independent of each other. If this dependency is taken into account, the resulting differential equation is no longer linear. Peterson and Stewart (1975) proposed a heuristic approach to account for this dependency which assumed the linear form and then adjusted the O_2Hb level iteratively based on the assumption of a linear relationship between COHb and O_2Hb. This approach was used in the COHb module of the original CO-NEM exposure model (Biller and Richmond, 1982, Johnson and Paul, 1983).

Alternatively, it is possible to determine COHb at any time by numerical integration of the nonlinear CFK equation if one assumes a particular relationship between COHb and O2Hb.

Muller and Barton (1987) demonstrated that assuming a linear relationship between COHb and O2Hb leads to a form of the CFK equation equivalent to the Michaelis-Menten kinetic model which is analytically integrable. However, the analytical solution in this case cannot be solved explicitly for COHb. Muller and Barton (1987) demonstrated a binary search method for determining the COHb value.

The COHb module used in pNEM/CO employed a linear relationship between COHb and O_2Hb which was consistent with the basic assumptions of the CFK model. The approach differed from the linear forms used by other modelers in that the Muller and Barton (1987) solution was employed. However, instead of the simple binary search described in the Muller and Barton paper, a combination of the binary search and Newton-Raphson root finding methods was used to solve for COHb (Press et al., 1986).

As mentioned above, the current COHb module included in APEX is based on the solution to the non-linear CFK equation using the assumption adopted by Muller and Barton (1987) which employs a linear relationship between O_2Hb and COHb. The CFK equation does not have an explicit solution, so an iterative solution or approximation is needed to calculate each percent COHb value. APEX4.3 solves the CFK equation using a fourth-order Taylor's series with subintervals. This method, first incorporated in APEX3, is described in detail by Glen (2002) and summarized in Appendix C. The selected method (fourth order Taylor series with subintervals) was chosen because of its simplicity, fast execution speed, and ability to produce relatively accurate estimates of percent COHb at both low and high levels of CO exposure.

5.3.8 Model Output

All of the output files written by APEX are ASCII text files. Appendix D lists each of the output data files written for these simulations and provides descriptions of their content. Additional output files that can be produced by APEX are listed in Table 5-1 of the APEX User's Guide (US EPA, 2008a). These include tabulations of hourly exposure, ventilation, and energy expenditures. Detailed event-level information can also be output. Specific outputs generated for the purposes of the current CO exposure and dose assessment are discussed in section 6.1.

5.3.9 Model Limitations

APEX attempts to reasonably represent a sample of individuals who reside within a specific geographic area, and estimates the contact with the air pollutant given the inherent variability in peoples' locations and activities. This sample of individuals is a "virtual" sample, created by the model according to the relative frequencies of various demographic variables and census data, with the goal of obtaining a representative sample (to the extent possible) of the actual population of interest in the study area. The activity patterns of the sampled individuals (e.g., the specification of indoor and other microenvironments visited and the time spent in each) are assumed by the model to be comparable to individuals with similar demographic characteristics, and are represented by actual time-location-activity patterns compiled in CHAD (US EPA, 2002; McCurdy et al., 2000). The air pollutant exposure concentrations are estimated by the model using a set of user-input ambient outdoor concentrations and information on the physical factors that relate ambient pollutant to concentrations expected in various microenvironments. Although this aspect of APEX is not fully employed in the current simplified, screening-level assessment, the model structure would allow one to account for the most significant factors contributing to inhalation exposure – the temporal and spatial distribution of people and pollutant concentrations throughout the study area and among the microenvironments, providing there is sufficient input data to characterize these distributions – while also providing the flexibility to adjust some of these factors to meet the exposure assessment objectives. This may include exposure scenarios where ambient air quality is adjusted to simulate just meeting the current or alternative standards under consideration.

While APEX is designed to represent the most important personal attributes and physical factors that influence human exposure, all models have limitations and require the use of assumptions. Some of the general limitations of APEX are associated with the representativeness of the data distributions input to the model (e.g., human activity patterns) and assumptions made within various model algorithms including the following.

- The population activity pattern data used in APEX (i.e., CHAD) are compiled from studies conducted in a variety of geographic areas and during time periods that differed as to season and calendar year, though a large portion of CHAD is from studies of national scope. Consequently, the data base may not have data diaries available that fully represent a particular study scenario. However, to better match the activity pattern data to the simulated population residing in a particular location, diary pools can be created by APEX that are for specific seasons and temperature ranges.
- Commuting pattern data were derived from the 2000 U.S. Census. The commuting data address only home-to-work travel. The population not employed outside the home is assumed to always remain in the residential census tract. Furthermore, although several of the APEX microenvironments account for time spent in travel, the travel activity is typically assumed to occur in a composite of the home and work tract. No provision is made for the possibility of passing through other tracts during travel.
- APEX creates seasonal or annual sequences of daily activities for a simulated individual by sampling human activity data from more than one subject. While there are input variables (e.g., time spent outdoors) used to simulate the correlation of day-to-day

- The model currently does not capture certain correlations among human activities that can impact microenvironmental concentrations (for example, cigarette smoking leading to an individual opening a window, which in turn affects the rate that outdoor air enters the residence or vehicle).
- Certain aspects of the personal profiles (e.g., weight) are held constant, though in reality they change as an individual ages. This is generally only an issue for simulations with long timeframes.

These and other uncertainties in model inputs and algorithms, and how they may affect the estimated exposures and dose, are discussed in section 6.4.

5.4 PERSONAL EXPOSURE AND THE IN-VEHICLE MICROENVIRONMENT

This section summarizes key findings from personal exposure studies with particular attention to microenvironments of importance to ambient CO exposures.

5.4.1 Personal Exposure Monitoring Studies

This section summarizes some of the findings from personal exposure studies, in particular, through identifying the important microenvironments in assessing CO exposure and providing context for measured CO exposure levels relevant to this draft REA. Details regarding personal exposure measurement studies of target populations are discussed in section 8.2 of the 1991 CO AQCD (US EPA, 1991), chapter 4 of the 2000 CO AQCD (US EPA, 2000), and section 3.6 of the draft ISA.

As ambient CO concentrations have decreased dramatically over time, so have personal CO exposure levels.[2] However, while CO concentrations have declined over the past few decades, some general patterns in the relationship between ambient, microenvironmental, and exposure concentration still remain.

First, as a result of the significant time people spend indoors - whether at home, at school, workplace, or other indoor location (section 3.6.2, draft ISA) - indoor CO concentrations are an important determinant of an individual's CO exposures. Recent population exposure studies conducted in Milan, Italy support this conclusion (Bruinen de Bruin et al., 2004), indicating that over 80% of the population exposure to CO can occur in indoor microenvironments (draft ISA, Table 3-13). Taking into account the infiltration of ambient CO

[2] Many recently-conducted personal exposure studies in the U.S. have not included CO as an analyte, possibly due to high detection limits of personal exposure monitoring devices relative to ambient concentrations.

indoors, indoor CO concentrations are similarly an important determinant in an individual's exposure to ambient CO.

Second, there is variability in the relationship between personal exposure and ambient concentrations, particularly when considering microenvironmental exposures. For example, the draft ISA summarized the relationship between personal CO exposures in five broadly defined microenvironments (i.e., indoor residence, indoor other, outdoor near road, outdoor other, and in-vehicle) and ambient CO concentrations in Baltimore, MD based on data provided in Chang et al. (2000). On average, the indoor-to-ambient and outdoor-to-ambient ratios were about one, though most of the ratios observed across this set of indoor and outdoor microenvironments were less than one. With the exception of those for the in-vehicle microenvironments, which as a group were generally above one, few ratios were above unity (draft ISA, p. 3-102, Figure 3-43). Given the expected stability of CO as it infiltrates indoor microenvironments from outdoor air and the lack of significant removal mechanisms of CO in outdoor microenvironments, it is likely that the variability in personal/microenvironmental-to-ambient and outdoor-to-ambient ratios is the result of spatial and temporal variability in outdoor concentrations with respect to simultaneously measured ambient concentrations at fixed-site monitors, and also reflects the impact of lag time associated with attaining steady state relationships, as well as potential presence of non-ambient sources.

Third, because motor vehicles remain important contributors to ambient CO concentrations, both the time spent in motor vehicles and the presence of elevated on-road CO concentrations continue to be important contributors to personal exposures. For example, in the same study summarized by the draft ISA on personal exposures occurring within particular microenvironments (i.e., Chang et al., 2000), in-vehicle exposures were, on average, a factor of 3 to 4 greater than ambient concentrations (distance of ambient monitor to roadway not specified), with most in-vehicle exposure-to-ambient concentration ratios greater than one (median of approximately 2.5). Given this relationship, it should not be surprising that while about 8% of a person's time per day is spent in transit, 13-17% of their total daily exposure occurs within an in-vehicle microenvironment (e.g., Bruinen de Bruin et al., 2004; Scotto di Marco et al., 2005).

And finally, as for CO population exposure studies conducted in the U.S., two pertinent studies could be found: one conducted in Denver CO and the other in Washington, DC during the winter of 1982 and 1983 (Akland et al., 1985). Both studies collected measurements and activity pattern diaries from a random sample of the population, defined as including non-institutionalized, non-smoking residents, 18 to 70 years of age, who lived in each respective city's metropolitan area. In both cities, when comparing the distribution of measured CO concentrations from the monitoring network to measured personal exposures, two common phenomena were observed. At the lowest percentiles of each distribution, ambient CO concentrations were consistently greater than the personal exposures. At the highest percentiles of each distribution, ambient concentrations were consistently lower than the personal exposures (US EPA, 2000). Again, ambient concentrations may be a reasonable indicator of exposure for a portion of the population, but given spatial and temporal variability in ambient concentrations and exposures associated with high concentration microenvironments, there will likely be a combination of exposures that are under- and over-estimated when considering ambient concentrations alone. As an example of the potential to underestimate exposure concentration when solely relying on ambient fixed-site concentrations as an indicator of exposure, over 10% of the daily maximum 8-hour personal exposures in Denver exceeded the NAAQS of 9 ppm, and about 4% did so in Washington (Akland et al., 1985). This is in contrast to simultaneous CO measurements at ambient fixed-site monitors where CO concentrations exceeded 9 ppm about 3% of the time in Denver and never exceeded 9 ppm in Washington D.C. (Akland et al., 1985).

Consistent with the above discussion, the Denver and Washington studies determined that the highest average CO concentrations occurred when subjects were in a mobile source influenced microenvironment (e.g., inside parking garages, in-vehicles). Commute time was also a factor; those who commuted 6 hours or more per week had higher average exposures than those who commuted fewer hours per week. Furthermore, mean CO concentrations within in-vehicle microenvironments (ranging from 7.0 to 9.8 ppm) were greater than common outdoor locations (ranging from 1.4 to 3.2 ppm) (US EPA, 2000). In considering the results from the Denver and Washington personal exposure studies it is important to recognize that CO emissions from motor vehicle sources have declined dramatically since the early 1980's when these studies were conducted. Consequently, both ambient fixed-site CO concentrations and in-vehicle CO concentrations have also been reduced significantly since that time period.

5.4.2 In-Vehicle CO Concentrations

Given the contribution of in-vehicle exposures to total CO exposure and our focus on exposure to ambient CO, consideration of the contribution of ambient CO to in-vehicle concentrations is important to CO exposure assessment. Information useful to this consideration includes the relationship between CO concentrations within vehicles to concentrations simultaneously measured outside of vehicles and also at nearby fixed-site monitors. The utility of such data that has been reported in the extant literature to the assessment conducted here can be determined by broadly evaluating the fundamental study design and by considering potential influential factors that might affect measured CO concentrations (e.g., fleet characteristics, monitor siting). Accordingly, staff evaluated data reported in several U.S. and non-U.S. studies that measured CO concentrations inside vehicles, immediately outside vehicles, at roadside locations, and at fixed-site monitors. Particular attention is given to data available within the published literature that may be most appropriate for the purposes of the current exposure assessment. The research findings from a few of the more recent studies (i.e., since 1991) are summarized below. In addition, discussion regarding these and supporting information from studies conducted in the 1980's follows.

5.4.2.1 Studies Comparing CO Concentrations Inside and Outside Motor Vehicles

Table 3-1 summarizes four relevant studies selected by staff that provided data comparing CO concentrations inside a motor vehicle with concentrations immediately outside the vehicle. Two of the studies reviewed were conducted in the U.S. (Chan et al., 1991; Rodes et al., 1998). Given the low-reactivity of CO, it is expected that the ratio of the two concentrations (inside-vehicle versus outside-vehicle or I/O) would be equivalent to one (in the absence of in-vehicle sources).

Boulter and McCrae (2005) measured CO concentrations inside vehicles, immediately outside the vehicles, and under a range of vehicle ventilation conditions within two tunnels: one in Graz, Austria and the other in Liverpool, England. On average the I/O ratio ranged from one to slightly above unity. Statistical analysis indicated that the air conditioning (AC), fan, and window operating conditions did not have a statistically significant affect on the I/O ratios.

Chan et al. (1991) measured inside-vehicle concentrations of volatile organic compounds (VOCs) and three criteria air pollutants (ozone, CO, and NO_2) during the summer of 1988 in Raleigh, North Carolina. Two four-door sedans of different ages were used to evaluate in-vehicle concentrations of these compounds under different driving conditions. The study evaluated a variety of factors that could influence driver exposure, including varying traffic patterns, car models, vehicle ventilation conditions, and driving periods. The median I/O ratio for these two vehicles operated under a variety of conditions was 1.1 (Table 3.1). Chan et al. (1991) note that the slightly higher in-vehicle concentration may be a function of differences in interior and exterior sampling locations, and engine running loss emissions that contributed CO to the interior of the vehicle.

During September and October 1997, Rodes et al. (1998) collected 2-hour pollutant concentration measurements inside two vehicles during scripted commutes in Sacramento and Los Angeles. Similar measurements were made simultaneously outside the vehicles, along the roadways, and at the nearest ambient monitoring stations. A variety of scenarios were studied based on variables such as roadway type, traffic congestion, ventilation setting, and vehicle type. Two commutes, one in the morning and one in the afternoon, were typically conducted for each scenario.[3] On average, all I/O ratios were less than one in both locations, though within the range of other researchers reporting this ratio.

Sharp and Tight (1997) measured inside- and outside-vehicle CO concentrations using a single automobile and considering four different ventilation settings. The averaging time for CO measurements was one minute, thus the authors calculated I/O ratios based on both average data and peak data (Table 3-1). The I/O ratios were consistent with those of similar studies, with in-vehicle CO levels being slightly higher than those measured directly outside the vehicle. Peak concentration (inside and outside of the vehicle) comparisons did span a wider range of values that included I/O ratios both below and above unity. The choice of ventilation setting (i.e., window open or mechanical ventilation) had an effect on average and peak CO concentrations; in general, conditions associated with the lowest air exchange rates (i.e., windows closed and no mechanical ventilation) had the lowest I/O ratios in these studies.

The findings reported in each of the above four studies are supported by a review by Flachsbart (1999) regarding other studies published between 1982 and 1992 that measured interior and exterior CO concentrations simultaneously during motor vehicle trips. The I/O ratio was similar for two studies: Petersen and Allen (1982) reported a ratio of 0.92 for a study in Los Angeles, California; and Koushi et al. (1992) reported a ratio of 0.84 for a study in Riyadh, Saudi Arabia. Both of these research studies reported no affect from altering ventilation conditions.

In contrast, one study reported indicated I/O ratios could exceed unity with the ventilation set to recirculate vehicle air (Abi Esber and El-Fadel, 2008). It is possible that this was the result of a gradual build-up of CO concentrations within the vehicle cabin (ISA, section 3.6.6.2). In addition, Colwill and Hickman (1980) reported that internal CO levels were about 30 – 80% of exterior concentrations for a study conducted in London. However, the large difference in these I/O ratios when compared with those reported by most other researchers could be explained by the location of the exterior probe (i.e., at bumper height compared with probes commonly placed higher on the vehicle) (Flachsbart, 1999).

[3] The study design also included several other driving scenarios: (1) a California school bus following a student route in Sacramento, (2) comparison of a sedan traveling in a Los Angeles carpool lane versus one traveling in a congested right hand lane, and (3) a sedan encountering situations to maximize the in-vehicle pollutant concentration levels. These data are not included in this summary.

Table 5-2. Carbon Monoxide Concentrations Inside and Immediately Outside Vehicles, and Indoor/Outdoor Vehicle Ratios.

Study	CO concentration (ppm)		Indoor/Outdoor (I/O) Ratio	Drive Conditions	Averaging Times
	Inside Vehicle	Outside Vehicle			
Boulter and McCrae (2005)	6.19 ± 2.08 4.94 ± 1.80 (mean ± std)	7.13 ± 1.92 4.88 ± 1.86 (mean ± std)	0.99 ± 0.07 1.10 ± 0.07 (mean ± std)	Plabutsch Tunnel in Graz, Austria Kingsway Tunnel in Liverpool, England	Statistics are based on average CO concentrations for trips through tunnels.
Chan et al. (1991)	11.0 (median)	10.0 (median)	1.10 (median)	Two sedans were driven on three road types (urban, interstate, rural) in Raleigh, NC during summer 1988	Statistics are based on air samples collected over one hour periods.
Rodes et al. (1998)	Sacramento: 1.4 – 3.5 Los Angeles: 3.5 – 5.4 (mean range)	Sacramento: 2.2 – 4.2 Los Angeles: 4.4 – 5.6 (mean range)	Sacramento: 0.73 – 0.90 Los Angeles: 0.88 – 0.96 (mean range)	Two vehicles (lead and following) were driven on various road types in Sacramento and Los Angeles during September and October 1997. Note, minimum quantitation limit was 2 ppm for Draeger Model 190 monitors used.	Statistics are based on averages of 120 one-minute values measured during two-hour morning and afternoon commute periods.
Sharp and Tight (1997)			1.19 to 1.43 (mean range) 0.65 to 1.38 (max range)	Nine test runs were conducted in Leeds, England on three road types under four ventilation conditions. Lowest values associated with windows closed and no mechanical ventilation.	Statistics are based on mean and maximum (max) CO concentrations recorded during each minute of each test run.

In general, the above results suggest that the I/O ratio tends toward unity when there are no interior sources of CO, the automobile engine does not contribute directly to its own interior concentrations, and the measurement probes are properly installed on the vehicle.[4] This conclusion is consistent with theoretical expectations for a non-reactive pollutant. For example, CO concentrations inside vehicles can be estimated as a function of outside CO concentration, air exchange rate, a penetration factor, and the emission rates of indoor sources (e.g., exhaust leaks, smoking). If one assumes that (1) steady-state ventilation conditions exist, (2) the indoor removal rate (k) is zero (i.e., no loss of CO as it moves from outside to inside the vehicle), and (3) there are zero emissions from interior sources, then the CO concentration inside a vehicle can be simplified to a function of outside CO concentrations and the penetration rate (i.e., infiltration is generally equivalent to penetration).[5] Under these stated conditions, the I/O ratio would ultimately converge to unity.

5.4.2.2 Studies Comparing CO Concentrations Inside Motor Vehicles to Concentrations at Fixed-Site Monitors and Roadside Locations

A report by Shikiya et al. (1989) describes an in-vehicle study conducted in the South Coast Air Basin of California during the summer of 1987 and winter of 1988. Participants were randomly-selected home-to-work commuters from a non-industrial business park. Measurements of hazardous air pollutants (HAPs), CO, and Pb were collected from within vehicles and contrasted with measurements at existing fixed-site monitoring stations. A total of 192 CO measurements were made each representing the average concentration of the round-trip commute.[6]

On average, CO concentrations were 8.6 ppm, and even though the maximum observed CO concentration in a vehicle was as high as 46 ppm, only 3 percent of the in-vehicle commuting concentration measurements were greater than 20 ppm (Table 3-2). Shikiya et al. (1989) also investigated several potentially influential variables. Statistical differences in concentration were noted for season ($p = 0.01$), and age of vehicle ($p = 0.05$). Mean concentrations using several other classification variables did not differ significantly at the $p = 0.05$ level (e.g., ventilation status, vehicle speed, freeway density during commute).

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[4] Interior sources of CO to in-vehicle concentrations may include self-pollution such as that associated with defective exhaust systems or inadequate internal ventilation (draft ISA, p. 3-105). While automobile technology has advanced with improvements in these areas (e.g., Flachsbart et al., 1999), interior sources may contribute in some instances (e.g., older school buses, draft ISA, p. 3-105).

[5] See section 3.6.2 of the draft ISA.

[6] The average one-way commute time was 33 minutes.

Table 3-2 also presents descriptive statistics for averages of individual 4-hour integrated samples collected during peak commuting hours at three fixed-site monitors that encompassed the general routes of the commuters: Long Beach (a coastal location), Los Angeles (a central location), and Pomona (an inland location). On average, CO concentrations were 3.7 ppm, though maximum CO concentrations were as high as 8.7 ppm. Other monitoring sites located in Los Angeles, Rubidoux, and Upland reported ambient 24-hour average CO concentrations of 2.2 ppm during the summer. This group of monitors were designated by Shikiya et al. (1987) to be less influenced by local roadway emissions compared with the three other fixed-site monitors. Using the mean for all in-vehicle CO concentrations during round-trip commutes (8.6 ppm) and dividing by the mean of the integrated fixed-site concentrations measured during peak commuting hours (3.7 ppm) gives an in-vehicle to ambient monitor ratio of about 2.4.

Table 5-3. Descriptive Statistics for CO Concentrations Measured Inside Vehicles and at Fixed-Site Monitors (from Shikiya et al., 1989).

Measurement	Grouping variable	Category	Number of samples	CO concentration (ppm)[a]		
				Mean	Std	Max
Average in-vehicle CO concentration during round-trip commute	All	--	192	8.6	5.0	46.4
	Season[b]	Summer	80	6.5	2.2	14.6
		Winter	112	10.1	5.8	46.4
	Vehicle year[c]	1973 - 83		9.4		
		1984 - 88		7.8		
Integrated fixed-site concentration during peak commuting hours (Long Beach, Los Angeles, and Pomona stations)	All	--	19	3.7	2.1	8.6

Notes:
[a] Mean, std and max are the arithmetic mean, arithmetic standard deviation, and maximum CO concentrations.
[b] Statistically significant at p = 0.01 level.[c] Summer: May – October, Winter: November – March.
[c] Statistically significant at p = 0.05 level.

Further, the draft ISA notes that studies summarized in the 2000 CO AQCD found that in-vehicle CO concentrations were generally two to five times higher than ambient CO concentrations obtained at fixed-site monitors within the cities studied. However, several of these studies were conducted when CO vehicle emissions were much higher and/or under situations that are less relevant to the two urban areas of the U.S. included in the current exposure and dose assessment, discussed below in section 5.5. As described above, the findings reported by Shikiya et al. (1989) in a study conducted in Los Angles supports a ratio of about two. We note, however, that based on several factors discussed above, such as the traffic characteristics of the roadway and the site characteristics of the fixed-site monitor, the relationship can vary (e.g., higher ratios would be obtained using more remotely sited monitors, and the size of relationship may vary with absolute magnitude of roadway concentrations).

5.5 STRATEGY FOR CO EXPOSURE/DOSE ASSESSMENT FOR THE CURRENT REVIEW

5.5.1 Background for Current Assessment Strategy

The draft Scope and Methods Plan for the current review of the primary CO NAAQS (US EPA, 2009b) described an approach based on the application of APEX to estimate human exposures to CO and the resulting dose and to characterize the potential health risks that are associated with recent ambient levels of CO and with ambient levels that just meet the existing standards in two urban study areas (Denver and Los Angeles). The characterization of health risks focused on development of estimates of COHb levels and the number of people and the total number of occurrences for which potential COHb benchmark levels are exceeded.

In consideration of information on current locations of CO monitors discussed in chapter 3 of this document and in the draft ISA (sections 3.5-3.7), and CASAC comments on both the draft Scope and Methods Plan and the first draft ISA, however, staff notes significant limitations of the currently available CO monitors related to their use in detailed population exposure assessment.

- The number of CO monitors in Denver and Los Angeles counties has decreased since the previous review, from 9 to 3 or 4 monitors operating in Denver (depending on the year considered) and from 21 to 12 in Los Angeles.
- The current levels of ambient CO concentrations are much lower than in the last review, and a significant number of the measurements are near or below detection limits.
- Concentrations of ambient CO occurring in key microenvironments are not reflected by ambient monitors. As stated by the CASAC CO Panel, "Relying only on EPA's fixed monitoring network CO measurements may underestimate CO exposures for specific vulnerable populations such as individuals residing near heavily trafficked roads and who commute to work on a daily basis" (Brain and Samet, 2009, p.2).
- As discussed chapter 3 above, the currently available CO monitors pose significant limitations in our ability to fully characterize the current spatial and temporal variability in CO ambient concentrations across the two urban areas of focus for this assessment, Denver and Los Angeles. These limitations affect our ability to derive detailed relationships about CO concentrations in ambient air across the study area from which detailed microenvironmental concentrations can be estimated. More broadly, the

CASAC CO Panel expressed the view that "the current ambient monitoring network is not well designed to characterize spatial and temporal variability in ambient concentrations. Thus, it does not adequately support detailed assessments of human exposure or air quality modeling such as for photochemical oxidants" (Brain and Samet, 2009, p.11).

In light of these limitations in the air quality data, including CASAC's concerns about the adequacy of the monitoring network to perform detailed exposure analyses, and in light of the findings from the CO assessments completed for the 1994 review (USEPA, 1994) and subsequently (Johnson, et al., 2000), as well as the lack of new evidence in the draft ISA to support a quantitative risk characterization approach different from past assessments, staff decided not to perform a detailed analysis involving multiple monitors and comprehensive estimation of exposure concentrations in multiple microenvironments, as has been done in the past. Rather than develop such a detailed analysis using the available air quality data that has been recognized as limited by CASAC for such a purpose, we developed an alternative simplified, screening-level approach. We recognize that there are uncertainties associated with the revised approach and, thus, its utility is primarily as a screening assessment to provide some perspective on current ambient CO concentrations and associated CO exposure, dose and risk. One purpose of this draft document is to seek CASAC views on the extent to which this assessment design provides information useful to this current CO NAAQS review.

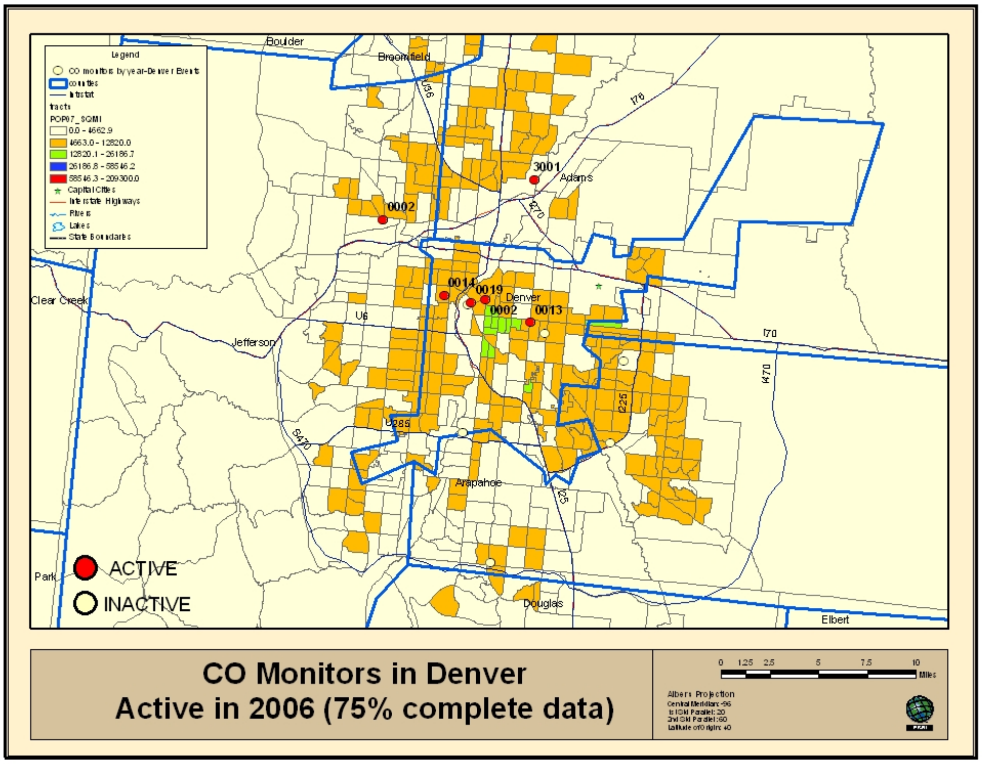
The following section presents the approach used to develop the current CO exposures and COHb estimates for the two urban study areas presented in this document.

5.5.2 Selected Approach for Current Review

As discussed in section 5.5.1 above, despite the capabilities of the APEX model, staff felt that the lack of spatial and temporal variability in available ambient monitoring data precluded the development of a credible broad-scale urban exposure assessment such as that conducted recently for the O3 NAAQS (US EPA, 2007). Therefore, staff decided to perform a limited exposure analysis using APEX and ambient data at a single monitor each in Denver and Los Angeles counties.

In developing the approach, staff evaluated the monitoring data available in the selected locations (i.e., Denver County and Los Angeles County) for years 2005 through 2007 (see Table 3-1 for sites IDs, locations, and number of sample-hours). Staff noted that, following the examination of the existing and active monitors in Denver and Los Angeles counties and using a 75% completeness criterion, only two of the Denver County monitors had data for 2007. Three of the six Denver sites used in the exposure assessment conducted in 2000 (Johnson et al. 2000) have been removed from the monitoring network and are no longer reporting CO concentrations in Denver (Figure 5-1). Based on these observations, 2006 was chosen to be the most recent year to be analyzed. As a result of this choice, there were four monitors in Denver County and twelve monitors in Los Angeles County (Figure 5-1) with complete air quality data available.

The monitor siting characteristics and breadth of spatial coverage are also important features to consider in representing the air quality in an area. Most of the monitors in Denver County are clustered within the central portion of the Denver County, with two monitors (IDs 080310002 and 080310019) within 1 mile of one another and generally having a similar concentration distribution when considering their 1-hour and 8-hour average CO concentrations (Figure 5-2). There is limited spatial variation among the twelve Los Angeles County monitors (Figure 5-3). Further, of the monitors available in Denver County to use in an exposure assessment, one monitor appears to best represent the highest population density in Denver County (draft ISA, Figure 3.4-3). This monitor (ID 08-031-0002) is located at 2105 Broadway. This particular monitor was included in the previous reviews and continues to report the some of the highest concentrations in the area (Figure 5-2 and Table 3-1). It is described as a micro-scale site, within 6 meters from a roadway having 17,200 vehicles/day traffic volume, 7 meters from a road with 10,000 vehicles/day, and 16 meters from a road with 1,000 vehicles/day. Based on the same criteria (i.e., to envelop a study area that captures the population centers and where ambient CO levels tend to be high), a single monitor in Los Angeles County (ID 060371301) was selected for use in the exposure assessment for the Los Angeles study area. This monitor is described as representing a middle scale, and it is near to an arterial road, but 350 m from a major freeway (the I-105) with a traffic count close to 35,000 vehicles/day. Staff note, however, that a study of ambient CO concentrations related to motor vehicle traffic in Los Angeles and Sacramento (Rodes et al., 1998) observed little difference in CO concentrations between arterial roads and freeways for Los Angeles (draft ISA, p. 3-65).



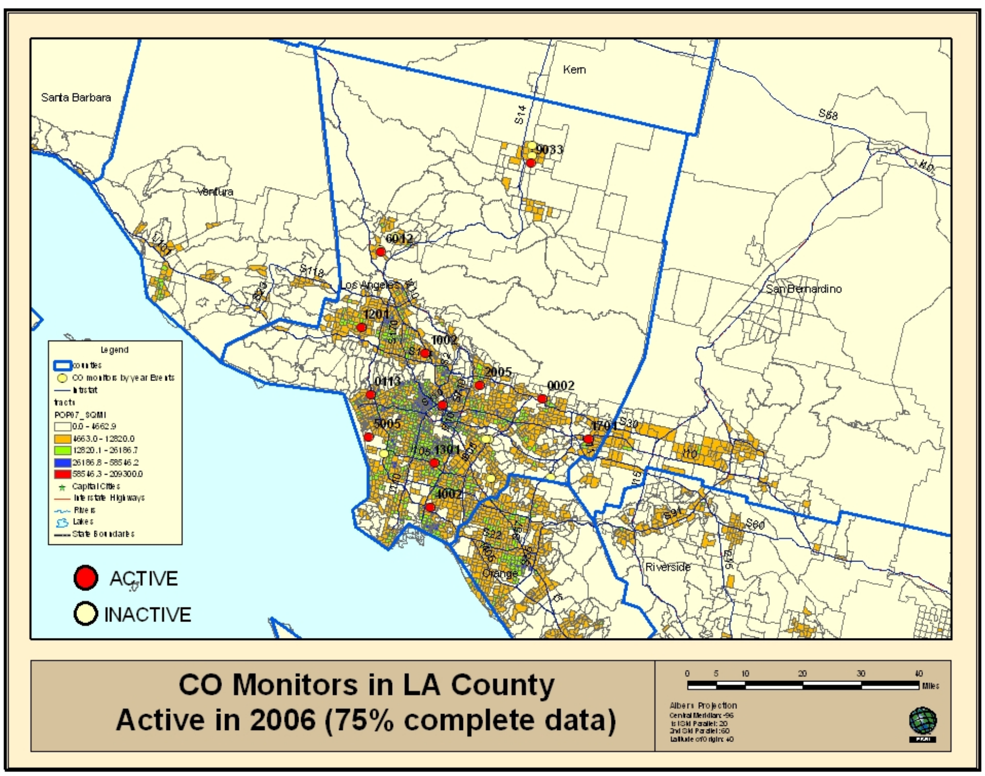


Figure 5-1. Locations of active ambient CO monitors meeting 75% completeness criterion in 2006 along with locations of inactive ambient CO monitors, within the metropolitan Denver (top) and metropolitan Los Angeles (bottom).

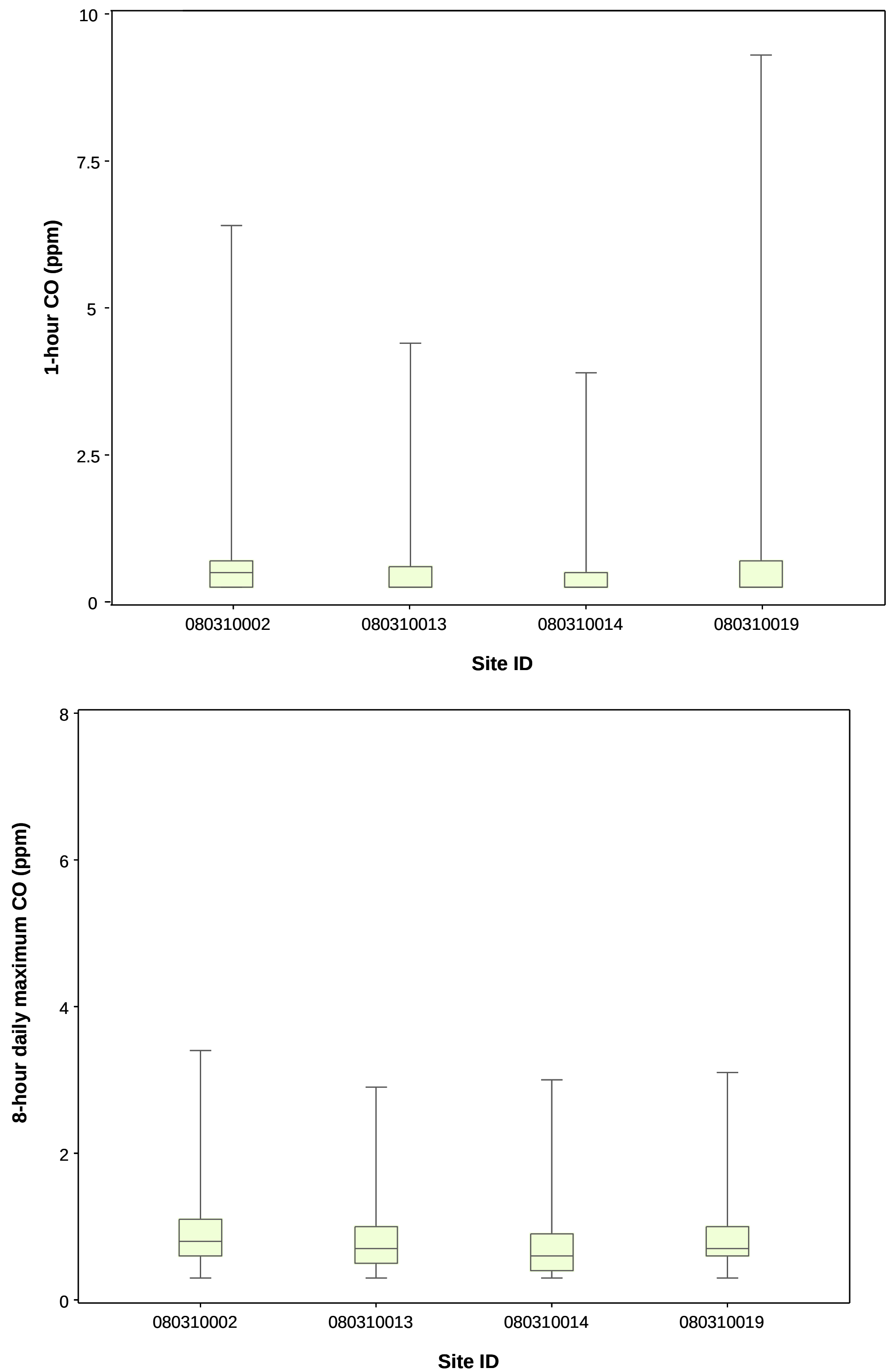


Figure 5-2. Distribution of 1-hour (top) and 8-hour average daily maximum (bottom) CO concentrations at ambient CO monitors in Denver County, year 2006.

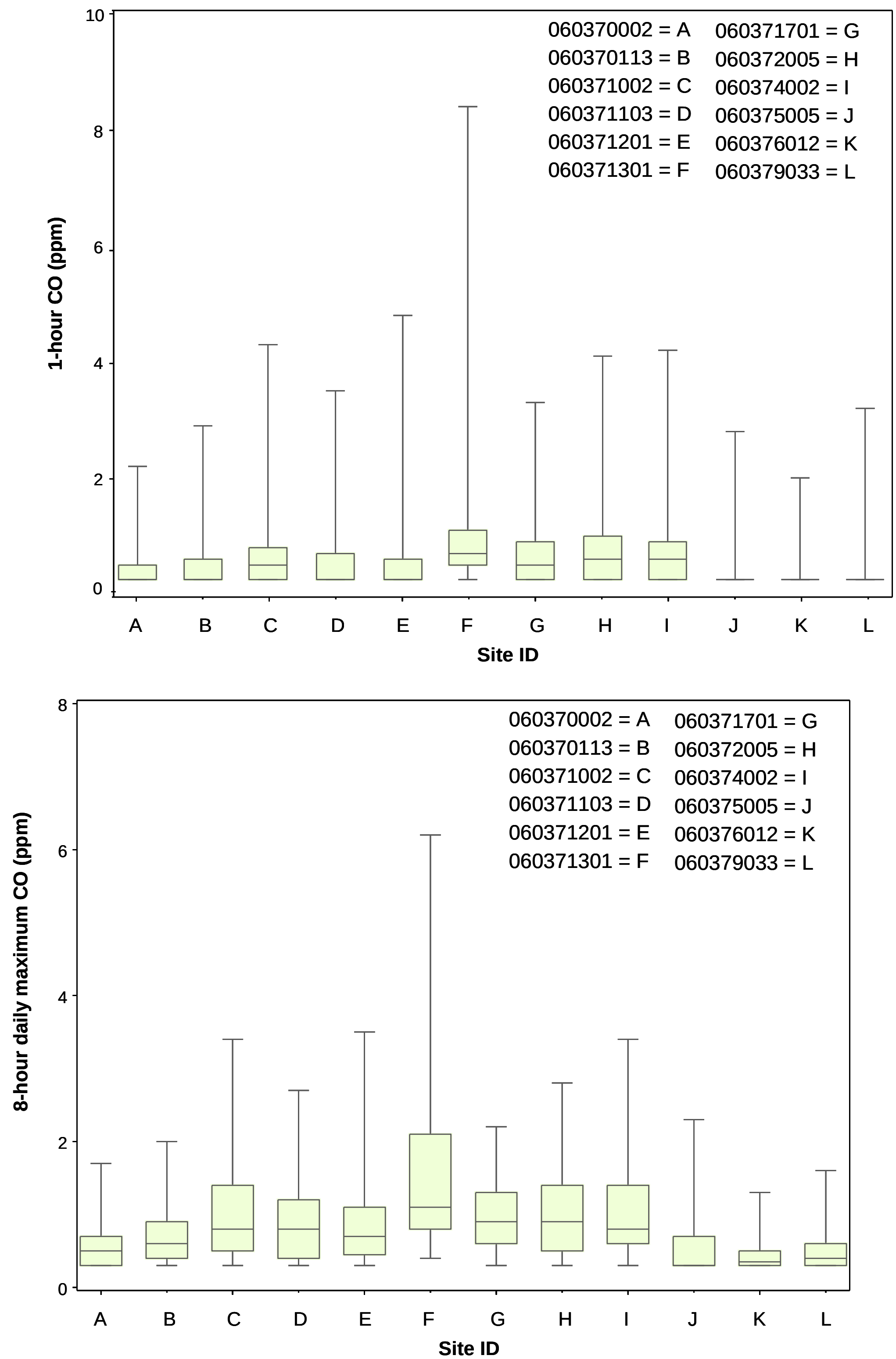


Figure 5-3. Distribution of 1-hour (top) and 8-hour average daily maximum (bottom) CO concentrations at ambient CO monitors in Los Angeles County, year 2006.

In each of the two study areas, two broadly defined air quality scenarios were investigated. In the first scenario ("Scenario A"), all microenvironmental concentrations are set equal to the ambient concentrations measured at the single fixed-site monitor selected to represent each exposure modeling domain. Staff used APEX to estimate the COHb levels in blood of the at-risk population (i.e., adults with CHD) by assuming that the population is exposed to the ambient concentrations measured at the selected near-road monitor for each study area throughout the entire simulation period. This general assumption likely results in over-estimates of CO exposure and COHb levels for much of the population because CO peak hourly concentrations are typically somewhat lower indoors than outdoors due to consideration of air exchange (in the absence of indoor sources of CO). This scenario, however, may underestimate CO exposure for some small portion of the population that may live in close proximity to heavily trafficked roadways and spend appreciable time in transit on such roadways. These individuals, based on the analysis of air quality relationships and personal exposure measurements, would likely have periods of higher exposures than represented by Scenario A since CO concentrations in vehicles, and exposure concentrations for individuals in transit on roadways, are typically higher than the concentrations measured at a near-road monitor. The impact of such higher exposure periods on an individual's COHb levels will vary depending on the magnitude and pattern of exposures in the prior and subsequent hours.

In the second scenario ("Scenario B"), we assume that the concentration outside a motor vehicle is twice the ambient concentration and that the concentration inside the vehicle is the same as the concentration immediately outside the vehicle; that is, the in-vehicle microenvironment is set equal to twice the ambient monitor concentrations. For Scenario B, all other microenvironmental concentrations are set equal to the ambient concentration based on the fixed-site monitor concentration, consistent with their treatment in Scenario A. The intent of this scenario is to determine the magnitude of the change in exposure and COHb levels when incorporating a rough estimate of the greater exposure concentrations occurring inside motor vehicles. Further details regarding the air quality scenarios and specific exposure modeling input data used for the assessment are given in chapter 6.

5.6 KEY OBSERVATIONS

Presented below are key observations related to the approach for the population assessment of CO exposure and dose.

- APEX, an EPA human exposure and dose model, has a long history of use in estimating exposure and dose for many of the criteria pollutants including CO, O_3, SO_2, and NO_2. Over time, staff have improved and developed new model algorithms, incorporated newer available input data and parameter distributions, as well as performed several model evaluations, sensitivity analyses, and uncertainty characterizations for the same pollutants. Based on this analysis, APEX was judged to be an appropriate model to use for assessing CO exposure and dose.
- Personal CO exposure studies indicate that in general, indoor exposures contribute the greatest portion of an individual's total daily exposure, though variability in exposure concentrations may be driven largely by exposure in certain microenvironments, such as, with regard to ambient CO, inside motor vehicles or when outdoors near roadways. Accordingly, in estimating CO exposures and associated COHb levels an approach is needed to estimate the generally higher in-vehicle and in-transit exposure concentrations compared to the generally lower ambient concentrations concurrently reported by fixed site ambient monitors.
- Given the limitations in the number of ambient monitors currently in operation, the limited spatial and temporal representation of ambient concentrations provided by the current monitoring network, and limited number of CO concentrations at or above the instrument detection limit, the simplified, screening-level approach used in this exposure assessment does not employ detailed microenvironmental concentration modeling and uses a single fixed-site monitor in each study area. The single monitoring site selected in each location typically reported a higher range of CO concentrations when compared with other monitors in each area, and thus, when used as an input to an exposure model, is generally considered likely to generate conservative (i.e., higher) estimates of exposure for the large majority of the population.

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6 EXPOSURE/DOSE ASSESSMENT AND RISK CHARACTERIZATION

This chapter describes the draft assessment of ambient CO exposure and dose and associated characterization of risk and uncertainty. Section 6.1 provides an overview of the application of the APEX model in this assessment. In section 6.2, we present the exposure and dose estimates and describe the estimates in the context of potential health benchmarks. The current assessment and associated exposure and dose estimates are described in comparison to estimates from an earlier CO assessment (Johnson et al., 2000) in section 6.3. The final section presents an analysis of how variability was considered by staff in this assessment followed by a qualitative characterization of uncertainty (section 6.4).

6.1 APPLICATION OF APEX4.3 TO CARBON MONOXIDE

The previous analysis of population exposure to carbon monoxide (CO) employed the pNEM/CO model (summarized in section 5.2 above) and focused on Denver and Los Angeles study areas, comprising the majority of census tracts within those metropolitan areas (Johnson et al., 2000). Air quality data were obtained from multiple fixed-site monitors within the study areas, and the exposure assessment accounted for the effects of geographic location, a diverse set of microenvironments, commuting within the study area, and selected indoor sources (e.g., environmental tobacco smoke, gas stoves).

In the specific application of APEX4.3 described in this report, a different approach has been taken. The simplified approach presented is intended to emphasize the contribution of CO exposures occurring in vehicles to overall CO exposures. The contribution of in-vehicle exposures is thought to be influential in producing the highest exposures to ambient CO and resulting COHb levels (draft ISA, section 3.6.6.2). The ambient CO concentration throughout the study areas and all microenvironmental concentrations are generally assumed to equal the hourly-average concentrations measured by a single high CO concentration monitor in one of the two scenarios (Scenario A). In a second scenario, in-vehicle concentrations are assumed to equal twice the ambient monitor concentrations (Scenario B). Therefore, the locations visited by simulated persons in the study area are represented by at most two microenvironments (*in-vehicle* and *all other*). The study areas and scenarios are briefly described in sections 6.1.1 and 6.1.2 below. The study area population of interest was limited to adults with coronary heart disease (CHD) that reside within a defined distance of a single downtown fixed-site monitor (as discussed in sections 5.5.2 and 6.1.3). Given simplified assumptions in the approach, the generated results would tend to represent population exposures experienced by persons residing/travelling in high CO (of ambient origin) concentration microenvironments. However, note that this assessment does not include the contribution of indoor sources to total CO exposure, which in prior assessments have been shown to be important contributors to total exposures (see US EPA, 1992; Johnson et al., 2000).

A general description of APEX4.3 and its capabilities, as well as the history of the pNEM/APEX series of exposure models can be found in chapter 5. This section focuses on the development of the specific input files and parameters used in the current application of APEX4.3 to CO in the Denver and Los Angeles study areas. In particular, this section (and associated appendices) describes the

- Geographic areas and time periods defined for the exposure analyses,
- Exposure scenarios under evaluation,
- Populations-at-risk and the associated prevalence rates for CHD,
- Air quality and meteorological data used for each study area,
- Microenvironments defined for each exposure scenario, and
- Methods used to construct a composite diary for each simulated individual.

In addition to the application-specific input data bases described in this section, we used a number of default databases provided with APEX4.3 as inputs to the model. These included national data files obtained from the U.S. Census Bureau (i.e., the 2000 Census data) for the following types of information (http://www.epa.gov/ttn/fera/apex_download.html#input):

- Population data by race, gender, age, and census tract;
- Employment probabilities by gender, age, and census tract;
- Locations of census tracts (latitude and longitude); and
- Commuting flows for combinations of home and work census tracts.

Another default input file provided tables of age- and gender-specific physiological parameters (e.g., weight). The contents of these default files will not be described in this section; they are described in detail in the APEX Users Guide (US EPA, 2008a) and the APEX Technical Support Document (US EPA, 2008b).

6.1.1 Study Areas and Exposure Periods

As discussed in section 3.2, EPA selected areas within Denver, Colorado, and Los Angeles, California, for the exposure assessment. Briefly, considerations in selection of these areas include: the prior analysis of these locations in CO NAAQS reviews, the areas having historically elevated CO concentrations, and the areas currently having some of the most complete ambient monitoring data available. The actual study areas were defined as including all census tracts within 20 km of the following fixed-site monitors.

Denver: Monitor No. 080310002; 2105 Broadway, Denver, CO (CAMP site).

Los Angeles: Monitor No. 060371301; 11220 Long Beach Blvd., Lynwood, CA.

The Denver study area includes most of the urbanized area inside the arc defined by Highway 470 (Figure 6-1) within Denver County. The Los Angeles study area is centered at Lynwood, CA and includes large portions of Los Angeles and Long Beach within Los Angles County (Figure 6-2).

EPA selected the following calendar years as the study periods for each area.

Denver: 1995 and 2006

Los Angeles: 1997 and 2006

The year 2006 was selected for both cities because it was the most recent year of monitoring data that met the 75% completeness requirement for the fixed-site monitors listed above. The CO levels reported for 2006 were well below the 8-hour NAAQS and were considered representative of current conditions in each study area. The year 1995 for Denver and the year 1997 for Los Angeles were selected as periods for which the monitoring data indicated higher CO conditions near or exceeding, the 8-hour CO NAAQS (9 ppm). As discussed in section 6.1.4.3, staff applied an adjustment to the monitoring data reported for these years to simulate ambient CO levels that would just meet the current 8-hour NAAQS.

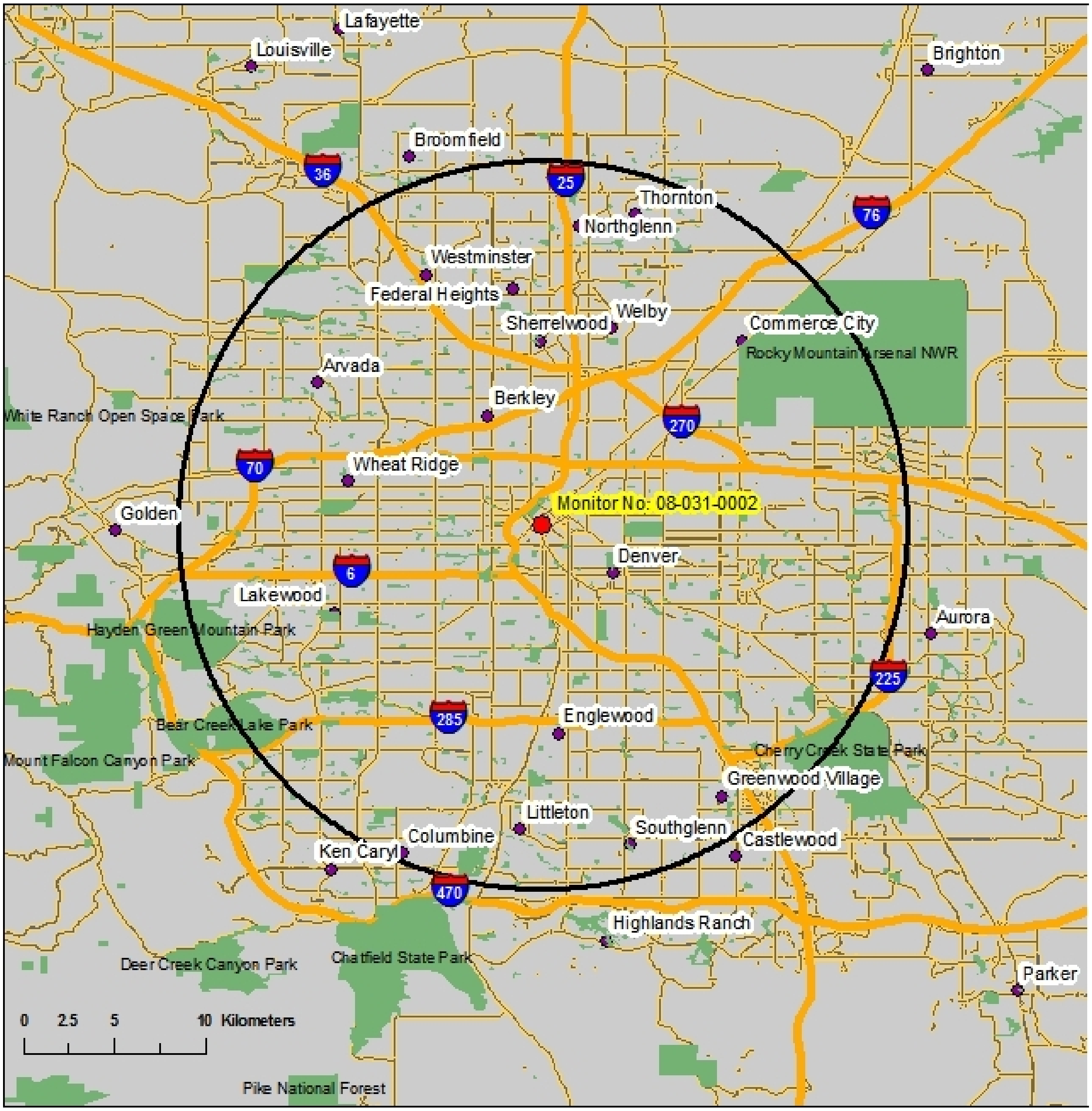


Figure 6-1. Map of the Denver Study Area Defined as a Circle with Radius = 20 km Centered on Fixed-Site Monitor ID 080310002.

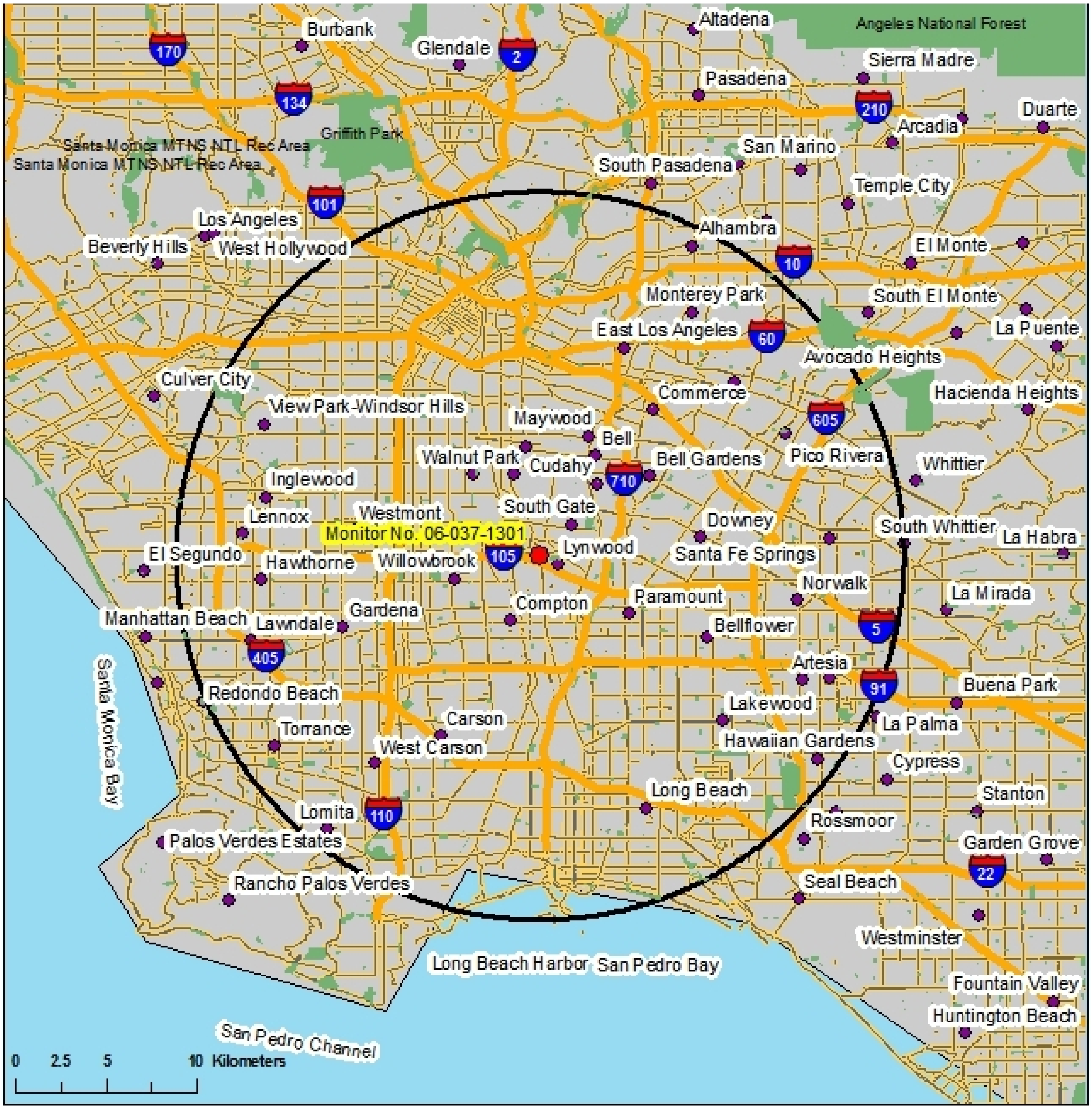


Figure 6-2. Map of the Los Angeles Study Area Defined as a Circle with radius = 20 km Centered on Fixed-Site Monitor No. 060371301.

6.1.2 Exposure Scenarios

Two exposure scenarios were evaluated for each study area, designated as Scenario A and Scenario B. The scenarios differed according to the modeling factors assumed for the two broadly defined microenvironments modeled (i.e., *in-vehicle* and *all others*). See section 6.1.5 for additional details regarding microenvironments. Both Scenario A and B were focused on the adult CHD population living within each study area and are described in more detail below.

6.1.2.1 Scenario A

In this scenario, the sequence of concentrations in each microenvironment was set equal to the ambient concentrations derived from the fixed-site monitor selected to represent the study area. Essentially, the microenvironment assignments in each diary entry for each simulated individual did not affect exposure concentration levels (i.e., the individual was exposed to the ambient concentrations as measured at the fixed-site monitor for all hours in the exposure period).

The time/activity database that was used as the input for this scenario included all adult diaries in CHAD and thus was not necessarily specific to the study area. Note however that the APEX model samples from this pool of diaries to reflect the actual population distribution based on the specific age and gender residing in each census tract. In addition, the sampling from the broad diary pool is also guided by several temperature ranges and applied to observed temperatures for the specific geographic region.

6.1.2.2 Scenario B

Scenario B assumed that the concentrations outside a motor vehicle were greater than that measured at the ambient fixed-site monitor and that the concentrations inside the vehicle were the same as the concentrations immediately outside the vehicle. The CO concentrations in all other microenvironments were set equal to the ambient concentrations as measured at the fixed-site monitor, consistent with their treatment in Scenario A. As in Scenario A, the input time/activity database included all diaries in CHAD.

6.1.3 Populations-at-Risk

Staff defined the population group at risk within each study area to include adults ages 18 or older with CHD. Coronary heart disease is caused by inadequate circulation of the blood to the heart muscle, which is a result of the coronary arteries being blocked by cholesterol deposits (ISA, section 5.2.1.9). The focus on adults with CHD is consistent with the previous (2000) review of the CO NAAQS. The current and previous assessments focused on adults as the incidence of CHD in younger individuals is extremely small.

At the time of the review completed in 1994, the estimated number of individuals with CHD represented about 3% of the entire (all ages) U.S. population (US EPA, 1992). More recently however, the National Health Interview Survey for 2007 reported a prevalence rate for CHD of about 6 percent for the population above 18 years of age (CDC, 2009; draft ISA, section 5.7.2.1). The current exposure/dose assessment requires estimates (by age and gender) of the fraction of the population in the Denver and Los Angeles study areas who have CHD. Given the general similarity in regional rates for CHD, staff decided to apply national prevalence rates for CHD to each of the two study areas. Table 6-1 provides national prevalence data for CHD by age obtained from the National Health Interview Survey of 2007 (CDC, 2009). Table 6-2 provides national prevalence rates for CHD by gender obtained from the same source. These data were used to estimate gender-specific adjustment factors of 1.31 = males/total = 0.080/0.061 for males and 0.74 = females/total = 0.045/0.061 for females. Table 6-3 provides estimated national prevalence rates for CHD by age range adjusted for gender differences using these values.

Table 6-1. National Prevalence Rates for Coronary Heart Disease by Age Range.

Age range	Prevalence rate (fraction) for coronary heart disease[a]
18 to 44	0.009
45 to 64	0.067
65 to 74	0.187
75+	0.236

[a]Source: Coronary heart disease statistics in Table 2, "Summary Health Statistics for U.S. Adults: National Health Interview Survey, 2007," U.S. Department of Health and Human Services, Center for Disease Control, Hyattsville, MD, May 2009.

Table 6-2. National Prevalence Rates for Coronary Heart Disease by Gender.

Age range	Prevalence rate (fraction) for coronary heart disease[a]		
	Total	Males	Females
18+	0.061	0.080	0.045

[a]Source: Coronary heart disease statistics in Table 2, "Summary Health Statistics for U.S. Adults: National Health Interview Survey, 2007," U.S. Department of Health and Human Services, Center for Disease Control, Hyattsville, MD, May 2009.

Table 6-3. National Prevalence Rates for Coronary Heart Disease Used in APEX, Stratified by Age and Gender.

Age range	Prevalence rate (fraction) for coronary heart disease[a]	
	Males	Females
18 to 44	0.012	0.007
45 to 64	0.088	0.050
65 to 74	0.244	0.138
75+	0.310	0.175

[a]Source: Values listed in Table 6-2 were multiplied by 1.31 (= 0.080/0.061) for males and 0.74 (= 0.045/0.061) for females.

6.1.4 Air Quality and Meteorological Data

6.1.4.1 Selection of Fixed-Site Monitors

Based on considerations described in sections 3.2 and 5.5.2, staff selected the downtown "CAMP" monitor (ID 080310002) to represent ambient CO concentrations in the Denver, CO study area and monitor 060371301 in Lynwood, CA to represent ambient CO concentrations in the Los Angeles study area. Details regarding each monitor's site characteristics are given in (Table 6-4). Note that the ambient monitor in Denver is a microscale monitor sited within the urban core and generally records the highest hourly CO concentrations within the county (Table 3-1). Similarly, the middle scale monitor in the Los Angeles study also reported the highest CO concentration levels in the Los Angeles study area (Table 3-2).

Table 6-4. Site Characteristics of Fixed-site CO Monitors Selected to Represent the Denver and Los Angeles Study Areas.

Site Characteristic	Denver	Los Angeles
Site ID	080310002	060371301
Street address	2105 Broadway	11220 Long Beach Blvd.
Town	Denver, CO	Lynwood, CA
Local site name	CAMP	
Latitude	39.751184	33.928990
Longitude	-104.987625	-118.210710
Elevation (above sea level), meters	1593	27
Monitor start date	January 1, 1971	January 1, 1973
Measurement scale	Microscale	Middle scale
Sample collection frequency	1 hour	1 hour
Sample analysis method	Non-dispersive infrared	Non-dispersive infrared
Monitor type	SLAMS	SLAMS
Reporting agency	Colorado Department of Public health and Environment	South Coast Air Quality Management District

6.1.4.2 Estimation of Missing Air Quality Values

APEX requires that each site-year of monitoring data be complete (i.e., it is free of hourly gaps in concentration levels). The missing values in each data set were estimated by the sequential application of the following three methods.

1) If the data gap was less than six continuous missing values, the missing values were estimated by linear interpolation using the valid values at the ends of the gap.

2) Where possible, data gaps of at least 6 hours were estimated as linear functions of hourly values reported by other ambient CO monitors in the area. Linear regression was used to develop a set of models that were specific to a time-of-day and at each monitor. The model selected to estimate missing values for a particular time of day was the model that maximized the variance explained (R^2) for that hour, subject to the constraints that regression model R^2 was greater than 0.5 and the number of measurements used in constructing the model was at least 50.

3) In cases where method 2 (above) could not be used (i.e., no models were available for a particular time-of-day) and the gap was less than 9 hours, the missing values were estimated by linear interpolation between the valid values at the ends of the gap.

Table 6-5 provides descriptive statistics for 1-hour CO concentrations in each data set, before and after estimating missing values. The agreement between these statistics indicates that the addition of the estimated missing-value concentrations did not significantly affect the distribution of the hourly CO data.

Table 6-5. Descriptive Statistics for 1-hour CO Concentrations Reported by the Selected Denver and Los Angeles Monitors Before and After Estimation of Missing Values.

Area	Year	Missing value substitution	Samples (n)	1-hour CO concentrations (ppm)								
				Mean	Std	Percentile 50	90	95	99	99.9	2nd highest	Max
Denver[a]	1995	No	8697	1.5	1.2	1.2	2.7	3.4	6.1	13.1	16.4	24.5
		Yes	8760	1.5	1.2	1.2	2.7	3.4	6.1	13.1	16.4	24.5
	2006	No	8672	0.6	0.4	0.5	1.0	1.3	2.2	4.1	4.6	6.4
		Yes	8760	0.6	0.4	0.5	1.0	1.3	2.1	4.1	4.6	6.4
Los Angeles[b]	1997	No	8302	2.4	2.2	1.7	4.9	6.8	11.2	17.2	18.8	19.2
		Yes	8760	2.3	2.2	1.7	4.9	6.7	11.2	17.2	18.8	19.2
	2006	No	8275	1.0	0. 9	0.7	2.0	2.9	4.7	6.8	8.2	8.4
		Yes	8760	1.0	0.90	0.7	2.0	2.9	4.6	6.8	8.2	8.4

[a]Site ID 080310002
[b]Site ID 060371301

6.1.4.3 Air Quality Adjustment to Simulate Just Meeting NAAQS

In addition to modeling exposures based on recent air quality, exposures and resulting dose were estimated for air quality conditions that just meet the current 8-hour CO NAAQS of 9 ppm.[1] Because CO concentrations in recent years were significantly lower than the current NAAQS, staff first selected an earlier year for each city (1995 for Denver and 1997 for Los Angeles) to represent air quality conditions that were near the 8-hour CO standard. Consistent with the data adjustment approach employed in the previous draft CO exposure assessment (Johnson et al., 2000) and risk and exposure assessments for other pollutants conducted in support of other recent NAAQS reviews (e.g., US EPA, 2008c), as discussed in section 3.1.4 staff concluded (1) that the policy-relevant background levels of CO were negligible in each area and (2) that the fixed-site monitoring data could be adjusted to simulate just meeting the current CO standards by use of a simple proportional adjustment of all hourly values. Consequently, the following adjustment equation was employed:

$$CO_{adj}(m,h) = (NAAQS/DV) \times CO(m,h). \qquad (6\text{-}1)$$

$CO(m,h)$ is the 1-hour CO concentration at hour h for monitor m. It follows that $CO_{adj}(m,h)$ is the adjusted CO concentration for hour h at monitor m through the use of the specific design value (DV) for monitor m. Although the current 8-hour NAAQS for CO specifies a maximum

[1] The 8-hour CO NAAQS of 9 ppm was selected for purposes of simulating just meeting the CO NAAQS because it is the controlling standard from a control strategy development viewpoint.

concentration of 9 ppm, which is not to be exceeded more than 1 time in a year, the NAAQS term in Equation 6-1 is equivalent to 9.4 ppm due to the application of a standard data rounding convention used in calculating design values[2] (DVs) for CO (Laxton, 1990).

The DVs for Denver for the year 1995 and for Los Angeles for 1997 were 9.5 ppm and 15 ppm, respectively. The Denver DV is calculated as the second-highest 8-hour CO concentration reported by monitor ID 080310002 for 1995. The adjustment factor (or NAAQS/DV) that was applied equally to all 8,760 hourly ambient CO concentrations at that monitor is thus 9.4/9.5, or 0.99. In a similar manner, the DV used in Los Angeles is the second-highest 8-hour CO concentration reported at monitor 060371301 for 1997, giving an ambient concentration adjustment factor of 9.4/15, or 0.63 which was applied equally to all 8,760 hourly ambient CO concentrations from the Los Angeles monitor.

Table 6-6 lists descriptive statistics for the Denver and Los Angeles 1-hour data sets before and after adjustment. As expected, the adjusted data set for Denver 1995 is very similar to the unadjusted data set given that the adjustment factor used was close to unity. For example, the maximum concentration was reduced from 24.5 ppm to 24.2 ppm. The change in CO concentrations was greater as a result of adjusting the Los Angeles ambient data. For example, the maximum CO concentration was reduced from 19.2 ppm to 12.0 ppm. The adjusted data sets, representing air quality simulated to just meet the current 8-hour CO NAAQS,for Denver and Los Angeles, exhibit their greatest differences at the extreme upper percentiles of the distribution (i.e., the 99.9th percentile and above).

Table 6-6. Descriptive Statistics for 1-hour Carbon Monoxide Concentrations Reported by the Denver and Los Angeles Monitors Before and After Adjustment to Simulate Just Meeting the Current 8-Hour CO NAAQS.

Area	Year	Adjusted to just meeting NAAQS	1-hour CO concentrations (ppm)								
			Mean	Std	Percentile					2nd highest	Max
					50	90	95	99	99.9		
Denver[a]	1995	No	1.5	1.2	1.2	2.7	3.4	6.1	13.1	16.4	24.5
		Yes	1.5	1.2	1.2	2.7	3.4	6.0	12.9	16.2	24.2
Los Angeles[b]	1997	No	2.3	2.2	1.7	4.9	6.7	11.2	17.2	18.8	19.2
		Yes	1.5	1.4	1.1	3.1	4.2	7.0	10.8	11.8	12.0

[a]Site ID 080310002
[b]Site ID 060371301

[2] A design value is a statistic that describes the air quality status of a given area or monitor relative to the level of the NAAQS. For the CO 8-hour standard, the design value is the second highest daily, non-overlapping, maximum 8-hour average concentration over a year. The design value for the 1-hour standard is the second highest daily maximum 1-hour average concentration over a year. The latest update (2007-2008) on the CO design values can be found at: http://www.epa.gov/airtrends/pdfs/dv_co_2006_2008.pdf

6.1.4.4 Meteorological Stations

A few algorithms within APEX require meteorological data (primarily temperature) from stations located within the study area. For the analyses described in this report, hourly temperature data were obtained from meteorological stations located at or near the fixed-site CO monitor specified for each study area. Table 6-7 identifies the meteorological stations used and selected site characteristics.

Table 6-7. Site Characteristics of Meteorological Monitoring Stations Selected to Represent the Denver and Los Angeles Study Areas.

Site Characteristic	Denver	Los Angeles Site 1	Los Angeles Site 2
Site ID	080310002	060374002	
Street address	2105 Broadway	3648 N. Long Beach Blvd.	Daugherty Field
Town	Denver	Long Beach, CA	Long Beach, CA
Latitude	39.751184	33.823760	33.81667
Longitude	-104.987625	-118.189210	-118.15
Elevation (above sea level), meters	1593	6	9.4
Sample collection frequency	1 hour	1 hour	1 hour
Reporting agency	Colorado Department of Public Health and Environment	South Coast Air Quality Management District	

The procedure used for generating a complete meteorological data set was as follows.

- Staff first checked on the availability of hourly temperature data for the specified years at each CO fixed-site monitor specified for each study area.
- For Los Angeles, temperature data were not available for the specified CO monitoring site (Site ID 060371301). Consequently, we evaluated two alternative sites: Site 1 (located at CO monitoring site 060374002) and site 2 (located at Daugherty Field), which are approximately 12 km and 15 km, respectively, from site 060371301. These sites were separated from each other by a distance of only 3.6 km. Temperature data for the two years considered for the exposure analysis (i.e., 1997 and 2006) were reported by both sites. Because Site 1 had fewer missing values for 2006, it was selected as the primary meteorological site to represent the Los Angeles area for that year. Temperature data from Site 2 were used to fill the single missing value in the Site 1 data set for year 2006. However, the 1997 data contained 2,263 missing values for Site 1 and only 9 missing values for Site 2. Consequently, Site 2 was selected as the primary meteorological site to represent the Los Angeles area for 1997. Two of the nine missing values from Site 2 were available from Site 1; staff replaced these two missing values with corresponding values from Site 1. A linear interpolation, using the values at the end

of existing gaps, was used to fill in the seven remaining missing values in the 1997 data set in Site 2.[3]

- For Denver, temperature data were available for the CO ambient monitoring site used (i.e., Site ID: 080310002) and both years considered in the exposure assessment (1995 and 2006). Linear interpolation was used to fill 18 of 41 missing values considering the 1995 data and 11 of 11 missing values considering the 2006 data. In one instance, the gap in hourly temperature data was 23 continuous hours. Staff considered a linear interpolation to be inappropriate in this situation because it would likely not produce reasonable estimates of the variability in temperature (particularly the daily maximum) occurring during the 23-hour gap. An alternative approach was used in which the temperature data for corresponding hours in the previous day were substituted for the missing data.

6.1.5 Microenvironments

As mentioned earlier, two general microenvironments were defined for the exposure analyses: *in vehicle* and *all other*. Each microenvironment was defined as an aggregation of the location codes used in CHAD to specify where each exposure event occurred. Note that location is interpreted here as referring to the microenvironmental characteristics of a place (e.g., indoors at school), rather than the particular geographic location. Appendix E provides the mapping of the CHAD location codes to the two APEX modeled microenvironments.

The factors approach was used to estimate a CO concentration in the two microenvironments for each hour of the specified study period (Equation 5-1, section 5.3.4). The penetration factor for all microenvironments was set equal to 1 for both scenarios (see draft ISA, section 3.6.5.1 for all indoor microenvironments and section 5.4.2.1 for the in-vehicle microenvironment). The proximity factor was set equal to 1 for scenario A in both microenvironments modeled (i.e., in vehicle and all other) and equal to 2 for the in-vehicle microenvironment and 1 for the all other microenvironment in scenario B. The values used in representing in-vehicle concentrations for scenario B were based on staff's evaluation of measurement studies that simultaneously measured CO concentrations within motor vehicles and at nearby fixed-site monitors (see section 5.4.2.2).

Staff did not adjust ambient concentrations to estimate near-road microenvironmental CO concentrations. This was because the ambient CO concentrations from the two monitors used in this assessment had the highest hourly CO concentrations recorded in each study area, and based on the AQS noted monitoring scale, were already designated to capture near road CO concentrations (i.e., microscale and middle scale). While higher near-road CO concentrations are possible, staff judged that these ambient data would already represent upper percentile

[3] We used PROC EXPAND along with the JOIN option in SAS. The JOIN option fits a continuous curve to the data by connecting successive straight line segments.

ambient CO concentrations experienced by most persons residing or spending time near roadways in each study area.

6.1.6 Time/Activity Patterns

APEX constructs a 365-day longitudinal diary for each simulated individual by selecting 24-hour diaries from those available in CHAD. In performing the exposure assessments described in this report, all available diaries for persons above age 17 in the CHAD database were used regardless of particular commuting patterns.

6.1.6.1 Construction of Longitudinal Diaries

As discussed in section 5.3.3, APEX provides a longitudinal diary assembly algorithm that enables the user to create composite diaries that reflect the tendency of individuals to repeat day-to-day activities. The user specifies values for two statistical variables (*D* and *A*) that relate to a key daily variable, typically the time spent per day in a particular microenvironment (e.g., in a motor vehicle). The *D* statistic reflects the relative importance of intra- and inter-personal variance within the selected key daily variable. The *A* variable quantifies the day-to-day autocorrelation in the selected key daily variable. APEX then constructs composite diaries that exhibit the statistical properties defined by the specified values of *D* and *A*.

In this exposure assessment, we used the longitudinal diary algorithm to construct year-long activity patterns for each simulated individual to reflect the day-to-day correlation of time spent inside motor vehicles. Each diary day in the CHAD database was tagged with the number of minutes spent in the vehicle microenvironment. Parameter settings of $D = 0.31$ and $A = 0.19$ were specified to control the day-to-day repetition of time spent in motor vehicles in the constructed composite diaries. These particular *D* and *A* values were obtained from Isaacs et al. (2009) (see Appendix F).

In selecting particular diaries to represent the simulated population, the CHAD data are categorized or separated by APEX into data pools. In Scenario A and B, the pools were defined by three ranges for the maximum temperature of the diary day (< 55.0 °F, between 55.0 and 83.9 °F, and ≥84.0 °F) and two day-types (i.e., weekend and week day); thus, there were 3 x 2 = 6 diary pools. The window for age was set at 15%. For example, diaries can be selected for a simulated individual of age 60 from CHAD individuals ranging from ages 51 though 69.

6.2 EXPOSURE AND DOSE ESTIMATES AND RISK CHARACTERIZATION

6.2.1 Denver – Scenarios A and B

Output files for APEX4.3 runs were generated for various combinations of calendar year (1995 and 2006), exposure scenario (A or B), and air quality condition (*as is* or just meeting the

8-hour NAAQS) in the Denver study area. These results are summarized in a series of tables that follow (Tables 6-8 through Table 6-14).

Table 6-8 presents estimates for the number of person-days during the calendar year in which members of the Denver population-at-risk experienced a 1-hour daily maximum CO exposure at or above each of the indicated CO concentrations. Results are presented for Scenarios A and B for each of two air quality conditions: *as is* conditions represented by 2006 monitoring data and *just meeting* conditions as represented by 1995 monitoring data adjusted to simulate just meeting the 8-hour NAAQS. The maximum possible value for person-days of exposure is about 23.4 million person-days – the product of the estimated population-at-risk (about 64,000) and the number of days in the specified exposure period (365).

Using a format similar to Table 6-8, Table 6-9 presents estimates of the number of persons in the population-at risk that experienced at least one 1-hour daily maximum CO exposure at or above each of the indicated CO concentrations. In this table, the maximum possible value is about 64,000 people – the estimated number of people in the population-at-risk. Thus, each person can be counted no more than once in determining the value in Table 6-9.

Table 6-10 and Table 6-11 are comparable to Table 6-8 and Table 6-9, respectively though they provide estimates for 8-hour daily maximum exposures rather than 1-hour daily maximum exposures. Again, the maximum possible value for person-days of exposure in Table 6-10 is about 23.4 million person-days; the maximum possible value of persons exposed in Table 6-11 is about 64,000 people.

Table 6-12 and 6-13 are also analogous to the prior tables, though they present estimates of the number of person-days in which members of the Denver population-at-risk experienced a daily maximum end-of-hour COHb level at or above each of the indicated levels. Again, the maximum possible value for person-days is about 23.4 million for Table 6-12 and the maximum number of persons experiencing a maximum COHb level in the year in the population-at-risk is about 64,000 for Table 6-13.

Table 6-14 provides estimates for the mean number of days per person in which the person experienced a daily maximum end-of-hour COHb level at or above each of the indicated levels. These values were calculated by dividing the values listed in Table 6-12 (total number of person-days) by the comparable values in Table 6-13 (number of people); hence the maximum possible value is 365.

Table 6-9 through Table 6-15 exhibit general patterns that are consistent with the input data and parameter settings specified for the associated model runs. The Scenario B values are greater than the comparable Scenario A values because Scenario B specifically accounts for in-vehicle microenvironmental CO concentrations, while Scenario A assumes in-vehicle CO concentrations (and all other microenvironments) are equal to the ambient fixed-site monitor concentrations. However, the effect of better accounting for in-vehicle exposures (Scenario B) to the overall estimated population exposures and doses is primarily limited to differences observed in the upper percentiles of the distribution. For example, about 4.8% of simulated individuals are estimated to experience an end-of-hour COHb concentration at or above 1.0% when considering Scenario A and the *as is* air quality (Table 6-13). When considering Scenario B and *as is* air quality, about 7.0% of the population experiences an end-of-hour COHb level at or above 1.0%. Note however that when considering either scenario A or B, these data also indicate that between 93 and 95% of the population experienced an end-of-hour COHb concentration below 1.0%, suggesting that only an additional 2% of the population was affected by the addition of the in-vehicle microenvironment. The effect of accounting for in-vehicle concentrations (i.e, Scenario A results compared with Scenario B) was greater when considering the air quality adjusted to just meeting the current standard. For example, approximately 11% of simulated individuals were estimated to experience at least one end-of-hour COHb above 2.5% when considering Scenario B compared with over an order of magnitude fewer persons when considering Scenario A.

The estimated number of person-days and persons considering air quality just meeting the current standard is greater than that estimated considering *as is* air quality at comparable target concentrations. For example, the entire simulated population was estimated to experience at least one end-of-hour COHb concentration at or above 1.5% when considering the air quality just meeting the current standard and Scenario A. This same COHb level was only experienced by approximately 0.2% of the population when considering the *as is* air quality and Scenario A (Table 6-13). This of course is because the monitoring data used to represent ambient *as is* air quality have significantly lower CO levels than the data used to represent just meeting the 8-hour standard conditions in Denver (i.e., the adjusted 1995 air quality simulation).

As described in sections 2.6 and 4.2, our characterization of health risk for CO in this assessment focuses on several risk metrics involving comparison of estimated COHb levels in the adult CHD population to potential health benchmarks (1.5-3.0% COHb). Assessment results involving this comparison for the Denver study area are emphasized in bold type in Tables 6-12 through 6-14. Well below 1 percent of the at-risk population was estimated to reach COHb levels at or above 1.5% under *as is* conditions in both scenarios. Under air quality conditions just meeting the current standard, substantially greater percentages of the population were estimated to reach COHb levels at or above all of the potential health benchmark levels, with 100% of the at-risk population estimated to reach COHb levels ≥ 1.5% in Scenario B for these conditions (Table 6-13).

Table 6-8. Number of Person-days for Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience a 1-hour Daily Maximum CO Exposure at or Above the Specified Concentration.

CO Concentration (ppm)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	2.8E+03
30	0	0	0	1.5E+04
20	0	0	6.4E+04	1.0E+05
15	0	0	1.3E+05	2.4E+05
12	0	2.0E+03	3.2E+05	5.9E+05
9	0	1.1E+04	8.3E+05	1.1E+06
6	6.4E+04	1.4E+05	2.3E+06	3.2E+06
3	9.6E+05	1.4E+06	1.0E+07	1.3E+07
0	2.3E+07	2.3E+07	2.3E+07	2.3E+07

[a] "As Is" air quality data are for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-9. Number of Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience a 1-hour Daily Maximum CO Exposure at or Above the Specified Concentration.

CO Concentration (ppm)	Number of persons			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	2,800
30	0	0	0	14,000
20	0	0	64,000	64,000
15	0	0	64,000	64,000
12	0	2,000	64,000	64,000
9	0	9,700	64,000	64,000
6	64,000	64,000	64,000	64,000
3	64,000	64,000	64,000	64,000
0	64,000	64,000	64,000	64,000

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-10. Number of Person-days for Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience an 8-hour Daily Maximum CO Exposure at or Above the Specified Concentration.

CO Concentration (ppm)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	3.4E+02
15	0	0	0	2.4E+03
12	0	0	0	2.0E+04
9	0	0	1.3E+05	1.5E+05
6	0	7.4E+01	4.5E+05	6.1E+05
3	1.3E+05	2.1E+05	4.1E+06	5.0E+06
0	2.3E+07	2.3E+07	2.3E+07	2.3E+07

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-11. Number of Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience an 8-hour Daily Maximum CO Exposure at or Above the Specified Concentration.

CO Concentration (ppm)	Number of persons			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	340
15	0	0	0	2,400
12	0	0	0	17,000
9	0	0	64,000	64,000
6	0	74	64,000	64,000
3	64,000	64,000	64,000	64,000
0	64,000	64,000	64,000	64,000

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-12. Number of Person-days for Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience a Daily Maximum End-of-hour COHb Level at or Above the Specified Concentration.

COHb concentration (percent)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	2.5E+01
3.0	**0**	**0**	**4.9E+01**	**1.8E+03**
2.5	**1.9E+03**	**1.9E+03**	**3.3E+03**	**1.1E+04**
2.0	**3.9E+03**	**3.9E+03**	**2.6E+04**	**5.8E+04**
1.5	**9.2E+03**	**9.3E+03**	**1.8E+05**	**2.4E+05**
1.0	2.0E+05	2.1E+05	1.4E+06	1.7E+06
0	2.3E+07	2.3E+07	2.3E+07	2.3E+07

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-13. Number (and Percent) of Adults with Coronary Heart Disease (CHD) in the Denver Study Area Estimated to Experience a Daily Maximum End-of-hour COHb Level at or Above the Specified Concentration.

COHb concentration (percent)	Number of persons (percent[c])			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	25 (<0.1)
3.0	**0**	**0**	**12 (<0.1)**	**1,700 (3)**
2.5	**12 (<0.1)**	**12 (<0.1)**	**250 (0.4)**	**7,100 (11)**
2.0	**12 (<0.1)**	**12 (<0.1)**	**16,000 (26)**	**36,000 (56)**
1.5	**160 (0.2)**	**160 (0.2)**	**64,000 (100)**	**64,000 (100)**
1.0	3,100 (5)	4,500 (7)	64,000 (100)	64,000 (100)
0	64,000 (100)	64,000 (100)	64,000 (100)	64,000 (100)

[a] "As Is" air quality data are for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
[c] Percent of adult CHD population.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

Table 6-14. Estimated Average Number of Days with a Daily Maximum End-of-hour COHb Level At or Above the Specified Concentration Per Adult With Coronary Heart Disease (CHD) in the Denver Study Area.

COHb concentration (percent)	Average of person-days/person			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1995)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	0
3.0	**0**	**0**	**<0.1**	**<0.1**
2.5	**<0.1**	**<0.1**	**<0.1**	**0.2**
2.0	**<0.1**	**<0.1**	**0.4**	**0.9**
1.5	**0.1**	**0.1**	**2.9**	**3.8**
1.0	3.1	3.2	22	27
0	365	365	365	365

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1995 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Denver study area is estimated to be about 64,000.

6.2.2 Los Angeles – Scenarios A and B

Output files for APEX4.3 runs were generated for various combinations of calendar year (1997 and 2006), exposure scenario (A or B), and air quality condition (*as is* or just meeting the 8-hour NAAQS) in the Los Angeles study area. These results are summarized in a series of tables that follow (Tables 6-15 through Table 6-21).

The same general patterns identified above using the Denver results were observed in the Los Angles results when considering either modeling scenario and air quality condition. For example in Scenario A, approximately 3% of the simulated population experienced an end-of-hour COHb level at or above 1.5% considering the *as is* air quality compared with about 67% of the population having the same or greater COHb level when using air quality adjusted to just meeting the current standard (Table 6-20). This is as expected given the fixed-site input data for 2006 used to represent ambient *as is* conditions in Los Angeles having lower CO concentrations than the data used to represent just meeting the current standard (Table 6-5 and 6-6). Similarly, a greater number of persons and person-days are estimated when considering scenario B compared with scenario A. For example, when considering the *as is air* quality, approximately 3% of the simulated population experienced an end-of-hour COHb level at or above 1.5% considering Scenario A compared with about 8% of the simulated population when separately accounting for in-vehicle exposures (Scenario B). This is also as expected because, as in the case of Denver, Scenario B assumes CO concentrations in the Los Angeles in-vehicle microenvironment were twice the ambient concentrations, while Scenario A assumes the in-vehicle concentrations (and all other microenvironments) are equal to the ambient concentrations measured at the fixed-site monitor.

As described in sections 2.6 and 4.2, our characterization of health risk for CO in this assessment focuses on several risk metrics involving comparison of COHb levels in adults with CHD to potential health benchmarks (1.5-3.0% COHb). Assessment results involving this comparison for the Los Angeles study area are emphasized in bold type in Tables 6-19 – 6-21. Fewer than 1 percent of the at-risk population was estimated to reach COHB levels at or above 2.0% under *as is* conditions when considering both scenarios, with 3% and 8% at or above 1.5% COHb in Scenarios A and B, respectively. Under air quality conditions just meeting the current standards, substantially greater percentages of the population were estimated to reach COHb levels at or above all of the potential health benchmark levels, with 67% and 80% of the at-risk population estimated reach COHb levels ≥ 1.5% in Scenarios A and B, respectively, for these conditions (Table 6-20).

Table 6-15. Number of Person-Days for Adults with Coronary Heart Disease (CHD) in the Los Angeles Study Area Estimated to Experience a 1-hour Daily Maximum CO Exposure At or Above the Specified Concentration.

CO Concentration (ppm)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	1.3E+04
15	0	9.2E+03	0	1.4E+05
12	0	6.3E+04	1.6E+05	6.1E+05
9	0	3.3E+05	2.4E+06	3.2E+06
6	1.9E+06	2.8E+06	7.9E+06	9.2E+06
3	1.5E+07	1.7E+07	2.4E+07	2.5E+07
0	5.7E+-7	5.7E+07	5.7E+07	5.7E+07

[a] "As Is" air quality data are for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be about 160,000.

Table 6-16. Number of Adults with Coronary Heart Disease (CHD) in the Los Angeles Study Area Estimated to Experience a 1-hour Daily Maximum CO Exposure At or Above the Specified Concentration.

CO Concentration (ppm)	Number of persons			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	12,000
15	0	8,800	0	75,000
12	0	44,000	160,000	160,000
9	0	110,000	160,000	160,000
6	160,000	160,000	160,000	160,000
3	160,000	160,000	160,000	160,000
0	160,000	160,000	160,000	160,000

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be 160,000.

Table 6-17. Number Of Person-Days For Adults with Coronary Heart Disease (CHD) in the Los Angeles Study Area Estimated to Experience an 8-hour Daily Maximum CO Exposure At or Above the Specified Concentration.

CO Concentration (ppm)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	0
15	0	0	0	6.8E+02
12	0	3.2E+01	0	8.5E+03
9	0	2.9E+03	3.1E+05	3.7E+05
6	1.6E+05	2.3E+05	2.2E+06	2.7E+06
3	6.3E+06	7.0E+06	1.6E+07	1.6E+07
0	5.7E+07	5.7E+07	5.7E+07	5.7E+07

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be about 160,000.

Table 6-18. Number of Adults with Coronary Heart Disease (CHD) in the Los Angeles Estimated to Experience an 8-hour Daily Maximum CO Exposure At or Above the Specified Concentration.

CO Concentration (ppm)	Number of persons			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
80	0	0	0	0
60	0	0	0	0
40	0	0	0	0
30	0	0	0	0
20	0	0	0	0
15	0	0	0	610
12	0	32	0	6,900
9	0	2,300	160,000	160,000
6	160,000	160,000	160,000	160,000
3	160,000	160,000	160,000	160,000
0	160,000	160,000	160,000	160,000

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be about 160,000.

Table 6-19. Number of Person-Days For Adults With Coronary Heart Disease (CHD) in the Los Angeles Study Area Estimated to Experience a Daily Maximum End-of-hour COHb Level At or Above the Specified Concentration.

COHb concentration (percent)	Number of person-days			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	0
3.0	**0**	**0**	**0**	**0**
2.5	**0**	**0**	**6.5E+01**	**6.8E+02**
2.0	**1.6E+02**	**3.2E+02**	**6.1E+03**	**1.6E+04**
1.5	**2.8E+04**	**4.1E+04**	**3.2E+05**	**4.8E+05**
1.0	1.6E+06	1.8E+06	5.1E+06	5.9E+0
0	5.7E+07	5.7E+07	5.7E+07	5.7E+07

[a] "As Is" air quality data is for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be about 160,000.

Table 6-20. Number (and Percent) of Adults with Coronary Heart Disease (CHD) in the Los Angeles Study Area Estimated to Experience a Daily Maximum End-of-hour COHb Level At or Above the Specified Concentration.

COHb concentration (percent)	Number of persons (percent)[c]			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	0
3.0	**0**	**0**	**0**	**0**
2.5	**0**	**0**	**65 (<0.1)**	**680 (0.4)**
2.0	**130 (<0.1)**	**290 (0.2)**	**3,900 (2)**	**10,000 (7)**
1.5	**4,600 (3)**	**13,000 (8)**	**110,000 (67)**	**127,000 (80)**
1.0	147,000 (93)	150,000 (97)	160,000 (100)	160,000 (100)
0	160,000 (100)	160,000 (100)	160,000 (100)	160,000 (100)

[a] "As Is" air quality data are for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.
[c] Percent of adult CHD population.
Note: Total adult population with CHD in the Los Angeles study area is estimated to be about 160,000.

Table 6-21 Estimated Average Number of Days with a Daily Maximum End-of-hour COHb Level At or Above the Specified Concentration Per Adult with Coronary Heart Disease (CHD) in the Los Angeles Study Area.

COHb concentration (percent)	Average of person-days/person			
	"As Is" Air Quality (2006)[a]		"Just Meeting" Air Quality (1997)[b]	
	Scenario A	Scenario B	Scenario A	Scenario B
8.0	0	0	0	0
6.0	0	0	0	0
5.0	0	0	0	0
4.0	0	0	0	0
3.0	**0**	**0**	**0**	**0**
2.5	**0**	**0**	**0**	**0**
2.0	**<0.1**	**<0.1**	**<0.1**	**0.1**
1.5	**0.2**	**0.3**	**2.1**	**3.0**
1.0	9.9	12	32	37
0	365	365	365	365

[a] "As Is" air quality data are for the year 2006.
[b] Air quality data for the year 1997 adjusted downwards to just meet 9 ppm, 8-hour NAAQS.

6.2.3 Comparison of Denver and Los Angeles Estimates for End-of-hour COHb Levels

We can best compare Denver and Los Angeles estimates using the results provided in Tables 6-13 and 6-20. These tables provide estimates for the percentage of people in the population-at-risk that are estimated to experience a daily maximum end-of-hour COHb level at or above the specified value. For either scenario, the percentage of people with COHb levels at or above 1.5 percent is greater for Los Angeles than for Denver when considering the *as is* air quality. For example, in Los Angeles it was estimated that 3 and 8 percent of persons experienced an end-of hour COHb level at or above this level for Scenarios A and B, respectively, for the *as is* case. In Denver, virtually no persons (0.2%) experienced an end-of-hour COHb at or above 1.5% associated with the *as is* case. This pattern is consistent with the fact that the monitoring data used to represent *as is* conditions in Los Angeles exhibited higher CO levels than Denver (Table 6-5).

The pattern noted above is reversed when considering air quality that just meets the current standard. For example, the estimated percent of persons having a COHb level at or above 2 percent for Scenarios A and B are 26 percent and 56 percent, respectively for Denver (Table 6-13); the comparable estimates for Los Angeles are about 2 percent for Scenario A and 7 percent for Scenario B (Table 6-20). This pattern is also expected, since the air quality data used to represent just meeting the current standard in Denver has higher CO levels at the upper percentiles of the distribution than the Los Angeles data (Table 6-6).

6.3 COMPARISON OF COHB ESTIMATES OBTAINED FROM THE 2000 PNEM/CO AND DRAFT 2009 APEX/CO ASSESSMENTS

As part of the review of the CO NAAQS initiated in 1997, a draft CO exposure assessment was prepared (Johnson, et al., 1999). Subsequent to the discontinuation of that CO NAAQS review, a revised document was completed (Johnson et al., 2000). The 2000 document was subsequently subject to peer review by several exposure modeling experts (SAIC, 2001). The 2000 CO population exposure assessment was conducted for Denver using air quality data for 1995 and for Los Angeles using air quality data for 1997. The exposure and dose estimates were obtained by applying pNEM/CO, a predecessor to APEX, to adults with ischemic heart disease residing in a defined study area within each city (Johnson et al., 2000). As part of current (2009) draft exposure assessment described in section 6.1, staff has again used APEX to estimate CO exposures and resulting COHb levels in a portion of Denver using 1995 air quality data and in a portion of Los Angeles using 1997 air quality data. In this case, the population-at-risk was defined as adults with CHD which is approximately equivalent to the ischemic heart disease definition used in the prior review.

In comparing the earlier pNEM/CO results with the exposure and dose estimates obtained from the current draft APEX/CO assessment for the same cities and years, it is important to understand the differences between the methodologies employed in the two assessments. The methods and results associated with the 2000 pNEM/CO analysis are described in detail in a report by Johnson et al. (2000). The methods used in the current (2009) draft APEX exposure assessment are described above in section 6.1. Section 6.3.1 provides a brief discussion of the important differences between the two assessments that may account for some of the observed differences in the exposure estimates. Section 6.3.2 presents estimates of COHb levels in adults with CHD obtained from the two assessments.

6.3.1 Important Differences Between the 2000 pNEM/CO and 2009 draft APEX/CO Exposure/Dose Assessments

In the 2000 pNEM/CO assessment, the Denver study area was defined to include the census tracts located within 10 km of each of six fixed-site monitors in the Denver metropolitan area. Air quality data for 1995 reported by these fixed-site monitors were used to represent "existing conditions" in the study area. Because the second non-overlapping 8-hour maximum CO concentration (design value) equaled 9.5 ppm, the existing conditions in Denver for 1995 were considered to approximate just meeting the 8-hour standard in which the DV equals 9.4 ppm.

In a similar manner, the Los Angeles study area was defined to include all census tracts within 10 km of ten fixed-site monitors in the Los Angeles metropolitan area. Air quality data for 1997 reported by these fixed-site monitors were used to represent "existing conditions" in the study area. Because the 1997 CO levels in Los Angeles exceeded the 8-hour NAAQS, the concentrations at each monitoring site were adjusted downwards so that the concentrations associated with the DV site exactly met the 8-hour NAAQS (i.e., the adjusted maximum CO concentration at the DV site equaled 9.4 ppm).

Note that the air quality data used in the pNEM/CO assessments for each city included data from multiple sites (6 in Denver, 10 in Los Angeles) that represented areas of varying CO levels. The monitoring data associated with the DV (highest CO) site were only applied to those people who resided in the circular area within 10 km of that particular monitor.[4] Data from other (lower CO) sites were applied to the people in the study area who resided within the 10 km circular areas centered on those sites.

In the 2009 draft APEX/CO assessment, the Denver and Los Angeles study areas are each defined to include all census tracts within 20 km of a single fixed-site monitor. This

[4] In Denver, there was one instance where two monitors in close proximity to each other were geographically combined to represent a single composite monitoring location.

monitor is the DV site for the specified year of the assessment (1995 for Denver, 1997 for Los Angeles). Consequently, monitoring data associated with the DV (highest CO) site are applied to all people within the surrounding study area. This focus on high concentration CO monitors in the current assessment would tend to produce a greater percentage of persons exposed to higher CO levels than would the approach used in the 2000 pNEM/CO assessment.

In the 2000 exposure assessment, pNEM/CO was set up to account for 15 distinct microenvironments. Each of the 12 enclosed microenvironments (including 3 motor vehicle microenvironments) was modeled using a sophisticated mass balance model. This model used probabilistic techniques to account for outdoor (ambient) air quality, air exchange rate, and indoor emissions. When applied to building microenvironments characterized by relatively low air exchange rates, the mass balance model in pNEM/CO yields hourly-average CO concentrations in the building that tend to have less variance than the corresponding hourly-average ambient concentrations outside the building. Relative to the ambient concentrations outside the building, the indoor concentrations have lower peak values and the peaks are delayed in time. This effect is not significant for in-vehicle microenvironments that are characterized by relatively high air exchange rates. In addition, two indoor sources of CO were evaluated in the 2000 pNEM/CO assessment for residential microenvironments: gas stoves and passive smoking. The model was set up so that these sources could be turned on and off within the model. The estimated number of people with COHb levels above 2.5 percent was noticeably higher when pNEM/CO accounted for the specified indoor sources.

The 2009 draft APEX/CO assessment specifies only two microenvironments (i.e., in vehicle and all other). The CO concentrations in these microenvironments are modeled using a simple proportionality factor (the proximity factor) applied to the corresponding ambient air quality concentrations based on the fixed-site monitor values. For the in-vehicle microenvironment, the proximity factor equals 1 for Scenario A and 2 for Scenario B. The proximity factor for all other microenvironments equals 1 for both scenarios. And finally, no provision has been made to account for the effects of indoor sources in this draft of the current CO assessment given the simplified approach used.

6.3.2 Comparison of Estimated COHb Levels in Adults with Coronary Heart Disease using the 2000 pNEM/CO and 2009 Draft APEX/CO Assessments

Table 6-22 presents estimates for the percentage of Denver adults with CHD who would experience a daily maximum end-of-hour COHb level at or above the specified level under the specified air quality conditions for 1995. Table 6-23 presents similar estimates for Los Angeles. Each table provides two sets of estimates for the 2000 pNEM/CO assessment (indoor sources "on" and "off") and two sets for the current (2009) draft APEX/CO assessment (Scenarios A and

B). See section 6.3.1 above for a brief discussion of the modeling assumptions used in developing each set of estimates.

As expected, the COHb levels estimated by the 2000 pNEM/CO assessment are higher when internal sources are turned on. As stated above, it was also expected that estimated COHb levels would be higher for Scenario B than for Scenario A in the current assessment, since Scenario B uses a larger proximity factor for the in-vehicle microenvironment.

Because of the significant differences in modeling approaches employed by the two assessments, it is difficult to make a direct comparison of the results for pNEM/CO 2000 with the results for current APEX/CO draft assessment. As discussed in section 6.3.1, the two assessments differ according to:

- Boundaries of the study area defined for each city,
- Monitors used to represent ambient CO levels,
- Defined microenvironments,
- Microenvironmental modeling approach used, and
- Treatment of indoor sources.

With these caveats in mind, we observe that the estimated percentage of Denver adults with CHD that experience end-of-hour COHb levels at or above 2 percent is higher for the 2009 draft APEX/CO assessment (Scenario A or Scenario B for the just meeting the current 8-hour standard case) than for the 2000 pNEM/CO assessment (*as is* case which was very close to just meeting the 9 ppm CO NAAQS), regardless of whether internal sources are turned on or off in the pNEM assessment (Table 6-22). The corresponding results for Los Angeles (Table 6-23) for the *just meeting* the standard case show values for the 2009 draft APEX/CO assessment (Scenario A or Scenario B) that are lower than the 2000 pNEM/CO assessment for the *just meeting* the standard case when internal sources are turned on and higher when the sources are turned off. Note that these patterns are not consistent across all COHb levels. For example, the estimate listed for either study area for COHb levels at or above 4 percent is higher for 2000 pNEM/CO (sources on) than for the corresponding values for 2009 draft APEX/CO assessment (Scenarios A and B).

In the current assessment, assuming the ambient concentrations contributing to all microenvironments are equal to the concentrations reported at the fixed-site monitor (for Scenario A) indicates that there would not be any spatial heterogeneity in CO concentrations across the study area, that is, the single monitor used in each study area is assumed to represent all outdoor CO concentrations. However, there are other ambient monitors within the 20 km study area having lower CO concentrations and these were used in the previous 2000 assessment. Therefore, the assumption of spatial homogeneity would tend to contribute to the greater CO population exposures estimated in the current assessment compared to those estimated in the previous 2000 assessment, when holding all other factors constant. Staff also assumed in the current assessment that the penetration of CO into all microenvironments was equivalent to one. This assumption would lead to a lack of attenuation of peak outdoor ambient CO concentrations that is expected to occur in indoor microenvironments when not accounting for physical processes described above. Therefore, greater population exposures would be estimated for the current assessment when compared with the exposures estimated in the prior 2000 assessment, holding all other factors constant. The impact of these simplifying assumptions is best illustrated in Figure 6-3 using the data provided in Tables 6-22 and 6-23 for the situation where no indoor sources were modeled. Clearly, in the current assessment nearly all of the simulated population reaches a higher estimated daily maximum COHb level (at least once per year) for both areas when compared with the previous 2000 assessment. Once accounting for this higher population distribution at COHb levels up to about 1% COHb, the general shape of the population distribution is very similar for both the locations when compared with results in the previous assessment, particularly when including the contribution of the in-vehicle microenvironment separately (Scenario B) in estimating exposures.

Table 6-22. Percentage of Denver Adults with Coronary Heart Disease (CHD) Estimated to Experience a Daily Maximum End-of-hour COHb Level At or Above the Specified Percentage Under Specified Air Quality Conditions for 1995.

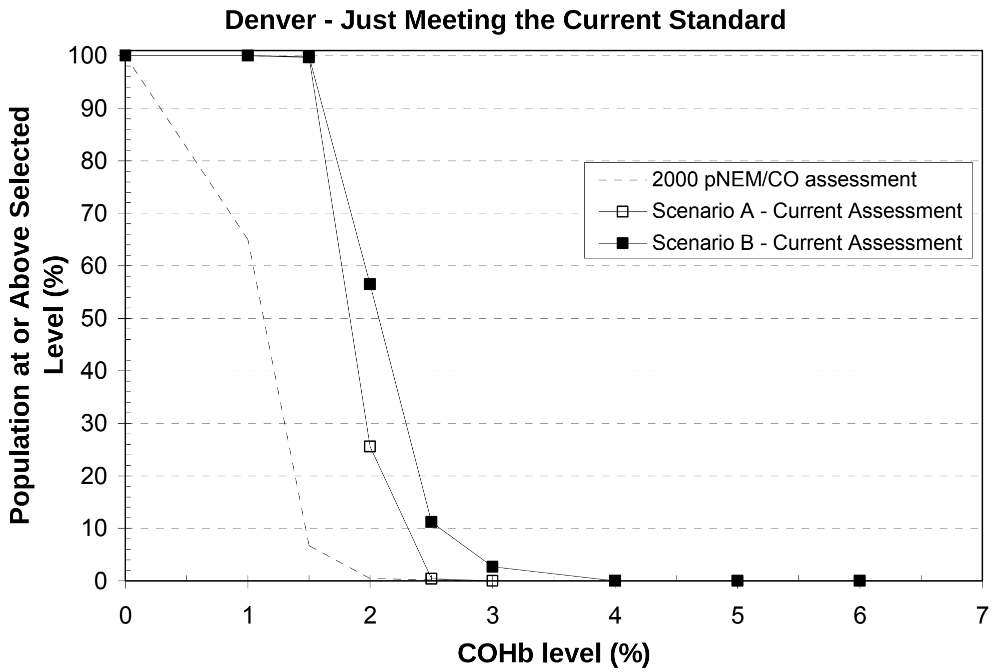
COHb concentration (percent)	Percentage of adults with coronary heart disease[a] estimated to experience a daily maximum end-of-hour COHb level at or above the specified percentage			
	2000 pNEM/CO assessment for "existing" conditions[b]		2009 draft APEX/CO assessment for "just meeting" conditions[c]	
	Internal sources on	Internal sources off	Internal sources off	
			Scenario A	Scenario B
6.0	0.2	0	0	0
5.0	0.6	0	0	0
4.0	1.6	0	0	<0.1
3.0	5.5	< 0.1	<0.1	2.7
2.5	10.4	0.2	0.4	11.2
2.0	19.9	0.5	25.6	56.5
1.5	37.6	6.7	99.7	99.8
1.0	83.2	65.0	100	100
0	100	100	100	100

[a] Characterized as "ischemic heart disease" in the 2000 pNEM/CO exposure assessment.
[b] "Existing" conditions: Denver CO conditions during 1995 with no adjustment. Second non-overlapping 8-hour maximum CO concentration (design value) equals 9.5 ppm. These conditions approximate "just meeting" conditions for Denver (i.e., design value equals 9.4 ppm).
[c] "Just meeting" conditions: 1995 CO levels in Denver adjusted to simulate conditions when the second non-overlapping 8-hour maximum CO concentration at the design value site equals 9.4 ppm.

Table 6-23. Percentage of Los Angeles Adults with Coronary Heart Disease (CHD)[a] Estimated to Experience a Daily Maximum End-of-hour COHb Level At or Above the Specified Percentage Under "Just Meeting"Conditions[b] for 1997.

COHb concentration (percent)	Percentage of adults with coronary heart disease[a] estimated to experience a daily maximum end-of-hour COHb level at or above the specified percentage			
	2000 pNEM/CO assessment		2009 draft APEX/CO assessment	
	Internal sources on	Internal sources off	Internal sources off	
			Scenario A	Scenario B
6.0	0.2	0	0	0
5.0	0.8	0	0	0
4.0	2.2	0	0	0
3.0	5.1	<0.1	0	0
2.5	9.0	<0.1	<0.1	0.4
2.0	16.8	0.5	2.4	6.6
1.5	32.3	5.2	67.0	80.5
1.0	79.0	58.1	100	100
0	100	100	100	100

[a] Characterized as "ischemic heart disease" in the 2000 pNEM/CO exposure assessment.
[b] "Just meeting" conditions: 1997 CO levels in Los Angeles adjusted to simulate conditions when the second non-overlapping 8-hour maximum CO concentration at the design value site equals 9.4 ppm.



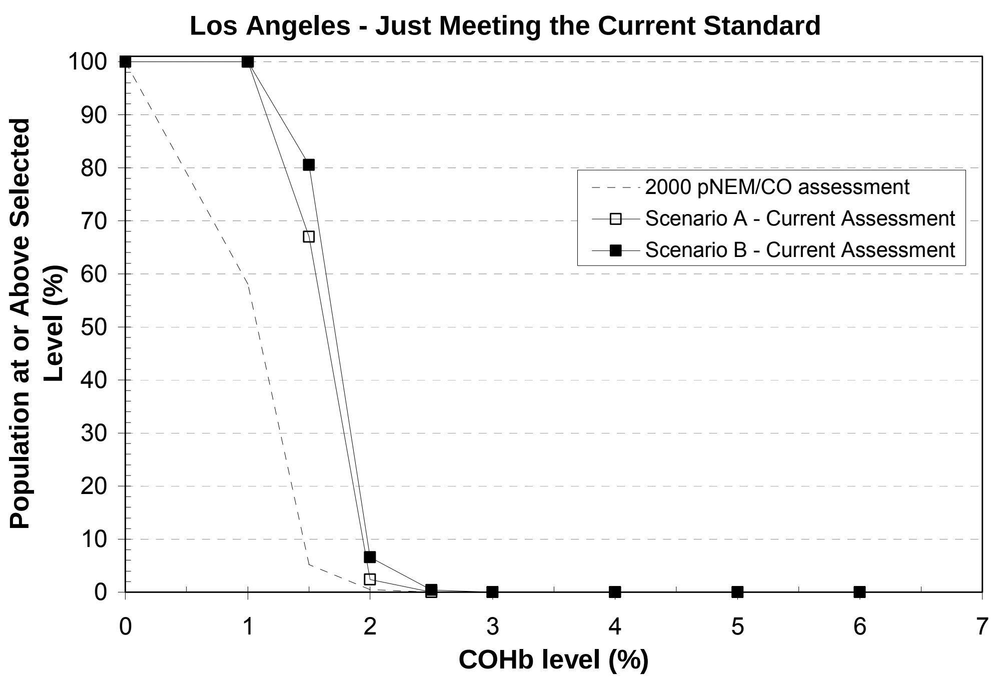


Figure 6-3. Percentage of Los Angeles and Denver Adults with Coronary Heart Disease (CHD) Estimated to Experience a Daily Maximum End-of-hour COHb Level At or Above the Specified Percentage for Air Quality Adjusted to Just Meeting the Current Standard. Data taken from Tables 6-22 and 6-23.

6.4 VARIABILITY ANALYSIS AND UNCERTAINTY CHARACTERIZATION

An important issue associated with any population exposure or risk assessment is the characterization of variability and uncertainty. *Variability* refers to the inherent heterogeneity in a population or variable of interest (e.g., residential air exchange rates) and cannot be reduced through further research, only better characterized with additional measurement. *Uncertainty* refers to the lack of knowledge regarding the values of model input variables (i.e., *parameter uncertainty*), the physical systems or relationships used (i.e., use of input variables to estimate exposure or risk or *model uncertainty*), and in specifying the scenario that is consistent with purpose of the assessment (i.e., *scenario uncertainty*). Uncertainty is, ideally, reduced to the maximum extent possible through improved measurement of key parameters and iterative model refinement. The approaches used to assess variability and to characterize uncertainty in this REA are discussed in the following two sections. Each section also contains a concise summary of the identified components contributing to uncertainty and how each source may affect the estimated exposures.

6.4.1 Analysis of Variability

The purpose for addressing variability in this REA is to ensure that the estimates of exposure and risk reflect the variability of ambient CO concentrations and associated CO exposure and health risk across the study locations and population. In this draft assessment, there are several algorithms that account for variability of input data when generating the number of estimated benchmark exceedances or health risk outputs. For example, variability may arise from differences in the population residing within census tracts (e.g., age distribution) and the activities that may affect CO population exposure and dose (e.g., time spent inside vehicles, moderate or greater exertion outdoors). A complete range of potential exposure levels and associated risk estimates can be generated when appropriately addressing variability in exposure and risk assessments; note however that the range of values obtained would be within the constraints of the input parameters, algorithms, or modeling system used, not the complete range of the true exposure or risk values.

Where possible, staff identified and incorporated the observed variability in input data sets and estimated parameters within the exposure and dose assessment performed rather than employing standard default assumptions and/or using point estimates to describe model inputs. The details regarding any variability distributions used in data inputs are described in section 6.1. To the extent possible given the data available for the assessment, staff accounted for variability within the exposure and dose modeling. APEX has been designed to account for variability in some of the input data, including the physiological variables that are important inputs to determining ventilation rates and COHb dose levels. As a result, APEX addresses much of the

Table 6-24. Summary of How Variability Was Incorporated Into the Exposure and Dose Assessment.

Component	Variability Source	Comment
Simulated Individuals	Population data	Individuals are randomly sampled from U.S. census tracts used in model domains, by age (single years) and gender.
	Activity patterns	Data diaries are randomly selected from CHAD using six diary pools stratified by two day-types (weekday, weekend) and three temperature ranges (< 55.0 °F, between 55.0 and 83.9°F, and ≥84.0 °F).
	Coronary heart disease (CHD) prevalence	CHD prevalence is stratified by four age groups (18-44, 45-64, 65-74, and 75+) and both genders.
Ambient Input	Measured ambient CO concentrations	Temporal: 1-hour CO for an entire year predicted using ambient monitoring data.
	Meteorological data	Spatial: Local surface NWS stations used. Temporal: 1-hour NWS temperature data for each year.
Physiological Factors Relevant to Ventilation Rate and Estimation of COHb Levels	Resting metabolic rate	Three age-group (18-29, 30-59, and 60+) by gender specific regression equations were used with body mass as the independent variable (Johnson et al., 2000).
	Metabolic equivalents by activity (METS)	Values randomly sampled from distributions developed for specific activities (some age-specific) (US EPA, 2002).
	Oxygen uptake per unit of energy expended	Values randomly sampled from a uniform distribution (Johnson et al., 2000).
	Weight (body mass)	Randomly selected from population-weighted lognormal distribution with geometric mean (GM) and geometric standard deviation (GSD) distribution specific to age and gender derived from data from the National Health and Nutrition Examination Survey (NHANES), for the years 1999-2004.
	Height	Values randomly sampled from distribution based on equations developed for each gender developed from analyses (Johnson, 1998) of height and weight data (Brainard and Burmaster, 1992) (see Appendix C for details)
	Blood volume	Values determined according to gender using equations based on work by Allen et al (1956) (see Appendix C for details).
	Hemoglobin content of the blood	Values randomly selected from distributions developed by gender and age categories based on NHANES study (US DHHS, 1982) (see Appendix C for details).
	Pulmonary CO diffusion rate	Values selected according to gender, height, and age based on equations adapted from Salorinne (1976) (see Appendix C for details).
	Endogenous CO production rate	Values randomly selected from lognormal distributions according to equations specific to age, gender, and menstrual phase (see Appendix C for details).

variability in exposure and dose estimates given variability in factors that affect human exposure and dose. The variability accounted for in this analysis is summarized in Table 6-24.

6.4.2 Characterization of Uncertainty

While it may be possible to capture a range of exposure or risk values by accounting for variability inherent to influential factors, the true exposure or risk for any given individual is largely unknown. To characterize health risks, exposure and risk assessors commonly use an iterative process of gathering data, developing models, and estimating exposures and risks, given the goals of the assessment, scale of the assessment performed, and the limitations of the input data available. However, significant uncertainty often remains and emphasis is then placed on characterizing the nature of that uncertainty and its impact on exposure and risk estimates.

The characterization of uncertainty can include either qualitative or quantitative evaluations, or perhaps a combination of both. The approach can also be tiered, that is, the analysis can begin with a simple qualitative uncertainty characterization then progress to a complex probabilistic uncertainty analysis. This may follow when a lower tier analysis indicates there is a high degree of uncertainty for certain identified sources, the sources of uncertainty are highly influential variables in estimating the exposure and risk, and sufficient information and other resources are available to conduct a quantitative uncertainty assessment. This is not to suggest that quantitative uncertainty analyses should always be performed in all exposure and risk assessments. The decision regarding the type of uncertainty characterization performed is also informed by the intended scope and purpose of the assessment, whether the selected analysis will provide additional information to the overall decision regarding health protection, whether sufficient data are available to conduct a complex quantitative analysis, and whether time and resources are available for higher tier characterizations (US EPA, 2004; WHO, 2008).

The primary purpose of the uncertainty characterization approach selected in this draft REA is to identify and compare the relative impact important sources of uncertainty may have on the estimated potential health effect endpoints. The approach used to evaluate uncertainty was adapted from guidelines outlining how to conduct a qualitative uncertainty characterization (WHO, 2008) and applied in the most recent NO_2 (US EPA, 2008c) and SO_2 NAAQS reviews (US EPA, 2009). While it may be considered ideal to follow a tiered approach in the REA to quantitatively characterize all identified uncertainties, staff selected the mainly qualitative approach given the extremely limited data available to inform probabilistic analyses.

The qualitative approach used in this REA varies from that of WHO (2008) in that a greater focus of the characterization performed was placed on evaluating the direction and the magnitude[5] of the uncertainty; that is, qualitatively rating how the source of uncertainty, in the presence of alternative information, may affect the estimated exposures and health risk results. In addition and consistent with the WHO (2008) guidance, staff discuss the uncertainty in the knowledge-base (e.g., the accuracy of the data used, acknowledgement of data gaps) and decisions made where possible (e.g., selection of particular model forms), though qualitative ratings were assigned only to uncertainty regarding the knowledge-base.

First, staff identified the key aspects of the assessment approach that may contribute to uncertainty in the exposure and risk estimates and provide the rationale for their inclusion. Then, staff characterized the magnitude and direction of the influence on the assessment results for each of these identified sources of uncertainty. Consistent with the WHO (2008) guidance, staff subjectively scaled the overall impact of the uncertainty by considering the degree of severity of the uncertainty as implied by the relationship between the source of the uncertainty and the output of the air quality characterization. Where the magnitude of uncertainty was rated *low*, it was judged that large changes within the source of uncertainty would have only a small effect on the exposure results. A designation of *medium* implies that a change within the source of uncertainty would likely have a moderate (or proportional) effect on the results. A characterization of *high* implies that a small change in the source would have a large effect on results. Staff also included the direction of influence, indicating how the source of uncertainty was judged to affect estimated exposures or risk estimates; either the estimated values were likely *over*- or *under-estimated*. In the instance where the component of uncertainty can affect the assessment endpoint in either direction, the influence was judged as *both*. Staff characterized the direction of influence as *unknown* when there was no evidence available to judge the directional nature of uncertainty associated with the particular source. Staff also subjectively scaled the knowledge-base uncertainty associated with each identified source using a three level scale: *low* indicated significant confidence in the data used and its applicability to the assessment endpoints, *medium* implied that there were some limitations regarding consistency and completeness of the data used or scientific evidence presented, and *high* indicated the knowledge-base was extremely limited.

The output of the uncertainty characterization was a summary describing, for each identified source of uncertainty, the magnitude of the impact and the direction of influence the uncertainty may have on the exposure and risk characterization results. There are several sources of uncertainty associated with this simplified approach for modeling CO population exposure/dose and associated potential health risk, each summarized and discussed in Table 6-25.

[5] This is synonymous with the "level of uncertainty" discussed in WHO (2008), section 5.1.2.2.

Table 6-25. Characterization of Key Uncertainties in the Draft Assessment for Denver and Los Angeles Areas.

Sources of Uncertainty		Influence of Uncertainty on Exposure/Dose or Risk Estimates		Knowledge-Base Uncertainty	Comments[a]
Category	Element	Direction	Magnitude		
Ambient CO Concentrations	Database Quality	Over	Low	Low	INF: There may be a limited number of poor quality high concentration data within the analytical data sets, potentially influencing the number of benchmark dose level exceedances. KB: EPA's Air Quality System data used in the analyses are of high quality. There is no other source of monitoring data as comprehensive. Data are being used in a manner consistent with one of the defined objectives of ambient monitoring.
	Spatial and Temporal Representation	Over	Medium	High	INF: Use of a single fixed-site ambient CO monitor likely does not adequately represent spatial temporal variability in ambient CO levels throughout each study area. Given that typical in-vehicle to ambient concentration ratios range from 2 to 4 and on-road sources tend to dominate CO emissions, it is likely that the spatial variability in ambient concentrations across a region would be less than this value. Given that the single monitor selected for use in the exposure assessment had generally greater concentrations than other monitors within the broader metropolitan area, it is likely that exposures are overestimated for most simulated individuals. KB: In the absence of 1) a monitoring network designed to measure spatial variability in CO concentrations, 2) performing air quality modeling to estimate spatial and temporal variability in CO concentrations and, 3) analysis of any existing and representative monitoring data that can potentially indicate spatial concentration gradients, staff judge the uncertainty in the knowledge-base as high.
	Missing Data Substitution	Under	Low	Low	INF: Assuming there is an equal probability of missing low and high concentration hourly values, and that substituted data are limited by the bounds of the algorithm (i.e., as defined by limits in the measurement data), there may be a few missing high concentration data that could lead to underestimation in exposure concentrations and doses. This assumes that the substitution of low-level concentration data with potentially higher concentrations (within the bounds of the algorithm) does not affect exposure results. KB: All available measurement data are quality assured. Very few data values were substituted with respect to the number of measured values available in each location.
Adjustment of Air Quality to Simulate Just Meeting the	Historical Data Used	Unknown	Medium	High	INF & KB: Even though the historical data represent a real air quality condition that may be similar to concentrations levels expected to just meet the 8-hour current standard, the condition simulated is hypothetical. It is largely unknown how influential factors such as emission levels per vehicle, vehicular traffic, and meteorology compare between an earlier period of time and the hypothetical condition of just meeting the current standard.

Sources of Uncertainty		Influence of Uncertainty on Exposure/Dose or Risk Estimates		Knowledge-Base Uncertainty	Comments[a]
Category	Element	Direction	Magnitude		
Current 8-Hour Standard	Proportional Approach Used	Both	Low	Low	INF: The magnitude of the adjustment applied to historical ambient concentration data was minimal for Denver (i.e., 0.99 was the adjustment applied), though greater for Los Angeles (0.63). In comparing recent and historical ambient CO concentrations (Table 6-5), a linear relationship exists between the range of concentrations reported for the two time periods in both locations. More importantly, a strong proportional relationship is present when comparing the recent and historic CO concentrations measured at the Los Angeles monitor. KB: A similar proportional approach was judged adequate in simulating air quality conditions just meeting the 8-hour CO NAAQS in prior assessments (US EPA, 1992; Johnson et al., 2000). An analysis of the CO concentration distributions comparing 1995 and 1997 CO air quality data in the Denver and Los Angeles study areas, respectively with more recent CO air quality data (i.e., 2006) in these same two areas shows a roughly linear or proportional change throughout the distribution.
APEX Inputs and Algorithms	Population Database	Both	Low	Low	INF & KB: Population data are from the US Census Bureau, a reliable and quality assured source. Data used are specifically for census tracts modeled in Denver and Los Angeles. Staff assumed any remaining uncertainties in the database would have negligible influence on exposure and dose results.
	Activity Pattern Database	Unknown	Low-Medium	Medium	INF: Data are actual records of the time spent in specific locations while performing specific activities in particular locations. While not specific to a particular area, the activity patterns of a population are generally well represented by the mainly population-based and nationally-representative survey data (e.g., see Table G-1 in Appendix G regarding the patterns of typical commuting in CHAD versus the urban locations modeled in this assessment). KB: Data are from a reliable and quality assured source (CHAD) and are from surveys of real persons. Features of an individual's activity pattern are well represented, adjustments are made to represent the population distribution in a specific area (using age and gender), and temperature is used to link CHAD diaries with the simulated individuals residing in a specific area. However, there are several assumptions made that contribute to uncertainty in its use. For example, activity patterns of persons surveyed over 30 years ago are assumed to represent a current persons activity patterns.
	Longitudinal Profile Algorithm	Both	Low – Medium	Medium	INF: The magnitude of potential influence would be mostly directed toward estimates of multi-day exposures, not the number or percent of persons having at least one exposure or dose above a selected level. KB: In developing the longitudinal method, the evaluation indicated that both the *D* and *A* statistics are reasonably reproduced for the population. In addition, the approach was compared to two other independent methods used for constructing longitudinal activity patterns (see Appendix B, Attachment 5 of US EPA , 2009). Note however, long-term diary profiles (i.e., monthly, annual) do not exist for a population.
	Meteorological Data	Both	Low	Low	INF & KB: Data are from the National Weather Service, a well-known and quality-assured source. Daily maximum temperatures are only used when selecting appropriate diaries to simulate individuals.

Sources of Uncertainty		Influence of Uncertainty on Exposure/Dose or Risk Estimates		Knowledge-Base Uncertainty	Comments[a]
Category	Element	Direction	Magnitude		
	Algorithm and Input Data for In-Vehicle CO Concentrations	Both	Medium	Medium	INF: Given that on-road and in-vehicle CO concentrations are typically higher than ambient CO concentrations, Scenario A likely underestimates in-vehicle exposures. There is variability between in-vehicle and ambient CO concentrations that is not accounted for by using a single value to represent the relationship (i.e., a factor of two) such as traffic density, local meteorology, driving conditions, and differences in vehicle age, technology, design and time of operation. KB: While most studies reviewed indicate that, on average, there may be a factor of two difference between the ambient and in-vehicle CO concentrations, there are a limited number of studies that measured these concentrations and even fewer were located in the U.S. It is largely unknown how this and other identified influential factors might influence the true relationship between in-vehicle and ambient CO concentrations.
	Algorithm and Input Data for All Other Microenvironmental CO Concentrations	Over	Low-Medium	Medium	INF & KB: Even though CO is considered relatively inert, it is likely that the ambient contribution to exposures in all indoor microenvironments are overestimated. This is a result of not considering air exchange that would delay and limit infiltration of outdoor CO concentrations, thereby reducing indoor microenvironmental peak concentrations due to CO of ambient origin. It is also possible that the residential indoor or outdoor microenvironment concentrations of simulated individuals residing in close proximity to major roads may be underestimated. This is because the current ambient monitors are unlikely to reflect the higher CO concentrations expected to occur near all major roads (draft ISA, section 3.6.6.2). The simplified approach used an ambient monitor that may be representative of outdoor near-road CO concentrations (i.e., microscale and middle scale monitors) experienced by only a portion of the population in each study area. However, given the larger portion of time spent in locations other than in vehicles and outdoors near-roads and the limited difference in exposures estimated when comparing scenario A to scenario B, it is likely that exposures and doses have an overall tendency to be overestimated for most of the simulated population.
	Commuting Algorithm Not Used	Over	Medium	Low	INF & KB: In using the ambient monitor that has the greatest CO concentrations compared to other monitoring data in an area, it is assumed that these concentrations would represent conservative estimates of air quality in the area. This would lead to overestimates in exposures, particularly when not considering commuting to other lower ambient concentration locations.
	CHD Prevalence	Both	Low	Low	INF & KB: Data are from the Centers for Disease Control, a well-known and quality-assured source. Though prevalence data are not specific for each region, the national prevalence data were stratified by selected age-groups and gender.
Potential Health Effect Benchmark Levels	Susceptible Population	Unknown	Low	Medium	INF & KB: Data from a well-conducted multi-center controlled human exposure study demonstrate cardiovascular effects in subjects with moderate to severe coronary artery disease at COHb levels as low as 2.0-2.4%. No laboratory study has evaluated the effect of exposure to CO resulting in COHb levels below 2.0%. There is no established no adverse effect level and, thus there is greater uncertainty about the lowest benchmark level used (i.e., 1.5%) and uncertainty about whether individuals with the most severe CHD are adequately represented. Given that the evidence supporting the choice of benchmark levels is based on controlled human exposure data, we judge the influence of this uncertainty on the risk characterization as being low.

[a]INF refers to comments associated with the influence rating; KB refers to comments associated with the knowledge-base rating.

Based on the qualitative judgments made by staff for a range of sources of uncertainty and their characterization as to direction and magnitude of influence on exposures and doses, the exposure and dose estimates are possibly overestimated for a larger portion of the population the assessment is intended to represent (i.e., those residing/travelling in high CO concentration microenvironments). This is because:

- Of the four sources of uncertainty associated with potential overestimation (i.e., spatial/temporal representation of monitoring data, data base quality, and absence of movement among different air quality districts during commutes, algorithm and input data for all other microenvironmental CO concentrations), three were estimated as having medium magnitude of influence, while the remaining source (i.e., ambient monitoring database quality) was ranked as having a low or a negligible magnitude of influence.
- The one source of uncertainty associated with potential underestimation (i.e., missing data substitution) was judged to have a low magnitude of influence on estimated exposures and doses.
- Of the remaining identified sources of uncertainty judged by staff to have either bidirectional influence (six sources) or unknown (three sources) direction, five sources were judged to have a low magnitude of influence on estimated exposures and doses.

While there was a wide-ranging level of uncertainty in the knowledge-base for the identified sources, there is relatively less uncertainty in staff judgments regarding the sources associated with potential overestimation of CO exposure and resulting COHb levels.

- A high degree of uncertainty in the knowledge-base was assigned to two sources: the spatial/temporal representation of monitoring data (direction of influence characterized as over, with a medium rated magnitude) and the use of historical data in representing air quality that just meet the current standard (direction of influence characterized as unknown, with magnitude rated as medium).
- The knowledge-base uncertainty was low for three of the five sources identified above as being associated with either under- or overestimating exposures (the rating for the remaining two sources was medium and high).
- The knowledge-base uncertainty for sources with unknown or bidirectional influence was low (five sources), medium (four sources), and high (one source).

6.5 KEY OBSERVATIONS

Presented below are key observations resulting from the exposure and dose assessment for ambient CO.

- An important limitation in the assessment for this review is the lack of detailed spatial representation of the current ambient monitoring data, which creates challenges for estimating the spatial variability of CO concentrations across a study area. This limitation contributed in part to the reasoning for the development of the simplified approach used in this assessment.
    - In this simplified approach, staff used a single monitor recording the highest CO concentrations to represent the ambient air quality in each area. This was done to accommodate the potentially greater CO exposures expected to occur to persons residing in areas with higher CO concentrations (i.e., those occurring on or immediately near major roadways).
    - Using a single monitor in each study area, however, still posed difficulties in characterizing the full range of microenvironmental CO concentrations, such as CO levels in vehicles or near major roadways, concentrations outside residences, as well as those occurring within indoor microenvironments for the simulated population. This is a result of the limited information across a broad geographic area regarding the relationships between specific ambient monitor concentrations and microenvironmental concentrations.
- One-hour and 8-hour average daily maximum exposures and the daily maximum end-of-hour COHb blood levels were estimated using a simplified exposure modeling approach involving two scenarios in two study areas: urban areas of Denver and Los Angeles counties. In Scenario A, CO concentrations in all microenvironments were set equal to the ambient monitor concentrations and in Scenario B, the CO concentration for the in-vehicle microenvironment were increased over those of the ambient monitor and all other microenvironments were set equal to the ambient monitor concentrations. The two air quality conditions investigated by staff included *as is* air quality, and air quality for higher CO levels, adjusted to simulate just meeting the current 8-hour CO NAAQS (section 6.2).
    - Fewer than 1% of the study population in each study area ($\leq$ 0.2%) were estimated to experience a daily maximum end-of-hour COHB level at or above 2.0% under *as is* air quality conditions in either scenario.
    - Results for the two study areas differed appreciably for air quality adjusted to just meet the current standard. For these conditions, the estimates of percent of population experiencing a daily maximum end-of-hour COHB level at or above potential health benchmarks were substantially greater for the Denver study area (e.g., differing by a factor of 8 or more for the 2% COHb benchmark).
- Results generated in the current assessment for the air quality conditions just meeting the current NAAQS were compared with estimates from the assessment conducted in 2000 (Johnson et al., 2000) for similar conditions in the Denver and Los Angeles study areas

(section 6.3). While focused on similar air quality conditions, the two assessments employed different versions of the exposure model (APEX vs pNEM) and there were significant differences in the approach used in each assessment. For example, as compared to the current assessment, the 2000 assessment employed more monitors to represent ambient CO levels, differentially treated a much greater number of microenvironments, and encompassed larger study areas.

  - The estimated percent of persons with daily maximum end-of-hour COHb blood levels when using air quality adjusted to just meet the current standard in both Denver and Los Angeles was substantially greater in the current assessment when compared to that estimated in the 2000 assessment (e.g., a difference of a factor of 10 or more at the 2% COHb benchmark).

- Based on an overall qualitative judgment of the identified sources of uncertainty in the assessment approach, selections made regarding input data, and algorithms used, and their characterization as to direction and magnitude of influence, the exposure and dose estimates for much of the simulated population represented by either scenario in this assessment are likely overestimated (section 6.4, Table 6-25). There may be a smaller fraction of the simulated population (e.g., those residing in close proximity to major roads, persons regularly commuting for extended periods of time) where some periods of exposure are underestimated due to the simplified assumptions made in estimating in-vehicle and near-road CO exposures, although likely less so and for a yet smaller portion of the population in scenario B. The impact of such potentially higher exposure periods on the population COHb levels will vary depending on the overall pattern of exposures.

- Given the considerations described above regarding the characterization of uncertainty and the tendency of the assessment approach to overestimate exposure and dose, staff finds the utility of this assessment for the purpose of considering the adequacy of the current standards to be limited.

6.6 REFERENCES

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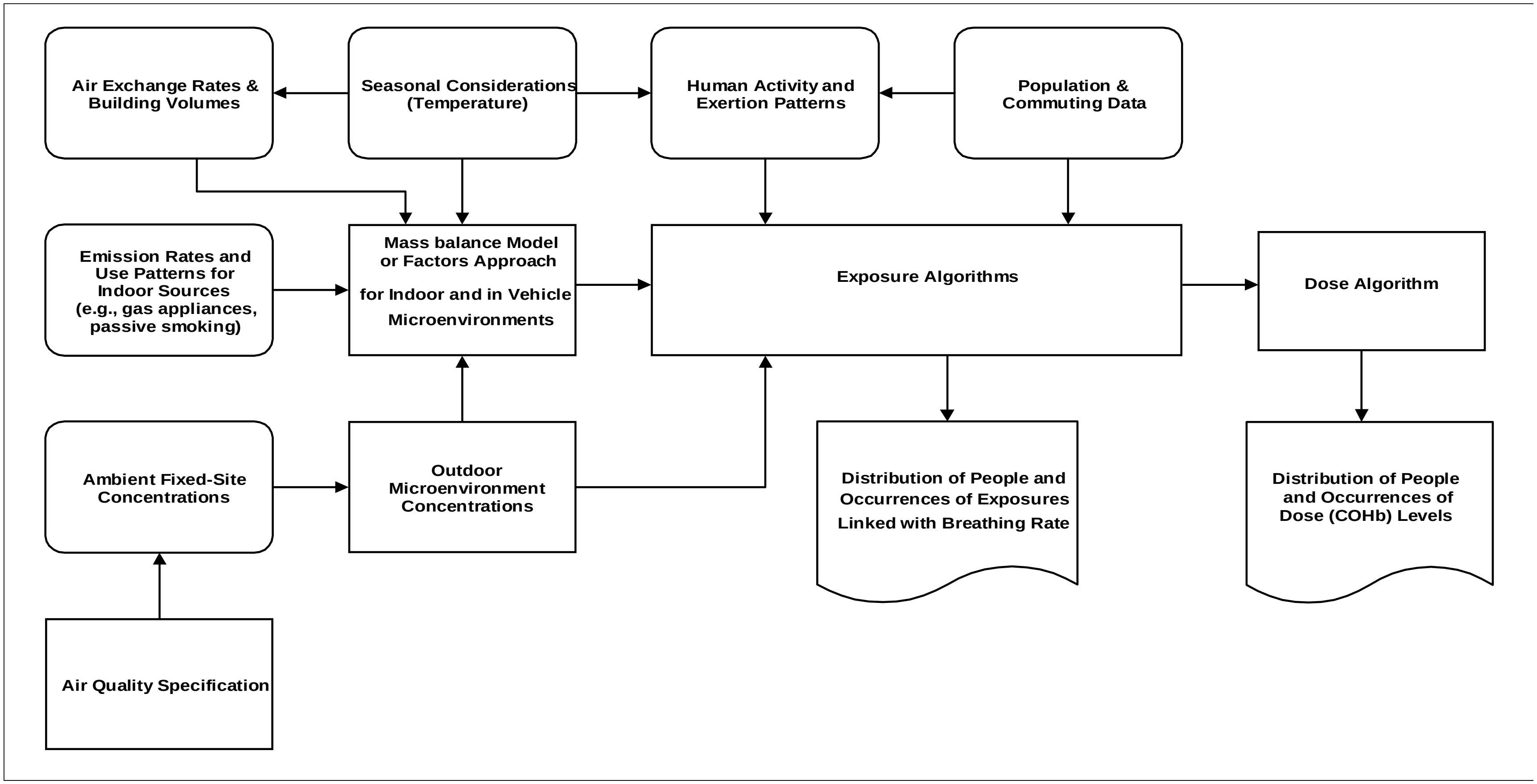
Appendix A

Conceptual Model and Simplified Data Flow of APEX.



Appendix A. Conceptual Model and Simplified Data Flow of APEX.

Appendix B

Mass Balance Model in APEX

The mass balance method models an enclosed microenvironment as a well-mixed volume in which the air concentration is spatially uniform at any specific time. The concentration of an air pollutant in such a microenvironment is estimated using the following four processes:

- Inflow of air into the microenvironment;
- Outflow of air from the microenvironment;
- Removal of a pollutant from the microenvironment due to deposition, filtration, and/or chemical degradation; and
- Emissions from sources of a pollutant inside the microenvironment.

Table B-1 lists the parameters required by the mass balance method to calculate concentrations in a microenvironment. The **proximity factor ($f_{proximity}$)** is used to account for differences in ambient concentrations between the geographic location represented by the ambient air quality data (e.g., a regional fixed-site monitor) and the geographic location of the microenvironment (e.g., near a roadway). This factor could take a value either greater than or less than 1. **Emission source (ES)** represents the emission rate for the emission source, and **concentration source (CS)** is the mean air concentration resulting from the source. $\mathbf{R}_{removal}$ is defined as the removal rate of a pollutant from a microenvironment due to deposition, filtration, and chemical reaction. The **air exchange rate** ($\mathbf{R}_{air\ exchange}$) is expressed in air changes per hour.

- **Table B-1. Parameters of the Mass Balance Model**

Variable	Definition	Units	Value Range
$f_{proximity}$	Proximity factor	N/A	$f_{proximity} > 0$
CS	Concentration source	ppm	$CS \geq 0$
ES	Emission source	µg/hr	$ES \geq 0$
$R_{removal}$	Removal rate due to deposition, filtration, and chemical reaction	1/hr	$R_{removal} \geq 0$
$R_{air\ exchange}$	Air exchange rate	1/hr	$R_{air\ exchange} \geq 0$
V	Volume of microenvironment	m^3	$V > 0$

The mass balance equation for a pollutant in a microenvironment is described by the differential equation

$$\frac{\mathrm{dC_{ME}(t)}}{\mathrm{dt}} = \Delta C_{in} - \Delta C_{out} - \Delta C_{removal} + \Delta C_{source} \qquad \text{(B-1)}$$

where:

$dC_{ME}(t)$ = Change in concentration in a microenvironment at time *t* (ppm),

ΔC_{in} = Rate of change in microenvironmental concentration due to influx of air (ppm/hour),

ΔC_{out} = Rate of change in microenvironmental concentration due to outflux of air (ppm/hour),

$\Delta C_{removal}$ = Rate of change in microenvironmental concentration due to removal processes (ppm/hour), and

ΔC_{source} = Rate of change in microenvironmental concentration due to an emission source inside the microenvironment (ppm/hour).

Within the time period of an hour each of the rates of change, ΔC_{in}, ΔC_{out}, $\Delta C_{removal}$, and ΔC_{source}, is assumed to be constant.

The change in microenvironmental concentration due to influx of air is represented by the following equation:

$$\Delta C_{in} = \frac{dC_{in}(t)}{dt} = C_{ambient}\ x\ f_{proximity}\ x\ f_{penetration}\ x\ R_{air\ exchange} \qquad \text{(B-2)}$$

where:

$C_{ambient}$	=	Ambient hourly outdoor concentration (ppm)
$f_{proximity}$	=	Proximity factor
$f_{penetration}$	=	Penetration factor
$R_{air\ exchange}$	=	Air exchange rate (1/hour)

The change in microenvironmental concentration due to outflux of air is described by:

$$\Delta C_{out} = \frac{dC_{out}(t)}{dt} = R_{air\ exchange} \times C_{ME}(t) \qquad \text{(B-3)}$$

The change in concentration due to deposition, filtration, and chemical degradation in a microenvironment is simulated by the first-order equation:

$$\Delta C_{removal} = \frac{dC_{removal}(t)}{dt} = (R_{deposition} + R_{filtration} + R_{chemical})C_{ME}(t) = R_{remova} \times C_{ME}(t) \qquad \text{(B-4)}$$

where:

$R_{deposition}$	=	Removal rate of a pollutant from a microenvironment due to deposition (1/hour)
$R_{filtration}$	=	Removal rate of a pollutant from a microenvironment due to filtration (1/hour)
$R_{chemical}$	=	Removal rate of a pollutant from a microenvironment due to chemical degradation (1/hour)
$R_{removal}$	=	Removal rate of a pollutant from a microenvironment due to overall removal (1/hour)

As discussed in Section 6.2, EPA decided not to model indoor emissions of CO in the current exposure assessment; consequently, the optional term ΔC_{source} was uniformly set equal to 0.0 for this study.

Combining Equation B-1 with Equations B-2, B-3, and B-4 yields

$$\frac{dC_{ME}(t)}{dt} = \Delta C_{in} - R_{air\ exchange} \times C_{ME}(t) - R_{removal} \times C_{ME}(t) \qquad \text{(B-5)}$$

The solution to this differential equation is

$$C_{ME}(t)=\frac{\Delta C_{in}}{R_{combined}}+(C_{ME}(0)-\frac{\Delta C_{in}}{R_{combined}})\exp(-R_{combined}t) \quad \text{(B-6)}$$

where:

$C_{ME}(0)$	=	Concentration of a pollutant in a microenvironment at the beginning of a hour (ppm)
$C_{ME}(t)$	=	Concentration of a pollutant in a microenvironment at time *t* within the time period of a hour (ppm)
$R_{combined}$	=	$R_{air\ exchange}+R_{removal}$ (1/hour)

Based on Equation B-6, the following three hourly concentrations in a microenvironment are calculated:

$$C_{ME}^{equil}=C_{ME}(t\rightarrow\infty)=\frac{\Delta C_{in}}{R_{combined}} \quad \text{(B-7)}$$

$$C_{ME}^{hourly\,end}=C_{ME}^{equil}+(C_{ME}(0)-C_{ME}^{equil})\exp(-R_{combined}) \quad \text{(B-8)}$$

$$C_{ME}^{hourlymean}=\frac{\int_0^1 C(t)dt}{\int_0^1 dt}=C_{ME}^{equil}+(C_{ME}(0)-C_{ME}^{equil})\frac{1-\exp(-R_{combined})}{R_{combined}} \quad \text{(B-9)}$$

where:

C_{ME}^{equil}	=	Equilibrium concentration in a microenvironment (ppm)
$C_{ME}(0)$	=	Concentration in a microenvironment at the beginning of an hour (ppm)
$C_{ME}^{hourly\,end}$	=	Concentration in a microenvironment at the end of an hour (ppm)
$C_{ME}^{hourlymean}$	=	Hourly mean concentration in a microenvironment (ppm)

At each hour time step of the simulation period, APEX uses Equations B-7, B-8, and B-9 to calculate the hourly equilibrium, hourly ending, and hourly mean concentrations. APEX reports hourly mean concentration as hourly concentration for a specific hour. The calculation continues to the next hour by using $C_{ME}^{hourly\,end}$ for the previous hour as $C_{ME}(0)$.

Appendix C

COHb Module for APEX4.3

This appendix describes the probabilistic carboxyhemoglobin (COHb) module used in the current APEX4.3 model. The approach described here is based primarily on the COHb module originally described by Biller and Richmond in two reports (Johnson et al., 1992; Johnson et al., 2000) and used in EPA probabilistic NAAQS exposure model for CO (pNEM/CO), a predecessor of APEX4.3. This appendix also describes the principal changes made to the COHb module when it was incorporated into APEX4.3, including a change in the method used to solve the Coburn-Forster-Kane (CFK) equation (Coburn et al., 1965).

C.1 The Base Physiological Model for Computing COHb Levels

Using time/activity data obtained from various diary studies, APEX constructs a composite diary for each simulated person in the specified population at risk. The composite diary consists of a sequence of events spanning the specified period of the exposure assessment (typically one calendar year). Each event is defined by a start time, a duration, a geographic location, a microenvironment, and an activity. Using various algorithms described in Section 5 of this report, APEX4.3 provides estimates of CO concentration and alveolar ventilation rate for each event in the composite diary. APEX4.3 then uses these data, together with estimates of various physiological parameters specific to the simulated individual, to estimate the percent COHb in the blood (%COHb) as an average %COHb value over the duration of each exposure event and as an instantaneous %COHb level at the end of each event.

The %COHb calculation is based on the solution to the non-linear CFK equation, previously described in Appendix E of Johnson et al. (2000). The CFK model describes the rate of change of COHb blood levels as a function of the following quantities:

1. Inspired CO pressure
2. COHb level
3. Oxyhemoglobin (O_2Hb) level
4. Hemoglobin (Hb) content of blood
5. Blood volume
6. Alveolar ventilation rate
7. Endogenous CO production rate
8. Mean pulmonary capillary oxygen pressure
9. Pulmonary diffusion rate of CO
10. Haldane coefficient (M)
11. Barometric pressure
12. Vapor pressure of water at body temperature (i.e., 47 torr).

If all of the listed quantities except COHb level are constant over some time interval, the CFK equation has a linear form over the interval and is readily integrated. The solution to the linear form gives reasonably accurate results for lower levels of COHb. However, CO and oxygen compete for the available hemoglobin and are, therefore, not independent of each other.

If this dependency is taken into account, the resulting differential equation is no longer linear. Peterson and Stewart (1975) proposed a heuristic approach to account for this dependency which assumed the linear form and then adjusted the O_2Hb level iteratively based on the assumption of a linear relationship between COHb and O_2Hb. This approach was used in the COHb module of the original CO-NEM exposure model (Biller and Richmond, 1982, Johnson and Paul, 1983).

Alternatively, it is possible to determine COHb at any time by numerical integration of the nonlinear CFK equation (e.g., by use of the Runge-Kutta method) if one assumes a particular relationship between COHb and O_2Hb. Muller and Barton (1987) demonstrated that assuming a linear relationship between COHb and O_2Hb leads to a form of the CFK equation equivalent to the Michaelis-Menton kinetic model which can be analytically integrated. However, the analytical solution in this case cannot be solved explicitly for COHb. Muller and Barton (1987) demonstrated a binary search method for determining the COHb value.

The COHb module used in pNEM/CO employed a linear relationship between COHb and O_2Hb which was consistent with the basic assumptions of the CFK model. The approach differed from the linear forms used by other modelers in that the Muller and Barton (1987) solution was employed. However, instead of the simple binary search described by Muller and Barton (1987), a combination of the binary search and Newton-Raphson root-finding methods was used to solve for COHb (Press et al., 1986). Using the Muller and Barton (1987) solution increased computation time compared to the Peterson and Stewart (1975) method but was shown to be faster than fourth-order Runge-Kutta numerical integration.

APEX4.3 employs a different approach in which the CFK equation is solved using a fourth-order Taylor's series expansion with subintervals. This method, first incorporated in Version 3 of APEX, is described in Section C.2 of this appendix. A more detailed description can be found in the Programmer's Guide for the APEX3 model (Glen, 2002).

C.2 The CFK Model for Estimation of Carboxyhemoglobin

Table C-1 defines the variables which appear in the equations of this section. Coburn, Forster, and Kane (1965) derived the following differential equation governing COHb levels in the blood upon exposure to CO.

$$\frac{d[COHb]}{dt} = \frac{\dot{V}_{co}}{V_b} + \frac{P_{Ico}}{BV_b} - \frac{\overline{P}_{CO_2}[COHb]}{MBV_b[O_2Hb]} \qquad \text{(Eq. C-1)}$$

where,

$$B = \frac{1}{D_{Lco}} + \frac{P_B - P_{H_2O}}{\dot{V}_A} \qquad \text{(Eq. C-2)}$$

Table C-1. Definitions of CFK Model Variables.

Variable	Definition	Units
t	Time from start of an exposure event	minutes
[COHb]	Concentration of carboxyhemoglobin (COHb) in blood at time t	ml CO per ml blood at STPD
[O_2Hb]	Concentration of oxyhemoglobin (O_2Hb) in blood at time t	ml O_2 per ml blood at STPD
[RHb]	Concentration of reduced hemoglobin in blood	equivalent ml CO per ml of blood at STPD
$[COHb]_0$	[COHb] at t = 0	ml CO per ml blood at STPD
$[THb]_0$	[RHb] + [COHb] + [O_2Hb]	
%[COHb]	[COHb] expressed as percent of $[RHb]_0$	%
%[O_2Hb]	[O_2Hb] expressed as percent of $[RHb]_0$	%
$\%[COHb]_0$	[COHb] at t = 0	%
$\%[COHB]_\infty$	[COHb] at t = ∞	%
$P_{I_{CO}}$	Pressure of inspired CO in air saturated with water vapor at body temperature	torr
$\overline{P}_{C_{CO}}$	Mean pulmonary capillary CO pressure	torr
$\overline{P}_{C_{O_2}}$	Mean pulmonary capillary O_2 pressure	torr
P_B	Barometric pressure	torr
P_{H_2O}	Vapor pressure of water at body temperature, or 47	torr
$\dot{V}_A$	Alveolar ventilation rate	ml/min STPD
$\dot{V}_{CO}$	Endogenous CO production rate	ml/min STPD
$D_{L_{CO}}$	Pulmonary CO diffusion rate	ml/min/torr, STPD
M	Haldane coefficient	
k	Equilibrium constant for reaction O_2 + RHb = O_2Hb	
V_b	Blood volume	ml
Hb	Total hemoglobin in blood	g/100ml
%MetHb	Methemoglobin as weight percent of Hb	%

Notes:
[1] Standard Temperature Pressure, and Dry (STPD)

If the only quantity in equation (C-1) that can vary with time is [COHb], the CFK equation is linear and can be readily integrated. However, since oxygen (O_2) and CO compete for the available Hb, [COHb] and [O_2Hb] must be related. Increasing [COHb] will result in decreasing [O_2Hb]. Thus the CFK equation is not linear and requires the relationship between the two quantities to be known if it is to be accurately integrated over a wide range of COHb levels.

Various linear relationships between [COHb] and [O_2Hb] have been used (see Marcus, 1980; McCartney, 1990; Muller and Barton, 1987; and Tikuisis et al., 1987). A relationship not previously used follows directly from the basic assumptions of the CFK model. The CFK model employs the Haldane coefficient, which is the equilibrium constant associated with the following reaction representing the replacement of O_2 in O_2Hb by CO:

$$CO + O_2Hb \leftrightarrow O_2 + COHb \qquad \text{(Eq. C-3)}$$

The following equation, the Haldane relationship, applies approximately at equilibrium conditions.

$$\frac{\overline{P}c_{O_2}[COHb]}{\overline{P}c_{CO}[O_2Hb]} = M \qquad \text{(Eq. C-4)}$$

The Haldane coefficient, M, is the chemical equilibrium constant for reaction (C-3). The above reaction can also be viewed as the difference between two competing chemical reactions:

$$CO + RHb \leftrightarrow COHb \qquad \text{(Eq. C-5)}$$

$$O_2 + RHb \leftrightarrow O_2Hb \qquad \text{(Eq. C-6)}$$

Subtracting (C-6) from (C-5) yields (C-3). If (C-3) is in equilibrium, then (C-5) and (C-6) are in equilibrium. If *k* represents the equilibrium constant for (C-6) then:

$$\frac{[O_2Hb]}{\overline{P}c_{O_2}[RHb]} = k \qquad \text{(Eq. C-7)}$$

It is known that an individual breathing air free of CO for an extended period will have about 97% of their reactive Hb bound with oxygen (O_2Hb) and the remainder (3%) as the reduced form (RHb). It is also known that at one atmosphere barometric pressure, the mean pulmonary capillary oxygen pressure is approximately 100 torr. Substituting into (C-7) yields 0.32 as the approximate value of *k* at body temperature. From mass balance considerations:

$$[O_2Hb] + [COHb] + [RHb] = [THb]_O \qquad \text{(Eq. C-8)}$$

Eliminating [RHb] between (C-7) and (C-8) and solving for [O_2Hb] yields:

$$[O_2Hb] = \frac{k\overline{P}c_{O_2}}{1 + k\overline{P}c_{O_2}}([THb]_0 - [COHb]) \quad \text{(Eq. C-9)}$$

This equation represents the aforementioned linear form of the CFK equation. It has the same form as a relationship given by McCartney (1990), but replaces the constant in the McCartney equation by the term in (C-9) involving the mean pulmonary capillary oxygen pressure and the equilibrium constant *k*. Substituting (C-9) into (C-1) yields a CFK equation free of [O_2Hb] and fully consistent with Coburn, Forster, and Kane's original derivation.

$$\frac{d[COHb]}{dt} = \frac{\dot{V}_{CO}}{\dot{V}_b} + \frac{P_{I_{CO}}}{BV_b} - \frac{[COHb]}{[THb]_O - [COHb]} \times \frac{1 + k\overline{P}c_{O_2}}{kMBV_b} \quad \text{(Eq. C-10)}$$

In working with the CFK model it is convenient to express COHb as a percent of $[RHb]_0$. Multiplying (C-10) by 100 and dividing by $[RHb]_0$ yields the expression

$$\frac{d\%[COHb]}{dt} = \frac{100}{[THb]_O}\left(\frac{\dot{V}_{CO}}{V_b} + \frac{P_{I_{CO}}}{BV_b}\right) - \frac{\%[COHb]}{100 - \%[COHb]} \times \frac{100(1 + k\overline{P}_{CO_2})}{k[RHb]_O MBV_b} \quad \text{(Eq. C-11)}$$

Equation (C-11) can be written in the form suggested by Muller and Barton (1987):

$$\frac{d\%[COHb]}{dt} = C_O - C_1 \frac{\%[COHb]}{100 - \%[COHb]} \quad \text{(Eq.C-12)}$$

where,

$$C_O = \frac{100}{[THb]_O}\left(\frac{\dot{V}_{CO}}{V_b} + \frac{P_{I_{CO}}}{BV_b}\right) \quad \text{(Eq. C-13)}$$

$$C_1 = \frac{100(1 + k\overline{P}_{CO_2})}{k[THb]_O MBV_b} \quad \text{(Eq. C-14)}$$

Given values for the atmospheric pressure and the physiological variables in equations (C-12) through (C-14), the value of %[COHb] at time *t* can be found by numerical integration using such techniques as the fourth-order Runge-Kutta method (Press et al., 1986). Muller and Barton (1987) demonstrated that an equation of the form of (C-12) is equivalent to a Michaelis-Menton kinetics model which can be integrated. The integration yields:

$$-(C_O + C_1)t + \%[COHb] - \%[COHb]_O - (100 - \%[COHb]_\infty)\ln\frac{(\%[COHb]_\infty - \%[COHb])}{\%[COHb]_\infty - \%[COHb]_O} = 0 \quad \text{(Eq. C-15)}$$

The equation for $\%[COHb]_\infty$ is obtained by setting equation (C-12) equal to zero and solving for %[COHb], which is now equal to $\%[COHb]_\infty$:

$$\%[COHb]_\infty = \frac{100C_O}{(C_O + C_1)} \qquad \text{(Eq. C-16)}$$

Equation (C-15) cannot be solved explicitly for %[COHb]. Muller and Barton (1987) suggest the binary search method as one way to find the value of %[COHb]. Press et al. (1986) contend a combination of the binary search and Newton-Raphson methods is faster on average. Consequently, the pNEM/CO version of the COHb module used a combination of the binary search and Newton-Raphson root finding methods to solve for COHb (Press et al., 1986). Using the Muller and Barton (1987) solution increased the computation time when compared with the Peterson and Stewart (1975) method, however it was still shown to be faster than the fourth-order Runge-Kutta numerical integration.

The current version of APEX (APEX4.3) employs an alternative approach in which the CFK equation is solved using a fourth-order Taylor's series expansion with subintervals. This method, first incorporated in Version 3 of APEX, is described in detail in the Programmer's Guide for the APEX3 Model by Glen (2002). This reference also includes the results of various tests conducted on 10 candidate methods for solving the CFK equation. The selected method (fourth-order Taylor series with subintervals) was chosen because of its simplicity, fast execution speed, and ability to produce relatively accurate estimates of %COHb at both low and high levels of CO exposure. Additional information concerning the %COHb calculation method and its theoretical basis can be found in Section 10.2 of US EPA (2008).

In developing the fourth-order Taylor Series expansion approach, Glen (2002) began by defining *N(t)* as the %COHb level in the blood at time *t*, a quantity that is mathematically restricted to range between 0 and 100 (percent). *N(t)* satisfies the following differential equation:

$$N`(t) = C_0 - C_1 N(t) / (100 - N(t)) \qquad \text{(Eq. C-17)}$$

where C_0 and C_1 are constants (at least over the duration of one event) that depend on physical and physiological parameters and on the CO concentration in the air. Equation (C-17) is equivalent to (C-12) above, except that (C-12) uses the symbol %[COHb] instead of N(t).

The task of expanding *N(t)* in a Taylor's series becomes simpler if the following new variables are defined:

$$D_0 = 1 - N(0) / 100 \qquad \text{(Eq. C-18)}$$

$$A_0 = C_0 / (C_0 + C_1) \qquad \text{(Eq. C-19)}$$

$$A_1 = C_1 / (C_0 + C_1) \qquad \text{(Eq. C-20)}$$

$$D = D_0 - A_1 \qquad \text{(Eq. C-21)}$$

$$z = (C_0 + C_1)\, t / (100 * D_0 * D_0) \qquad \text{(Eq. C-22)}$$

The *z* variable is a re-scaled time variable that is dimensionless. It is used as the independent variable for the Taylor's series expansion. In equations expressed as functions of *z* rather than *t*, any primes will indicate the derivatives with respect to *z*.

Expressing (C-17) as a function of *z* yields the expression

$$N`(z) = D_0\ 2\ A_0 - D_0\ 2\ A_1\ N(z) / (\ 100 - N(z)\ ) \qquad \text{(Eq. C-23)}$$

The Taylor's series about the origin (z = 0) for N(z) is given by

$$N(z) = N(0) + N`(0)\ z + N``(0)\ z^2 / 2 + N```(0)\ z^3 / 6 + N^{iv}(0)\ z^4 / 24 + ... \qquad \text{(Eq. C-24)}$$

Through a series of algebraic substitutions, Glen (2002) shows that the Taylor series expansion of N(z) truncated to the fourth order can be represented by

$$T4(z) = T3(z) - 100\ A_1\ D_0\ D\ \ (A_1{}^2 - 8\ D\ A_1 + 6\ D^2)\ \ z^4 / 24 \qquad \text{(Eq. C-25)}$$

where

$$T3(z) = N(0) + 100\ D_0\ D\ z - 100\ A_1\ D_0\ D\ z^2 / 2 + 100\ A_1\ D_0\ D\ (A_1 - 2D)\ z^3 / 6 \qquad \text{(Eq. C-26)}$$

Tests showed that the fourth-order Taylor series expansion (C-25) provided greater accuracy than the third-order expansion for *z* values close to one. Glen (2002) found that *z* values below one generally correspond to N(0) values below forty to fifty percent for one-hour exposure events.

The *z* value for a given event depends on the event duration, the initial %COHb level N(0), and on the physiological parameters, and can be directly evaluated at the start of each event. For events with a *z* value above some threshold, it is possible to improve the performance of (C-25) by dividing the event into smaller events ("subintervals"), each with a shorter duration and hence smaller *z* value. As the subinterval duration decreases, accuracy increases at the expense of program execution time. APEX4.3 enables the user to select a limit on *z* which in turn determines the number of subintervals to be used in applying the fourth-order Taylor expansion. Glen (2002) recommends that the limit on *z* be set at 0.4 or 0.5.

C.3 Application of the COHb Model in APEX4.3

Description of APEX4.3 for CO

APEX4.3 follows the daily activities over an extended period of a finite set of simulated individuals residing within a given geographic area. The period may be a single season or a calendar year. Each simulated individual is defined by a set of general demographic characteristics that includes age, gender, and body weight. The values of these factors are used to derive values for blood volume, menstrual phase, endogenous CO production rate, and other factors required by the COHb module (see Section C.4). The exposure of each individual is represented by a continuous sequence of exposure events which span the time period of interest. Each exposure event represents a time interval of 60 minutes or less during which the individual resides in a single environment and engages in a single activity. To permit calculation of hourly average exposures, exposure events are not permitted to fall in more than one clock hour. Consequently, the passage from one exposure event to the next is indicated by a change in microenvironment, activity, or clock hour. Algorithms within APEX4.3 calculate an average CO concentration for each exposure event according to the time, district, and microenvironment specified for the event. As the exposure events for a simulated individual are contiguous, the model can combine these concentrations to output distributions of one-hour and running eight-hour exposures for each individual. The exposures calculated for the simulated individuals can then be population-weighted to produce exposure distributions for population groups of particular interest (e.g., people with coronary heart disease).

APEX4.3 constructs a year-long time/activity pattern for each simulated individual by sampling 24-hour activity patterns from the Consolidated Human Activity Data Base (CHAD), which is described in Section 5.3.3 of this report. The sampling approach attempts to match the 24-hour activity patterns to the simulated individual and exposure period according to the demographic characteristics of the individual and the season, day type (weekday/weekend), and maximum temperature of each day in the specified exposure period.

The COHb Module

The COHb module in APEX4.3 currently employs the version of the CFK model represented by equations (C-12) through (C-14) to compute an average COHb value over the duration of each exposure event and an instantaneous COHb level at the end of each event. To perform these computations, the COHb module requires information on each of the quantities listed in the section describing the CFK model. In addition, the COHb level at the beginning of the exposure event must be known. This latter quantity is usually the COHb level computed at the end of the previous contiguous exposure event. To obtain the initial COHb at the start of the exposure period, the computation is started one day before the beginning of the period. The effect of the initial COHb value on the end value is negligible after about 15 hours. The program stores the calculated COHb values for each exposure event and outputs distributions of COHb levels by population group for averaging times ranging from one hour to one day.

Assignment of CFK Model Input Data for an Exposure Event

Section C.4 describes the equations and procedures used by the APEX4.3 COHb module to obtain the values of the input variables for equations (C-2) and (C-13) through (C-16). A brief overview is given here.

The actual inspired CO level can change significantly during an exposure event. The model supplies an average exposure concentration for the event, which is used as the CO input. The time constant for the change in COHb is sufficiently large that the use of concentrations based on averaging times up to one hour can be used in place of the instantaneous concentrations over the averaging time period with little loss of accuracy in estimating the COHb level at the end of the exposure event. Furthermore, applying the average concentrations to a contiguous sequence of exposure events does not cause an accumulation of error.

The COHb model presently used in APEX4.3 does not account for changing barometric pressure. It uses a constant barometric pressure which is a function of the average elevation of an area above sea level. The pressure at sea level is taken to be 760 torr.

The remaining input variables to the CFK model are all physiological parameters. While the Haldane coefficient, the equilibrium constant k, and average pulmonary capillary oxygen pressure are treated as having the same constant values for all individuals, the remaining physiological input variables will vary among individuals. The next section describes the methods used to generate the various physiological input variables for each combination of individual and calendar day processed by APEX.

C.4 Computation of Input Data for the COHb Module

As discussed in the previous section and in Sections 5.3.5 and 5.3.7 of the main body of this report, the algorithms used to estimate V_E and COHb require values for various physiological parameters such as body mass, blood volume, and pulmonary diffusion rate. Table C-2 provides a list and description of the principal parameters; additional parameters are listed and described in Chapter 5 of US EPA (2008). An algorithm within APEX4.3 probabilistically generates a value for each parameter on the list (collectively referred to as a physiological profile) for each simulated individual. Figure C-1 is a flow diagram showing the process by which each physiological profile is generated. Each of the generated physiological profiles is internally consistent, in that the functional relationships among the various parameters are maintained. For example, blood volume is determined as a function of weight and height, where height is estimated as a function of weight. Weight in turn is selected from a distribution specific to gender and age.

For each simulated individual, APEX4.3 computes exposure for a contiguous sequence of exposure events spanning the total time period of the computation. This multi-day sequence of exposure events is determined by random sampling day-long event sequences from a set of pools of 24-hour activity patterns. An individual 24-hour pattern in one of these pools is referred to here as a unit exposure sequence (UES). Each pool consists of a collection of UESs that are specific to selected demographic characteristics of the individual (e.g., age and gender), season, day type (weekday/weekend), and maximum daily temperature.

A UES is a contiguous set of exposure events spanning 24 hours. Each event is characterized by start time, duration in minutes, home/work status, microenvironment, and activity. All exposure events are constrained to occur entirely within a clock hour.

The CFK model within the COHb module is called for each exposure event. For each event it requires the following data.

Time duration of event, min
Inspired CO partial pressure averaged over the event, torr
Percent COHb at the start of the event
Alveolar ventilation rate, ml/min STPD
Average pulmonary capillary oxygen pressure, torr

Haldane Coefficient
Equilibrium constant for the reaction of O_2
Atmospheric pressure, torr
Blood volume, ml
Total potential reduced hemoglobin content of blood, ml CO/ml STPD
Pulmonary CO diffusion rate, ml/min/torr STPD
Endogenous CO production rate, ml/min STPD

Table C-2. Principal Parameters Included in the Physiological Profile for Adults for Applications of APEX4.3.

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Age	COHb Ventilation rate	Demographic group	Randomly selected from population-weighted distribution specific to demographic group
Gender	COHb Ventilation rate	Demographic group	Randomly selected from population-weighted distribution specific to demographic group
Body Weight	COHb Ventilation rate	Gender Age	Randomly selected from population-weighted lognormal distribution with geometric mean (GM) and geometric standard deviation (GSD) distribution specific to age and gender derived from data from the National Health and Nutrition Examination Survey (NHANES), for the years 1999-2004 (Isaacs and Smith, 2005)
Height	COHb	Weight Gender	Estimated using equations developed by Johnson (1998) using height and weight data provided by Brainard and Burmaster (1992). Males: height = 34.43 inches + (6.67)[ln(weight)] + (2.38 inches)(z) Females: height = 48.07 inches + (3.07)[ln(weight)] + (2.48 inches)(z) The z term is randomly selected from a unit normal [N(0,1)] distribution. Units: height (inches), weight (lbs).
Menstrual phase	COHb	Gender Age	If gender = female, menstrual phase was randomly assigned in alternating 14-day cycles according to the following age-specific probabilities. Age < 12 or >50: 100% premenstrual Age 12 through 50: 50% premenstrual, 50% postmenstrual.

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Blood volume	COHb	Gender Weight Height	Blood volume (V_b) was determined according to gender by the following equations which are based on work by Allen et al. (1956) which was modified to accept the units used for height and weight. Males: $V_b = (20.4)(\text{weight}) + (0.00683)(H^3) - 30$ Females: $V_b = (14.6)(\text{weight}) + (0.00678)(H^3) - 30$ Units: blood volume (ml), weight (lbs), height (inches).
Hemoglobin content of the blood, Hb	COHb	Gender Age	Randomly selected from normal distribution with arithmetic mean (AM) and arithmetic standard deviation (ASD) determined by gender and age based obtained from data from the National Health and Nutrition Examination Survey (NHANES), for the years 1999-2004. (Isaacs and Smith, 2005)Units: grams of Hb per deciliter of blood

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Pulmonary CO diffusion rate, $D_{L_{CO}}$	COHb	Gender Height Age	Pulmonary CO diffusion rate (DL) was determined according to gender, height, and age according to the following equations obtained from a paper by Salorinne (1976) and modified to conform to the units used in the COHb module. Males: $D_{L_{CO}}$ = (0.361)(height) - (0.232)(age) + 16.3 ml/min/torr Females: $D_{L_{CO}}$ = (0.556)(height) - (0.115)(age) - 5.97 ml/min/torr Units: $D_{L_{CO}}$ (ml/min/torr), height (inches), age (years). Given the alveolar ventilation rate for the exposure event the associated adjusted pulmonary diffusion rate is calculated as: $D_{L_{CO}}(Adjusted) = D_{L_{CO}}(Base) + 0.000845\dot{V}_A - 5.7$

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Endogenous CO production rate	COHb	Gender Age Menstrual phase	Endogenous CO production rate was randomly selected from a lognormal distribution with geometric mean (GM) and geometric standard deviation (GSD) determined according to the following equations specific to age, gender, and menstrual phase. Males, 18+: GM = 0.473, GSD = 1.316 Females, 18+, premenstrual: GM = 0.497, GSD = 1.459 Females, 18+, postmenstrual: GM = 0.311, GSD = 1.459 Units: GM (ml/hr), GSD (dimensionless).
Resting metabolic rate (RMR)	Ventilation rate	Gender Age Body Weight	See Section 5.3.5 of this report and Chapter 5 of US EPA (2008).
Energy conversion factor (ECF)	Ventilation rate	Gender	See Section 5.3.5 of this report and Chapter 5 of US EPA (2008).
NVO_{2max}	Ventilation rate	Gender Age	See Section 5.3.5 of this report and Chapter 5 of US EPA (2008).
VO_{2max}	Ventilation rate	NVO_{2max} Body Weight	See Section 5.3.5 of this report and Chapter 5 of US EPA (2008).

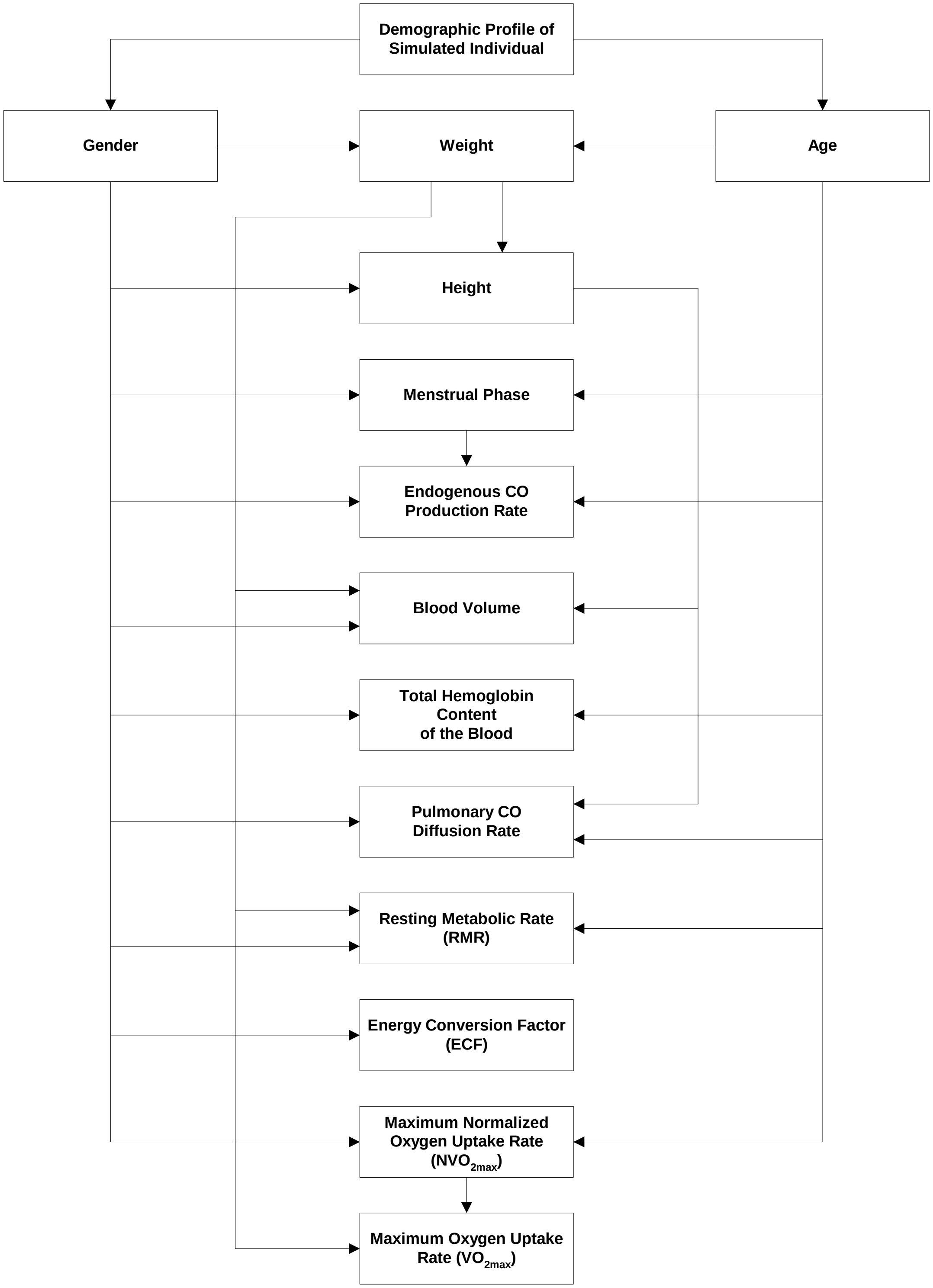


Figure C-1. Flow Diagram for Physiological Profile Generator. Input data is supplied at the start of the APEX4.3 computation.

Given these data as inputs, the module computes the percent COHb at the end of the exposure event. This value is used by the module as the initial percent COHb for the next contiguous exposure event. The module also computes the average percent COHb value for each exposure event. The main program retains these values and uses them to calculate percent COHb values for averaging times ranging from one hour to one day.

Some of the above data do not change during an APEX4.3 computer run and, therefore, need to be supplied to the computer program only once at the start. Some of the data vary with the individual and therefore need to be supplied at the beginning of each activity day. Other data tend to change with the exposure event and therefore need to be supplied for each new exposure event.

Barometric Pressure

A constant barometric pressure is assumed for the study area based on the average height above sea level:

$$P_B = 760 \times \exp(-0.0000386 \times Altitude) \qquad \text{(Eq. C-27)}$$

where altitude is the average height (in feet) of the study area above sea level (US EPA, 1978). The altitude was set at 5,183 feet for Denver and 328 feet for Los Angeles.

Average Pulmonary Capillary Oxygen Pressure

The equation employed is based on an approximation used by Peterson and Stewart (1975) in which 49 torr is subtracted from the partial pressure of inspired oxygen. This leads to the following approximate relationship:

$$\overline{P}c_{O_2} = 0.209(P_B - 47) - 49 \qquad \text{(Eq. C-28)}$$

where 0.209 is the mole fraction of O_2 in dry air and 47 is the vapor pressure of water at body temperature. This expression was used in an investigation of the CFK equation by Tikuisis et al. (1987). Often times a value 100 torr is commonly used as Equation (C-28) generates this value for a barometric pressure equivalent to 760 torr.

Haldane Coefficient

The value of 218 was used for the Haldane coefficient. While measured values in the range 210 to 270 have been reported in the extent literature, most researchers use values within the range of 210 to 240. In the early 1980's, the Clean Air Scientific Advisory Committee (CASAC) expressed the opinion to EPA (Friedlander, 1982) that the most careful work done in this area was that by Rodkey (1969), who determined a value of 218. This value was selected for use in the COHb module of the earlier CO-NEM exposure model. Other researchers using values in the range 218 to 220 include Peterson and Stewart, 1970; Marcus, 1980; Collier and

Goldsmith, 1983; and Muller and Barton, 1987. As the value 218 falls within the range currently used by researchers, EPA analysts have elected to continue using this value in APEX4.3.

Equilibrium Constant for the Reaction of O_2 and RHb

This quantity was estimated in Section C.2 to have the value 0.32 based on the observation that %[RHb] is about 3% in individuals breathing air which is free of CO and a value of 100 torr for $\bar{P}_{CO_2}$.

Total Reduced Hemoglobin in the Absence of O_2 and CO

The quantity $[THb]_0$ is expressed as equivalent milliliters of O_2 or CO at STPD per milliliter of blood. Total Hb blood levels are customarily expressed as grams per deciliter of blood. The total Hb level in the absence of COHb and O_2Hb would consist principally of RHb which can react with O_2 or CO and MetHb which cannot. Total Hb blood levels also tend to be higher in people living at higher altitudes. To relate $[THb]_0$ to Hb, it is therefore necessary to correct for the MetHb present, adjust for the effect of altitude, and convert to equivalent milliliters of CO at STPD. The later conversion is based on the observation that a gram of reduced Hb can react with a maximum of 1.39 ml of O_2 or CO at STPD. The application of these three factors yields the equation:

$$[RHb]_O = 1.39 \times Hb(100 - \%MetHb) \times \left(1 + \frac{HbAlt}{100}\right) \qquad \text{(Eq. C-29)}$$

where HbAlt is the percent increase in Hb due to exposure to altitude and is given by (EPA 1978):

$$HbAlt = 2.76e^{0.0001249\,Altitude}$$

Hb in equation (C-29) is a sea level value. Hb level in a human population is normally distributed with the mean Hb and standard deviation both dependent on gender and age class (see entry in Table C-2 for the distributions of Hb by age and gender). Given the hemoglobin content of the blood based on the distributions listed in Table C-2, $[THb]_0$ is calculated using equation (29). The weight percent MetHB, %MetHB, is taken to be 0.5% of the weight of Hb (Muller and Barton, 1987).

Determination of Weight

Body mass or weight (in kg) was determined by fitting lognormal distributions to data organized by age and gender from the National Health and Nutrition Examination Survey for the years 1999-2004 (Isaacs and Smith, 2005). Distribution parameters were estimated for single-year age cohorts for both genders for ages 0-85. As the NHANES 1999-2004 studies only covered persons up to age 85, linear forecasts for the parameters were made for ages 86-100, as based on the data for ages 60 and greater.

Determination of Height

The following equations were used to estimate height as a function of gender and weight. Equations C-30 and C-31 were derived by Johnson (1998) using height and weight data provided by Brainard and Burmaster (1992).

males: height = 34.43 inches + (6.67)[ln(weight)] + (2.38 inches)(z) (Eq. C-30)

females: height = 48.07 inches + (3.07)[ln(weight)] + (2.48 inches)(z) (Eq. C-31)

where the *z* term was randomly selected from a unit normal [N(0,1)] distribution.

Base Pulmonary Diffusion Rate of CO

A base lung diffusivity of CO for the individual is calculated as follows:

$$\text{Men:}\quad D_{L_{CO}} = 0.361 \times height - 0.232 \times age + 16.3 \qquad \text{(Eq. C-32)}$$

$$\text{Women:}\quad D_{L_{CO}} = 0.556 \times height - 0.115 \times age - 5.97 \qquad \text{(Eq. C-33)}$$

where height is in inches and age is in years.

The regression equations were obtained from a paper by Salorinne (1976) and modified to conform to the units used in the COHb module. The Salorinne data were obtained for non-exercising individuals. Tikuisis et al. (1992), working with eleven male subjects at various exercise levels, showed significant increase in lung diffusivity of CO with increasing alveolar ventilation rate. Regression analyses of data provided by Tikuisis for the individual subjects in the study showed the relationship to be linear. From this relationship and the heights and ages of the subjects in the Tikuisis et al. study, it was determined that the Salorinne equations for male subjects correspond to an alveolar ventilation rate of 6.69 l/min STPD. In the absence of other data it is assumed that this same value applies to women. Thus, for each twenty-four hour period equations C-32 and C-33 are used to compute lung diffusion rates of CO for a base case alveolar ventilation rate of 6.69 1/min STPD. As will be seen, this value is adjusted to account for the actual ventilation rate experienced by the simulated individual during each individual exposure event.

Endogenous Rate of CO Production

The endogenous CO production rates taken from a number of sources show the rate to be distributed lognormally in the population (see Table C-3 for data and sources). The distribution is different for men and women. For a woman there is a further difference depending on whether she is in her premenstrual or postmenstrual phase. Table C-2 presents these distributions classified by class, gender, and menstrual phase.

For each male individual, APEX4.3 specifies a single value for endogenous CO production rate and uses it for all days of the year. For each female individual between 18 and 64 years of age, APEX4.3 specifies one value of endogenous CO production rate to represent premenstrual days and one value to represent postmenstrual days. Female individuals under 12 years and older than 50 are assumed to be premenstrual; consequently, APEX4.3 specifies a single value for endogenous CO production rate to be used for all days of the year. The specified values are randomly selected from the appropriate distributions presented in Table C-2. A random number, z, is sampled from the standardized normal distribution, N(0,1) to make each selection. The appropriate endogenous CO production rate is then obtained from:

$$\dot{V}_{CO} = 0.01667 \times (geom.mean) \times (geom.S.D.)^{z} \qquad \text{(Eq. C-34)}$$

The constant term converts ml/hr to ml/min.

A probabilistic algorithm within APEX4.3 assigns a menstrual phase to each day of the year for female individuals aged 12 to 50 years. The algorithm randomly assigns a number between 1 and 28 to January 1. The number is increased by one for each successive day until number 28 is reached. The next day is numbered 1 and the 28-day numbering cycle is repeated until each day of the year has been assigned a number between 1 and 28. Days numbered 1 through 14 are identified as post-menstrual days; days numbered 15 through 28 are identified as pre-menstrual days.

<u>INPUT DATA SUPPLIED WITH EACH EXPOSURE EVENT</u>

<u>Duration of Exposure Event</u>

The duration of the exposure event in minutes is supplied by the main program to the COHb module.

<u>Partial Pressure of Inspired Carbon Monoxide</u>

The main program supplies the inspired CO concentration averaged over the duration of the exposure expressed as ppm. This quantity is converted to pressure via:

$$P_{I_{CO}} = (CO) \times (P_b - 47) \times 10^{-6} \qquad \text{(Eq. C-35)}$$

<u>Initial Percent COHb Level at Start of Exposure Event</u>

The program retains the percent COHb computed at the end of the previous exposure event and uses this value as the initial percent COHb for the present event. The starting COHb at the beginning of an activity day is the final COHb level at the end of the preceding activity day. This latter procedure is used for the first activity day of the overall computation since the program starts the day before the overall period covered by the APEX4.3 computation.

Alveolar Ventilation Rate

The main program supplies the COHb module with ventilation rate derived from the algorithm discussed in Section 5.3.5 of this report.

Adjusted Pulmonary Diffusion Rate of CO

Given the alveolar ventilation rate for the exposure event the associated adjusted pulmonary diffusion rate can be calculated from:

$$D_{L_{CO}}(Adjusted) = D_{L_{CO}}(Base) + 0.000845\dot{V}_A - 5.7 \quad \text{(Eq. C-36)}$$

Table C-3. Literature Data Used to Derive Geometric Mean and Standard Deviation Lognormal Distribution of Endogenous CO Production Rate.

Study Author	Values for Endogenous CO Production Rate							
Brouillard et al. (1975)	0.81	0.57	0.33	0.7	0.58	0.38	0.51	0.55
	0.37	0.49	0.45	0.5	0.33	0.45	0.36	
Burke et al. (1974)	0.43	0.58	0.52	0.59	0.8	0.72	0.54	
Coburn et al. (1963)	0.35	0.4	0.39	0.43	0.35	0.51	0.42	0.57
	0.45							
Delivoria-Papadopoules et al. (1974)	0.45	0.26	0.6	0.45	0.39	0.4		
	0.57	0.54	0.72	0.99	0.48	0.53	0.43	
	0.23	0.51	0.34	0.41	0.26	0.16	0.3	
Luomanmaki and Coburn (1969)	0.38	0.42	0.41	0.54	0.38			
Lynch and Moede (1972)	0.4	0.81	0.26	0.65	0.51	0.62	0.44	
	0.72	0.37	0.23	0.33	0.42	0.44	0.29	0.48
	0.48	0.23	0.25	0.2	0.22	0.15	0.21	
Merke et al. (1975)	0.64	0.86	0.35	0.52	0.8	0.54	0.68	0.28
	0.4	0.47	0.23	0.24	0.55	0.32	0.43	0.35
Werner and Lindahl (1980)	0.54	0.76	0.48	0.31	0.7	0.36	0.65	

C.5 References

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Appendix D

Apex Output Files

Appendix D. Apex Output Files.

Output File Type	Description
Log	The *Log* file contains the record of the APEX model simulation as it progresses. If the simulation completes successfully, the log file indicates the input files and parameter settings used for the simulation and reports on a number of different factors. If the simulation ends prematurely, the log file contains error messages describing the critical errors that caused the simulation to end.
Profile Summary	The *Profile Summary* file provides a summary of each profile modeled in the simulation. Each line lists the person's age, gender and race, in addition to a number of other personal profile variables that the model uses to simulate exposure.
Sites	The *Sites* file lists the sectors, air districts, and zones in the study area, and identifies the mapping between them.
Hourly	The *Hourly* file provides an hour-by-hour time series of exposures, doses, and other variables for each modeled profile.
Daily	The *Daily* file provides a day-by-day time series of exposures, doses, and other variables for each modeled profile.
Events	The *Events* file contains event-level information (including MET, exposure, ventilation, and dose) for individuals in the simulation. Settings in the *Control* file allow the user to write this information for all persons, every Nth person, or for a set of specified profile IDs.
Microenvironment Summary	The *Microenvironment Summary* file provides a summary of the time and exposure by microenvironment for each profile modeled in the simulation.
Microenvironment Results	The *Microenvironment Results* file provides an hour-by-hour time series of microenvironment concentrations and parameters for a pollutant for each modeled profile for each location ("Home", "Work", and "Other"). A *Microenvironment Results* file is generated for each pollutant.
Output Tables	The *Output Tables* file contains a series of tables summarizing the exposure (and dose, if calculated) results of the simulation for a pollutant. The percentiles and exposure/dose cut-off points used in these tables are defined in the *Control* file. A *Tables* file is generated for each pollutant.

Appendix E

Mapping of CHAD Location Codes to Microenvironments Defined for Application of APEX4.3 to Carbon Monoxide.

Appendix E. Mapping Of Chad Location Codes To Microenvironments Defined For Application Of Apex4.3 To Carbon Monoxide.

```
! Mapping of CHAD activity locations to two APEX microenvironments: in-vehicle (2) and other (1)
CHAD Loc.  Description                            APEX
---------  ---------------------------------------------
U          Uncertain of correct code            =   1  H
X          No data                              =   1  H
30000      Residence, general                   =   1  H
30010      Your residence                       =   1  H
30020      Other residence                      =   1  H
30100      Residence, indoor                    =   1  H
30120      Your residence, indoor               =   1  H
30121      ..., kitchen                         =   1  H
30122      ..., living room or family room      =   1  H
30123      ..., dining room                     =   1  H
30124      ..., bathroom                        =   1  H
30125      ..., bedroom                         =   1  H
30126      ..., study or office                 =   1  H
30127      ..., basement                        =   1  H
30128      ..., utility or laundry room         =   1  H
30129      ..., other indoor                    =   1  H
30130      Other residence, indoor              =   1  H
30131      ..., kitchen                         =   1  H
30132      ..., living room or family room      =   1  H
30133      ..., dining room                     =   1  H
30134      ..., bathroom                        =   1  H
30135      ..., bedroom                         =   1  H
30136      ..., study or office                 =   1  H
30137      ..., basement                        =   1  H
30138      ..., utility or laundry room         =   1  H
30139      ..., other indoor                    =   1  H
30200      Residence, outdoor                   =   1  H
30210      Your residence, outdoor              =   1  H
30211      ..., pool or spa                     =   1  H
30219      ..., other outdoor                   =   1  H
30220      Other residence, outdoor             =   1  H
30221      ..., pool or spa                     =   1  H
30229      ..., other outdoor                   =   1  H
30300      Residential garage or carport        =   1  H
30310      ..., indoor                          =   1  H
30320      ..., outdoor                         =   1  H
30330      Your garage or carport               =   1  H
30331      ..., indoor                          =   1  H
30332      ..., outdoor                         =   1  H
30340      Other residential garage or carport  =   1  H
30341      ..., indoor                          =   1  H
30342      ..., outdoor                         =   1  H
30400      Residence, none of the above         =   1  H
31000      Travel, general                      =   1  H
31100      Motorized travel                     =   2  H
31110      Car                                  =   2  H
31120      Truck                                =   2  H
31121      Truck (pickup or van)                =   2  H
31122      Truck (not pickup or van)            =   2  H
31130      Motorcycle or moped                  =   2  H
31140      Bus                                  =   2  H
31150      Train or subway                      =   1  H
31160      Airplane                             =   1  H
31170      Boat                                 =   1  H
31171      Boat, motorized                      =   1  H
31172      Boat, other                          =   1  H
31900      Travel, other                        =   2  H
31910      ..., other vehicle                   =   2  H
31200      Non-motorized travel                 =   1  H
31210      Walk                                 =   1  H
31220      Bicycle or inline skates/skateboard  =   1  H
31230      In stroller or carried by adult      =   1  H
31300      Waiting for travel                   =   1  H
```

31310	..., bus or train stop	=	1	H
31320	..., indoors	=	1	H
31900	Travel, other	=	2	H
31910	..., other vehicle	=	2	H
32000	Non-residence indoor, general	=	1	H
32100	Office building/ bank/ post office	=	1	H
32200	Industrial/ factory/ warehouse	=	1	H
32300	Grocery store/ convenience store	=	1	H
32400	Shopping mall/ non-grocery store	=	1	H
32500	Bar/ night club/ bowling alley	=	1	H
32510	Bar or night club	=	1	H
32520	Bowling alley	=	1	H
32600	Repair shop	=	1	H
32610	Auto repair shop/ gas station	=	1	H
32620	Other repair shop	=	1	H
32700	Indoor gym /health club	=	1	H
32800	Childcare facility	=	1	H
32810	..., house	=	1	H
32820	..., commercial	=	1	H
32900	Large public building	=	1	H
32910	Auditorium/ arena/ concert hall	=	1	H
32920	Library/ courtroom/ museum/ theater	=	1	H
33100	Laundromat	=	1	H
31200	Non-motorized travel	=	1	H
31210	Walk	=	1	H
31220	Bicycle or inline skates/skateboard	=	1	H
31230	In stroller or carried by adult	=	1	H
31300	Waiting for travel	=	1	H
31310	..., bus or train stop	=	1	H
31320	..., indoors	=	1	H
31900	Travel, other	=	2	H
31910	..., other vehicle	=	2	H
32000	Non-residence indoor, general	=	1	H
32100	Office building/ bank/ post office	=	1	H
32200	Industrial/ factory/ warehouse	=	1	H
32300	Grocery store/ convenience store	=	1	H
32400	Shopping mall/ non-grocery store	=	1	H
32500	Bar/ night club/ bowling alley	=	1	H
32510	Bar or night club	=	1	H
32520	Bowling alley	=	1	H
32600	Repair shop	=	1	H
32610	Auto repair shop/ gas station	=	1	H
32620	Other repair shop	=	1	H
32700	Indoor gym /health club	=	1	H
32800	Childcare facility	=	1	H
32810	..., house	=	1	H
32820	..., commercial	=	1	H
32900	Large public building	=	1	H
32910	Auditorium/ arena/ concert hall	=	1	H
32920	Library/ courtroom/ museum/ theater	=	1	H
33100	Laundromat	=	1	H
33200	Hospital/ medical care facility	=	1	H
33300	Barber/ hair dresser/ beauty parlor	=	1	H
33400	Indoors, moving among locations	=	1	H
33500	School	=	1	H
33600	Restaurant	=	1	H
33700	Church	=	1	H
33800	Hotel/ motel	=	1	H
33900	Dry cleaners	=	1	H
34100	Indoor parking garage	=	1	H
34200	Laboratory	=	1	H
34300	Indoor, none of the above	=	1	H
35000	Non-residence outdoor, general	=	1	H
35100	Sidewalk, street	=	1	H
35110	Within 10 yards of street	=	1	H
35200	Outdoor public parking lot /garage	=	1	H
35210	..., public garage	=	1	H
35220	..., parking lot	=	1	H
35300	Service station/ gas station	=	1	H
35400	Construction site	=	1	H
35500	Amusement park	=	1	H

35600	Playground	=	1	H
35610	..., school grounds	=	1	H
35620	..., public or park	=	1	H
35700	Stadium or amphitheater	=	1	H
35800	Park/ golf course	=	1	H
35810	Park	=	1	H
35820	Golf course	=	1	H
35900	Pool/ river/ lake	=	1	H
36100	Outdoor restaurant/ picnic	=	1	H
36200	Farm	=	1	H
36300	Outdoor, none of the above	=	1	H

Appendix F

Isaacs et al. (2009) Reference Used in Developing D and A Statistics Input to APEX Model

The following presents a reformatted version of the Isaacs et al. (2009) presentation to allow for easier reading. The presentation is included at the end of the Appendix in its entirety.

Statistical Properties of Longitudinal Time-Activity Data for Use in EPA Exposure Models

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ABSTRACT

Realistic simulation of longitudinal activity patterns is necessary for appropriately reproducing the frequency and duration of pollutant exposures in human exposure models. In EPA's exposure models, longitudinal activity diaries for simulated persons are constructed from the 1-day cross sectional activity diaries in the Consolidated Human Activity Database (CHAD). Recently, new algorithms have been developed to construct longitudinal diaries from CHAD diaries based on realistic variance and autocorrelation properties of diary characteristics relevant to pollutant exposure. Characteristics of particular interest include time spent in particular microenvironments and time spent in activities that produce high ventilation rates. However, few multi-day data are currently available for estimating accurate statistical properties for these quantities. Results from a recent time-activity study of 10 adults and one newborn child are presented here. The participants recorded their personal location and activity for two-week periods in each of four seasons in 2006 and 2007. The data were recorded 24 hours a day, in increments as small as one minute. Additional recording periods for these same individuals are expected in the future. The diaries for all subjects were assessed to calculate the between-person variance, the within-person variance, and the autocorrelation for various lags in the time spent in outdoor, residence, indoor (non-residence), and vehicle microenvironments, as well as for time spent performing high-METS activities. The effectiveness of various day-type definitions (for example, weekend versus weekday, or workday versus non-workday) for grouping similar diary days is examined. Seasonal variation in activity patterns is analyzed. These data have the potential to aid in the development of improved input variance and autocorrelation statistics for longitudinal diary assembly algorithms in EPA's human exposure models.

INTRODUCTION

Recently, new methods of assembling multi-day diaries in human exposure models from cross-sectional single-day diaries have been proposed that are based on the variance and autocorrelation statistics of the simulated population (Glen et al. 2007). Appropriately modeling intra- and interindividual variability using such algorithms may be essential in producing appropriate estimates of exposure. In addition, reproducing realistic autocorrelations in key diary properties may be required for the modeling of episodic exposure patterns.

Previously, longitudinal time activity-location data collected in children in the Southern California Chronic Ozone Exposure Study (Geyh et al. 1999) have been analyzed to obtain estimates of appropriate measures of variance and autocorrelation for use in the longitudinal algorithm. Data from a new study in adults are now presented.

BACKGROUND

Exposure models require construction of human activity diaries that cover the entire simulation period of a model run. This period is often several months, a year, or even longer. In EPA's models, human activity diaries are usually drawn from EPA's CHAD (Consolidated Human Activity Database; McCurdy et al., 2000; http://www.epa.gov/chadnet1), which typically includes just one day (24 hours) of activities from each person. A "longitudinal" diary is one that covers the same person over a long period of time. While the SHEDS modeling period may be of user-specified duration, it is assumed in this section to be one year, to provide a concrete example.

Recently, a new longitudinal diary assembly algorithm has been developed (Glen et al. 2007) based on the variance and autocorrelation properties of the modeled simulation. The new method requires the user to:

1) select the diary property most relevant to exposure for the current application (such as outdoor time or time spent in vehicles)

2) specify the D statistic, which relates the within-person and between-person variances for this diary property; and

3) specify the 1-day lag autocorrelation in this diary property.

The new method is currently implemented in EPA's APEX and SHEDS-Air Toxics models. The new method allows the modeler to apportion the total variance in the key diary property into the within- and between-person variances $\sigma_w 2$ and $\sigma_b 2$ by specifying the D statistic, defined to be

$$D = \frac{\sigma_b^2}{\sigma^2} = \frac{\sigma_b^2}{\sigma_b^2 + \sigma_w^2}$$

D pertains to the population as a whole and is bounded by zero and one. A value of zero implies all persons have the same average behavior, whereas a value of one implies the greatest possible difference in mean behavior that is consistent with the total variance.

In addition to targeting the within-person and between-person variances through setting the D statistic, the new diary assembly method optionally allows targeting of the day-to-day autocorrelation. This is a measure of the tendency for similar diaries to occur on consecutive days. The lag-one autocorrelation in a variable y is for a person defined as

$$A = \sum_{j=1}^{N-1} \left(y_j - \bar{y}\right)\left(y_{j+1} - \bar{y}\right) / \sum_{j=1}^{N} \left(y_j - \bar{y}\right)^2$$

The population autocorrelation A is the mean of the A values for all individuals. Autocorrelation could be of interest to the exposure modeler if the concentration time series were strongly episodic, for example. In the diary assembly, a positive autocorrelation indicates a tendency for diaries with x-scores near each other to be used on consecutive days, while a negative autocorrelation indicates a tendency for dissimilar x-scores to be used on consecutive days. Some preliminary values of A have been derived from the same data that were used to estimate D (Glen et al., 2007).

METHODS

Activity Diary Study

Activity-location data were collected from 10 adults. Nine of the adults were working professionals; one was a stay-at-home parent. Nine of the adults recorded their personal location and activity for two-week periods in each of four seasons in 2006 and 2007. Additional data were collected in one of the male subjects in 1999, another male (the 10th adult) in 2002, and in one of the females in 2008 (collected during maternity leave). The data were recorded 24 hours a day, in increments as small as one minute. In this preliminary analysis, the time spent outdoors, indoors, in travel, and performing hard work each day were calculated from the diaries. "Hard work" was self-reported by each individual, as defined as activities requiring heavy breathing and/or sweating. Daily high temperatures and precipitation amounts were acquired for each day of the study.

Variance and Autocorrelation Statistics

Variance and lag-one autocorrelation statistics were calculated for the studied individuals. Variance statistics were estimated for both the raw measured variables (ie. time in minutes) and the scaled ranks of the variable for each person on a given day. The ratio of the between-person variance to the total variance (the sum of the between- and within-person variance) was calculated for the population. This ratio, calculated using the raw variables, is the intraclass correlation coefficient (ICC), while the same ratio, calculated using the ranks, is D, the diversity statistic. The autocorrelation A was also calculated using both the raw variables and the scaled ranks of the variables on each day for each person in the study.

Analysis of Time Spent in Locations/Activities

The longitudinal data were assessed to support decisions on optimal diary pools for exposure modeling. Time spent in each of the examined locations/activities were assessed as a function of day of the week (weekday versus weekend), day type (workday versus nonworkday), season, temperature, precipitation, and gender. These analyses were undertaken to assess the utility of different diary pool definitions. Optimal definitions of diary pools can adequately capture temporal patterns in activities while maximizing the number of activity diaries available for sampling on a given day for a simulated individual.

Differences between groups were assessed with the Wilcoxon signed rank test (for 2 groups) or the Kruskal-Wallis test (for more than 2 groups). The Wilcoxon rank sum (two-sample) test was used to test differences between genders.

RESULTS AND DISCUSSION

Individual Variability

Figure 1 shows an example of the individual variability in time spent in different locations/activities for a single male subject; a 367-day period from this subject is depicted. Distributions of time for this subject are also shown. These figures demonstrate the large amount of intra-individual variability that can be seen in longitudinal activity studies. Distributions of time spent in locations/activities for the population is shown in **Figure 4[*sic 2*]**.

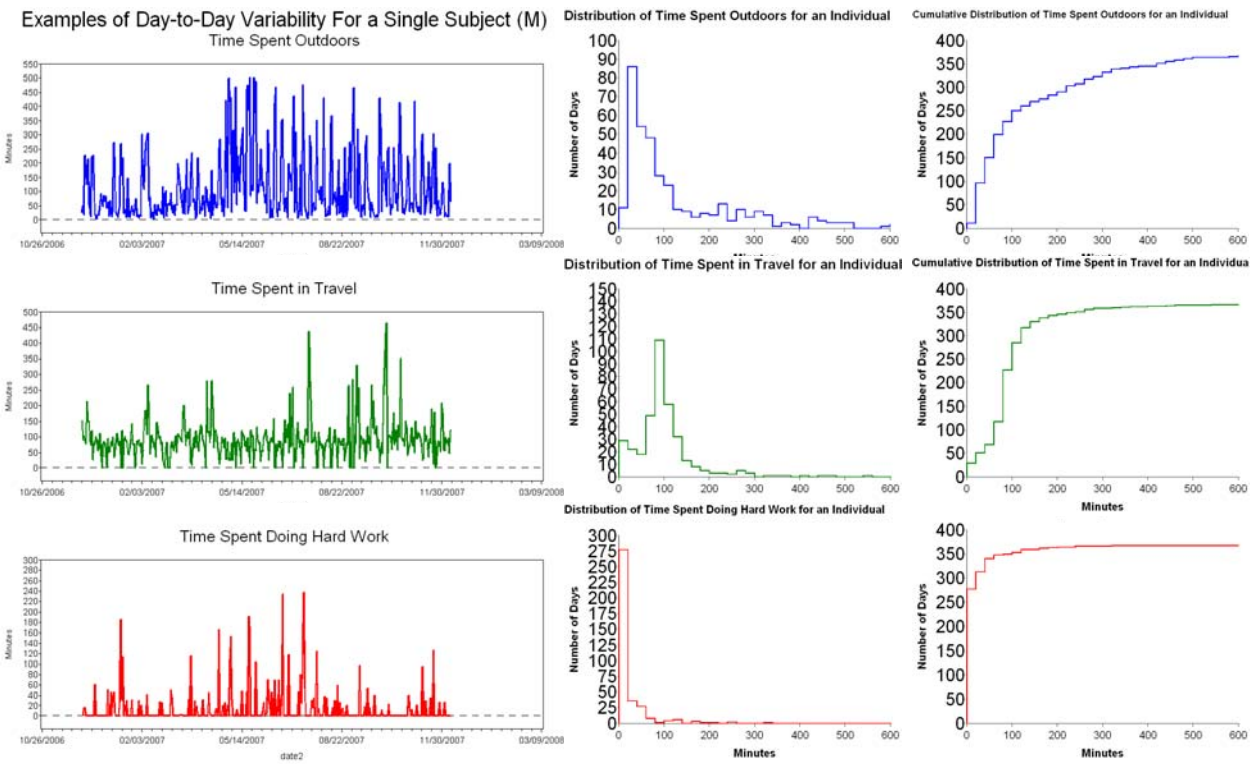

Figure 1. Time series and distributions of time spent in locations/activities for 367 days of data from a single male subject. Note high degree of interpersonal variability in behavior.

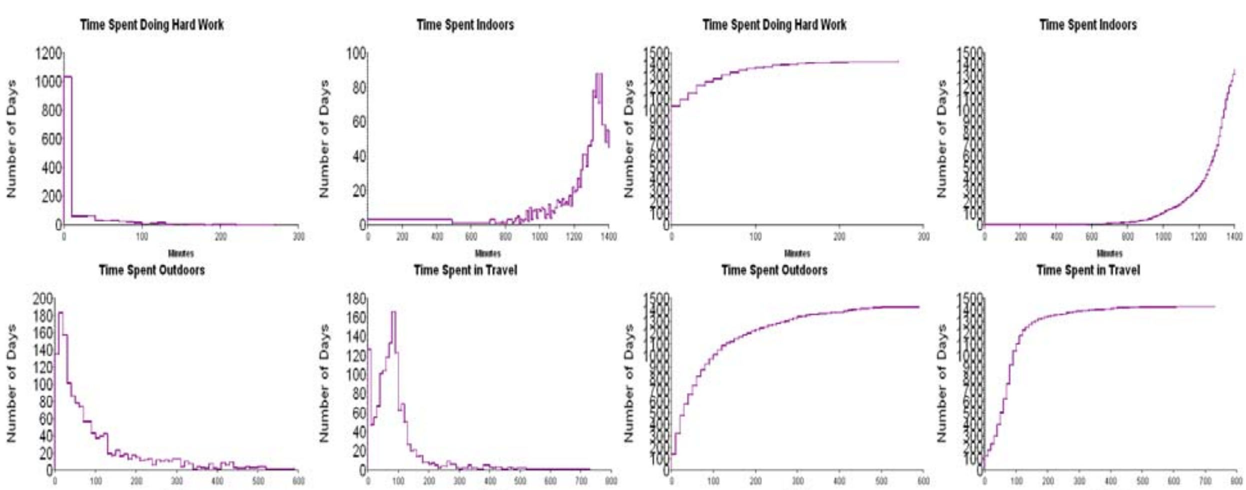

Figure 2. Distributions of time spent in different activities for all days for all subjects.

Variance and Autocorrelation Statistics

D, ICC, and A values for the population for time spent in different locations/activities are given in **Table 1**. Values of the ICC are lower than D; while A for the raw variables were higher than A for the scaled ranks. These trends were also consistent with observed tends in the Southern California data. Values were also calculated by gender (**Table 2**), temperature categories (**Table 3**), and daytypes (**Table 4**) where possible.

The D and ranked A values were compared to those calculated for children from the Southern California Chronic Ozone Exposure Study (SCCOES). The diversity (D) for this group of adults for outdoor time were higher than those calculated for the children (0.38 versus 0.19). The D values for travel time in the current study were also higher (0.18 in children versus 0.36 in this study). These differences reflect the increased heterogeneity in these variable in the studied adults versus the (relatively homogenous) studied children. The A values calculated for outdoor time in this study were virtually identical to those estimated using data from SCCOES.
In general, differences between D by temperature and daytypes were notable, even considering the small number subjects in this study. There were gender differences observed in D; the mechanism of these differences is unclear, but are likely influenced by the activity patterns of the female who was not a worker.

There were observed differences in A by temperature, but especially by daytype. This is not unexpected, as it is reasonable that the behavior of working adults is more consistent day-to-day on workdays. These trends should be confirmed by analysis of other longitudinal data. Note however, that such differences in are only important when strongly episodic behavior or exposure is of interest. In general, the values of D are much more relevant to exposure.

Table 1. Variance and Autocorrelation Statistics: All Days/Subjects

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Indoors	0.26	0.33	0.23	0.34
Outdoors	0.16	0.38	0.22	0.31
Travel	0.14	0.31	0.12	0.19
Hard Work	0.18	0.22	0.17	0.19

Table 2. Variance and Autocorrelation Statistics: By Gender

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Males				
Indoors	0.36	0.54	0.25	0.16
Outdoors	0.14	0.22	0.24	0.22
Travel	0.36	0.46	0.17	0.08
Hard Work	-0.01	0.15	0.22	0.20
Females				
Indoors	0.08	0.09	0.37	0.25
Outdoors	0.07	0.27	0.35	0.18
Travel	0.05	0.16	0.15	0.11
Hard Work	0.15	0.24	0.16	0.21

Table 3. Variance and Autocorrelation Statistics: By Temperature

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Days with max temp less than 50 degrees				
Indoors	0.37	0.37	0.23	0.19
Outdoors	0.20	0.27	0.33	0.18
Travel	0.23	0.37	0.20	0.09
Hard Work	0.21	0.31	0.14	0.14
Days with max temp greater or equal to 50 degrees				
Indoors	0.12	0.26	0.45	0.23
Outdoors	0.09	0.24	0.39	0.20
Travel	0.10	0.24	0.34	0.09
Hard Work	0.01	0.20	0.35	0.14

Table 4. Variance and Autocorrelation Statistics: By Daytype

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Workday				
Indoors	0.37	0.47	0.56	0.05
Outdoors	0.19	0.31	0.78	0.07
Travel	0.45	0.47	0.30	0.01
Hard Work	0.20	0.25	0.53	-0.12
NonWorkday				
Indoors	0.12	0.21	0.59	0.24
Outdoors	0.11	0.14	0.60	0.19
Travel	0.09	0.24	0.38	0.08
Hard Work	0.06	0.07	0.43	0.18

Time Spent in Different Locations/Activities

The time spent in different locations/activities for different day types, seasons, temperature categories are presented in **Figures 3-6**. The effects of gender and precipitation were also studied. There were no significant differences for these categories, and thus plots are not shown. The plotted data represent all days for all subjects. The medians are represented by the midline of the boxes, the first and third quartiles by the ends of the boxes, and the means by the stars. The whiskers extend to cover data that lies beyond the boxedbut within the quartiles plus 1.5 times the interquartile range. Points outside this range are plotted.

Results by day of the week and day type are presented in **Figure 3**. Day type (workday versus nonworkday) was at least as good as day of the week in categorizing time/activities. This trend is similar to that seen in a recent analysis of the larger, cross-sectional database of diaries from The National Human Activity Pattern Survey (NHAPS, data not shown). That analysis indicated that a workday/nonworkday was a better discriminator of time spent outside than a weekday/weekend split. As such, further comparisons are also presented for both workdays and nonworkdays.

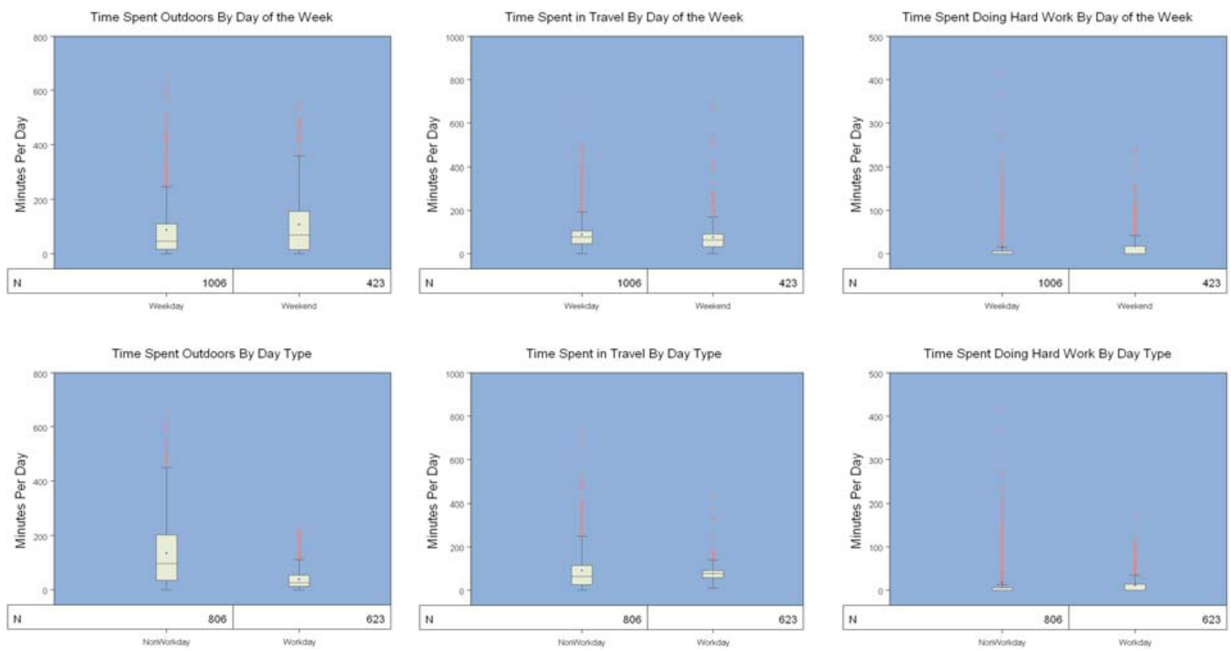

Figure 3. Time spent in different locations/activities as a function of day of the week, and daytype (workday versus nonworkdays).

The effect of season on time spent in locations/activities is shown in **Figure 4**. Seasonal effects were apparent for time spent outdoors on nonworkdays, and for time spent doing hard work. Travel was also affected by season, likely due to the large number of work-related travel days in the fall for this particular group of workers.

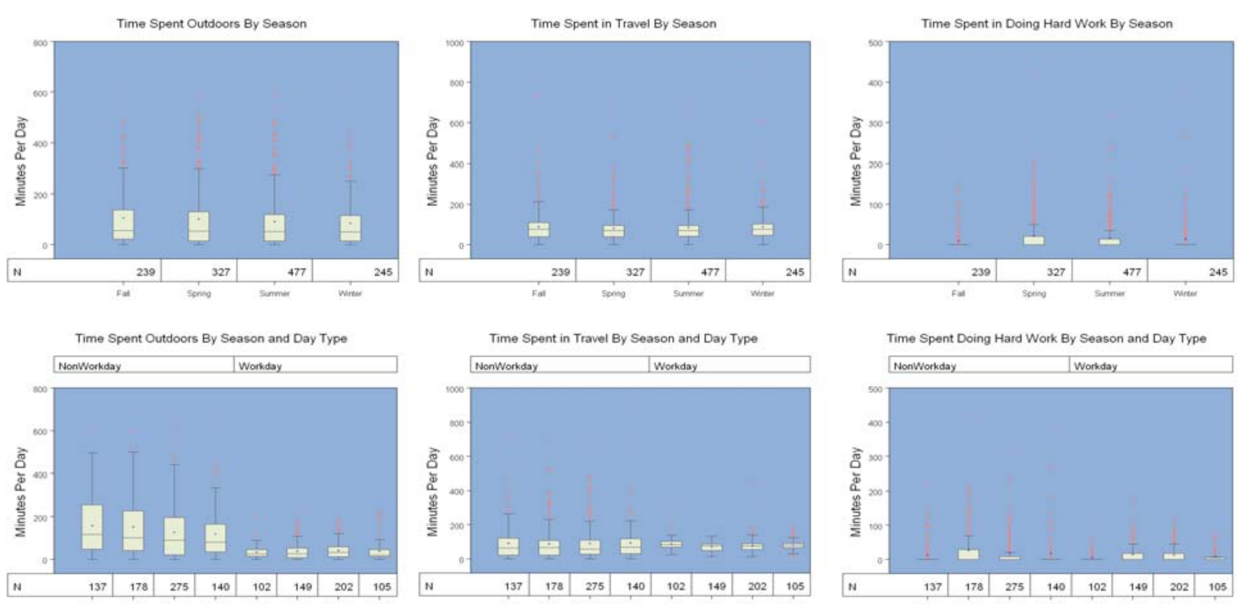

Figure 4. Time spent in different locations/activities as a function of season and daytype.

The effect of temperature category is shown in **Figure 5**. The temperature category was defined as warmer = maximum temperature greater than or equal to 75 degrees, colder= maximum temperature less than 75 degrees. Temperature category was better than or as good as season in discriminating behavior in time spent outdoors, even when daytype was considered.

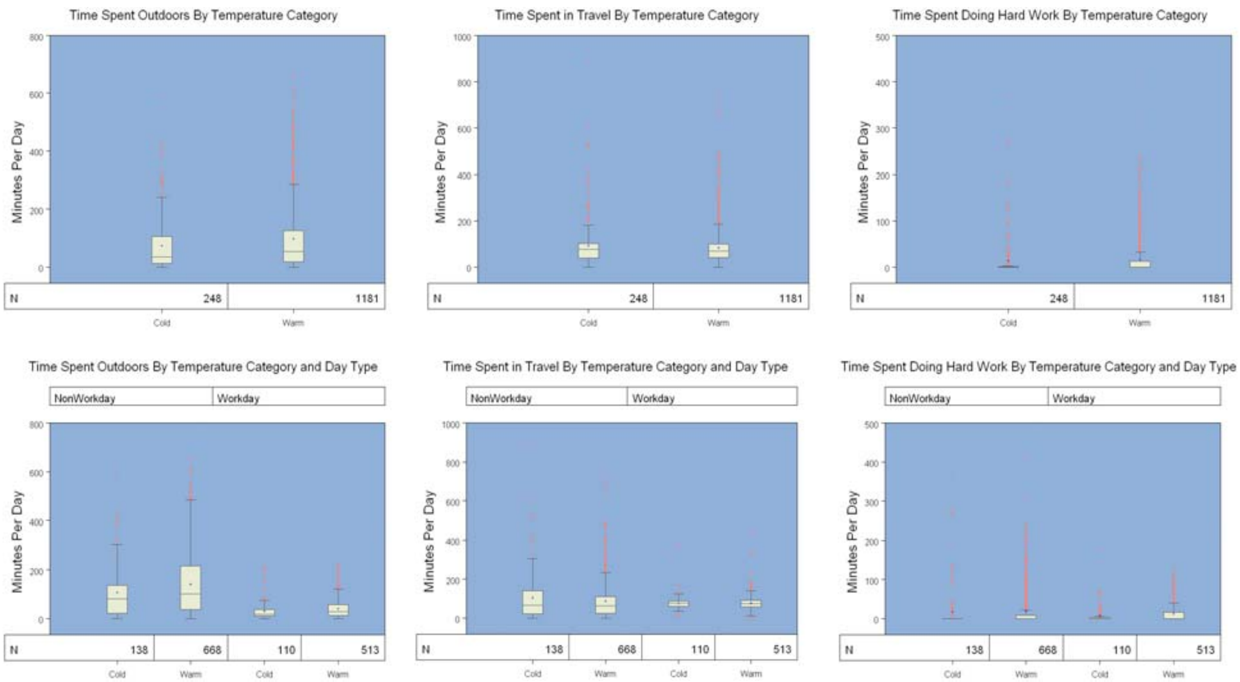

Figure 5. Time spent in different locations/activities as a function of temperature category (colder: max temp< 75 degrees, warmer: max temp≥ 75 degrees) and daytype.

CONCLUSIONS

- The diversity (D) and autocorrelation (A) for this group of adults for outdoor time were higher than those calculated for children in a previous study. Thus these data provide some justification for considering age when considering D and A input values for EPA's exposure models.
- While the current data suggest possible effects of temperature, daytype and gender on diversity (D) and autocorrelation (A), more data from this and other studies are needed to confirm these findings. Such results could aid in the fine-tuning of the longitudinal diary algorithm.
- The analysis of the time spent in locations was consistent with recent findings from from cross-sectional diary studies indicating that workdays/nonworkdays may be a better grouping for diary pools than weekdays/weekends.
- Temperature category was at least as good as season in discriminating behavior for this population for time sprnt outdoors, especially when daytype was considered. Such breakdowns by temperature and daytype may eliminate the need for diary pools different seasons, providing larger pools for diary sampling on a given day. Further analysis with other time-activity data can confirm this trend.

FUTURE WORK

- We plan to repeat this type of study periodically. Data will be compared to/combined with analyses of other available longitudinal time/location/activity studies.

DISCLAIMER

The information in this document has been funded wholly (or in part) by the U. S. Environmental Protection Agency (EPA contract 68-D-00-206). It has been subjected to review by the EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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Statistical Properties of Longitudinal Time-Activity Data for Use in EPA Exposure Models

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ABSTRACT

Realistic simulation of longitudinal activity patterns is necessary for appropriately reproducing the frequency and duration of pollutant exposures in human exposure models. In EPA's exposure models, longitudinal activity diaries for simulated persons are constructed from the 1-day cross sectional activity diaries in the Consolidated Human Activity Database (CHAD). Recently, new algorithms have been developed to construct longitudinal diaries from CHAD diaries based on realistic variance and autocorrelation properties of diary characteristics relevant to pollutant exposure. Characteristics of particular interest include time spent in particular microenvironments and time spent in activities that produce high ventilation rates. However, few multi-day data are currently available for estimating accurate statistical properties for these quantities. Results from a recent time-activity study of 10 adults and one newborn child are presented here. The participants recorded their personal location and activity for two-week periods in each of four seasons in 2006 and 2007. The data were recorded 24 hours a day, in increments as small as one minute. Additional recording periods for these same individuals are expected in the future. The diaries for all subjects were assessed to calculate the between-person variance, the within-person variance, and the autocorrelation for various lags in the time spent in outdoor, residence, indoor (non-residence), and vehicle microenvironments, as well as for time spent performing high-METS activities. The effectiveness of various day-type definitions (for example, weekend versus weekday, or workday versus non-workday) for grouping similar diary days is examined. Seasonal variation in activity patterns is analyzed. These data have the potential to aid in the development of improved input variance and autocorrelation statistics for longitudinal diary assembly algorithms in EPA's human exposure models.

INTRODUCTION

Recently, new methods of assembling multi-day diaries in human exposure models from cross-sectional single-day diaries have been proposed that are based on the variance and autocorrelation statistics of the simulated population (Glen et al. 2007). Appropriately modeling intra- and interindividual variability using such algorithms may be essential in producing appropriate estimates of exposure. In addition, reproducing realistic autocorrelations in key diary properties may be required for the modeling of episodic exposure patterns.

Previously, longitudinal time activity-location data collected in children in the Southern California Chronic Ozone Exposure Study (Geyh et al. 1999) have been analyzed to obtain estimates of appropriate measures of variance and autocorrelation for use in the longitudinal algorithm. Data from a new study in adults are now presented.

BACKGROUND

Exposure models require construction of human activity diaries that cover the entire simulation period of a model run. This period is often several months, a year, or even longer. In EPA's models, human activity diaries are usually drawn from EPA's CHAD (Consolidated Human Activity Database; McCurdy et al., 2000; http://www.epa.gov/chadnet1), which typically includes just one day (24 hours) of activities from each person. A "longitudinal" diary is one that covers the same person over a long period of time. While the SHEDS modeling period may be of user-specified duration, it is assumed in this section to be one year, to provide a concrete example.

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1) select the diary property most relevant to exposure for the current application (such as outdoor time or time spent in vehicles)

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The new method is currently implemented in EPA's APEX and SHEDS-Air Toxics models.

The new method allows the modeler to apportion the total variance in the key diary property into the within- and between-person variances $\sigma_w 2$ and $\sigma_b 2$ by specifying the D statistic, defined to be

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In addition to targeting the within-person and between-person variances through setting the D statistic, the new diary assembly method optionally allows targeting of the day-to-day autocorrelation. This is a measure of the tendency for similar diaries to occur on consecutive days. The lag-one autocorrelation in a variable y is for a person defined as

$$A = \sum_{j=1}^{N-1} (y_j - \bar{y})(y_{j+1} - \bar{y}) / \sum_{j=1}^{N} (y_j - \bar{y})^2$$

The population autocorrelation A is the mean of the A values for all individuals. Autocorrelation could be of interest to the exposure modeler if the concentration time series were strongly episodic, for example. In the diary assembly, a positive autocorrelation indicates a tendency for diaries with x-scores near each other to be used on consecutive days, while a negative autocorrelation indicates a tendency for dissimilar x-scores to be used on consecutive days. Some preliminary values of A have been derived from the same data that were used to estimate D (Glen et al., 2007).

METHODS

Activity Diary Study

Activity-location data were collected from 10 adults. Nine of the adults were working professionals; one was a stay-at-home parent. Nine of the adults recorded their personal location and activity for two-week periods in each of four seasons in 2006 and 2007. Additional data were collected in one of the male subjects in 1999, another male (the 10th adult) in 2002, and in one of the females in 2008 (collected during maternity leave). The data were recorded 24 hours a day, in increments as small as one minute. In this preliminary analysis, the time spent outdoors, indoors, in travel, and performing hard work each day were calculated from the diaries. "Hard work" was self-reported by each individual, as defined as activities requiring heavy breathing and/or sweating. Daily high temperatures and precipitation amounts were acquired for each day of the study.

Variance and Autocorrelation Statistics

Variance and lag-one autocorrelation statistics were calculated for the studied individuals. Variance statistics were estimated for both the raw measured variables (ie. time in minutes) and the scaled ranks of the variable for each person on a given day. The ratio of the between-person variance to the total variance (the sum of the between- and within-person variance) was calculated for the population. This ratio, calculated using the raw variables, is the intraclass correlation coefficient (ICC), while the same ratio, calculated using the ranks, is D, the diversity statistic. The autocorrelation A was also calculated using both the raw variables and the scaled ranks of the variables on each day for each person in the study.

Analysis of Time Spent in Locations/Activities

The longitudinal data were assessed to support decisions on optimal diary pools for exposure modeling. Time spent in each of the examined locations/activities were assessed as a function of day of the week (weekday versus weekend), day type (workday versus nonworkday), season, temperature, precipitation, and gender. These analyses were undertaken to assess the utility of different diary pool definitions. Optimal definitions of diary pools can adequately capture temporal patterns in activities while maximizing the number of activity diaries available for sampling on a given day for a simulated individual.

Differences between groups were assessed with the Wilcoxon signed rank test (for 2 groups) or the Kruskal-Wallis test (for more than 2 groups). The Wilcoxon rank sum (two-sample) test was used to test differences between genders.

Figure 1. Time series and distributions of time spent in locations/activities for 367 days of data from a single male subject. Note high degree of interpersonal variability in behavior.

Figure 2. Distributions of time spent in different activities for all days for all subjects.

Table 1. Variance and Autocorrelation Statistics: All Days/Subjects

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Indoors	0.26	0.33	0.23	0.34
Outdoors	0.16	0.38	0.22	0.31
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Hard Work	0.18	0.22	0.17	0.19

Table 2. Variance and Autocorrelation Statistics: By Gender

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Males				
Indoors	0.36	0.54	0.25	0.16
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Travel	0.05	0.16	0.15	0.11
Hard Work	0.15	0.24	0.16	0.21

Table 3. Variance and Autocorrelation Statistics: By Temperature

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Days with max temp less than 50 degrees				
Indoors	0.37	0.37	0.23	0.19
Outdoors	0.20	0.27	0.33	0.18
Travel	0.23	0.37	0.20	0.09
Hard Work	0.21	0.31	0.14	0.14
Days with max temp greater or equal to 50 degrees				
Indoors	0.12	0.26	0.45	0.23
Outdoors	0.09	0.24	0.39	0.20
Travel	0.10	0.24	0.34	0.09
Hard Work	0.01	0.20	0.35	0.14

Table 4. Variance and Autocorrelation Statistics: By Daytype

Location/Activity	ICC	D	A (Raw)	A (Ranks)
Workday				
Indoors	0.37	0.47	0.56	0.05
Outdoors	0.19	0.31	0.78	0.07
Travel	0.45	0.47	0.30	0.01
Hard Work	0.20	0.25	0.53	-0.12
NonWorkday				
Indoors	0.12	0.21	0.59	0.24
Outdoors	0.11	0.14	0.65	0.19
Travel	0.09	0.24	0.38	0.08
Hard Work	0.06	0.07	0.43	0.18

Figure 3. Time spent in different locations/activities as a function of day of the week, and daytype (workday versus nonworkdays).

Figure 4. Time spent in different locations/activities as a function of season and daytype.

Figure 5. Time spent in different locations/activities as a function of temperature category (colder: max temp< 75 degrees, warmer: max temp≥ 75 degrees) and daytype.

RESULTS AND DISCUSSION

Individual Variability

Figure 1 shows an example of the individual variability in time spent in different locations/activities for a single male subject; a 367-day period from this subject is depicted. Distributions of time for this subject are also shown. These figures demonstrate the large amount of intra-individual variability that can be seen in longitudinal activity studies. Distributions of time spent in locations/activities for the population is shown in **Figure 4**.

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D, ICC, and A values for the population for time spent in different locations/activities are given in **Table 1**. Values of the ICC are lower than D; while A for the raw variables were higher than A for the scaled ranks. These trends were also consistent with observed tends in the Southern California data. Values were also calculated by gender (**Table 2**), temperature categories (**Table 3**), and daytypes (**Table 4**) where possible.

The D and ranked A values were compared to those calculated for children from the Southern California Chronic Ozone Exposure Study (SCCOES). The diversity (D) for this group of adults for outdoor time were higher than those calculated for the children (0.38 versus 0.19). The D values for travel time in the current study were also higher (0.18 in children versus 0.36 in this study). These differences reflect the increased heterogeneity in these variable in the studied adults versus the (relatively homogenous) studied children. The A values calculated for outdoor time in this study were virtually identical to those estimated using data from SCCOES.

In general, differences between D by temperature and daytypes were notable, even considering the small number subjects in this study. There were gender differences observed in D; the mechanism of these differences is unclear, but are likely influenced by the activity patterns of the female who was not a worker.

There were observed differences in A by temperature, but especially by daytype. This is not unexpected, as it is reasonable that the behavior of working adults is more consistent day-to-day on workdays. These trends should be confirmed by analysis of other longitudinal data. Note however, that such differences in are only important when strongly episodic behavior or exposure is of interest. In general, the values of D are much more relevant to exposure.

Time Spent in Different Locations/Activities

The time spent in different locations/activities for different day types, seasons, temperature categories are presented in **Figures 3-6**. The effects of gender and precipitation were also studied. There were no significant differences for these categories, and thus plots are not shown.

The plotted data represent all days for all subjects. The medians are represented by the midline of the boxes, the first and third quartiles by the ends of the boxes, and the means by the stars. The whiskers extend to cover data that lies beyond the boxedbut within the quartiles plus 1.5 times the interquartile range. Points outside this range are plotted.

Results by day of the week and day type are presented in **Figure 3**. Day type (workday versus nonworkday) was at least as good as day of the week in categorizing time/activities. This trend is similar to that seen in a recent analysis of the larger, cross-sectional database of diaries from The National Human Activity Pattern Survey (NHAPS, data not shown). That analysis indicated that a workday/nonworkday was a better discriminator of time spent outside than a weekday/weekend split. As such, further comparisons are also presented for both workdays and nonworkdays.

The effect of season on time spent in locations/activities is shown in **Figure 4**. Seasonal effects were apparent for time spent outdoors on nonworkdays, and for time spent doing hard work. Travel was also affected by season, likely due to the large number of work-related travel days in the fall for this particular group of workers.

The effect of temperature category is shown in **Figure 5**. The temperature category was defined as warmer = maximum temperature greater than or equal to 75 degrees, colder= maximum temperature less than 75 degrees. Temperature category was better than or as good as season in discriminating behavior in time spent outdoors, even when daytype was considered.

CONCLUSIONS

- The diversity (D) and autocorrelation (A) for this group of adults for outdoor time were higher than those calculated for children in a previous study. Thus these data provide some justification for considering age when considering D and A input values for EPA's exposure models.
- While the current data suggest possible effects of temperature, daytype and gender on diversity (D) and autocorrelation (A), more data from this and other studies are needed to confirm these findings. Such results could aid in the fine-tuning of the longitudinal diary algorithm.
- The analysis of the time spent in locations was consistent with recent findings from from cross-sectional diary studies indicating that workdays/nonworkdays may be a better grouping for diary pools than weekdays/weekends.
- Temperature category was at least as good as season in discriminating behavior for this population for time sprnt outdoors, especially when daytype was considered. Such breakdowns by temperature and daytype may eliminate the need for diary pools different seasons, providing larger pools for diary sampling on a given day. Further analysis with other time-activity data can confirm this trend.

FUTURE WORK

- We plan to repeat this type of study periodically. Data will be compared to/combined with analyses of other available longitudinal time/location/activity studies.

DISCLAIMER

The information in this document has been funded wholly (or in part) by the U. S. Environmental Protection Agency (EPA contract 68-D-00-206). It has been subjected to review by the EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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Appendix G

Analysis of CHAD Diaries for Time Spent in Vehicles.

The U. S. Census Bureau (2009) provides an on-line facility for accessing the detailed census data included in their Summary File 3 (SF3). Using this resource, we obtained information on travel time to work for "workers 16 years and over" (US Census Bureau, 2009, Table P31) specific to Denver County, Colorado and Los Angeles, CA. The counts in Table P31 for trips to work places other than home were converted into the percentages listed in Columns 2 and 3 of Table G-1. Although the P31 statistics applied to people 16 years or older, we assumed that the statistics were generally applicable to people 18 years or older.

We next determined the number of 24-hour diaries in CHAD that met the following criteria: the subject was 18+ years of age and the diary reported at least one minute in a motor vehicle between 6 am and 9 am. The number of these diaries that had in-vehicle times corresponding to the bins listed in Table G-1 are listed in Column 4 in and the values were converted to the percentage values listed in Column 5.

Table G-1. Representation of Denver and LA Commuting Characteristics in CHAD Diaries.

Travel time (minutes) (1)	**Percent of commuters according to SF3 census data for Denver County (2)**	**Percent of commuters according to SF3 census data for Los Angeles County (3)**	**24-hour diaries meeting inclusion criteria[a]**	
			Number in CHAD (4)	**Percent in CHAD (5)**
1 to 9	10.28	7.75	563	9.79
10 to 19	31.96	25.92	1,676	29.16
20 to 29	24.15	21.04	1,068	18.58
30 to 39	18.60	21.37	1,111	19.33
40 to 59	9.29	13.57	665	11.57
60 to 89	3.80	6.99	407	7.08
90+	1.73	3.35	258	4.49
Total	100.00	100.00	5,748	100.00

[a]Subjects are 18+ years of age. Diaries include 1+ minute in motor vehicle between 6 am and 9 am.

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