Johnson et al., *Cogent Environmental Science* (2018), 4: 1453022
https://doi.org/10.1080/23311843.2018.1453022

cogent environmental science

ENVIRONMENTAL HEALTH | RESEARCH ARTICLE

A multipollutant evaluation of APEX using microenvironmental ozone, carbon monoxide, and particulate matter ($PM_{2.5}$) concentrations measured in Los Angeles by the exposure classification project

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Received: 12 October 2017
Accepted: 12 March 2018
First Published: 19 March 2018

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Reviewing editor:
Alberto Bezama, Helmholtz Center for Environmental Research, Germany

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Abstract: This paper describes an operational evaluation of the US Environmental Protection Agency's (EPA) Air Pollution Exposure Model (APEX). APEX simulations for a multipollutant ambient air mixture, i.e. ozone (O_3), carbon monoxide (CO), and particulate matter 2.5 microns in diameter or less ($PM_{2.5}$), were performed for two seasons in three study areas in central Los Angeles. APEX predicted microenvironmental concentrations were compared with concentrations of these three pollutants monitored in the Exposure Classification Project (ECP) study during the same periods. The ECP was designed expressly for evaluating exposure models and measured concentrations inside and outside 40 microenvironments. This evaluation study identifies important uncertainties in APEX inputs and model predictions useful for guiding further exposure model input data and algorithm development efforts. This paper also presents summaries of the concentrations in the different microenvironments.

ABOUT THE AUTHORS

Ted R. Johnson is the President and Research Director of TRJ Environmental, Inc., a consulting company specializing in analysis of air quality data and estimation of population exposure. He has designed exposure models used by the US EPA to simulate the exposure of urban populations to air pollution.

John E. Langstaff and Dr Stephen Graham are exposure modelers at the US EPA. Their research encompasses the development and application of exposure modeling techniques.

Dr Eric M. Fujita, emeritus research professor at the Desert Research Institute (DRI), was the Principal Investigator for the ECP sampling and analysis project. His research interests included chemical characterization of emission sources and measurement and characterization of exposures to toxic air contaminants.

Dave E. Campbell is an associate research scientist at DRI, whose research interests include characterization and apportionment of gaseous and aerosol pollutants from mobile sources, and the influence of mobile source contributions on photochemical processes.

PUBLIC INTEREST STATEMENT

Decades of research and numerous studies have consistently indicated air pollution contributes to sickness, disease development, and premature death. To best understand the relationship between air pollution and the negative impacts to human health, it is crucial to account for how people might come in contact with pollutants and experience the important features of exposure, such as the magnitude, duration, frequency, and pattern of pollutant concentrations that occur in their immediate surroundings. In this study, we use a novel multipollutant exposure modeling approach that combines the complexities of human behavior with air pollutant concentrations that vary across an urban area considering movement across space, time, and interaction within built-environments. While reasonable agreement was observed between model estimations and measured concentrations, the most significant uncertainties are identified to further enhance the benefits associated with using a model based approach to estimate multipollutant exposures.

Subjects: Environmental Sciences; Environment & Health; Pollution

Keywords: multipollutant exposure model; microenvironment measurements; ozone; particulate matter; carbon monoxide

1. Introduction

The EPA has used APEX to estimate human exposure to ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and other air pollutants (US EPA, 2008, 2009a, 2010a, 2014), in support of reviews of the National Ambient Air Quality Standards (NAAQS). APEX is used because of its flexible, user-defined physical-based microenvironmental approach and, when combined with extensive activity pattern and population databases, temporally resolved ambient concentrations, and well-parameterized distributions that capture variability in other model inputs, can probabilistically and more realistically estimate population-based human exposures to air pollutants. In each of these past NAAQS exposure assessments, the agency has applied APEX to a single pollutant. Because of growing interest in health effects associated with multiple chemical stressors, APEX has also been recently developed to estimate simultaneous exposures to ambient air pollutants.

This paper describes an evaluation of a multipollutant application of APEX by comparing microenvironmental concentrations of O_3, CO, and fine particulates ($PM_{2.5}$) estimated by APEX in each of three study areas within central Los Angeles with corresponding microenvironmental concentrations measured by the Exposure Classification Project (ECP) in the same three study areas. There are a number of other air pollution exposure models, for example, INDAIR-2/EXPAIR (Dimitroulopoulou, Ashmore, & Terry, 2017), LHEM (Smith et al., 2016), EMI (Breen et al., 2015), HAPEM (US EPA, 2015), EXPAND (Soares et al., 2014), MENTOR (Georgopolis and Lioy, 2006), EXPOLIS (Kruize, Hanninen, Breugelmans, Lebret, & Jantunen, 2003), and SHEDS (Burke, Zufall, & Ozkaynak, 2001). APEX was selected for this evaluation since it is used in regulatory applications and it can model short-term exposures to multiple pollutants in multiple microenvironments.

The three pollutants were selected in this evaluation due to their having been the subject of NAAQS-related exposure and/or risk assessments (US EPA, 2010a, 2010c, 2014) and, as such, are widespread air pollutants having multiple sources and are reasonably expected to endanger public health. More specifically, O_3 is formed photo-chemically via sunlight and precursor chemical emissions from anthropogenic (largely combustion-related) and natural sources. The strongest evidence is for adverse health effects that are respiratory-related and result from short-term (hours to weeks) O_3 exposures, as O_3 has been determined to cause clinically significant lung function impairment and is associated with increased hospital admissions and emergency department visits (US EPA, 2013). Although there are a limited number of studies, short-term O_3 exposure has also been linked with cardiovascular-related morbidity (US EPA, 2013). Regarding CO, a pollutant largely emitted from internal combustion engines (e.g. gasoline powered automobiles), clinical studies among individuals with coronary artery disease showed consistent decreases in the time to onset of exercise-induced angina and ventricular repolarization (or ST-segment) changes following short-term (one hour to a few hours) CO exposures (US EPA, 2010b). Combustion sources are also largely responsible for ambient $PM_{2.5}$, and epidemiological studies show consistent, significant associations of both short-term and long-term $PM_{2.5}$ exposures with a variety of cardiovascular- and respiratory-related health effects, including mortality (US EPA, 2009b). Therefore, given a general correspondence of select exposure- and health-related attributes for each individual chemical (e.g. short-term exposure and cardiovascular effects), realistically quantifying the simultaneous time series exposure profiles for each of these pollutants by understanding when the highest multi-chemical exposures occur could be very important in better understanding their potential cumulative health effects.

2. The air pollution exposure model (APEX)

The Air Pollution Exposure Model (APEX; US EPA, 2017), has its origins in the NAAQS Exposure Model (NEM) initially developed in the early 1980s (Biller et al., 1981; McCurdy, 1994, 1995). APEX simulates the movement of individuals through time and space and their exposure to a given pollutant in indoor, outdoor, and in-vehicle microenvironments.

The model stochastically generates simulated individual characteristics and behaviors using Census-derived probability distributions for their demographics. Any number of simulated individuals can be modeled; by design, they can represent a random sample of the study area population. Survey-derived time activity data, or diaries, are used to construct a sequence of activity events (locations visited and activities performed) for each simulated individual for a day or longer up to a year. The selected diary data are consistent with the individual's demographic characteristics (e.g. age, gender) and account for the influential effects of day-type (e.g. weekday, weekend) and outdoor temperature on daily activities. APEX calculates the concentration in the microenvironment associated with each event in an individual's activity pattern and time-averages the event-specific exposures within each user-specified timestep (typically 1 h). It then uses this information to obtain a continuous time series of exposures spanning the duration of interest. From these exposure estimates, APEX calculates exposures for averaging times greater than the timestep—8 h and 24 h averages from 1 h timesteps; 1 h averages from 5 min timesteps (US EPA, 2014).

APEX employs a flexible approach for simulating microenvironmental concentrations, where the user can define any number of microenvironments to be modeled and their associated characteristics. The concentrations in each microenvironment can be calculated using either a factors or mass-balance approach, depending upon data availability. Probability distributions are used to represent the variability (rather than the uncertainty) of the input data that enter into the calculations (e.g. indoor–outdoor air exchange rates). The parameters of the distributions can vary temporally and spatially and can be set-up to depend on the values of other model input variables. For example, the distribution of air exchange rates in a home may depend on average outdoor temperature and whether air conditioning is present. The value of a stochastic variable can be kept constant for an individual for the entire simulation (e.g. house volume), or a new value can be drawn hourly, daily, or seasonally from specified distributions. APEX also allows the specification of diurnal, weekly, and seasonal patterns for microenvironmental variables (US EPA, 2014).

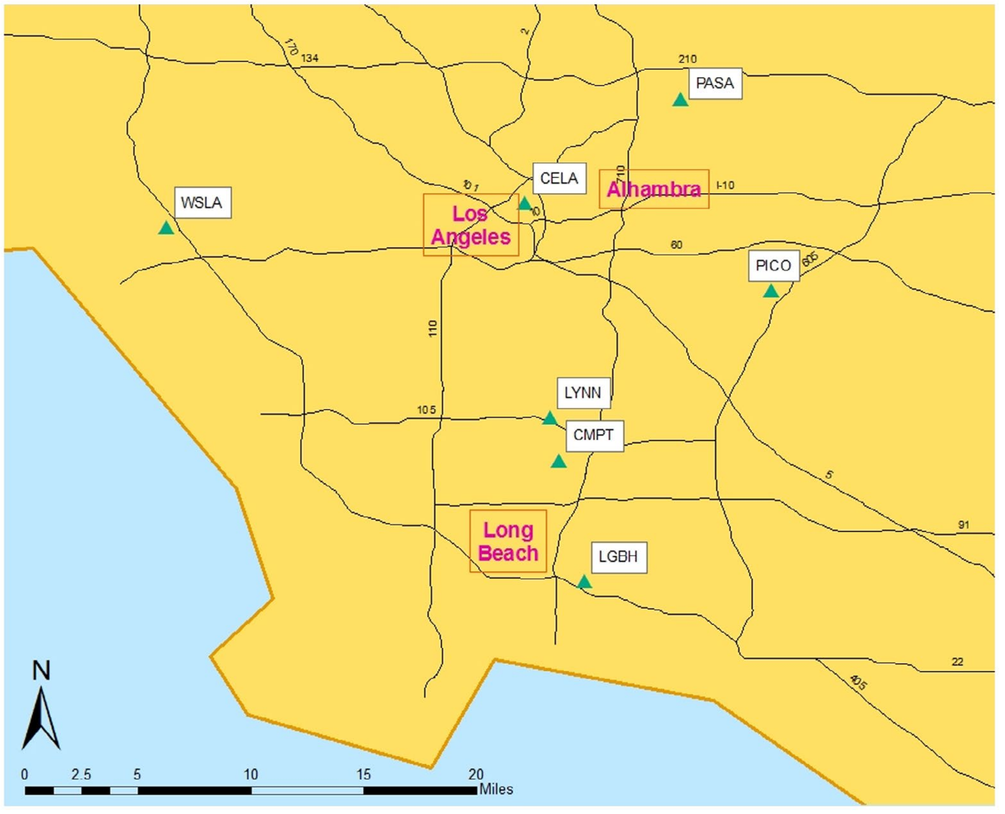
3. The exposure classification project (ECP)

Field studies that measure pollutant concentrations in microenvironments can be useful in developing and validating models for specific microenvironments. The Exposure Classification Project (ECP) was designed specifically to provide such data. The Desert Research Institute (DRI) measured personal breathing-zone concentrations within several microenvironments including in-vehicle, near-road, and various public indoor and outdoor microenvironments. Air pollutants measured included O_3, $PM_{2.5}$ mass, ultrafine particles, black carbon, volatile air toxics (benzene, toluene, ethylbenzene, xylenes, 1,3-butadiene), CO, carbon dioxide (CO_2), additional volatile organic compounds (VOCs), and nitrogen oxides (NO_X). The microenvironmental measurements discussed in this paper were made during two field campaigns: Season 1 (12 days between 9/13/08 and 10/8/08) and Season 2 (11 days between 3/2/09 and 3/19/09) in three study areas in the Los Angeles metropolitan area: Carson/Long Beach, downtown Los Angeles, and Alhambra/Monterey Park (Figure 1). Corresponding outdoor measurements were made immediately following or preceding many of the indoor microenvironmental measurements. In-vehicle measurements were made throughout Los Angeles County for various types of roads and traffic conditions. The lower detection limits were ~1.5 ppb for O_3, ~1 ppm for CO, and ~1 µg/m^3 for $PM_{2.5}$. The experimental protocols are described by Fujita, Campbell, Arnott, Johnson, and Ollison (2014) and in two interim reports prepared by Fujita, Campbell, and Zielinska (2009a, 2009b).

The ECP microenvironmental measurements were made during a series of tests that followed a prepared script. During each test, the technician measured concentrations of various air pollutants in a single microenvironment for a time period that varied from 1 min to 60 min (median = 12 min), during which local temperature, relative humidity, and wind speed were also recorded. In addition, the technician provided a written description of the location and microenvironment. Each multipollutant measurement in the ECP database was assigned a unique test number and was labeled as to date,

Figure 1. Microenvironmental measurements were made in three study areas, downtown Los Angeles, Alhambra, and Long Beach.

Note: Triangles indicate locations of nearby air monitoring stations of the South Coast Air Quality Management District (SCAQMD).



time, geographic location, and microenvironment. Each test belongs to a group of tests that were made at the same geographic location on the same date within a period of two hours or less. In total there were 87 of these "test groups" having pollutant concentrations measured in one or more micro-environments; 39 occurred during the 2008 measurement campaign while 48 occurred in 2009. These test groups provide a means of analyzing the relationships (e.g. ratios, differences, correlations) between the air pollutant concentrations measured in two different microenvironments at the same geographic location and occurring at approximately the same time. The final microenvironmental measurements totaled 419 tests. Technicians attempted to measure all of the target pollutants in 331 of the 419 tests; the target pollutants were limited to $PM_{2.5}$, VOC, and CO in the remaining 88 tests.

Ideally in this study, corresponding pollutant concentrations estimated by APEX for the same three Los Angeles locations under similar conditions would have statistical properties similar to those of the ECP data. In particular, we would expect a similarity in the ratios of pollutant concentrations measured simultaneously in specific pairs of related microenvironments, such as inside a school and immediately outside the same school. We calculated three sets of ratios for each the APEX generated and ECP measurement concentrations: (1) microenvironmental concentrations to outside concentrations, (2) microenvironmental concentrations to ambient monitor concentrations and, (3) microenvironmental concentrations to near-road concentrations (ECP measurement data only). Descriptive statistics (minimum, median, and maximum) were used to compare and contrast the overall distribution of each the corresponding APEX and ECP datasets.

The Supplemental Material presents statistical summaries of the ECP data. Descriptive statistics are presented for the O_3, CO, and $PM_{2.5}$ concentrations in each of the 40 microenvironments assigned to the ECP data. Percentiles of the ratios of mean O_3, CO, and $PM_{2.5}$ concentrations for specified pairs of microenvironments based on measurements made during the same test group are also given for 19 pairings of microenvironments.

4. Similar measurement studies

Several studies have made measurements of pollutants in microenvironments. Some studies report indoor/outdoor (I/O) ratios where the outdoor measurements are just outside the microenvironment, others report indoor/ambient ratios, where "ambient" is at fixed site central monitor(s). In this paper, we distinguish between these. The majority of these studies are for $PM_{2.5}$ in residential microenvironments (Mohammed et al., 2015). Breen et al. (2015), in an evaluation of the Exposure Model for Individuals (EMI), measured a mean $PM_{2.5}$ I/O ratio of 0.58 (5th to 95th percentiles 0.32 to 0.84) in residences. Allen et al. (2012) in a study of 353 homes, found a mean I/O ratio of 0.62 (standard deviation 0.21), ranging from 0.47 to 0.82 across seven communities. Long, Suh, and Koutrakis (2000) measured $PM_{2.5}$ at 9 residences and report the mean I/O ratios as 2.4 ± 14 (range 0.03–257) for daytime and 0.74 ± 0.41 (range 0.03–3.7) for nighttime. Lai et al. (2004) found a residential $PM_{2.5}$ I/O ratio of means to be 1.9. Meng, Spector, Colome, and Turpin (2009), in a 3-city study of 114 homes found a mean I/O ratio of 0.69 (standard deviation 0.23), ranging from 0.1 to 1.3. The PTEAM tudy (Pellizzari, Thomas, Clayton, Whitmore, & Shores, 1992) found the median 24 h I/O ratios to be 0.94, with 10th and 90th percentiles 0.40 and 2.05, for 178 residences.

There are some studies of non-residential microenvironments and of O_3, CO, and $PM_{2.5}$. Challoner and Gill (2014) looked at 10 commercial buildings and measured $PM_{2.5}$ I/O ratios ranging from 0.47 to 4.68 with a median of 1.26. Zhang and Zhu (2012) measured $PM_{2.5}$ at five schools in Texas and found I/O ratios at the schools to be 0.34, 0.30, 0.38, 0.27, and 0.53. Crist, Liu, Kim, Deshpande, and John (2008) found I/O ratios for $PM_{2.5}$ of 2.61, 1.71, and 2.98 on school days at three schools in Ohio. Ratios on non-school days were much lower. Hanninen, Kruize, Lebret, and Jantunen (2003), in an evaluation of the EXPOLIS model, reports for $PM_{2.5}$ in residences a mean indoor/ambient ratio of 0.93 and a work indoors/ambient ratio of 1.01. Chaloulakou, Mavroidis, and Duci (2003) measured CO at an office and a school. Mean daily I/O ratios ranged from 0.74 to 1.00 at the office and 0.53 to 0.89 at the school. Weschler (2000) summarized the I/O ratios for O_3 from 55 sets of measurements in homes and several other microenvironments, ranging from < 0.1 to 1.0. These previous measurements are generally consistent with the ECP measurements in this study, except for the high values recorded by Long et al. (2000), which were due to indoor sources. Our study differs from previous studies in that ECP sampled several pollutants in 40 microenvironments, both inside and outside the microenvironments.

Branco, Alvim-Ferraz, Martins, and Sousa (2014) point out the need for evaluation of the microenvironment modeling approach and Milner, Vardoulakis, Chalabi, and Wilkinson (2011) state "There is a need for further measurement studies on indoor air exposure to provide independent monitoring data-sets for testing of exposure models. Large-scale studies should, where possible, make simultaneous observations on indoor and outdoor concentrations …" Kruize et al. (2003) noted "it would be very helpful if more databases on (indoor) concentration data … were published and made available." This study makes a significant addition to the literature reporting on indoor and outdoor microenvironmental concentrations.

5. APEX inputs for the multipollutant evaluation

As described above, based on an evaluation of ECP and fixed-site monitoring data availability, we focused our multipollutant evaluation on three pollutants: O_3, CO, and $PM_{2.5}$. Therefore, we set up a multipollutant APEX simulation which modeled population exposures to all three pollutants using a single set of simulated individuals. In this way, the daily activity patterns used to estimate the exposures of each individual are the same for all three pollutants (i.e. the same locations visited, activities performed, and microenvironmental settings, all occurring at the same times of the day). One thousand individuals were simulated for each season and each of the three communities, for a total of six APEX simulations. Preliminary simulations showed that modeling this number of individuals provided sufficient numbers of values (at least 300 in each microenviroment) for the statistical analyses conducted. Note that we are not comparing exposures, but concentrations in microenviroments, so the population demographics are not relevant.

In setting up an APEX simulation that includes CO and $PM_{2.5}$ exposures, the user can enter parameter values that account for specific indoor sources of CO (e.g. smoking and gas stoves) and $PM_{2.5}$ (numerous sources). We determined that modeling these sources within the multipollutant APEX run would unnecessarily complicate the comparison of APEX exposure estimates and ECP pollutant measurements, since we can theoretically identify the APEX events affected by indoor sources but not necessarily the ECP measurements. Therefore, the contribution of CO and $PM_{2.5}$ from indoor sources was not modeled by APEX.

APEX has several options and types of input data that allow an application to be tailored to a specific area and scenario. In order to conduct an unbiased evaluation of a typical model application, we used the model options and inputs that were used in a recent application of APEX for O_3 to the Los Angeles area (US EPA, 2014), except adjusting the time periods modeled to coincide with the ECP sample collection dates. The microenvironmental definitions were revised to match them with the microenvironments in the ECP database, but the microenvironmental parameter settings were not changed, except for the proximity factors, which were updated to account for the spatial variability of concentrations between monitors. Proximity factors are stochastic ratios between monitors and other outdoor locations.

The APEX input data fall into the following general categories: human activity data; population, employment, and commuting data; air quality data; temperature data; physiological data; and microenvironmental data or variables. The human activity data are from the Consolidated Human Activity Database (CHAD) (McCurdy, Glen, Smith, & Lakkadi, 2000; US EPA, 2002), which contains over 50,000 daily activity diaries. The population demographics were obtained from the 2000 US Census data at the tract level, and a national commuting database based on 2000 Census data provides home-to-work commuting flows between tracts. Hourly surface temperature measurements were obtained from the National Weather Service data files (http://www.ncdc.noaa.gov/oa/ climate/surfaceinventories.html). APEX assigns the data from the closest weather station to each Census tract. Temperatures are used by APEX both in selecting activity diaries used to simulate the exposed individual and in estimating air exchange rates (AERs) for indoor microenvironments. The default APEX physiological data were used (e.g. distributions of body mass by age and gender, see Isaacs & Smith, 2005). Microenvironmental variables include AERs, decay rates, penetration rates, and proximity factors. The $PM_{2.5}$ decay (deposition) rates are taken from Bouilly, Karim, Claudine, and Allard (2005). The data underlying the other microenvironment variables are described in US EPA (2014).

The parameters describing the distributions used in estimating microenvironmental concentrations are listed in Table 1. Because air exchange is a physical characteristic of the indoor microenvironment, the AERs appropriately apply to all pollutants. The mass balance model is used for the indoor microenvironments and the regression factors model is used for outdoor and in-vehicle microenvironments. 100% pollutant indoor penetration rates are assumed in lieu of data; as penetration rate measurements become available, the distributions input to APEX can be updated. These models and the various inputs are described in greater detail in the APEX user's guides (EPA, 2017).

Air quality data reported by seven fixed-site monitors within and around the ECP sampling locations were used for input to APEX. APEX uses the ambient concentration data from the closest air quality monitoring site to each Census tract. Figure 1 shows the locations of the seven monitoring sites: Central Los Angeles (CELA), Compton (CMPT), Long Beach (LGBH), Lynwood (LYNN), Pasadena (PASA), Pico Rivera (PICO), West Los Angeles (WSLA). Hourly measurements of ambient O_3, $PM_{2.5}$, and CO and daily measurements of $PM_{2.5}$ were compiled from EPA's Air Quality System (https://www.epa.gov/aqs). Adequate 1 h monitoring data were available surrounding the three study areas for CO and O_3. However, the availability of 1 h $PM_{2.5}$ data were limited. There are two sites (CELA and Glendora) within 20 miles of the study areas that have 1 h $PM_{2.5}$ data for 2008. There are six monitor sites (CELA, LGBH, Anaheim, Burbank, Glendora, and Reseda) within that radius that have 1 h $PM_{2.5}$ data for 2009. Monitored data for the remaining ECP pollutants were insufficient to perform comparisons with APEX.

Table 1. APEX microenvironment parameters

Microenvironment	Parameter	Conditions	Distribution
Indoors—residence	AER	Temp < 68; A/C: central	Log*N*(0.577, 1.897, 0.1, 10)
		Temp 68–76; A/C: central	Log*N*(1.084, 2.336, 0.1, 10)
		Temp 77–85; A/C: central	Log*N*(0.861, 2.415, 0.1, 10)
		Temp > 85; A/C: central	Log*N*(0.861, 2.344, 0.1, 10)
		Temp < 68; A/C: room	Log*N*(0.672, 1.863, 0.1, 10)
		Temp 68–76; A/C: room	Log*N*(1.674, 2.223, 0.1, 10)
		Temp > 76; A/C: room	Log*N*(0.949, 1.644, 0.1, 10)
		Temp < 50; A/C: none	Log*N*(0.543, 3.087, 0.1, 10)
		Temp 50–67; A/C: none	Log*N*(0.747, 2.085, 0.1, 10)
		Temp 68–76; A/C: none	Log*N*(1.372, 2.283, 0.1, 10)
		Temp > 76; A/C: none	Log*N*(0.988, 1.967, 0.1, 10)
Indoors–school	AER	All	Discrete (range 0.1 to 3.0)
Indoors–restaurant, bar, night club, café	AER	All	Log*N*(3.712, 1.855, 1.46, 9.07)
Indoors-other	AER	All	Log*N*(1.109, 3.015, 0.07, 13.8)
Indoors-All	O_3 Decay rate	All	Log*N*(2.51, 1.53, 0.95, 8.05)
	PM_{25} Decay rate	All	Uniform(0.1,1.1)
	CO Decay rate	All	No decay
	O_3 Proximity	All	Normal(1.0, 0.07, 0.9, 1.1)
All MEs	PM_{25} Proximity	All	Normal(1.0, 0.07, 0.9, 1.1)
All MEs	CO Proximity	All	Normal(1.0, 0.15, 0.8, 1.2)
Outdoors-near road	O_3 Proximity	All	Normal(0.755, 0.203, 0.422, 1.0)
Outdoors-other	O_3 Proximity	All	Normal(1.0, 0.07, 0.9, 1.1)
In-vehicle	O_3 Proximity	Local roads (6%)	Normal(0.755, 0.203, 0.422, 1.0)
		Urban roads (65%)	Normal(0.754, 0.243, 0.355, 1.0)
		Interstates (29%)	Normal(0.364, 0.165, 0.093, 1.0)
	O_3 Penetration	All	Normal(0.300, 0.232, 0.1, 1.0)

Notes: Temp is daily average temperature in degrees Fahrenheit. A/C indicates the type of air conditioning. Log*N* is lognormal(geometric mean, geometric standard deviation, minimum, maximum). Normal is Gaussian(mean, standard deviation, minimum, maximum). When a sampled value is below the minimum or above the maximum, it is resampled by APEX (Gaussian and lognormal distributions).

The APEX results presented in this paper were calculated from the APEX events output files (i.e. the complete time-series of concentrations in each microenviroment, on a minute-by-minute basis) and were subset to times between 7 am and 8 pm, since the ECP data were collected during these hours of the day.

6. Preparation of the ECP database

To facilitate future statistical analyses, we created a set of 40 ECP codes for classifying the microenvironments where measurements were collected, based on the ECP descriptions of the sampled microenvironments. The codes include 14 indoor microenvironments, 17 outdoor microenvironments, and 9 in-vehicle microenvironments. This code set was considered to provide adequate specificity while also increasing sample sizes for most microenvironments. In addition, the code set provided several microenvironmental classifications that were specific to certain locations within the study area, such as the Metro transit center.

To further increase the number of measurements representing each microenvironment while maintaining sufficient specificity, we defined a condensed set of 24 microenvironments which we used in the APEX modeling, such that each of the 40 ECP microenvironments could be mapped to one of the 24 APEX microenvironments (Table 2). CO and $PM_{2.5}$ were measured in all 24 microenvironments, while for O_3, there are measurements in all of the APEX microenvironments except

Table 2. Mapping of 40 ECP microenvironments to condensed set of 24 APEX microenvironments

APEX microenvironment	ECP microenvironment
Indoors	
01: indoors–residence	11: indoors–apartment
02: indoors–community center or auditorium	12: indoors–community center or auditorium
03: indoors–restaurant	13: indoors–food court
	17: indoors–restaurant–fast food
04: indoors–hotel/motel	14: indoors–hotel
05: indoors–office building, bank, post office	15: indoors–office/office building
	16: indoors–public building (post office, etc.)
06: indoors–bar, night club, café	18: indoors–restaurant–café or other
07: indoors–school	19: indoors–school
08: indoors–shopping mall/non-grocery store	20: indoors–shopping mall or enclosed courtyard
	24: indoors–non-food store (department, pharmacy, etc.)
09: indoors–grocery store/convenience store	21: indoors–food store (bakery, supermarket, etc.)
10: indoors–metro-subway-train station	22: indoors–subway station or train station
11: indoors–hospital/medical care facility	23: indoors–hospital
Outdoors-other	
12: outdoors–residential	35: outdoors–neighborhood background or residential grounds
13: outdoors–general non-residential	32: outdoors–community or retirement center
	34: outdoors–mall, market, patio, or plaza
	41: outdoors–public building
14: outdoors–park or golf course	36: outdoors–park or golf course
15: outdoors–restaurant or café	42: outdoors–restaurant/picnic
16: outdoors–school grounds	43: outdoors–school grounds
Outdoors-near road	
17: outdoors–metro-subway-train stop	31: outdoors–bus stop
	46: outdoors–metro station platform
	47: outdoors–bus transit center
18: outdoors–within 10 yards of street	33: outdoors–freeway edge or gradient, pedestrian overpass
	40: outdoors–pedestrian walk
	45: outdoors–street–residential
19: outdoors–garage (covered or below ground)	37: outdoors–parking garage or covered parking
	38: outdoors–parking garage–below ground
20: outdoors–parking lot (open), street parking	39: parking lot (open), street parking, window shopping
21: outdoors–service station	44: outdoors–service station
In-Vehicle	
22: vehicle–car	51: vehicle–auto–commercial strip, surface street
	52: vehicle–auto–freeway
	53: vehicle–auto–garage–underground
	54: vehicle–auto–refueling
	55: vehicle–auto–residential street
	56: vehicle–auto–restaurant drive-through
	57: vehicle–auto–urban canyon or urban streets
23: vehicle–bus	58: vehicle–bus
24: vehicle–train or subway	59: vehicle–train

microenvironments 6, 11, 23, and 24. Table 2 also shows how the microenvironments are grouped within four general microenvironments ("Indoors," "Outdoors-near road," "Outdoors-other," and "in-Vehicle"). These general microenvironments are used in statistical analyses to increase sample size and overall strength of inference.

7. Fixed-site monitors selected for analysis

We identified fixed-site monitors that were relatively close to each of the three ECP study areas and that provided relatively complete data for each of the two ECP study periods. We assigned the central Los Angeles site (CELA) to the Alhambra and downtown Los Angeles study areas, and the Long Beach site (LGBH) to the Carson/Long Beach study area. These monitors were used for all analyses that paired ECP measurements with concurrent fixed-site measurements. In the case of $PM_{2.5}$, fixed-site monitoring data were only available for the LGBH site for 2009. Consequently, the $PM_{2.5}$ analyses that pair ECP data to LGBH data are limited to 2009 data.

8. Ratios of microenvironmental concentrations to outdoor concentrations

As discussed above, each multipollutant measurement (referred to as a "test") is labeled with the corresponding date, time, geographic location, and microenvironment. Each test belongs to a group of tests that were made at the same geographic location on the same date within a period of two hours or less. There are 87 of these "test groups" in which DRI measured pollutant concentrations in one or more microenvironments; 39 occurred in 2008 and 48 in 2009. The use of test groups provides a means of analyzing the relationships (ratios, differences, correlations, etc.) between pollutant concentrations measured in two different microenvironments at the same geographic location at approximately the same time. The APEX distributions in microenvironments used in these analyses are the distributions of the daytime hourly values predicted by APEX in the microenvironments. We have not attempted to match the APEX and ECP concentrations by day or time-of-day. In both cases we are consolidating concentrations for the same period of time. To the extent that the concentrations vary by time of day there will be some mismatch in time. However, the indoor-outdoor ratios modeled in APEX do not directly depend on concentration levels, so this potential mismatch will not affect comparisons of indoor-outdoor ratios, which is why we focus the comparisons on these ratios.

We have a particular interest in the relationships between indoor and nearby outdoor concentrations, since this is one of the key relationships being modeled by APEX. Table 3 presents the minimum, median, and maximum indoor/outdoor ratios for ECP O_3 concentrations for all indoor microenvironments and for cases when the outdoor microenvironment is either "Outdoors-other" or "Outdoors-near road." We expect indoor/outdoor ratios to be less than one due to decay of O_3 indoors, absent substantial positive O_3 monitor interferences. The median ratio for all indoors to outdoors-other (0.30) is lower than the median ratio for all indoors to outdoors-near road (0.37). This result is likely because the titration of O_3 by on-road NO emissions tends to cause a reduction in near-road concentrations of O_3 compared with other outdoor locations.

Table 3 also lists the median indoor/outdoor ratios determined by applying APEX to the ECP study area. These are limited to the "Outdoors-other" category only because APEX does not continuously estimate the concentrations at the near-road location closest to a given (non-near-road) microenvironment. The median of the indoor/outdoor ratios for each indoor microenvironment range from 0.16 to 0.58 for ECP and from 0.22 to 0.60 for APEX. The APEX median ratio for all indoors to outdoors-other is 0.24, lower than the corresponding ECP median ratio (0.30).

Table 4 lists statistics for CO ratios. In general, we expect the indoor/outdoor ratios to be about one due to the limited reactivity of CO indoors. The APEX indoor/outdoor median ratios are all between 1.0 and 1.08, while the ECP ratios exhibit wider variation. The APEX median ratio for all indoors

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Table 3. Comparisons of APEX estimated ratios of indoor microenvironmental O_3 concentration to simultaneous nearby outdoor microenvironmental O_3 concentration obtained from ECP measurements

Indoor microenvironment		Outdoor microenvironment	Indoor-to-Outdoor O_3 ratio						
			ECP measurements				APEX		
	Description		N^a	Min	Med	Max	Min	Med	Max
1	Residence	Other	3	0.11	0.24	1.41	0.01	0.23	2.71
		Near-road	1	–	1.02	–	–	–	–
2	Community Center or auditorium	Other	4	0.07	0.18	0.28	0.03	0.30	0.86
		Near-road	7	0.07	0.13	0.46	–	–	–
3	Restaurant	Other	11	0.07	0.30	1.00	0.16	0.59	1.79
		Near-road	10	0.16	0.48	14.3	–	–	–
4	Hotel/motel	Other	1	–	0.54	–	0.01	0.30	1.85
		Near-road	3	0.56	0.65	0.77	–	–	–
5	Office building, bank, post office	Other	6	0.16	0.58	1.94	0.01	0.29	2.04
		Near-road	11	0.14	0.42	1.38	–	–	–
7	School	Other	5	0.34	0.37	0.65	0.01	0.22	1.98
		Near-road	2	0.37	0.63	0.89	–	–	–
8	Shopping mall, non-grocery store	Other	5	0.10	0.31	0.40	0.01	0.29	1.43
		Near-road	4	0.10	0.25	0.42	–	–	–
9	Grocery store, convenience store	Other	3	0.14	0.16	0.90	0.01	0.30	1.79
		Near-road	6	0.14	0.29	0.66	–	–	–
All	All indoors[b]	Other	25	0.07	0.30	1.94	0.01	0.38	2.71
		Near-road	29	0.09	0.37	14.3	–	–	–

Notes: The "all indoors ME" value for a particular test group may combine (average) pollutant values from two or more indoor MEs that were measured at about the same time. So the "all" *N* value may be less than the sum of the *N* values for individual MEs.

[a]*N* is the number of ratios of measured values. The APEX statistics are based on >1000 simulated values.

[b]The values in the "all indoors" rows (e.g. the 29 and 0.09 in the last row) are not expected to be consistent with the numbers above.

to outdoors-other is 1.01, slightly lower than the corresponding ECP median ratio (1.10). Very high APEX indoor/outdoor ratios occur when the outdoor concentration drops rapidly to close to zero, while the indoor concentration takes longer to decrease if all windows and doors are closed. There are no measured ratios as high as these since measurements were not made under these conditions.

Table 5 presents the corresponding statistics for $PM_{2.5}$ ratios. In general, we expect indoor/outdoor ratios to be less than one due to $PM_{2.5}$ removal processes indoors, though indoor sources (e.g. frying) and other human activities could (e.g. vacuuming) could increase this ratio above unity. The ECP median ratios for all indoors to outdoors-other and indoors to outdoors-near road are very close (0.55 and 0.52). The median indoor-to-outdoors-other ratio from APEX is 0.76, somewhat higher than the ECP ratio (0.55).

Table 4. Comparisons of APEX estimated ratios of indoor microenvironmental CO concentration to simultaneous nearby outdoor microenvironmental CO concentration obtained from ECP measurements

Indoor microenvironment		Outdoor ME	Indoor-to-Outdoor CO ratio						
			ECP measurements				APEX		
	Description		*N*[a]	Min	Med	Max	Min	Med	Max
1	Residence	Other	2	0.71	0.85	1.00	0.07	1.00	336
		Near-road	0	–	–	–	–	–	–
2	Community Center or auditorium	Other	3	0.48	1.28	2.00	0.39	1.04	380
		Near-road	7	0.73	1.13	2.88	–	–	–
3	Restaurant	Other	12	0.63	1.62	19.0	0.48	1.00	95
		Near-road	10	0.64	1.06	7.00	–	–	–
4	Hotel/motel	Other	1	–	0.39	–	0.16	1.00	315
		Near-road	3	0.88	0.93	1.20	–	–	–
5	Office building, bank, post office	Other	7	0.78	1.00	1.60	0.05	1.05	485
		Near-road	11	0.50	1.00	1.80	–	–	–
7	School	Other	5	0.09	0.69	2.00	0.10	1.08	416
		Near-road	2	1.00	2.00	3.00	–	–	–
8	Shopping mall, non-grocery store	Other	5	0.55	1.33	1.80	0.06	1.03	371
		Near-road	5	0.69	1.00	1.92	–	–	–
9	Grocery store, convenience store	Other	3	1.26	1.80	17.6	0.08	1.02	507
		Near-road	7	0.52	1.00	1.93	–	–	–
All	All indoors[b]	Other	25	0.55	1.10	19.0	0.05	1.01	507
		Near-road	29	0.64	1.00	3.33	–	–	–

Notes: The "all indoors ME" value for a particular test group may combine (average) pollutant values from two or more indoor MEs that were measured at about the same time. So the "all" *N* value may be less than the sum of the *N* values for individual MEs.

[a]*N* is the number of ratios of measured values. The APEX statistics are based on >1000 simulated values.

[b]The values in the "all indoors" rows are not expected to be consistent with the numbers above.

Table 5. Comparisons of APEX estimated ratios of indoor microenvironmental $PM_{2.5}$ concentration to simultaneous nearby outdoor microenvironmental $PM_{2.5}$ concentration obtained from ECP measurements

Indoor microenvironment		Outdoor ME	Indoor-to-Outdoor $PM_{2.5}$ ratio						
			ECP measurements				APEX		
	Description		*N*[a]	Min	Med	Max	Min	Med	Max
1	Residence	Other	3	0.29	0.33	0.89	0.04	0.60	7.37
		Near-road	1	–	0.37	–	–	–	–
2	Community Center or auditorium	Other	4	0.16	0.37	0.61	0.07	0.69	4.57
		Near-road	8	0.13	0.36	0.67	–	–	–
3	Restaurant	Other	12	0.30	0.98	34.25	0.39	0.87	6.97
		Near-road	10	0.33	1.00	15.36	–	–	–
4	Hotel/motel	Other	1	–	0.80	–	0.04	0.68	4.71
		Near-road	3	0.16	0.70	1.78	–	–	–
5	Office building, bank, post office	Other	7	0.10	0.28	0.50	0.04	0.68	7.34
		Near-road	11	0.13	0.24	0.78	–	–	–
7	School	Other	5	0.13	0.41	0.53	0.04	0.58	7.41
		Near-road	2	0.10	3.01	5.91	–	–	–
8	Shopping mall, non-grocery store	Other	5	0.08	0.55	2.00	0.03	0.68	6.59
		Near-road	5	0.10	0.34	0.57	–	–	–
9	Grocery store, convenience store	Other	3	0.51	0.56	1.31	0.04	0.69	6.84
		Near-road	7	0.48	2.11	12.43	–	–	–
All	All indoors[b]	Other	26	0.08	0.55	24.14	0.03	0.76	7.41
		Near-road	30	0.10	0.52	15.36	–	–	–

Notes: The "all indoors ME" value for a particular test group may combine (average) pollutant values from two or more indoor MEs that were measured at about the same time. So the "all" *N* value may be less than the sum of the *N* values for individual MEs.

[a]*N* is the number of ratios of measured values. The APEX statistics are based on >1000 simulated values.

[b]The values in the "all indoors" rows are not expected to be consistent with the numbers above.

9. Ratios of microenvironmental concentrations to fixed-site concentrations

9.1. Ozone

Table 6 provides minimum, median, and maximum microenvironment-to-monitor ratios based on ECP O_3 data and estimates obtained from the APEX runs for each of the 24 APEX microenvironments.

General patterns in the O_3 results can be identified by examining the median ratios for the four general microenvironments for the two study periods combined (see the code = "All" listings in Table 6). In the indoor microenvironments, the median ECP ratio (0.29) is 20 percent smaller than the APEX ratio (0.36), although 5 of the 9 indoor microenvironments have ECP median ratios higher than the APEX median ratios. The ECP and APEX median ratios for the other outdoor microenvironments are quite close, however, the ECP measurements have a much wider range than APEX. ECP ratios also have a wider range than APEX for the near-road outdoor microenvironments, while the median ECP ratio (0.84) is 14 percent higher than the APEX ratio (0.74). The ECP and APEX median ratios differ the most for the in-vehicle microenvironment. In this case, the ECP median ratio (0.46) is approximately 30 percent lower than the APEX median ratio (0.63). The direction of this difference is unexpected due to the fact that the ECP vehicles were operated under high ventilation conditions during the tests, whereas APEX models a variety of ventilation conditions.

For three of the general microenvironments (Outdoors-near road, Outdoors-other, and in-Vehicle), there is little or no variation in the median APEX ratios listed for the individual microenvironments (Table 6). This finding is the result of the method currently employed by APEX to estimate O_3 concentrations in these microenvironments. In each case, the microenvironmental O_3 concentration is estimated as a linear function (with variability) of the O_3 concentration at a nearby fixed-site monitor, and these functions do not vary substantially among the individual microenvironments.

Additional differences between the ECP and APEX ratios can be observed in Table 7. This table provides descriptive statistics that characterize the distributions of the ECP and APEX ME-to-monitor ratios. To provide adequate sample size for calculating the ECP statistics, the tables are limited to the four general microenvironments used in previous analyses (Indoors, Outdoors-near road, Outdoors-other, and in-Vehicle).

General patterns observed in the ECP and APEX ratios in Table 7 and the corresponding Figure 2 for each of the four general microenvironments are as follows:

(1) *Indoors*: The ECP values tend to be roughly equal to the APEX values for the 5th through 75th percentiles. The 90th and 95th percentile ECP values are significantly larger than the corresponding APEX values. However, the ECP values for these high percentiles are based on relatively small sample sizes.

(2) *Outdoors-near road*: The median (50th percentile) ECP ratio (0.84) is larger than the median APEX value (0.74). The ECP values also exhibit a larger variance than the APEX values. ECP values for percentiles below the median are equal to or less than the corresponding APEX values. ECP values for percentiles above the median are larger than the corresponding APEX values.

(3) *Outdoors-other*: The APEX values vary over a narrow range from 0.90 to 1.10. This results from the distribution of proximity factors, which ranges from 0.90 to 1.10. The median APEX value (1.00) is comparable to the median percentile value listed for the ECP values (0.98). However, the ECP ratio values exhibit a much wider range than the APEX ratios, with a 10th percentile value of 0.60 and a 90th percentile value of 1.60.

(4) *in-Vehicle*: The median ECP ratio is 0.46; the median APEX ratio is 0.63. Up to the 75th percentile, ECP values are always lower than the corresponding APEX values. ECP ratios values exceed the corresponding APEX ratio values for higher percentiles.

Table 6. Comparison of APEX estimated ratios of microenvironmental O_3 concentrations to simultaneous fixed-site O_3 concentrations obtained from ECP measurements

Microenvironment		Microenvironment-to-monitor O_3 ratios						
		ECP measurements			APEX estimates			
Code	**Description**	***N*[a]**	**Min**	**Med**	**Max**	**Min**	**Med**	**Max**
Indoors								
1	Residence	3	0.08	0.26	1.55	0.01	0.23	2.74
2	Community Center or auditorium	6	0.12	0.19	0.57	0.02	0.29	0.90
3	Restaurant	15	0.05	0.26	10.00	0.16	0.58	1.81
4	Hotel/motel	2	0.24	0.28	0.33	0.01	0.30	1.80
5	Office building, bank, post office	8	0.15	0.55	1.65	0.01	0.29	1.88
7	School	8	0.13	0.31	0.84	0.01	0.22	1.85
8	Shopping mall, non-grocery store	5	0.07	0.20	0.37	0.01	0.29	1.41
9	Grocery store, convenience store	7	0.14	0.33	0.51	0.01	0.30	1.91
10	Metro–sub-way–train	2	0.86	0.90	0.93	0.03	0.27	0.92
All	All indoors	56	0.05	0.29	10.00	0.01	0.36	2.74
Outdoors-Other								
12	Residential grounds	4	0.85	0.97	1.10	0.90	1.00	1.10
13	General–non-residential	16	0.36	0.91	2.06	0.90	1.00	1.10
14	Park or golf course	17	0.47	0.98	1.53	0.90	1.00	1.10
15	Restaurant or café	15	0.55	1.00	3.40	0.90	1.00	1.10
16	School grounds	11	0.50	1.02	2.82	0.90	1.00	1.10
All	All outdoors—other	63	0.36	0.98	3.40	0.90	1.00	1.10
Outdoors-Near road								
17	Metro–sub-way–train stop	15	0.33	0.81	1.12	0.42	0.73	1.00
18	Within 10 yards of street	28	0.14	0.73	6.40	0.42	0.74	1.00
19	Parking garage	10	0.18	0.58	1.14	0.42	0.72	1.00
20	Parking lot (open), street parking	36	0.20	0.92	6.10	0.42	0.74	1.00
21	Service station	7	0.55	0.98	2.03	0.42	0.73	1.00
All	All outdoors-near road	96	0.14	0.84	6.40	0.42	0.74	1.00
Vehicle								
22	Car	57	0.11	0.46	1.90	0.09	0.63	1.00
All	All vehicle	57	0.11	0.46	1.90	0.09	0.63	1.00

[a]Number of ratios.

9.2. Carbon monoxide

Tables 8 and 9 provide statistics for microenvironment-to-monitor CO ratios that follow the table formats used by Tables 6 and 7. Table 8 provides minimum, median, and maximum microenvironment-to-monitor ratios based on ECP CO data and on estimates obtained from the APEX CO runs for each of the 24 APEX microenvironments. General patterns in the CO results can be identified by examining the median ratios for the four general microenvironments for the two study periods combined (see Table 8). The ECP medians are consistently higher than the corresponding APEX median ratios (which tend to be near 1.0).

The APEX medians listed for individual microenvironments in Table 8 for the general indoor microenvironment are all slightly larger than 1.0. This pattern is due to the frequency with which ambient CO concentrations rapidly decrease at certain times of the day. If this happens when the indoor ventilation rate is low (e.g. when windows are closed), the outdoor concentration falls more rapidly than the indoor concentration, resulting in an indoor/outdoor concentration ratio less than 1. When the ambient CO concentrations fall to very small values, this ratio can be relatively large, even exceeding 500 (see Table 9).

If we focus on the median ECP ratios in Table 8, we see values above 1.7 for individual microenvironments #3: restaurant (ratio = 2.50), #8: shopping mall or non-grocery store (1.79), #9: grocery store or convenience store (1.88), #16: school grounds (2.00), #18: within 10 yards of street (2.10), #22: car (1.91), and #23: bus (2.18). Some of these microenvironments would be expected to contain CO sources associated with gas stoves (e.g. restaurant) or motor vehicles (e.g. within 10 yards of street, car and bus).

Median ratio values below 1.2 are associated with #1: residence (1.09), #2: community center or auditorium (1.08), #5: office building, bank, or post office (1.00), #7: school (1.06), #12: residential grounds (0.28), #14: park or golf course (1.14), #15: outside restaurant or café (1.14), and #24: train (0.94). Note that some of these ratios are based on a small sample size ($n < 5$) (microenvironment #s 1,12, and 23).

Table 7. Comparisons of descriptive statistics for ratios of microenvironmental O_3 concentrations to simultaneous fixed-site O_3 concentrations obtained from ECP measurements and APEX estimates—grouped microenvironments

Statistic	Microenvironment-to-monitor O_3 ratio							
	Indoors		Outdoors-Other		Outdoors-Near road		Vehicle	
	ECP	APEX	ECP	APEX	ECP	APEX	ECP	APEX
Number of values	56	>1000	63	>1000	96	>1000	57	>1000
Mean	0.58	0.39	1.09	1.00	1.05	0.73	0.57	0.62
SD	1.33	0.24	0.50	0.05	0.99	0.15	0.39	0.22
Minimum	0.05	0.01	0.36	0.90	0.14	0.42	0.11	0.09
5th pct	0.08	0.07	0.50	0.92	0.26	0.48	0.13	0.24
10th pct	0.12	0.10	0.60	0.93	0.34	0.52	0.20	0.32
25th pct	0.19	0.19	0.83	0.96	0.62	0.62	0.32	0.46
50th pct	0.29	0.36	0.98	1.00	0.84	0.74	0.46	0.63
75th pct	0.56	0.56	1.30	1.04	1.10	0.85	0.64	0.80
90th pct	0.97	0.69	1.59	1.07	1.86	0.93	1.17	0.91
95th pct	1.56	0.76	1.99	1.08	2.67	0.96	1.47	0.95
Maximum	10.00	2.74	3.40	1.10	6.40	1.00	1.90	1.00

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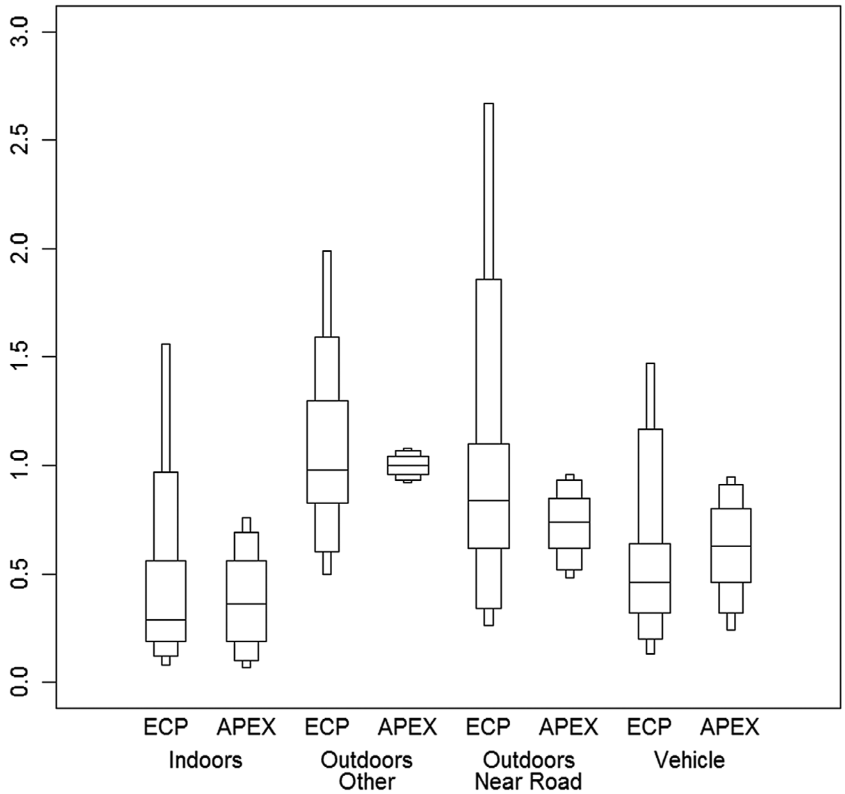
Figure 2. Microenvironment-to-monitor O_3 ratios.



Thickest bars indicate the 25th, 50th, and 75th percentiles. Secondary bars extend to the 10th and 90th percentiles. Tertiary bars extend to the 5th and 95th percentiles.

Table 8. Comparison of ratios of microenvironmental CO concentrations to simultaneous fixed-site CO concentrations obtained from ECP measurements and APEX estimates

Microenvironment		Microenvironment-to-monitor CO ratios						
		ECP measurements			APEX estimates			
Code	Description	N[a]	Min	Med	Max	Min	Med	Max
Indoors								
1	Residence	2	0.92	1.09	1.25	0.07	1.01	389
2	Community Center or auditorium	5	0.67	1.08	1.38	0.36	1.08	339
3	Restaurant	16	0.63	2.50	35.7	0.39	1.02	97
4	Hotel/motel	6	0.71	1.50	2.18	0.16	0.98	329
5	Office building, bank, post office	9	0.33	1.00	2.33	0.06	1.07	511
6	Bar, night club, cafe	8	0.44	1.24	4.78	0.53	1.00	53
7	School	10	0.44	1.06	1.63	0.09	1.10	349
8	Shopping mall, non-grocery store	20	0.57	1.79	5.00	0.06	1.07	419

(*Continued*)

Table 8. (*Continued*)

Microenvironment		Microenvironment-to-monitor CO ratios						
		ECP measurements				APEX estimates		
Code	**Description**	**N[a]**	**Min**	**Med**	**Max**	**Min**	**Med**	**Max**
9	Grocery store, convenience store	9	0.33	1.88	6.29	0.08	1.06	414
10	Metro–sub-way–train	16	0.29	1.46	24.2	0.33	1.04	72
11	Hospital, medical care facility	6	0.83	1.32	4.75	0.07	1.07	331
All	All indoors	107	0.29	1.36	35.7	0.06	1.04	511
Outdoors-Other								
12	Residential grounds	4	0.00	0.28	1.32	0.80	1.00	1.20
13	General–non-residential	15	0.43	1.40	2.50	0.80	1.00	1.20
14	Park or golf course	19	0.20	1.14	12.0	0.80	1.00	1.20
15	Restaurant or café	14	0.22	1.14	5.67	0.80	1.00	1.20
16	School grounds	11	0.25	2.00	18.1	0.80	1.00	1.20
All	All outdoors-other	63	0.00	1.33	18.1	0.80	1.00	1.20
Outdoors-Near road								
17	Metro–sub-way–train stop	23	0.35	1.27	4.75	0.80	1.00	1.20
18	Within 10 yards of street	28	0.29	2.10	5.60	0.80	1.00	1.20
19	Parking garage	10	0.00	1.52	37.4	0.80	1.00	1.20
20	Parking lot (open), street parking	36	0.25	1.40	6.00	0.80	1.00	1.20
21	Service station	6	0.86	1.60	4.00	0.80	1.00	1.20
All	All outdoors-near road	103	0.00	1.60	37.4	0.80	1.00	1.20
Vehicle								
22	Car	57	0.17	1.91	6.67	0.80	1.00	1.20
23	Bus	1	–	2.18	–	0.80	1.00	1.20
24	Train	6	0.71	0.94	5.18	0.80	1.00	1.20
All	All vehicle	64	0.17	1.79	6.67	0.80	1.00	1.20

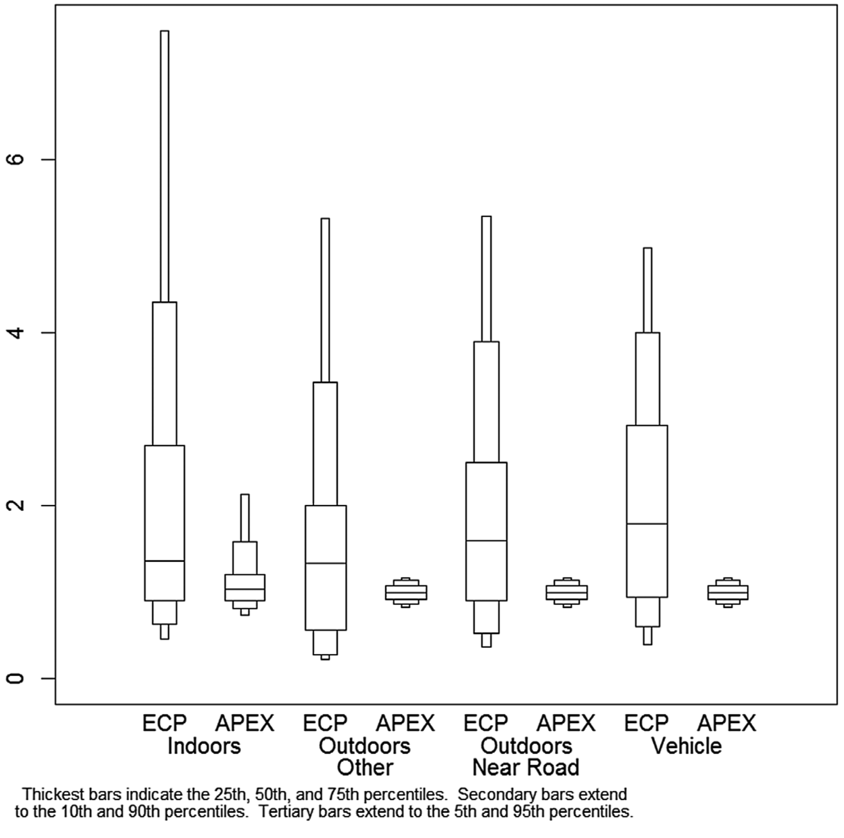
[a]Number of ratios.

Table 9 and the corresponding Figure 3 provide descriptive statistics that characterize the distributions of the ECP and APEX microenvironment-to-monitor ratios by general microenvironment. For the indoors microenvironment, the ECP value is higher than the APEX values for the 50th through 95th percentiles. The high APEX standard deviation is the result of a few very high values (explained above). Approximately 0.9% of the APEX indoor/monitor ratios are > 35. For the outdoors-other and outdoors-near road microenvironments, the ECP value exceeds the APEX value for the 50th through

Table 9. Comparisons of descriptive statistics for ratios of microenvironmental CO concentrations to simultaneous fixed-site CO concentrations obtained from ECP measurements and APEX estimates—grouped microenvironments

Statistic	Microenvironment-to-monitor CO ratio							
	Indoors		Outdoors-Other		Outdoors-Near road		Vehicle	
	ECP	APEX	ECP	APEX	ECP	APEX	ECP	APEX
Number of values	107	>1000	63	>1000	103	>1000	64	>1000
Mean	2.54	3.14	1.90	1.00	2.21	1.00	2.05	1.00
SD	4.29	23.28	2.70	0.10	3.73	0.10	1.38	0.10
Minimum	0.29	0.06	0.00	0.80	0.00	0.80	0.17	0.80
5th pct	0.46	0.74	0.23	0.83	0.37	0.83	0.39	0.83
10th pct	0.63	0.81	0.28	0.86	0.52	0.86	0.60	0.86
25th pct	0.91	0.91	0.57	0.92	0.91	0.92	0.94	0.92
50th pct	1.36	1.04	1.33	1.00	1.60	1.00	1.79	1.00
75th pct	2.70	1.20	2.00	1.08	2.50	1.08	2.93	1.08
90th pct	4.36	1.58	3.43	1.14	3.90	1.14	4.00	1.14
95th pct	7.51	2.13	5.33	1.17	5.35	1.17	4.98	1.17
Maximum	35.7	510	18.13	1.20	37.40	1.20	6.67	1.20

Figure 3. Microenvironment-to-monitor CO ratios.



95th percentiles. For the in-vehicle general microenvironment, the ECP value is larger than the APEX value for the 25th through 95th percentiles. The APEX distributions for the outdoors-other, outdoors-near road, and vehicle microenvironments are the same as a result of having the same distributions of proximity factors.

9.3. $PM_{2.5}$

Tables 10 and 11 provide statistics for microenvironment-to-monitor $PM_{2.5}$ that follow the table formats used by Tables 6 and 7. These values are consistent with expectations; they show generally lower ratios for indoor microenvironments and higher ratios for the vehicle and outdoors-near road microenvironments.

Table 10 provides minimum, median, and maximum microenvironment-to-monitor ratios based on ECP $PM_{2.5}$ data and estimates obtained from the APEX $PM_{2.5}$ runs for each of the 24 APEX microenvironments. Reviewing the results for the four general microenvironments, we see that the ECP median ratio of 1.19 for the general indoor microenvironment is almost double the median APEX ratio for this microenvironment (0.73). A value less than 1 would be expected for the APEX median ratio since APEX currently accounts for indoor particle deposition (which lowers the ratio) but not for indoor $PM_{2.5}$ sources (which increases the ratio). The median APEX ratio is 1.0 for each of the individual microenvironments in the outdoors-other, outdoors-near road, and vehicle general microenvironments. In each of these cases, APEX currently models the microenvironment using a proximity factor with mean = 1.

Focusing on the median ECP ratios in Table 10, we see values above 1.50 for individual microenvironments #3: restaurant (1.93), #6: bar, night club, or café (1.52), #9: grocery store or convenience store (2.33), #10: inside metro, subway, or train (1.58), #14: park or golf course (1.80), #15: outdoor restaurant or café (1.95), #16: school grounds (2.10), #17: outdoor metro, subway, or train stop (1.61), #18: within 10 yards of street (1.71), #20: open parking lot or street parking (1.68), #22: car (1.96), and #23: bus (1.62). Median ratio values below 1.00 are associated with #1: residence (0.51), #2: community center or auditorium (0.70), #5: office building, bank, or post office (0.33), #7: school (0.70), #8: shopping mall or non-grocery store (0.91), and #11: hospital or medical care facility (0.84). Note again that some of these ratios (microenvironment #s 1, 12, and 23) are based on small samples ($n < 5$).

Table 11 and the corresponding Figure 4 provide descriptive statistics that characterize the distributions of the ECP and APEX microenvironment-to-monitor ratios by general microenvironment. Listed below are general patterns that can be observed for each of the four general microenvironments. The APEX distributions for the outdoors-other, outdoors-near road, and vehicle microenvironments are the same as a result of having the same distributions of proximity factors.

(1) *Indoors*: The ECP values tend to be larger than the corresponding APEX values with the difference increasing toward the higher percentiles. The median ratios are 1.19 for ECP and 0.73 for APEX.

(2) *Outdoors-other*: The median ECP ratio (1.500) is larger than the median APEX value (1.00). The APEX ratios vary over a narrow range from 0.90 to 1.10. The ECP ratios exhibit a much larger variability, with a 10th percentile value of 0.75 and a 90th percentile value of 3.64.

(3) *Outdoors-near road*: The median ECP ratio (1.61) is larger than the APEX ratio (1.00). The APEX ratios values vary over the same narrow range as the outdoors-other ratios with the same percentile values. The ECP ratios exhibit a much larger variability, with a 10th percentile value of 0.88 and a 90th percentile value of 3.67.

Table 10. Comparison of ratios of microenvironmental $PM_{2.5}$ concentrations to simultaneous fixed-site $PM_{2.5}$ concentrations obtained from ECP measurements and APEX estimates

Microenvironment		Microenvironment-to-monitor $PM_{2.5}$ ratios						
		ECP measurements			APEX estimates			
Code	**Description**	**N[a]**	**Min**	**Med**	**Max**	**Min**	**Med**	**Max**
Indoors								
1	Residence	2	0.43	0.51	0.58	0.04	0.60	7.74
2	Community Center or auditorium	5	0.33	0.70	0.84	0.08	0.68	4.81
3	Restaurant	14	0.97	1.93	31.17	0.38	0.87	7.03
4	Hotel/motel	6	0.33	1.08	3.92	0.04	0.68	5.03
5	Office building, bank, post office	9	0.27	0.33	1.12	0.03	0.68	7.89
6	Bar, night club, cafe	7	1.11	1.52	2.92	0.45	0.86	2.33
7	School	10	0.09	0.70	12.36	0.04	0.58	7.96
8	Shopping mall, non-grocery store	17	0.13	0.91	2.22	0.03	0.68	6.90
9	Grocery store, convenience store	9	0.83	2.33	6.00	0.04	0.68	7.16
10	Metro–sub-way–train	14	0.70	1.58	4.40	0.08	0.62	2.81
11	Hospital, medical care facility	6	0.44	0.84	1.34	0.04	0.67	7.34
All	All indoors	99	0.09	1.19	31.17	0.03	0.73	7.96
Outdoors-Other								
12	Residential grounds	3	1.14	1.28	1.61	0.90	1.00	1.10
13	General–non-residential	15	0.55	1.32	2.04	0.90	1.00	1.10
14	Park or golf course	18	0.46	1.80	8.00	0.90	1.00	1.10
15	Restaurant or café	12	0.96	1.95	18.00	0.90	1.00	1.10
16	School grounds	9	0.58	2.10	4.23	0.90	1.00	1.10
All	All outdoors-other	57	0.46	1.50	18.00	0.90	1.00	1.10
Outdoors-Near road								
17	Metro–sub-way–train stop	22	0.41	1.61	5.40	0.90	1.00	1.10
18	Within 10 yards of street	24	0.41	1.71	4.60	0.90	1.00	1.10
19	Parking garage	10	0.80	1.11	4.00	0.90	1.00	1.10
20	Parking lot (open), street parking	30	0.34	1.68	6.67	0.90	1.00	1.10

(*Continued*)

Table 10. (*Continued*)

Microenvironment		Microenvironment-to-monitor $PM_{2.5}$ ratios						
		ECP measurements				APEX estimates		
Code	Description	N[a]	Min	Med	Max	Min	Med	Max
21	Service station	6	0.73	1.21	1.60	0.90	1.00	1.10
All	All outdoors-near road	92	0.34	1.61	6.67	0.90	1.00	1.10
Vehicle								
22	Car	45	0.46	1.96	13.10	0.90	1.00	1.10
23	Bus	1	–	1.62	–	0.90	1.00	1.10
24	Train	6	0.70	1.17	1.40	0.90	1.00	1.10
All	All vehicle	52	0.46	1.64	13.10	0.90	1.00	1.10

[a]Number of ratios.

Table 11. Comparisons of descriptive statistics for ratios of microenvironmental $PM_{2.5}$ concentrations to simultaneous fixed-site $PM_{2.5}$ concentrations obtained from ECP measurements and APEX estimates—grouped microenvironments

Statistic	Microenvironment-to-monitor $PM_{2.5}$ ratio							
	Indoors		Outdoors-Other		Outdoors-Near road		Vehicle	
	ECP	APEX	ECP	APEX	ECP	APEX	ECP	APEX
Number of values	99	>1000	57	>1000	92	>1000	52	>1000
Mean	2.23	0.73	2.16	1.00	1.98	1.00	2.61	1.00
SD	4.27	0.50	2.47	0.05	1.23	0.05	2.66	0.05
Minimum	0.09	0.03	0.46	0.90	0.35	0.90	0.46	0.90
5th pct	0.28	0.24	0.58	0.92	0.72	0.92	0.58	0.92
10th pct	0.34	0.33	0.75	0.93	0.88	0.93	0.73	0.93
25th pct	0.77	0.51	1.17	0.96	1.12	0.96	1.26	0.96
50th pct	1.19	0.73	1.50	1.00	1.61	1.00	1.64	1.00
75th pct	1.91	0.88	2.23	1.04	2.41	1.04	2.79	1.04
90th pct	3.82	1.01	3.64	1.07	3.67	1.07	6.10	1.07
95th pct	9.62	1.12	4.76	1.08	4.28	1.08	10.7	1.08
Maximum	31.2	7.96	18.0	1.10	6.67	1.10	13.1	1.10

(4) *in-Vehicle*: These statistics exhibit patterns similar to those observed in the statistics for outdoors-other and outdoors-near road. The median ECP ratio is 1.64; the median APEX ration is 1.00. The APEX ratios values vary over the same narrow range as the outdoor ratios with the same percentile values. The ECP ratios exhibit a much larger variability, with a 10th percentile value of 0.73 and a 90th percentile value of 6.09.

https://doi.org/10.1080/23311843.2018.1453022

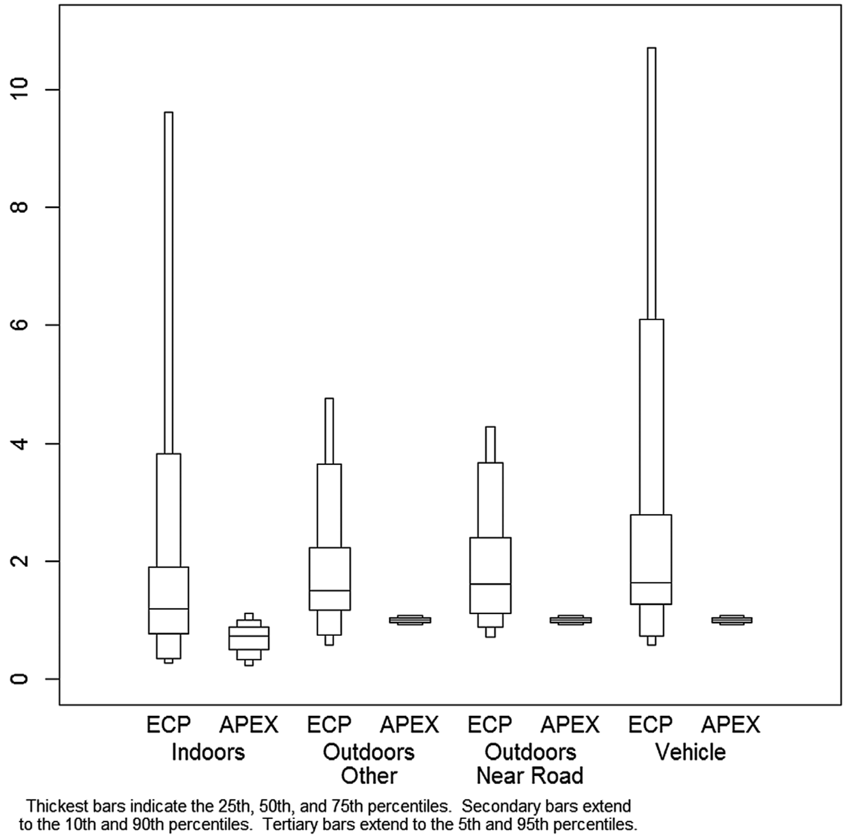


Figure 4. Microenvironment-to-monitor $PM_{2.5}$ ratios.

10. Discussion

Exposure assessment using exposure models is continually evolving and is of growing importance and complexity within the criteria pollutant NAAQS reviews performed by EPA. There has been growing recognition that people are differentially exposed to outdoor ambient pollution concentrations depending on where they are and what they are doing. To better estimate health risks there is a need for an improved methodology for estimating these differential exposures. The evaluation of APEX presented here will guide further model development and is consistent with the advice to EPA from stakeholders and scientific advisory committees that calls for more extensive evaluation of exposure models that inform regulatory decisions.

Personal exposures are a time-weighted average of microenvironment concentrations, weighted by the time spent in each microenvironment, and modeled personal exposures depend on both the microenvironment concentrations and the activities of individuals. APEX estimates concentrations outside a microenvironment by applying a stochastic proximity factor to concentrations measured at a fixed-site monitor, and for O_3 also adjusting for titration by NO near roadways. The concentrations inside a microenvironment are estimated by APEX using either (1) a compartmental mass-balance model based on air exchange and deposition/decay rates for indoor microenvironments or (2) a regression factors model for in-vehicle microenvironments. In applications of APEX, analysts tend to focus on the simulated distributions of microenvironmental concentrations and associated exposure estimates rather than the exposures estimated for specific individuals at specific times. For these reasons, we have compared the distributions of ECP-measured and APEX-estimated concentrations, indoor/outdoor ratios, and indoor/fixed-site ratios for microenvironments typical of those defined in recent EPA risk assessments for O_3 and CO.

The ratios of microenvironment concentrations to the fixed-site measurements, sometimes referred to as exposure factors, were examined. APEX underestimated the median O_3 microenvironment/fixed-site ratios for the near-road microenvironment and underestimated the ratios greater than one for all four of the microenvironment groups (Table 2 defines the groups). For CO, APEX underestimated the median ratio for all four groups. With the exception of a few very high ratios for indoor microenvironments predicted by APEX, APEX underestimated the ratios at the percentiles above the medians for all four of the microenvironment groups. For $PM_{2.5}$, APEX underestimated the median ratios and the 75th and higher percentiles by a factor of two or more for all four of the microenvironment groups. The systematic underestimation of the microenvironment/fixed-site ratios is mostly driven by ambient concentrations that were higher at locations where the ECP measurements were made than at the locations of the fixed-site monitors. For O_3 at the near-road and in-vehicle microenvironments, the APEX ratios are lowered further by the proximity factors, which are intended to account for titration of O_3 by NO.

The lack of spatial resolution of the ambient (fixed monitor-based) concentrations (Figure 1) contributes to the uncertainties of the APEX predictions. Non-representativeness of the APEX distributions of mass-balance and factor model parameters and the proximity factors also lead to differences between the ECP and APEX results. One aspect of these comparisons that stands out is the significantly higher variability of the ECP outdoor-to-monitor ratios than the comparable APEX ratios (see Figures 2–4). This indicates that the distribution of proximity factors is too narrow for all three pollutants. This implies that the variability of estimated exposures is significantly underestimated in this application.

The uncertainty of the mass-balance model and its parameters can be measured by comparing the modeled and measured ratios of indoor concentrations to outdoor concentrations, where the outdoor concentrations are modeled or measured just outside the indoor microenvironment (not at the fixed-site monitor). The concentrations of O_3, CO, and $PM_{2.5}$ in indoor microenvironments were modeled in APEX using a mass-balance model, where the AERs and decay rates are the critical parameters for determining how much outdoor air goes indoors and how long it remains indoors. APEX was set up to estimate concentrations outside the microenvironments by applying a stochastic proximity factor to concentrations measured at a fixed-site monitor, which includes adjustments for titration of O_3 by NO on and near roadways. The ratio of the indoor concentrations to the concentrations outside the microenvironment is a measure that is approximately independent of the levels of the concentrations and independent of proximity factors; consequently this ratio is a good measure for evaluating the mass-balance model and the parameters driving it.

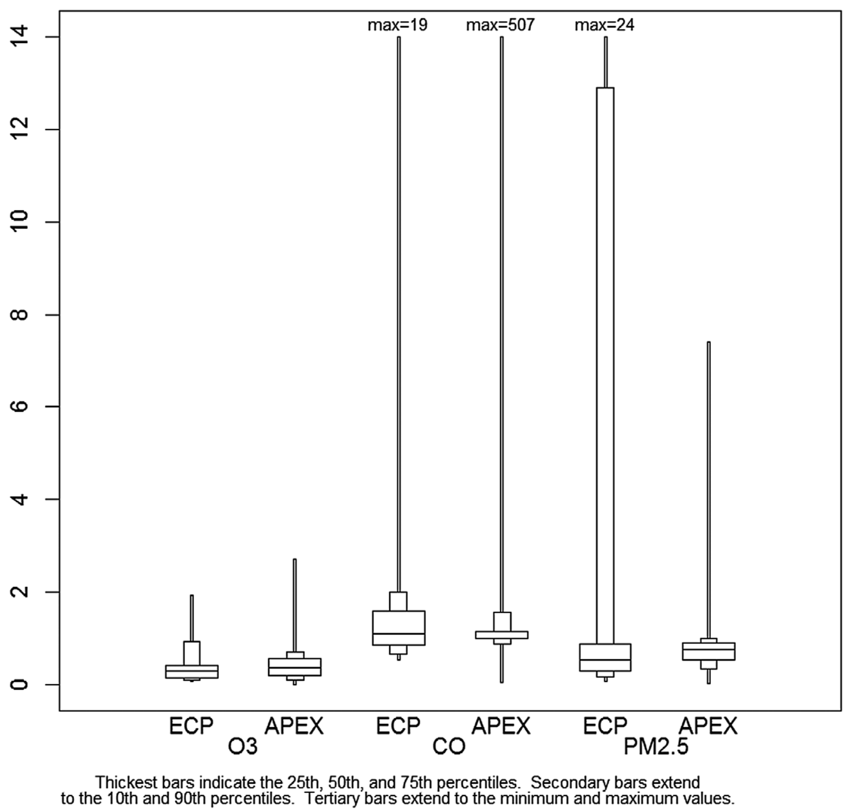
11. Results and conclusions

In general, except for the smallest ratios and the highest ratios for CO and $PM_{2.5}$, the indoor/outdoor ratios predicted by APEX are within a factor of two of the measured ratios over most of the ranges of the ratios for all three pollutants. The distributions of the indoor/outdoor ratios for O_3 reflected in the ECP measurements compare fairly well with the APEX predictions, with the APEX median (0.38) slightly higher than the measured median (0.30) and the range of the APEX predictions (0.01–2.71) somewhat wider than the range of the measurement data-set ratios (0.07–1.94) (Table 12, Figure 5). For CO, the medians of the ECP and APEX ratios are quite close, while the range of the APEX ratios is much wider than the ECP ratios. The very high APEX ratios for CO result from conditions when the indoor microenvironment is not well ventilated and the outdoor concentrations rapidly decrease to values close to zero while the indoor concentrations decrease more slowly. This tends to happen in the evening in residences with low AERs. ECP sampled four residences, between 8 am and 8 pm, and did not observe this phenomenon. For $PM_{2.5}$, APEX is overestimating in the central range of the distribution and underestimating the highest ratios, which in the ECP samples could be due to pollutant emissions from indoor sources or positive interference pollutant measurement bias, influential attributes not controlled for in that study or modeled by APEX. One finding of particular interest is that the variability of estimated exposures is significantly underestimated compared with fixed-site monitors in this application (Figures 2–4). For the grouped microenvironments (Tables 7, 9 and 11),

Table 12. Comparison of distributions of indoor/outdoor ratios: ECP measurements and APEX predictions

	O_3		CO		$PM_{2.5}$	
Statistic	**ECP**	**APEX**	**ECP**	**APEX**	**ECP**	**APEX**
Number of values	25	>1000	25	>1000	26	>1000
Minimum	0.07	0.01	0.55	0.05	0.08	0.03
10th pctile	0.10	0.10	0.67	0.89	0.17	0.34
25th pctile	0.16	0.20	0.87	1.00	0.29	0.54
Median	0.30	0.38	1.10	1.01	0.55	0.76
75th pctile	0.43	0.57	1.60	1.16	0.88	0.90
90th pctile	0.92	0.70	2.00	1.56	12.9	1.00
Maximum	1.94	2.71	19.0	507	24.1	7.41

Figure 5. Comparison of distributions of indoor/outdoor ratios: ECP measurements and APEX predictions.



APEX always underestimates the top 50% of the distributions of ratios to fixed-site monitors, except for O_3 in vehicles, where APEX underestimates the top 10% of the distribution.

The results of this evaluation should be interpreted keeping in mind certain limitations of this study. One geographic area (Los Angeles) was studied, and the relationships between microenvironments and fixed site monitors are unlikely to be representative of a range of geographic areas. The measurements were all made during the day (when people typically experience higher exposures); nighttime microenvironment concentrations are not included in the results. Indoor sources of O_3, CO, and $PM_{2.5}$ were not simulated in APEX, nor were sources of interferences to their measurement methods, whereas some of the microenvironments sampled by ECP may have had concentrations influenced by indoor source emissions. Limited availability of hourly $PM_{2.5}$ fixed-site measurements increased the uncertainties of the APEX microenvironment concentrations. The results of this evaluation will be a useful input to quantitative uncertainty assessments of APEX, and can provide direction in model improvements.

Supplementary material
Supplementary material for this article can be accessed https://doi.org/10.1080/23311843.2018.1453022.

Funding
This work was supported by the US Environmental Protection Agency [contract EP-D-08-100].

Competing interests
The authors declare no competing interest.

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Citation information
Cite this article as: A multipollutant evaluation of APEX using microenvironmental ozone, carbon monoxide, and particulate matter ($PM_{2.5}$) concentrations measured in Los Angeles by the exposure classification project, Ted R. Johnson, John E. Langstaff, Stephen Graham, Eric M. Fujita & David E. Campbell, *Cogent Environmental Science* (2018), 4: 1453022.

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