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Evaluation of the Modeling of Exposure to Environmental Tobacco Smoke (ETS) in the SHEDS-PM Model

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ABSTRACT

Environmental tobacco smoke (ETS) is estimated to be a major contributor to indoor PM concentration and human exposures to fine particulate matter of 2.5 microns or smaller ($PM_{2.5}$). The Stochastic Human Exposure and Dose Simulation for Particulate Matter (SHEDS-PM) model developed by the US Environmental Protection Agency estimates distributions of outdoor and indoor $PM_{2.5}$ exposure for a specified population based on ambient concentrations and indoor emissions sources. Because indoor exposures to ETS can be high, especially in indoor residential microenvironments, a critical assessment was conducted of the methodology and data used in SHEDS-PM for estimation of indoor exposure to ETS. For the residential microenvironment, SHEDS uses a mass-balance approach which is comparable to best practices. The default inputs in SHEDS-PM were reviewed and more recent and extensive data sources were identified. Sensitivity analysis was used to determine which inputs should be prioritized for updating. Data regarding the cigarette emission rate was found to be the most important. SHEDS-PM does not currently account for in-vehicle ETS exposure; however, in-vehicle ETS-related $PM_{2.5}$ levels can exceed those in residential microenvironments by a factor of 10 or more. Therefore, a mass-balance based methodology for estimating in-vehicle ETS $PM_{2.5}$ concentration is evaluated. Recommendations are made regarding updating of input data and algorithms related to ETS exposure in the SHEDS-PM model.

INTRODUCTION

There is ongoing research to identify associations between human exposure to $PM_{2.5}$ and adverse health effects. Epidemiological studies of health effects associated with $PM_{2.5}$ are typically based on using ambient concentration as a surrogate for human exposures.[1-3] However, most people spend the vast majority of their time indoors. Hence, there is growing reorganization of the need to attempt to quantify human exposure to $PM_{2.5}$ as an alternative basis for characterizing associated health effects.[4]

Indoor $PM_{2.5}$ concentrations are influenced by penetration of ambient $PM_{2.5}$ and by indoor sources of $PM_{2.5}$ such as cooking and smoking.[5-10] Since environmental tobacco smoke (ETS) is

a key component of indoor $PM_{2.5}$, it is necessary to account for the contribution of smoking to indoor $PM_{2.5}$ when estimating total exposures to $PM_{2.5}$ each day for each individual. This paper focuses on evaluating the data and methods used to simulate human exposure to ETS in selected indoor microenvironments.

ETS, also referred to second-hand smoke, includes sidestream smoke and mainstream smoke. Sidestream smoke is given off by the burning end of a tobacco product. Mainstream smoke is exhaled by the smoker. Smoking is associated with a significantly increased risk of heart disease, stroke, lung and chronic lung diseases.[11-13]

A scenario-based inhalation exposure simulation model is intended to estimate exposures to simulated individuals by estimating the movement of such individuals through a series of microenvironments, each with its own air pollutant concentrations.[14] A microenvironment is a physical compartment or defined space with relatively homogeneous or well characterizes air pollution concentrations.[15] "Home," "restaurant," "office," "in vehicle" and "outdoor" are examples of microenvironments. The exposure of an individual during a day is based on the time-weighted concentration from the microenvironments in which the individual spent time. Here, several examples of scenario-based exposure simulation models are identified and briefly discussed. An example of a scenario based simulation model is the Stochastic Human Exposure and Dose Simulation model for $PM_{2.5}$ (SHEDS-PM).

The Stochastic Human Exposure and Dose Simulation model for Particulate Matter (SHEDS-PM) was developed by US EPA's National Exposure Research Laboratory (NERL).[16] The objective of SHEDS-PM is to predict individual and population exposures to $PM_{2.5}$.

SHEDS-PM uses a probabilistic approach to estimate distributions of outdoor and indoor $PM_{2.5}$ exposure for a population of simulated individuals based on ambient $PM_{2.5}$ concentrations and sources of indoor $PM_{2.5}$ emissions.[16, 17]

Currently, SHEDS accounts for ETS exposure only for three microenvironments: home, restaurant, and bar. For the home microenvironment, the ETS contribution to indoor $PM_{2.5}$ concentration is estimated based on a mass balance approach, taking into account the presence of a smoker, the cigarette emission rate, and the number of cigarettes smoked. For the restaurant and bar microenvironments, the $PM_{2.5}$ concentration attributable to ETS is estimated based on an Active Smoking Count (ASC) and an emission rate for cigarette smoking using the methodology of Ott *et al*., (1996).[18] The ASC is the average rate of the number of cigarettes being actively smoked in the microenvironment during a defined time interval.[18] ETS exposure in other microenvironments, such as in-vehicle, may also be important but are not currently included within SHEDS-PM.

The objectives of this paper are to answer four key questions:

- Are the inputs currently used in SHEDS based on the most recent data?
- Are the algorithms currently used in SHEDS based on best practice?
- What are the key factors to which exposure is sensitive for ETS in selected microenvironments?
- What are the key factors leading to geographic and inter-individual variability in ETS exposure?

MODELING OF ENVIRONMENTAL TOBACCO SMOKE EXPOSURE

This section discusses the input data and the algorithms for ETS in SHEDS-PM. The key input data for SHEDS-PM include human activity data, demographic data, and ambient $PM_{2.5}$ concentration.

The Consolidated Human Activity Database (CHAD) is comprised of human activity pattern diary data compiled by EPA/NERL based on a variety of activity studies.[19-23] CHAD is typically used to provide human activity input data for SHEDS.

The demographic data used in SHEDS-PM were obtained from the US Census for the year 2000. The census database includes data on population demographics (age, gender), distribution of housing types, and distribution of employment status for each of the 65,443 census tracts in the United States. There are 31 age groups for each gender, 10 housing types, and 4 employment categories for each gender.

The ambient $PM_{2.5}$ concentration data for each census tract for the geographic area of interest is the only input data that must be supplied by the user. The averaging time can be 24-hour, 12-hour, or hourly. The $PM_{2.5}$ concentration must be in units of micrograms per cubic meter ($\mu g/m^3$). $PM_{2.5}$ concentrations can be based on monitored data, air quality model outputs, or user-specified values. Preprocessing of monitored or modeled air quality data is needed in order to convert from their spatial resolution to that of census tracts.

A mass balance approach is applied in residential microenvironment based on the assumption of single and steady-state zone, and on parameters for penetration of outdoor $PM_{2.5}$, air exchange rate, deposition rate, and indoor volume. Linear regression is used for the restaurant and bar microenvironments to estimate indoor concentration based on outdoor concentration, emissions from cigarette smoking, and indoor background concentration. Microenvironmental $PM_{2.5}$ concentrations are calculated in each location and are associated with the assigned activity diary record. The rate of cigarette smoking is estimated based on user-specified ETS inputs. The time series of $PM_{2.5}$ exposure for each individual is determined from the calculated microenvironmental $PM_{2.5}$ concentrations and the sequence of time spent in each microenvironment.
Cigarette emission rates, proportions of smokers, and the number of cigarettes smoked are

required for calculating the ETS-based $PM_{2.5}$ concentration in the home residential microenvironment. The default input for cigarette emission rate in SHEDS-PM is 10.9 mg per cigarette.[24, 25]

Emissions from cigarette smoking in the home are divided into two categories: (1) emissions from smoking by someone who is a smoker; and (2) emissions from smoking by others present in the home, who are referred to as "other smokers." These support assessments of ETS-based $PM_{2.5}$ exposures for smokers and non-smokers, respectively. SHEDS-PM input data include the proportion of smokers and the proportion of "other smokers" present in the home by age and gender. The default data for the proportion of smokers are based upon DHHS (1998)[26] for adults 18 years and older. Data for adolescents 12-17 years old are based on the 1994 and 1995 National Household Survey on Drug Abuse.[27]

In the restaurant and bar microenvironments, ASC and the ASC-based emission rate are the two key inputs required. These inputs are used in a linear regression equation for calculating ETS-related PM concentration.[18]

The ASC-based emission rate is a $PM_{2.5}$ concentration caused by one smoked cigarette in a typical indoor environment. The default ASC-based emission rate is 32.0 $\mu g/m^3$ per cigarette for restaurants and 40.4 $\mu g/m^3$ per cigarette for bars.

METHODOLOGY

Based on the key questions, the methodology includes: (1) review of existing default data and algorithms used as ETS inputs to SHEDS-PM; (2) literature review for updated data and algorithms; (3) sensitivity analysis for identify the key factors to which exposure is sensitive for ETS in different microenvironments; (4) running SHEDS-PM to characterize mean exposures, inter-individual variability in exposures; (5) assessment of the effect of updated data and algorithms by re-running SHEDS-PM with the updated data, compare to results from default data, and assess the effect of updated or new algorithms on results from SHEDS.

Sensitivity analysis of exposure model can help identify the most significant factors to aid in risk management or to prioritize additional research to reduce uncertainty in the estimates.[28] Nominal range sensitivity analysis evaluates the effect on model outputs exerted by individually varying only one of the model inputs across its entire range of plausible values, while holding all other inputs at their nominal or base-case values.[29] The difference in the model output due to the change in the input variable is referred to as the sensitivity or swing weight of the model to that particular input variable.[30] During the sensitivity analysis, all variables were held at their default values except for one, which was varied by plus or minus 25 percent. The sensitivity in each microenvironment is based on the $PM_{2.5}$ concentration for the 50th, 90th, and 99th percentile.
In order to evaluate the effects of updated data, comparison of the mean exposure estimated by

SHEDS-PM based on default inputs and updated data are given. Default inputs in SHEDS-PM are used to characterize the mean $PM_{2.5}$ exposures for ETS in the residential, restaurant, and bar microenvironments. SHEDS-PM version 3.5 is used for simulation. For identifying the difference between default inputs and updated data, the default ambient $PM_{2.5}$ concentration, sample size and selected census tracts are the same for each simulation. Algorithms used in each microenvironment are the same as those of sensitivity analysis. The outputs are the mean values of total exposures in each microenvironment.

Inter-individual, regional, and seasonable variability in exposure to $PM_{2.5}$ from ETS may be associated with variability in health effects, therefore, it is necessary to evaluate the inter-individual variability in ETS exposure. The variability in exposure is estimated for specific sources of $PM_{2.5}$ including: (a) infiltration of outdoor air; (b) indoor sources other than smoking; and (c) ETS from smoking. SHEDS-PM cannot show the outputs of exposure values attributable to each source separately, therefore, three simulations are needed in order to compare taken in the residential the microenvironment. Algorithm, ambient $PM_{2.5}$ concentration inputs, demographic data are the same as those in the sensitivity analysis. During each simulation, only one source of indoor $PM_{2.5}$ is selected. Outputs are given as cumulative frequency distributions. Distribution statistics for each simulation are given.

Smoking prevalence varies in geographic areas. In 2006, the median prevalence of current cigarette smoking among adults in the 50 states and the District of Columbia was 20.2%, with a nearly threefold difference among states with the lowest and highest prevalence.[31] Based on different proportions of smokers in the residential microenvironment, four typical areas including: North Carolina (Wake County), New York (New York County), Texas (Harris County), and California (San Francisco County) were selected as a basis for comparison of ETS exposures. Ten Census tracts in each county were randomly selected. Algorithms, ambient $PM_{2.5}$ concentration inputs, and other ETS-related inputs except proportion of smokers are the same as those in the sensitivity analysis. Statistical data for each simulation are given.

RESULTS

Based on literature review, the results of updated inputs and algorithms are given in comparison to those based on defaults. A new algorithm for the in-vehicle microenvironment is evaluated using sensitivity analysis. Inter-individual and geographic variability in ETS-related exposure are given.

ETS Inputs in the Residential Microenvironment

The most recent national data for the proportion of smokers and "other smokers" present at home by age and gender is given in Tables 1 and 2, respectively. The default proportion of smokers at home is greater than that of the most recent data, especially for adolescents aged from 12-17. Thus, the default inputs are updated by the data in Table 1.

Table 1. Comparison of Updated and Default Inputs for the Proportion of Smokers by Age and Gender in the Stochastic Human Exposure and Dose Simulation Model for $PM_{2.5}$

	Male		Female	
Age Group	SHEDS (%)	Updated Input	SHEDS (%)	Updated Input
12-13	10.05	1.8	10.05	1.8
14-15	20.10	8.4	20.10	8.4
16-17	29.35	18.9	29.35	18.9
18-24	28.40	28.5	23.90	19.3
25-34	31.50	27.4	28.70	21.5
35-44	32.45	24.8	27.35	20.6
45-64	28.90	24.5	24.55	19.3
>64	14.80	12.6	11.45	8.3

Data: The default data for the proportion of smokers are based upon DHHS (1998) for adults 18 years and older.[26] Data for adolescents 12-17 years old are based on the 1994 and 1995 National Household Survey on Drug Abuse. [35] The Updated data for the proportion of smokers are based upon DHHS (2007) for adults 18 years and older.[36] Data for adolescents 12-17 years old are based on the 2007 National Survey on Drug Use and Health: National Findings.[37]

Table 2. Comparison of Updated and Default Inputs for the Proportion of "Other Smokers" by Age in the Stochastic Human Exposure and Dose Simulation Model for $PM_{2.5}$

			SHEDS	Updated Input
Smoking Status	Age Group	Gender	Proportion of "other smokers"	Proportion of "other smokers"
Smoker	12-17	Males	0.73	(0.49, 0.62)
		Females	0.89	
	18-46	Males	0.35	(0.37, 0.55)
		Females	0.38	
	65+	Males	0.16	(0.32, 0.39)
		Females	0.28	
Non-smoker	12-17	Males	0.31	(0.17, 0.23)
		Females	0.35	
	18-46	Males	0.10	(0.05, 0.09)
		Females	0.12	
	65+	Males	0.04	(0.04, 0.06)
		Females	0.05	

Data: Default data in SHEDS-PM are calculated from the National Human Activity Pattern Survey (NHAPS) questionnaire date.[38, 39] Updated Inputs are based on "Health Consequences of Involuntary Exposure to Tobacco Smoke: A Report of the Surgeon General".[32]

There are no recent data regarding the proportion of "other smokers" by gender. However, updated data are available for age categories in Table 2. Children aged from 0 to 11 years are not included in SHEDS-PM with respect to exposure to ETS from others who smoke. However, 24.9% of children in this age group are exposed to cigarette smoking at home.[32] National

Health Interview Survey (NHIS) data indicate that 35 percent of U.S. children lived in homes where they had contact with a smoker at least one day per week.[33] On the basis of self-reported data on smoking among household residents, the U.S. National Centers for Disease Control and Prevention (CDC) estimated in 1996 that 21.9 percent of U.S. children had been exposed to secondhand smoke in their homes.[34] Therefore, children in this age group should be included in SHEDS-PM model. Proportions of "other smokers" present at home for the 3 to 11 year old age group range from 0.22 to 0.35.

The default cigarette $PM_{2.5}$ emission rate is 10.9 mg/cig. Typical cigarette emission rates reported in the literature are from 10.8 to 22.4 mg/cig.[40] The mean value of $PM_{2.5}$ emission rate among the 50 top brands of cigarettes is 13.8 mg/cig, with a standard deviation of 3.1 mg/cig. The range of these emission rates is from 8 to 23 mg/cig based on a sample size of 111.[41,42] Nazaroff and Klepeis (2003) summarized 14 papers and reports on $PM_{2.5}$ emissions from cigarettes: the mean emission rate was found to be 13.7 mg/cig.[43] Nine of the 14 results are in the range of 7.8 to 13.8 mg/cig. Emissions of PM are measured for six types of commercial cigarettes. When total emissions are considered, PM emissions averaged 18 +/- 2 mg/cig.[44] Thus, the default input is lower than the mean value of cigarette emission rate based on various studies. It is reasonable to assume an updated emission rate of approximately 13.8 mg/cig.

Due to lack of recent data for the number of cigarettes smoked by smokers and "other smokers" in different age categories and by gender, the current default inputs used in SHEDS-PM based on National Human Activity Pattern Survey (NHAPS) are retained.

Based on CHAD data, the time people spend in a vehicle is almost 10 times less than that at home. However, in-vehicle $PM_{2.5}$ concentrations associated with smoking have been measured or estimated to be as high as 658 $\mu g/m^3$, depending on the status of vehicle windows and air condition system.[45]

ETS Exposure for In-vehicle Microenvironment

A mass balance approach can be used to calculate in-vehicle $PM_{2.5}$ concentration. Typical values of air exchange rates for selected variations of vehicle speed, and status of windows, and ventilation system are given in Table 3. Other inputs for the mass balance equation are vehicle interior cabin volume (2 to 6 m^3), cigarette emission rate (1.4 to 2.8 mg/ (min·cig), ASC (0 to 3 cig/hr), and duration of active smoking of an individual (8 min).

Table 3. In-Vehicle PM2.5 Concentrations for ETS Exposure Scenarios

Speed (mph)	Status of Windows	Status of Ventilation System	Air exchange rate (h^{-1})	$PM_{2.5}$ concentrations ($\mu g/m^3$)
0 (Parked)	Window fully open	Off	6.50	1354
20	All closed	Vent on	30.0	293
20	All closed	AC on	29.4	299
50	Window open 3"	Off	51.7	170
60	All closed	Vent on	33.9	260

Inputs: vehicle interior cabin volume: 4 m^3, cigarette emission rate: 2.2 mg/(min·cig), ASC: 2 cig/hr, and duration of active smoking of an individual: 8 min.

Environmental Tobacco Smoke Algorithms in SHEDS-PM

SHEDS-PM estimates the $PM_{2.5}$ concentration from ETS but not for direct inhalation by a smoker from active smoking. Default algorithms used in SHEDS-PM for the residential microenvironment is reviewed.

$PM_{2.5}$ concentrations in the residential microenvironment are calculated by a mass balance: [24, 25]

$$C_{Home} = \frac{P \cdot a}{a+k} C_{ambient} + \frac{E_{cig} N_{cig} + E_{cook} t_{cook} + E_{clean} t_{clean} + E_{other} t_{other}}{(a+k)VT} \quad \textbf{(Eq. 1)}$$

Where:

a = air exchange rate (h^{-1});
C_{Home} = $PM_{2.5}$ concentration in the home ($\mu g/m^3$);
$C_{ambient}$ = ambient outdoor $PM_{2.5}$ concentration ($\mu g/m^3$);
E_{cig} = emission rate for cigarette smoking (μg/cig);
E_{cook} = emission rate for cooking (mg/m^3);
E_{clean} = emission rate for cleaning (mg/m^3);
E_{other} = emission rate for all other activities (mg/m^3);
k = deposition rate (h^{-1});
N_{cig} = number of cigarettes smoked during model time step (cig);
P = penetration factor (unitless);
T = model time step (min);
t_{cook} = duration of time spent cooking during model time step (min);
t_{clean} = duration of time spent cleaning during model time step (min);
t_{clean} = duration of time spent doing other activities during model time step (min);
V = volume of microenvironment (m^3).

The indoor $PM_{2.5}$ concentration attributable to penetration of ambient $PM_{2.5}$ is estimated based

on penetration factor, deposition rate, air exchange rate, and indoor volume, which is the first term in Equation (1). The second term in Equation (1) describes the contribution from indoor emission sources, including smoking, cooking, cleaning, and other sources.

Review of ETS-related Algorithms and Models

Many models have been developed for estimating indoor $PM_{2.5}$ concentrations attributable to ETS, most typically based on a mass balance.

Turk (1963) developed a mass balance equation which contains both indoor and outdoor emission sources for calculating concentrations in a chamber.[46] Ott *et al.* (1992a) summarized previous studies, and described and evaluated a mass balance equation used in a chamber.[15] Examples of exposure models using mass balance approaches are Simulation of Human Activity and Pollutant Exposure (SHAPE) Model,[47] Total Human Exposure Model (THEM),[48] Air Pollution Exposure (APEX) model,[49] Sequential Cigarette Exposure Model (SCEM),[15] Multi-Chamber Concentration and Exposure Model (MCCEM),[50] and European Population Particle Exposure Model (EXPOLIS).[51] Therefore, mathematical models that use the mass balance approach are typical of best practice for estimating indoor air pollutant concentrations.

Ott *et al.* (1996)[18] conducted a $PM_{2.5}$ study in a tavern and evaluated a linear regression equation[40] for estimation of respirable suspended particle (RSP) concentration using an indoor air quality model. They concluded that the linear regression approach can be applied to estimate RSP concentrations from ETS in other similar taverns. Sufficient data were not available from which to apply a mass balance model to estimate $PM_{2.5}$ concentrations in the nonresidential microenvironments; therefore, the current version of SHEDS-PM uses the simplified linear regression approach for the restaurant and bar microenvironments.

A typical mass balance approach model for estimation of in-vehicle concentration is SCEM. SCEM was developed for predicting the time series of concentration in a well-mixed vehicle for any cigarette smoking activity pattern. Ott *et al*. (1992a) evaluated the performance of SCEM in several experiments, and concluded that the mass balance approach can be used to predict ETS exposure in vehicles.[15] Ott *et al*. (2008) used the same approach to predict $PM_{2.5}$ concentrations in a vehicle with various air exchange rates, and concluded that there was a satisfactory fit of the model to the experimental data.[45]

The mathematical mass balance model applicable to estimation of $PM_{2.5}$ concentration associate with ETS in a vehicle is: [15]

$$C_{In-Vehicle} = \frac{ASC \cdot E_{cig} \cdot t}{a \cdot V} \qquad \textbf{(Eq. 2)}$$

Where:

a = air exchange rate (h^{-1});
$C_{In-Vehicle}$ = $PM_{2.5}$ concentration for the in-vehicle microenvironment ($\mu g/m^3$);
E_{cig} = emission rate for cigarette smoking [$\mu g/(min \cdot cig)$];
t = duration of active smoking of an individual (min/h);
V = vehicle interior cabin volume (m^3).

Sensitivity Analysis Results

In order to identify the key ETS-related inputs, ambient $PM_{2.5}$ concentration is set to 10 $\mu g/m^3$ for 24 hours and kept constant for each simulated day. Ten census tracts in Wake County, North Carolina are selected. Each census tract contains 5,000 simulation individuals. Thus, the sample size for each sensitivity analysis is 50,000 individuals.

Table 4. Results of Sensitivity Analysis of the SHEDS-PM Model for the Residential Microenvironment

Input Assumption	50th percentile Indoor $PM_{2.5}$ concentration ($\mu g/m^3$)	90th percentile Indoor $PM_{2.5}$ concentration ($\mu g/m^3$)	99th percentile Indoor $PM_{2.5}$ concentration ($\mu g/m^3$)	% change in 50th Percentile	% change in 90th Percentile	% change in 99th Percentile
Default Inputs	4.52	65.0	224			
Proportion of Smokers +25%	4.96	72.4	246	10	11	10
Proportion of Smokers -25%	4.02	58.5	204	11	-10	-9
Proportion of "Other Smokers" +25%	4.99	70.9	246	10	9	10
Proportion of "Other Smokers" -25%	4.05	59.4	202	-10	-9	-10
Emission Rate +25%	5.51	78.3	278	22	21	24
Emission Rate -25%	4.53	50.9	178	-22	-22	-22

Inputs: sample size: 50,000 individual, 10 census tracts in Wake County, NC; ambient $PM_{2.5}$ concentration: 10 $\mu g/m^3$; emission rate: 10.9 mg/cig.

For each of the residential, restaurant and bar microenvironments, sensitivity analysis was conducted based on default inputs. The effects of variations in the proportion of smokers and "other smokers" and cigarette emission rate in the residential microenvironment, are evaluated. The default inputs for the residential microenvironment are given in Tables 1 and 2. The default input for the cigarette emission rate is 10.9 mg/cig. The results of the sensitivity analysis for the residential microenvironment are given in Table 4.

Over 99 percent of the simulated population spent time in the residential microenvironment. Based on the default inputs, the number of smokers and "other smokers" present are about 12,200 and 8,900, respectively. The 99th percentile of inter-individual variability in exposure was most sensitive to variations in cigarette emission rate, and approximately half as sensitive to either the proportions of smokers or "other smokers".

Assessment of the Effect of Updated Inputs and Algorithms

The effect of updated inputs are compared by re-running SHEDS-PM with the updated data, compare to results from default inputs.

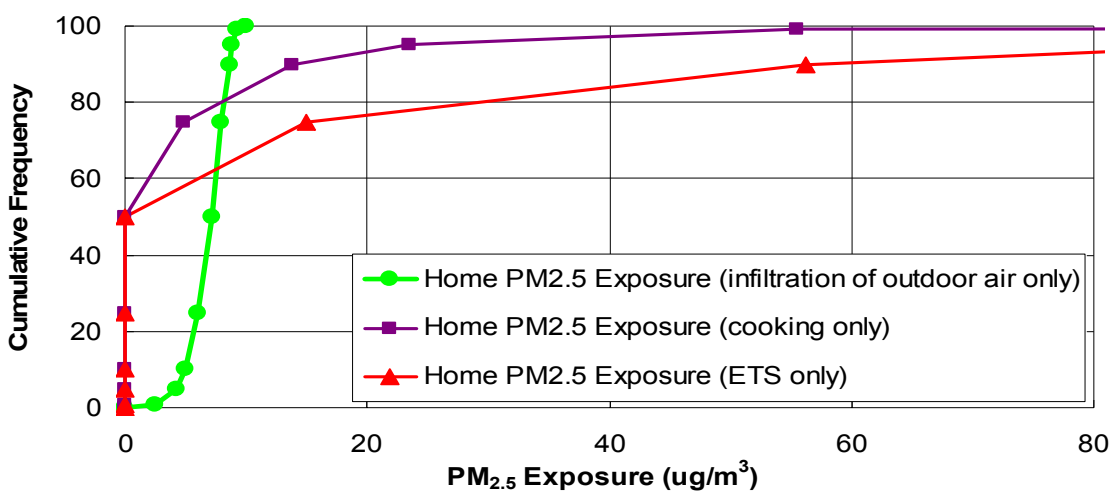
The general inputs of the simulation including, ambient $PM_{2.5}$ concentrations and demographic data, are the same as those of default inputs. The updated proportions of smokers, and "other smokers" used in the simulation are given in Tables 1 and 2. The emission rate is 13.8 mg/cig.

The ETS-related mean exposures in the residential microenvironment based on default and updated inputs are 17.7 μg/m^3 and 19.6 μg/m^3, respectively. The standard deviation based on default and updated inputs are 45.8 μg/m^3 and 61.6 μg/m^3, respectively. Mean exposures, and standard deviation based on updated data are about 10 and 35 percent higher, respectively, than those based on defaults.

Inter-individual Variability in Microenvironmental $PM_{2.5}$ Exposure with Default Inputs

Inter-individual variability in exposure was compared for three specific emission sources of $PM_{2.5}$ for the residential microenvironment. Results are given in Figure 1.

Figure 1. Comparison of Cumulative Frequency Distributions of Daily Average $PM_{2.5}$ Exposures (μg/m^3) in Microenvironments



The $PM_{2.5}$ concentration distribution attributable to only ETS for the residential microenvironment has a mean of 18 μg/m^3, with a range of 0 to 1257 μg/m^3, and a standard deviation of 46 μg/m^3. The exposure associated with infiltration of outdoor air is 7 μg/m^3, and with cooking is 5 μg/m^3. Hence, on average, ETS contributes to 60% percent of residential indoor exposures. However, the contribution of ETS to individual exposure is much higher for some individuals.

Geographic Variability for the Residential Microenvironmental PM2.5 Exposure with Default Inputs

Examples of geographic variability for ETS exposure are described. The inputs regarding the proportion of smokers in SHEDS-PM are required for different age groups by gender. Due to lack of recent data for the proportions of smokers by age groups in different states, assumptions of inputs for the age group from 12 to 17 years old are based on the data for middle school and high school students,[31] and the State Tobacco Activities Tracking and Evaluation (STATE) System in the website of CDC. The assumptions for people from 18 to 64 years old are based on the data for adults in each state,[52] and the STATE System in the website of CDC.

The prevalence of smokers in North Carolina is 22.1%, with a mean ETS-related $PM_{2.5}$ exposure of 16 μg/m^3, and a standard deviation of 24 μg/m^3. The prevalence of smokers in New York is 18.3%, with a mean ETS-related $PM_{2.5}$ exposure of 15 μg/m^3, and a standard deviation of 26 μg/m^3.The prevalence of smokers in Texas is 18.1%, with a mean ETS-related $PM_{2.5}$ exposure of 14 μg/m^3, and a standard deviation of 24 μg/m^3. The prevalence of smokers in California is 14.9%, with a mean ETS-related $PM_{2.5}$ exposure of 13 μg/m^3, and a standard deviation of 21 μg/m^3. There was approximately an 8 percent difference in the prevalence of smokers between North Carolina and California, which resulted in 24 percent increase in the mean ETS-related $PM_{2.5}$ exposures for NC versus CA.

CONCLUSIONS

SHEDS-PM default inputs regarding the proportion of smokers and "other smokers," and emission rate in the residential microenvironment should be updated.

The algorithms used for ETS exposure in the residential, restaurant, and bar microenvironments are generally based on best practice. ETS exposure in-vehicle may be a key contributor to total exposure. Such exposure could be modeled using a mass balance approach. Air exchange rate was found to be the most significant input affecting the in-vehicle $PM_{2.5}$ concentration.

Updated data resulted in 10 and 35 percent higher mean and standard deviation, respectively, for inter-individual variability in exposures than those based on defaults in the residential microenvironment.

In the residential microenvironment, cigarette emission rates have the most significant effect on the ETS exposure compared to other inputs. The ETS-based $PM_{2.5}$ concentration is less sensitive to the proportions of smokers and "other smokers" present at home. Compare to other indoor and outdoor emission sources, ETS contributed the most to total $PM_{2.5}$ exposures in the

residential microenvironment.

Based on difference in the prevalence of smokers in different geographic areas, variability for ETS-related $PM_{2.5}$ exposures in the residential microenvironment can be substantial. Thus, area-specific data for the proportion of smokers should be used.

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