Liu, Z., H.C. Frey, Y. Cao, and B. Deshpande, "Modeling of In-vehicle $PM_{2.5}$ Exposure Using the Stochastic Human Exposure and Dose Simulation Model," Paper 2009-A-238-AWMA, *Proceedings, 102nd Annual Conference and Exhibition*, Air & Waste Management Association, Detroit, Michigan, June 16-19, 2009.

Modeling of In-vehicle $PM_{2.5}$ Exposure Using the Stochastic Human Exposure and Dose Simulation Model

Paper: 2009-A-238-AWMA

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ABSTRACT

Factors that influence in-vehicle $PM_{2.5}$ exposure are indentified and assessed. The methodology used in the current version of Stochastic Exposure and Dose Simulation model for Particulate Matter (SHEDS-PM) for in-vehicle $PM_{2.5}$ concentration is reviewed, and alternative modeling approaches are identified and evaluated. SHEDS-PM uses a linear regression model to estimate in-vehicle $PM_{2.5}$ concentration based on ambient $PM_{2.5}$ concentration, such as from a fixed site monitor (FSM) or a grid cell average concentration estimate from an air quality model. The ratio of in-vehicle to FSM concentration varies substantially with respect to location, vehicle type and other factors. SHEDS-PM was used to estimate $PM_{2.5}$ exposure for 1% of people living in Wake County, NC in order to assess the importance of in-vehicle exposures. In-vehicle $PM_{2.5}$ exposure can be as much as half of the total exposure for some individuals, depending on employment status and the time spent in-vehicle during commuting. An alternative modeling approach is explored based on the use of a dispersion model to estimate near-road $PM_{2.5}$ concentration based on FSM data and a mass balance model for estimating in-vehicle concentration. Recommendations for updating the input data to the existing model, and implementation of the alternative modeling approach are made.

INTRODUCTION

Fine particulate matter ($PM_{2.5}$) includes particles that are 2.5 micrometers (microns) or less in aerodynamic diameter. Many epidemiology studies indicate that ambient PM exposure is associated with short-term and chronic respiratory effects. Such effects include exacerbation of asthma and increased susceptibility to infection.[1] Exposure to $PM_{2.5}$ also decreases lung function and can cause lung injuries.[1] Therefore, there is a need to investigate $PM_{2.5}$ human exposure in order to support assessment of the association between exposure and adverse health effects.

In 2007, 90% of US commuters drove to work, with a total number of 120 million vehicles.[2] Thus, the in-vehicle microenvironment is a potential significant contributor to human exposure

to pollutants, especially for commuters. A microenvironment is a location within which air pollutant concentrations are relatively uniform or can be well-characterized. In-vehicle $PM_{2.5}$ concentration is high compared to those of other microenvironments, such as houses.[3]

Scenario-based human exposure models simulate the movement of individuals through microenvironments and their contact with pollutants. Here the focus is on inhalation exposure to airborne $PM_{2.5}$. The Stochastic Human Exposure and Dose Simulation for $PM_{2.5}$ (SHEDS-PM) was developed by the US Environmental Protection Agency (USEPA) to simulate individual and population exposure to $PM_{2.5}$.[4]

Eight microenvironments are accounted for in SHEDS-PM, including outdoors, residence, office, school, store, restaurant, bar, and in-vehicle. For each individual, a time-weighted $PM_{2.5}$ concentration is estimated based on the amount of time spent in each microenvironment and the microenvironmental concentrations. For the in-vehicle microenvironment, SHEDS can simulate cars, trucks, buses, trains and "all other" in-vehicle microenvironments.

This paper reviews the in-vehicle exposure methodology, inputs, and the key factors that influence in-vehicle $PM_{2.5}$ exposure. The objectives of this paper are to: (a) evaluate the algorithm and inputs for estimating the in-vehicle $PM_{2.5}$ concentration; (b) assess the importance of in-vehicle $PM_{2.5}$ exposure; (c) identify and evaluate an alternative modeling approach for estimating in-vehicle $PM_{2.5}$ concentration, and (d) demonstrate the improved in-vehicle exposure modeling approach for implementation in SHEDS-PM.

OVERVIEW OF THE STOCHASTIC EXPOSURE AND DOSE SIMULATION MODEL FOR PARTICULATE MATTER

The key inputs and outputs in SHEDS-PM are reviewed. Furthermore, the algorithms and inputs for the in-vehicle microenvironment are reviewed.

Key Inputs and Outputs

The key input data for SHEDS-PM include: (a) ambient $PM_{2.5}$ concentration; (b) human activity data; (c) demographic data; (d) parameters for microenvironment-specific equations.
The ambient $PM_{2.5}$ concentration data for the population of interest is input data that must be supplied by the user. The data can be obtained from fixed monitoring sites (FMSs), gridded air quality models, or a combination of both. The ambient concentration data must be converted by the user to a census tract basis for input to SHEDS-PM.

Human activity data used in SHEDS-PM are from the Consolidated Human Activity Database (CHAD).[4] CHAD contains data obtained from multiple human activity studies that were collected at city, state, and national levels[5]. These data include diaries that describe the sequence and duration of time spent in each microenvironment.

Demographic data from the US Census are used to generate the population for the simulation on a census tract basis[6]. SHEDS-PM randomly selects an individual from the census database, and uses demographic characteristics such as age, gender and employment status of every individual to match with diary data from CHAD in order to quantify activity[6].

The $PM_{2.5}$ concentration in an indoor microenvironment can be estimated in one of three ways: (1) scaling, (2) linear regression, and (3) mass balance. Each microenvironment requires that parameters be specified according to the estimate method. These parameters have default values that can be overridden by the user.

The default outputs of SHEDS are daily average exposure for every individual. Inter-individual variability in exposure for all the microenvironments is also reported. The user can choose to view a time series of events, which characterize the concentration, time length and exposure for every activity in every microenvironment for any individuals during the simulated period.

Algorithms and Inputs for In-vehicle $PM_{2.5}$ Exposure

The calculation scheme used in SHEDS-PM for in-vehicle exposure is shown in Figure 1. To run SHEDS-PM, a user must specify the simulated geographic area in terms of census tracts, the number of individuals to be simulated, specific age and gender cohorts to be simulated, whether commuting is to be simulated, and a time frame for the simulation (number of days). Commuters are simulated only for employed individuals.

The in-vehicle $PM_{2.5}$ concentration is estimated as a linear function of ambient $PM_{2.5}$ concentration:

$$C_{\mathrm{iv,vt}} = k_{\mathrm{vt}} C_{\mathrm{amb}} + b_{\mathrm{vt}} + \varepsilon_{\mathrm{vt}} \qquad \textbf{(Eq. 1)}$$

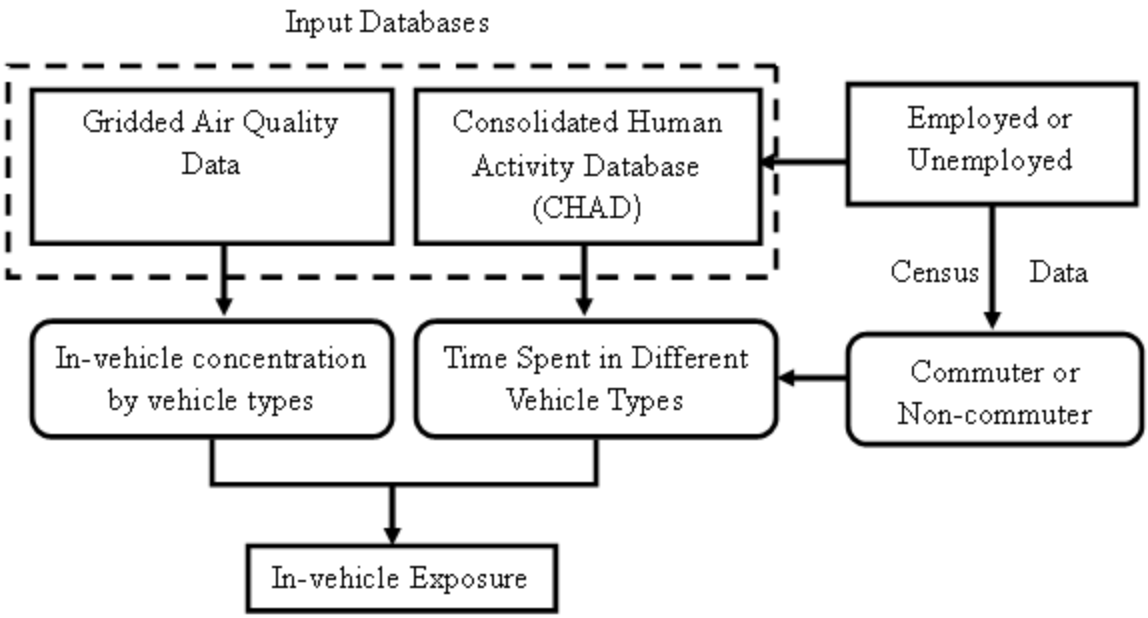
Where,

b_{vt} = in-vehicle non-ambient $PM_{2.5}$ concentration for vehicle type vt ($\mu g/m^3$)
$C_{iv,\,vt}$ = in-vehicle $PM_{2.5}$ concentration for vehicle type vt ($\mu g/m^3$)
C_{amb} = ambient $PM_{2.5}$ concentration ($\mu g/m^3$)
k_{vt} = in-vehicle/ambient ratio $PM_{2.5}$ concentration for vehicle type vt, constant
vt = vehicle types: car, bus, truck, train, and other vehicles
ε = error term for residual variability in in-vehicle $PM_{2.5}$ concentration, where

$\varepsilon \sim N(0, \sigma_\varepsilon)$ and σ_ε is the standard deviation ($\mu g/m^3$)

The ratio of in-vehicle to ambient $PM_{2.5}$ concentrations, k_{vt}, for vehicle type *vt* is determined by comparing in-vehicle measurement data with ambient data. The parameter b_{vt} is non-zero only when there are in-vehicle sources of $PM_{2.5}$, such as smoking.[6]

Figure 1. Conceptual Diagram of Current In-vehicle Exposure Calculation Scheme in the Stochastic Human Exposure and Dose Simulation Model



METHODOLOGY

The methodology includes: (1) identification, review, and assessment of the algorithm and inputs currently used in SHEDS-PM to estimate in-vehicle $PM_{2.5}$ concentration, based on literature review and assessment of variability in input data; (2) sensitivity analysis of SHEDS-PM to assess the contribution of in-vehicle exposure to total exposure and the uncertainty in such estimates attributable to unexplained variability in input data; (3) identification of key factors that influence or govern in-vehicle $PM_{2.5}$ concentration based on literature review; (4) identification and characterization of an alternative approach to estimating in-vehicle $PM_{2.5}$ based on integrating models for ambient and vehicle interior air quality; and (5) development and demonstration of a process for implementing the alternative modeling approach in SHEDS-PM.

As detailed in the results section, the literature review provides support for the hypothesis that in-vehicle $PM_{2.5}$ concentration can be estimated more accurately based on ambient concentration immediately outside the vehicle rather than by reference to ambient concentration: (a) measured at a receptor a significant distance away from the roadway, such as a fixed monitoring site; or (b) estimated by a gridded air quality model.

In order to develop the alternative modeling approach, a near roadway air quality model, CAlifornia LINE Source Dispersion Model, version 4 (CALINE4), was identified and selected as the basis for estimating the incremental component of ambient concentration in the vicinity of a roadway that is attributable to local emissions from vehicles operating on the roadway. This incremental concentration is superimposed with an area-wide concentration from a FMS or a gridded air quality model to estimate the total concentration surrounding the vehicles that operate on the roadway.

There is not an existing modeling tool that can accurately predict $PM_{2.5}$ concentration on a roadway in the flow path of vehicles. A challenge in making such estimates is to account for the effects of turbulence induced by the movement of vehicles. The methodology can be updated at a later time with a different air quality model if one becomes available.

For air quality inside the vehicle, a mass balance approach was adopted based on data and equations reported by Ott *et al.*[7], and Abadie *et al.* [8] Parameters for the mass balance model were estimated based on data from the literature.

The coupled use of the near-road and in-vehicle air quality models is demonstrated via example case studies that take into account variations in ambient conditions, traffic emissions, vehicle characteristics, and vehicle operation. The results obtained from the alternative modeling approach are compared to those obtained from the existing approach used in SHEDS-PM. The significance of differences in results is assessed.

RESULTS

The key results include the findings from review of the current in-vehicle exposure-related inputs and parameters of SHEDS-PM, identification of key factors that influence in-vehicle exposure; sensitivity analysis of SHEDS-PM to assess how in-vehicle exposure varies with respect to selected model inputs; identification and evaluation of an alternative approach for estimating in-vehicle exposure; design of a strategy for implementing the alternative approach using the current version of SHEDS-PM, and demonstration of the alternative approach for an illustrative case study.

Review of In-vehicle Inputs in SHEDS-PM

The key input to Equation (1) is the ratio of in-vehicle $PM_{2.5}$ concentration to ambient $PM_{2.5}$ concentration k_{vt}.

Studies such as Adams *et al*.,[3] Riediker *et al*.,[9] Gee *et al*.,[10] and Lai *et al*.[11] imply that the in-vehicle to FMS ambient ratio has a wide range of variability, depending on factors such as traffic counts. Furthermore, several investigators conclude that there is not a strong correlation between ambient $PM_{2.5}$ concentration and in-vehicle concentration.[12-14]

Key Factors that Influence In-vehicle $PM_{2.5}$ Concentration

Key factors influencing in-vehicle $PM_{2.5}$ exposure include traffic conditions, wind speed, wind direction, air exchange, vehicle types, and time spent in-vehicles.

Kaur *et al*.[14] identified traffic counts to be a significant determinant ($p<0.05$) of ultrafine particle count. In a toll gate worker exposure study, 8-hr averaged $PM_{2.5}$ concentrations measured during a 10-day period were highly related to vehicle counts.[11]

Adams *et al*.[12] measured in-vehicle $PM_{2.5}$ concentration for vehicles traveling on three connected routes in Central London, UK and found that wind speed measured at a wind center station, which was within one mile of the nearest route, was weakly correlated to in-vehicle $PM_{2.5}$ concentration, especially for private cars during the winter (r^2=-0.40). Several other studies suggest that wind speed and direction both have considerable impacts on the PM concentrations on or near the roadway;[15-17] however, the impact of wind direction on in-vehicle $PM_{2.5}$ exposure has not been addressed.

In-vehicle $PM_{2.5}$ concentrations are typically measured for different window openings (closed, fully open or partially open) and the status of operation of ventilation or air conditioners (A/C). Chan *et al*.[18] found significant differences in the in-vehicle PM_{10} concentration in taxis, when comparing air conditioned and non-air-conditioned vehicles. Rodes *et al*. [19] observed higher $PM_{2.5}$ levels in vehicles with windows open than vehicles with windows closed.

The in-vehicle $PM_{2.5}$ concentrations measured for different vehicle types, including cars, buses, and subways, vary substantially with vehicle types. For example, Tang *et al*. [20] measured in-vehicle $PM_{2.5}$ concentrations for passenger cars, taxis, buses and trucks in Macao, China to be 116, 192, 209, and 192 $\mu g/m^3$, respectively.

Sensitivity Analysis of SHEDS Based on a Case Study

Sensitivity analyses were conducted to assess the response of SHEDS-PM to variations in selected inputs. The sensitivity analysis is based on a case study for Wake County, NC. Wake

County contains 105 census tracts and had a 2000 population of 630,000 people. A random sample of one percent of these individuals was simulated. People of all ages and genders were included and commuting was considered. $PM_{2.5}$ concentration data for the case study are based on hourly data from July 1, 2002 to July 30, 2002 from the output of the Community Multiscale Air Quality (CMAQ) modeling system. CMAQ is an air quality modeling system which can simulate multiple air pollutants in various spacial scales[21]. The CMAQ air quality data used here was provided by the U.S. Environmental Protection Agency. The average $PM_{2.5}$ concentration during this time period is 12.7 $\mu g/m^3$. All the key input assumptions for each microenvironment are listed in Table 1 except for the in-vehicle microenvironment.

Three in-vehicle to ambient ratios of 0.71, 2.5, and 14.3 were used for sensitivity analysis. They were calculated from the studies of Riediker *et al*.,[9] Gee *et al*.,[10] and Lai *et al*.,[11] and represent low, medium, and high ratios, respectively. The SHEDS-PM model was run for the case study once for each ratio. Each model run was conducted on a Windows XP quad-processor computer and had an approximate runtime of 100 minutes. The sensitivity analysis results are given in Table 2. When the ratio is low (0.71), the portion of in-vehicle exposure relative to the total exposure was only 6% in average for all the simulated people. However, when the ratio is very high (14.3), the portion increases to 57%. Hence, the contribution of the in-vehicle microenvironment to total exposure is highly variable and can be significant.

Table 2. Sensitivity Analysis of Total and In-vehicle Exposure to $PM_{2.5}$ Based on Variation of the In-vehicle/ambient $PM_{2.5}$ Concentration Ratio k_{vt}

In-vehicle/ambient $PM_{2.5}$ Concentration Ratio k_{vt} (for all vehicles)	Total $PM_{2.5}$ Exposure ($\mu g/m^3$)	In-vehicle $PM_{2.5}$ Exposure ($\mu g/m^3$)	Percentage of Total Exposure that Occurs In-vehicle (%)
0.71	12.0	0.7	6.0
2.5	13.9	2.6	18.4
14.3	26.2	14.9	57.0

The results from SHEDS-PM are sensitive to the in-vehicle to ambient ratio. However, as discussed in the review of in-vehicle inputs in SHEDS-PM, the ambient concentration and in-vehicle concentration are not well-correlated. Ambient concentrations estimated using gridded air quality models such as CMAQ do not take into account local spatial variations in concentration on or near a roadway. The use of a ratio of in-vehicle to area-wide ambient concentration, such as k_{vt}, does not account for the influential local emission on the roadway, with respect to $PM_{2.5}$ concentrations surrounding the vehicle, nor factors that affect penetration of $PM_{2.5}$ from the surroundings of the vehicle into the vehicle interior.

Table 1. Key Inputs for North Carolina Case Study

Micro-environment	Calculation Scheme	Parameter	Distribution Type[c]	Distribution Values	Reference
All Outdoor	Scaling Factor[a]	Factor	Fixed	1.0	
Home	Mass Balance	Penetration	Normal	Mean=0.91, StdDev=0.1	Meng *et al.* (2005)
		Deposition	Normal	Mean=0.79, StdDev=0.31	
		Air Exchange Rate	Lognormal	Season3 (summer)[d]: GeoMean=0.555, GeoStd=1.844	Murray and Burmaster (1995)
Office	Linear Regression[b]	Slope	Fixed	0.18	Burke, *et al.* (2001)
		Intercept	Fixed	3.6	
		Residuals	Normal	Mean=0, StdDev=2.9	
School	Linear Regression	Slope	Fixed	0.6	Burke, *et al.* (2001)
		Intercept	Fixed	6.8	
		Residuals	Normal	Mean=0, StdDev=5.4	
Store	Linear Regression	Slope	Fixed	0.75	Burke, *et al.* (2001)
		Intercept	Fixed	9.0	
		Residuals	Normal	Mean=0, StdDev=2.1	
Restaurant	Linear Regression	Slope	Fixed	1.0	Burke, *et al.* (2001)
		Intercept	Fixed	9.8	
		Residuals	Normal	Mean=0, StdDev=10	
Bar	Linear Regression	Slope	Fixed	1.0	Burke, *et al.* (2001)
		Intercept	Fixed	9.8	
		Residuals	Normal	Mean=0, StdDev=10	
All Other Indoor	Linear Regression	Slope	Fixed	0.85	Burke, *et al.* (2001)
		Intercept	Fixed	8.4	
		Residuals	Normal	Mean=0, StdDev=4	

[a] Scaling factor equation: $C_{micro}=aC_{amb}$, where: C_{micro} = micro-environmental PM concentration; C_{amb} = ambient PM concentration; a = factor;

[b] Linear regression equation: $C_{micro} = kC_{amb}+b+\varepsilon$, where: k=slope; b= intercept; ε =residuals, which is used to calculate variability.

[c] Fixed refers to constant value; Normal refers to Normal distribution; Lognormal refers to Lognormal distribution.

[d] The modeling period is from July 1 to July 30, thus only season3 (summer) has been used.

Identification and Evaluation of an Alternative Approach

Three Gaussian models, CALINE4, CALINE3 with queuing and hot spot calculations (CAL3QHC) and the atmospheric dispersion modeling system (AERMOD), are recommended by US EPA to predict near-road $PM_{2.5}$ concentrations. Chen *et al*.[22] compared the estimates of the three models with near-road $PM_{2.5}$ concentration measurements and found that CALINE 4 performs best when accounting for background $PM_{2.5}$ concentration. Therefore, CALINE4 was selected as the dispersion model for the alternative approach.

Ott *et al*.[7] derived a mass balance model using air exchange rate for estimating in-vehicle $PM_{2.5}$ concentration, but simplified it by only accounting for interior PM sources such as smoking while assuming that the ambient $PM_{2.5}$ concentration was negligible. Abadie et al.[8] derived a more detailed mass balance model to estimate in-vehicle PM concentration due to smoking in French high-speed train (TGV) smoker cars. It accounted the effects of filtration, deposition and air exchange. A mass balance model is used here that takes into account penetration of ambient $PM_{2.5}$. The removal of $PM_{2.5}$ by both filtering and deposition is quantified by a constant efficiency coefficient rate η. Thus, the mass balance for in-vehicle air quality is:

$$\frac{VdC_{iv}(t)}{dt} = VC_{\mathrm{iv}}(t) + V \times \mathrm{ACH} \times (1-\eta)C_{sv} \qquad \textbf{(Eq. 2)}$$

Where,

V	= interior volume of the vehicle, m^3
t	= time, hr
ACH	= air exchange rate, hr^{-1}
C_{iv} (t)	= in-vehicle $PM_{2.5}$ concentration, $\mu g/m^3$
C_{sv}	= ambient $PM_{2.5}$ concentration surrounding the vehicle, $\mu g/m^3$
η	= filtration and deposition removal efficiency of $PM_{2.5}$, constant

The solution to the first order differential equation is:

$$C_{iv}(t) = C_{sv} r(1-\eta) \qquad \textbf{(Eq. 3)}$$

Where,

$$r = 1 - e^{-\mathrm{ACH} \times t} \qquad \textbf{(Eq. 4)}$$

The quantity *r* is the efficiency of air exchange between ambient air surrounding the vehicle and the interior air of the vehicle.

CALINE4 is able to model straight roads, curved roads, intersections, parking lots and other types of roadway geometry.[23] However, the CHAD diary data do not contain information regarding the time people spend on roadways of different geometries. Thus for simplicity, only

straight roads are modeled here. There are 3 types of roadways identified and modeled. The types are local, arterial and highway. The major difference among the categories is the lane width and the number of lanes.

A receptor location should be as close to road as possible in order to be a surrogate for on-road concentration. Validation studies of CALINE4 indicated that a distance of about 3.4 meters away from the emission source is appropriate.[18]

The near-road incremental $PM_{2.5}$ predicted by CALINE4 is linearly proportional to the vehicle average emission factor and traffic volume.[23] Therefore, only one set of emission factor and traffic volume estimates were used. If there is a need to estimate the near-road $PM_{2.5}$ increment for other sets of emission factors and traffic volumes, a linear proportion relative to the original increment is sufficient.

In CALINE4, the effect of wind direction is related to the road geometry. Since the road types used in this study are based on assumptions instead of real road geometry, it is not useful to specify an accurate wind direction. Therefore, the "worst case" scenario in CALINE4 which selects the wind angle that produce the highest concentrations at the receptor is chosen. Examples of near-road $PM_{2.5}$ increments predicted by CALINE4 are summarized in Table 3. The highest increment occurs for Local roadway and a wind speed of 1.0 m/s.

Table 3. Near-road $PM_{2.5}$ Increment ($\mu g/m^3$) for Road Type and Wind Speed Scenarios[a]

Wind Speed (m/s)		1.0	3.3	5.3
Stability Class		G	G	B
Road Type	Local	9.0	3.5	2.0
	Arterial	8.4	3.5	2.0
	Highway	6.8	3.2	1.9

[a] *All examples are based on an emission rate of 0.692 g/vehicle km traveled,*[18] *assuming the same traffic flow.*

Ott *et al*.[24] measured the air exchange rate of various scenarios for four vehicles with varying the vehicle speed, window opening and ventilation. The lowest mean ACH was 0.92 hr^{-1}, which was observed for a 2005 Toyota Corolla when the vehicle was stopped with the window closed and the fan off. The highest mean ACH of 78.6 hr^{-1} was observed for a 2005 Ford Taurus sedan at the speed of 20 mph with one window fully open, recirculation turned on and the ventilation fan turned off.

Based on calculations using Eq. 4, at a high ACH such as 71 h^{-1}, the air exchange efficiency *r* increases to approximately 100% in less than 10 min. At a low ACH, *r* increases slowly with time. In a typical commuting event which lasts about 40 min, r always increases to more than 50%. The average r ranges from 0.75 to 0.99 for the selected ACH.

Implementation of the Alternative Approach in SHEDS-PM

The alternative modeling approach using CALINE4 and a separate in-vehicle air quality model is too computationally intensive to implement directly in SHEDS-PM. However, the results of the alternative model can be used to develop values for the slope and intercept of Equation (1) as follows:

$$C_{iv} = r(1-\eta)C_{amb} + r(1-\eta)C_{icr} + \varepsilon \qquad \text{(Eq. 5)}$$

Where,

C_{icr} = the local incremental $PM_{2.5}$ contribution to the near-road $PM_{2.5}$ concentration

Thus, the alternative approach can be implemented in SHEDS-PM by replacing k_{vt} by r (1-η) and replacing b_{vt} by r (1-η)C_{icr}.

Table 4. Inputs and Outputs of Alternative Approach Demonstration Scenarios

		Scenario A	Scenario B	Current SHEDS-PM
CALINE4 Inputs	Wind Speed (m)	2.2	11.8	
	Road Type	Local	Highway	
	Road Width (m)	12.3	34.8	
CALINE4 Outputs	C_{icr} (μg/m^3)	9.0	1.9	
SHEDS-PM Inputs For In-vehicle Microenvironment	Slope	1.0	0.58	0.71
	Intercept (μg/m^3)	9.0	1.1	0.0
SHEDS-PM Outputs	$PM_{2.5}$ Exposure (μg/m^3)	12.9	12.0	12.0
	In-vehicle $PM_{2.5}$ Exposure(μg/m^3)	1.6	0.7	0.7
	Percentage of Total Exposure that Occurs In-vehicle (%)	12.2	5.7	6.0

Demonstration of the Alternative Approach

Two scenarios are chosen to demonstrate the alternative approach and are simulated in SHEDS-PM for Wake County, NC. Scenario A represents the in-vehicle $PM_{2.5}$ exposure when the vehicles travel on local roads with open windows and negligible removal efficiency η. Scenario B represents the in-vehicle $PM_{2.5}$ exposure when the vehicles travel on highways with closed windows and moderate removal efficiency η. The key inputs and selected outputs for each scenario are shown in Table 4. The outputs are compared with the case using the current SHEDS-PM typical settings k_{vt}=0.71 and b_{vt}=0. Scenario A uses a high value of C_{icr} and the upper limits of r and (1- η). Scenario B uses a low C_{icr} and a relatively low r(1- η), 58%, as measured by Rodes *et al.*.[16] Scenario A has a significant larger in-vehicle $PM_{2.5}$ exposure than the base case. However, Scenario B has a simulated in-vehicle exposure level approximately the same as that based on current SHEDS-PM approach.

CONCLUSIONS

The review of algorithms and inputs for SHEDS-PM indicate that the ratio of in-vehicle to ambient concentration is subject to substantial variability. A sensitivity analysis implies that in-vehicle exposure could make up more than half of an individual's exposure. Therefore, updates to in-vehicle microenvironmental inputs for SHEDS-PM are necessary.

An alternative approach which integrates a dispersion model for estimating near-roadway air quality and a mass balance approach for in-vehicle air quality can be used to develop improved inputs for SHEDS-PM.

There are not adequate data regarding ambient $PM_{2.5}$ concentration surrounding vehicles; therefore, the mass loss of ambient $PM_{2.5}$ when penetrating into the vehicle is difficult to quantify. This is a parameter for which additional data would be useful.

The alternative approach should be applied, for reasonable scenarios, to parameters of the linear equation used in SHEDS-PM for estimating in-vehicle $PM_{2.5}$ concentration.

ACKNOWLEDGMENTS

This work has been supported by National Institutes of Health under Grant No. 1 R01 ES014843-01A2. We would like to thank Janet Burke, Steve Perry and Vlad Isakov of U.S. Environmental Protection Agency for their support and help. This paper has not been subject to review by NIH and the authors are solely responsible for its content.

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KEYWORDS
Exposure model, SHEDS, in-vehicle, $PM_{2.5}$, on-road, near-road, microenvironment, air exchange