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Atmos Environ. Author manuscript; available in PMC 2012 October 23.

Published in final edited form as:
Atmos Environ. 2011 September 1; 45(27): 4745–4752. doi:10.1016/j.atmosenv.2011.04.019.

Modeling Of In-Vehicle Human Exposure to Ambient Fine Particulate Matter

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Abstract

A method for estimating in-vehicle $PM_{2.5}$ exposure as part of a scenario-based population simulation model is developed and assessed. In existing models, such as the Stochastic Exposure and Dose Simulation model for Particulate Matter (SHEDS-PM), in-vehicle exposure is estimated using linear regression based on area-wide ambient $PM_{2.5}$ concentration. An alternative modeling approach is explored based on estimation of near-road $PM_{2.5}$ concentration and an in-vehicle mass balance. Near-road $PM_{2.5}$ concentration is estimated using a dispersion model and fixed site monitor (FSM) data. In-vehicle concentration is estimated based on air exchange rate and filter efficiency. In-vehicle concentration varies with road type, traffic flow, windspeed, stability class, and ventilation. Average in-vehicle exposure is estimated to contribute 10 to 20 percent of average daily exposure. The contribution of in-vehicle exposure to total daily exposure can be higher for some individuals. Recommendations are made for updating exposure models and implementation of the alternative approach.

Keywords

particulate matter; vehicles; exposure; variability; sensitivity; simulation

1.0 Introduction

Fine particulate matter ($PM_{2.5}$) is defined as particles 2.5 microns or less in aerodynamic diameter. Human exposure to ambient $PM_{2.5}$ can lead to short-term and chronic respiratory effects, such as exacerbation of asthma, increased susceptibility to infection, decreased lung function, and mortality (USEPA, 2004).

The in-vehicle microenvironment is a potentially significant contributor to human exposure. A microenvironment is a location within which air pollutant concentrations are relatively uniform or well-characterized. Approximately 90% of US commuters drive to work (USDOT, 2008). In-vehicle $PM_{2.5}$ concentration is higher than that of other microenvironments, such as houses (Adams *et al.*, 2001a).

Movement of individuals through microenvironments and their contact with pollutants are simulated using scenario-based human exposure models. Several scenario-based models

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estimate inhalation exposure to airborne PM, such as The Total Human Exposure Model (THEM), Air Pollutants Exposure Model (APEX), and the Stochastic Human Exposure and Dose Simulation for $PM_{2.5}$ (SHEDS-PM) (Klepeis e*t al.*, 1994; USEPA, 2008; Burke, 2005). As an example, SHEDS-PM accounts for eight microenvironments, 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 time spent in each microenvironment and microenvironmental concentrations. The estimated in-vehicle concentration is based on a linear regression relative to fixed site monitor data (FSMs). However, in-vehicle concentration is only weakly related to an area-wide measurement of $PM_{2.5}$ (Adams *et al.*, 2001b). Hence, there is a need for an improved methodology for estimating in-vehicle $PM_{2.5}$ concentration.

The objectives of this paper are to: (a) compare in-vehicle $PM_{2.5}$ exposure to total daily exposure; (b) evaluate an alternative modeling approach for estimating in-vehicle $PM_{2.5}$ concentration; and (c) demonstrate the alternative approach.

2.0 Overview of Exposure Modeling

SHEDS-PM is used here as the basis for population-based exposure modeling. The aspects related to estimation of in-vehicle exposures are briefly reviewed.

2.1 Key Inputs and Outputs

There are four major categories of SHEDS-PM input data. These include: (a) ambient $PM_{2.5}$ concentration; (b) human activity diary data; (c) demographic data regarding population distribution and housing types; and (d) microenvironment-specific parameters for penetration of ambient $PM_{2.5}$ indoors and indoor emission sources (Burke *et al.*, 2001). The user may supply data for ambient $PM_{2.5}$ concentration for a specific geographic area and time period from FSMs, gridded air quality models, or both.

The $PM_{2.5}$ concentration in an indoor microenvironment is estimated in one of three ways: (1) scaled to the ambient concentration by a single fixed ratio; (2) a linear function of the ambient concentration with slope and intercept; or (3) mass balance taking into account penetration and indoor air exchange rates. The outputs include estimated daily average ambient, non-ambient, and total exposure for each individual for each microenvironment.

Commuting activities are simulated for employed individuals living in the study area. Ambient $PM_{2.5}$ concentrations for both the home and work census tracts are taken into account. If the work tract is outside the study area, then the concentrations in the home tract only are used. Commuter trips for people who live outside of the study area are not included.

2.2 In-Vehicle Concentration

The SHEDS-PM in-vehicle $PM_{2.5}$ concentration is estimated as a linear function of home tract ambient $PM_{2.5}$ concentration measured at a FSM or based on an area-wide average estimated from a gridded air quality model:

$$C_{\mathrm{iv,vt}}=k_{\mathrm{vt}}\,C_{\mathrm{amb}}+b_{\mathrm{vt}}+\varepsilon_{\mathrm{vt}} \quad (1)$$

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} = area-wide ambient $PM_{2.5}$ concentration ($\mu g/m^3$)

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k_{vt} = Ratio of in-vehicle to area-wide ambient $PM_{2.5}$ concentration for vehicle type vt, constant

vt = vehicle types: car, bus, truck, train, and other vehicles

ε = unbiased 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, k_{vt}, is estimated by comparing in-vehicle with area-wide ambient measured concentration. In-vehicle sources of $PM_{2.5}$, such as smoking, can be included in b_{vt} (Burke *et al.*, 2001).

3.0 Methodology

A preliminary methodology introduced by Liu *et al.* (2009) is extended and refined here. The methodology includes: (1) assessment of input data and the SHEDS-PM default in-vehicle method PM; (2) sensitivity analysis of the contribution of in-vehicle to total exposure; (3) an alternative approach to estimating in-vehicle $PM_{2.5}$; and (4) demonstration of the alternative approach. A key hypothesis is that in-vehicle $PM_{2.5}$ concentration is estimated more accurately based on ambient concentration immediately outside the vehicle rather than area-wide concentration.

A near roadway air quality model was selected to estimate the incremental component of ambient concentration near a roadway attributable to local emissions from vehicles operating on the roadway (Hatano *et al.*, 1989). This incremental concentration is superimposed with an area-wide concentration from a FSM or a gridded air quality model to estimate the total concentration surrounding vehicles on a roadway. An assumption is made that the contribution of vehicle emissions from the roadway of interest is very small compared to the observed area wide ambient concentration because a FSM is far from the roadway or because a gridded air quality model will typically underestimate near-road concentration because of horizontal and vertical averaging within a grid cell.

There is not an existing model reviewed in USEPA's Guideline on Air Quality Models (USEPA, 2005) that can accurately predict $PM_{2.5}$ concentration on the roadway in the vehicle flow path. CALINE4 can estimate near-roadway concentrations (Chen *et al.*, 2008). Thus, an assumption is made that the near-roadway estimated concentration is a surrogate for the on-road concentration. CALINE4 treats the region directly over the roadway as uniformly distributed mixing zone. Benson *et al.* (1979) verified that the dominant dispersive mechanisms within the mixing zone are mechanical turbulence created by moving vehicles and thermal turbulence from vehicle exhaust, except under highly unstable atmospheric conditions. CALINE4 is applicable for rural and urban scenarios within or outside of the U.S (Broderick *et al.*, 2005, Hatano *et al.*, 1989; Chen *et al.*, 2008). Thus the proposed model is applicable for these areas as well.

Sensitivity analysis was conducted to determine which factors significantly influence near-roadway air quality. The inputs that influence the predicted incremental concentration were compared and ranked.

To estimate in-vehicle air quality, a mass balance approach was adopted (Switzer and Ott, 1992; Abadie *et al.*, 2006). Sensitivity analysis was conducted to assess variability of in-vehicle $PM_{2.5}$ concentration as a function of time spent in-vehicle, air exchange rate and $PM_{2.5}$ filter efficiency.

The coupled near-road and in-vehicle models are demonstrated via example case studies. The case studies account for variations in key inputs including ambient conditions, traffic

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emissions, vehicle characteristics, and vehicle operation. The results from default SHEDS-PM and alternative modeling approaches are compared.

Recommendations are developed regarding how the alternative modeling approach can be simplified for implementation in a scenario-based exposure simulation model such as SHEDS-PM.

4.0 RESULTS

Literature on in-vehicle $PM_{2.5}$ exposure is reviewed with a focus on data that can be implemented as inputs to SHEDS-PM. Key factors influencing $PM_{2.5}$ concentrations are reviewed. Furthermore, sensitivity analysis illustrates the performance of SHEDS-PM. The alternative coupled air quality and in-vehicle modeling approach is presented. Demonstrations of the alternative approach are provided. Results from the alternative approach are used with SHEDS-PM to characterize sensitivity of exposure to the in-vehicle microenvironment.

4.1 Review of In-vehicle Inputs

Adams *et al.* (2001a) measured in-vehicle $PM_{2.5}$ concentration for buses, cars, and subways and compared to FSMs. The ratio of mean in-car to area-wide ambient $PM_{2.5}$ concentration was 1.7 and 2.5 in the summer and winter, respectively. Riediker *et al.* (2003) conducted in-vehicle $PM_{2.5}$ exposure studies with police patrol cars. The average ratio of in-vehicle to area-wide ambient $PM_{2.5}$ concentration was 0.71. Gee and Raper (1999) measured PM_4 on buses in Manchester, UK. The in-bus PM_4 concentration was 12 times higher than the PM_{10} concentration at the closest FSM. Since PM_4 is a component of PM_{10}, these results imply that PM levels for a given size range inside a vehicle can be much larger than that at the nearest FSM. Toll station worker $PM_{2.5}$ exposure was measured in Taipei (Lai *et al.*, 2004). The workers were exposed to $PM_{2.5}$ over 8 hours, with bus and truck lane concentrations averaging 308 μg/m^3, or 14.3 times greater than the nearest FSM.

There is not a strong correlation between FSM ambient and in-vehicle $PM_{2.5}$ concentration (Adams *et al.*, 2001b; Gulliver and Briggs, 2004; Kaur *et al.*, 2007). In-vehicle $PM_{2.5}$ concentrations are correlated with wind speeds and in-vehicle air exchange rates (Adams *et al.*, 2001b; Gomez-Perales *et al.*, 2004; Rodes *et al.*, 1998; Kaur *et al.*, 2005).

4.2 Sensitivity Analysis

Sensitivity analyses were conducted for a case study based on Wake County, NC. Wake County had a 2000 population of 630,000 people and 105 census tracts. A random sample of one percent of these individuals was simulated. The case study includes all ages and genders. Commuting was simulated. $PM_{2.5}$ concentration data are based on hourly 36-km by 36-km grid cell predictions for July 1, 2002 to July 30, 2002 produced by U.S. EPA from the CMAQ air quality model. Census tract ambient concentration is estimated based on the CMAQ grid cell that encloses the census tract centroid. On this basis, 15 grid cells of CMAQ predictions are used. The hourly average weekday $PM_{2.5}$ ambient concentration during 7–9 AM peak morning and 5–7 PM peak afternoon commute times is 18.6 and 15.7 μg/m^3, respectively. The concentrations at other times of day are not substantially different, averaging 18.1 μg/m^3 from midnight to 7 am, 19.7 μg/m^3 from 9 am to 5 pm, and 16.5 μg/m^3, from 7 pm to midnight. During the weekday peak commuting periods, employed people are estimated to spend an average of 70 minutes in a vehicle per day, versus only 42 minutes for people not employed. The daily average ambient $PM_{2.5}$ concentration among all simulated individuals during July 2002 is 12.7 μg/m^3.

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4.2.1 In-vehicle to Ambient Concentration Ratio—Three values of k_{vt} were selected to represent low and high bounding cases and a moderate case, based on real world conditions reported in the literature (Adams *et al.*, 2001a; Lai *et al.*, 2004; Riediker *et al.* 2003). SHEDS-PM Version 3.5 was run for each sensitivity case. Each run had an approximate runtime of 100 minutes on a Windows XP quad-processor computer. For k_{vt} =0.71, of in-vehicle exposure contributed only 6.0% to total exposure for an average individual. However, for k_{vt} =14.3, the average portion increases to 57%. The 95th percentile of inter-individual variability in in-vehicle is approximately 3.3 times the average in-vehicle exposure. Hence, the in-vehicle exposure and its contribution to total exposure are highly variable and can be substantial.

4.2.2 Vehicle Types—SHEDS simulates travel mode choice based on Consolidated Human Activity Data (CHAD) diary data (Burke, 2005). CHAD diaries include National Human Activity Pattern Survey (NHAPS) data from all 50 states of the US and individual study data from: Baltimore, Denver, California, Washington, D.C., Valdez, Cincinnati, and Los Angeles. The time period during which diaries were collected was 1985 to 1998 (McCurdy *et al.*, 2000). The sensitivity of total and in-vehicle exposure to vehicle type was evaluated by comparing four scenarios. In each scenario, one type of vehicle was assumed to have a moderately large in-vehicle to area-wide ambient concentration ratio (k_{vt}) of 2.5, while the other types were assigned ratios of 1.0, as shown in Table 1. A base case for which all k_{vt} were set to 1.0 is also given. The total exposure, in-vehicle exposure, and proportion of in-vehicle to total exposure were insensitive to variations in k_{vt} for the bus, truck and train-vehicles, but significantly affected by variability for cars. This is because relatively few simulated individuals spent time in buses, trucks, or trains. In the US, the average time people spend in cars is more than 90% of the average of time in-vehicle (USDOT, 2008). This proportion can differ locally depending on availability of public transit.

4.2.3 Employment Status—SHEDS-PM simulates in-vehicle exposure for employed and not employed people. The time spent in-vehicle is based on CHAD diaries. Diaries are selected to match the employment status of individuals, and age and gender. A comparison of in-vehicle exposure for employed people versus not employed people for selected values of k_{vt} is given in Table 2. The employed people are estimated to have 33 to 55 percent higher average in-vehicle exposure compared to those who are not employed. This is because employed people spend more time in-vehicles. The in-vehicle exposure and its proportion of total exposure increase with k_{vt} for both groups.

4.3 An Alternative Approach

The use of a ratio such as k_{vt} does not account for the influence of local emissions on the roadway nor factors that affect penetration of $PM_{2.5}$ from the surroundings into the vehicle interior. Key factors influencing in-vehicle $PM_{2.5}$ exposure include traffic conditions, wind speed, in-vehicle air exchange rate, and vehicle type (Adams *et al.*, 2001a, 2001b; Kaur *et al.*, 2005; Chan *et al.*, 2002; Gomez-Perales *et al.*, 2004; Lai *et al.*, 2004; Rodes *et al.*, 1998; Tang and Wang, 2006). To address these factors, a microscale dispersion model and an in-vehicle mass balance model are identified.

4.3.1 Dispersion Model—For predicting near-road concentration, USEPA recommends three Gaussian models: CALINE4, CALINE3 with queuing and hot spot calculations (CAL3QHC) and the atmospheric dispersion modeling system (AERMOD). Chen *et al.* (2008) found that CALINE4 performs best among these three. Key inputs to CALINE4 include road geometry, traffic volume, emission factor, wind speed, and stability class.

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Because existing models cannot predict on-road concentration, a roadside receptor is used as a surrogate. A receptor as close as 6.4 meters to the edge of the road is deemed valid (Chen *et al.*, 2008; Hatano *et al.*, 1989).

To represent variability in area-wide ambient concentrations attributable to roadway characteristics, three categories of roadways are evaluated, including highway, arterial, and local. These correspond to the U.S. Federal Highway Administration road function classifications of interstate, arterials, and collectors, respectively (FHWA, 2000). For local and highway categories, three variations are differentiated by the number of lanes and speed limits. The characteristics of the road types are summarized in Table 3. Results and analysis based on these road types are applicable to any roads that match with these geometric and traffic characteristics, regardless of how they are named in country-specific standards. Emissions factors and traffic flow are given for three traffic flow scenarios.

The near-road $PM_{2.5}$ concentration increments predicted by CALINE4 for various combinations of traffic flow, road type, atmospheric stability class, and wind speed are summarized in Table 4. The lowest wind speeds are specified based on a verification study of CALINE4 (Broderick, *et al.*, 2005). Other wind speeds are specified based on historic weather data for Wake County. The highest predicted concentration increment for each traffic flow scenario occurs for the Highway III roadway and at a wind speed of 1.0 m/s, when the stability class is G. The $PM_{2.5}$ increments are higher for highways than the other road types because the emission factors and traffic volumes are higher. The near- road incremental $PM_{2.5}$ concentrations decrease when wind speed increases. Among these factors, the road type, which is associated with variations in emission factors and traffic volume, has the largest impact on the near-road $PM_{2.5}$ increments.

4.3.2 In-vehicle Mass Balance Model—Switzer and Ott (1992) derived a mass balance model to simulate indoor and in-vehicle microenvironments:

$$\frac{dC_{in}}{dt} = P \times ACH \times C_{sv} - ACH \times C_{in} - C_{in}\beta \quad (2)$$

Where,

C_{in} = Concentration in the vehicle, μg/m^3

C_{sv} = Concentration surrounding the vehicle exterior, μg/m^3

P = Penetration efficiency, dimensionless

ACH= Air exchange rate, 1/hr

β = Deposition rate, 1/hr

This model treats the in-vehicle microenvironment as a well-mixed zone. Allen *et al.* (2007) evaluated the indoor mass balance model by comparing with hourly light scattering measurement data. The estimates of P and β were 1.01±0.10 and 0.26±0.10 hr^{-1}, respectively. They suggested that this model is more reliable than the simple linear regression model in which indoor PM concentrations are regressed on outdoor PM concentrations.

Abi Esber and EI-Fadel (2008) used a similar mass balance model to simulate in-vehicle CO with measured out-vehicle concentrations and field-recorded driving patterns. Removals by air cleaners and sinks were represented by a single term. Since CO is in the gas phase, the penetration rate is 1. The simulation results showed good agreement with measurements

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using the fractional bias (FB) and normalized mean square error (NMSE) as indicators, and most of the results are within 10% of the measurements.

Here, a similar mass balance model is derived based on the schematic of the vehicle cabin and heating, ventilating, and air conditioning (HVAC) system shown in Figure 1. The model is based on the following assumptions: (a) particles inside the vehicle cabin are well-mixed, leading to a uniform concentration; (b) particles enter the vehicle cabin due to advection from outside via windows, infiltration through cracks and by advection from the HVAC system; (c) in the HVAC system, air passes through a filter with filter efficiency η; (d) particles are removed from the vehicle cabin by advection to the outside via windows, exfiltration through cracks, advection to the HVAC system in the case of air recirculation, and deposition to surfaces inside the vehicle; (e) the deposition rate is time- and directionally-independent; (f) the filter removal efficiency for the HVAC system is time-independent and constant irrespective of particle concentration; and (g) the HVAC system can accept air either from the vehicle cabin or from the outdoors.

The mass balance model for the case of the HVAC system using outside air is:

$$\frac{dC_{in}}{dt}=(P'\lambda_{\inf}+\lambda_{adv})C_{sv}+(1-\eta)\lambda_{hvac}C_{sv}-(\lambda_{\inf}+\lambda_{adv}+\lambda_{hvac})C_{in}-C_{in}\beta \quad (3)$$

Where,

P' = Penetration efficiency through vehicle cracks and windows

λ_{inf} = Air exchange rate due to infiltration, 1/hr

λ_{adv} = Air exchange rate due to advection through windows, 1/hr

λ_{hvac} = Air exchange rate for the HVAC system, 1/hr

η = Filter removal efficiency, fraction

β = Deposition rate, 1/hr

The terms in the equation represent advection of outside air into the vehicle, advection of cabin air to the outside, advection of outside air via the HVAC system filter, and deposition inside the cabin. In the case for recirculation of cabin air via the HVAC system, the mass balance is:

$$\frac{dC_{in}}{dt}=[(P'\lambda_{\inf}+\lambda_{adv})C_{sv}-(\lambda_{\inf}+\lambda_{adv})C_{in}]+\eta\lambda_{hvac}C_{in}-C_{in}\beta \quad (4)$$

The terms for this mass balance include the net advection for outside air into the cabin versus cabin air to the outside, the net effect of cabin air that recirculates through the HVAC filter, and deposition inside the cabin.

If the penetration rate is approximately 1 as estimated by Allen *et al.* (2007), the mass balance is:

$$\frac{dC_{in}}{dt}=ACH(C_{sv}-C_{in})-\eta\lambda_{hvac}C_{in}-C_{in}\beta \quad (5)$$

Equations (4) and (5) are solved analytically. The results from these models can be used to specify the ratio of the in-cabin concentration, C_{in}, to the concentration surrounding the vehicle, C_{sv}, which is denoted as k_{vt}'. The estimate of k_{vt}' relative to the vehicle surrounding replaces k_{vt}, which is relative to an FSM in Equation (1).

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Air exchange rates were measured for four vehicles, taking into account variations in-vehicle speed, window opening and ventilation (Ott and Switzer, 2007). The mean ACH ranges from 0.92 hr^{-1} to 78.6 hr^{-1}. The lowest ACH was observed for a stopped 2005 Toyota Corolla with windows closed and no ventilation. The highest ACH was for a 2005 Ford Taurus sedan at a speed of 20 mph with one window fully open and no ventilation.

When all windows were closed and ventilation was set to low for the same vehicle, the air exchange rate ranged from 1.8 hr^{-1} when the vehicle was stopped to 5.6 hr^{-1} when the vehicle was moving at a speed of 35 mph. Hence, these air exchange rates are assumed to be representative of the HVAC system.

During the summer, the typical scenarios of vehicle operation are: (1) windows closed and ventilation on; and (2) windows open and ventilation off. ACH values corresponding to these two scenarios are 30.3 h^{-1} and 71 h^{-1}, respectively (Ott and Switzer, 2007). For scenario (1), air exchange is due to the effects of the ventilation system and vehicle speed. For scenario (2), air exchange is due to advection through windows in addition to the factors of scenario (1).

For a vehicle cabin air exchange rate of 30.3 hr^{-1}, and an HVAC system air exchange rate of 5.6 hr^{-1}, the dominant means of advection is exchange of outside air via windows. Hence, the filter processes only a small portion of the cabin air. At such high rates of advection of outside air, there is very little difference in interior $PM_{2.5}$ concentration between whether the HVAC system intakes outside or recirculated air.

In contrast, if the cabin air exchange rate was relatively low, such as 5 hr^{-1}, and if the HVAC system air exchange rate was comparable at 5.6 hr^{-1}, then at 50% filter efficiency the in-vehicle concentration would be reduced compared to outside air by 33 percent using fresh air, and by 43 percent using recirculated air. As filter efficiency approaches 100%, the cabin concentration would approach only 43 percent of the outside value for either HVAC intake source.

Deposition rates depend on particle size and air exchange rate (He *et al.*, 2005). The deposition rates measured by Thatcher and Layton (1995) in a residential environment for particle sizes of 1–2 μm and 2–3 μm are 0.25 hr^{-1} and 0.55 h^{-1}, respectively. Meng *et al.* (2005) measured a mean deposition rate of 0.79 hr^{-1} for $PM_{2.5}$ in a residential environment. As a bounding estimate of sensitivity, if the deposition rate were 0 hr^{-1} instead of 1.0 hr^{-1}, the cabin concentration would be 47 percent of the outside value. Hence, the results are not very sensitive to deposition rate.

For cases of high advection of outside air, the ratio of in-cabin to outdoor concentration is approximately 0.82 to 0.99, depending on the filter efficiency. When the windows are closed and the HVAC system is in recirculation mode, the ratio would be more likely to be in the range of 0.5 to 0.8.

4.4 Implementation in SHEDS-PM

The combination of CALINE4 and an in-vehicle air quality model is too computationally intensive for direct implementation in SHEDS-PM. However, the $PM_{2.5}$ concentration surrounding the vehicle (C_{sv}) is predicted by superimposing the incremental component of ambient concentration on a roadway (C_{icr}) that is attributable to local emissions from vehicles operating on the roadway to an area-wide concentration from a FSM or a gridded air quality model (C_{amb}). Therefore, the slope and intercept of Equation (1) can be estimated based on:

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$$C_{iv,vt}=k_{vt}'C_{amb}+k_{vt}'C_{icr}+b_{vt}+\varepsilon_{vt} \quad (6)$$

The term $k_{vt}'C_{icr}+b_{vt}$, can be substituted as the intercept in Equation (1). To demonstrate the application of the alternative approach, the near-road incremental $PM_{2.5}$ concentration estimation model and the in-vehicle air quality model are applied for various scenarios. The model inputs are varied to analyze the sensitivity of the modeling results and estimated exposure to selected inputs.

4.5 Demonstration of the Alternative Approach

In order to demonstrate the application of the alternative approach and compare with the approach used in SHEDS, the highest near-road $PM_{2.5}$ concentration increment scenario is used as an example. The largest incremental concentration in Table 4 is 23 μg/m^3 for free flow, 70 μg/m^3 for capacity flow, and 79 μg/m^3 for traffic congestion. Six cases of the in-vehicle mass balance are analyzed for each of the free flow, capacity and congestion traffic flow scenarios. Both employed and unemployed people are simulated. Selected in-vehicle mass balance model inputs for these scenarios are given in Table 5. These cases represent typical air exchange rates in combination with bounding estimates of filter removal efficiency between 0 and 1. The corresponding estimated daily average exposures are included in Table 5. In-vehicle daily average exposures for all simulated individuals and all days are calculated manually based on SHEDS-PM results:

$$E_{iv,vt}=E_{amb}\times k_{vt}'\frac{\overline{C_{amb}}+C_{icr}}{C_{amb}} \quad (7)$$

Where,

$E_{iv,\,vt}$ = estimated in-vehicle daily average exposures, μg/m^3

E_{amb} = daily average in-vehicle exposure to ambient $PM_{2.5}$ for all simulated individuals and all days estimated by SHEDS-PM using C_{amb}, μg/m^3

$\overline{C_{amb}}$ = average area-wide ambient concentration for all simulated individuals and all days during the study period, μg/m^3

A similar approach is used for 95th percentile, in which the in-vehicle concentration for the 95th percentile individual is estimated based on their respective daily average in-vehicle exposure and area-wide ambient concentration.

For the free flow scenario, the estimated in-vehicle concentrations range from 16 to 36 μg/m^3, with 24-hr average exposures ranging from 1.0 to 2.2 μg/m^3. For the capacity scenario, the in-vehicle concentration range is 36 to 82 μg/m^3, and for the congestion scenario, the in-vehicle concentration range is 40 to 91 μg/m^3. Riediker *et al.* (2003) measured in-vehicle $PM_{2.5}$ concentrations for selected vehicles in Wake County, NC in 2001 and observed a mean of 24 μg/m^3 with a range from 4 μg/m^3 to 54 μg/m^3. The range of estimated in-vehicle concentrations in Table 5 is similar to the range of observed concentrations measured by Riediker *et al.* (2003), and thus considered to be reasonable.

The congestion scenario has the highest incremental $PM_{2.5}$ concentration and thus the greatest in-vehicle $PM_{2.5}$ exposure comparing to other two scenarios for the same road type, meteorology and vehicle operator. This is mainly due to higher traffic flow than for the other scenarios.

For a given scenario, in-vehicle exposure is sensitive to filter efficiency for low values of ACH, but not at high values. For example, when ACH is low, the in-vehicle $PM_{2.5}$

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concentration and exposure decrease approximately 50% as the filter removal efficiency varies from 0 to an upper bound of 1. When ACH is high, the in-vehicle $PM_{2.5}$ concentration and exposure decrease less than 10% as the filter removal efficiency increases. Cars with open windows usually have high ACH values. Thus, having open windows and not using recirculation settings in a vehicle can be expected to reduce correlation with filter removal efficiency.

The in-vehicle exposure for the free flow scenario represents 8 to 17 percent of daily average exposure, which is comparable to the 6 to 18 percent contribution estimated in the sensitivity analysis from low to moderate values of the in-vehicle to ambient ratio based on independent studies. The contribution of in-vehicle to total exposure for the capacity scenario is higher by 5 to 7 percentage points than for the free-flow scenario. The congestion and capacity scenarios have similar contributions of in-vehicle to total exposure. The in-vehicle exposure is as much as 23 percent of the total estimated exposure.

The high end in-vehicle exposures are approximately 3.3 times higher than the mean exposures. This is due to variability in exposure duration. Based on the CHAD diaries, high end (97.5^{th} percentile) exposure duration is 330 minutes longer than low end (2.5^{th} percentile) durations. Longer commuting times are likely to represent occupational situations that involve a significant amount of driving. The CHAD database does not specifically distinguish commuting times with respect to purpose, but distinguishes driving that is related to 'work' versus that not related to 'work'.

5.0 Conclusions

The ratio of in-vehicle to ambient concentration is subject to substantial variability. In-vehicle exposure potentially can contribute more than half of an individual's daily $PM_{2.5}$ exposure. However, existing exposure models such as SHEDS-PM use highly simplified modeling techniques that are not able to account for key sources of variability in in-vehicle exposure. The in-vehicle concentrations are influenced by emissions on the roadway, whereas a FSM might be located sufficiently far from the roadway that it is not a good indicator of on-road air quality. Thus, the preferred method for estimating in-vehicle concentration is to estimate the ambient concentration surrounding the vehicle, from which the concentration inside the vehicle can be estimated. However, there is not yet an accepted modeling approach for estimating on-road concentration. The most relevant surrogate to on-road concentration that can be reliably estimated with existing tools, such as CALINE4, is near-road concentration.

An alternative approach based on near-road PM levels and mass transfer between the near-road air and interior of the vehicle cabin takes into account road width, on-road emission rate, traffic volume, wind speed, stability class, in-vehicle air exchange rate, filter efficiency, and deposition rate. The estimated results from the coupled near-road air quality and in-vehicle mass balance models are comparable to those obtained from in-vehicle measurements. This approach can be applied within the existing parameterization of SHEDS-PM.

SHEDS-PM accounts for inter-personal variability in activity patterns and ambient $PM_{2.5}$ concentrations, but does not allow for different in-vehicle linear regression parameters in a single run. The in-vehicle modeling approach demonstrated here can be implemented as a post processing step based on SHEDS-PM output estimates of ambient concentration and microenvironmental concentrations for each individual.

Depending on traffic flow, meteorological conditions, vehicle emission rates, the status of vehicle windows and HVAC system, and duration of time spent in-vehicle, the in-vehicle

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exposure may account for approximately 10 to 20 percent of total daily average exposure. However, high end in-vehicle exposures can be a factor of 3 greater than mean exposures, because of differences in exposure duration.

Typical driving scenarios, which are combinations of roadway types, meteorological conditions, and ventilation conditions, can be identified for a study area based on applicable emission factors, traffic volume data, historical meteorological data, and ventilation assumptions. Additional surveys of ventilation control behavior (window open or close, ventilation on or off) depending on weather would help to improve characterization of variability in-vehicle operation.

Field measurements of in-vehicle and surrounding-vehicle $PM_{2.5}$ concentrations are recommended to better estimate in-vehicle/out-vehicle penetration rate, HVAC filter efficiency and in-vehicle deposition rate, and to aid in evaluation and validation of the model.

The methodology presented here is a promising basis for refinement of population-based exposure simulation models in order to better account for the in-vehicle contribution to total exposure, both for the average and for variability between vehicle routes, vehicle operators and individual in-vehicle exposure durations.

Acknowledgments

This paper was developed in part under STAR Research Assistance Agreement No. R833863 awarded by the U.S. Environmental Protection Agency and by Grant No. 1 R01 ES014843-01A2 awarded by the National Institutes of Health. It has not been formally reviewed by the EPA or NIH. Janet M. Burke and Haluk Ozkaynak of the National Exposure Research Laboratory of the U.S. EPA provided access to SHEDS-PM and guidance. The views expressed in this document are solely those of the authors and the EPA and NIH do not endorse any products or commercial services mentioned in this paper.

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- Fine particulate matter (PM2.5) infiltrates into vehicle cabins.
- The magnitude of human exposures to fine particles inside vehicles are estimated.
- The in-vehicle microenvironment is a significant contributor to daily average total exposure.
- High end in-vehicle exposures can be a factor of three greater than mean exposures.

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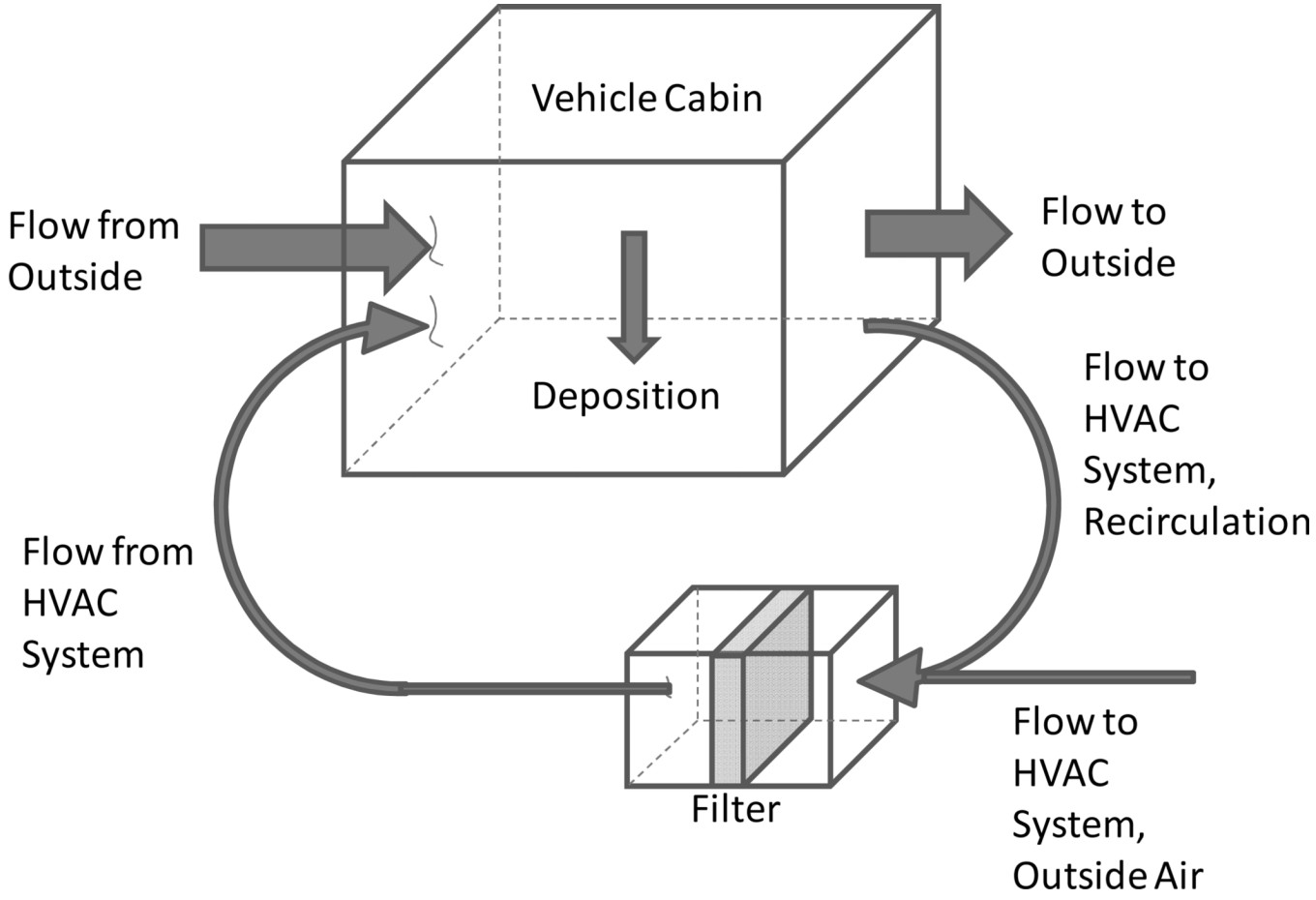

Figure 1.
Schematic of Air Flow Through the Vehicle Cabin and the Heating, Ventilating, and Air Conditioning (HVAC) System

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Table 1

Sensitivity of estimated total and in-vehicle exposure to variations in the in-vehicle to ambient $PM_{2.5}$ concentration ratios among four types of vehicles

	Input Ratio of In-vehicle to Ambient $PM_{2.5}$ Concentration (k_{vt})				Results from SHEDS-PM Model		
Scenario	**Car**	**Bus**	**Truck**	**Train**	**Average 24-hr Total $PM_{2.5}$ Exposure ($\mu g/m^3$)**	**Average 24-hr In-vehicle $PM_{2.5}$ Exposure ($\mu g/m^3$)**	**Percentage of Average Total Exposure that Occurs In-vehicle (%)**
1	2.5	1	1	1	13.7	2.4	18
2	1	2.5	1	1	12.4	1.1	8.6
3	1	1	2.5	1	12.4	1.1	8.7
4	1	1	1	2.5	12.3	1.0	8.4

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Table 2

Comparison of estimated in-vehicle $PM_{2.5}$ exposure for employed people versus not employed people[a]

		Results from SHEDS-PM Model for Daily $PM_{2.5}$ Exposure[b]					
		Employed People			People Not Employed[a]		
Scenario	Input Ratio of In-Vehicle to Ambient $PM_{2.5}$ Concentration (k_{vt})	Average In-Vehicle (μg/m^3)	95th Percentile In-Vehicle (μg/m^3)	Average Percent of Total that Occurs In Vehicle (%)	Average In-Vehicle (μg/m^3)	95th Percentile In-Vehicle (μg/m^3)	Average Percent of Total that Occurs In Vehicle (%)
1	0.71	0.8	2.6	6.8	0.6	2.0	4.9
2	2.5	3.0	9.3	21	2.0	7.2	16
3	14.3	18	55	61	12	40	51

[a]"People not employed" refers to those who do not work, including children and retired people.

[b]Results are based on 105 census tracts in Wake county, NC for a simulated population of 6300 people and hourly air quality estimates during July 2002 from CMAQ.

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Table 3

Characteristics of road types and traffic conditions.

Road Type	No. Lanes	Width (m)			Free Flow			Capacity			Congestion		
		Lane[a]	Road[b]	Mixing Zone[c]	Ave. Speed (mph)	$PM_{2.5}$ Emission Factor (g/vehicle-km)[d]	Traffic Flow (vehicles per hour)[e]	Ave. Speed (mph)	$PM_{2.5}$ Emission Factor (g/vehicle-km)[d]	Traffic Flow (vehicles per hour)[f]	Ave. Speed (mph)[g]	$PM_{2.5}$ Emission Factor (g/vehicle-km)[d]	Traffic Flow (vehicles per hour)[h]
Local I	2	3.15	6.3	12.3	30	0.033	1078	30	0.033	3234	7	0.033	4269
Local II	3	3.15	9.5	15.5	30	0.033	1617	30	0.033	4851	7	0.033	6403
Local III	4	3.15	12.6	18.6	30	0.033	2105	30	0.033	6315	7	0.033	8336
Arterial	4	3.45	13.8	19.8	45	0.041	2231	45	0.041	6693	13	0.033	8634
Highway I	4	3.6	14.4	20.4	60	0.100	2271	60	0.100	6813	53	0.100	7494
Highway II	6	3.6	21.6	27.6	60	0.100	3407	60	0.100	10221	50	0.100	11754
Highway III	8	3.6	28.8	34.8	60	0.100	4542	60	0.100	13626	50	0.100	15670

[a]Calculated by averaging the lower and uper limits of the AASHTO standard (AASHTO, 2007).

[b]Calculated by multiplying numbers of lanes and the lane width.

[c]Calculated by adding 3 meters on each side to the total width of the road (Hatano *et al.*, 1989).

[d]Based on vehicle speeds and emission factors from a tunnel study for mix of light duty and heavy duty vehicles by Kristensson *et al.* (2004)

[e]Time interval between vehicles in the same lane is 6 seconds.

[f]Time interval between vehicles in the same lane is 2 seconds.

[g]Based on vehicle speeds between level of service (LOS) E and F (TRB, 1994).

[h]Based on volume to capacity (v/c) ratio estimated by vehicle speeds (TRB, 1997).

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Table 4

Near-road $PM_{2.5}$ increment (μg/m^3) estimated using CALINE4 for selected traffic flow, road type, wind speed and stability class scenarios

Traffic Flow	Wind Speed[a] (m/s)	1.0		2.3		3.3		4.9		5.4	
	Stability Class[b]	A	G	A	G	A	G	B	E	B	E
	Road Type	Estimated Incremental $PM_{2.5}$ Concentration Near the Road Attributed to Onroad Emissions (μg/m^3)									
Free Flow	Local I	2.1	2.4	1.1	1.2	0.8	1.0	0.6	0.7	0.5	0.6
	Local II	3.1	3.5	1.7	1.9	1.2	1.4	0.9	1.0	0.8	0.9
	Local III	3.9	4.4	2.1	2.5	1.7	1.8	1.1	1.3	1.0	1.2
	Arterial	5.1	5.8	2.8	3.3	2.1	2.4	1.5	1.7	1.4	1.6
	Highway I	12	14	7.1	8.1	5.3	5.9	3.8	4.3	3.5	3.9
	Highway II	17	19	10	11	7.7	8.7	5.3	6.4	5.2	5.9
	Highway III	20	23	12	14	9.5	11	7.2	8.2	6.5	7.5
Capacity	Local I	6.3	7.2	3.3	3.6	2.4	3.0	1.8	2.1	1.5	1.8
	Local II	9.3	11	5.1	5.7	3.6	4.2	2.7	3.0	2.4	2.7
	Local III	12	13	6.3	7.5	5.1	5.4	3.3	3.9	3.0	3.6
	Arterial	15	17	8.4	9.9	6.3	7.2	4.5	5.1	4.2	4.8
	Highway I	36	42	21	24	16	18	11	13	11	12
	Highway II	51	57	30	33	23	26	16	19	16	18
	Highway III	60	70	36	42	29	33	22	25	20	23
Congestion	Local I	8.3	9.5	4.4	4.8	3.2	4.0	2.4	2.8	2.0	2.4
	Local II	12	14	6.7	7.5	4.8	5.5	3.6	4.0	3.2	3.6
	Local III	15	17	8.3	9.9	6.7	7.1	4.4	5.1	4.0	4.8
	Arterial	16	18	8.7	10	6.5	7.5	4.7	5.3	4.4	5.0
	Highway I	40	46	23	27	17	19	13	14	12	13
	Highway II	59	66	35	38	27	30	18	22	18	20
	Highway III	69	79	41	48	33	38	25	28	22	26

[a]The lowest wind speeds are chosen based on a verification study of CALINE4 (Broderick, *et al.*, 2005), and the other wind speeds are selected based on historic weather data for Wake County, NC.

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[b]Upper and lower bounds of stability classes are chosen. For high wind speeds such as 4.9 and 5.4 m/s, the stability class A, F and G are not possible.

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Table 5

In-vehicle exposure in-vehicle mass balance model inputs and corresponding estimated daily average and 95th percentile exposure, for selected highway traffic flow scenarios

Traffic Flow	Input Assumptions[a]			SHEDS-PM Output				
	Air Exchange Rate ACH (h^{-1})	Filter Removal Efficiency η	In-vehicle/ surroundings Ratio of $PM_{2.5}$ Concentration for Vehicle Type vt k_{vt}'	$PM_{2.5}$ Concentration in the Vehicle C_{iv} ($\mu g/m^3$)	Average 24-hr In-vehicle $PM_{2.5}$ Exposure ($\mu g/m^3$)	95th Percentile 24-hr In-vehicle $PM_{2.5}$ Exposure ($\mu g/m^3$)	Average 24-hr Total $PM_{2.5}$ Exposure ($\mu g/m^3$)	Percentage of Total Exposure that Occurs In Vehicle
Free Flow[b]	5	0	0.83	30	1.9	5.2	13	14
	5	1	0.43	16	1.0	2.7	12	8.3
	30.3	0	0.97	35	2.2	6.0	14	16
	30.3	1	0.82	30	1.9	5.2	13	14
	71	0	0.99	36	2.2	6.0	14	17
	71	1	0.91	33	2.1	5.7	13	15
Capacity[c]	5	0	0.83	69	4.3	10.8	21	21
	5	1	0.43	36	2.2	5.6	16	14
	30.3	0	0.97	80	5.0	13.1	23	22
	30.3	1	0.82	68	4.3	10.8	21	21
	71	0	0.99	82	5.0	13.1	23	22
	71	1	0.91	75	4.8	12.3	22	22
Congestion[d]	5	0	0.83	76	4.8	12.4	23	21
	5	1	0.43	40	2.5	6.3	17	15
	30.3	0	0.97	89	5.6	14.3	25	22
	30.3	1	0.82	76	4.8	12.2	23	21
	71	0	0.99	91	5.6	14.2	25	22
	71	1	0.91	84	5.3	13.4	24	23

[a]Area wide concentration is 12.7 $\mu g/m^3$. Deposition rate is 1.0 hr^{-1}. HVAC air exchange rate is 5.6 hr^{-1}.

[b]Incremental near roadway concentration is 23.3 ug/m^3. C_{SV} = 36.0 $\mu g/m^3$.

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[c] Incremental near roadway concentration is 69.9 ug/m^3. C_{SV} = 72.6 μg/m^3.

[d] Incremental near roadway concentration is 79.4 ug/m^3. C_{SV} = 92.1 μg/m^3.