

Passenger Vehicle Secondhand Smoke Particulate Measurements

David Bohac, PE

Member ASHRAE

Emily Waldart, MPH

Zheng Zhou, PhD

ABSTRACT

One in four Minnesota middle school students report that they have ridden in a car with someone who was smoking cigarettes in the preceding week (Minnesota Youth Tobacco and Asthma Survey, 2011), yet only seven U.S. states have policies prohibiting smoking with youth in vehicles.

This study expands on previous research by measuring secondhand smoke particulate concentrations under a comprehensive set of conditions that affect passenger exposure. A total of 171 trials were conducted, including duplicate trials to determine reliability. The monitoring included continuous photometer measurements of fine particles (PM_{2.5}) before, during, and after a participant drove and smoked a cigarette. The instruments were installed in 3 to 5 locations inside the vehicle and 1 location outside to measure and compensate for ambient air particulates. The monitoring was conducted for three vehicle types (sedan, minivan, SUV), two driving speeds, four window positions, and multiple ventilation operating conditions over both summer and winter conditions.

*When the windows were closed the peak 30 second average PM_{2.5} concentrations ranged from 359 to 5612 with an average of 2013 µg/m³. After smoking stopped, it took from 4 minutes to over 25 minutes for the particulate level to decrease to the background level. When the active smoking and post-smoking periods were combined, the passenger's total PM_{2.5} exposure averaged 12,250 min*µg/m³, which is about equal to sitting in a typical smoky bar for three hours (Bohac et al. 2010). The most significant factors on SHS exposure were window position, driving speed, ventilation operation, and smoking behavior. Opening the driver's window 2" reduced exposure by 93% and fully opening the window reduced exposure by another 62%. The average exposure was 63% lower for highway driving (60 mph) than city driving (30 mph). Operating the ventilation in recirculating mode did not have a significant effect, but operating in fresh air mode reduced exposure by 42% when driving 30 mph. Holding the cigarette and blowing smoke towards the window reduced exposure by 34% to 75% compared to holding the cigarette and blowing smoke toward the inside of the vehicle. There was little difference in exposure between interior locations except one of the far back seats of the minivan had significantly lower exposure.*

INTRODUCTION

Exposure to secondhand smoke (SHS) is a significant air quality concern that affects most organs in the human body with causal links to an increased risk of adverse health outcomes including lung cancer, asthma, coronary heart disease, stroke, and acute respiratory illness (SG 2014). SHS is a complex mixture of over 7,000 constituents, at least 69 of which can cause cancer, and any level of exposure carries some associated risk (SG 2014). Both particulate and gas-phase constituents have been linked to adverse health effects. For example, many carcinogens in SHS, including polycyclic aromatic hydrocarbons and tobacco-specific N-nitrosamines, are concentrated in the particle phase (Hoffman and Wynder 1986; Hecht and Hoffman 1988). Exposure to SHS is a particular concern for children with links to numerous health concerns including asthma, lower level of lung function, chronic respiratory symptoms, chronic middle ear effusion, and acute respiratory illness (SG 2014).

SHS in vehicles poses a significant health risk to passengers, especially children who are likely to be at greater risk

David Bohac is the Director of Research for the Center for Energy and Environment (CEE), Minneapolis, MN. **Emily Waldart** was a research analyst at CEE. **Zheng Zhou** is a Postdoctoral Research Scientist at Columbia University Medical Center, New York, NY.

from SHS exposure due to their more rapid breathing rate, less developed immune system, and inability to move away from the source. Recent research found that exposure in a simulated car setting could alter airway resistance and impedance, possibly leading to the development of respiratory disease (Vardavas et al. 2013). In another study, Kabir et al. (2009) found that Irish schoolchildren who reported SHS exposure in cars had increased likelihood of both respiratory and allergic symptoms. An analysis of SHS exposure of inner-city children ages 6 to 10 found that vehicles were the third most common location of SHS exposure after relatives' houses and their own houses (Chen et al. 2010). U.S. national and state surveys have shown that children are regularly exposed to SHS in vehicles. For example, the National Youth Tobacco Survey found that while the prevalence of grade 6 to 12 students' exposure to SHS in vehicles declined from 2000 to 2009, in 2009 over one-fifth of nonsmoking students were exposed to SHS (King, Dube, and Tynan 2012).

In the U.S., smoke-free legislation has led to significant changes in exposure to SHS in work settings and public places such as bars and restaurants. The identified health risks from SHS have led to comprehensive indoor smoking bans in 24 U.S. states, the District of Columbia (SG 2014), and many countries. However, there is a lack of legislation on smoking bans in cars. As of 2011 three countries, nine Canadian providences, six Australian states and territories had passed laws prohibiting smoking in vehicles carrying children (CCS 2011), and seven U.S. states and Puerto Rico have banned smoking in vehicles when children are present (PHLC 2016).

Previous Vehicle Particulate Measurements

Levels of SHS in cars can be extremely high due to the restricted area in which the smoke is circulated. Researchers have measured fine particulate (PM_{2.5}) concentrations under a variety of settings to better understand the range of exposure a passenger may experience (see Table 1). General¹ findings indicate that window configuration and speed have the greatest effect on exposure, and ventilation operation has a significant but lesser effect. The highest concentrations of PM_{2.5} are measured when a car is not moving and the windows are closed; in these instances cars typically exceed mean concentrations of 1000 µg/m³ during the exposure period². In contrast, concentrations are typically less than 100 µg/m³ during high speed trips with one or more windows open. An observational study found that the mean concentration of PM_{2.5} during smoking trips was 85 µg/m³ (Semple et al. 2012), hundreds of µg/m³ lower than typical averages reported in studies modeling a range of real life scenarios. For contextual reference, the Environmental Protection Agency's daily standard for ambient air is 35 µg/m³, with levels over 100 µg/m³ considered unhealthy for sensitive populations and levels over 300 µg/m³ considered hazardous for all populations.

Table 1. Summary of PM_{2.5} Results From Previous Studies

Study	# Cars	Test Conditions	PM _{2.5} Results (µg/m ³)
Liu and Zhu (2010)	1	0, 30, and 60 mph; 4 window, 5 ventilation; 2 traffic density	Mean concentration during 30 minute period with 5 to 6 minutes of active smoking = 47-1741
Northcross (2014)	1	0 mph; 2 window	Mean concentrations for two conditions = 746 and 1172
Offerman (2002)	1	19 mph; 3 ventilation	Mean concentration during smoking = 92-1195; total exposure mg-hr/m ³ = 9-868
Ott et al. (2008)	2	Several controlled conditions of speed, window position, and ventilation system status	Mean concentration during the exposure period = 82-1150
Rees and Connolly (2006)	3	40 mph; 2 window; no vents or heating/cooling	Highest observed mean concentration during smoking = 271
Semple et al. (2012)	17	Participants smoked and drove their own vehicles normally during 3-day study	Mean concentrations 85 and 7.4 during smoking and non-smoking car journeys, respectively

¹ It is difficult to make precise comparisons of results across studies due to differences in study design and methodology.

² The term "exposure period" is used loosely to capture the range of results found in previous literature. The exposure period typically starts when a cigarette is lit. The endpoint is either when the PM_{2.5} returns to ambient levels or after a pre-defined time period (i.e., 20 or 30 minutes).

Sendzik et al. (2009)	18	period Drove at normal speeds; varying window and vent	Mean concentrations during smoking = 60-3850; during 20-minute exposure period = 26-4377
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Study Objectives

Previous studies have generally focused on individual issues related to vehicle SHS exposure with each study conducted under a more limited set of vehicle operating conditions. This study was designed to not only measure SHS particulate exposure, but also compute the ventilation and particle removal rates that impact the concentration of gas and particle phase components of SHS. The experiments were configured to capture a broad range of real-life scenarios for three different types of vehicles. The variables included window position, ventilation system settings, driving speed, and weather. In addition, a limited number of trials were conducted to evaluate the impact of cigarette placement and multiple monitors were used inside the vehicles to assess the impact of location. The study results provide further guidance on the most critical variables that impact SHS exposure and on data that can be used for modelling studies for other components of SHS. This paper includes results of the impact of test variables on SHS particulate exposure. The particle removal and ventilation rate results are not included in this paper, but will be included in the project final report.

METHODOLOGY

A series of trials were conducted for differing combinations of variables that could potentially affect exposure to SHS in vehicles. The continuous monitoring included laser photometer PM_{2.5} concentration at three to five passenger locations and outdoors; carbon dioxide (CO₂) and carbon monoxide (CO) concentrations at three passenger locations and outdoors; and a Global Positioning System (GPS) for vehicle speed. The photometer zero stability is $\pm 1 \mu\text{g}/\text{m}^3$ over 24 hours and it has a temperature coefficient of $+0.5 \mu\text{g}/\text{m}^3$ per °C. The logging interval was set to 15 seconds and the unit was fitted with a 2.5 μm 50% cut point impactor with the flow rate adjusted to 1.7 liters per minute. A photometer calibration factor of 0.31 was used based on previous studies that reported factors from 0.295 to 0.328 for SHS (Klepeis, Ott, and Switzer 2007; Jenkins et al. 2004). The instrument was zero adjusted before each day of trials. A dual-wavelength, non-dispersive infrared sensor measured CO₂ with a range of 0 to 5000 ppm. An electrochemical sensor measured the CO concentration over a range of 0 to 500 ppm. The CO₂ and CO sensors were zero and span calibrated before each day of testing. The three concentrations were recorded at five second intervals, and the vehicle speed was recorded at one second intervals. For each interior location the height of the instrument inlet was designed to be at the head level of a young child so that the data collected will provide a reasonable estimate of a child's exposure to SHS. For all three vehicles a set of instruments was placed in the front passenger seat, with two sets in the rear seat behind the driver and front passenger. Another set of equipment was placed on the roof to monitor outdoor concentrations. For the minivan trials two additional sets of equipment were placed in the third row of seats directly behind the driver and front passenger locations. The outdoor air temperature, wind speed, and wind direction was obtained from the local National Oceanic and Atmospheric Administration weather station.

For each trial the participant configured the windows and ventilation system to the trial specifications and then drove for about five minutes to establish baseline concentrations. The participant then smoked a single cigarette from start to completion at their normal pace. During that time they also opened a valve to inject CO₂ into the vehicle to produce an elevated concentration. After the smoking was complete the injection was stopped and the participant continued to drive for 25 minutes with the vehicle window and ventilation in the same configuration. The windows were then opened for a five minute airing out period. If the PM_{2.5} did not return to baseline conditions, the vehicle was stopped and the doors opened to complete the airing out. Figure 1 displays the measurements for a trial with the minivan driven on local roads at a median speed of 31 mph. The rapid increases in PM_{2.5} and CO₂ concentrations occurred when the vehicle was stopped at a stop light. The concentration increases during smoking were typically more consistent when the vehicle speed was more consistent on expressways or local roads without long stops.

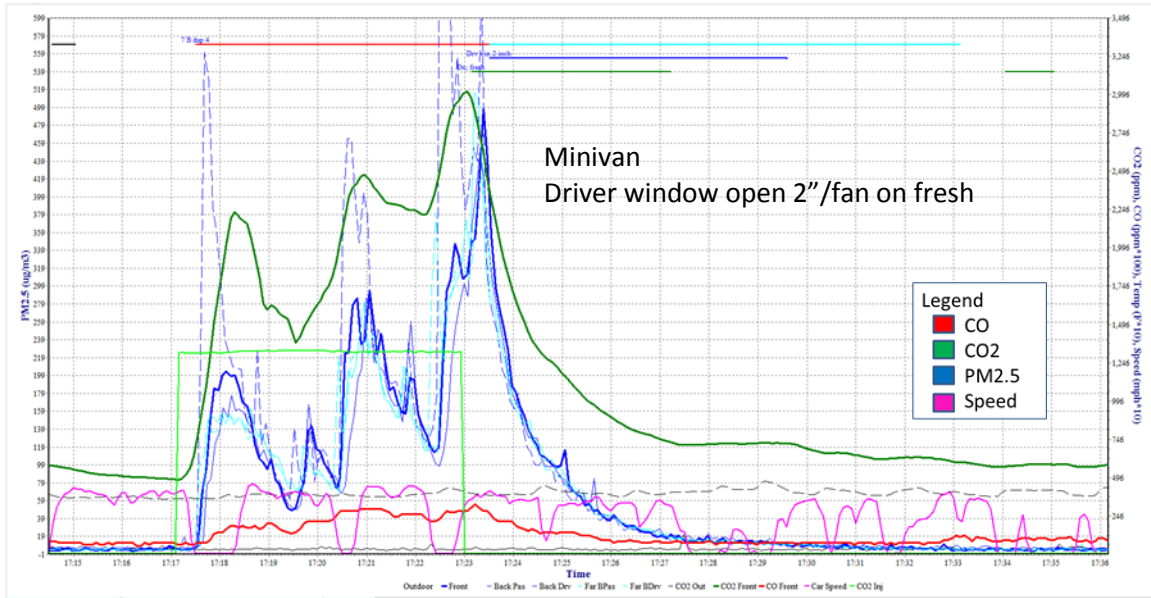


Figure 1 Continuous measurements for a typical trial. The red horizontal line at the top of the chart indicates the smoking period, the aqua line the post-smoking exposure period, the blue line the period used for the PM_{2.5} removal rate decay, the green line the CO₂ ventilation rate decay, and the far right green line the baseline period. The light green line indicates the CO₂ injection period.

A total of 46 unique trials were conducted for each of the three vehicles (sedan, minivan, SUV) with variations in season (summer and winter), driving speed (30 mph for local and 60 mph for expressway), window position (closed, open 2”, open driver window, and all windows open), ventilation (off, recirc, fresh, defrost, heat, and both) and cigarette position (normal, towards window, and towards inside). A trial was repeated when the protocol was not followed. When possible, trials were also repeated if the front passenger or both rear seat PM_{2.5} measurements were not complete, or when the vehicle speed criteria³ were not met. The average PM_{2.5} concentration for a one minute period prior to smoking or after exposure was used to compute the baseline concentration, and that value was subtracted from the concentrations during the exposure period to represent the PM_{2.5} concentration that was only due to smoking. The advantage of using a baseline measurement from the same instrument was that the approach compensated for hourly drift in the instrument’s zero offset. The disadvantage was that it did not compensate for variations that could have occurred during the smoking and exposure periods due to variations in location and vehicle emissions. However, the local driving was typically performed on parkways that had limited vehicle traffic, and the expressway driving was performed during off-commute hours when traffic was light and the vehicle could be driven at the posted speed. For 146 trials with outdoor PM_{2.5} measurements, the median of the standard deviation of PM_{2.5} over the exposure period was 1.7 µg/m³ with an interquartile range (IQR) of 1.6 µg/m³.

The start of the smoking period was identified by a rapid increase in PM_{2.5} concentration, and the end was set to be the peak concentration at the end of the build-up in concentration. The end of the exposure period was specified as the first time that the PM_{2.5} concentration was less than the average baseline concentration plus the standard deviation of baseline concentration for two consecutive five second measurement periods. The average and short duration (5, 10, 15, 30 second) maximum PM_{2.5} concentrations were computed for the smoking and total exposure periods (smoking and post-smoking decay) for each trial.

³ For local driving trials the speed was to be less than 15 mph and greater than 35 mph no more than 40% of the time and for expressway trials the speed was to be less than 50 or greater than 70 mph no more than 40% of the time.

The PM_{2.5} removal rate was computed from the decrease in PM_{2.5} concentration with time from near the end of the smoking period through the remaining exposure period. The rate was determined from the opposite of the slope of the linear regression of the log of the measured concentration adjusted for the baseline or outdoor concentration. The ventilation rate was computed using the same approach for either the CO or CO₂ measured concentrations. In general, the CO measurements were used for trials with lower ventilation when the accuracy of the CO concentration was acceptable and the CO₂ concentration did not reach steady state by the end of the exposure period. CO₂ measurements were used for trials with higher ventilation.

RESULTS AND DISCUSSION

Forty-three (20%) of the 214 trials were dropped due to issues with vehicle speed (16), PM_{2.5} instrumentation (15), and protocol compliance (12). In addition, five trials had a slight deviation from the speed criteria and could not be repeated, and the results were used in the analysis. There were measured results for 138 unique trials (46 unique trial types for each of the three vehicles) and 33 duplicate trials for a total of 171 trials with valid results. The average and standard deviation of the outside temperature for the summer trials was 70.4 ± 10.3 °F with an average wind speed of 10.0 ± 4.9 mph, and in the winter the average outside temperature was 18.4 ± 13.2 °F with an average wind speed of 11.1 ± 5.2 mph. The average vehicle speed for local driving trials was 22.5 ± 3.2 mph, and there was no statistically significant difference in the average between the three vehicles. The average speed for the expressway driving trials was 56.0 ± 7.4 mph. The sedan speed was statistically significantly lower than that for the minivan speed ($p=0.05$) and was marginally lower than that for the SUV speed ($p=0.12$). The average smoking duration was 5.1 ± 1.1 minutes with a statistically significantly longer duration for the summer (5.4 ± 1.0 minutes) than the winter (4.7 ± 1.0 minutes). The shorter winter smoking time was largely a result in a change to a different technician part way through the winter monitoring, with the smoking duration for the second technician typically 1.3 minutes shorter than that for the first technician.

The maximum 30 second average (or peak) PM_{2.5} concentration during the exposure period (e.g. from the start of smoking until concentration decreased to baseline) was compiled for all of the trials. The average peak concentration across the 36 trials was $2,013 \pm 1,283$ µg/m³ with a maximum of 5,612 µg/m³ for the SUV driven at 30 mph in the summer with the ventilation system off and a minimum of 359 µg/m³ for the SUV driven at 30 mph in the winter with the system on combined heat/defrost mode. Peak concentrations above 1,000 µg/m³ are consistent with values reported by previous studies (Offerman 2002 and Sendzik et al. 2009) and are higher than what is typically measured in bars where smoking is permitted. The high concentrations are due to the small vehicle volume where the smoke is released and low ventilation when windows are closed. For the 60 trials with the driver window open 2" the average peak concentration dropped to 378 ± 420 µg/m³ with a range of 29 to 2886 µg/m³. Comparing the average for 12 similar trials⁴, average peak concentration with the window opened 2" was 87% lower than the average with closed windows. For the same 12 trials the average peak concentration was 55% lower with the driver window fully opened compared to just 2" open, and it was 32% lower with all windows opened compared to only the driver window opened. Having all four windows opened decreased the average peak concentration by 96% compared to when the windows were closed. Another important issue is the time required for SHS PM_{2.5} concentrations to return to background levels after smoking stops. That decay time ranged from 4.3 minutes to over 25 minutes (average= 11.5 minutes) when the windows were closed. The average time was reduced to 4.2 minutes with the driver window opened 2" and 1.7 minutes with the driver window fully open.

A key concern for passenger exposure to SHS is not just the peak concentration or duration, but the total integrated exposure to SHS PM_{2.5}. This was computed as the average PM_{2.5} concentration over the exposure period multiplied by the exposure duration. The results for the 138 unique trials are displayed in Figure 2. The trends in these results are similar to those for peak concentration. For closed-window trials the average integrated exposure was

⁴ Summer monitoring with ventilation set to recirculation and fresh outdoor air for 30 and 60 mph speeds.

12,250 + 11,360 min* $\mu\text{g}/\text{m}^3$. This is roughly equal to sitting in a typical smoky bar for three hours (Bohac et al 2010). For the same set of 12 trial types, the exposure with the driver window open 2" was 94% lower than with windows closed, and the exposure for a fully open driver window was 65% less than with the window open 2". The reductions of 94% and 65% are similar to the reductions of 87% and 55% for the average peak concentrations.

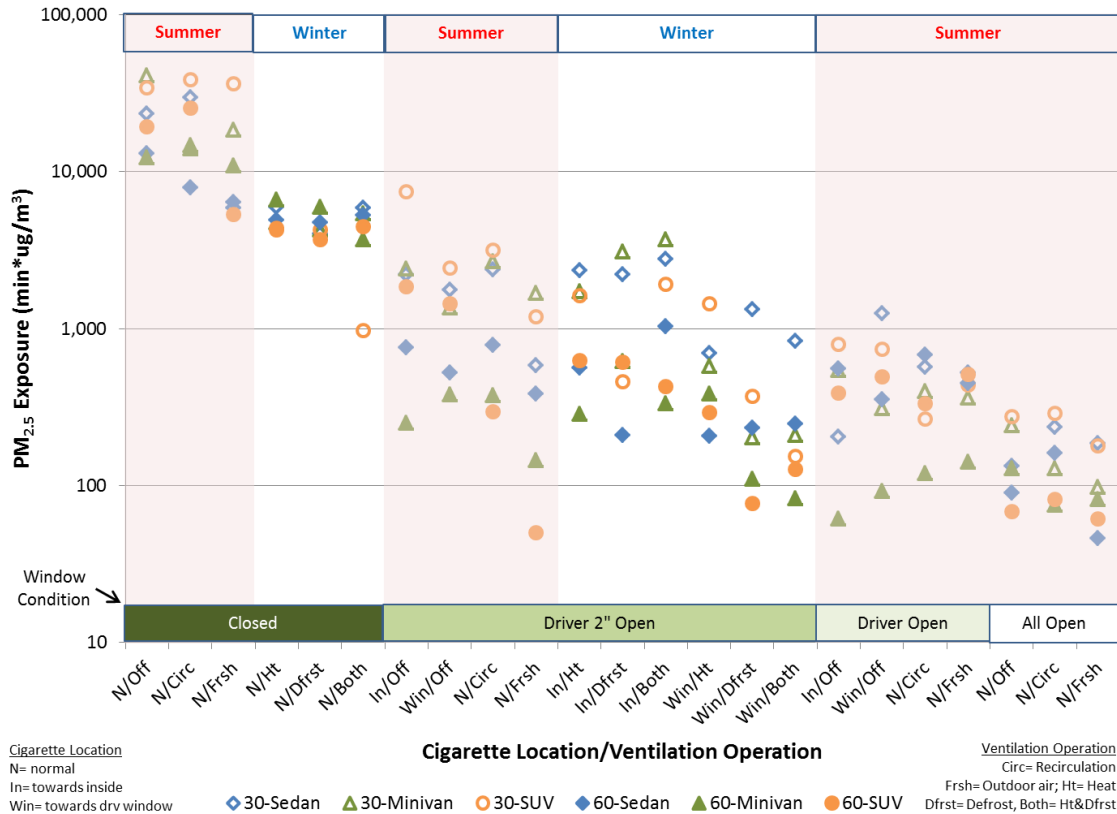


Figure 2 SHS PM_{2.5} exposure for summer (shaded red) and winter (white) trials.

While comparing average data for 12 similar trials conducted in the summer provides some results on the impact of window conditions, it does not fully utilize the information contained in the data set. A multivariable regression with the integrated exposure as the dependant variable was performed for the summer trial results to evaluate the impact of window position, vehicle speed, ventilation operation, vehicle, interior location, and cigarette position, as well as the interactive effects between some of the variables. Each monitoring location and all duplicate trials were treated as separate data points, resulting in 266 observations. The regression R-squared was 0.91. Charts of the adjusted mean or average marginal values are displayed in Figure 3. As expected, window position had the greatest impact. There was a 93% decrease from windows closed to 2" open, a 62% decrease from driver open to 2" open, and a 75% decrease from driver open to all open. The first two differences are statistically significant ($p < 0.01$), while the third is not ($p = 0.45$). The differences are similar to those for the average values for the similar set of 12 summer trials. There was no statistically significant difference between the fan off and the recirculating operation. The lower exposure for the fresh air mode of 42% for the 30 mph speed was significant, but the lower exposure of 49% for 60 mph driving was not statistically significant ($p = 0.38$). Over all driving speeds, the exposure was 46% greater ($p = 0.043$) for the minivan than for the sedan, and 69% greater ($p < 0.01$) for the SUV than for the sedan. However, when the results are broken out by speed, the differences are statistically significant for 30 mph and not for 60 mph ($p = 0.14$).

and 0.15; see chart Effect of Vehicle and Speed below). The 60 mph exposures were 68%, 53%, and 69% lower than the 30 mph values for the sedan, minivan, and SUV respectively, with all differences statistically significant. This is consistent with a previous study that found about a two to one variation in the 30 minute average PM_{2.5} concentration for 30 and 60 mph driving speeds (Liu and Zhu 2010). As indicated by the Effect of Passenger Location chart below, there was no statistically significant difference in exposure by location except for the driver's side of the last row of seats in the minivan.

A separate multivariable regression was conducted that included the impact of how the cigarette was smoked. The driver was told to either (1) smoke normally, (2) hold the cigarette and exhale smoke toward the window versus, or (3) hold the cigarette and exhale smoke toward the inside of the car. As shown by the Effect of Cigarette Position by Vehicle chart below, for all three vehicles there was a highly or marginally statistically significantly lower exposure for the second option. The reductions were 67%, 75%, and 34% for the sedan, minivan, and SUV respectively. This indicates that the driver's smoking behavior can have a very significant impact on the passenger SHS exposure.

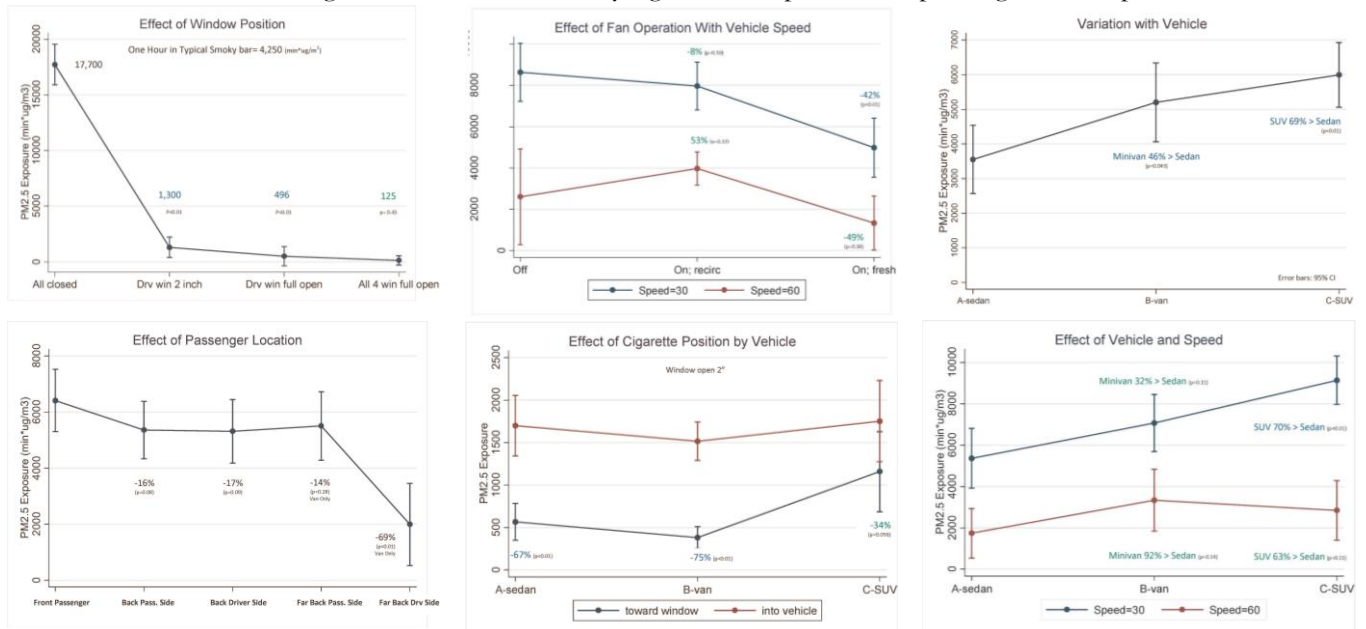


Figure 3 Multivariable regression margin results for SHS PM_{2.5} exposure trial data.

CONCLUSION

The 138 unique trials provided information for the impact of various operating conditions, interior location, and smoking behavior on SHS PM_{2.5} peak and integrated exposures. When the windows were closed, the peak 30 second average PM_{2.5} concentrations ranged from 359 to 5612 with an average of 2013 $\mu\text{g}/\text{m}^3$. Those levels are higher than concentrations typically found in bars where smoking is permitted and are mainly due to the small vehicle volume where the smoke is released. Average peak concentrations decreased by 87% when the driver window was open 2" and another 55% lower when the driver window was fully open. With all windows closed it took from 4.3 minutes to over 25 minutes after smoking stopped for the particulate level to decrease to the background level. The average time was reduced to 4.2 minutes with the driver window open 2" and 1.7 minutes with the driver window fully open.

When the active smoking and post-smoking periods were combined, the passenger's total PM_{2.5} exposure averaged 12,250 min*ug/m³, which is about equal to sitting in a typical smoky bar for three hours (Bohac et al. 2010). The most significant factors on SHS exposure were window position, driving speed, ventilation operation, and smoking behavior. Opening the driver's window 2" reduces exposure by 93% and fully opening the window reduces

exposure by another 62%. The average exposure was 63% lower for highway driving (60mph) than city driving (30mph). Operating the ventilation in recirculating mode did not have a significant effect, but turning it to the fresh air mode reduced exposure by 42% when driving 30 mph. Holding the cigarette and blowing smoke towards the window reduced exposure by 34% to 75% compared to holding it and blowing smoke towards the inside. There was little difference in exposure between interior locations except one of the far back seats of the minivan had significantly lower exposure.

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