An Experimental Investigation of Tobacco Smoke Pollution in Cars

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Executive Summary

This report presents the findings of a study examining levels of Tobacco Smoke Pollution (TSP, also known as second-hand smoke or environmental tobacco smoke) in cars. TSP has been identified as a serious public health threat. Although there has been a rapid increase in the number of jurisdictions that now prohibit smoking in public places, to date, there have been just a few successful attempts to pass similar laws prohibiting smoking in cars, where the small cabin space may contribute to concentrated exposure. In particular, TSP constitutes a potentially serious health hazard to children because of prolonged exposure and because of their small size. Evidence on the levels of TSP in cars is needed to determine whether laws prohibiting smoking in cars, particularly in the presence of children, are warranted.

The objective of this study was to identify levels of TSP in cars via the measurement of fine respirable particles (< 2.5 microns in diameter, or $PM_{2.5}$), an established marker for TSP, easily inhaled deep into the lungs. A second objective was to measure levels of TSP in cars under varying conditions to determine how differences in ventilation and air flow might reduce TSP.

Levels of $PM_{2.5}$ were measured in 18 different cars. Car owners smoked a single cigarette in their cars in each of five controlled *in vivo* air-sampling conditions. Each condition varied on movement of the car, presence of air conditioning, open windows, and combinations of these air flow influences. The conditions were created to capture the very broad range of air flow/ventilation environments from very little ventilation to the maximal possible air flow/ventilation situation (all 4 windows open all the way while the car was moving). Air quality readings were measured using a TSI Dustrak portable air monitoring device, with its inlet tube positioned in the middle of the back seat, at the level of a child's head in a car seat.

Smoking just a single cigarette in a car generated extremely high average levels of $PM_{2.5}$: >3,800 $\mu g/m^3$ in the condition with the least airflow (motionless car, windows closed). This is equivalent to over 100 times the U.S. Environmental Protection Agency's 24-hour standard for fine particle exposure of 35 $\mu g/m^3$, and 15 times the U.S. Environmental Protection Agency's 24-hour "hazardous" rating of 250 $\mu g/m^3$ for fine particle exposure. It should be noted that using the EPA ratings and those of other agencies as a guide in evaluating TSP may underestimate the actual hazard, given that TSP, which is known to contain many carcinogens, is likely more hazardous per unit weight than outdoor air pollution, for which these ratings have been created.[20]

In moderate ventilation conditions (air conditioning or having the smoking driver hold the cigarette next to a half-open window), the average levels of $PM_{2.5}$ were reduced, but still at significantly high levels (air conditioning = 844 $\mu g/m^3$; holding cigarette next to a half-open window = 223 $\mu g/m^3$).

This study demonstrates that TSP in cars reaches unhealthy levels, even under realistic ventilation conditions. Given the chronic nature of high TSP exposure that children can receive in cars, there is a need to inform the public that smoking in cars constitutes a potentially significant health hazard, particularly to children. These results lend support to the efforts occurring across a growing number of jurisdictions, including Ontario, to prohibit smoking in cars in the presence of children.

Introduction

Tobacco smoke pollution[i] (TSP) is a complex mixture of contaminants released by the burning and exhalation of tobacco products in the form of various gases and particulate matter. TSP is responsible for the preventable morbidity and mortality of hundreds of thousands of non-smokers worldwide.[1-9] TSP has been found to be a cause of lung cancer,[10,11] and heart disease.[12-14] Recently, a review of the epidemiological evidence by the California Environmental Protection Agency (EPA) concluded that TSP was associated with a significant increase in breast cancer.[2]

Accordingly there has been a movement for laws to reduce exposure to TSP in a number of countries, culminating in its inclusion in the recently adopted Framework Convention on Tobacco Control (FCTC).[15] So far, the scope of this protection has been public places, with much of the focus on hospitals, municipal buildings, and more recently, in restaurants and bars. The movement for this protection has been driven by health data and recent research on air quality demonstrating high TSP exposure in public places. Of particular concern are particles that measure less than 2.5 microns in diameter ($PM_{2.5}$) because they can be easily inhaled deeply into the lungs. $PM_{2.5}$ has previously been measured in bars and restaurants[16-19] where tobacco smoke contributes 90-95% of the $PM_{2.5}$ exposure concentration. These studies have been used to not only demonstrate exposure, but also to show that smoke-free spaces reduce overall $PM_{2.5}$ exposure and smoking consumption.[20,21,22]

As of yet, however, there have been few studies in personal spaces such as homes, and cars. Therefore, this study aims to assess the levels of TSP in cars under different conditions, and to compare the values obtained here with measurements taken in other venues, and with environmental standards for outdoor air.

Of great concern is the health hazard that TSP exposure poses to children who are still developing physically and biologically. Compared to adults, children breathe more rapidly, absorb more pollutants because of their small size, have less developed immune systems, and are more vulnerable to cellular mutations,[23] making them more susceptible to the effects of TSP exposure. TSP is associated with a greater likelihood of asthma, triggering an asthma attack, and chronic lung diseases,[11] and has been recognized as a cause of Sudden Infant Death Syndrome (SIDS).[11,24] It has been estimated that over 20 million children in the U.S. will be exposed to TSP on a daily basis with exposure often occurring in the home or family vehicle.[1] In Canada, 1.7 million children will be exposed to TSP in the home, and 1.4 million will be exposed to TSP in the car.[25]

Given the restricted area within which the smoke is circulated, the levels of TSP in cars would seem to pose a significant risk to children. According to a report by the Ontario Medical Association (OMA), TSP levels in vehicles can be 23 times greater than in a house.[26] In addition, results from an

[i] We use the term "tobacco smoke pollution", although other terms such as "environmental tobacco smoke", "second-hand smoke", and "passive smoke" have been used.

observational study examining the prevalence of smoking in cars by socioeconomic area, suggest that lower SES children may receive more frequent exposure, thus furthering health inequalities already being experienced by some of the most vulnerable members of society.[27]

Recognizing the need to protect children from TSP exposure in cars, several jurisdictions in Australia, the U.S., and Puerto Rico have enacted bans on smoking in cars while children are present.[28, 29] In Canada, the first successful measure to prohibit smoking in cars carrying children was passed in Wolfville, Nova Scotia and will be enacted June 1, 2008.[28] This action set an important precedent, inspiring other city and provincial governments to follow suit. To date, private members' bills have been introduced in the Yukon Territory and in the provinces of Nova Scotia, British Columbia, and Ontario. On December 6th, 2007, Ontario MPP David Orazietti introduced Bill 11, an amendment of the Smoke-Free Ontario Act aimed at prohibiting smoking in a vehicle where children under the age of 16 are present.[30] The bill offers an opportunity to represent the attitudes of most Ontarians who support legislation banning smoking in cars,[31,32] by implementing a policy designed to eliminate a significant potential threat to children's health.

Despite the significant health threat that TSP poses and the health benefits that reduced exposure offers, there are few studies that have attempted to measure the levels of TSP in cars and the methods by which the research was conducted vary in terms of quality, and in their findings.

Findings from tobacco industry affiliated studies using a wide-variety of TSP monitoring techniques from gas chromatography, to ambient nicotine, to particle monitoring, seem to offer mixed conclusions. In general these industry-supported studies have reported that nicotine and particulate levels in cars vary substantially (Range=0.4 $\mu g/m^3$ [negligible air quality value] to 1010 $\mu g/m^3$ [extremely poor air quality value]).[33] The majority of these studies conclude that, based on their findings, exposure to individuals is minimal, and therefore, not a concern. However, the results and generalizability of these studies should be interpreted with caution. A number of important factors are not controlled for or explained in some of the reports. For example, in one study that reported low concentrations of nicotine, no cigarettes were actually lit or smoked during the sampling period. Additionally, monitoring for this particular study was only conducted in one car.[34] These studies do not include discussion of basic details on the car sampling method such as the number of cigarettes smoked,[35,36] how long the sampling was conducted,[35,36] and if there were open windows or fans running in the car.[34-36] In addition, during the 1990s, a number of court trials lead to the release of internal tobacco industry documents revealing that some of this research[33-36] was sponsored by or orchestrated by the tobacco companies as part of a campaign to discredit emerging evidence suggesting that TSP was harmful.[37,38]

Since mid 2006, a new, independent body of evidence regarding TSP in cars has begun to emerge. In a preliminary study, Varadavas et al. measured respiratory particles ($PM_{2.5}$) in a stationary pick-up utility vehicle, small car, and station wagon under varying window settings.[39] The concentrations of $PM_{2.5}$ were very high (1,330 – 13,150$\mu g/m^3$), with the actual value dependent upon the size of the vehicle and setting of the window (fully open, half open, closed). In a second study, $PM_{2.5}$ and carbon monoxide were monitored in 3 cars over a standardized driving route with either the windows completely open or closed under a variety of smoking phases (no smoking, smoking one cigarette, and immediate post-smoking).[40] Rees et al. found that the mean levels of $PM_{2.5}$ were highest in the active smoking, windows closed condition (272µg/m^3), followed by the post-smoking, closed window condition, the active smoking, windows open condition, and the post-smoking windows open condition. The lowest mean levels were found in the no smoking, open and closed window conditions. Similar trends were found for mean carbon monoxide levels. In a third study examining the relationship between cigarette smoke and various vehicle air exchange rates, Ott et al. studied four vehicles under various moving and stationary conditions.[41] They found that increasing speed, opening windows, and adding ventilation through fans or air conditioning could affect the levels of $PM_{2.5}$ and carbon monoxide in each vehicle. However, these factors did not eliminate exposure, and in several circumstances, the monitored $PM_{2.5}$ levels exceeded EPA health-based $PM_{2.5}$ ambient standards for 24-hour exposure of 35µg/m^3.[ii] Together, these new findings offer alternate evidence of the levels of TSP and potential harm experienced in personal vehicles.

However, given the recent interest in banning smoking in cars where children are present and the few studies clearly documenting the levels of TSP, further research quantifying the levels of exposure is warranted. In addition, considering that smokers attempt to eliminate or reduce TSP in their cars using a wide variety of practices, research comparing the levels of TSP exposure in different cars under a variety of real-life scenarios is needed to help guide personal and public health policies.

Accordingly, the purpose of the present study was to quantify the levels of TSP exposure in cars under controlled conditions using established methods, employing the use of real-time $PM_{2.5}$ monitoring devices. TSP was measured in different cars under a broad range of ventilation and air flow conditions—from those with very low air flow/ventilation (car stopped, all 4 windows up) to a very high (possibly maximal) air flow/ventilation condition: car moving and with all 4 windows completely open, despite the likely impracticality of such an environment in a moving car. Between these two ends of the continuum were three conditions that captured more typical air flow/ventilation situations that would be experienced by smoking drivers and their passengers: (1) all windows up and with no fan or air conditioning on; (2) all windows up and with air conditioning on (a very common situation in high heat and also in cooler weather, particularly in cold climates when opening windows is generally not tolerable); and (3) the window of the driver open by 18 cm and with the driver holding the cigarette next to the open window while driving.

[ii] In Canada, the proposed national 24-hour ambient air quality standard for PM2.5 exposure has been set at 30 µg/m3. for the year 2010. http://www.ccme.ca/assets/pdf/pm_oz_2000_2005_rpt_e.pdf

Methods

Participants

Individuals who smoked and who owned cars were recruited through newspaper advertisements and hand flyers distributed in Southern Ontario between the summer of 2005 and the summer of 2007. Potential participants completed a pre-screening questionnaire to identify their smoking status, car ownership status, and whether they permitted smoking in their car. Individuals who identified themselves as being a current smoker (defined as having smoked for at least a year, and smoking at least once a week), owning a car, and permitting smoking in their car were invited to participate. There were a total of 18 participants.

Experimental Design

Each of the 18 participants participated in each of five experimental conditions. These five conditions varied on dimensions that were potentially related to differences in ventilation that would be naturally determined by a smoker in a car:

Condition 1: Participant smoked a single cigarette in their car with all windows closed and the engine off.
Condition 2: Participant smoked a single cigarette with all windows closed during a 20-minute drive.
Condition 3: Participant smoked a single cigarette with all windows completely open during a 20-minute drive.
Condition 4: Participant smoked a single cigarette with all windows closed except the driver's window, which was rolled 18cm down, approximately half-way, during a 20-minute drive. The participant was instructed to hold the cigarette close to the open window (not sticking it out the window lest the wind extinguish the cigarette) between puffs.
Condition 5: Participant smoked a single cigarette with all windows closed but with air conditioning running during a 20-minute drive.

In Conditions 1-4, the climate control fan inside the cars was turned off (set at zero), and the car left in a passive ventilation state (i.e., fresh air from outside the cabin without the aid of fans or blowers could naturally pass into the car). In Condition 5, the air conditioner and climate control fan were set to a medium speed (e.g., set at 2 or 3 on a 5 point cooling/speed scale). For all conditions, the air recirculation feature was turned off, allowing a fresh intake of air through the vents. Between each experimental condition, the car doors and/or windows were opened for several minutes to clear out the remaining TSP from the previous condition. Readings taken for several minutes prior to the beginning of the next condition indicated that this procedure was sufficient to effectively bring $PM_{2.5}$ back to baseline levels. There were no significant differences between the pre-condition and post-condition baseline levels for any of the five experimental conditions (all *p*s > .40). The sequence of conditions for each participant varied in their order, due to the need to adjust for weather conditions or comfort of the participant (e.g., if there was a rain shower in the middle of the appointment, or if the weather was too cold for participants to complete the conditions that called for a window or windows to be open).

Procedure

The researcher used the air quality monitoring equipment to measure the level of $PM_{2.5}$ for 25 minutes in the car during each condition, and for 5 minutes outside the car before and after the condition to control for outdoor ambient contributions.

Each condition began with participants completing a brief 2-minute questionnaire. Participants verified the type and age of their car, when the last cigarette had been smoked in the car, how many cigarettes had been smoked in their car in the last 24 hours, brand of cigarette most commonly smoked by the participant, and how much of a cigarette they typically smoked (right to the filter, nearly to the filter, most of the cigarette, about half of the cigarette). After the participants completed the questionnaire, the researcher installed the monitoring devices (see below) to monitor levels of $PM_{2.5}$ under each of five conditions.

Air quality in each vehicle was monitored using a TSI Dustrak.[iii] The TSI Dustrak is a portable battery operated aerosol monitor that measures several sizes of particle mass (PM) including $PM_{2.5}$, and is capable of measuring concentrations of particulates up to 100,000 $\mu g/m^3$. For this study the Dustrak was used with a 2.5 micron impactor to measure $PM_{2.5}$ and was calibrated prior to each experimental session with a HEPA filter according to manufacturer's specifications. The Dustrak was set to record the average $PM_{2.5}$ concentration every 60 seconds. A customized calibration factor of 0.32 was applied to the device, determined by calibrating the device in this study with other light-scattering photometers that have been calibrated for measuring TSP.[17-20] Two other devices were also placed in the car to monitor air quality parameters (e.g., carbon monoxide), but those data are not included in this analysis. Monitoring was conducted on one car at a time.

The monitors were placed in the participant's car using a Velcro harness, positioning the monitor devices centrally in the car. The location and height of the monitoring device was designed to be at head level for a young child sitting in a car seat in the middle of the back seat of each car so that the data collected would provide a reasonable estimate of exposure levels of $PM_{2.5}$ for a young child sitting in the back seat of the car. The experimental set-up of the monitoring devices is pictured in Figure 1.

[iii] The TSI Dustrak Aerosol Monitor (TSI Inc., Shoreview, MN, http://www.tsi.com/Product.aspx?Pid=11)

Figure 1: Photo of Equipment Set-up Inside a Participant's Car

Once the equipment was secure, participants received specific instructions about the set-up of the car. Table 1 presents the specific instructions that were given to each participant for each condition. Participants then stepped into the driver seat and closed the door immediately behind them. Participants were instructed not to turn on the car, open any windows or doors while inside the car, and not to turn on the air conditioning or fan, unless specified by the condition (Condition 5). Participants were allowed to listen to the radio.

Once in the car and comfortable, participants could light the cigarette and smoke it at a natural pace. Participants then either finished the cigarette and immediately left the vehicle, or drove for 20 minutes while consuming their cigarette before returning and exiting the vehicle. In all cases, the time from the door opening to the door shutting again during the exit period was less than 3 seconds, and did not appear to affect the levels of $PM_{2.5}$ in the car.

Table 1: Descriptive Summary of Conditions

Condition	Engine On	20-Minute Drive	Window Position	A/C On
Condition 1	No	No	All closed	No
Condition 2	Yes	Yes	All closed	No
Condition 3	Yes	Yes	All open	No
Condition 4	Yes	Yes	Driver's window open 18 cm*	No
Condition 5	Yes	Yes	All closed	Yes

* Participants completed this condition by holding their cigarette next to the half-open window when not inhaling the cigarette.

During each condition, the participant smoked only one cigarette. The start and end times for each cigarette consumed were recorded by the experimenter. The air monitoring devices remained in the car for at least 25 minutes following participant entry into the car to provide baseline comparison values before the car was started, and once the engine was started but before the cigarette was lit. For conditions 2-4, participants were asked to remain on city streets, maintaining speeds of approximately 50 kilometres per hour while obeying local traffic signs and regulations, and to drive the same route. Upon completion of the survey and air quality sample, each participant was thanked, given both a verbal and written summary of the research, and paid $10 CAD per condition as a token of our appreciation. For the safety of the participant, experimental conditions did not take place when the outside temperature exceeded 30° Celsius (86° Fahrenheit).[iv] All procedures were reviewed by and received ethics clearance from the Human Research Ethics Committee at the University of Waterloo.

Data were collected from 18 individuals each driving a 4-door car. According to manufacturers' specifications, the average size of the interior cabin space of the vehicles was $2.6m^3$, ranging from $2.4m^3$ to $2.9m^3$. All participants reported regularly smoking cigarettes in their cars. During each of the 5 experimental conditions, all participants smoked their regular brand of cigarette. In terms of the amount of the cigarette typically consumed, 1 participant reported smoking about half or less, 4 participants reported smoking most of the cigarette, 8 reported smoking nearly to the filter, and 5 reported smoking right to the filter.

Data Analysis

TrakPro software (Version 3.41; TSI Incorporated, St. Paul, MN.) was used to download data from the TSI Dustrak for analysis. Data were then exported to Microsoft Excel 97 (Microsoft Corporation, Redmond, WA) to create graphs. Data from the Sidepak and Dustrak were recorded every minute. Averages before, during and after sampling were computed. The distributions of the averages for each of the five conditions were highly positively skewed; thus, these data were subjected to a natural log transformation to eliminate the skewness.

Differences in average levels across conditions were tested using a one-way, repeated measures analysis of variance (ANOVA). Given that this approach to the analysis of repeated measures is sensitive to departures from sphericity, we tested for sphericity; Mauchly's Test of Sphericity was not statistically significant, χ^2 (df=9) = 13.69, p=.136. We therefore proceeded to conduct the tests of differences in $PM_{2.5}$ among conditions by employing the univariate repeated measures approach.[v]

[iv] All experimental conditions were completed when the outside temperature was between 0-29° Celsius (32-85° Fahrenheit).

[v] We also conducted the tests from a multivariate (MANOVA) approach and obtained the same pattern of results. For simplicity, we report only the results from the univariate repeated measures ANOVA.

Results

Mean results of each air quality monitoring condition and outdoor air baseline measures are reported in Table 2. Data from one vehicle were not included in the average values calculated for Conditions 2 and 5 because the cigarette consumption pattern did not meet procedural specifications. Instead of consuming the same cigarette continuously during the condition, the cigarette was extinguished part way through consumption, and then re-lit. Results for the relighting smoking pattern are presented later in this report. Data from this same car were not included in the calculations for Condition 4 due to machine failure.

Table 2: Summary of Average $PM_{2.5}$ Levels and Cigarette Consumption Time by Condition

Condition	Avg. $PM_{2.5}$ at Baseline ($\mu g/m^3$)		Avg. $PM_{2.5}$ Exposure ($\mu g/m^3$)			Ave. Peak ($\mu g/m^3$)	Ave. Cig. Time (min.)
	Before	After	Prior to lit cig.	During cig.	20 minutes		
Condition 1	14.7	15.8	13.4	3850.9	4377.5	6590.5	7.5
Condition 2*	15.1	16.3	16.6	2412.5	1729.6	3781.0	7.9
Condition 3†	14.1	15.0	13.7	60.4	26.3	142.1	5.9
Condition 4‡	14.3	15.4	13.2	222.5	91.3	382.1	6.6
Condition 5§	15.1	14.4	16.0	844.4	470.3	1249.7	7.3

* Average of 17 car monitoring sessions, one car excluded due to sequential lighting
† Average of 17 car monitoring sessions, one car excluded due to machine failure
‡ 20 minutes after the start of the cigarette
§ Refers to the time period in which the cigarette was consumed

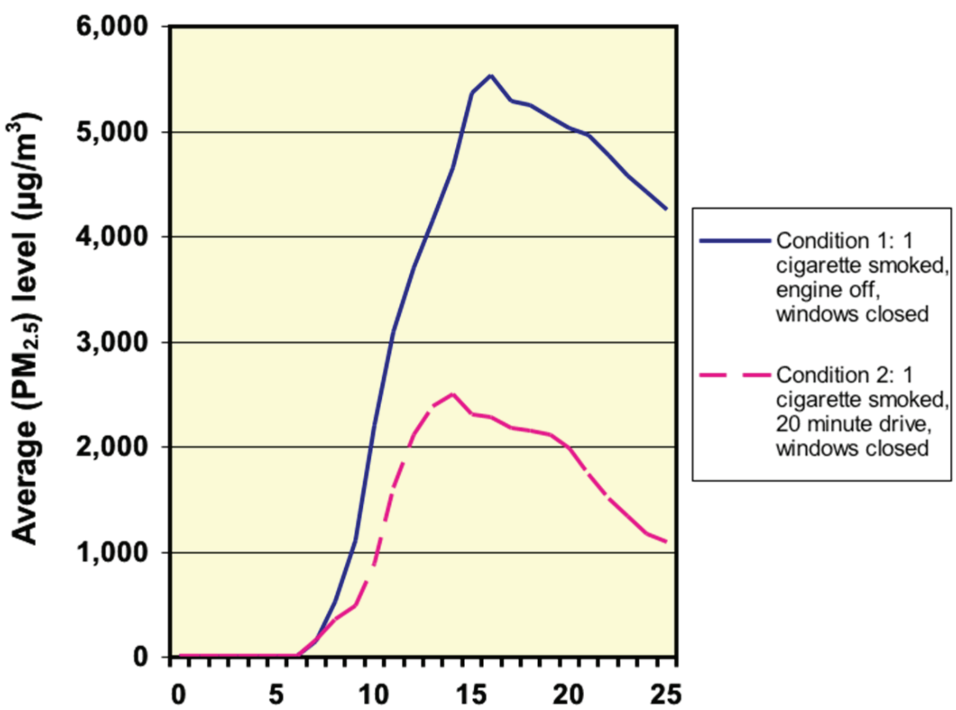
Average baseline levels of $PM_{2.5}$ for all 5 conditions were relatively low outside the car before and after each condition, as well as inside the car prior to the introduction of a lit cigarette. Once the cigarette was lit, $PM_{2.5}$ levels in all conditions quickly exceeded baseline measurements.

The repeated measures ANOVA on the average $PM_{2.5}$ levels recorded during the time the cigarette was being smoked revealed a main effect of condition, $F(4,64) = 214.8$, $p<.0001$. Bonferroni post-hoc tests for the pairwise comparisons indicated that every condition was significantly different from every other on $PM_{2.5}$ levels during the time the cigarette was being smoked (all at $p<.001$).

The same rank ordering of the conditions was obtained for the highest levels of $PM_{2.5}$ recorded during the monitoring period. The highest peaks were reached during Condition 1, when the windows were closed; there was no air conditioning, and no car movement. In Condition 1, peak $PM_{2.5}$ levels in all cars exceeded 2,485.2 $\mu g/m^3$, with the highest recorded peak reaching 14,171.5 $\mu g/m^3$. The second-highest peaks were reached in Condition 2 (windows close, no air conditioning, and car being driven around the neighborhood), where all cars exceeded 1,160.5 $\mu g/m^3$. The next-highest peaks were attained in Condition 5 (windows closed, air conditioning on, and car being driven around the neighborhood), of 2, 283.5 $\mu g/m^3$ and then in Condition 4 (with the driver's side window open about halfway, no air conditioning, and while driving), where the peak was 103.0 μg/m^3. The condition with the lowest peaks was Condition 3 at 30.0 μg/m^3. In Condition 3 (all windows open, no air conditioning, and 20-minute drive), the highest recorded peak reached 321.0 μg/m^3.

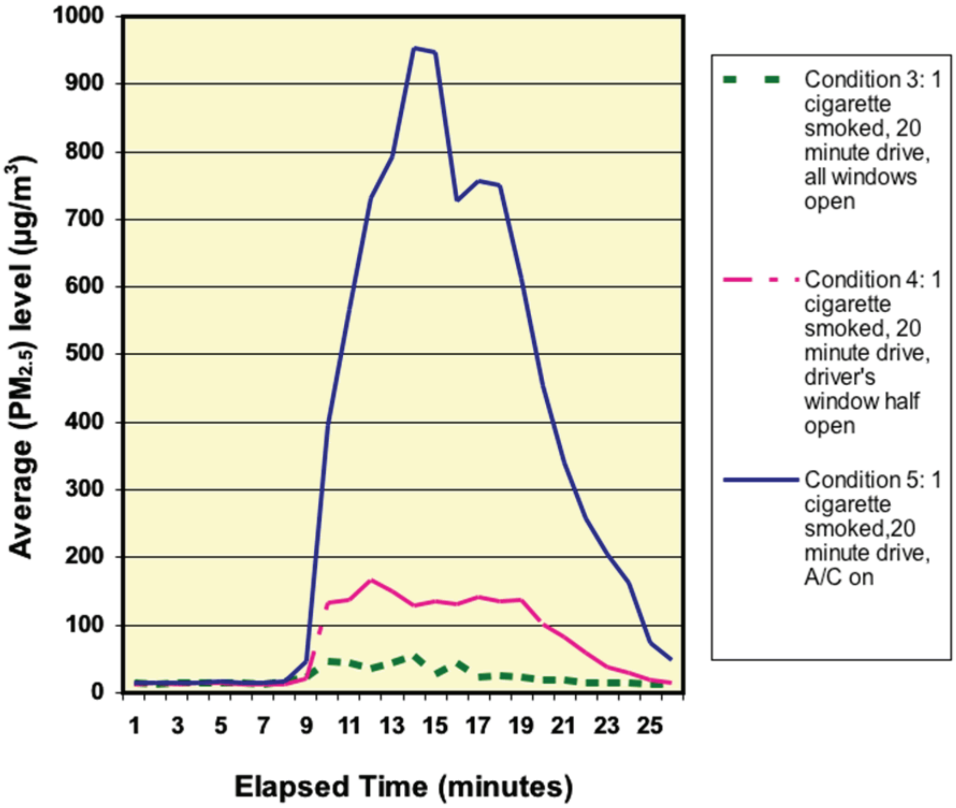
Figure 2 presents the real-time plots of the average levels of $PM_{2.5}$ in the two conditions in which there was no air flow, either through the windows or through the fan/air conditioner (Condition 1, which was a stationary, non-running car; Condition 2, which was a car taken on a 20-minute drive with no fan/air conditioner on and with no windows open). Figure 3 presents real-time plots of the average levels of $PM_{2.5}$ observed during the three conditions in which there was air flow/ventilation, either through windows or through the ventilation system. Results from the plots illustrate the general trend that, as sources of air circulation were added, the overall and peak levels of exposure decreased. $PM_{2.5}$ decay across conditions increased with the addition of car movement, air conditioning, and the opening of windows, with all windows open contributing to the greatest decay. However, even in the most ventilated condition, Condition 3, $PM_{2.5}$ exposure levels were not eliminated. In addition, the use of air conditioning was not effective at clearing the smoke ($p < 0.001$, $df = 32$).

Figure 2: Average Levels of $PM_{2.5}$ Measured in Conditions 1 and 2



Note: Average for Condition 2 excludes data collected in car 4 due to cigarette relighting.
The EPA 24-hour exposure limit is 35 μg/m^3.

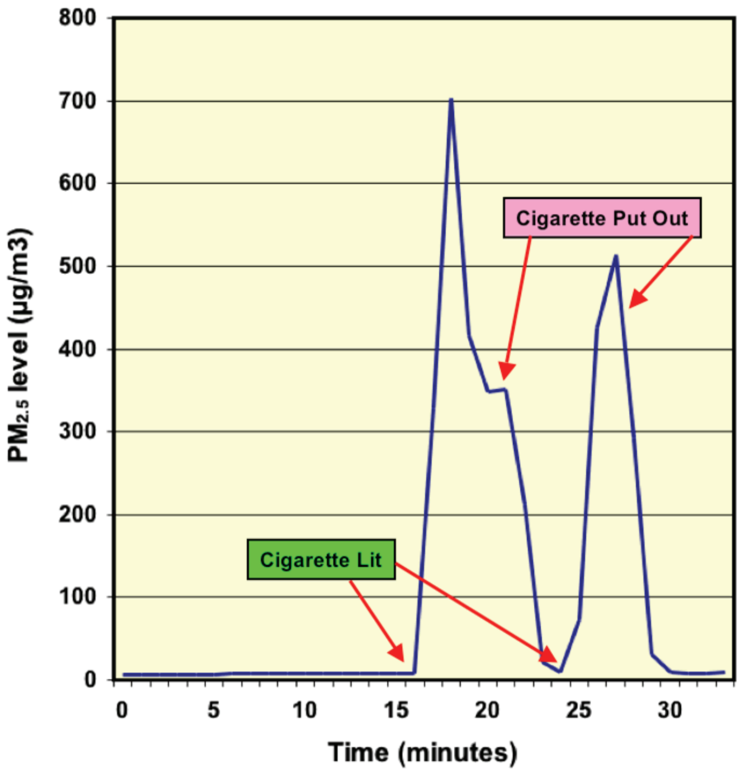
Figure 3: Average Levels of $PM_{2.5}$ Measured in Conditions 3 – 5



Note: Average for Condition 5 excludes data collected in Car 4 due to cigarette relighting. Average for Condition 4 excludes data collected in Car 4 due to machine failure.
The EPA 24-hour exposure limit is 35 µg/m³.

Data from the non compliant participant offered an opportunity to measure $PM_{2.5}$ levels when a cigarette goes out and is relit. Figure 4 presents the $PM_{2.5}$ levels and cigarette consumption timing for Condition 5 for this participant. Increasing $PM_{2.5}$ trends were observed within seconds of the cigarette being lit. Decreasing trends were observed shortly after the cigarette was extinguished. Peak levels during the relighting conditions were not as high as those observed during a constant burn. Comparing the situations when the cigarette was relit to those where the cigarette was smoked in one continuous event, the overall exposure appears to be equally distributed.

Figure 4: $PM_{2.5}$ Levels in Car 4 as a Result of Relighting in Condition 5



Note: The EPA 24-hour exposure limit is 35 µg/m³.

Discussion

Under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) created National Ambient Air Quality Standards (NAAQS) to protect public health, setting a $PM_{2.5}$ annual average exposure limit at 15 μg/m^3, and a 24-hour exposure limit at 35 μg/m^3.[43] Based on the research used to set these values, the U.S. EPA created an air quality index guide that links $PM_{2.5}$ exposure to corresponding health threat levels that range from good (0-15.4 μg/m^3) to hazardous (>250.5 μg/m^3).[45] It should be noted that these limits were established based on typical $PM_{2.5}$ found in outdoor air pollution that differs from the specific component pollutants of tobacco smoke. Given the widely acknowledged high toxicity and carcinogenic properties of tobacco smoke relative to air pollution, (including its designation as a Class A carcinogen by the EPA, indicating that scientific evidence has demonstrated tobacco smoke to be a definitive cause of cancer in humans),[9] it is very likely that TSP is more hazardous than typical air pollution.[20] Evaluating the hazards of TSP with reference to a scale established for outdoor air pollution would underestimate the "actual" hazards of the levels of TSP observed in cars in the present study.[vi]

During this study, the exposure levels measured inside the cars in all conditions quickly exceeded background levels, putting occupants at an increased health risk in terms of 24-hour and annual exposure. The levels of $PM_{2.5}$ observed in Condition 1 of this study would be classified as an unhealthy condition where all members of the population would be at risk of serious health effects, especially those with compromised health.

To provide some context about the $PM_{2.5}$ levels recorded in this study, in a recent report of $PM_{2.5}$ levels in Irish pubs throughout the world, the average level of $PM_{2.5}$ in 48 Irish pubs that allowed smoking was 340 μg/m^3.[42] In Condition 1 (motionless car with all windows closed), the average level during cigarette smoking (M = 3,850.9 μg/m^3, *range* = 1,696.8 to 7654.7 μg/m^3) was over 11 times the level of an Irish pub in which smoking was allowed. At the other extreme, in Condition 3 (all windows open all the way while driving), the $PM_{2.5}$ level was the lowest (M = 60.4 μg/m^3, *range* = 15.7 to 220.5 μg/m^3). In Condition 2 (all windows closed), the average level was about 7 times higher than the average Irish pub (M = 2,412.5 μg/m^3, *range* 760.6–6156.6 μg/m^3). In Condition 5 (air conditioning), the average level (M = 844.4 μg/m^3, *range* = 202.0 to 2,504.5 μg/m^3) was almost 2.5 times higher than the average Irish pub. In Condition 4 (holding the cigarette outside the half-open driver's window), the average level (M = 222.5 μg/m^3, *range* = 66.7 to 960.0 μg/m^3) was slightly lower than the levels of the average Irish pub in countries where smoking was allowed in bars/pubs.

Reports of high levels of $PM_{2.5}$ exposure in restaurants and bars have been used to convince individuals and legislators to take the necessary steps to implement smoking bans that protect

[vi] Klepeis et al. (2007) have recently drawn a similar conclusion: "Note that the EPA standard was devised for ambient air pollution, which is likely to have substantially different composition than tobacco smoke pollution. However, because secondhand smoke contains many toxic compounds, including carcinogens, it is likely that, at a given airborne particle concentration, OTS [outdoor tobacco smoke] carries the greater risk."[20]

themselves and others from the negative effects of TSP.[16-19] The present study reports conditions where peak exposure levels met or exceeded those reported in some of the smokiest bars and restaurants prior to the implementation of a smoking ban.[16-19] Peak levels in the conditions where the windows were open did not reach the same levels, probably due to the fact that open windows increase the number of air exchanges in the small space. However, even with the windows open, exposure was not completely eliminated. We explicitly tested this in Condition 3, which we created as an extreme (possibly maximal) example of full ventilation and air flow in a car. In Condition 3, all of the windows were completely open—a condition that may not be tolerable in actual practice, especially during winter. Even here, the average exposure level was 60.4 $\mu g/m^3$ during the time that the cigarette was smoked, which was four times greater than the average outdoor values measured at baseline, and at a level considered unhealthy to children and other sensitive groups with prolonged exposure.[44]

Under more realistic ventilation conditions, the findings demonstrated that individuals in a car with a smoking occupant are exposed to unsafe acute levels of TSP. Condition 4, in which the cigarette was held next to a half-open window when the cigarette was not being puffed—a common practice among smokers—led to an average exposure level of 222.5 $\mu g/m^3$, more than three times that of the level when all windows were completely opened, and well above the 24-hour EPA "unhealthy" levels for the general population.

It should be noted that our study examines the effect of just one cigarette and thus underestimates the actual exposure that would be experienced in the presence of more than one smoker or with multiple cigarettes being smoked by a single smoker over time.

It should also be noted that $PM_{2.5}$ can be produced by sources other than TSP. $PM_{2.5}$ can be found in outdoor air as a result of dust, factory pollutants, and the combustion of engines. Cars can produce and re-circulate $PM_{2.5}$, increasing localized exposure. However, our study controlled for the influence of other sources of $PM_{2.5}$, by noting the cigarette start and end times within the car, the influence of other $PM_{2.5}$ sources (existing outdoor levels, trucks, fireworks), and controlling the amount of time that the car was driven beyond the consumption of the cigarette. By design this study also controlled for the influence of $PM_{2.5}$ through the limited modification of each condition, thereby allowing the other conditions to serve as a control, providing a more accurate picture of TSP exposure.

Although efforts were made to maximize the applicability of these results to real life smoking and driving situations while maintaining control over the conditions, there are some limitations that should be considered in interpreting these results. First, data on the outside temperature, wind speed, and speed of the vehicles during each condition were not collected. These factors have been identified as having an impact on the air exchange rates inside the vehicle, which can affect the peak and washout rates. [41] Because these data were not collected, it is uncertain whether these factors may have contributed to an under- or over-estimation of $PM_{2.5}$ levels inside the vehicles. Given the consistency of the findings (specifically, the enormous differences across the five conditions) across all of the cars (which were tested across the varying conditions of time of day, temperature, humidity, wind speed, etc.), it is very unlikely that any of the unmeasured variables such as environmental parameters would have served as an alternative explanation for the separation in conditions we found. Moreover, the elevations in $PM_{2.5}$ were against the baseline measurements taken both before and after each condition, and thus, the unmeasured environmental variables were actually more or less controlled for in the difference between the pre and post baseline measures and the measures taken during the smoking of the cigarette in each condition.

Second, the monitoring device was set-up to monitor the back seat generally within a specific height zone to give a sense of the levels of TSP that a child may be exposed to. This does not provide information about what exposure might look like for the different sections of the car (i.e., front driver's seat, rear passenger seat), or occupants (i.e., adult in front passenger seat, dog in middle seat). Third, data for this study was collected from only compact to mid-size 4-door cars. Further data is needed to apply these results to trucks, minivans, cargo vans, Sport Utility Vehicles, Crossover Utility Vehicles, wagons, two-door, hatch-back, and convertible cars.

Despite these limitations, this study adds and extends what is already known about TSP levels in cars. Each of the existing studies varied some aspect of the environmental conditions within the car (either driving or air conditioning/ventilation fan or windows being opened) but no one study varied all of these factors within a single study. Moreover--we deliberately sought to measure TSP at both extremes: either no ventilation at all or the fullest possible ventilation (all four windows open all the way while driving), and also three realistic intermediate ventilation conditions that we suspected virtually all smoking drivers would employ. This study also contains, to date, the largest sample of smokers and cars (n = 18) used to examine levels of TSP in cars via the measurement of $PM_{2.5}$.

These findings add to those of recent studies indicating that TSP in cars is a serious health threat requiring immediate attention and action, and are consistent with recent findings by Rees et al. and Ott et al.[40,41] This study also supports findings that strategies to reduce TSP via ventilation/air flow are not successful in reducing TSP sufficiently.[41] The present study is important because it simulates real world conditions by collecting data from actual smokers using their own cars.

To better understand the full picture of TSP exposure in cars, further research needs to be conducted examining the effect of air exchange rates, and sources of airflow on the movement and concentration of $PM_{2.5}$. The findings of this research need to be combined with adult or computer simulation modeling studies on biological responses such as respiration and cardiovascular changes during and following TSP exposure to provide stronger evidence to inform better practices and policies to protect health. This type of research would be of particular importance to build the case for the need to protect children whose reactions to TSP exposure may be stronger. Children riding in cars where there is smoking have little or no control over their exposure, and thus would be especially vulnerable.

Conclusion

This study demonstrates that TSP in cars can reach unhealthy levels under the most realistic ventilation conditions. Smoking just one cigarette in a car can lead to levels of tobacco smoke pollution that match and exceed by several times the levels found in the smokiest bars and restaurants. Efforts to reduce TSP in cars should be aimed at informing the public about the potentially high levels and risks of exposure, even under optimal ventilation conditions. These findings offer additional evidence to support the recent interest among policymakers to adopt smoke-free car policies, including the announcement by Ontario Premier Dalton McGuinty that the Government will introduce legislation to ban smoking in cars with children in the new session of the Legislative Assembly.

The findings of this study, when combined with current biological and epidemiological evidence on the effects of tobacco smoke exposure, contribute to the evidence base justifying the implementation of personal and public policies to eliminate exposure to tobacco smoke in cars in the presence of children.

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