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Original Investigation

An experimental investigation of tobacco smoke pollution in cars

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Abstract

Introduction: Tobacco smoke pollution (TSP) has been identified as a serious public health threat. Although the number of jurisdictions that prohibit smoking in public places has increased rapidly, just a few successful attempts have been made to pass similar laws prohibiting smoking in cars, where the cabin space may contribute to concentrated exposure. In particular, TSP constitutes a potentially serious health hazard to children because of prolonged exposure and their small size.

Methods: The present study investigated the levels of TSP in 18 cars via the measurement of fine respirable particles (<2.5 microns in diameter or $PM_{2.5}$) under a variety of in vivo conditions. Car owners smoked a single cigarette in their cars in each of five controlled air-sampling conditions. Each condition varied on movement of the car, presence of air conditioning, open windows, and combinations of these airflow influences.

Results: Smoking just a single cigarette in a car generated extremely high average levels of $PM_{2.5}$: more than 3,800 μg/m^3 in the condition with the least airflow (motionless car, windows closed). 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 μg/m^3; holding cigarette next to a half-open window = 223 μg/m^3).

Discussion: This study demonstrates that TSP in cars reaches unhealthy levels, even under realistic ventilation conditions, lending support to efforts occurring across a growing number of jurisdictions to educate people and prohibit smoking in cars in the presence of children.

Introduction

Tobacco smoke pollution (TSP; also known as environmental tobacco smoke, secondhand smoke, and passive smoke) 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 nonsmokers worldwide (California Environmental Protection Agency, Air Resources Board, 2005; Fellows, Trosclair, Adams, & Rivera, 2002; Jamrozik, 2005; Klerman, 2004; National Cancer Institute, 1999; The Smoke Free Partnership, 2006; U.S. Environmental Protection Agency [U.S. EPA], 1992; Wigle, Collishaw, Kirkbride, & Mao, 1987; Woodward, Hill, & Blakey, 2004). TSP has been found to be a cause of lung cancer (National Research Council, 1986; U.S. Department of Health and Human Services [USDHHS], 1986) and heart disease (Glantz & Parmley, 1995; Law, Morris, & Wald, 1997; Taylor, Johnson, & Kazemi, 1992). Recently, a review of the epidemiological evidence concluded that TSP was associated with a significant increase in breast cancer among premenopausal women (California Environmental Protection Agency, Air Resources Board, 2005).

Of great concern is the health hazard that TSP exposure poses to children who are still developing physically and biologically. Compared with 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 (Bearer, 2005), 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 (USDHHS, 1986), and it has been recognized as a cause of sudden infant death syndrome (Anderson, & Cook, 1997; USDHHS, 1986). It has been estimated that more than 20 million children in the United States will be exposed to TSP on a daily basis, with exposure often occurring in the home or the family vehicle (Klerman, 2004).

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. In a longitudinal study, Sly, Deverell, Kusel, and Holt (2007) found that by age 14, children exposed to TSP in cars were more likely to have a current wheeze, a persistent wheeze, and decreased lung function, relative to children who

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were not exposed. These risks for children exposed in cars were greater than that of children exposed in the home. Furthermore, results from an observational study in New Zealand (Martin et al., 2006) suggest that children of lower socioeconomic status may receive more frequent exposure to TSP in cars, thus furthering health inequalities already being experienced by some of the most vulnerable members of society.

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

Findings from tobacco industry–affiliated studies have reported that nicotine and particulate levels in cars vary substantially (range = 0.4 μg/m^3 [negligible air quality value] to 1,010 μg/m^3 [extremely poor air quality value]; Guerin, Jenkins, & Tomkins, 2002). The majority of these studies conclude that exposure to individuals is minimal and, therefore, not a concern. However, the results and generalizability of these studies should be interpreted with caution given that basic details on the car sampling method, such as details about open windows or running fans in the car, are missing (Kirk, Hunter, Baeck, Lester, & Perry, 1988; Muramatsu, Umemura, Okada, & Tomita, 1984; Ogden & Malolo, 1989). Moreover, during the 1990s, court-released tobacco industry documents revealed that some of this research (Guerin et al., 2002; Kirk et al., 1988; Muramatsu et al., 1984; Ogden & Malolo, 1989) was orchestrated to discredit evidence suggesting that TSP was harmful (Barnes & Bero, 1996; U.S. District Court for the District of Columbia, 2006).

Since mid-2006, a new, independent body of evidence regarding TSP in cars has begun to emerge. Rees and Connolly (2006) monitored $PM_{2.5}$ in three cars over a standardized driving route with the windows either completely open or closed under a variety of smoking phases (no smoking, smoking one cigarette, and immediately after smoking). The mean levels of $PM_{2.5}$ were highest with active smoking and closed windows (272 μg/m^3) and were lowest when there was no smoking and open windows. Ott, Klepeis, and Switzer (2008) studied four vehicles under various moving and stationary conditions. They found that increasing speed, opening windows, and adding ventilation through fans or air conditioning could affect the levels of $PM_{2.5}$ in each vehicle. However, these factors did not eliminate exposure, and in several circumstances levels exceeded the EPA health-based $PM_{2.5}$ ambient standard for 24-hr exposure of 35 μg/m^3. Together, these new findings offer alternate evidence of the levels of TSP in personal vehicles.

Although existing studies have varied some aspect of the environmental conditions within the car, they provide only a limited picture of actual exposure. No known study to date has demonstrated the variability of exposure that may occur under the typical range of practices used while smoking in a car (i.e., stationary with no ventilation [no ventilation] to driving average roads speeds with all four windows completely open [fullest realistic ventilation]). Further, this research has been conducted using a small number of vehicles and smokers. Accordingly, the purpose of the present study was to quantify the levels of TSP exposure under controlled conditions using established methods, with the use of real-time $PM_{2.5}$ monitoring devices in a variety of different cars under a broad range of ventilation and airflow conditions.

Methods

The present study measured the levels of TSP inside cars via the measurement of $PM_{2.5}$ under a variety of in vivo conditions. A total of 18 car owners were asked to smoke a single cigarette in their own cars, completing five controlled air-sampling conditions each.

Participants

Individuals who smoked and who owned cars were recruited through newspaper advertisements distributed in Southern Ontario between summer 2005 and summer 2007. Potential participants completed a prescreening questionnaire to identify their smoking status, their car ownership status, and whether they permitted smoking in their car. The participants were those individuals who identified themselves as being a current smoker (defined as having smoked for at least a year and currently smoking at least once a week), who owned a car, and who permitted smoking in their car.

Experimental design

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

- **Condition 1.** Participant smoked a single cigarette in the car with all windows closed and the engine off.
- **Condition 2.** Participant smoked a single cigarette with all windows closed during a 20-min drive.
- **Condition 3.** Participant smoked a single cigarette with all windows completely open during a 20-min drive.
- **Condition 4.** Participant smoked a single cigarette with all windows closed except the driver's window, which was rolled down 18 cm, approximately halfway, during a 20-min 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-min drive.

In Conditions 1–4, the climate-control fan inside the cars was turned off (set at 0), and the car left in a passive ventilation state (i.e., fresh air from outside could naturally pass into the car without the aid of the fan). 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 at least 10 min 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 bring $PM_{2.5}$ back to baseline levels.

We found no significant differences between the precondition and postcondition baseline levels for any of the five experimental conditions (all p values > .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 it was too cold for participants to complete the open window conditions).

Procedures

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

Each experimental session began with participant completing a brief 2-min questionnaire. The participant verified the type and age of the car, when the last cigarette had been smoked in the car, and how many cigarettes had been smoked in the car in the past 24 hr. After the participant completed the questionnaire, the researcher installed the monitoring device to monitor levels of $PM_{2.5}$ under each of five conditions.

Air quality in each vehicle was monitored using a TSI Dustrak aerosol monitor (TSI Inc., Shoreview, MN). The Dustrak was used with a 2.5-micron impactor to measure $PM_{2.5}$ and was calibrated prior to each experimental session with an high efficiency particulate air filter according to the manufacturer's specifications. The Dustrak was set to record the average $PM_{2.5}$ concentration every 60 s. A customized calibration factor of 0.32 was applied to the device, determined by calibrating the device in the present study with other light-scattering photometers measuring TSP (Hyland, Travers, & Repace, 2004; Repace, 2004; Travers et al., 2004, 2007). Two other devices were 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 monitor was secured in the participant's car (Figure 1). The location and height of the monitoring device inlet 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.

Once the equipment was secure, the participant received specific instructions about the setup of the car. Table 1 presents the specific instructions that were given to each participant for each condition. The participant then sat in the driver's seat and closed the door immediately. The participant was instructed not to turn on the car, open any windows or doors while inside the car, or turn on the air conditioning or fan, unless specified by the condition (i.e., Condition 5).

Figure 1. Photo of equipment setup inside a participant's car.

Once in the car, the participant lit the cigarette and smoked it at a natural pace. The participant then either finished the cigarette and immediately left the vehicle or drove for 20 min while consuming the 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 s and did not appear to affect the levels of $PM_{2.5}$ in the car.

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 device remained in the car for at least 25 min 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, the participant was asked to remain on city streets, maintaining speeds of approximately 50 km/hr while obeying local traffic signs and regulations and to drive the same route. Study procedures were reviewed by and received ethics clearance from the Human Research Ethics Committee at the University of Waterloo.

Data were collected from individuals driving four-door cars. According to the manufacturer's specifications, the average size of the interior cabin space of the vehicles was 2.6 m^3, ranging from 2.4 to 2.9 m^3. All participants reported regularly smoking cigarettes in their cars. During each of the five experimental conditions, all participants smoked their regular brand of cigarette.

Data analyses

TrakPro software (version 3.41; TSI Inc., St. Paul, MN) was used to download data from the TSI Dustrak for analysis. Data were then exported to Microsoft Excel 97 to create graphs. Data from the Sidepak and Dustrak were recorded every minute. Averages before, during, and after sampling were computed. 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).

Table 1. Descriptive summary of conditions

Condition	Engine on	Driving (20 min)	Window position	Air conditioner on
1	No	No	All closed	No
2	Yes	Yes	All closed	No
3	Yes	Yes	All open	No
4	Yes	Yes	Driver's window open 18 cm	No
5	Yes	Yes	All closed	Yes

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

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, $\chi^2(df = 9) = 13.69$, $p = .136$. Because the power to detect departures from sphericity was low, we also conducted the analyses using the Greenhouse–Geisser correction. None of the findings we discuss below changed as a result. We report the Greenhouse–-Geisser corrected degrees of freedom in each analysis. We also conducted the tests from a multivariate analysis of variance approach and obtained the same pattern of results. For simplicity, we report only the results from the univariate repeated-measures ANOVA with the Greenhouse–Geisser correction.

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 (all windows up while driving) and 5 (all windows up but with air conditioning while driving) because the cigarette consumption pattern did not meet procedural specifications. Results for this participant's smoking pattern, involving relighting of the cigarette, are presented later in this report. Data from this same car were not included in the calculations for Condition 4 (driver's window open halfway while driving) due to machine failure.

Average baseline levels of $PM_{2.5}$ for all five 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, $F(4, 45.7) = 214.8$, $p < .0001$ (The Greenhouse–Geisser correction for departures from sphericity is performed by multiplying the unadjusted univariate degrees of freedom (error) by epsilon, which varies from 0 to 1, with greater departures from sphericity being associated with lower epsilon. In our data, epsilon = .714; thus, the degrees of freedom (error) was reduced from 64 to 45.7. As indicated here, the application of this correction did not change any of the conclusions.). Bonferroni post-hoc tests for the pairwise comparisons indicated that every condition was significantly different from every other one 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 and there was no air conditioning and no car movement. In Condition 1, peak $PM_{2.5}$ levels in all cars exceeded 2,485.2 μg/m³, with the highest recorded peak reaching 14,171.5 μg/m³. The second-highest peaks were reached in Condition 2 (windows closed, no air conditioning, and car being driven); all cars exceeded 1,160.5 μg/m³. The next-highest peaks were attained in Condition 5 (windows closed, air conditioning on, and car being driven), at 2,283.5 μg/m³, and 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/m³. The condition with the lowest peaks was Condition 3, at 30.0 μg/m³. In Condition 3 (all windows open, no air conditioning, and a 20-min drive), the highest recorded peak reached 321.0 μg/m³.

Figure 2 presents the real-time plots of the average levels of $PM_{2.5}$ in the two conditions in which there was no airflow, either through windows or through the fan or air conditioner (Condition 1, a stationary, nonrunning car; Condition 2, a 20-min drive with no fan or 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 airflow/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 ($p < .001$, Greenhouse–Geisser $df = 22.8$).

Data from the noncompliant participant offered an opportunity to measure $PM_{2.5}$ levels when a cigarette is relit. Figure 4

Table 2. Summary of average $PM_{2.5}$ levels and cigarette consumption time by condition

Condition	Mean $PM_{2.5}$ at baseline (μg/m³) Before	After	Mean $PM_{2.5}$ exposure (μg/m³) Prior to lit cigarette	During cigarette[a]	Two minutes[b]	Mean peak (μg/m³)	Mean cigarette time (min)
1	14.7	15.8	13.4	3,850.9	4,377.5	6,590.5	7.5
2[c]	15.1	16.3	16.6	2,412.5	1,729.6	3,781.0	7.9
3	14.1	15.0	13.7	60.4	26.3	142.1	5.9
4[d]	14.3	15.4	13.2	222.5	91.3	382.1	6.6
5[c]	15.1	14.4	16.0	844.4	470.3	1,249.7	7.3

Note. [a]Refers to the time period in which the cigarette was consumed.
[b]Two minutes after the start of the cigarette.
[c]Mean of 17 car monitoring sessions, one car excluded due to relighting of cigarette.
[d]Mean of 17 car monitoring sessions, once car excluded due to machine failure.

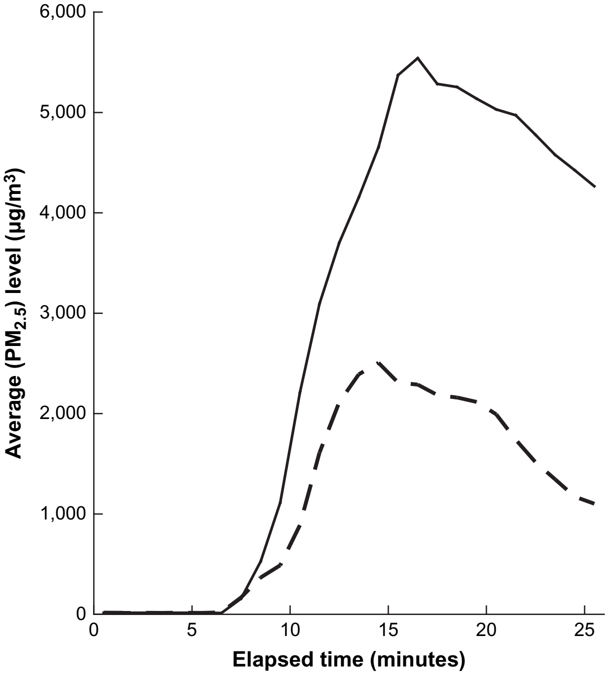

Figure 2. Average levels of $PM_{2.5}$ measured in Conditions 1 and 2. (a) Average for Condition 2 excludes data collected in car 4 due to cigarette relighting. (b) The EPA 24-hr exposure limit is 35 μg/m³. Solid line = Condition 1, one cigarette smoked, engine off, and windows closed. Broken line = Condition 2, one cigarette smoked, 20-min drive, and windows closed.

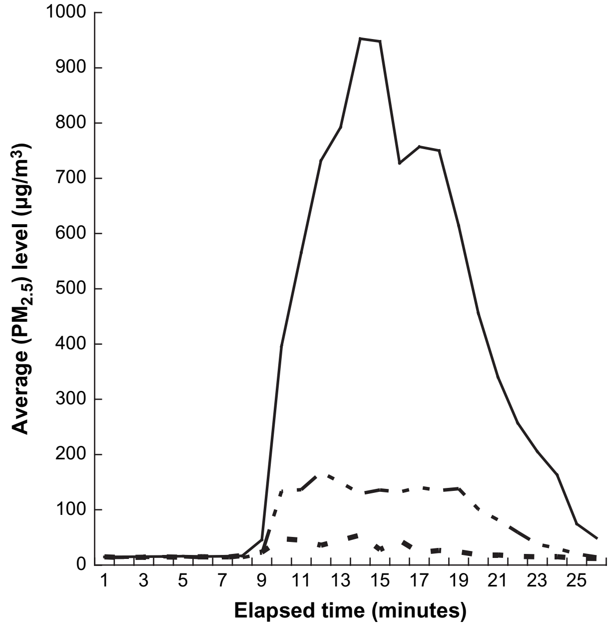

Figure 3. Average levels of $PM_{2.5}$ measured in Conditions 3, 4, and 5. (a) Average for Condition 5 excludes data collected in car 4 due to cigarette relighting. (b) Average for Condition 4 excludes data collected in car 4 due to machine failure. (c) The EPA 24-hr exposure limit is 35 μg/m³. Solid line = Condition 3, one cigarette smoked, 20-min drive, and all windows open. Long–short dashed line = Condition 4, one cigarette smoked, 20-min drive, and driver's window half-open. Dashed line = Condition 5, one cigarette smoked, 20-min drive, and air conditioner on.

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 situations when the cigarette was relit to those when the cigarette was smoked continuously, the overall exposure appears to be distributed equally.

Discussion

Under the Clean Air Act, the U.S. EPA created National Ambient Air Quality Standards to protect public health, setting a $PM_{2.5}$ annual average exposure limit at 15 μg/m³, and a 24-hr exposure limit at 35 μg/m³ (U.S. EPA, 2006). 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/m³) to hazardous (>250.5 μg/m³; U.S. Office of Air Quality, 1999).

The EPA air quality index limits were established based on typical $PM_{2.5}$ levels found in outdoor air pollution, and air pollution 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 U.S. EPA, indicating that scientific evidence has demonstrated tobacco smoke to be a definitive cause of cancer in humans; U.S. EPA, 1992), it is very likely that TSP is more hazardous than typical air pollution. 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 (see also Klepeis, Ott, & Switzer, 2007). In addition, gas-phase components of TSP were not captured by our $PM_{2.5}$ measurements. Certain semivolatile gas-phase components, such as nicotine, may remain for some time after smoking has occurred, being deposited in dust, on surfaces, and

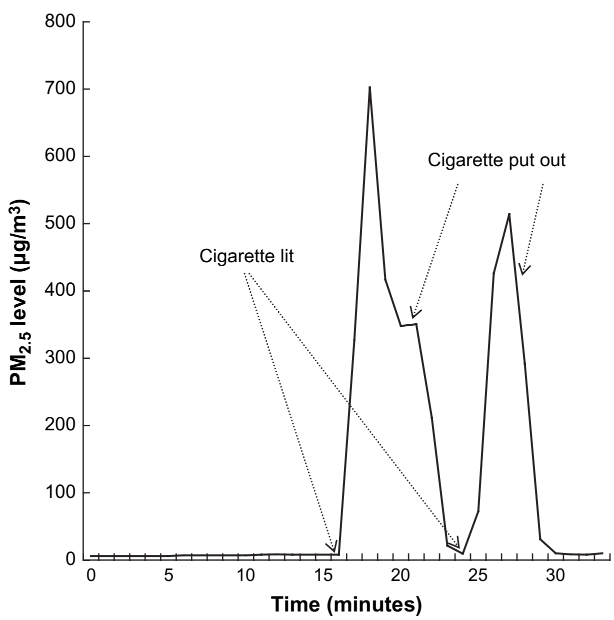

Figure 4. $PM_{2.5}$ levels in car 4 as a result of relighting in Condition 5. (a) The EPA 24-hr exposure limit is 35 μg/m³.

in the air of the car (Matt, 2007). As a result, the hazards of exposure may be much higher and last much longer than suggested by the $PM_{2.5}$ measurements reported in the present study.

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

To provide some context to 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 $\mu g/m^3$ (Connolly et al., 2006). In Condition 1 (motionless car with all windows closed), the average level during cigarette smoking (M = 3,850.9 $\mu g/m^3$, range = 1,696.8–7,654.7 $\mu g/m^3$) was over 11 times the level in 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 $\mu g/m^3$, range = 15.7–220.5 $\mu g/m^3$). In Condition 2 (all windows closed), the average level (M = 2,412.5 $\mu g/m^3$, range = 760.6–6,156.6 $\mu g/m^3$) was about 7 times higher than in the average Irish pub. In Condition 5 (air conditioning), the average level (M = 844.4 $\mu g/m^3$, range = 202.0–2,504.5 $\mu g/m^3$) was almost 2.5 times higher than in the average Irish pub. In Condition 4 (holding the cigarette outside the half-open driver's window), the average level (M = 222.5 $\mu g/m^3$, range = 66.7–960.0 $\mu g/m^3$) was slightly lower than the levels in 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 by legislators to implement smoke-free policies (Hyland et al., 2004; Repace, 2004; Travers et al., 2004, 2007). 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 (Repace, 2004; Travers et al., 2004, 2007). Peak levels in the conditions in which the windows were open did not reach the same levels, probably because open windows increase the number of air exchanges in the small space. However, even with the windows open, exposure was not eliminated completely. We explicitly tested this in Condition 3, which we created as an extreme (possibly maximal) example of full ventilation and airflow in a car. In Condition 3, all the windows were completely open while driving—a condition that may not be tolerable in 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 (U.S. Office of Air Quality, 1999).

Under more realistic ventilation conditions, the levels of TSP were high. 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 the level when all windows were completely opened and well above the 24-hr EPA unhealthy levels for the general population.

$PM_{2.5}$ can be produced by sources other than TSP. It can be found in outdoor air as a result of dust, factory pollutants, and the combustion of engines. Cars can produce and recirculate $PM_{2.5}$, increasing localized exposure. However, the present study controlled for the influence of other sources of $PM_{2.5}$ by noting the cigarette start and end times within the car and the influence of other $PM_{2.5}$ sources (existing outdoor levels, trucks, fireworks) and by 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, some limitations 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 (Ott et al., 2008). Given the consistency of the findings (specifically, the enormous differences across the five conditions) across all the cars (which were tested across the varying conditions of time of day, temperature, humidity, wind speed, and the like), these environmental parameters are unlikely to explain the separation in conditions. Moreover, the elevations in $PM_{2.5}$ were against the baseline measurements taken both before and after each condition; thus, the unmeasured environmental variables were 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, data for the present study were collected from only compact to mid-size four-door cars. Further data are needed to apply these results to trucks, vans, SUVs, CUVs, two-door, hatchback, and convertible cars.

Despite these limitations, the present study extends and adds to what is already known about TSP levels in cars. Each of the existing studies varied some aspect of the environmental conditions within the car (driving, air conditioning/ventilation fan, or windows being opened), but no one study varied all these factors within a single study. Moreover, we deliberately sought to measure TSP at both extremes—either with no ventilation at all or with the fullest possible ventilation (all four windows open all the way while driving)—and in three realistic intermediate ventilation conditions that we suspected virtually all smoking drivers would use. 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 findings by Rees and Connolly (2006) and Ott et al. (2008). This study also supports findings that strategies to reduce TSP via ventilation/airflow are not successful in reducing TSP sufficiently (Ott et al., 2008).

To better understand the full picture of TSP exposure in cars, further research needs to be conducted examining the types of and prevalence of various smoking behaviors in cars, the effect of air exchange rates, and sources of airflow on the movement and concentration of $PM_{2.5}$, as well as other components of TSP. 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 inform better practices and policies to protect health. This type of research would be particularly important in building 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.

Recognizing the need to protect children from TSP exposure in cars, several jurisdictions have been attempting to educate the public. Further recognizing the serious hazard that TSP in cars represents to children, as of March 1, 2009, several jurisdictions in the U.S. (Arkansas, Louisiana, California, and Maine), Canada (Nova Scotia, Yukon Territory, British Columbia, and Ontario), Australia (South Australia and Tasmania), as well as South Africa and Puerto Rico have passed smoke-free policies covering cars where children are present (Blumenfeld, 2007; DeRosenroll & Cunningham, 2008). Such policies are being considered in a number of other jurisdictions.

The present study demonstrates that TSP in cars can reach unhealthy levels under realistic ventilation conditions. Smoking just one cigarette in a car can lead to levels of TSP 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.

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, particularly in the presence of children.

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Declaration of Interests

None declared.

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