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Air change rates of motor vehicles and in-vehicle pollutant concentrations from secondhand smoke

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The air change rates of motor vehicles are relevant to the sheltering effect from air pollutants entering from outside a vehicle and also to the interior concentrations from any sources inside its passenger compartment. We made more than 100 air change rate measurements on four motor vehicles under moving and stationary conditions; we also measured the carbon monoxide (CO) and fine particle ($PM_{2.5}$) decay rates from 14 cigarettes smoked inside the vehicle. With the vehicle stationary and the fan off, the ventilation rate in air changes per hour (ACH) was less than 1 h^{-1} with the windows closed and increased to 6.5 h^{-1} with one window fully opened. The vehicle speed, window position, ventilation system, and air conditioner setting was found to affect the ACH. For closed windows and *passive ventilation* (fan off and no recirculation), the ACH was linearly related to the vehicle speed over the range from 15 to 72 mph (25 to 116 km h^{-1}). With a vehicle moving, windows closed, and the ventilation system off (or the air conditioner set to AC Max), the ACH was less than 6.6 h^{-1} for speeds ranging from 20 to 72 mph (32 to 116 km h^{-1}). Opening a single window by 3″ (7.6 cm) increased the ACH by 8–16 times. For the 14 cigarettes smoked in vehicles, the deposition rate k and the air change rate a were correlated, following the equation $k = 1.3a$ ($R^2 = 82\%$; $n = 14$). With recirculation on (or AC Max) and closed windows, the interior $PM_{2.5}$ concentration exceeded 2000 $\mu g\, m^{-3}$ momentarily for all cigarettes tested, regardless of speed. The concentration time series measured inside the vehicle followed the mathematical solutions of the indoor mass balance model, and the 24-h average personal exposure to $PM_{2.5}$ could exceed 35 $\mu g\, m^{-3}$ for just two cigarettes smoked inside the vehicle.
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Introduction

Time budget studies using diaries show that Americans spend, on average, more than an hour (5–6% of the day) in enclosed vehicles such as buses, vans, automobiles, and trucks (Klepeis et al., 2001). Because of its small physical volume, smoking in a motor vehicle's passenger compartment potentially can expose children and other passengers in a car or van to very high concentrations of the pollutants from secondhand smoke. An important factor affecting interior concentrations is the ventilation rate, usually reported in air changes per hour (ACH), which is affected by the vehicle speed, ventilation settings, and window positions. Our literature review indicates there have been relatively few published measurement studies of secondhand smoke in motor vehicles, nor of the factors affecting interior concentrations. This study presents new air change rate measurement data on stationary and moving vehicles, including experiments and concentration measurements with a real smoker inside the vehicle. These results are intended to help us understand and predict in-vehicle exposures from interior sources as well as the infiltration effects from pollutants on roadways.

Review of studies

We briefly review past studies of vehicular air change rates, with emphasis on studies examining the effect of vehicle speed and ventilation settings on air change rates.

Engelmann et al. (1992) studied five stationary automobiles to determine the "sheltering effect" that an enclosed vehicle offers against accidental releases of toxic airborne gases and particles outside the vehicle on or near the roadway. They conducted experiments with tracer gases (ethane and ethylene) in a garage to measure the air change rates of stationary vehicles. Using solutions to the mass balance equation, they reported that a parked car with the windows closed provides a substantial level of protection over short time periods. With the air conditioning (AC) system off, they found that the ACHs for a stationary vehicle ranged from 0.42 to 1.09 h^{-1}. With the AC on, their reported ACHs ranged from 1.96 to 3.23 h^{-1} and with the AC off and the fan on, from 8.7 to 10.7 h^{-1}.

Ott et al. (1992) used a Langan L15 CO monitor to measure carbon monoxide (CO) concentrations and a MIE

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Miniram PDM-3 optical scattering monitor to measure respirable particle concentrations (RSP or $PM_{3.5}$) in a 1986 Mazda four-door sedan with a real smoker. The smoker sat in the front passenger seat and smoked a cigarette every 15 min while the vehicle traveled at 20 mph on residential streets free of traffic. With the windows closed and the vent open, they observed a "sawtooth" concentration time series, with CO concentrations reaching peak values of approximately 16 ppm for each cigarette. Based on this Miniram optical particle monitor, they reported maximum RSP concentrations above $2000\,\mu g\,m^{-3}$. They calculated the vehicle's ACH as $7.27\,h^{-1}$ using the measured decay rate of interior CO concentrations. They used a tape measure to determine the vehicle's volume as $3.7\,m^3$ and thus the rate of air flow into the vehicle with the open vent and windows closed at 20 mph was $(3.7\,m^3)(7.27\,h^{-1}) = 26.9\,m^3\,h^{-1}$. They did not report a decay rate for particulate matter for the vehicle, but they studied an enclosed chamber with volume similar to that of a car ($3.07\,m^3$) and found an ACH of $5.71\,h^{-1}$ with a particle decay rate of $7.26\,h^{-1}$. They note that the difference between the particle decay rate and the ACH is due to deposition of particles on interior surfaces, but they did not investigate the effect of different window positions or ventilation system settings on the ACH.

Ott et al. (1994) reported an ACH of $1.4\,h^{-1}$ on a Volkswagon station wagon ("Squareback") when it was stationary. With the windows closed and the vehicle moving at 20 mph, they reported an ACH of $13\,h^{-1}$. With the driver's window fully open and the front passenger window open 3″ (1.2 cm), they measured an ACH ranging from 60 to $120\,h^{-1}$.

Fletcher and Saunders (1994) studied the air change rates of five vehicles for different wind speeds and wind directions. They determined leakage characteristics with the vents open and with them closed. They used a tracer gas method to release sulfur hexaflouide (SF_6) inside one vehicle to measure its ACH at constant speeds between 35 and 70 mph (56 and $113\,km\,h^{-1}$). They reported that the ACH for a vehicle moving at a particular speed was greater than for a stationary vehicle with wind passing it at the same speed, presumably because the leakage characteristics of a moving vehicle on the road are different than for a parked vehicle. Using their measurement data, they derived an empirical equation for the ACH *versus* speed that we will test in this paper.

Park et al. (1998) measured the ACHs under four different conditions in three stationary automobiles. With the windows closed and no mechanical ventilation, they reported the ACH between 1.0 and $3.0\,h^{-1}$; with the ventilation set on recirculation, they reported the ACH between 1.8 and $3.7\,h^{-1}$. With windows closed and the fan set on fresh air, the ACH was between 13.3 and $26.1\,h^{-1}$. With a window open, but no mechanical ventilation, the ACH ranged from 36.2 to $47.5\,h^{-1}$. They used the single-compartment mass balance model to estimate interior concentrations from dry-cleaned clothes and cigarette smoking, but they did not make measurements of interior pollutant concentrations for cigarettes.

Rodes et al. (1998) reported the ACH of a 1997 Ford Explorer with the windows closed and the vent fan set on Low as $1.8\,h^{-1}$ stationary; $5.6\,h^{-1}$ at 35 mph; and $13.5\,h^{-1}$ at 55 mph. For the vent set on high, they reported the ACH of $10.7\,h^{-1}$ with the vehicle stationary; $35.7\,h^{-1}$ at 35 mph; and $55.5\,h^{-1}$ at 55 mph. For a 1997 Ford Taurus at 55 mph, they found an ACH of $14\,h^{-1}$ at the low vent setting and $76\,h^{-1}$ at the high vent setting. Although their study did not investigate the effect of window positions and vent settings for all the vehicles, they reported that the ACH was associated with the vehicle speed for the Ford Explorer.

Offermann et al. (2002) measured pollutant concentrations with a smoker in a 1996 minivan driving at an average speed of 18 mph under three different ventilation scenarios: (a) driver's window open and ventilation system off, (b) windows closed and ventilation system on, and (c) windows closed with ventilation off. With the window open and the ventilation system off, they reported an ACH of $71\,h^{-1}$. With the ventilation system on and the windows closed, they measured an ACH of $60\,h^{-1}$, which dropped to $4.9\,h^{-1}$ when the ventilation system was turned off. Interior respirable particle concentrations from smoking varied by factors from 13 to 300 times the outdoor concentration, depending on the ventilation setting. They estimated that the particle exposure for a 5-h automobile trip with two cigarettes smoked per hour would be 25 times higher than the same exposure scenario in a residence.

Park et al. (1998) conclude that the air change rate of a vehicle is important for predicting the interior concentrations of pollutants. With the exception of Fletcher and Saunders (1994) and the measurements in Ott et al. (1994), our literature review found no other published studies of ACHs in moving vehicles under different ventilation and window settings. Because of the importance of the vehicle's air change rate for exposure analysis, we made new measurements of the ACHs of 4 motor vehicles under a variety of conditions.

Approach

This study measured the air change rates of stationary and moving vehicles under different ventilation conditions and window positions to examine six hypotheses:

- A moving vehicle's ACH is a function of the ventilation system settings, window positions, and vehicle speed.
- With recirculation system off (vent open), the ACH will follow the empirical equation for the vehicle's speed proposed by Fletcher and Saunders (1994) for *passive ventilation*.

- At speeds above 20 mph, opening a single window by 3″ (1.2 cm) causes a relatively large increase in the vehicle's ACH.
- The piecewise continuous exponential solutions to the mass balance equation can predict accurately the concentrations inside the motor vehicle.
- The ACH of the vehicle is important for estimating interior air pollutant exposures.
- A single cigarette smoked inside a vehicle can elevate interior fine particle ($PM_{2.5}$) mass concentrations above 2000 $\mu g\,m^{-3}$.

A main study goal was to provide new data on the ventilation rates of motor vehicles under both stationary and moving conditions. We also hoped to verify the high particle concentrations for smoking predicted by Ott et al. (1992) and by Park et al. (1998).

We studied the factors affecting the vehicle's ventilation rates and the interior concentrations of four motor vehicles (see Table 1) when a cigarette was smoked in the passenger compartment. We used three basic approaches: (1) fixed quantities of tracer gases released into the passenger compartment that became well mixed and caused a concentration decay with time that was measured; (2) cigarettes smoked by a smoker inside the vehicle, and (3) tracer gas releases at controlled emission rates—for example, SF_6—to determine the vehicle's parameters. In our moving vehicle studies, we located long roadway segments with minimal traffic during the day on which it was possible to drive at a constant speed for adequate time periods. Background concentrations were measured both before and after each source emission.

Measurement Methods

The measurement methods and instruments included a Brüel and Kjær Multi-gas Model 1302 monitor, TSI Model AM510 SidePak™ Personal Aerosol Monitor, TSI Model 8510 Piezobalance mass monitor, 2 Langan T15 CO monitors for the front and back seats, a constant flow pump (Amtek Alpha-2 Air Sampler) with Tedlar™ bags (SKC-West Inc., Fullerton, CA, USA) that were shipped to a participating laboratory (AtmAA Inc., Calabasas, CA, USA) for benzene analysis by gas chromatography (GC).

The TSI AM510 SidePak™ personal aerosol monitor is a portable (10.5 × 12.7 × 7.1 cm), battery-operated instrument that uses 90° light scattering with a 670-nm laser diode. It is designed to measure over a concentration range of 1 $\mu g\,m^{-3}$ to 20 $mg\,m^{-3}$ and was equipped for our studies with a size impactor measuring fine particles with diameters under 2.5 μm ($PM_{2.5}$). This monitor arrives from the manufacturer factory-calibrated to the respirable fraction of ISO 12103-1,A1 test dust (formerly Arizona test dust) and the operations manual recommends that the user reset its "custom calibration factor" for the aerosol under investigation (TSI, 2003). We conducted nine experiments in a 44 m^3 room with Marlboro regular filter cigarettes under controlled conditions and compared the SidePak monitor with our laboratory standard TSI 8510 piezobalance mass monitors. We then reset the SidePak's custom calibration factor from its factory setting of 1.0 to 0.33 based on these results, as recommended by the manufacturer. The calibration of the laboratory TSI piezobalance monitors has been verified in nine earlier experiments in an 8.9 m^3 chamber in which piezobalance mass readings were compared with two cyclone mass filters that were weighed on a precision laboratory scale ($R^2 = 97\%$).

Determining Air Change Rates and Vehicle Volumes

An obvious way to determine the volume of a vehicle is to measure its interior dimensions manually with a tape measure. We divided the interior of each vehicle into several large rectangular volumes and we measured the length, width, and height of each volume. Internal furnishings, such as seats, dashboard, and middle separators were converted to estimated volumes that were subtracted from the overall volume. Because some portions of seats and curved surfaces are hollow, some smaller compartments may be unintentionally omitted, thus underestimating the true vehicle's volume.

An alternative approach relied on a large cylinder of SF_6 tracer gas and a mass flow controller to provide a constant SF_6 flow rate, with the Brüel and Kjær 1302 Multi-gas monitor measuring the SF_6 concentrations inside the vehicle continuously. We tested this method and found the vehicle often required several hours for its mixing volume to reach an equilibrium concentration (neither increasing nor decreasing). The interior mixing volume obtained with this method was slightly larger than for the manual method, and we found it necessary to place the vehicle in a partly enclosed garage to reduce the effect of time-varying winds. Although this approach worked for a stationary vehicle, it could not be used on a moving vehicle, because the Brüel and Kjær monitor was sensitive to vibration, and moving the monitor caused a malfunction with repeated error messages on the digital display.

Table 1. Dimensions of motor vehicles in study.

Vehicle	Year and model	Length	Height	Width	Measured volume (m^3)	Volume by decay (m^3)
A	2005 Toyota Corolla (compact)	178.3″ (70.2 cm)	58.5″ (23 cm)	66.9″ (26.3 cm)	2.6	2.7
B	2005 Ford Taurus (mid-size)	197.6″ (77.8 cm)	56.1″ (22.1 cm)	73.0″ (28.8 cm)	2.2	2.4
C	1999 Lexus RX-300 (SUV)	180.1″ (71 cm)	65.7″ (25.9 cm)	70.5″ (27.8 cm)	4.7	5.5
D	1999 Jeep Grand Cherokee Limited	183″ (72 cm)	65″ (25.6 cm)	70.5″ (27.8 cm)	2.6	3.0

A third approach was to fill a Tedlar sampling bag with a known quantity of tracer gas, release the full contents of the bag rapidly inside the vehicle, and measure the concentration decay in the vehicle as a function of time. CO has the advantage that existing ambient levels were extremely low in California (typically less than 1.5 ppm) and CO can be measured with high precision using real-time monitors with automatic data loggers (Langan Products, San Francisco, CA, USA). To fill each bag with a known quantity of CO, we used an electronic mass flow controller (Brooks 5896) attached to a Size D gas cylinder containing 99.99% pure CO from Scott Specialty Gases (Longmont, CO, USA), a Gilibrator primary flow calibrator (Sensidyne, Clearwater, FL, USA), and a stop watch (see Figure 1). By setting the mass flow controller flow rate to $200\,\mathrm{cm^3\,min^{-1}}$ and timing the flow with the stop watch to 2 min, for example, a 1 l empty bag was filled with $(200\,\mathrm{cm^3\,min^{-1}})(2\,\mathrm{min}) = 400\,\mathrm{cm^3}$. Figure 1 shows an acrylic plastic bag squeezer apparatus that we constructed for this study, permitting the full amount of gas inside the bag to be released rapidly inside the test vehicle. When the vehicle was stationary, the bag's valve was opened inside the vehicle with a weight placed on the bag squeezer, and the car door was promptly closed before the contents were emitted. When the vehicle was moving, the investigators were traveling inside the car, and a third CO instrument with a digital display was used to verify the safety levels of the interior concentrations, which were kept under 100 ppm. The contents of the bag were fully emptied by this quick release method in less than a minute, or nearly instantaneously relative to the longer residence times of the air in the vehicle.

Mage and Ott (1996) observed that the pollutant concentration in a mixing volume reaches its well-mixed state, or *gamma period*, after a short period of time with normal convective mixing, and thereafter the concentration time series follows an exponential decay curve. By making a semi-log plot of the concentration *versus* time for the well-mixed portion of the curve, one can extend this curve backward in time and use the *peak estimation* approach to find the concentration that would have occurred if the volume were well mixed when the tracer gas was initially released from the bag (Ott, 2006).

Results

Figure 2 illustrates how we determined the volume of Vehicle C, a 1999 Lexus RX 300, by the rapid tracer gas release of a $400\,\mathrm{cm^3}$ bag of pure CO at time $t = 37$ min. The vehicle was parked with its windows closed, and CO concentrations were measured at 12-s time intervals on both the front and rear sets. The exponential function was fitted by linear regression to the portions of the decay curve after $t = 65$ min, when the two curves became very close together. Once the parameters of this exponential function were determined, we computed the mixing volume v of Vehicle C by dividing the $400\,\mathrm{cm^3}$ released by the concentration $x_{\mathrm{coincident}} = 72.7$ ppm predicted to occur at the bag-release time if the vehicle had been uniformly mixed for the entire time period:

$$v = \frac{400\,\mathrm{cm^3}}{x_{\mathrm{coincident}}} = \frac{400\,\mathrm{cm^3}}{72.7\,\mathrm{ppm}} = \frac{400\times10^{-6}\,\mathrm{m^3}}{72.7\times10^{-6}} = 5.5\,\mathrm{m^3} \quad (1)$$

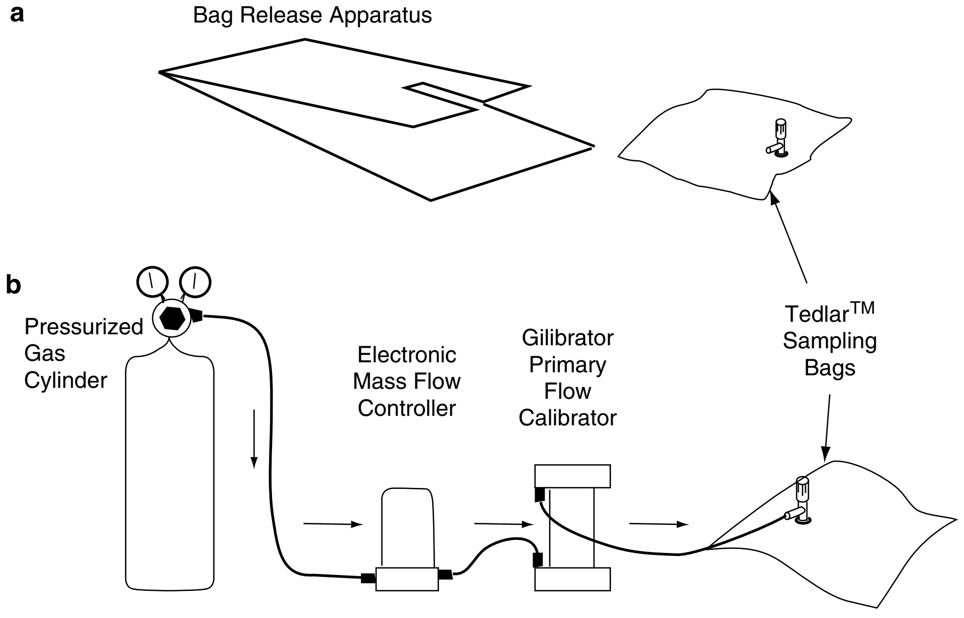

Figure 1. Diagram showing (a) system used to fill sampling bags with a specific quantity of tracer gas and (b) bag release apparatus constructed of Acrylic plastic with a hinge to squeeze the bag, causing a rapid release of the bag's contents inside the motor vehicle.

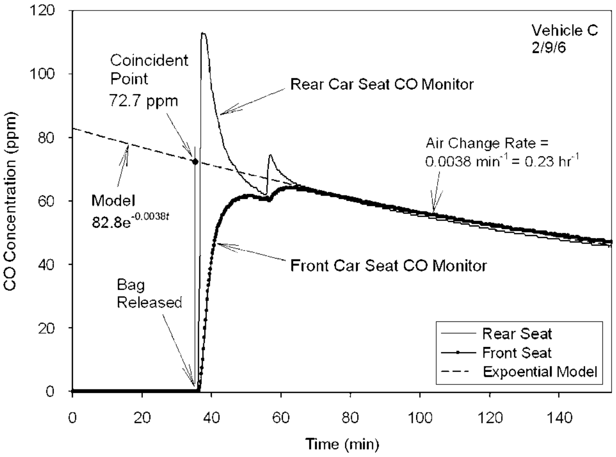

Figure 2. CO concentration *versus* time for a 400 cm^3 bag of pure CO release in Vehicle C while it was parked to measure the vehicle's air change rate and mixing volume. The concentration at the coincident release point of 72.7 ppm gives a calculated mixing volume of (400 cm^3)/(72.7 ppm) = 5.5 m^3.

Table 2. Air change rate measurements on Vehicle A (2005 Toyota Corolla).

Speed (mph)	Windows and doors	Recirc.	Fan	Air change rate (h^{-1})		
				Front seat	Rear seat	Mean
0 (Parked)	All Closed	On	Off	0.92	—	0.92
20	All Closed	On	Off	1.6	1.5	1.6
20	All Closed	On	Off	2.4	2.4	2.4
20	All Closed	On	Off	2.8	1.5	2.2
20	All Closed	Off	Off	12	12	12
20	All Closed	Off	Low	34	35	35
20	Pass. Open 3″	On	Off	38	33	36
20	Driver + Pass. open 6″	Off	Off	44	63	54
20	Pass. Fully Open	On	Off	77	60	69
20	All Fully Open	On	Off	71	—	71

ACH of Vehicle A

Vehicle A was a 2005 Toyota Corolla rented from a dealer, and we used the CO tracer gas release method to measure the ACHs for various window and door positions (Table 2). The front and rear seat ACHs were similar and were averaged. At 20 mph (32 km h^{-1}), we found that the mean ACH ranged from 1.6 to 71 h^{-1} depending on the fan, window, and recirculation system settings. With the vehicle parked or traveling at 20 mph and recirculation on but the fan off, which limits the entry of outdoor air, the ACH was 2.4 h^{-1} or less. Turning off the recirculation control raised the ACH to 12 h^{-1} and setting the fan to Low increased the ACH to 35 h^{-1}. Opening the passenger window by 3″ (7.6 cm) had approximately the same effect as setting the fan to its lowest position (36 h^{-1}), while opening both the driver and passenger windows by 6″ increased the ACH to 54 h^{-1}. Opening one passenger window fully had about the same effect as opening both front windows together (69 and 71 h^{-1}, respectively).

ACH of Vehicle B

Vehicle B was a 2005 Ford Taurus sedan that we rented from a dealer for 4 days and we used the CO tracer gas controlled release method to measure the ACH at constant speeds ranging from 20 to 72 mph (32 to 116 km h^{-1}) for a variety of window settings and ventilation system settings (Table 3; Figures 3 and 4). During a 4.5-h time period of measurements, this vehicle also was driven at constant speeds on low-traffic roads with a real smoker present in the front passenger seat (Figure 6).

This Ford sedan has just two main ventilation controls: a fan control on the left side of the dashboard and a ventilation system control on the right side. The fan control was set to its lowest position and remained there, while the ventilation system control was changed to each of 4 cases: Vent Off, Vent On, AC On, and AC Max. There was no clearly labeled recirculation control on the dashboard, although the Vent Off and AC Max settings caused a recirculation state. We investigated three cases of Vehicle B parked (stationary), along with 21 cases of speeds at 20, 25, 50, 60, and 72 mph (Table 3).

In most experiments, the measured front seat ACH and rear seat ACH were nearly the same, indicating relatively uniform mixing inside the vehicles (Tables 2 and 3). When Vehicle B was parked and its front passenger seat window was fully open, the measured front and rear seat ACHs were 6.6 and 6.4 h^{-1}, respectively (Table 3). On the two stationary experiments in which the right front passenger door was fully opened after the tracer gas was released, the front seat monitor reported a higher ACH than the rear seat monitor, which is explained by the increased air flow through the open front door. With an open door, the average ACHs in the two experiments were 68.6 and 57.9 h^{-1}, or about 10 times higher than with the door closed and one window open.

At 20 mph with the Vent Off and windows closed, the ACH measured in Vehicle B was 1.9 h^{-1} (Table 3), which was Vehicle B's lowest ACH while driving and was in the same range as Vehicle A's ACH at 20 mp with its recirculation control On (Table 2). At 50 mph (80.5 km h^{-1}) with the same Vent Off setting, Table 3 shows that Vehicle B's ACH was 4.1 h^{-1}; at 72 mph (km/h), the ACH was 5.0 h^{-1}. With the ventilation system set to AC Max and the windows closed, we measured an ACH of 5.6 h^{-1} at 60 mph, and the ACH's for the two drives at 72 mph with AC Max were 6.6 and 6.0 h^{-1}. Opening one window by just 3″ (7.6 cm) during the Vent Off case caused the ACH to increase from 1.9 to 28.9–30.8 h^{-1} at 20 mph

Table 3. Air change rate measurements of Vehicle B (2005 Ford Taurus).

Speed (mph)	Windows and doors	Ventilation system	Air change rate (h^{-1})		
			Front seat	Rear seat	Mean
0 (Parked)	Window fully open	Off	6.6	6.4	6.5
0 (Parked)	Door fully open	Vent on	81.0	56.1	68.6
0 (Parked)	Door fully open	Vent on	74.9	40.8	57.9
20	All closed	Vent off	1.9	1.9	1.9
20	Window opened 3″	″	31.4	30.2	30.8
20	All closed	AC on	28.0	30.7	29.4
20	All closed	Vent on	30.3	30.2	30.3
20	Window opened 3″	Vent off	29.1	28.7	28.9
25	All closed	Vent on	38.8	31.1	35.0
50	All closed	Vent off	3.9	4.3	4.1
50	Window opened 3″	Vent off	47.4	55.9	51.7
60	All closed	Vent on	22.9	33.9	28.4
60	All closed	Vent on	40.5	30.7	35.6
60	All closed	AC on	27.4	30.0	28.7
60	All closed	AC max	5.5	5.6	5.6
60	Window opened 3″	AC max	44.8	52.1	48.5
72	All closed	Vent off	4.0	5.9	5.0
72	Window opened 3″	″	44.3	44.4	44.4
72	All closed	Vent on	29.0	36.8	32.9
72	All closed	AC on	27.3	32.5	29.9
72	All closed	AC max	6.4	6.7	6.6
72	Window opened 3″	″	41.6	66.3	54.0
72	All closed	AC max	6.1	5.9	6.0
72	Window opened 3″	″	43.8	49.7	46.8

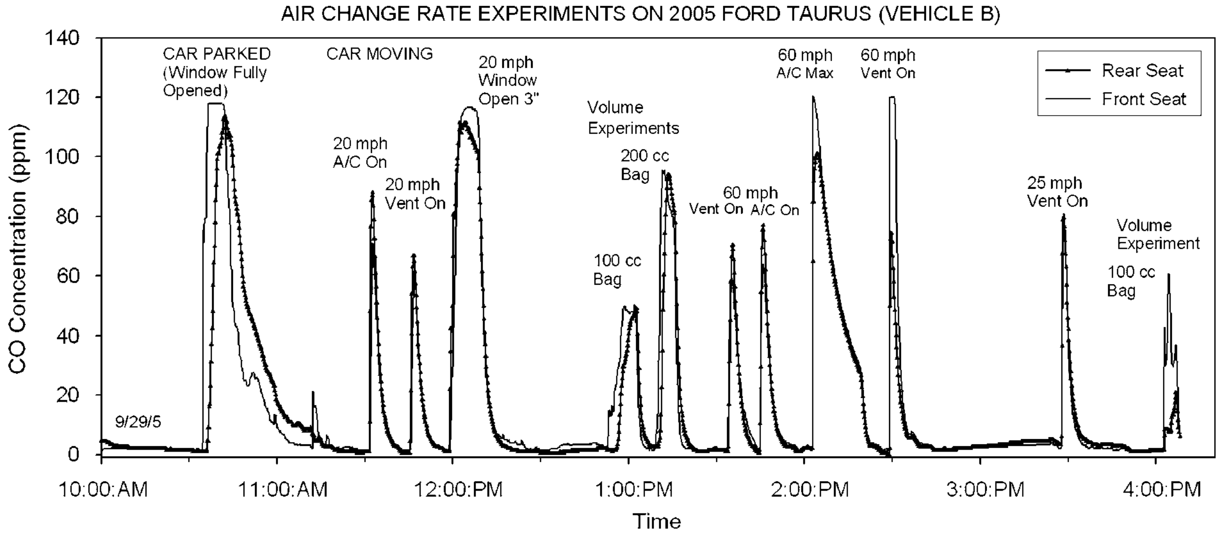

Figure 3. CO concentrations measured in the front and rear seats of Vehicle B for bag release experiments at a variety of speeds and ventilation system settings.

(32 km h^{-1}); from 4.1 to 51.7 h^{-1} at 50 mph (80 km h^{-1}); and from 5.0 to 44.4 h^{-1} at 72 mph (116 km h^{-1}). Similarly, opening the passenger window by 3″ in the AC Max setting caused the ACH to increase from 5.6 to 48.5 h^{-1} at 60 mph (96.5 km h^{-1}) and from 6.6 to 54.0 h^{-1} at 72 mph (116 km h^{-1}). The results show that opening a single window by 3″ increased the vehicle's ACH by 8 to 12 times, and the ACH depended on the vehicle speed once the window was open.

Finally, with the Vent On and the windows closed, Table 3 shows that Vehicle B's ACH was 30.3 h^{-1} at 20 mph (32 km h^{-1}); 28.4 and 35.6 h^{-1} on two successive drives at 60 mph (96.5 km h^{-1}); and 32.9 h^{-1} on one drive at 72 mph

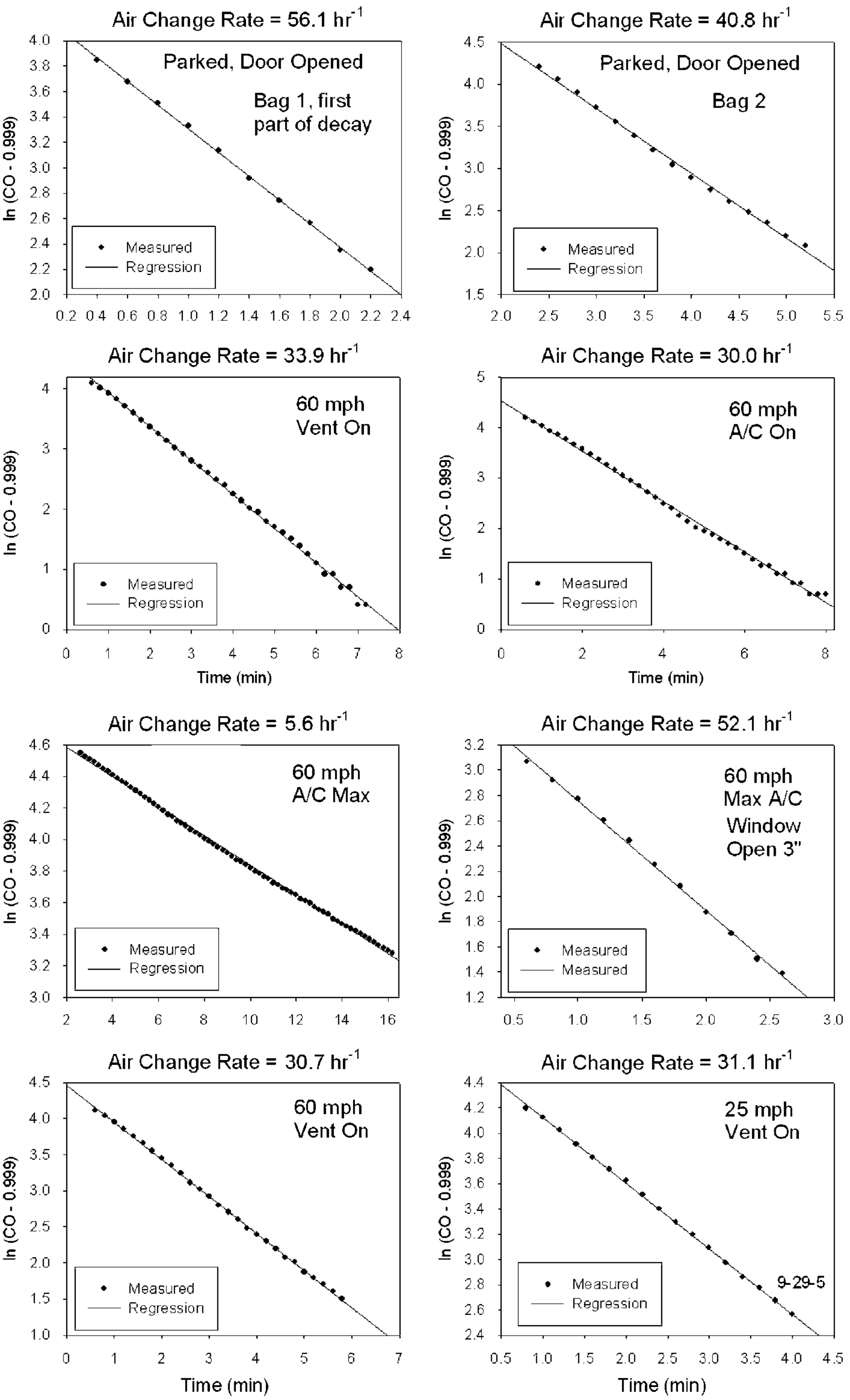

Figure 4. Examples of CO concentration decay curves for eight air change rate measurement experiments in Vehicle B. The rapid bag release occurred in the front seat, and the monitor was located in the back seat of the vehicle.

(116 km h^{-1}). Similarly, with the AC On, the ACH was 29.4 h^{-1} at 20 mph; 28.7 h^{-1} at 60 mph, and 29.9 h^{-1} at 72 mph. There is no evidence that the ACH was correlated with the vehicle speed during the eight Vent On and AC On cases. A possible explanation is that the Ford Taurus automatically turns on its ventilation fan for these cases, and the strong fan activity dominates the ventilation inside the car's passenger compartment. It is noteworthy that for

eight cases of Vent On or AC On with the windows closed, the ACHs ranged from 28.4 to 35.6 h^{-1}, indicating that the Vent On and AC On settings caused relatively high air change rates above 28 h^{-1} for all the speeds tested.

In contrast, Driving Vehicle B with the Vent Off or AC Max settings with the windows closed produced a relatively low ACH of 6.6 h^{-1} or less at nearly all speeds. The lowest air change rate while moving (1.9 h^{-1}) was at 20 mph with the Vent Off setting. In comparison, as described above, selecting Vent On, AC On, or opening a passenger window by 3″ increased the vehicle's ACH to more than 28 h^{-1}, or by a factor of four or more.

Passive Ventilation State

Differences in ventilation control designs of the vehicles made it difficult to set the recirculation system of all the vehicles in the exact same manner. Vehicles A and C each had a clearly marked "recirculation control" on the dashboard that could be set On or Off, but Vehicles B and D did not have recirculation controls. We concluded that setting the AC control, fan control, and recirculation control to Off on Vehicles A and C opened the fresh air vents without the mechanical ventilation system operating, which was the same as the *passive ventilation* case for the vehicles studied by Fletcher and Saunders (1994). We made 50 measurements of the ACH in Vehicles A and C for this passive ventilation case and the regression analysis gave a straight line was not too different from the empirical equation $A = 0.60V^{1.25}$ developed by Fletcher and Saunders (see Figure 5). Because their exponent 1.25 is close to 1.0, their equation plots nearly as a straight line and it appears close to the slope of our regression line. Our straight-line regression equation $A = 0.62\,V - 3.4$ covered a speed range from 15 to 72 mph, giving an observed ACH ranging from 5.9 to 41.2 h^{-1}. Because we could not set the controls on Vehicles B and D to a similar *passive ventilation* state (recirculation off and no fan operating), we could not test the empirical equation of Fletcher and Saunders (1994) on these two vehicles.

Effect of Smoking on Interior Concentrations

In our first cigarette test in Vehicle A, we lit a Marlboro regular filter cigarette in the passenger compartment and let it smolder until putting it out just before its filter was ignited. At 20 mph with the windows closed and the fan and air conditioner Off, the peak CO concentration was 19 ppm with a mean of 11.2 ppm for a 40-min time period. The measured ACH was approximately 1.9 h^{-1} (1.96 h^{-1} from the back seat monitor; 1.8 h^{-1} from the front seat monitor). The peak $PM_{2.5}$ concentration was 3035 $\mu g\,m^{-3}$ and the mean was 1163 $\mu g\,m^{-3}$ averaged over 46 min. The particle decay rate was 6.1 h^{-1}, which corresponds to a calculated particle deposition rate of $6.1 - 2 = 4.1\ \mu g\,m^{-3}$.

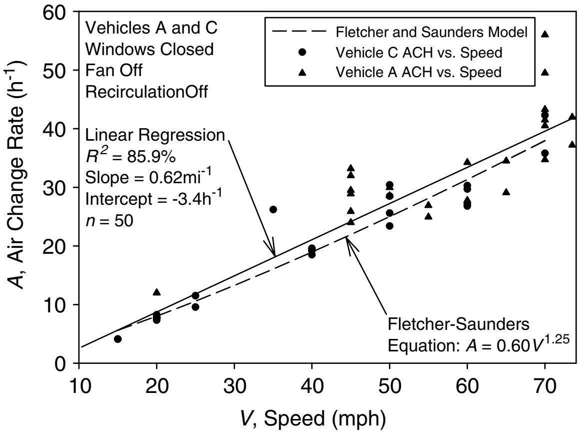

Figure 5. Observed air change rate *versus* speed for Vehicles A and C with the windows closed and *passive ventilation* (fan and recirculation system off), showing closeness of the linear regression line for our data to the empirical equation $A = 0.60V^{1.25}$ proposed by Fletcher and Saunders (1994).

For Vehicles B and D, we contacted volunteer smokers and asked them to sit in the front passenger seat and smoke a series of cigarettes at prescribed times while we drove the vehicles at constant speeds, fixed window settings, and specified ventilation and air conditioner settings. We selected roadways with minimal traffic, allowing the vehicle to maintain a constant speed for an extended time period: the full time over which the cigarette was smoked including its decay period. We made simultaneous measurements of continuous CO and $PM_{2.5}$ concentrations inside the passenger compartment of the vehicle.

In a test drive of Vehicle B, a Marlboro regular filter cigarette first was smoked by the volunteer smoker with the vehicle stationary (Cig no. 1 in Figure 6, top panel); then four cigarettes were smoked at 20 mph and three were smoked at 60 mph (Figure 6, bottom). With the vehicle stationary and the front passenger window fully open, the average $PM_{2.5}$ concentration was 82.4 $\mu g\,m^{-3}$ (averaged over 38.7 min), with a maximum 12-s concentration of 705 $\mu g\,m^{-3}$ (Table 4). The maximum 12-s reading usually exhibited much variability during the smoking period and, except where noted in Table 4, the averaging time for each cigarette usually was long enough to cover the entire time period until the cigarette's concentration was no longer detectable by the monitor.

The average concentration for Cig no. 1 can be converted to a common 24-h reference time for comparison by using the ratio of the cigarette averaging times to the number of minutes in a day; that is, $(24\,h\,day^{-1})(60\,min\,h^{-1}) = 1440\,min\,day^{-1}$.

$$\overline{x_{24\mathrm{h}}} = (82.4\,\mu g\,m^{-3})\frac{38.7\ \text{min}}{1440\ \text{min}} = 2.2\,\mu g\,m^{-3} \qquad (2)$$

Here, the average concentration of $\overline{x_{24h}} = 2.2\,\mu g\,m^{-3}$ can be interpreted as the 24-h *incremental exposure* (IE_{24}) that a nonsmoking passenger in the car would receive if that

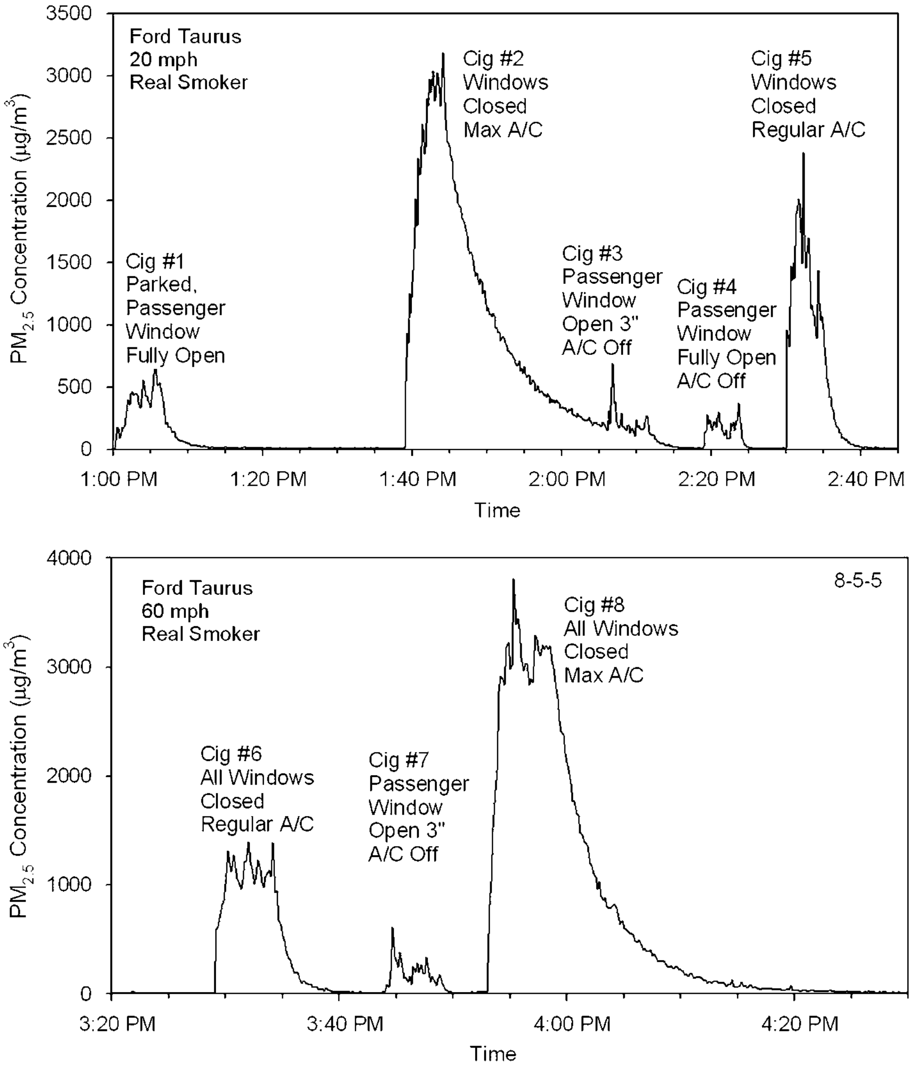

Figure 6. PM$_{2.5}$ concentration measured inside Vehicle B at two different speeds —20 mph (top panel) and 60 mph (bottom panel)—while a real smoker smoked eight Marlboro regular filter cigarettes for various window and ventilation system settings.

Table 4. Particulate mass concentrations in vehicles with a smoker smoking a cigarette.

Vehicle	Cig. No.	Speed (mph)	Windows	Ventilation system	Max. PM$_{2.5}$ (μg m^{-3})	Avg. time (min)	Mean PM$_{2.5}$ (μg m^{-3})
B	1	0	Parked, passenger window open	All off	705	38.7	82.4
B	2	20	Windows closed	AC max	3184	27.2[a]	1113
B	3	20	Passenger window open 3″	AC off	685	12.5	119
B	4	20	Passenger window fully open	AC off	371	10.8	96.6
B	5	20	Windows closed	AC regular	2,389	15.0	529
B	6	60	Windows closed	AC regular	1394	14.5	465
B	7	60	Passenger window open 3″	AC off	608	9.0	119
B	8	59	Windows closed	AC max	3808	43.0[a]	658
D	1	62	Windows closed	Vent off, recirc.	3212	25.7	1150
D	2	62	Windows closed	AC on, recirc.	2828	31.0	1060
D	3	62	Windows closed	AC on, no recirc.	1138	14.5	420
D	4	60	Windows closed	AC on, no recirc.	1051	25.7	203.6
D	5	60	Windows closed, opened 2″	Vent off, recirc.	3104	37.3[a]	627.6

[a] Decay period not fully completed.

person's exposure were zero during the remainder of the 24-h time period. Although Cig no. 2 of Vehicle B did not fully complete its decay period, its mean concentration of $1113\,\mu\mathrm{g\,m^{-3}}$ for 27.2 min gave an incremental exposure of $21\,\mu\mathrm{g\,m^{-3}}$ for 24 h using Eq. 2. Thus, smoking four cigarettes in this car at 60 mph with AC Max and the windows closed would cause a 24-h incremental exposure of $IE_{24} = (4)(21\,\mu\mathrm{g\,m^{-3}}) = 84\,\mu\mathrm{g\,m^{-3}}$, which is well above the EPA health-based ambient standard of $35\,\mu\mathrm{g\,m^{-3}}$ for 24 h, whereas smoking two cigarettes would give $IE_{24} = (2)(21\,\mu\mathrm{g\,m^{-3}}) = 42\,\mu\mathrm{g\,m^{-3}}$, which is also above EPA's $PM_{2.5}$ standard of $35\,\mu\mathrm{g\,m^{-3}}$ averaged over 24 h.

ACH and Particle Decay Parameters

A smoking cigarette emits both particulate matter and CO and the resulting concentrations can be measured as a function of time. By subtracting the background CO concentration and plotting the measured CO concentration time series on semilogarithmic paper during the decay period, the slope of the CO time series plot gives the ventilation rate a of the vehicle. The particulate matter concentration decay rate $\phi_P = a + k$ is obtained in a similar manner, except that it is the sum of the air change rate a and the particle deposition rate k, because particles tend to plate out on interior surfaces of the vehicle. We solved for the particle deposition rate k as $k = \phi_P - a$. Ott et al. (1992) derive these equations for a motor vehicle and they are discussed more generally in Ott (2006) and Wallace and Smith (2006) (in the equations predicted in Ott, Langan, and Switzer (1992), the definition of the deposition parameter k is slightly different but represents the same deposition phenomenon).

In the eight smoking experiments on Vehicle B (Table 5) and five smoking experiments on Vehicle D (Table 6), we measured both the air change rates and particle decay rates using cigarettes smoked by the smokers as the sources of the elevated interior CO and particulate matter. The ACH ranged from 3.0 to $78.6\,\mathrm{h^{-1}}$ and the particle decay rate ranged from 7.7 to $194.4\,\mathrm{h^{-1}}$; the particle decay rate was found to be correlated with the ACH. Including the 1 cigarette smoked in Vehicle A, the combined regression analysis for 14 cigarettes gave $R^2 = 82\%$ and the particle decay rate was 2.3 times the ACH, or $\phi_P = 2.3a$. Subtracting the ACH from the decay rate gives a relationship between the deposition rate and the ACH as $k = 1.3a$. The individual deposition parameters ranging from $k = 1.7\,\mathrm{h^{-1}}$ to $k = 138\,\mathrm{h^{-1}}$ also were correlated with the ventilatory air change rate a ($R^2 = 61\%$). The increased rate of particle deposition with the increased ACH is important and is explained by the greater turbulence associated with higher ventilation activity. Using the relationship of $k = 1.3a$ for the fine particle deposition rate, and solving for the indoor–outdoor ratio $a/(a+k)$ used in indoor air models, we obtain $a/(a+k) = a/(a + 1.3a) = 1/2.3 = 0.44$, which is the predicted ratio of the long-term average indoor concentration to the outdoor concentration for fine particulate matter infiltrating indoors. This result is expected to be relevant to other indoor air quality modeling settings, such as rooms and homes.

Mathematical Modeling of Concentrations

In the drive shown in Figure 6, the smoker began smoking Cig no. 2 in Vehicle B at 1:39 PM and finished the cigarette at 1:44 PM, so the cigarette lasted 5 min. We can apply the piecewise continuous exponential solutions to the mass balance equation described by Ott et al. (1992) to the data for Cig no. 2. For particulate matter, the model requires parameter values for the particle deposition rate k and the source emission rate in $\mathrm{mg\,min^{-1}}$.

For Cig no. 2 in Vehicle B, the overall particle decay rate was estimated as $\phi_P = 7.7\,\mathrm{h^{-1}}$ (Table 5). The cigarette lasted for 5 min and the mixing volume of the vehicle determined by the CO tracer gas decay method was $2.4\,\mathrm{m^3}$ (Table 1). Using these values and a revised version of the QuickBASIC computer program described in Ott et al. (1992) for predicting concentrations for a single cigarette at 10-s time increments, a satisfactory fit of the model to the data was found for a $PM_{2.5}$ source strength of $2.2\,\mathrm{mg\,min^{-1}}$. The total $PM_{2.5}$ emissions for this cigarette based on its 5-min smoking time would be $(5\,\mathrm{min})(2.2\,\mathrm{mg\,min^{-1}}) = 11\,\mathrm{mg}$, which is consistent with the $PM_{2.5}$ emission factors reported by Daisey et al. (1998). Klepeis et al. (1996) report a lower

Table 5. Air change and particle decay rates from smoking in a 2005 Ford Taurus sedan (Vehicle B).

Cig No.	Speed (mph)	Windows	Air conditioner	Decay rate ϕ_P ($\mathrm{h^{-1}}$)	ACH a ($\mathrm{h^{-1}}$)	Deposition rate k ($\mathrm{h^{-1}}$)[a]
1	0	One fully open	AC off	39.5	19.2	20.3
2	20	All closed	AC max	7.7	3.0	4.7
3	20	One open 3″	AC off	42.4	20.9	21.5
4	20	One fully open	AC off	151.4	78.6	72.8
5	20	All closed	AC regular	48.0	32.1	15.9
6	60	All closed	AC regular	48.8	38.6	16.7
7	60	One open 3″	AC off	194.4	56.4	138.0
8	60	All closed	AC max	12.9	5.1	7.8

[a] The deposition rate k is the particle decay rate minus the air change rate a; that is, $k = \phi_P - a$.

Table 6. Air change rates and particle decay parameters from smoking in a 1999 Jeep Cherokee (Vehicle D).

Cig No.	Speed (mph)	Windows	Air conditioner	Decay rate ϕ_P (h^{-1})	ACH a (h^{-1})	Deposition rate k (h^{-1})
1	62	All closed	All off	7.7	6.0	1.7
2	62	All closed	AC on	12.7	8.2	4.5
3	62	All closed	AC on, no recirc	59.6	28.4	31.0
4	60	All closed	AC on, no recirc.	59.6	23.4	36.9
5	60	Open 3″	All off	10.9	7.7	3.2

emission rate of 1.43 mg min^{-1} of RSP ($PM_{3.5}$) based on measurements at two smoking lounges where a mixture of brands were smoked with a typical smoking time of 10 min. Their results give a source strength of 14.3 mg for multiple brands, which is relatively close to the source strength of 11 mg for this particular Marlboro regular filter cigarette.

Figure 7 shows the $PM_{2.5}$ concentration measured for Cig no. 2 in Vehicle B and the concentration predicted by the model. The slight difference in timing of the maxima of the two curves probably results from imperfect mixing inside the vehicle as well as uncertainty about the exact time at which the cigarette stopped its emission after it was extinguished. The two time series curves are similar in shape, indicating that the air in the vehicle behaved like a well-mixed compartment to a reasonable approximation and that published source emission rates can be used to model cigarette concentrations inside the vehicle with reasonable accuracy.

Benzene Example

We can illustrate a practical use of these findings by applying this methodology to a new vehicle not used in our study and to another air pollutant. We rented a Chevrolet Malibou sedan and asked a volunteer smoker to smoke three cigarettes, one every 15 min, while riding in the passenger seat of the the vehicle. While the cigarettes were being smoked, we used a 200 cm^3 min^{-1} pump to collect seven samples by filling Tedlar bags inside the vehicle for subsequent laboratory GC analysis of benzene concentrations. The vehicle was driven at 20 mph in residential neighborhoods during the day when there was virtually no other vehicular traffic on these residential streets. The windows were closed and the recirculation was Off with the ventilation fan set to Off. Using the linear equation in Figure 5 for the ACH *versus* speed, which gives approximately the same result as the equation of Fletcher and Saunders (1994), we estimate the ACH of this vehicle as 9 h^{-1}. Daisey et al. (1998) report an emission factor for benzene of 406 ± 71 μg per cigarette for an average of six American cigarettes representing 62.5% of the brands sold in California, which gives a benzene emission rate for a 10-min cigarette in their study of 40.6 μg min^{-1}. In our test car, the first cigarette smoked by the smoker lasted 7 min and the second and the third cigarettes lasted 8 min. Using the sequential mass balance equations (Ott et al., 1992) and a car volume of 3.7 m^3, the calculated benzene concentration curve for the first cigarette reached 52 μg m^{-3} and then decayed downward until reaching the upward trend caused by the next cigarette, with the three cigarettes resembling three teeth of a "sawtooth" pattern (Figure 8). The air samples were collected in seven sampling bags and the height of each crosshatched rectangle is the average benzene concentration measured during the bag's collection period. The correlation coefficient between the predicted concentration for each bag and the measured concentration was $r = 0.68$, and the model overestimated the benzene concentration for the first cigarette but showed better agreement on the second and third cigarettes. The mean of the measured benzene concentrations for the three cigarettes was 25 μg m^{-3} averaged over 1 h.

Discussion

The motor vehicle shows a much wider range of air change rates than those measured in homes. When the vehicle was stationary, the measured ACH typically was less than 1 h^{-1}. Park et al. (1998) observed an ACH less than 3 h^{-1} for a stationary vehicle with closed windows and no mechanical ventilation. Their study found that the ACH of a stationary vehicle was affected by winds, which we confirmed and therefore conducted our stationary vehicle ACH measurements in a partially enclosed garage. In our studies, opening fully a single window of a parked vehicle increased the ACH to 6.5 h^{-1} and opening a door increased the ACH to 68 h^{-1}. The vehicle speed had a significant effect on the ACH, especially when a vent or window was open. For closed windows, we observed a linear relationship between the ACH and vehicle speed over the wide range of speeds from 15 to 72 mph, which was similar to the curvilinear equation developed by Fletcher and Saunders (1994). This finding applies only to vehicles that can be set to a *passive ventilation* state with an open vent and no mechanical ventilation (recirculation control off and no fan operating). For a moving vehicle with the windows closed, the lowest ACH occurred with the ventilation system off or the air conditioner set to its maximum setting (AC Max) and was less than 7 h^{-1}

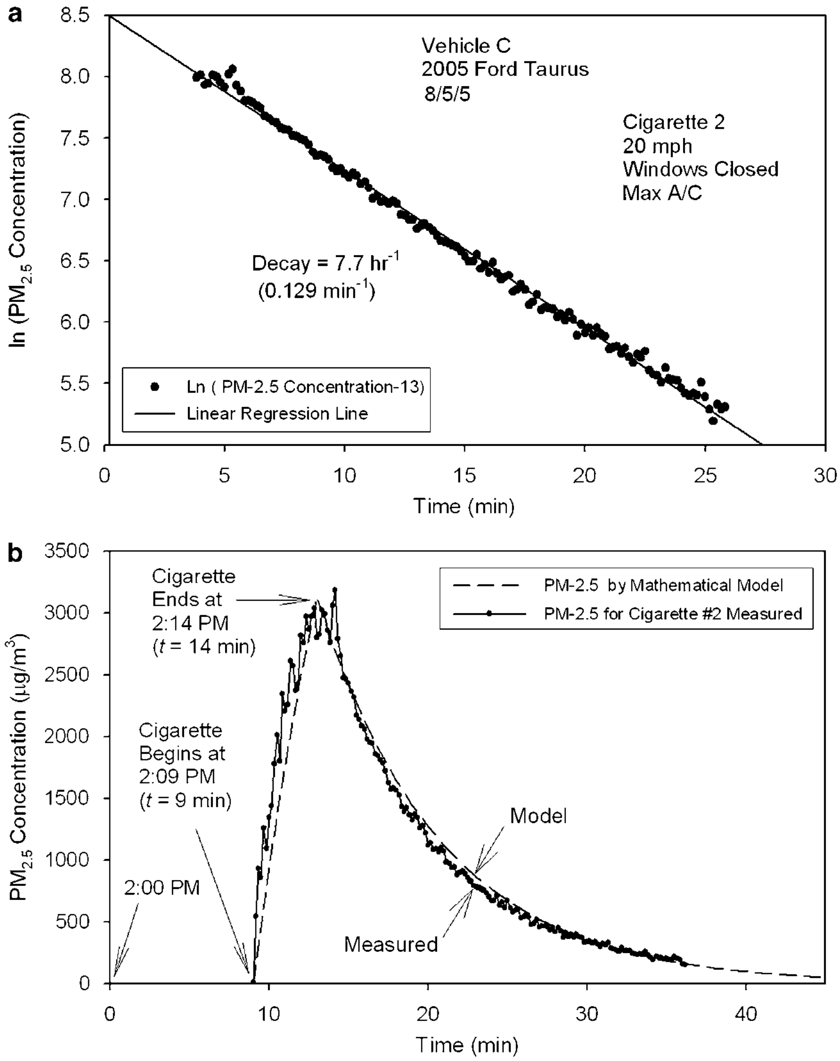

Figure 7. $PM_{2.5}$ measurements in Vehicle C for Marlboro Regular Filter Cigarette No. 2 smoked by a real smoker at 20 mph showing (a) semi-log plot of particle decay period, and (b) time series predicted using a mathematical model with cigarette emission of 14 mg, compared with the measure $PM_{2.5}$ concentration time series.

for all speeds ranging from 20 to 72 mph (32 to 116 km h^{-1}). Opening a single window by even a small amount (3″) increased the ACH by 8–16 times; with the vent off, for example, Vehcile B's ACH increased from 1.9 to 30.8 h^{-1} at 20 mph; from 4.1 to 51.7 h^{-1} at 50 mph; and from 6 to 46.8 h^{-1} at 72 mph.

Smoking a cigarette in a car allows determining both air change rate from the CO concentration time series and the fine particle decay rate from the particle concentration time series. Our studies confirmed the predictions by Park et al. (1998) from a model that fine particle concentrations could exceed 2000–3000 μg m^{-3} in a moving vehicle with the windows closed, and our findings also verified the high in-vehicle particle concentrations measured by Ott et al. (1992) in one vehicle. Our studies produced results similar to the findings of Rees and Connolly (2006), who measured CO

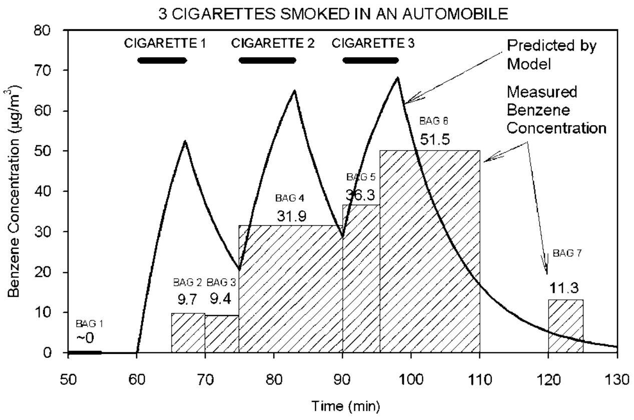

Figure 8. Measured benzene concentration for a smoker in a Chevrolet Malibou driving at 20 mph with the window closed, compared with piecewise continuous benzene concentrations calculated for three cigarettes using the mass balance equations.

and $PM_{2.5}$ in three automobiles during 45 trials with volunteer drivers and smokers recruited from the general community. They reported mean $PM_{2.5}$ concentrations of $272\,\mu g\,m^{-3}$ for the windows closed and $51\,\mu g\,m^{-3}$ for the windows open during 5-min smoking periods, with higher peak levels observed briefly ($505\,\mu g\,m^{-3}$ closed and $104\,\mu g\,m^{-3}$ open). Their drivers maintained speeds between 30 and 40 mph, and they did not use air conditioning or air recirculation, which helps explain why their peak concentrations were less than $2000\,\mu g\,m^{-3}$. They also report that legislation banning smoking in cars with young children present was adopted in Arkansas in 2006, and similar smoking bans with children have been introduced in the states of California, Georgia, Michigan, New Jersey, New York, Pennsylvania, and Vermont. An important new scientific finding of our study was that the particle deposition rate was correlated with the air change rate, producing a relatively simple equation for calculating the deposition rate for particulate matter in a car from cigarette smoking. The high particle concentrations inside cars with smokers are due to the small volumes of the passenger compartments, and the concentrations become extremely high with the low air change rates caused by closing windows and air conditioning. These extremely high particle concentrations constitute a serious health risk for adults and children who are passengers in a car with a smoker.

Conclusions

This study has provided new measurement data on air change rates in moving vehicles and their relationship to vehicle speed, ventilation settings, and window positions. It also provided information for estimating interior concentrations from smoking inside a vehicle. Our main findings are:

- The rapid release of a known quantity of tracer gas inside the vehicle allows calculation of both the air change rate and the mixing volume.
- Opening a single window by 3″ increased the vehicle's air change rate by about tenfold, ranging from 8 to12 times for various speeds and ventilation settings.
- With the vent open (recirculation off), the air change rate for Vehicles A and C was related to the speed by the empirical equation of Fletcher and Saunders (1994), which should be valid for any vehicle under *passive ventilation* conditions.
- Using parameters estimated from the motor vehicle measurements, the time series of particulate matter and CO concentrations predicted by the model agreed well with the concentrations measured in the vehicle.
- A cigarette is a source of CO and fine particles that can be used for simultaneously determining the air change rate and the particle decay rate in a vehicle.
- Smoking a single Marlboro Regular Filter cigarette with the vehicle stationary and the passenger window fully open caused a 38.7-min $PM_{2.5}$ average of $82.4\,\mu g\,m^{-3}$.
- With recirculation on (or AC Max) and closed windows, the $PM_{2.5}$ mass concentration momentarily exceeded $2000\,\mu g/m^3$ for all cigarettes smoked in the vehicles and the mean $PM_{2.5}$ concentration from a single cigarette at 20 mph in Vehicle A was $1113\,\mu g\,m^{-3}$ averaged over 27.2 min.
- The 24-h incremental exposure for one cigarette was $21\,\mu g\,m^{-3}$, so only two cigarettes smoked in this manner would cause an incremental 24-h exposure of $42\,\mu g\,m^{-3}$, which is above the recent EPA health-based $PM_{2.5}$ ambient standard of $35\,\mu g/m^3$ for 24 h.
- The relatively high $PM_{2.5}$ concentrations from smoking inside a vehicle can be explained by two factors: (a) the high particle source emissions of a cigarette (about 12–14 mg), and (b) the relatively small mixing volume of a motor vehicle (2–6 m^3).
- The particle decay rate ϕ_P was found to be correlated with the air change rate a in the vehicles tested ($\phi_P = 2.3a$; $R^2 = 82\%$; $n = 14$); these results give an indoor–outdoor ratio of $a/(a+k) = 0.43$.
- For three cigarettes smoked inside a vehicle, the interior benzene concentration was measured to be $25\,\mu g\,m^{-3}$ averaged over 60 min.

There are few published studies available in the literature on the air change rates of motor vehicles, especially moving vehicles. The air change rate is relevant both to the interior concentrations caused by sources inside the vehicle and to the "sheltering effect" of a vehicle from toxic releases infiltrating from outside into the vehicle. It is hoped that these measurements of air change rates and interior concentrations from smoking under different conditions will give useful data to improve the accuracy of estimates of air pollutant exposures inside motor vehicles.

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