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Simultaneously reducing CO_2 and particulate exposures via fractional recirculation of vehicle cabin air

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Abstract

Prior studies demonstrate that air recirculation can reduce exposure to nanoparticles in vehicle cabins. However when people occupy confined spaces, air recirculation can lead to carbon dioxide (CO_2) accumulation which can potentially lead to deleterious effects on cognitive function. This study proposes a fractional air recirculation system for reducing nanoparticle concentration while simultaneously suppressing CO_2 levels in the cabin. Several recirculation scenarios were tested using a custom-programmed HVAC (heat, ventilation, air conditioning) unit that varied the recirculation door angle in the test vehicle. Operating the recirculation system with a standard cabin filter reduced particle concentrations to 1000 particles/cm^3, although CO_2 levels rose to 3000 ppm. When as little as 25% fresh air was introduced (75% recirculation), CO_2 levels dropped to 1000 ppm, while particle concentrations remained below 5000 particles/cm^3. We found that nanoparticles were removed selectively during recirculation and demonstrated the trade-off between cabin CO_2 concentration and cabin particle concentration using fractional air recirculation. Data showed significant increases in CO_2 levels during 100% recirculation. For various fan speeds, recirculation fractions of 50–75% maintained lower CO_2 levels in the cabin, while still reducing particulate levels. We recommend fractional recirculation as a simple method to reduce occupants' exposures to particulate matter and CO_2 in vehicles. A design with several fractional recirculation settings could allow air exchange adequate for reducing both particulate and CO_2 exposures. Developing this technology could lead to reductions in airborne nanoparticle exposure, while also mitigating safety risks from CO_2 accumulation.

Keywords

Automobile; Filtration; Particle exposure; CO_2 exposure

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1. Introduction

The impact of air pollution on human health is a major concern and various anthropogenic sources of particulate exposure are under investigation to better understand their contributions to adverse health effects. Travel in vehicles represents a primary source of human exposure to particulate matter. A recent report estimated that for Los Angeles residents, 33–45% of exposure to ultrafine particles occurs while traveling in vehicles (Fruin et al., 2008). Commuters on highways may be at particular risk, since particulate levels are demonstrably higher on highways. Zhu et al. (2002) measured concentration of particulate matter as a function of distance from a highway, and found particulate concentrations about 25 times higher on highways than background concentrations. Importantly, data for that study were not collected during rush hour, when particulate levels on the highway typically are higher. Other research has shown that ultrafine particulate concentrations on the highway can be 10 times higher in vehicle cabins than in background ambient air (Zhu et al., 2007). Zhu et al. (2007) estimate that for Los Angeles commuters, 50% of total daily ultrafine particulate exposure comes from this source. When it comes to human exposure to particles penetrated into the vehicle cabin, particle size has more influence than chemical composition. Chemical composition of particles observed on the road and also inside cabin are related to the composition based on modal characteristics such as nucleation mode vs accumulation mode.

Engine-emitted particles are especially concerning due to their size and composition, as many fall into the “ultrafine” category (size < 100 nm), which makes it much easier for them to diffuse into the alveoli and deposit on lung walls (Daigle et al., 2003; Fruin et al., 2008). Moreover, ultrafine particles have demonstrated potential for enhanced bioavailability and thus detrimental health effects (Ibald-Mulli et al., 2002; Kandlikar et al., 2007; Oberdöorster, 2000). The increased bioavailability is related to the higher specific surface area of such small particles, as evidenced by a correlation between particle surface area and inflammatory response for certain materials (Karakoti et al., 2006; Sager and Castranova, 2009; Sager et al., 2008). Furthermore, engine emissions can contain trace metals originating from lubricating oil (Jung et al., 2003, 2005; Lee et al., 2006; Mayer et al., 2010; Schauer et al., 2006), and engine wear (Grütering et al., 2007; Toner et al., 2006). These trace metals can also adversely affect health. New technologies such as additives containing organo-metallic compounds used in fuel-borne catalysts are another concern, since they affect formation and toxicity of particles emitted by diesel engines (Bugarski et al., 2015).

One approach to reduce drivers’ exposure to particulate matter is to isolate the driver from the outside air, as is sometimes accomplished by vehicle ventilation systems. However, for most automobiles, when air is not being recirculated, it is being drawn from outside the vehicle. Previous studies have shown that this causes the particle concentration in vehicle cabins to mimic the outdoor concentration, albeit at slightly lower levels due to adherence to transfer ducts and cabin air filters (Pui et al., 2008; Qi et al., 2008; Zhu et al., 2007). A possible solution would be to use high-efficiency cabin air filters (Zhu et al., 2007), but automobile manufacturers typically do not do this, because high-efficiency filters lower the effective power of the ventilation fan, require more frequent replacement, in general cost more than standard filters.

Recirculating cabin air can decrease the particle concentration inside the vehicle (Qi et al., 2008; Zhu et al., 2007), since cabin air passes through the filter multiple times and particles also adhere to duct walls. Pui et al. (2008) proposed that recirculating in-cabin air can lower exposure to airborne nanoparticles significantly, but it also has the potential to introduce a new hazard. During recirculation, the subsequent reduction in outside air exchange can cause CO_2 exhaled by occupants to accumulate (Qi et al., 2008; Zhu et al., 2007), which could be problematic from a safety perspective.

Fresh air entering vehicle cabins typically contains ~400 ppm of CO_2 from the atmosphere. Passengers exhale CO_2 at much higher concentrations, ranging from 38,000 to 56,000 ppm (Clayton and Clayton, 1991; NIOSH, 1976; Scott et al., 2009). Absent any outside ventilation, normal breathing from occupants in an enclosed space will tend to promote buildup of CO_2. Researchers have recorded CO_2 levels ranging from 700 to 1 600 ppm in taxi cabs (Shu et al., 2015), from 400 ppm to > 3000 ppm in tour buses (Chiu et al., 2015; Hsu and Huang, 2009), and from 630 to 2 500 ppm in various types of passenger vehicles (Fruin et al., 2011; Lee and Zhu, 2014). Due to the relatively confined space inside cars, CO_2 levels in occupied vehicles can accumulate quickly. Zhu et al. (2007) showed that CO_2 concentrations can rise to 4 500 ppm in as little as 10 min for a passenger car with 3 passengers during air-recirculation mode.

Carbon dioxide has generally not been considered hazardous to humans at low levels, such as those typically measured in vehicles. However, recent studies suggest that CO_2 can have deleterious effects on cognitive function and decision making, even at low-to-moderate concentrations and with short exposure times. Kajtar et al. (2003, 2006) showed human exposure to 2000 and 5 000 ppm CO_2 resulted in subtle differences on proofreading tests in some cases. More recently, Satish et al. (2012) reported that human subjects exposed to 1 000–2 500 ppm CO_2 over a 2.5 h session displayed statistically significant decreases in decision making performance, and two other groups have corroborated their results (Allen et al., 2015; Maddalena et al., 2015). For comparison, the National Institute of Occupational Safety and Health (NIOSH) recommends exposure limits of 5 000 ppm CO_2 for an 8-h time-weighted average, and 30,000 ppm for a short-term exposure limit (NIOSH, 2016).

These studies suggest that accumulation of CO_2 in vehicle cabins may have the potential to compromise passengers' safety. Therefore, operating air recirculation systems without suppressing the accumulation of CO_2 in the cabin may not be the best solution for reducing particulate exposures. To address this conundrum, Grady et al. (2013) proposed a system to recirculate a fraction of the cabin air (as opposed to 100% of the cabin air) to reduce PM concentrations while suppressing CO_2 increase. Likewise, Mathur (2008, 2009a, b) proposed a controlled recirculation scheme incorporating an on/off control of the recirculation door and alternating between full and no recirculation at 2–6-min intervals. However, the latter may not be a viable option for car manufacturers as it may cause reliability issues due to frequent operation of the actuator system.

The goal of this study was to provide validation of Grady et al.'s (2013) earlier proposed fractional air recirculation system, and to evaluate whether such a system can reduce passengers' exposure to particle pollutants while preventing high CO_2 concentrations in the cabin. We tested four different scenarios using a custom-programmed vehicle HVAC control unit which was able to vary the recirculation door angle in a test vehicle HVAC system. A test vehicle was driven in a parking lot at a constant speed mimicking slow traffic conditions, and the time-resolved concentration of both CO_2 and particulate matter was measured for each recirculation setting. We also measured particle “active surface area” during the test, by which we evaluated size dependent particle concentration reduction. A final test was done to show the feasibility of varying the recirculation fraction to control cabin CO_2 concentrations within a target range based on open-loop control.

The primary aims of this study were to determine (1) How quickly and how much the particulate levels were reduced during 100% air recirculation, (2) How quickly and how high CO_2 levels rose during 100% air recirculation, (3) whether any fraction of recirculated/fresh air tested led to meaningful reductions in both particulate and CO_2 levels, and (4) whether a simulated open-loop recirculation control system could be used to meet a target CO_2 concentration.

2. Materials and methods

2.1. Vehicle and driving conditions

The test vehicle was a standard SUV (2014 Hyundai Tucson, ~7000 miles) from a local rental company. The cabin volume was ~3.6 m^3 and the vehicle contained a driver and a passenger during the test. A baseline test was performed with no air recirculation (test 1; see below). During this test the vehicle was driven continuously for 22 min at 15 miles per hour around the perimeter of an 800 ft by 200 ft parking lot. In each of three subsequent tests (tests 2–4, detailed below) the vehicle was driven continuously for 90 min at 15 miles per hour around the same parking lot used for test 1. In all tests, the speed was chosen to mimic the slow driving of heavy rush hour traffic. The speed was kept as constant as possible to minimize variability in the air exchange rate between the cabin and the outside atmosphere owing to leakage through window fixtures, door seals, and vents (the vehicle was assumed not to be completely airtight).

2.2. Air sampling conditions

Outside air was sampled from near the right front passenger window. The glass window was opened to allow a 2-inch gap from the window frame and a wooden insert, fabricated to seal the 2-inch gap tightly, was placed to allow a 3/8-inch copper sampling tube to protrude from the window. The sampling tube had a gradual 90° bend just outside the window so that the inlet faced forward. This served as the outside air source for both a CO_2 gas analyzer and one of two condensation particle counters placed inside the vehicle. Particle counter exhaust was vented out through the driver's side rear window, using plastic sealing tape to seal the gap made by the exhaust tube. During the trial, the HVAC vents were set to blow at chest level (as opposed to foot level or at the wind shield). In-cabin air was sampled at the shoulder level of the driver above the center console, with air inlets facing toward the rear to prevent airflow from the vents from interfering with measurements.

2.3. Carbon dioxide and particulate measurement

CO_2 in the cabin was measured using a non-dispersive infrared gas analyzer (CIRAS-2 SC, PP-Systems). The linearity of this instrument is better than 1% throughout the range used in this study, with precision of 3 μmol/mol. The samples were taken continuously. The instrument auto-zeroed periodically to maintain accuracy. Discontinuities exist in part of the data due to a malfunction of the data cable. Data segments during auto-zeroing and cable malfunctions were manually removed and best fit lines were added for better presentation.

Particle concentrations were monitored using two separate Condensation Particle Counters (CPCs) (model 3007, TSI, MN, Shoreview) with a lower cut-off diameter of 10 nm. One counter monitored outside air and the other monitored in-cabin air. For each time point, the two devices recorded simultaneous measurements of particulate concentrations: one from inside the vehicle, the other from outside the vehicle, expressed as particles/cm^3.

Particle surface area was monitored using an Electrical Aerosol Detector (EAD) (model 3070A, TSI, MN, Shoreview). This instrument measures the so-called active surface area of particles using diffusion charging. Evolution of the geometric mean diameter (GMD) of particles in the cabin could be determined using the ratio of particle surface area (PS) over particle number concentration (PN) measured by EAD and CPC using equation (1) (Pham and Jung, 2016):

$$\text{GMD}=\frac{\left(\frac{1}{c}\right)^{1.13}}{\exp\left[\frac{1.13}{2}\ln^2\sigma_g\right]}\cdot\left(\frac{\text{EAD response}}{\text{CPC response}}\right)^{\frac{1}{1.13}} \quad (1)$$

Where c is $5.146\cdot10^{-4}$ for mm/cm^3 unit of EAD response and σ_g is assumed as 1.7, mimicking geometric standard deviation of accumulation mode particles. This analysis, enabled by the simultaneous measurement of GMD and particle concentration, was meant to show the effectiveness of cabin air recirculation for reducing concentrations of small particles in particular, such as nanoparticles and ultrafine particles.

2.4. Fractional recirculation system design

Fig. 1 depicts the concept of fractional recirculation. Fresh outside air comes into the vehicle cabin through the inlet duct near the bottom of the windshield. Incoming air circulates through the cabin, mixes with interior air to varying degrees depending on a number of factors (fan speed, leakage from doors, vehicle speed, and position of vent doors) and exits through the rear grill, typically in the back of the car.

The vehicle's original heating, ventilation and air conditioning (HVAC) system allowed for either 100% or 0% recirculated air (e.g., all air drawn from inside the cabin, or all air drawn from outside the cabin). The driver selects between the two modes by setting a 2-position switch that opens or closes a recirculation door in the HVAC system. For the tests in this study, that system was replaced with a programmable system that could position the recirculation door at any angle. This allowed the system to draw from both inside and outside air at different ratios depending on the angle of the intake door. Of note, the original

HVAC system had 8 possible settings for fan speed, speed 8 being the highest speed. This aspect of the HVAC system was not modified.

2.5. Recirculation settings tested

The goal of the tests was to shed light on the balance between in-cabin levels of CO_2 and particulate matter under various scenarios. The variables that affect those levels include the fan speed, recirculation ratio/percent, number of passengers, and vehicle body leakage flow. The vehicle speed and number of passengers kept constant, while the remainder were measured or controlled as outlined in Table 1 and in the following test descriptions. Vehicle body leakage flow is a function of vehicle speed and pressure difference across the air recirculation door. Note that before each test, the two front windows were opened to initialize the starting condition with outside air, and then closed at the start of the test.

2.6. Governing equation

The trade-off between particle concentration and CO_2 gives an opportunity to determine optimum recirculation percentage (or fraction) for a vehicle at various conditions with respect to passenger number, vehicle speed, cabin volume, vehicle body leakage flow rate, and fan speed. Such a control is possible after understanding these parameters. Jung (2013) derived a governing equation for a vehicle cabin air system for such a purpose (equation (2)):

$$V_c \cdot \frac{\mathrm{dC}_c}{\mathrm{dt}} = n \cdot C_{\mathrm{ex}} \cdot Q_{\mathrm{ex}} + C_o \cdot Q_l - C_c \cdot Q_l \quad (2)$$

Where V_c is the cabin volume, C_c is the CO_2 concentration in the cabin, t is the time, n is the number of passengers, C_{ex} is the concentration of CO_2 in exhalations of passengers, Q_{ex} is the flow rate of exhalation, C_o is the CO_2 concentration outside the vehicle, and Q_l is the body leakage flow rate. Vehicle body leakage flow rate determines the air exchange rate of a vehicle cabin as

$$\mathrm{AER} = \frac{Q_l}{V_c} = \frac{1}{\tau} \quad (3)$$

When the cabin volume is given. Note that the time constant of the vehicle cabin air system and so-called air exchange rate (AER) are inversely related. At a given vehicle body leakage flow rate or air exchange rate, equilibrium of cabin CO_2 concentration is determined as a function of source strength (number of passengers) and cabin volume (2013). equation (2) can be further organized after dividing both side with V_c as

$$\frac{\mathrm{dC}_c}{\mathrm{dt}} - \frac{n \cdot C_{\mathrm{ex}} \cdot Q_{\mathrm{ex}}}{V_c} + (C_0 - C_c) \cdot \frac{Q_l}{V_c} \quad (4)$$

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Equation (4) is the same equation as the governing equation for vehicle cabin air with *AER* (Air Exchange Rate) used by Fruin et al. (2011) as

$$\frac{\mathrm{dC_{in}}}{\mathrm{dt}}=\frac{s}{V}+(C_{\mathrm{amb}}-C_{\mathrm{in}})\cdot\mathrm{AER} \quad (5)$$

where C_{in} is CO_2 concentration in cabin and *S/V* is vehicle-volume-specific-source strength, C_{amb} is ambient CO_2 concentration, and *AER* is air exchange rate. Equation (4) shows more detailed information compared to Equation (5): *AER* is dependent on cabin volume and vehicle-volume-specific source strength is a function of number of passengers, average concentration of CO_2 in exhalation of passengers, and average flow rate of exhalation of passengers. The flow rate of exhalation of passengers can be estimated if weight sensors in the car seat measure body weight of individual passengers and correlations exist between the passenger body weight and metabolism which is responsible for C_{ex} and Q_{ex}. For modeling or simulations, use of this more detailed governing equation (Equation (4)) and estimation of vehicle-volume-specific-source strength given cabin volume and body weight of individual passengers would remove the need to conduct test using multiple cars with different cabin volumes. In other words, generalization of the open-loop control approach shown in this study using a single vehicle is justifiable as there is no unknowns in the governing equation except each vehicle will have different flow resistance of the cabin air system. In other words, body leakage flow rate (Q_l) will be different for each car at different conditions with respect to number of passengers, vehicle speed, and fan speed.

Previous work (Fruin et al., 2011), which used Equation (5), collected data from multiple cars (to cover different cabin volumes and different characteristic flow resistance) at multiple ventilation conditions (to cover different leakage flow rates) due to the lack of this detailed information which Equation (4) provides. The use of Equation (4), which is a bottom-up approach, with all parameters clearly specified, eliminates the need of multiple tests with multiple cars which would be required using a top-down approach to determine *AER* and *S/V*. When applying Equation (4), *AER* can be determined by fitting the measured CO_2 to the general solution form of

$$C_{\mathrm{Cabin}}(t)=(A-B)\exp(-\mathrm{Ct})+B \quad (6)$$

Where A is in-cabin CO_2 concentration at t = 0, B and C are coefficients to be determined by fitting to the measured CO_2 concentrations (Jung, 2013). This is the same approach adopted by Fruin et al. (2011). Time constant, $\tau = 1/C$, of the vehicle cabin air system determined by fitting to the data is equal to 1/*AER* (Jung, 2013). Once the time constant is determined then the body leakage flow rate (Q_l) is determined at a given cabin volume (V_c).

Fruin et al. (2011) took a black box approach to predict *AER* as a function of vehicle manufacturer, age of vehicle etc. They were somewhat successful in finding correlations but this paper can provide further details to better understand vehicle cabin air system. It should be noted that modern vehicles have a well-sealed vehicle cabin. Most of cases a vehicle has one distinctive air intake and one or two outlets. The intake is typically located under the hood or at the interface between windshield and bonnet. The outlet is called external grille and typically hidden at the bottom (for a single outlet) or side (for a double outlets) of the trunk space. Body leakage flow through other places is negligible considering high flow resistances in other places compared to distinctive inlet and outlet(s). The size of outlet is determined as a compromise between noise penetration, cabin pressure build-up as well as cabin air ventilation. The larger the external grille, the bigger the outside noise penetration into cabin, the less the pressure build-up (recall passengers experience of ear deafening when a vehicle comes down a steep downhill causing rapid pressure change), and the better the cabin air ventilation. The reason Fruin et al. (2011) found different *AER* trends between German and Japanese auto manufacturers compared to U.S. automakers is likely to do with different criteria to determine optimum size and shape of the external grille by auto manufacturers.

Test 1- Baseline—The first test was done to understand effect of the original cabin recirculation/filtration system on cabin air quality. Particle concentrations and CO_2 levels for outside and cabin air were simultaneously measured while the vehicle was driven at 15 mph. At the start of the test, the two front windows were closed and the fan speed was set at level 2 with 100% recirculation. As a quality control check, the front windows were opened again at 22 min to confirm that the particle counters sampling outside air and cabin air were measuring similar particulate levels.

Test 2- On/Off recirculation—To assess the feasibility of an on/off control of cabin air recirculation and to understand the trade-offs between cabin particle and CO_2 concentrations, this test entailed changing both the fan speed and the recirculation mode (0% or 100%). The goal was to measure how the cabin air quality varied when adjusting the fan speed and choosing between the two recirculation settings, which are the only settings provided by the manufacturer. The first segment of this test (from0 to 23 min) used 100% recirculation and fan speed 2. The second segment (23–38 min) used 100% fresh air and fan speed 2. The third segment (36–58 min) used 100% recirculation and fan speed 8. The final segment (58–75 min) used 100% fresh air and fan speed 8.

Test 3- Fractional recirculation—In this test, partial (or fractional) recirculation was studied as a way to avoid frequent on-off switching of the recirculation between the 0% and 100% modes. The recirculation door of the test car was controlled to stay at specific angles such that fractions of the total recirculation volume could be chosen. The tests were conducted in the order of 100, 75 and 50% recirculation. The recirculation values presented in this study are based on recirculation door angle openings, and are expressed as the percent of the total opening angle. Note that actual percentage of recirculation by the ratio of volumetric flow (e.g. recirculated flow/total flow) may not be the same as the ratio of the recirculation door angles and would need to be determined by another method. After each fractional recirculation test, the recirculation door was opened to the 0% position, (fresh air mode) to ensure the similar starting conditions.

Test 4- Recirculation control strategy (open vs closed loop control)—This fourth test was designed to show the feasibility of varying the recirculation fraction in order to control cabin CO_2 concentration to meet a target. A concentration of 2000 ppm in the cabin was arbitrarily chosen as a target level for the test. Higher or lower target CO_2 concentrations would require a smaller or larger fraction of recirculation, respectively. Three-step adjustment of the recirculation door angle was applied, starting at 100% recirculation and progressing to 92%, then 85% recirculation door angle opening. This was to ensure rapid response of the system until it approached the target CO_2 concentration.

3. Results

3.1. Test 1 – baseline

Before the start of the first test, with the windows open, particle concentrations measured by two CPCs were similar inside and outside the vehicle as shown in Fig. 2. The test began by rolling up the windows and setting the recirculation to 0%, in other words fresh air mode which allows outside air comes into the cabin through the in-cabin filtration system. As filtered air replaced the existing air in the cabin, the ratio of outside particle concentrations over cabin concentrations – the penetration efficiency – reached 0.7 within the first 5 min and ranged from 0.65 to 0.8 during the remaining 17 min (Fig. 2). Particle concentrations in the cabin showed peaks corresponding to peaks in outside air measurements, but at much reduced concentrations. After 22 min both CPCs measured particle concentrations inside the cabin to confirm that two CPCs are measuring the same concentration.

3.2. Test 2 – on/off recirculation

To investigate the trade-offs between cabin particle and CO_2 concentrations, this test entailed changing both the recirculation mode and fan speed. During the first part of the test (zero to 23 min), using 100% recirculation and fan speed 2, cabin particle concentrations dropped to 950 particles/cm^3. This was reflected in the particle penetration to dropping to 10% by 22 min (Fig. 3). During this time, CO_2 concentration increased to 3 000 ppm. When the recirculation was set to 100% fresh air mode at approximately 23 min, cabin particle concentration increased rapidly while cabin CO_2 concentration decreased rapidly. At 36 min, recirculation was set back to 100%, and the fan was set to the maximum speed (speed 8). Compared to the test done at fan speed 2, at fan speed 8 the rate of reduction for particle concentrations was lower and the minimum particle penetration was 30%. At 58 min the recirculation mode was changed back to 100% fresh air and particle concentration increased while CO_2 concentration decreased once again. Compared to the test done using fresh air at fan speed 2, at fan speed 8 the cabin particle concentration increased even more rapidly and reached a higher maximum level (Fig. 3).

3.3. Test 3–Fractional recirculation

This test involved 3 different fractions of recirculated air conducted in the order of 100, 75 and 50% recirculation (vent door opening angle was used as a surrogate for recirculated air fraction). After each fractional recirculation test, the recirculation mode was switched to 100% fresh air mode to ensure the similar starting conditions. The results of this test are shown in Fig. 4a–c. At the start of the test, windows were left open for 5 min to equilibrate air inside and outside the cabin. After 5 min recirculation was set to 100% at fan speed 2. During 100% recirculation mode, from 5 to 22 min, cabin particle concentrations reached a minimum of 980 particles/cm^3 while cabin CO_2 concentrations reached a maximum of 2 800 ppm. Using 75% recirculation, from 35 to 51 min, cabin particle concentrations fell but remained higher than during 100% recirculation. During this period CO_2 concentration rose to a maximum of 1 200 ppm. Using 50% recirculation, from 67 to 82 min, particle counts fell to 3 800 particles/cm^3 (compared to a maximum of nearly 15,000 outside the cabin) but CO_2 concentrations plateaued at about 1 000 ppm. For this test series, particle penetration showed minimum values of 0.13, 0.32, and 0.45 for 100, 75, and 50% recirculation, respectively (Fig. 4c).

3.4. Test 4 – recirculation control strategy (open vs closed loop control)

In this test, the recirculation fraction was controlled to meet a target cabin CO_2 concentration, to demonstrate the feasibility of such a system. A concentration of 2000 ppm in the cabin was arbitrarily chosen as a target CO_2 level for the test. Results are summarized in Fig. 5. At time zero, the recirculation door was 100% open (i.e. full recirculation condition), and within 8 min CO_2 concentration reached near 1 600 ppm, at which time the door angle was reduced to 92% open to lower the rate of change in CO_2. This caused cabin CO_2 concentration to reach an equilibrium of 2 400 ppm–400 ppm above the target.

At 49 min the recirculation door was 85% open and the CO_2 levels dropped, reaching an equilibrium concentration around 1 600 ppm–400 ppm below the target. Particle penetration, which is the ratio of cabin particle concentration to outside particle concentration, remained below 0.4 during the duration of the test (Fig. 5). After the first 15 min the penetration fell to approximately 0.3 and remained steady for more than 1 h with minimal adjustment of the recirculation door.

Air exchange rate was plotted when vehicle speed was 15 mph at fan speed 2 with two passengers in Fig. 6. *AER* data is from Figs. 3–5 and the data for open-loop test was marked with solid symbols. It was noted that low *AER* values, which has high time constant, were ideal for open-loop control. The leakage flow rates were maintained less than ~350 lpm for the open-loop test shown in Fig. 5.

4. Discussion

4.1. Baseline and on/off control of air recirculation using the original HVAC system

With the manufacturer's original HVAC system set to fresh air mode, particulate concentration fell rapidly within the first 5 min of the test. This was mirrored by a reduction in particle penetration efficiency from 1 to 0.7 (Fig. 2). These results are consistent with Grady et al.'s (2013) prior study which showed ~30% reduction in particle concentrations due to the cabin air filter, and are also similar to other prior works (Pui et al., 2008; Zhu et al., 2007). Particle concentrations in the cabin showed peaks corresponding to peaks in outside air measurements, but at much reduced concentrations. It is likely that the high peaks are mainly composed of nanoparticles which are quickly filtered out due to their high diffusivity (Hinds, 1982).

During Test 2, an effect of fan speed was observed, such that at a higher fan speed (speed 8 versus speed 2) the reduction in particulate concentration in the cabin was less efficient. The lowest particle penetration efficiency at fan speed 8 was 0.3, compared to 0.1 at fan speed 2. This is consistent with Grady et al.'s (2013) findings. This is a result of the greater fan speed creating a larger pressure drop across the recirculation door, resulting in higher leakage flow rate from outside into the vehicle cabin. For the same reason, the rate of CO_2 increase was more gradual at fan speed 8 compared to fan speed 2.

Overall, results from Test 2 highlight the limitations of a simple on-off control system. Using a manual control and a slow switching frequency, neither particle concentrations nor CO_2 concentrations were controlled within a desirable range (Fig. 3). An automated, more rapidly alternating switch could be used to control the CO_2 level within a target range, similar to what Mathur previously tested (2008, 2009a, b) but in such a system the mechanical or electric actuator of the recirculation door would have a short life-time and would require frequent maintenance or replacement. Therefore this approach is less well-suited for a passenger vehicle HVAC system.

4.2. Selective reduction of small particles in the cabin using recirculation

Previous work by Pham and Jung (2016) has shown that the ratio of particle surface area to particle number concentration is indicative of the average particle diameter (equation (1), methods). Over the course of Test 3, air recirculation reduced particulate concentrations in the cabin as expected. During recirculation periods the geometric mean diameter of an equivalent lognormal distribution (to total particle surface area measured) increased, suggesting small particles with high diffusivities were selectively removed. For example, with 100% recirculation the geometric mean diameter changed from 43 to 68 nm (Fig. 4d, 5–22 min). This suggests that small particles, especially nanoparticles and ultrafine particles, were preferentially reduced due to their high diffusivity and filtration efficiencies. Considering the high lung deposition properties of ultrafine particles and high concentrations of nanoparticles when there is nucleation, this size-selective reduction of nano- and ultrafine particles during cabin air recirculation is significant in terms of passengers' exposure to the highest-risk airborne pollutants.

4.3. Feasibility of a control strategy (open vs closed loop control)

Test 4 showed the feasibility of a closed-loop feedback system for controlling CO_2 levels within a target range. Given research suggesting that CO_2 concentrations below 2000 ppm can have a negative effect cognitive function (Allen et al., 2015; Kajtar et al., 2003, 2006; Maddalena et al., 2015; Satish et al., 2012), it may be desirable to set a lower target for CO_2 concentration during real-world application of this concept. Nevertheless, the test showed that fractional recirculation can be used to adjust CO_2 levels by introducing progressively higher fractions of fresh air into the vehicle cabin as needed, while still protecting to some degree against infiltration by particulate matter. During Test 4, particle penetration, which is the ratio of cabin particle concentration to outside particle concentration, remained below 0.4 during the duration of the test (Fig. 5). The advantages of the fractional recirculation system as opposed to simple on/off control system include less frequent adjustment of the vent door opening, leading to a longer actuator life, and the benefit of continuous clean cabin air during travel. Brewer and Jung (2016) recently reported that fractional recirculation of cabin air during summer months can also reduce vehicle air conditioner power consumption leading to higher mileage.

The simulated control method is just one possible algorithm for an open loop control. Note that the results shown in Fig. 5 are for only one specific set of conditions with respect to vehicle type, vehicle speed, body leakage, passenger number, fan speed, and fractional recirculation ratio. Under different conditions the air exchange rate of the vehicle would change, so a fractional recirculation system would need to account for this by changing the recirculation door angle according to the air exchange rate. Predicting the results of such changes is possible using equation (2), the governing equation of the vehicle cabin air system if body leakage flows are determined for a range of vehicle speeds. Body leakage flow at different vehicle speeds and fan speeds depend on individual vehicle design. Preliminary tests showed the leakage flow rate can be fitted well using quadratic equations since ΔP (the driving force of the body leakage flow) of the vehicle cabin system is quadratically related to the velocity of the vehicle (data not shown) (de Flart, 2016). Prediction by Fruin et al. (2011) based on testing of multiple vehicles also showed that AER, which is Q_l/V_c, is quadratically related to the vehicle speed (see their Fig. 3), which is consistent with de Flart (2016)'s result. Further investigation can corroborate the relationship between body leakage flow rate and vehicle speed.

The next step of our research will be to determine body leakage flow rate as a function of controlling parameters such as number of passengers, fan speed, and vehicle speed etc. for an open loop control. The main idea of that detailed modeling procedure will be to treat the system as a flow circuit similar to a thermal circuit, which is often used to solve a complex heat transfer problem by using an analogy to an electric circuit. A flow circuit such as shown in Fig. 7 will be used to determine body leakage flow at every different condition in terms of controlling parameters. The external pressure difference, ΔP_{ext}, is determined based on vehicle external body dimension, shape, corresponding Reynolds number, and flow regime (laminar vs turbulent). The external pressure difference at different vehicle speeds can be determined either by experiment with a small scale model car using a Reynolds theorem or by computational fluid mechanics conveniently. Flow resistance of each flow passage in the diagram can be determined either by modular experiment or by a set of experiments with different settings (in terms of fan speed and vehicle speed for example) and solve for each flow resistance. The utility of this method is that we have a flow circuit that is solvable. The complexity may come from the fact that flow regimes (Stokes regime, laminar flow, and turbulent flow or maybe even a flow in transition regime) of both internal (flow passages inside the car) and external flow (flow over the exterior of the car) changes as a function of internal and external characteristic length dimensions, fan speed, and vehicle speed. Regardless once flow resistances in the flow circuit are determined and internal and external pressure difference by vehicle motion and ventilation fan are known, then the body leakage flow rate of the vehicle can be determined for any possible condition. A complete validation of the aforementioned method at multiple conditions will be the main topic of a follow up study.

Closed loop control is another possible strategy for controlling cabin air quality. It would require an on-board CO_2 sensor and a feedback/control system, but would potentially manage target concentrations precisely. The cost of CO_2 sensors and the required feedback/control system may be a deterrent, but if and when such technology becomes less expensive, a closed loop control system incorporating fractional air recirculation could become practical.

To the authors' knowledge automakers are investigating and considering fractional air recirculation due to its benefit. It is hoped that automakers will eventually adopt this technology since commercial implementation of fractional recirculation systems would represent a public health benefit.

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HIGHLIGHTS

- Bottom-up approach using a flow circuit to characterize vehicle cabin air system.
- Comparison between detailed and simplified governing equations.
- Tradeoff between accumulation of CO_2 and reduction of particle concentrations.

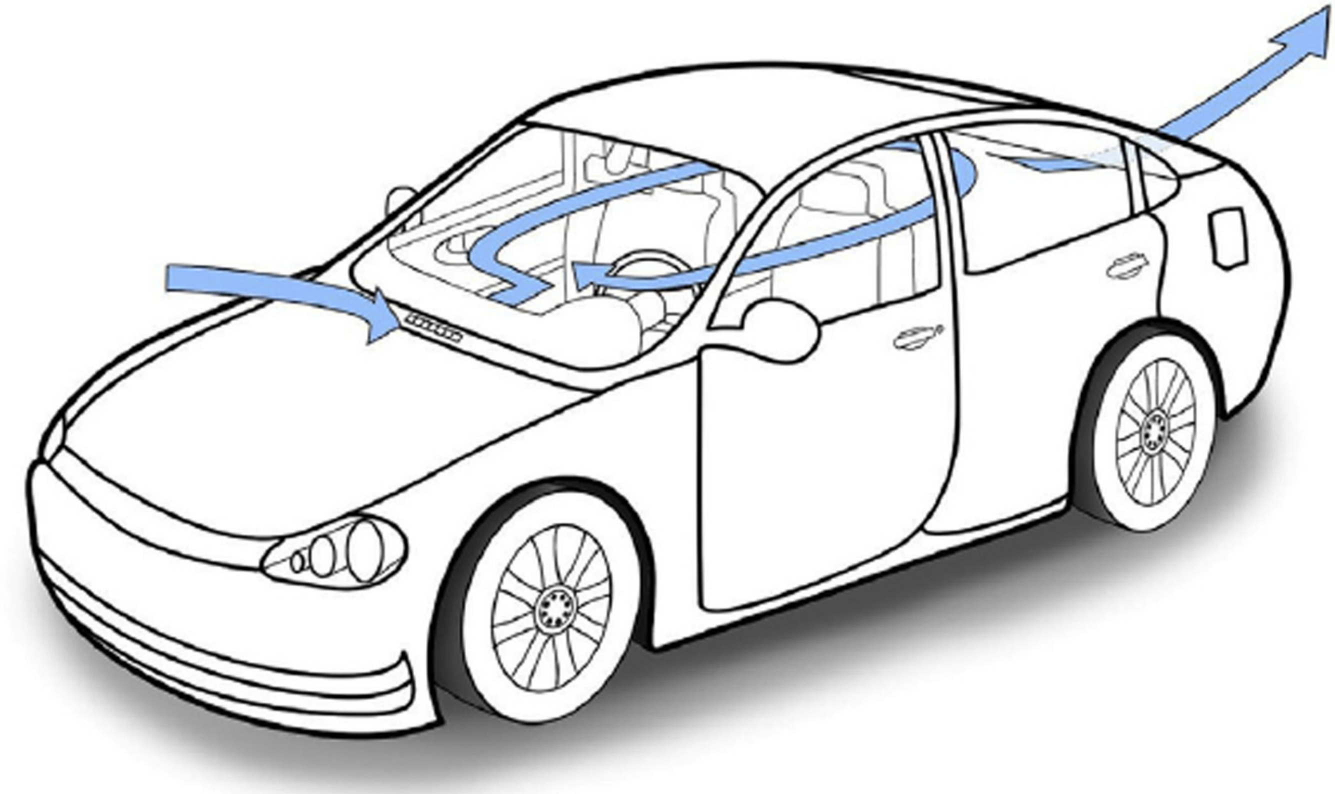

Fig. 1.
Schematic diagram of the fractional cabin air recirculation system.

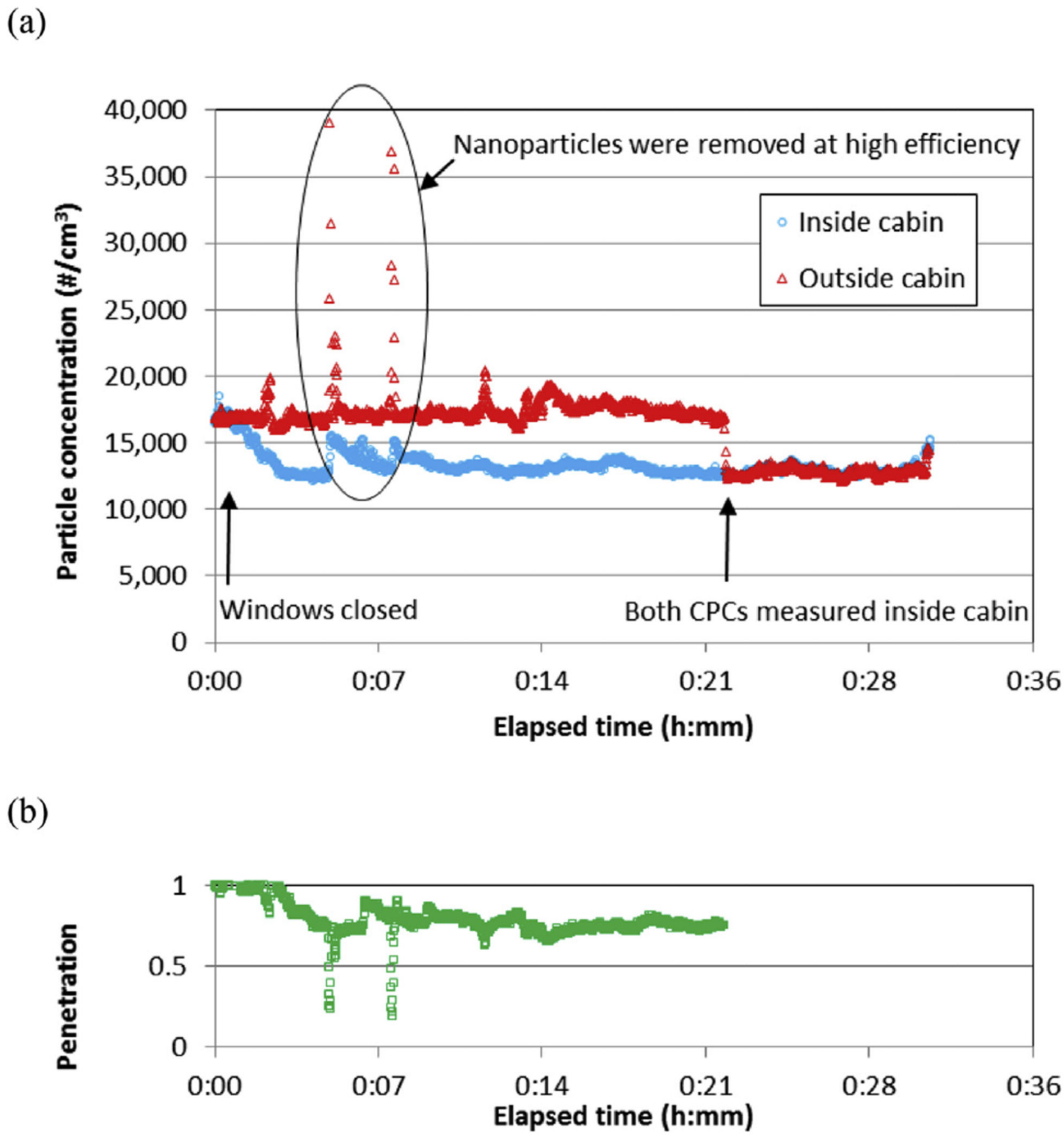

Fig. 2.

Baseline test: Comparison of particle concentrations measured inside and outside of vehicle cabin with windows closed. Vehicle speed was 15 mph, vent mode was 0% recirculation door opening (or fresh air mode), fan speed was at 2, and there were two passengers including the driver. After 22 min both CPCs measured inside the cabin for calibration (a) Particle concentration inside and outside cabin (b) Particle penetration.

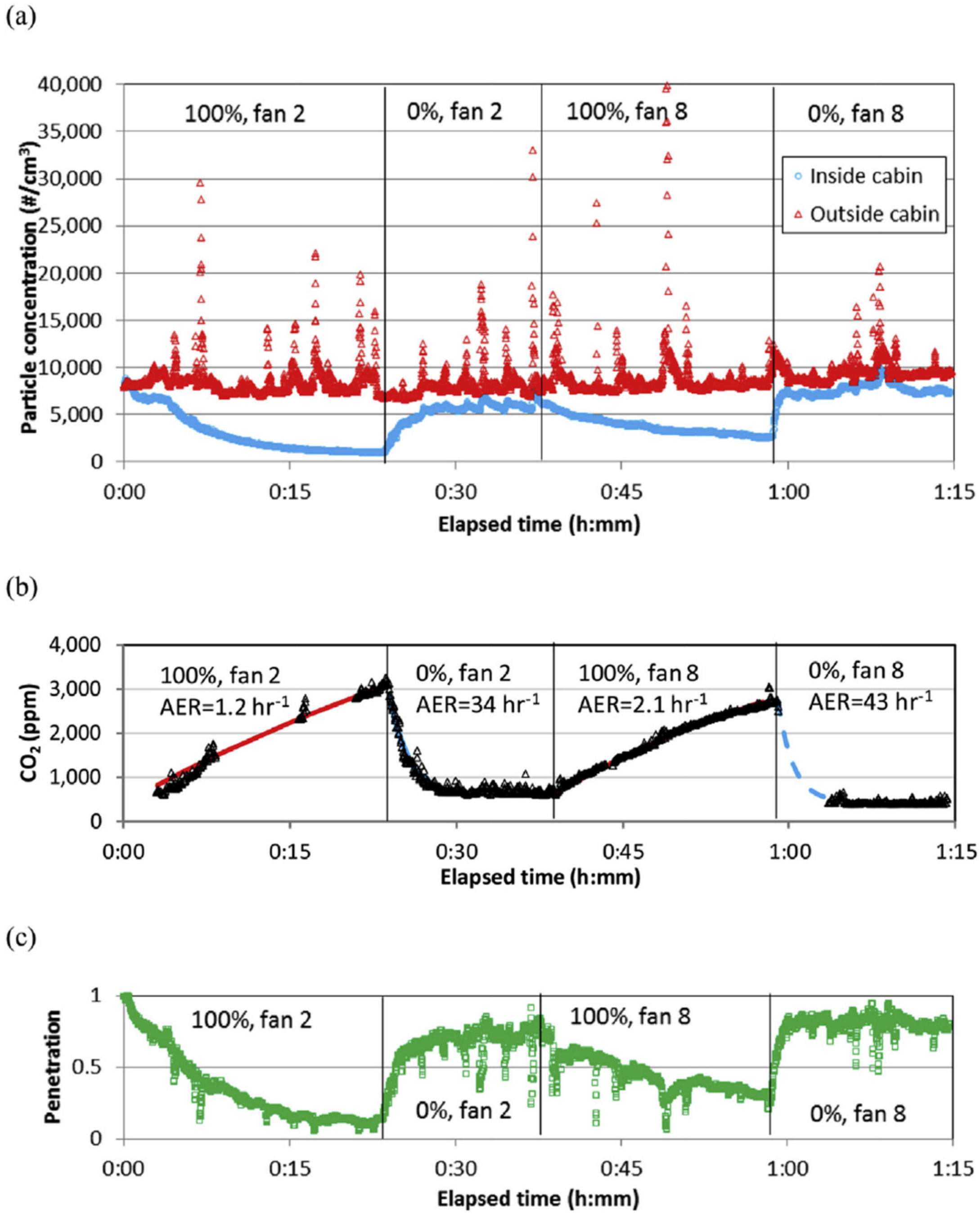

Fig. 3.

On-off recirculation test: In-cabin particle and CO_2 concentrations during 100 and 0% recirculation door opening at different ventilation fan speeds. Note 100% recirculation door opening means full recirculation mode and 0% door opening means fresh air mode. Percentage shown in the figure is recirculation door opening percentage. Also note CO_2 data was fitted using equation (2). Vehicle speed was 15 mph and there were two passengers including the driver. (a) Particle concentration inside and outside cabin (b) Cabin CO_2 concentration (c) Particle penetration.

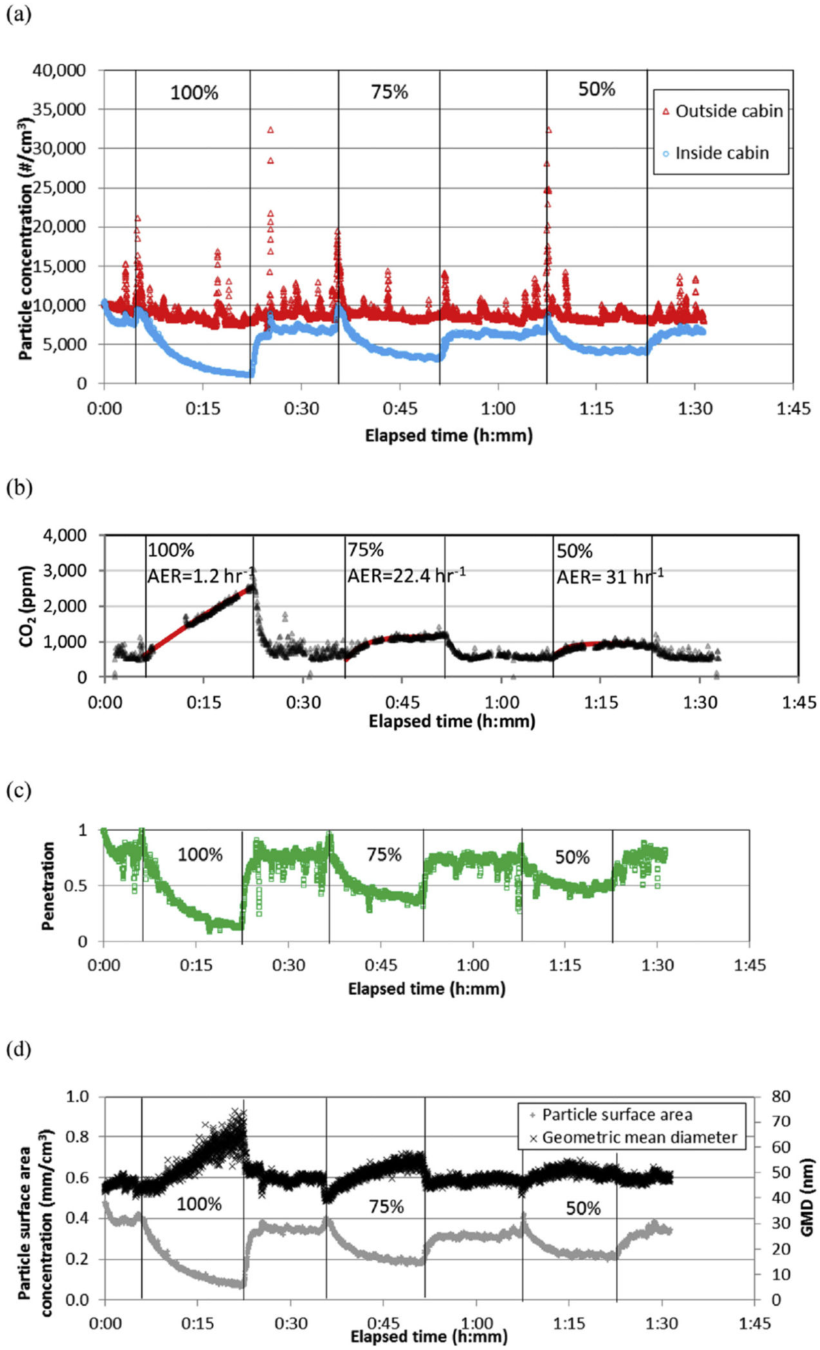

Fig. 4.

Fractional recirculation test: In-cabin particle concentrations, CO_2 concentrations, and mean particle diameter and surface area during 100, 75 and 50% recirculation door opening at fan speed 2. Percentage shown in the figure is recirculation door opening percentage. Vehicle speed was 15 mph and there were two passengers including the driver. (a) Particle concentration inside and outside cabin (b) Cabin CO_2 concentration (c) Particle penetration (d) Particle surface area and geometric mean diameter.

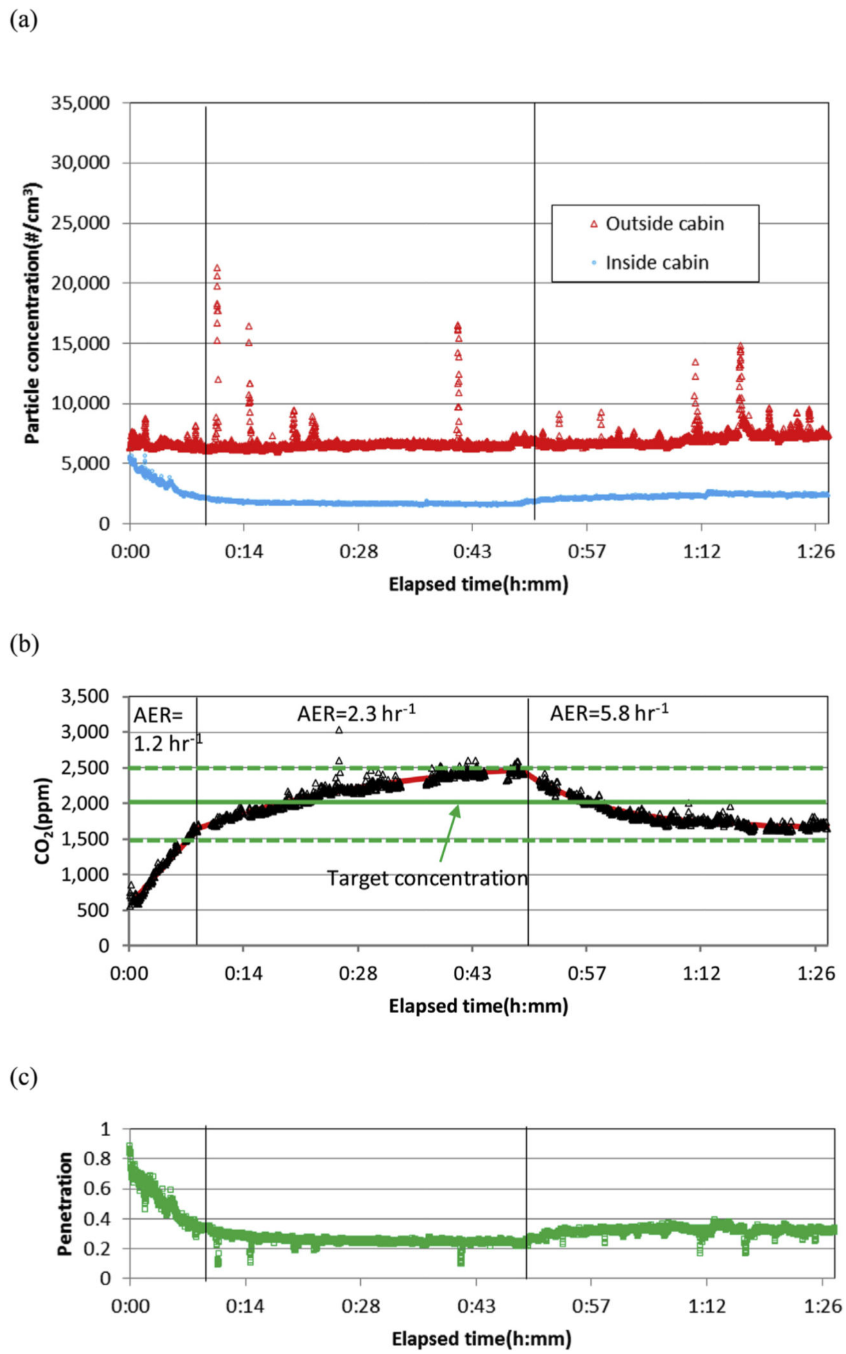

Fig. 5.

Open-loop recirculation control test: In-cabin particle and CO_2 concentrations during fractional recirculation at fan speed 2. Recirculation door opening percentage was set at 100% initially, changed to 92% after 8min, then changed to 85% after 49 min. Vehicle speed was 15 mph and there were two passengers including the driver. (a) Particle concentration inside and outside cabin (b) Cabin CO_2 concentration (c) Particle penetration.

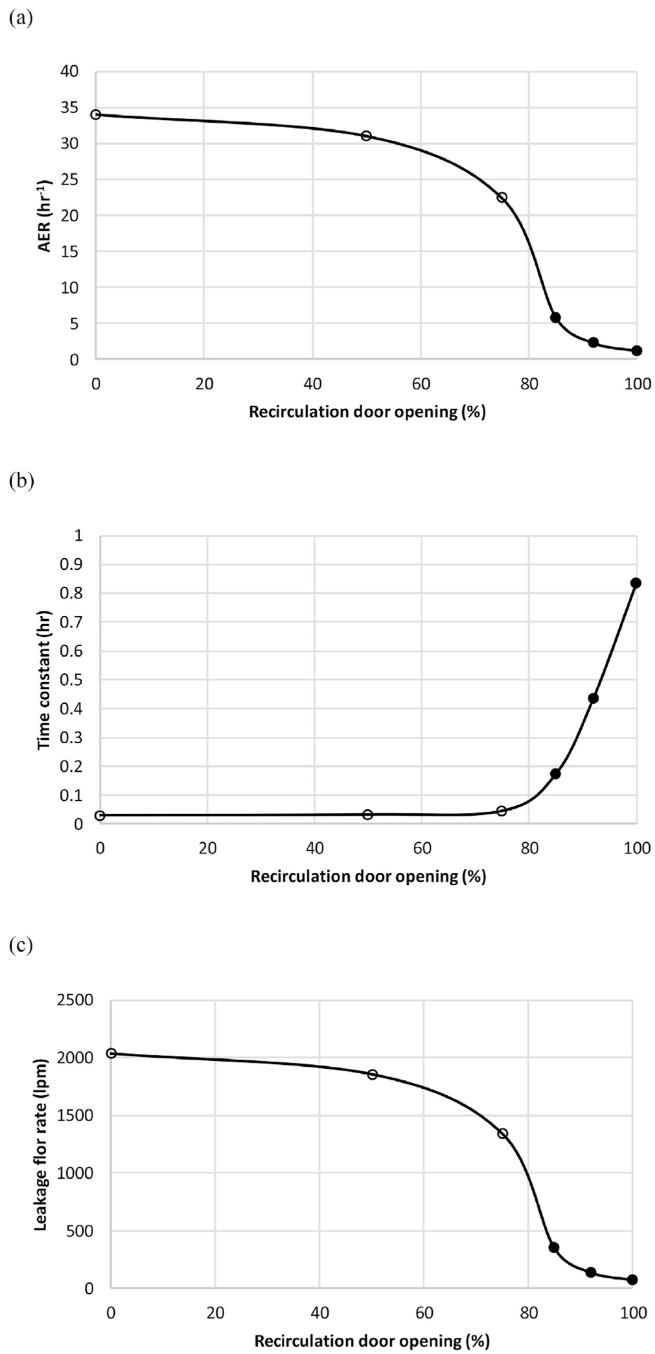

Fig. 6.

Air Exchange Rate (*AER*), time constant, and leakage flow rate as a function of recirculation door opening percentage at fan speed 2. Vehicle speed was 15 mph and there were two passengers including the driver. Note solid markers represent operation regime of the open-loop control shown in Fig. 5.

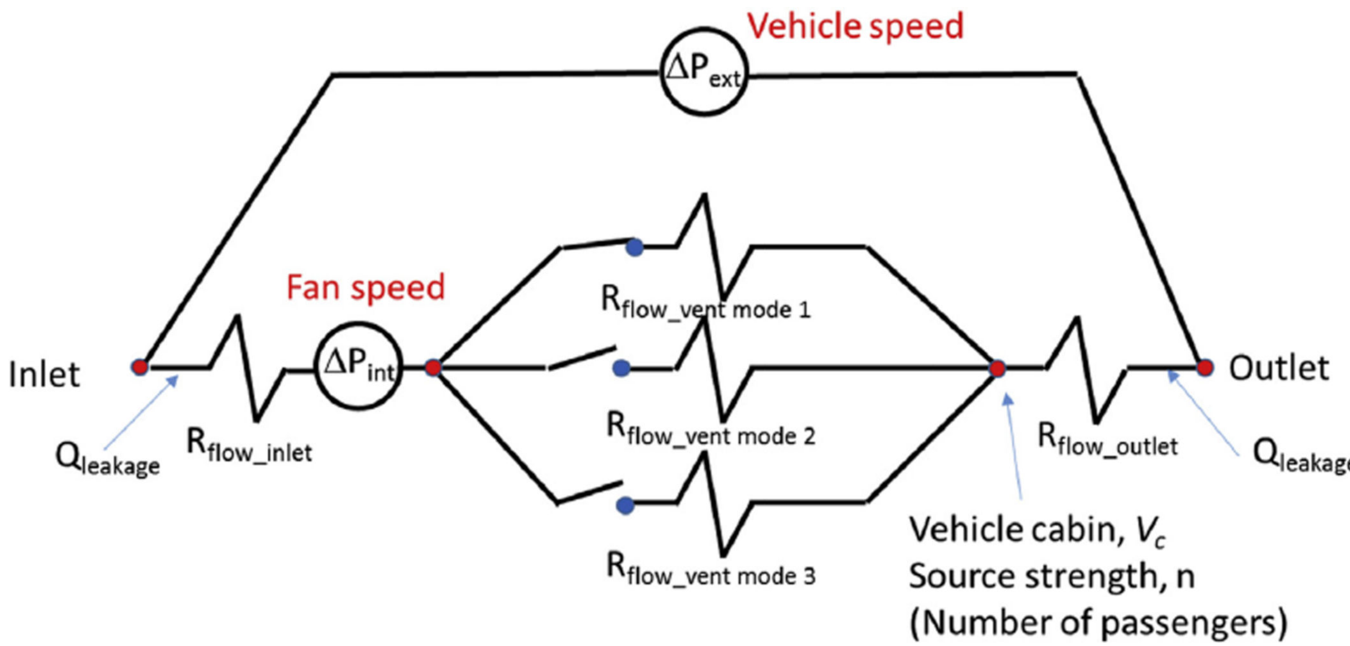

Fig. 7.
Schematic diagram of flow resistance model.

Table 1

Overview of the experimental design for each of 4 tests.

	Pre-trial	Test 1	Test 2	Test 3	Test 4
Vehicle speed	0 mph	15 mph	15 mph	15 mph	15 mph
Windows	open	closed	closed	closed	closed
Recirculation setting	off	0%	0% or 100%	50/75/100%	variable
Fan speed	off	speed 2	speed 2 or 8	speed 2	speed 2
Time	up to time 0	22 min	90 min	90 min	90 min