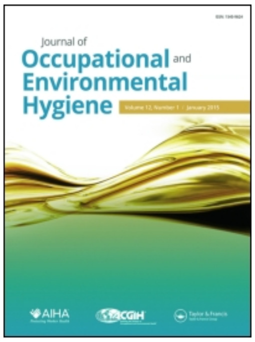

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Aerosol Generation by Blower Motors as a Bias in Assessing Aerosol Penetration into Cabin Filtration Systems

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In cabin filtration systems, blower motors pressurize a vehicle cabin with clean filtered air and recirculate air through an air-conditioning evaporator coil and a heater core. The exposure reduction offered by these cabins is evaluated by optical particle counters that measure size-dependent aerosol concentration inside and outside the cabin. The ratio of the inside-to-outside concentration is termed penetration. Blower motors use stationary carbon brushes to transmit an electrical current through a rotating armature that abrades the carbon brushes. This creates airborne dust that may affect experimental evaluations of aerosol penetration. To evaluate the magnitude of these dust emissions, blower motors were placed in a test chamber and operated at 12 and 13.5 volts DC. A vacuum cleaner drew 76 m^3/hour (45 cfm) of air through HEPA filters, the test chamber, and through a 5 cm diameter pipe. An optical particle counter drew air through an isokinetic sampling probe and measured the size-dependent particle concentrations from 0.3 to 15 μm. The concentration of blower motor aerosol was between 2×10^5 and 1.8×10^6 particles/m^3. Aerosol penetration into three stationary vehicles, two pesticide application vehicles and one tractor, were measured at two conditions: low concentration (outside in the winter) and high concentration (inside repair shops and burning incense sticks used as a supplemental aerosol source). For particles smaller than 1 μm, the in-cabin concentrations can be explained by the blower motor emissions. For particles larger than 1 μm, other aerosol sources, such as resuspended dirt, are present. Aerosol generated by the operation of the blower motor and by other sources can bias the exposure reduction measured by optical particle counters.

Keywords aerosol generated, bias, cabin filtration, carbon brushes

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INTRODUCTION

In a vehicle cabin filtration system, the vehicle cabin is pressurized so the wind cannot force air contaminants into the cabin. When the air supplied to these pressurized cabins is appropriately filtered, worker exposure to dangerous air contaminants should be reduced by at least a factor of 10.[1,2] These cabin filtration systems reduce worker exposure to aerosols, such as pesticides, crystalline silica-containing dusts generated during construction and surface mining, particulate diesel emissions, and bioaerosols generated during agricultural and construction operations.[3–6] Because the cabin filtration system is an integral component of the equipment, these cabins must function throughout the vehicle's useful life.

Because these cabin filtration systems are mainly used to control worker exposure to particulate air contaminants, optical particle counters (OPC) are used to evaluate aerosol penetration into a cabin filtration system.[7,8] These instruments measure size-dependent particle number concentration inside and outside the cabin. The ratio of particle number concentration inside the cabin to particle number concentration outside the cabin is termed penetration, which is typically plotted as a function of particle size. The carbon brushes used in cabin filtration systems can be an extraneous source of particulate that can noticeably increase the particle number concentration measured downstream of the filters. Such aerosol generation will bias measurement of aerosol penetration through filtration systems. In vacuum cleaners, carbon brushes are reportedly abraded, creating an aerosol that contributed to particle number concentrations downstream of the filters.[9]

This study evaluated the emissions generated by the operation of blower motors used in cabin filtration systems. This information is presently needed to develop and refine testing procedures used to evaluate these cabin filtration systems.

Penetration measured with optical particle counters is used to validate the design of a vehicle's cabin filtration systems.[7,8] During validation tests described by the American Society of Agricultural Engineers Standard S525, the vehicles are driven over an unpaved surface for about 2 hours, and particle number concentrations are measured inside and outside the vehicle's cabin. Recent studies have found that manufacturing mistakes, bowed flanges, and deteriorated gasket material caused increased penetration into the cabin filtration systems.[10,11] This situation suggests that tests are needed to evaluate aerosol

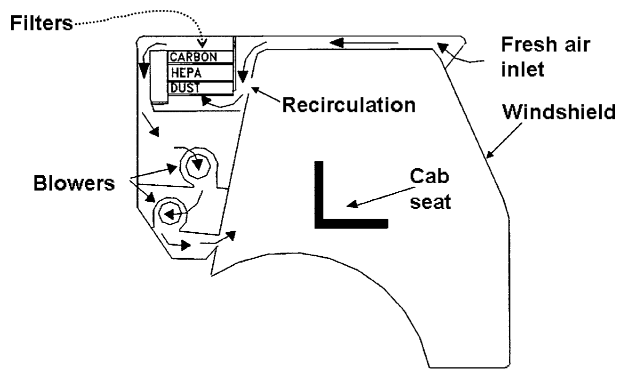

FIGURE 1. Schematic description of cabin filtration system

penetration into cabins as part of maintenance and quality control programs so that each cabin filtration system provides the expected exposure reduction. Using optical particle counters, only 10–15 min may be needed to measure aerosol penetration into a cabin. Perhaps such relatively quick testing procedures can be used in quality control and maintenance programs.

The cabin filtration system includes the air inlet, the filtration for incoming fresh air, the vehicle's cabin, recirculation filters for dust generated in the cabin, blowers, ducting to and from the vehicle heating and cooling equipment, and seals and fittings needed to connect all of these components. Cabin filtration systems are generally constructed from impervious materials to protect workers from dermal and respiratory exposures.

Figure 1 is a schematic illustration of a cabin filtration system for a cabin that is retrofitted to the tractor and that does not include recirculation filters. Typically, recirculation filters are positioned upstream of the vehicle's evaporator and heater cores. This equipment needs to be assembled so that outside air must pass through the filter where harmful air contaminants are removed. The system is pressurized so that wind or radiator-fan driven air infiltration cannot occur. Small holes, in the presence of negative static pressure downstream of the filtration system, will cause air contaminants to bypass the filters and flow into the vehicle's cabin.

From an occupational safety and health perspective, these cabin filtration systems should be regarded as multicomponent systems that offer potential protection from a variety of air contaminants in surface mining, agricultural, and construction environments. Because these vehicles can be in use for many years, such systems may deteriorate with time and may eventually need to be refurbished. This suggests a need to periodically evaluate aerosol penetration into existing equipment. These systems are used on vehicles that are so large (4–5 m high) that laboratory testing is impractical.

In cabin filtration systems, one or two blower motors pressurize the cabin with filtered air and recirculate air through the vehicle's heating, ventilation, and air conditioning box. Blower motors, like many other electrical motors, contain carbon brushes that are abraded during the routine operation of the blower motor. The carbon brushes are small blocks of graphite that are about 0.7 × 0.7 cm square and about 1–2 cm long. Springs force these graphite brushes against the rotating commutator. Electrical current flows through the stationary graphite and a split-ring commutator that contacts and abrades the carbon brush. The commutator, which is split into several segments, is connected to a coil of wire that is wrapped around the blower's shaft. The current flowing through the wires generates a magnetic field.[12]

The interaction between this magnetic field and fixed magnets located on the periphery of the motor causes the armature (the assembly containing the commutator, the wire coil, and the attached shaft) to rotate.[13,14] This motion abrades the carbon brushes and is an obvious source of aerosol emissions. During routine operation of similar electrical motors used in vacuum cleaners, carbon brushes were reportedly abraded, creating an aerosol.[9]

The abrasion of the carbon brushes is inevitable during the routine operation of many electrical motors, such as blower motors. Although the magnitude of this aerosol generation in cabin filtration systems has not been documented, the available data indicate that in-cabin aerosol concentrations are about 10^6 particles/m^3.[15] Particulate emissions created by the abrasion of the carbon brush will affect the measurement of in-cabin aerosol concentration measurements, thus biasing the measurement of aerosol penetration (ratio of inside- to outside-the-cabin particle concentration). When the test aerosol concentration outside the cabin is too low, this extraneous aerosol apparently caused the rejection cabin filtration systems that was acceptable.[16]

This work was conducted to measure the aerosol emissions from the blower motors and to characterize the background aerosol concentrations in some stationary tractors and pesticide application vehicles. Laboratory testing was conducted to measure the number concentration and size distribution of particles generated by blower motors used in cabin filtration systems. In addition, limited testing on actual cabin filtration systems was conducted to compare measured aerosol concentrations in the cabin with the concentration of blower motor aerosol that is expected based on laboratory testing.

METHODS

Laboratory Study

To measure the number concentration distribution of particles generated by the blower motors (including the carbon brushes), the blower motors were placed in a test chamber (Figure 2). Some blower motors did not have housings because the blower's housing was a component of another structure. The blower motors were simply operated in the test chamber. The test chamber inlet was a bank of two HEPA filters (24″ × 24″ × 11.5″ Astrocel I filters, American Air Filter, Louisville, Ky.) in series. The measured penetration through each filter was under 0.02%. The test chamber flow rate was 76 m^3/hour (45 cfm), and the rated flow rate for these filters was 1000 cfm. The use of a large filter area minimized the pressure loss and therefore reduced filter by-pass leakage.

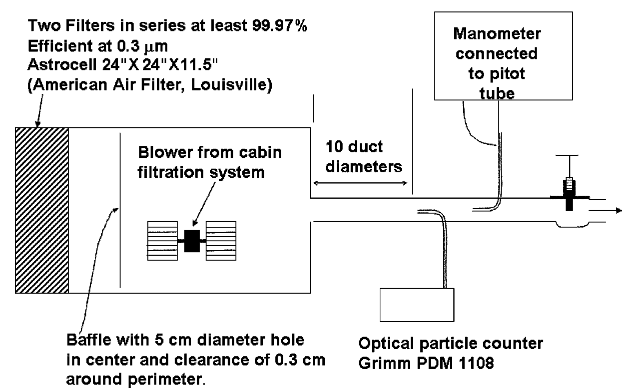

FIGURE 2. Schematic illustration of test chamber used for measuring blower motor emissions

The blower motors were operated in the test chamber at the 12 volts that would be used during stationary testing and at the 13.5 volts typical of vehicle operation. A constant voltage power supply (model 1791, B & K Precision, Placentia, Calif.) provided the required voltages to within 0.2% for a constant line load and temperature. A commercially available vacuum cleaner was used to draw 76 m^3/hr of air into the test chamber through the HEPA filters and into a 5 cm diameter pipe (2-inch schedule 40 PVC pipe). To sample the air in the duct, an optical particle counter (Portable Dust Monitor model 1108, Grimm Technologies, Ainring, Germany) extracted air through an isokinetic sampling probe (model 1.1052, Grimm Technologies). In the optical particle counter, individual particles passed through a beam of light. The OPC detected the amount of light scattered by individual particles and classified particles into 15 sizes between 0.3 and 15 μm. The number of particles in each size range was counted.

Size-dependent particle number concentrations were measured before, during, and after the blower motor operation. The size-dependent blower motor emissions are the product of the flow rate and particle concentration. Because some aerosol leaked into the test chamber (Figure 2), the blower motor concentration was the difference between the concentration measured during blower motor operation and the average concentration measured before and after the blower motor operations. However, the background concentrations were under 5000 particles/m^3, and the background correction was typically 1000 to 2000 particles/m^3. The source of this leakage was not determined.

Blower motors listed in Table I were tested at routine operating conditions reflecting the operation on sole battery power (12.0 volts DC) and under fully operational conditions (engine power, approximately 13.5 volts DC). The voltage supplied to the blower motors was digitally recorded every minute. The Grimm PDM1108 has the capacity to record three channels of analog data. This instrument has a 10-bit analog to digital converter for the range 0–10 volts and records digital voltage with a resolution of slightly less than 0.01 volts. Because the voltages for these tests were greater than 10 volts, the voltage measurements were made across a voltage divider circuit that was placed in parallel with the power supply. This circuit consisted of a 0.9 and a 0.4 mega-ohm resistor that were in series. The voltage across the 0.4 mega-ohm resistor was logged. Because the A/D converter acts like a resistor in parallel with the 0.4 mega-ohm resistor, the resistance across the 0.4 mega-ohm resistor and the A/D converter was measured to be 0.361 mega-ohm. These resistance measurements were made with a multimeter (Fluke model 112 True RMS Multimeter, Everett, Wash.). Thus, the input voltage was reduced by a factor of 3.78. The applied voltage was constant to within 0.2 volts.

The Grimm PDM 1108 sampled 1.2 L/min from the centerline of the 5 cm diameter pipe. The Grimm isokinetic sampling probe was used with a 1.5 mm inlet diameter. To obtain isokinetic sampling conditions, the gate valve (see Figure 2) was adjusted to obtain a centerline velocity of 11.50 m/sec

TABLE I. Description of Blower Motors

	12 Volt		13.5 Volt		
Blower Motor	Rotational Speed (rpm)	Current (Amperes)	Rotational Speed (rpm)	Current (Amperes)	Description
CNH (recirculation)	3100	20.2	Power supply maxed out		Used for recirculation, electrical brushes and windings cooled by air motion, double sided blower
CNH (pressurizer)	2574	7.6	2812	9	Sealed motor, used to pressurize cab
	2530	8	2865	9.6	
John Deere	3494	5.6	3825	6.7	Sealed motor, used to pressurize cab
	3512	6.4	3875	7.4	
AGCO	4156	9.3	4600	11.4	Electrical brushes and windings cooled by blower motor, double sided motor, used for recirculation
	4318	10.1	4600	12.2	
Nelson	3120	15.5	4600	11.4	Uses two blowers in series to move air through a cabins; the motor housing has vent holes and the brushes are visible
	3154	18.7	4700	12.2	

(2260 ft/min). A pitot tube and an inclined manometer were used to measure the centerline air velocity. Based on Hangal and Willeke's models for isokinetic sampling, the errors for sampling particles smaller than 4 μm conditions are under 1%.[17] The airflow from the test chamber was the product of the centerline velocity, the duct area, and a pipe factor 0.9.[18] This airflow was estimated to be 76 m^3/hr (45 cfm).

At least two new motors of each type of blower motor, listed in Table I, were tested. Emissions from each blower motor were tested 30–480 min. Some measurements were shortened because the power supply was unable to supply a constant voltage to some motors. The motor's impedance might have changed as the armature abraded the carbon brushes.

Stationary Testing

Stationary tests of cabin filtration system efficiency were conducted with relatively low and high aerosol concentration to obtain insight as to the actual magnitude of the cabin-generated aerosol. Clearly, electrical motors generate aerosol by abrading the carbon brushes. These stationary tests were conducted to determine whether additional aerosol sources were present. Ideally, one would like to measure the aerosol concentration inside the cabin in a facility where the concentration outside the cabin is nearly zero and there was no need to adjust the data for aerosol penetration into the cabin. To do this, each vehicle would need to be placed in a cleanroom where the air has been filtered to remove all the aerosols. However, this approach is impractical because of vehicle size. For example, an AGCO Terra-Gator is 4 m high, 3.5 m wide, and 6.3 m long. Furthermore, these vehicles were dirty from actual use, and aerosol may have been resuspended by air flowing around the vehicle or from the operation of the vehicle's equipment.

Because of these practical issues, stationary tests were conducted during conditions of high and low concentration. As described in the following paragraphs, algebraic manipulation was used to estimate the concentration of cabin-generated aerosol and the penetration into the cabin, which will be termed the algebraically estimated penetration (P_a). The cabin-generated aerosol included the motor generated aerosol and any addition generated or resuspended particles within the cabin filtration system.

This testing was done for two pesticide application vehicles and one tractor. The cabin filtration systems for these vehicles were designed to meet the ASAE S525 consensus standard. An AGCO pesticide application vehicle and a John Deere tractor were tested near Iowa City. Both of these vehicles had been in service for at least 1 year. A newly manufactured, unused CNH pesticide application vehicle was tested at CNH's manufacturing facility in Benson, Minn.

The stationary tests were conducted outdoors during late December and in February in the hope that ambient particulate concentrations were reduced. During conditions involving low ambient aerosol concentrations, aerosol penetration into a cabin filtration system was measured while the cabin filtration system was operated from battery power and the vehicle was outdoors. The inside-the-cabin concentrations were measured by placing the Grimm PDM on the vehicle's seat. The outside-the-vehicle concentrations were measured near the vehicle's door. For a period of at least 30 min, two Grimm PDM 1108s were used to measure the particle number concentration inside and outside the cabin. Then the vehicle was moved into a shop maintenance area and parked. The vehicle cabin filtration system was operated from battery power. Supplemental aerosol was generated by burning enough incense sticks to produce concentrations larger than 10^8 particles/m^3. The incense sticks were placed under the vehicle, and random air currents dispersed the incense throughout the room. This data was termed the incense or high concentration data.

The high and low concentration tests were used to estimate the aerosol penetration into the cabin and the concentration of cabin-generated aerosol. For each particle size channel, the following two equations were solved for the concentration of cabin-generated aerosol (C_g) and an algebraically-estimated penetration (P_a) in to the cabin:

$$C_{i,h} = C_g + P_a C_{o,h} \tag{1}$$

$$C_{i,l} = C_g + P_a C_{o,l} \tag{2}$$

where C = concentration with subscript; h = high challenge concentration (incense stick as a supplemental aerosol); i = inside cabin; l = low challenge concentration; o = outside cabin.

Equations 1 and 2 can be solved for C_g and P_a:

$$P_a = (C_{i,h} - C_{i,l})/(C_{o,h} - C_{o,l}) \tag{3}$$

$$C_g = C_{i,l} - P_a C_{o,l} \tag{4}$$

Propagation of errors calculations was used to estimate the coefficients of variation for each value of P_a and C_g.[19,20] Because the computation of P_a involved concentration differences and ratios, the estimation of experimental variability for individual values of C_g and P_a was complicated. The concentrations were particle number concentrations measured by counting the number of particles in a volume of air. The precision of the particle number concentrations was based on the number of particles counted. Based on the Poisson distribution, the variance was the number of particles counted.[21] Thus, the standard deviation for the number concentrations was computed:

$$S_{p,t} = (N_{p,t})^{0.5}/(QT_t) \tag{6}$$

where N = number of particles counted; Q = sampling rate; T = sampling time; p = sampling position, either inside (i) or outside (o) the cabin; t = test conditions, either high (h) or low (l) concentrations.

Equations 3 and 4 involve the concentration differences. The standard deviation of a difference was computed as the square root of the sum the variances for the two standard deviations. For the purposes of assessing the uncertainty in P_a computed from equation, P_a was stated as:

$$P_a = D_i/D_o \tag{7}$$

where

$$D_i = C_{i,h} - C_{i,l} \tag{8}$$

$$D_o = C_{o,h} - C_{o,l}. \tag{9}$$

The standard deviations s_{di} and s_{do} for, respectively, D_i and D_o was computed as follows:

$$s_{di} = (N_{i,l}/(QT_l)^2 + N_{i,h}/(QT_h)^2)^{0.5} \quad (10)$$

$$s_{do} = (N_{o,l}/(QT_l)^2 + N_{o,h}/(QT_h)^2)^{0.5} \quad (11)$$

For a variable $f(x_1,x_2)$, its variance, s_f^2 was estimated as:[20]

$$s_f^2 = \left(\frac{\partial f(x_1,x_2)}{\partial x_1}\right)^2 s_{x_1}^2 + \left(\frac{\partial f(x_1,x_2)}{\partial x_2}\right)^2 s_{x_2}^2 + 2\left(\frac{\partial f(x_1,x_2)}{\partial x_1}\right)\left(\frac{\partial f(x_1,x_2)}{\partial x_2}\right) s_{x_1,x_2} \quad (12)$$

In Equation 12, $s_{x1,x2}$ was the covariance of X_1 and X_2. For each value of P_a and C_g, computed from Equations 3 and 4, the uncertainty or standard deviations, s_{pa} and s_{cg}, was estimated using Equation 12:

$$s_{pa} = \left(s_{di}^2 - s_{do}^2 P_a^2\right)^{0.5} / D_o \quad (13)$$

$$s_{cg} = \left(s_{i,l}^2 + s_{pa}^2 C_{o,l}^2 + s_{o,l}^2 P_a^2\right)^{0.5} \quad (14)$$

The use of Equation 12 to estimate the standard deviations assumes small errors in the measurement of the independent variables in Equations 3 and 4. The estimation of s_{cg} assumed that the covariance between P_a and $C_{o,l}$ is zero. The cited references do not provide a means for evaluating these assumptions. From an inspection of Equations 7–14, the random errors associated with using Equations 3 and 4 to estimate P_a and C_g were minimized by a large concentration difference between the high and low test concentrations outside the cabin and sufficiently long sampling times so that a large number of particles were counted.

RESULTS

Figure 3 and Table II present the fractional size distribution and the number concentrations of the blower motor emissions measured in the test chamber. In Figure 3, the fraction is the number of particles counted in a size channel divided by the total number of particles counted. This fraction is divided by the difference of natural logarithm of the upper and lower sizes for each channel. This data presentation eliminates artifacts caused by the varying channel widths of the Grimm PDM 1108. Size distribution shape did not vary appreciably with

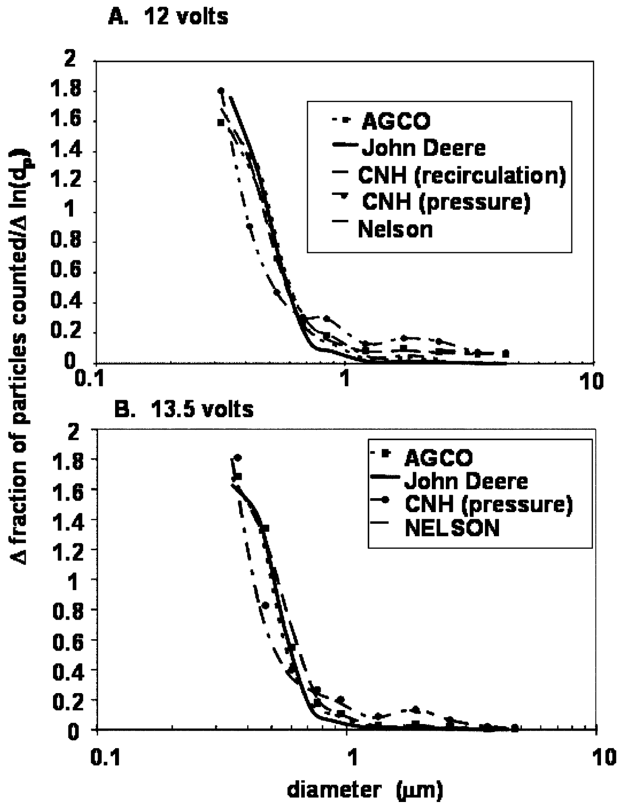

FIGURE 3. The size distribution of the blower motor aerosol is unaffected by operating voltage or the source of the blower motor.

the blower motor or the operating voltage. Particle number concentration decreases as particle size increases. There are very few particles generated that are larger than 1 μm.

Table II presents the particle number concentrations for the different blowers tested. Increasing the blower motor voltage increases the blower rotational speed and the emission rate. Enclosing the blower motor does appear to reduce the blower motor emissions. However, some of these motors may need to be cooled by the airflow to prevent heat from accumulating, causing damage to components.

During each experimental run, the blower motor emissions appear to fluctuate with time as shown in Figure 4. The concentration peaks when the power is first applied to the blower.

TABLE II. Particle Concentration Exiting the Test Chamber (Particles $> 0.3\ \mu$m/L)

		12 Volt		13.5 Volt	
Blower Motor	n	Mean	Standard Deviation	Mean	Standard Deviation
AGCO	3	983	484	1775	553
John Deere (enclosed)	3	446	35	768	30
CNH (recirculation)	2	1788	185	Could not obtain 13.5 volts	
CNH pressurizer (enclosed)	2	209	258	271	338
Nelson Industries	2	1111	520	1869	576

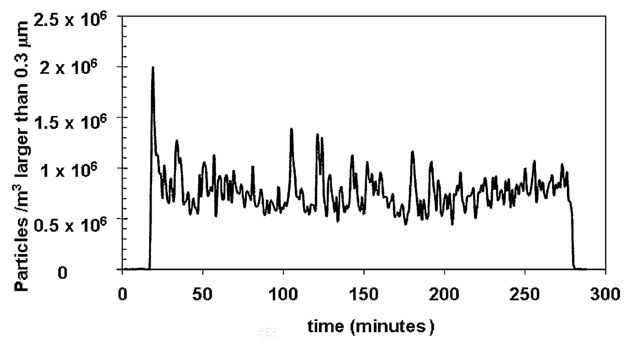

FIGURE 4. Measured blower motor emissions vary with time

Then the concentration approaches steady-state in about 5–6 minutes. In Figure 4, the concentration seems to fluctuate between 4.40×10^5 to 10^6 particles/m^3 with an average of 7.60×10^5 particles/m^3. If stationary tests are based on 1- or 2-min samples, sufficient time must be allowed to permit blower motor emission rates and in-cabin concentrations to reach steady state.

Figure 5 presents the fractional size distribution of the incense aerosol used to test penetration into the stationary vehicle. The particle number concentrations outside the AGCO, CNH, and John Deere cabins were, respectively, 6.12×10^8, 1.25×10^8 and 2.1×10^8 particles/m^3. Inspection of Figure 5 reveals that the fraction of particles larger than 1 μm is too small for data analysis to be useful. Figures 6–8 describe the results from the stationary testing conducted on the three agricultural vehicles. In Figure 6, the coefficients of variation (CV) estimated from uncertainty analysis are plotted as a function of particle size for both P_a and C_g. The estimates for CV were dominated by $s_{d,i}$ and $s_{i,l}$ for, respectively, the algebraically estimated penetration and the cabin-generated aerosol. For both plots, CV increases with particle size because the number of particles counted decreases with increasing particle size. For the penetration plots, the CV remains below

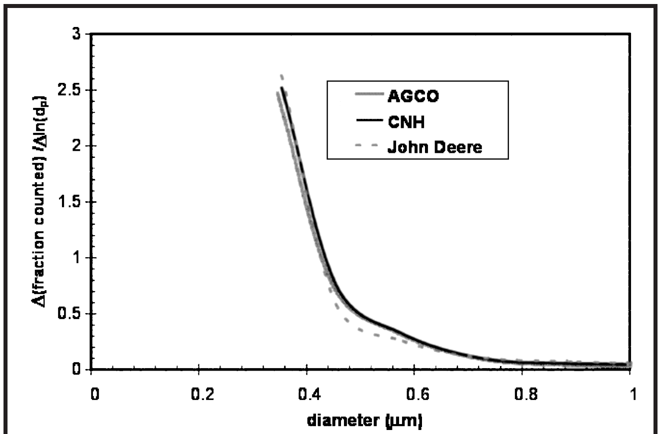

FIGURE 5. Size distribution of incense aerosol measured outside vehicle cabs

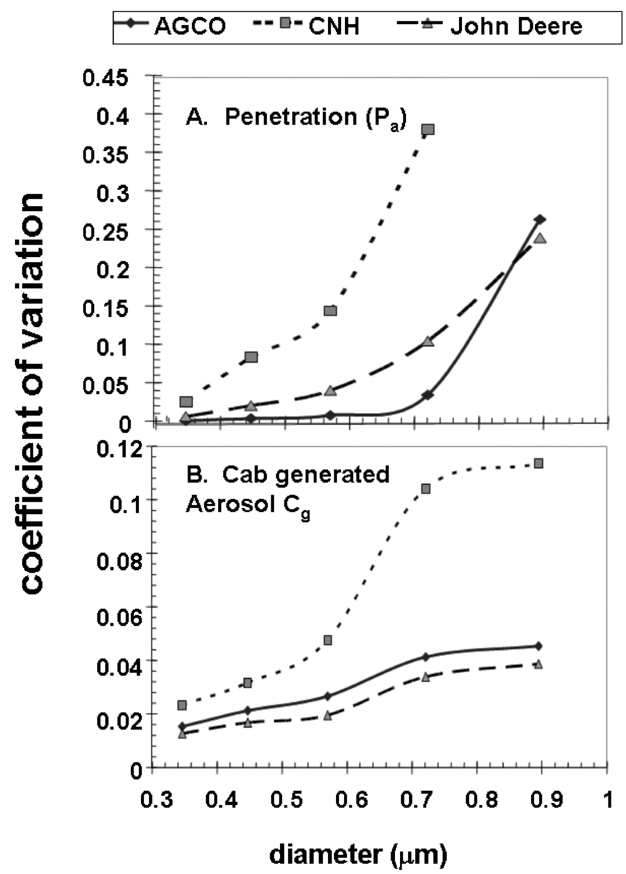

FIGURE 6. The estimated coefficients of variation increase with particle size. The coefficients of variation were estimated based on uncertainty analysis.

15% for particles in the 0.3–0.65 μm range, the smallest three channels for the Grimm PM 1108. As particle size increases, the CV for penetration increases because the number concentrations decrease inside and outside the cabin. The CV for cabin-generated aerosol does not have as much variability. For particles in the 0.3 to 0.65 μm range, the coefficient of variation is under 0.05. For the CNH pesticide applicator, the CV remained below 0.12 for particles smaller than 1 μm. For the John Deere and AGCO vehicles, the CV for cabin-generated aerosol remained below 0.05.

During low concentration testing, the outside-the-cabin concentrations and the penetration were so low that the inside cabin concentration is mostly the aerosol generated in the cabin (see Figure 7). The variability of C_g is mostly attributed to the variability of concentration measured inside the cabin during low concentration testing.

Figure 7 presents particle number concentration distributions for aerosols in the cabin. In Figure 7, the number concentration in each particle size channel, ΔC, is divided by the difference of natural logarithm of the upper and lower sizes for each channel. This data presentation eliminates artifacts caused by the varying channel widths of the Grimm PDM 1108. Figure 7 compares three number concentration distributions:

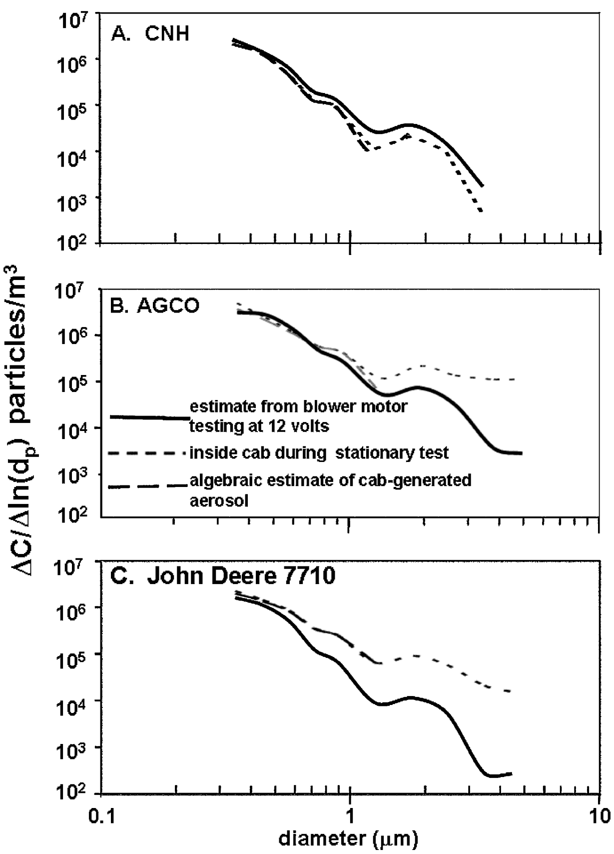

FIGURE 7. Three size-dependent aerosol concentrations: measured in cab during low concentration stationary test, blower motor aerosol estimated from laboratory testing, and the cabin generated aerosol estimated by Equation 4. The actual concentration measured during low concentration stationary testing and the estimated concentration cab generated aerosol are nearly identical. To estimate the blower motor aerosol concentration, the blower motor concentration measured during laboratory testing was multiplied by the ratio of the test chamber airflow to the airflow into the vehicle cab.

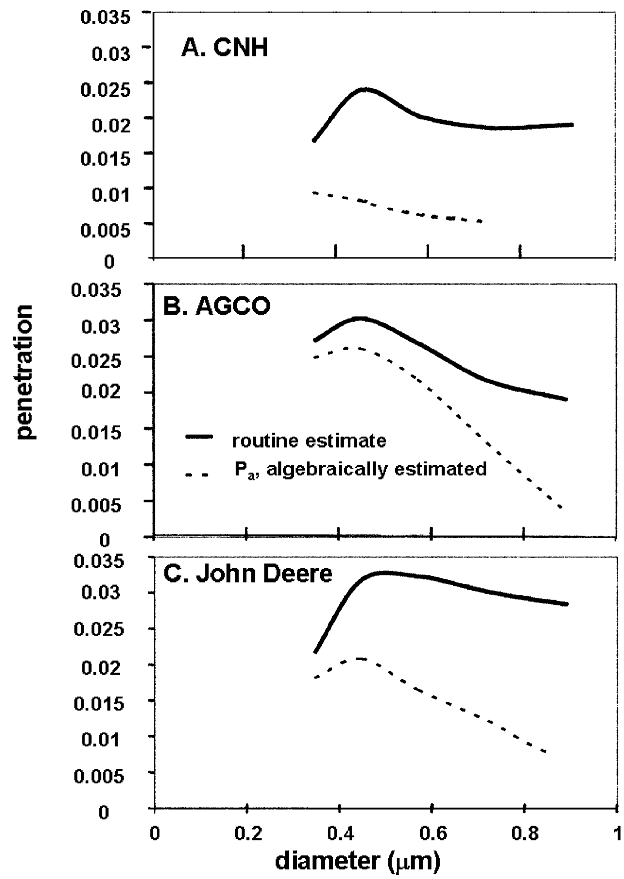

FIGURE 8. Two estimates of aerosol penetration into the cab. The routine estimate of penetration is the inside concentration divided by the outside concentration during the testing with incense sticks. The algebraic estimate of penetration into the cab adjusts for cab-generated aerosol as described by Equation 3.

1. C_g, the cabin-generated aerosol. This is estimated using Equation 4.
2. Blower motor aerosol. This is estimated by multiplying the blower motor concentration measured during laboratory testing by the ratio of airflow during the laboratory to airflow into the cabin.
3. Inside-the-cabin aerosol. This is the measured aerosol concentration in the cabin during low concentration testing.

In all three plots, the concentration distributions of inside-the-cabin aerosol and the cabin-generated aerosol are in close agreement and these plots overlay each other. For the newly manufactured CNH vehicle, the cabin-generated aerosol and blower motor aerosol measured during laboratory testing have approximately the same number concentration distribution. For the AGCO and the John Deere vehicles, the blower motor aerosol and the inside-the-cabin aerosol concentration distributions are in close agreement for particles smaller than 1 μm. For particles larger than 1 μm, the two distributions noticeably diverge. The blower motor aerosol distribution continues to decrease as particle size increases. However, the inside-the-cabin aerosol distribution is relatively constant for particles between 1–4 μm. In this size range, there is a 1–2 order of magnitude difference between the blower motor aerosol and the inside-the-cabin aerosol concentration distributions. The John Deere and AGCO vehicles had been in service for at least 1 year. In contrast, the unused CNH vehicle had just been manufactured at CNH's Benson, Minnesota, facility. This difference in vehicle age and use suggests that internally generated aerosol, such as resuspended dirt, contributes to the measured aerosol inside the cabin.

In Figure 8, penetration is plotted as a function of particle size for the three stationary vehicles. The routinely estimated penetration, obtained during testing with aerosol generated by burning incense sticks, is the inside-the-cabin concentration divided by the concentration outside the cabin. The algebraically estimated penetration, P_a, is computed using Equation 3. As particle size increases, the difference between the routine estimate of penetrations and the algebraically estimated penetration increases. Because the estimated variability (see Figure 6) increases with increasing particle size, caution is needed in interpreting Figure 8. Figure 6 indicates that the coefficient of variation for the 0.3–0.4 μm particles is under 0.03. In Figure 8, the two estimates of penetration are in closest agreement for the 0.3–0.4 μm particles. At this particle size, concentration of the incense aerosol is so large that the biases caused by the cabin-generated aerosol are minimized. As particle size increases from 0.3 to 1 μm, the difference between the two estimates of penetration increases and the estimated coefficient of variation for the penetration measures increases from 0.03 to larger than 0.25 (see Figure 6). A broader distribution of test aerosol is needed should a reasonably precise estimates of penetration be needed over a wider range of particle sizes. However, this is probably not needed for screening purposes.

DISCUSSION

Testing programs that use optical particle counters to evaluate aerosol penetration into cabin filtration systems need to address the aerosol generated by the blower motors and other aerosol generated in the cabin. The carbon brushes on the blower motors function as aerosol generators for particles smaller than 1 μm. As shown in Figure 8, cabin-generated aerosol can noticeably bias penetration measurements. Such biases can cause the inappropriate rejection of acceptable cabins. Adjusting aerosol penetration measurements for cabin-generated aerosol is probably impractical.

As shown in Figure 4, blower motors are not stable aerosol generators. An adjustment of penetration measurements for cabin-generated aerosol would need to consider the variability associated with the aerosol generation process. A simple, practical approach is to use a sufficiently high aerosol concentration over the particle size range of interest so that the biases caused by cabin-generated aerosol are minimized. To do this, the emission rate of blower motor needs to be obtained. One approach is to use a test chamber similar to the one described in Figure 1. Another approach is to measure the inside-the-cabin and outside-the-cabin concentrations when the outside-the-cabin concentration is very low and very high. Then Equations 1 and 2 can be solved for the concentration of cabin-generated aerosol. The specified minimum test concentration is the product of the expected blower motor aerosol concentration, the expected exposure reduction (reciprocal of penetration), and a safety factor.

The incense smoke appeared to produce a test aerosol useful for measuring particle penetration into the cabin over the 0.3 to 0.65 μm range. Incense stick aerosol is reported to be smaller than 0.5 μm and consists of solid or liquid spheres that appear to be formed from evaporation and condensation phenomena.[24,25] This range is similar to the range observed for maximum penetrating particle sizes in filters. However, cracks in buildings are reported to have maximum penetrating particles sizes over a wider range. For cracks that are 0.025 cm wide, particle penetration appears to be near its maximum over the range of 0.1 to 1 μm.[26]

To enhance the user's ability to conduct useful stationary tests, the in-cabin aerosol generation needs to be suppressed or controlled so that biases are minimized. When motor cooling is not an issue, blower motors could be enclosed to control the dust debris generation by the brushes. However, enclosing the blower motor may cause an accumulation of heat that may damage components.

High-quality recirculation filters can be used to further reduce concentration of blower motor aerosol and other sources of cabin-generated aerosol. For dangerous air contaminants such as respirable crystalline silica, pesticides, and endotoxins, dust resuspended from the floor or other interior surfaces is a potential health hazard. In an enclosed cabin for a surface mining drill, resuspended dust did cause excessive exposure to respirable crystalline silica.[27] Simply replacing the existing recirculation filters with a more efficient mechanical filter can increase the pressure loss through the filter and decrease the airflow being recirculated through the air-conditioning evaporator core and the heater core. This suggests a need to carefully select and design recirculation filters so that adequate recirculation airflow is maintained and the cabin-generated aerosols are adequately controlled.

The inside-the-cabin particle concentrations measured during this study should not present a health hazard for the vehicle operators. The Nelson blower motor appeared to create the highest particle number concentrations in Table II. Mass concentrations were estimated for the blower motor aerosol. This calculation assumed that the particles were spheres with a density of 2.2 gram/cm^3 (the density of graphite).[22] For particles smaller than 10 μm, the mass concentration of the blower motor aerosol was estimated to be 0.5 μg/m^3 for one blower motor. In reality, the Nelson cabin uses two blower motors in series and the estimated worker exposure to blower motor aerosol is 1 μg/m^3. In contrast the threshold limit value for nonfibrous graphite is 2 mg/m^3.[23]

CONCLUSION

The number concentration of blower motor emissions decreases as particle size increases from 0.3 to 1 μm. Such emissions can bias stationary tests used to evaluate the efficiency of cabin filtration systems. Blower motor emissions vary with time and tend to peak when the blower motor is started. Thus, adjusting efficiency for blower motor emissions would involve additional sources of variability that further complicate the analysis. A less complicated approach is to use a sufficiently high test concentration so that the biases caused by blower motor emissions are unimportant. This will enable aerosol penetration into a cabin to be estimated as the inside concentration divided by the outside concentration. However, optical particle counter measurements may require dilution to prevent coincidence errors.[28]

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