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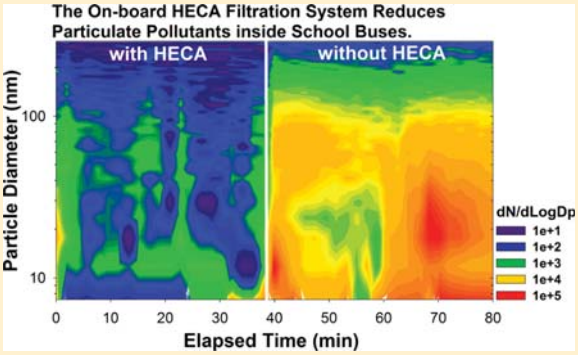
Evaluation of a High Efficiency Cabin Air (HECA) Filtration System for Reducing Particulate Pollutants Inside School Buses

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Supporting Information

ABSTRACT: An increasing number of studies have reported deleterious health effects of vehicle-emitted particulate matter (PM), including $PM_{2.5}$ (aerodynamic diameter ≤2.5 μm), black carbon (BC), and ultrafine particles (UFPs, diameter ≤100 nm). When commuting inside school buses, children are exposed to high level of these pollutants due to emissions from both school bus itself and other on-road vehicles. This study developed an on-board high efficiency cabin air (HECA) filtration system for reducing children's exposure inside school buses. Six school buses were driven on two typical routes to evaluate to what extent the system reduces particulate pollutant levels inside the buses. The testing routes included freeways and major arterial roadways in Los Angeles, CA. UFP number concentrations and size distributions as well as BC and $PM_{2.5}$ concentrations were monitored concurrently inside and outside of each bus. With the HECA filtration system on, in-cabin UFP and BC levels were reduced by 88 ± 6% and 84 ± 5% on averages across all driving conditions, respectively. The system was less effective for $PM_{2.5}$ (55 ± 22%) but successfully kept its levels below 12 $\mu g/m^3$ inside all the buses. For all three types of particulate pollutants, in-cabin reductions were higher on freeways than on arterial roadways.



INTRODUCTION

Epidemiological studies have reported deleterious health effects of traffic emissions,[1] containing particulate matter (PM) of different sizes such as $PM_{2.5}$ (aerodynamic diameter ≤2.5 μm), black carbon (BC), and ultrafine particles (UFPs, diameter ≤100 nm). Exposures to high levels of UFPs, BC, and $PM_{2.5}$ have been associated with pulmonary and cardiovascular health risks.[2−4] UFPs have been shown to induce oxidative stress, mitochondria damage, and acute pulmonary inflammation.[5−7] Since children are in the developing stage for pulmonary function and immune system, they are a particularly vulnerable subpopulation.[8,9] In addition, school-age children's exposures to particulate pollutants were also found to be associated with poor academic performance.[10]

Previous studies have shown that traffic emissions significantly increase concentrations of UFP, BC, and $PM_{2.5}$ on local arterial roadways and freeways.[11−13] In addition to the pollutants originating from surrounding traffic, school buses' own exhaust can also penetrate into the bus cabin, the so-called self-pollution.[9,14−16] High pollutant levels have been observed not only under driving conditions, but also under idling.[17] Children commuting in school buses may be exposed to even higher pollutant concentrations than regular commuters in passenger cars.[18]

Retrofitting school buses with diesel oxidation catalysts and crankcase filtration systems have been widely used. The effectiveness of the retrofit technologies is promising for tailpipe emission control but not necessarily true for in-cabin exposure reduction.[19−22] A majority of school buses are not equipped with any mechanical filtration systems. Although some newer school buses have an air-conditioning unit with an air filter, the purpose of the filter is primarily for removing large debris to protect the mechanical ventilation system.

Our previous proof-of-concept study demonstrated that commercially available household air purifiers can reduce UFP levels inside school buses.[23] However, household air purifiers were not designed for school buses. Despite the novelty of the work, in-cabin UFP reductions were limited at approximately 40 and 50% when operating one and two air purifiers, respectively.[23]

Recently, Lee and Zhu[24] successfully applied high efficiency cabin air (HECA) filters to reduce UFP concentrations inside passenger vehicles by 93% under realistic driving conditions. Using the same type of HECA filter, this study developed a prototype on-board HECA filtration system specifically for school buses and evaluated its performance in six buses under various field conditions.

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Figure 1. HECA filtration system prototypes with two air delivery systems: (a) jet diffusers and (b) air distribution ducts. The arrows illustrate supply airflow patterns of two air delivery systems.

Table 1. Test School Bus Model Specifications

test bus ID[a]	school bus manufacturer	model year	passenger capacity	est. internal volume[b] (m^3)	fuel type	engine location	exhaust location
A	Thomas	2006	22	22.3	diesel	front	rear right
B	International	2007	42	35.9	diesel	front	rear left
C	Bluebird	2013	48	32.3	propane	front	side left
D	International	2007	63	53.8	diesel	rear	side left
E	Bluebird	2010	78	52.4	CNG	rear	rear left
F	Thomas	2011	80	50.6	diesel	rear	rear left

[a]Test school bus E was equipped with air distribution ducts, while the others had jet diffusers. [b]Internal cabin volumes were estimated from measurements of internal dimensions.

MATERIALS AND METHODS

The HECA Filtration System. A prototype on-board HECA filtration system was developed in collaboration with an industry partner. It uses HECA filters that were developed and evaluated in our previous passenger vehicle study.[24] The HECA filters have a pleated panel structure and are fabricated with nonchanged fibers in the diameter of ~0.6 μm. The fiber diameter is much smaller than commercial cabin air filters (i.e., 2−5 μm in diameter). The use of nano fibers increases particle removal efficiency for vehicle emitted particulates (e.g., UFPs, BC, and $PM_{2.5}$), while maintaining a relatively low pressure drop. When used in passenger vehicles, the HECA filters had 20% reductions in ventilation airflow rates, suggesting a little bit more pressure drop than the commercial cabin air filter.[24] When challenged with 0.3 μm potassium chloride particles in the minimum efficiency reporting value (MERV) test at a standardized laboratory setting,[25] the same HECA filter achieved an average filtration efficiency of 99%. This is equivalent to a MERV rating of 16.

Two types of air delivery systems were used in this study to achieve an even distribution of filtered air inside school buses of different sizes. Note that the cabin volume of the selected buses ranged from 22−54 m^3, which is an order of magnitude larger than passenger cars (i.e., 3−7 m^3). Two HECA filtration units were installed in the back of school bus cabins (shown in Figure 1). Through diffusers located on the sides of each unit, cabin air was drawn in and filtered by the HECA filters. Filtered air was then delivered at a constant airflow rate either of 1360 m^3/h through jet diffusers (Figure 1a) or 1160 m^3/h through air distribution ducts (Figure 1b). The air distribution ducts delivered the filtered air through a number of punch-holes (1 cm in diameter). Decreasing numbers of punch-holes were applied with respect to the extended distance from the units and provided a consistent air velocity (~1 m/s) at each punch-hole diffuser. The jet diffuser supplied the filtered air at an air velocity of ~8 m/s. The use of jet diffuser and air distribution duct aims to provide even distribution of filtered air inside the school bus cabin. When the on-board HECA filtration system was on, the in-cabin noise level was increased by only 1−3 dB (see Supporting Information S1).

The sampling locations are relative to the size of different school buses. In this study, we used the percentile distance from the first row seats to determine the front, middle, and rear sampling locations. For instance, sampling at the front part of the school bus cabin was conducted at 25 percentile distance from the first row seats, 50 percentile for the middle, and 75 percentile for the rear.

School Bus Selection. The effectiveness of the HECA filtration system was evaluated inside six school buses of different types. Table 1 shows the characteristics of the six buses. The selected school buses have a wide range of model year (i.e., 2006 to 2013) and passenger capacity (i.e., 22 to 80). The school bus selection took into account different locations of engine (i.e., front and rear) and exhaust tail-pipe (i.e., rear right, rear left, and side left). Buses with different fuel types (i.e., diesel, propane, and CNG) were also considered. All diesel-fuel buses tested in this study were equipped with a diesel particulate filter.

Test Routes. Each school bus was driven on two typical routes as well as idled at a background site to evaluate to what extent the HECA filtration system reduces the in-cabin concentrations for UFPs, BC, and $PM_{2.5}$. The testing routes were selected from existing charter and local school bus routes in Los Angeles, CA. Although the local route included freeways, that is, I-405 (3 km) and I-10 (10 km), sampling on these freeways did not exceed more than 5% of the total sampling time under this scenario. In comparison, the freeway testing route (i.e., charter route) included I-10 (21 km), I-110 (13 km), and I-405 (27 km). The selected routes represent typical school bus commuting on freeways and typical pick-up/drop-

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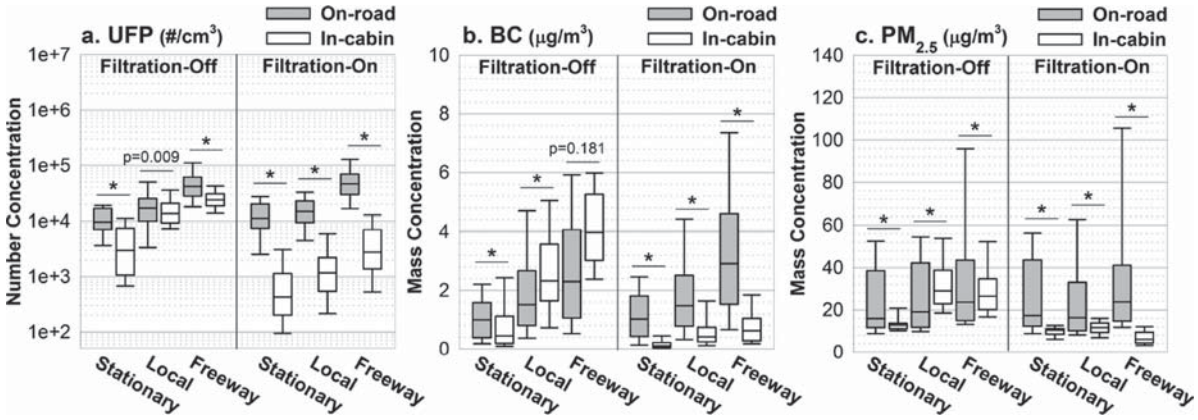


Figure 2. On-road (gray) and in-cabin (white) concentrations of (a) UFPs, (b) BC, and (c) $PM_{2.5}$ with and without operating HECA filtration systems. The data from all six buses tested in this study are presented under different driving conditions: stationary, local roadway, and freeway. Each box indicates lower (25%) and upper (75%) quartile values. The center bar in the box is the median value and the error bar indicates minimum and maximum values excluding outliers. * indicates $p < 0.001$.

off scenarios in residential areas (See Supporting Information S2 for more detail.)

Field Measurements. Field measurements were conducted in each test school bus with and without operating the on-board HECA filtration system. Data were collected with one driver and two researchers inside the buses. No children were present for logistic reasons. To assess in-cabin pollutant reductions, UFP number concentration and size distribution as well as BC and $PM_{2.5}$ levels were monitored concurrently inside and outside of the six school buses.

Two comparable sets of instrument were deployed for on-road and in-cabin measurements. Both sets were located inside the school bus cabin. One set sampled the on-road air through a 3 mm isokinetic probe mounted on a slightly open (1 cm) window. The window gap was sealed with heavy duty duct tape similar to previous studies.[24,26] The other set monitored at the breathing zone (i.e., 1 m above the floor) in the back of the school bus cabin (i.e., at the 75 percentile distance from the first row seats). Another sampling probe of the same length was used for in-cabin air sampling to compensate for any diffusion loss in the sampling lines.

Two sets of scanning mobility particle sizer (SMPS, model 3081, TSI Inc., Shoreview, MN) were deployed to measure particle size distributions in the size range of 7.37−289 nm and total particle number concentrations. The applied scanning and retrace times were 100 and 20 s, respectively. Two DustTrak (model 8520, TSI Inc., Shoreview, MN) and two Qtrak monitors (model 8554, TSI Inc., Shoreview, MN) were used to concurrently measure the in-cabin and on-road concentrations of $PM_{2.5}$ and CO_2, respectively. Similarly, the BC concentrations inside and outside of the buses were measured by two aethalometers (models AE-22 and AE-42, Magee Scientific Co., Berkeley, CA). All instruments were calibrated prior to their deployment for field sampling. Data logging intervals were set to 1 s for all instruments except for the aethalometers, which were set to their minimum logging interval of 1 min.

In addition, two condensation particle counters (CPCs, model 3007, TSI Inc., Shoreview, MN) also measured UFP concentrations at the breathing zone (1 m above floor) in the front and the middle of each school bus (i.e., at the 25 and 50 percentile distance from the first seat, respectively). These data will be presented in a future study focusing on spatial distribution of UFPs inside school buses. Each pair of instruments was collocated before and after the field sampling for data quality assurance and good correlation with little bias was observed (see Supporting Information S3−5).

For each bus, data were collected under three different driving conditions: stationary, local roadway, and freeway conditions. Stationary sampling was conducted in an open terrain area approximately 400 m downwind from the Pacific Coast Highway (PCH, CA-1), which runs along the Pacific coastline in the Pacific Palisade area of the greater Los Angeles. The background particle concentrations were at 3000−5000 cm^{-3}. The school bus was parked heading leeward of the sea breeze and engine was running during the stationary sampling. Local roadway conditions were evaluated while driving on major arterial roadways, whereas freeway conditions were evaluated on major freeways in Los Angeles, CA. Pick-up/drop-off activities of 1 min each were simulated on local (nine stops) and freeway (three stops) routes.

Two different filtration scenarios (i.e., with and without operating the on-board HECA system) were examined for 60−70 min each under local and freeway driving conditions. The school buses in this study were not equipped with any filtration or ventilation system; therefore, the scenario without operating the on-board HECA filtration system represents a typical school bus operation. Stationary data were collected with and without operating the on-board HECA filtration system for 20−25 min each. In-cabin and on-road pollutants were concurrently monitored and logged. The collected data covered 36 different experimental conditions.

I/O Ratio Reduction. In passenger vehicles, the level of exposure reduction can be expressed using pollutant I/O ratios as $(1 - I/O) \times 100\%$. It works well for passenger cars, where no significant self-pollution is observed. However, self-pollution in school buses can result in higher in-cabin concentrations than on-road (i.e., I/O > 1.0, see Supporting Information S6). Thus, this study defines pollutant reduction inside school buses by comparing two I/O ratios with and without operating the HECA filtration system (i.e., intervention and control scenarios, respectively). Since self-pollution occurs under both conditions, I/O Reduction was defined based on $(I/O)_{HECA\text{-}On}$ normalized by $(I/O)_{HECA\text{-}Off}$, as followed:

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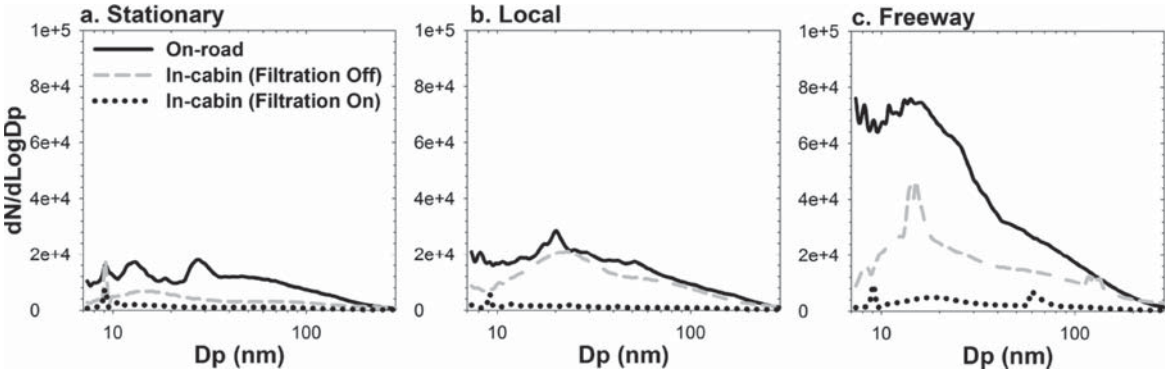


Figure 3. Particle size distribution data collected for the on-road and in-cabin environments with and without operating HECA filtration systems under (a) stationary, (b) local roadway, and (c) freeway driving conditions. The normalized particle number concentration (dN/dLogDp) data are the averages of measurements from all six school bus models with respect to particle diameter (Dp).

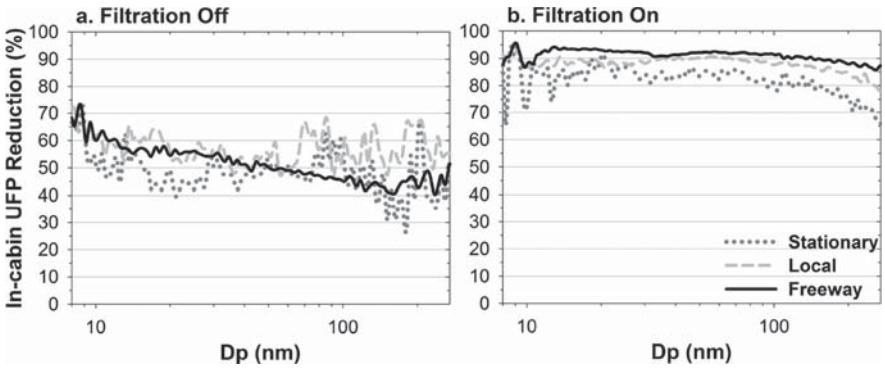


Figure 4. Comparisons of size-resolved in-cabin UFP reductions under stationary (dots), local roadway (dash), and freeway (solid) scenarios. The averaged data from all six test school buses are plotted with respect to particle diameter (Dp). See Supporting Information S9 for standard deviation data.

$$\text{I/O Reduction}(\%) = \left(1 - \frac{(\text{I/O})_{\text{HECA-On}}}{(\text{I/O})_{\text{HECA-Off}}}\right) \times 100 \quad (1)$$

where $(\text{I/O})_{\text{HECA-Off}}$: in-cabin/on-road concentration ratio without operating HECA filtration system and $(\text{I/O})_{\text{HECA-on}}$: in-cabin/on-road concentration ratio with operating HECA filtration system

RESULTS AND DISCUSSION

In-Cabin Reduction for UFPs, BC, and $PM_{2.5}$. Figure 2 illustrates the measured concentrations of UFPs, BC, and $PM_{2.5}$ inside (white) and outside (gray) of tested school buses. Measurements with (right) and without (left) operating the on-board HECA filtration system were presented. Overall, on-road concentrations of all three pollutants were the highest on freeways, followed by local and stationary conditions. Similar patterns were observed inside school buses either with or without operating the HECA system, but in a reduced magnitude. Supporting Information S7 summarizes in-cabin and on-road pollutant concentrations under different driving conditions.

Under stationary condition without operating the on-board HECA system (i.e., the left panels in Figure 2), UFP concentrations inside the buses were 70% lower than outside (Figure 2a). An in-cabin reduction of 55% was observed for BC and 22% for $PM_{2.5}$ under stationary condition without operating the HECA filtration system (Figures 2b and c). With the HECA system off, in-cabin BC concentrations were 50% and 67% greater than on-road concentrations on local streets and freeways, respectively (Figure 2b). Similarly, the $PM_{2.5}$ concentrations were 48% and 17% higher inside the school bus than on local streets and freeways, respectively (Figure 2c).

For $PM_{2.5}$, it is presumably because particles may be resuspended from the surface due to human activities[27,28] and high airflow rate from the jet-diffusers. For BC and UFPs, school bus self-pollution may contribute to the observed higher in-cabin pollutant levels. The in-cabin BC concentration was often higher than on-road in most school buses tested in this study. The in-cabin UFP concentrations were higher than on-road concentrations in the school buses E and F; but not necessarily in the others (i.e., Buses A, B, C, and D). Note that Figure 2 plotted the UFP data from all school buses tested in this study. Supporting Information S6 presents the I/O measurements from each school bus.

When the HECA filtration system was on (the right panels in Figure 2), in-cabin pollutant concentrations were significantly lower than on-road levels and were reduced by 94−97% for UFPs (Figure 2a), 80−90% for BC (Figure 2b), and 30−75% for $PM_{2.5}$ (Figure 2c). Our previous study observed similar magnitude of reductions when HECA filters were used in passenger vehicles.[24] The filtration system was more effective during freeway driving than under stationary or local driving conditions. Note that smaller UFPs dominate particle number concentrations on freeways and particle removal efficiency of

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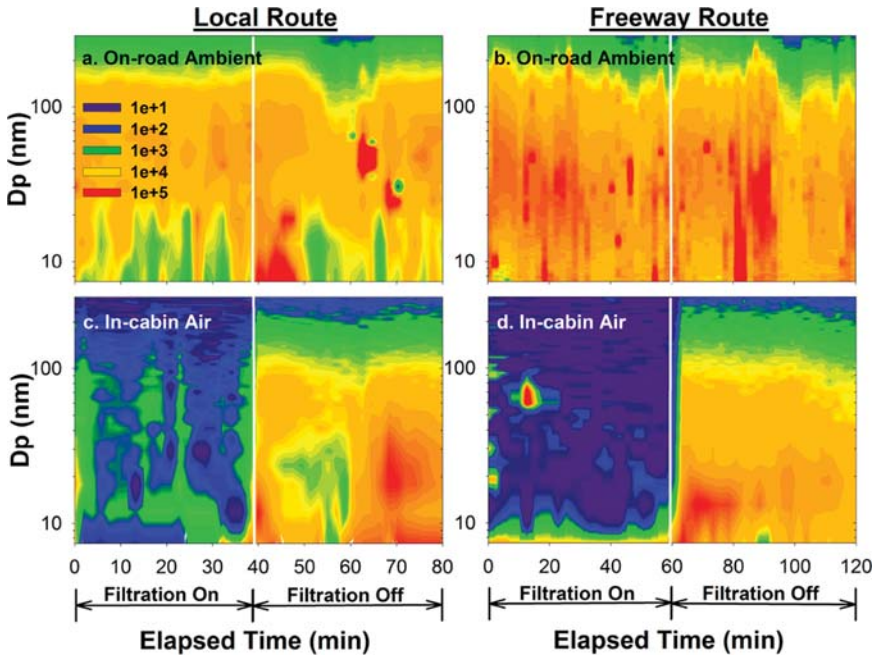


Figure 5. Time- and size-resolved UFP concentration contour plots for local driving conditions (i.e., panels a and c) and freeway driving conditions (i.e., panels b and d). The color intensity is the normalized particle concentration (dN/dLogDp) using a log-scale, in units of particles/cm^3. The *y*-axis is particle diameter (Dp). The top row panels (a) and (b) provides on-road concentrations. The bottom row panels (c) and (d) show in-cabin concentrations. In-cabin concentration data were collected with (left in each panel) and without (right in each panel) operating HECA filtration systems in the school bus C.

HECA filters is particularly high for UFPs. The following sections discuss this more in details.

Particle Size Distributions. Figure 3 presents the normalized particle number concentrations (dN/dLogDp) under stationary, local, and freeway driving conditions. Similar to Figure 2, freeway measurements were higher than local or stationary measurements across the measured size range. Throughout different driving scenarios (i.e., stationary, local, and freeway), the size-resolved concentration data indicate high on-road concentrations of particles below 20 nm. It is important to note that these nucleation mode particles are likely from the test school bus itself rather than surrounding vehicle emissions because they were also observed even during stationary sampling in clean background environments.

Across the measured size range, on-road emissions substantially affected in-cabin concentrations under normal school bus operations (i.e., with the HECA system off). The in-cabin concentrations were particularly high under local and freeway driving conditions. Without operating the HECA filtration system, high levels of in-cabin UFP concentrations were detected due to infiltration and self-pollution. With the HECA filtration system on, in-cabin particle concentrations were substantially reduced inside school buses. Total particle number concentrations were maintained below 1600, 2000, and 3400 cm^{-3} under stationary, local, and freeway scenarios, respectively. These in-cabin concentrations are even lower than the ambient background levels (3000−5000 cm^{-3}) measured in this study.

Size-Resolved In-Cabin UFP Reduction. Figure 4 compares size-resolved in-cabin UFP reductions, defined as $(1 - I/O) \times 100\%$, with and without operating the HECA filtration system. It is important to note that the in-cabin UFP reduction used in this study is not the filtration efficiency of HECA filters. In-cabin UFP reduction is used here to indicate potential exposure reductions, which conflates several particle gain and loss mechanisms under realistic field conditions (e.g., self-pollution, infiltration, and surface deposition). Under normal school bus operations (i.e., HECA filtration system off), infiltration can bring on-road UFPs into the school bus cabin through the gaps of the windows and door because of higher air exchange rates (See Supporting Information S8 for air exchange rates measured in this study). Particle loss naturally occurs due to diffusion during the infiltration process[29] and particle deposition to interior surface.[30]

Without operating the HECA filtration system (Figure 4a), the UFP reduction was relatively low, about 30−70% for particles in the size range of 7.37−289 nm. Under freeway driving scenarios, the in-cabin UFP reduction becomes higher for smaller particles (up to 70% for particles smaller than 10 nm) presumably because of particle diffusion loss. With operating the HECA filtration system (Figure 4b), the in-cabin reduction was greater than 70% under the same condition (i.e., stationary and local driving scenarios). Under the freeway driving scenario, in-cabin UFP reductions were the greatest and stayed above 87% for particles with the diameter smaller than 289 nm. Different driving conditions did not make significant differences for the in-cabin UFP reductions as long as the HECA filtration system was operating. Supporting Information S9 provides standard deviations of the averaged data plotted in Figure 4.

UFP Reduction in Time-Series. Time-resolved UFP size distributions inside and outside of one of the school buses are shown in contour plots in Figure 5. The data collected in the school bus C were plotted for discussion and similar patterns were also observed in the other five buses. The *x*-axis is the elapsed time at which data were collected and the *y*-axis is the particle diameter in log scale. The color intensity presents the normalized particle number concentration (dN/dLogDp) for a

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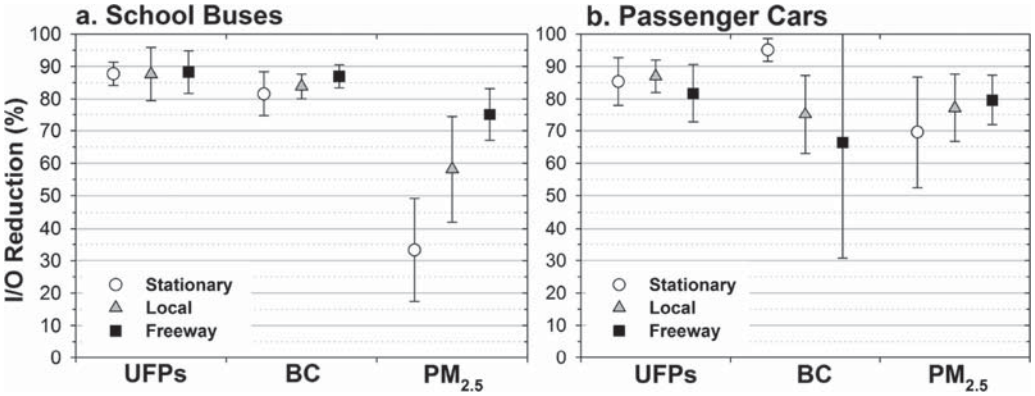


Figure 6. I/O reductions for UFPs, BC, and $PM_{2.5}$ under different driving conditions: stationary (circle), local roadway (triangle) and freeway (square). Each pair of symbol and error bar represents the mean and standard deviation of 1 min averaged data from all six test school buses. Figure 6b was created with data from Lee and Zhu, 2014.[24]

given particle size and time. The same scale and color intensity are used for Figures 5a–d.

As seen in Figures 5a and b, the on-road particle concentration changed dramatically because of surrounding traffic emissions. For instance, measurement on local arterial roadways exhibited particle size distributions with a mode diameter of 50–80 nm; whereas, on freeways, a smaller mode diameter was observed ranging from 8 to 30 nm. In comparison to the local and freeway on-road concentrations (Figures 5a and b), Figures 5c and d show that the HECA filtration system instantaneously reduced in-cabin UFP concentrations by 1 or 2 orders of magnitude compared with on-road concentrations. Under local and freeway driving scenarios, the HECA filtration system effectively reduced in-cabin UFP concentrations across the measured size range (i.e., 7.37–289 nm) as shown on the left-hand side of Figures 5c and d. In comparison, the right-hand side of Figures 5c and 5d support this point by showing the data collected without operating the HECA filtration system.

Figure 5 also provides corroborative evidence of self-pollution inside school buses. Under normal school bus operations (i.e., without operating the HECA filtration system), below 20 nm, particle concentration inside the school bus was 1 or 2 orders of magnitude higher than the on-road concentration in the same size range. It is particularly noticeable around the 55–80 min period in Figure 5c, as well as, the 60–80 min period in Figure 5d. When operating the HECA filtration system, the normalized in-cabin particle concentration (dN/dLogDp) were mostly (i.e., > 90% of time) below 100 cm^{-3} across the measured size range during the 0–60 min period (Figure 5d). However, for particles smaller than 20 nm, the dN/dLogDp often reached up to 10 000 cm^{-3}. Similar patterns were also observed in other tested school buses.

This was not observed in passenger vehicles when similar HECA filters were tested.[24] There was no noticeable UFP emission source inside the test school bus. Freshly emitted particles from vehicle tailpipes are usually in the nucleation mode with diameter less than 20 nm. Thus, the observed increase in nucleation mode particles inside school buses is likely due to self-pollution as previously observed in other studies.[14,15]

I/O Ratio Reductions. The on-board HECA filtration system effectively reduced particulate pollutants (i.e., UFP, BC, and $PM_{2.5}$) inside school buses. Figure 6 summarizes average I/O Reductions with the HECA filtration system on relative to off, that is, estimated from eq 1. It should be noted, self-pollution can increase the I/O ratio; however, the I/O Reduction in eq 1 cancels out the effects of self-pollution with and without operating the filtration system. The data points in Figure 6a are the means of the 1 min averaged data for each of the six tested school buses under different driving conditions (i.e., stationary, local, and freeway conditions). In comparison, Figure 6b were reproduced from Lee and Zhu[24] using eq 1 showing the level of pollutant reduction in passenger vehicles. The prototype HECA filtration system effectively reduced UFPs, BC, and $PM_{2.5}$ levels inside both passenger vehicles and school buses.

As shown in Figure 6a, this study found that the on-board HECA filtration system substantially reduced particulate pollutant levels inside school buses under both stationary and realistic local and freeway driving conditions. Relative to normal school bus operations (i.e., without operating the HECA system), operating the HECA system achieved an I/O Reduction above 80% for both UFPs and BC. The I/O Reduction ranged from 85 to 90% on average for UFPs under all driving conditions. Sporadic door operations had insignificant impacts on the UFP I/O ratio when operating the HECA filtration system inside the buses (See Supporting Information S10). For BC, the reductions ranged from 80 to 90% on average, and the greatest reductions were observed on freeways. $PM_{2.5}$ measurements showed an I/O Reduction ranging from 35 to 75% on average.

Figure 6a also illustrates the calculated I/O Reduction under each test condition (i.e., stationary, local, and freeway). The greatest I/O Reduction occurred on freeways and the minimum occurred under stationary condition. The same was observed for all types of pollutants, less clear for UFPs, but more clear for BC and $PM_{2.5}$. This is likely because particles in different driving environments have different size ranges, which can result in different levels of I/O Reduction. Similarly, the greatest overall reduction was observed for UFPs, but less for $PM_{2.5}$. UFPs are dominated by particles with diameter less than 100 nm, whereas BC is typically in the submicron size range. $PM_{2.5}$ is dominated by particles with diameters less than but close to 2.5 μm. Overall, the highest I/O Reduction occurred for smallest UFPs, whereas the $PM_{2.5}$ I/O Reduction was the lowest among the three types of particulate pollutants in this study.

The filtration efficiency of a filter is size-dependent thus can be affected by the size of source particles. Smaller particles (e.g.,

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UFP and BC) are removed by diffusion mechanism; whereas, larger particles are removed more by impaction due to particle inertia. In addition, the removal of BC and $PM_{2.5}$ can be largely driven by the losses of larger particles because BC and $PM_{2.5}$ were measured in units of mass concentration. The penetration of a few relatively large particles can substantially affect BC and $PM_{2.5}$ I/O Reductions.

The prototype on-board HECA system achieved comparable levels of pollutant reductions inside school buses even in the presence of self-pollution. Figure 6b provides in-cabin I/O Reduction data with HECA filters inside passenger vehicles from our previous study.[24] The relative reductions were comparable to data collected inside school buses. One should note that some differences might originate from different experimental conditions such as ventilation system, air exchange rate, cabin volume size, and occupancy-related particle resuspension. First, the HECA filters were evaluated under outdoor air (OA) mode ventilation setting in passenger vehicles. In contrast, school buses tested in this study have no ventilation system. Second, school buses have higher air exchange rates (e.g., ~10 h^{-1} at 80 km/h, as shown in Supporting Information S8) than passenger cars (e.g., ~8 h^{-1} at 80 km/h under recirculation mode).[31] Third, school buses have a larger cabin volume (i.e., 22−54 m^3) than passenger cars (e.g., 3−7 m^3) which leads to a lower surface area to volume ratio that may reduce particle deposition to surface.[30] Finally, deposited fine particles may be resuspended due to occupancy-related activity and high airflow rate from the jet-diffusers inside buses that contributes to the relatively low I/O Reduction for $PM_{2.5}$.[27,28]

$PM_{2.5}$ Removal. It is important to emphasize that the HECA filtration system is also effective for removing $PM_{2.5}$. Figure 7 illustrates the in-cabin $PM_{2.5}$ concentrations with and without operating the HECA filtration system. The presented data are means and standard deviations of measured $PM_{2.5}$ concentrations inside both passenger vehicles and school buses. Operating the HECA system improved $PM_{2.5}$ removal by a factor of 2−3 for both cases. When the HECA filtration system was on, the $PM_{2.5}$ level was decreased to approximately 10 $\mu g/m^3$ inside school buses. To put this level into perspective, the ambient National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ are 35 and 12 $\mu g/m^3$ for 24 h and annual averages, respectively. Note that the NAAQS only serves as a reference here because different methods are used for NAAQS and school bus measurements. Currently, there is no regulatory standard for in-cabin air quality.

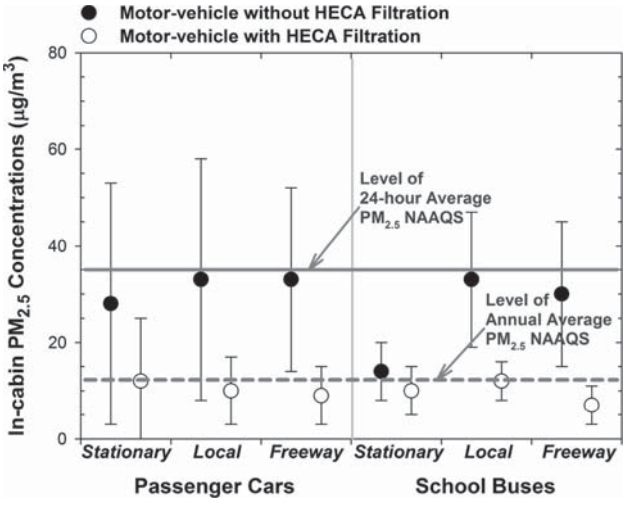


Figure 7. In-cabin $PM_{2.5}$ exposure levels with (white) and without (black) operating the HECA filtration system passenger cars and school buses.

In summary, a prototype on-board HECA filtration system was developed and evaluated for particulate pollutant reduction inside six school buses. The developed HECA filtration system has a great potential to substantially reduce children's exposure to vehicular pollutants while commuting inside school buses. Regardless of the pollutant sources (e.g., surrounding traffic emissions or self-pollution), this system effectively reduced UFPs by 88 ± 6% and BC by 84 ± 5% on averages across all driving conditions inside school buses. Although the effectiveness of the system was relatively lower for $PM_{2.5}$ (55 ± 22%), it reduced in-cabin $PM_{2.5}$ level by a factor of 2−3 and kept it below 12 $\mu g/m^3$.

■ ASSOCIATED CONTENT

Supporting Information

Figure S1 shows in-cabin noise measurements with and without operating on-board HECA filtration system. Figure S2 illustrates the selected school bus testing routes. Figure S3, S4, and S5 provide instrument collocation data for UFPs, BC and $PM_{2.5}$, and CO_2, respectively. The box plots in Figure S6 show a summary of in-cabin/on-road (I/O) concentration ratios observed in each school bus. Table S1 summarizes the in-cabin and on-road measurements for UFP, BC, and $PM_{2.5}$. Figure S7 provides air exchange rate data from the six school buses tested in this study. Figure S8 shows size-resolved in-cabin UFP reductions with standard deviation data. Finally, the time-series plot in Figure S9 presents the changes of UFP I/O ratio by door operations. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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