HEPA filters to improve vehicle cabin air quality – advantages and limitations

Dixin Wei*[1,2], Anders Löfvendahl[2]

1 Chalmers University of Technology
Division of Building Services Engineering
Gothenburg, Sweden
**Corresponding author: dixin.wei@volvocars.com;*

2 Volvo Car Corporation
Climate Department
Gothenburg, Sweden

ABSTRACT

Maintaining a good indoor air quality level has received growing attention in the past years. Especially the smaller particles like $PM_{2.5}$ (particles of aerodynamic diameter less than 2.5 μm) and UFP (ultrafine particles, aerodynamic diameter less than 100 nm) might lead to higher health risks. Vehicle cabin is one challenging environment due to the elevated particle concentrations from the surroundings.

The main protection against outdoor pollutants is from the filter in the vehicle HVAC (Heating, ventilation, and air conditioning) unit. During the past decade, the state-of-the-art solution has been synthetic filters with integrated activated carbons to also cope with gaseous pollutants. These conventional filters, however, are limited by factors including space, reduced efficiency whilst dust-loading, and relatively low efficiencies around the particle size of 100-300 nm. Widely varying efficiency values (20%-90%) have been reported from different vehicles.

There is now an interest to introduce filters with higher efficiencies, for example HEPA (High-Efficiency Particulate Air) filters in vehicles. Besides improved efficiencies, another advantage is that the efficiency does not decrease much whilst dust loading. The disadvantages are increased pressure-drop and space requirements, which make them harder to implement in the compact vehicle environment.

One potential improvement in the short run is to use a HEPA-filter placed in the engine bay as a pre-filter, to protect and potentially extend lifetime of the HVAC filter. The combined particle filtration efficiency is improved, and the increased pressure-drop can be acceptable when the HEPA-filter has relatively large dimension.

In this study two filter prototypes (EPA and HEPA level) were manufactured to investigate applications of pre-filter in a production vehicle. Vehicle test with generated particles (NaCl and Di-Ethyl-Hexyl-Sebacat) and road particles were performed. The inside and outside particle concentrations were measured simultaneously under different fan speeds and combinations of prototypes. One prototype was aged and tested in the vehicle as well.

The tested system showed considerably improved air quality, also with an aged filter. With pre-filters applied, the in-cabin UFP and $PM_{2.5}$ removal could achieve 99%, much higher than the original filter alone (76% and 87% respectively). More importantly in the particle size range below 100 nm, higher than 97% removal was achieved for all sizes. The limitation of such system is mainly the added pressure-drop and space in the vehicle, which demands a balance with the improved filter efficiency.

KEYWORDS

Pre-filtration; HEPA; vehicle cabin; particulate matter

1 INTRODUCTION

Maintaining a good indoor air quality level has received growing attention in the past years. One important focus is the airborne particulate matter, especially small particles like $PM_{2.5}$ (particles of aerodynamic diameter less than 2.5 µm) and UFP (ultrafine particles, aerodynamic diameter less than 100 nm). Epidemiology studies have stated their correlations with higher risks of respiratory and cardiovascular diseases (Mitsakou et al. 2007; Gan et al. 2011; Shiraiwa et al. 2017).

Vehicle cabin is one challenging indoor environment due to elevated particle concentrations from surrounding traffic (Ramos et al. 2016). The main protection against outdoor particles is achieved by the vehicle heating, ventilation, and air-conditioning (HVAC) system through filtration, combined with improved airtightness and air recirculation. The efficiency of common vehicle HVAC filters have a wide distribution between reported values of 20% to 90% (Xu et al. 2011). Electrostatically charged multi-layer filters containing active carbon exist in premium car models. However these filters are mainly limited by loss of efficiency as electrical charges deteriorate, together with increased pressure-drop (dP) due to dust loading. Besides, these filters normally provide lower removal (down to 20%) at the most penetrating particle size (MPPS) around 100-300 nm (Xu et al. 2011).

A comprehensive study on the state-of-the-art performance, including field measurements in cars (Wei et al. 2020), development of a model to simulate the air quality (Wei et al. 2022) and the energy use under different air recirculation (Wei et al. 2023) have been carried out.

There is now interest to introduce filters with higher efficiencies, such as HEPA (High-Efficiency Particulate Air) filters which have been used in appliances like air cleaners, clean rooms, nuclear industrial applications etc. (Xu et al. 2016). HEPA filters, according EN1822 (CEN: European Committee for Standardization, 2019), have efficiencies equal to or above 99.95% at the MPPS. EPA (Efficient Particulate Air) filters have efficiency equal to or above 85% at MPPS. The dust loading, unlike traditional cabin filters, normally elevates the filtration efficiency due to the domination of mechanical filtration. While the obvious limitation is the high pressure-drop from the dense material design. Accordingly, there is increased demand of space to limit the pressure-drop, which is more complex to meet in the vehicle context in comparison to more common building applications. Elevated pressure-drop in the vehicle climate system means higher energy consumption to deliver the same airflow, and higher risks of noise, vibration, and harshness (NVH) problems.

Xu et al. (2013) performed measurements on HEPA filters applied in airlines. Filter usage between 2000-8000 hours contributed to around 10% of efficiency increase, however 800% of pressure-drop increase. Lee and Zhu (2014) studied applying improved filters in vehicles, which showed up to 93% removal of UFP, yet lead to 7% to 22% decrease of the airflow rate. There have also been investigations of building an auxiliary HEPA filtration box inside a modified van to filter the in-cabin air, which showed that more than 97% of UFP was removed (Zhu et al. 2008). The application however requires large modification, e.g., the entire first row of seats was removed.

This study investigates one potential improvement, an EPA/HEPA-filter placed in the engine bay as a pre-filter for the original HVAC-filter. Both lab and road measurements were performed in a slightly modified vehicle, under common climate settings. Reduction of $PM_{2.5}$ and UFP were compared under different filtration scenarios: original HVAC filter, two-step filtration; and with different particle types: road, DEHS (Di-Ethyl-Hexyl-Sebacat) and NaCl. Other factors including pressure-drop, and practical installation limitations in the vehicles are investigated.

2 METHODS

2.1 Filter Prototypes

All the studied filters are listed in **Table 1**. Two pre-filter prototypes were manufactured in collaboration with an industry partner. The filter dimensions are designed according to available space in an existing production vehicle's thermal bay. The two prototypes (P1, P2) have similar design, pleated particle filter (no activated carbon) made of multi-layer synthetic fiber. P2 (HEPA level) has slightly higher efficiency than P1 (EPA level). The tested vehicle has an original HVAC filter, which is an electrostatically charged multi-layer synthetic filter with activated carbon. The main difference of pre-filters is the media design (e.g., material, diameter), which allow them to achieve much higher efficiencies than conventional HVAC filter. Both prototypes could be stacked with a coarse protection filter of the same dimension, for the purpose of extending the lifetime. P2 was also loaded with ISO 12103-1 A2 Fine Dust (International Organization for Standardization, 2016) and environmental cycle until pressure-drop increased by 50 Pa (80 L/s) compared to new status, to represent an aged filter status. Pictures of filters are shown in

Figure *1*. The prototypes are also tested at certified filter test agency for pressure-drop, efficiency values following the standard for vehicle compartment filters DIN 71460-1 (German Institute for Standardization, 2006).

Table 1: Prototype dimensions and status

Filter	Type	size	status
P1	EPA synthetic filter	400*314* 30 mm	new
P2	HEPA synthetic filter	400*314* 30 mm	new
P2	HEPA synthetic filter	400*314* 30 mm	aged
P1 + protection filter (Two pieces stacked)	EPA synthetic filter + protection particle filter	400*314* 30 mm * 2 pcs	new
P2 + protection filter (Two pieces stacked)	HEPA synthetic filter + protection particle filter	400*314* 30 mm * 2 pcs	new
Original HVAC filter	Synthetic filter with activated carbon	247*289*40 mm	new

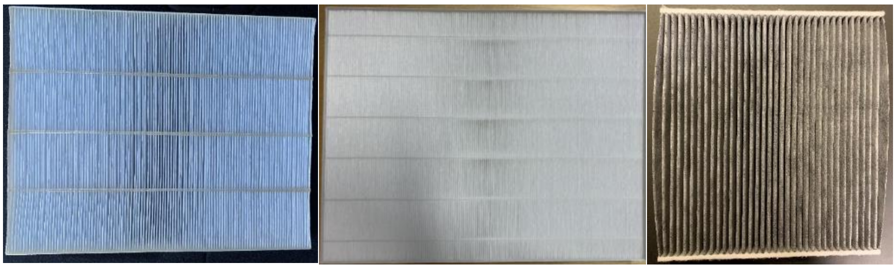

Figure 1 Filter prototypes. Left: P1, Middle: P2, Right: original HVAC filter

2.2 Instrumentation

Two inter-calibrated GRIMM MiniWRAS (Mini Wide Range Aerosol Spectrometer) model 1.371 were used in the rig and vehicle measurements. The instrument measures particles of aerodynamic diameter from 10 nm to 35 µm, distributed into 41 channels with log interval of one minute. The measurable mass concentration range is 0.1 µg/m^3 to 100 mg/m^3 (GRIMM, 2023). The mass and number concentration of all size channels are acquired, including PM$_{2.5}$, UFP counts from 10 nm to 100 nm. Annual calibration was performed by supplier and automatic self-test done by instrument at each start-up.

Two TSI Portable Test Aerosol Generators (Model 3073) were deployed to generate test dust of NaCl and DEHS. These atomizer-type devices generate particle concentrations from 85 /cm^3 to >10^7 /cm^3 and has an output flow rate adjustable from 0.3 to 4.5 L/min. According to specification the generated DEHS aerosol distribution has mode diameter between 0.15 to 0.3 µm, and for NaCl 0.05-0.2 µm (TSI, 2023).

2.3 Vehicle measurement

The prototypes (P1, P2) were installed in a production vehicle's thermal bay as pre-filters (VOLVO XC40 BEV model-year 2021) as shown in **Figure 2**. Part of the original storage accessory was removed and replaced with a 3D-printed filter holder, which was connected to the original HVAC system air inlet. The air intake to the pre-filter is from the front grille. The holder is designed so that the hood could be closed as normal. The vehicle measurements were performed both inside an indoor vehicle test room with generated particles, and in a road tunnel in Gothenburg, Sweden (at emergency parking). On both occasions the vehicle was standing-still with climate system operating.

Figure 2 Pre-filter prototype installation in an existing production vehicle‘s thermal compartment

Vehicle measurements were performed between February and June 2022. The measurement method is the same as described in the Methods section of a previous paper (Wei et al. 2020). Here a brief description is given.

The climate settings were AC off and desired temperature of 22 °C, as well as a constant ratio of airflow at panel and floor vents, no air recirculation. The varied climate parameters are mainly the airflow rates (extra low (Xlow), low, medium, high), which were controlled by a software connected to the vehicle climate control unit (Estimated airflow rates at these 4 levels are around 20, 40, 60, 85 L/s respectively). Different scenarios were tested: original HVAC filter alone, and pre-filter (P1 or P2) + original HVAC filter.

The in-cabin and outside particle concentrations were measured simultaneously. An outside sampling tube was placed in front of the pre-filter. The inside sampling tube was placed above the middle armrest between the front seats. A data collection interval of around 5-10 minutes is logged when the in-cabin concentration is relatively stable. At least 3 repetitions were logged for each combination of parameters, leading to in total 164 valid datasets collected.

3 RESULTS

3.1 Removal of UFP and $PM_{2.5}$ from generated particles

The average in-cabin removal percentage of $PM_{2.5}$ and UFP with generated particles are presented in **Table 2**. Different filter combinations are compared. The removal percentage is calculated from the simultaneously measured inside to outside (I/O) concentration ratio, i.e., Removal percentage = 1 –I/O ratio. The mass concentration of $PM_{2.5}$ ($\mu g/m^3$) and count concentration of UFP (N/cm^3) are used in calculation. All the data points are the means of repetitions under the same test conditions.

Table 2 Comparison of in-cabin removal percentage of UFP and $PM_{2.5}$ with different filter combinations and dust type (DEHS and NaCl). Original: the original HVAC filter alone. Airflow Low level (around 40 L/s), no recirculation. Standard deviations are not presented due to smaller than 3% units in all cases. Each arithmetic mean is based on around 20 repetition samples.

	$PM_{2.5}$ removal percentage Arithmetic Mean		**UFP removal percentage Arithmetic Mean**	
	NaCl	**DEHS**	**NaCl**	**DEHS**
Original	94.6%	98.2%	94.5%	78.2%
P2 + Original	99.8%	99.9%	99.9%	99.1%
P2 aged + Original	99.9%	99.9%	99.9%	98.2%

Table 2 shows that application of P2 as pre-filter achieved removal percentage higher than 99% in all conditions for both $PM_{2.5}$ and UFP. Even after P2 is loaded with dust to represent aged status, 98% removal was maintained. In comparison, when only the vehicle's original HVAC filter is installed, average removal of DEHS UFP is 78%, which is lower than NaCl UFP removal of 94%. The atomized aerosols in this study are not neutralized. According to investigation from Shi et al. (2013), DEHS is practically without electrical charges. This could result in the original HVAC filter has lower efficiency of removing the DEHS UFP.

Furthermore, independent sample t-tests were performed on results in **Table 2** and p-values are summarized in **Table 3**. All comparisons showed statistically significant difference, except that P2 aged+Original is able to maintain the same level of UFP NaCl removal as P2 + Original.

Table 3 P values of independent sample t-tests between three filter combinations, categorized by particle type and particle size.

	$PM_{2.5}$		**UFP**	
	NaCl	DEHS	NaCl	DEHS
Original & P2+Original	4.15E-11	3.62E-10	4.50E-09	2.44E-11
Original & P2 aged +Original	2.55E-11	5.73E-10	4.52E-09	2.38E-11
P2 + Original & P2 aged +Original	1.81E-03	1.48E-03	4.44E-01	1.32E-02

3.2 Removal of UFP and $PM_{2.5}$ from road particles

Table 4 Comparison of in-cabin removal percentage of UFP and $PM_{2.5}$ with different filter combinations. Measurements performed with road particles in Lundby tunnel, Gothenburg, Sweden. Original: the original HVAC filter alone. Airflow Low level (around 40 L/s), no recirculation.

	Removal percentage of road particles			
	$PM_{2.5}$		**UFP**	
	Arithmetic Mean	**Standard Deviation**	**Arithmetic Mean**	**Standard Deviation**
Original	86.8%	3.9%	75.7%	5.9%
P1	97.6%	0	93.1%	0
P2	98.3%	0.5%	98.7%	0.5%
P1 + Original	99.7%	0	96.0%	0
P2 + Original	99.1%	0.7%	99.3%	0.6%

In **Table 4** the similar comparison of particle removal percentage is presented for measurements performed on the road. Clearly the application of pre-filter, either P1 or P2 enhances the removal of particles. Especially with P2 as pre-filter, the removal of UFP and $PM_{2.5}$ is 99%. The original filter removes only 76%-87% of particles. Applying P1 as pre-filter improves the UFP removal up to 96% and $PM_{2.5}$ to 99%.

3.3 Size-resolved removal percentage of particles

Generated particles and road particles have different size distributions, and the removal percentages vary with size. **Figure 3** presents the comparison of size-resolved removal percentage of all particles. When only the HVAC filter is installed, the removal at MPPS is 69% for road particles, 70% for DEHS and 87% for NaCl. The combination of original HVAC filter with P2, either new or aged, lead to an enhancement. In all sizes, higher than 97%, up to 99% removal of particles are achieved. This enhancement is very important since UFP has more potential of entering human body, thus lead to cardiovascular problems.

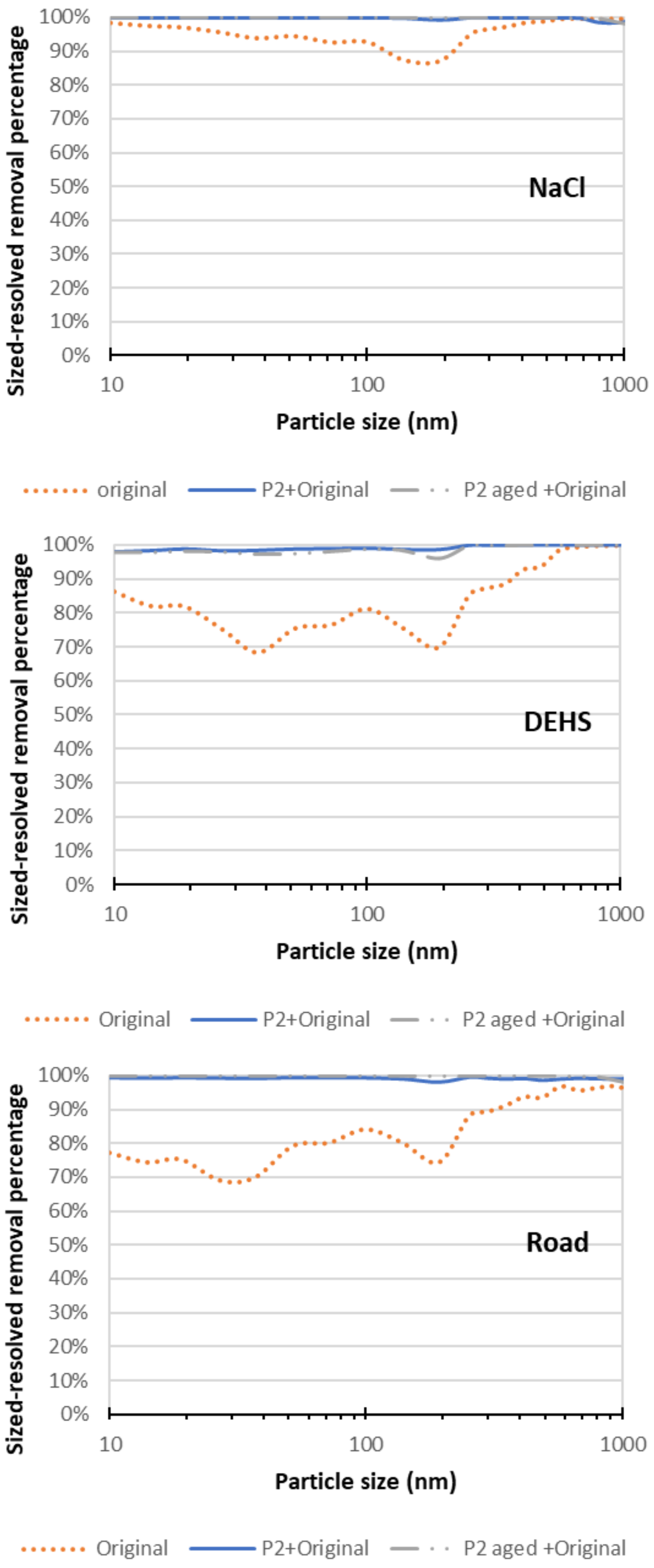

Figure 3 Size-resolved in-cabin removal percentage of particles in the vehicle measurements. NaCl, DEHS and road particles are compared. Plotted data are the average of all repetitions. Original: the original HVAC filter alone. Airflow Low level (around 40 L/s), no recirculation. The *P2 aged+original* line almost overlap with *P2+Original* line in all graphs.

3.4 Pressure-drop

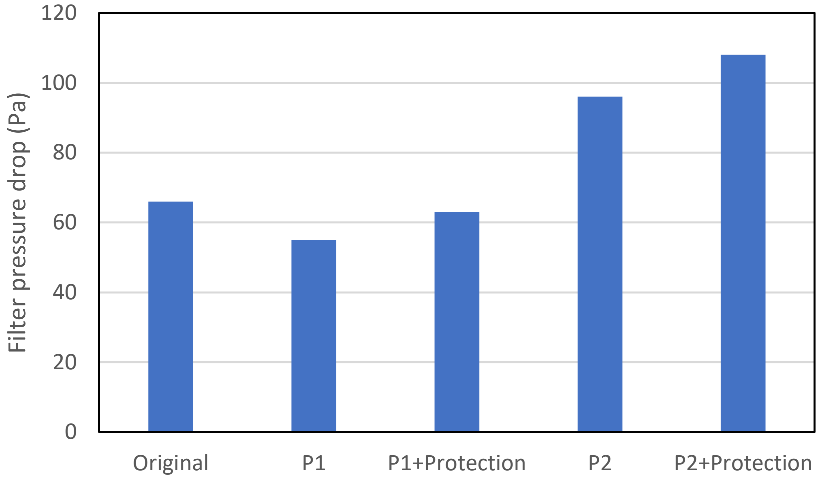

Figure 4 Pressure-drop of filter prototypes measured following standard DIN 71460-1. Test airflow 80L/s

Figure 4 presents the pressure-drop of filter prototypes under airflow 80 L/s measured in certified agency, following the standard DIN 71460-1, Air filters for passenger compartments. The pressure-drop of P2 is higher than P1 due to the filter media and layer design. When a protection filter is applied before, 8 Pa and 12 Pa are added on P1 and P2 respectively.

It should be noted that the dimension of original filter is smaller than the pre-filter (see **Table 1**). P1 has similar level of pressure-drop as the original HVAC filter, which means the application of pre-filter almost doubles the total pressure-drop from filters. The influence on the climate system operation, specifically the fan power depends on the fan control strategy.

4 DISCUSSION

The same filters showed somewhat different removal percentages when tested with different aerosols. This could be related to the particle characteristics such as size distribution, which influences the filtration performance, and also particle loss in the ducting etc. These factors are now discussed.

Figure 5 presents four examples of different particle size distributions, for NaCl, DEHS, road air in this study, and a previous road air measurement in China (Wei et al. 2020) respectively. All examples have outside $PM_{2.5}$ concentration around 100 µg/m^3. While from the figure it's observed that the particle distributions are quite different.

The road measurement in this study has a large mass portion around 100 nm and 3 µm. The previous China measurement however has more mass in the nano-meter range, with two peaks around 100 nm and 3 µm. The NaCl and DEHS are more focused in only one peak, around 100 nm and 2 µm respectively. When the count distribution is compared, a different trend is that all the examples only have one mode around 70-100 nm. And DEHS has 5-15 times lower count concentration in the mode size than others.

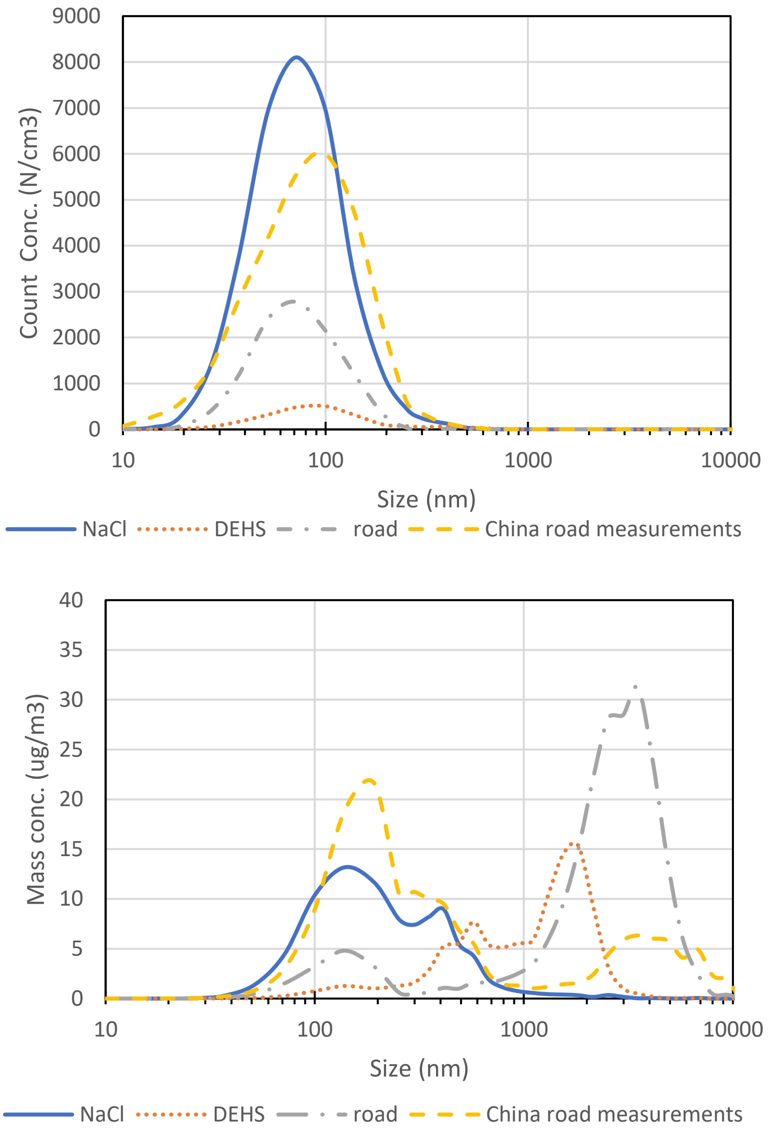

Figure 5 Outside air particle size distribution comparison of both count concentration (N/cm^3) and mass concentration(μg/m^3). Examples of the generated dust of DEHS, NaCl, road air in this study and a previous measurement in China 2019 (Wei et al. 2020) are compared. Four examples all have PM$_{2.5}$ concentration around 100 μg/m^3

This comparison point out that, different aerosol types would mean different challenges for the filters, and thus different removal of PM$_{2.5}$ or UFP. For example, the NaCl mass size distribution is close to the MPPS which may lead to a low PM$_{2.5}$ removal as opposed to the case with DEHS in **Table 2****Table 2** Comparison of in-cabin removal percentage of UFP and PM$_{2.5}$ with different filter combinations and dust type (DEHS and NaCl). Original: the original HVAC filter alone. Airflow Low level (around 40 L/s), no recirculation. Standard deviations are not presented due to smaller than 3% units in all cases. Each arithmetic mean is based on around 20 repetition samples.

	PM$_{2.5}$ removal percentage Arithmetic Mean		**UFP removal percentage Arithmetic Mean**	
	NaCl	**DEHS**	**NaCl**	**DEHS**
Original	94.6%	98.2%	94.5%	78.2%
P2 + Original	99.8%	99.9%	99.9%	99.1%

P2 aged + Original	99.9%	99.9%	99.9%	98.2%

, which has a peak mass concentration at far larger particles where the filter efficiency is high.

On the other hand, when the MPPS efficiency is compared in **Figure 3**, DEHS and road particles show similar values around 70%, yet NaCl with substantially higher 84%. One possible reason could be that the NaCl aerosol can be expected to have more electrostatic charges.

It should also be noted that the removal percentages are reflecting the particles lost in the filter and other surface in the HVAC system. Qi et al. (2008) have reported 8% in non-winter condition and 39% in winter of particle removal when no filter is installed in the vehicle. This value would be influenced by the particle type. Moreover, the modification of ducting in this study added more surface and duct bends, where particle losses are more likely to happen compared with straight ducts (Jeong et al. 2009).

In general, vehicle tests with real particles from roadways may differ from the vehicle test and laboratory test with standardized particles (Lee and Zhu 2014). Road measurements are closer to the real application scenarios, while standardized test rigs provide stable and more repeatable conditions. A combination of extensive test methods would be beneficial. To correlate the results, for example the NaCl possibly need to be neutralized according to Shi et al., (2013). Another useful measure is to compare the MPPS efficiency in addition to the total removal of $PM_{2.5}$ or UFP, where the comparison is more straightforward in a narrow size range.

5 CONCLUSION

This study investigates the application of a pre-filter in an existing vehicle with small modifications, which improves the overall particle removal, and thus the cabin air quality.

Two prototypes were tested feasible with regards to achieving better cabin air quality. The vehicle removal of $PM_{2.5}$ was improved from 87% to 99% with both prototypes. The removal of UFP was improved from 76% to above 96% with prototype 1 and 99% with prototype 2. This performance was also maintained with an aged prototype 2. It means that the service interval is possibly mainly dependent on the pressure-drop increase and other aspects like gas absorption, microbial growth etc., not the particle efficiency.

On the other hand, the choice of filter quality in real vehicles would be a complex balance between filtration efficiency, dimension, cost, climate comfort and pressure-drop to reduce the fan power, i.e. the energy consumption and to reduce NVH problems. For example, the application of P1 would give considerable improvement on filtration as well as adding lower pressure-drop. The cost per filter unit is also normally lower for P1 than P2.

Furthermore, the pre-filters with a protection filter had similar performance and slight increase of the pressure-drop; around 10 Pa. It could possibly extend the pre-filter lifetime if space is adequate. The studied pre-filters could also be applied alone to filter particles effectively, which however demands proper design to required gas absorption.

This study also aimed at contributing to the development of vehicle particle filtration test methods, especially by comparing on road tests and lab tests with generated particles. Different characteristics and behaviours of particles are observed. The same vehicle test setup of original HVAC filter removes 76% of road UFP, while corresponding values for DEHS and NaCl are 78% and 94%. This points out the need of further correlating standardized tests with real road conditions, where the latter is the user scenario.

The findings provide inputs to the design of vehicle climate system with good air quality and pressure-drop balance. Relationships among efficiencies, pressure-drop and filter age could be further studied to facilitate the decision on proper filter service interval.

ACKNOWLEDGEMENTS

This project is funded by the Swedish Energy Agency (Energimyndigheten).

REFERENCES

CEN: European Committee for Standardization. (2019, April). EN1822-1 High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking.

Gan WQ, Koehoorn M, Davies HW, et al (2011) Long-term exposure to traffic-related air pollution and the risk of coronary heart disease hospitalization and mortality. Environ Health Perspect 119:501–507. https://doi.org/10.1289/ehp.1002511

German Institute for Standardization. (2006). DIN 71460-1 Road vehicles - Air filters for motor passenger compartments - Part 1: Test for particulate filtration.

GRIMM. (2023, Feb). MINI WIDE RANGE AEROSOL SPECTROMETER. Retrieved from https://www.grimm-aerosol.com/products-en/indoor-air-quality/the-wide-range-hybrid/1371/

International Organization for Standardization. (2016). ISO 12103-1:2016 Road vehicles — Test contaminants for filter evaluation — Part 1: Arizona test dust.

Jeong JW, Bem J, Bahnfleth WP, et al (2009) Critical review of aerosol particle transport models for building HVAC ducts. J. Archit. Eng. 15:74–83

Lee ES, Zhu Y (2014) Application of a high-efficiency cabin air filter for simultaneous mitigation of ultrafine particle and carbon dioxide exposures inside passenger vehicles. Environ Sci Technol 48:2328–2335. https://doi.org/10.1021/es404952q

Mitsakou C, Housiadas C, Eleftheriadis K, et al (2007) Lung deposition of fine and ultrafine particles outdoors and indoors during a cooking event and a no activity period. Indoor Air 17:143–152. https://doi.org/10.1111/j.1600-0668.2006.00464.x

Qi C, Stanley N, Pui DYH, Kuehn TH (2008) Laboratory and On-Road Evaluations of Cabin Air Filters Using Number and Surface Area Concentration Monitors. Environ Sci Technol 42:4128–4132

Ramos CA, Wolterbeek HT, Almeida SM (2016) Air pollutant exposure and inhaled dose during urban commuting: a comparison between cycling and motorized modes. Air Qual Atmos Heal 9:867–879. https://doi.org/10.1007/s11869-015-0389-5

Shi B, Ekberg LE, Langer S, et al (2013) Intermediate Air Filters for General Ventilation Applications : An Experimental Evaluation of Various Filtration Efficiency Expressions Intermediate Air Filters for General Ventilation Applications : An Experimental Evaluation of Various Filtration Effici. 6826:. https://doi.org/10.1080/02786826.2013.766667

Shiraiwa M, Ueda K, Pozzer A, et al (2017) Aerosol Health Effects from Molecular to Global Scales. Environ Sci Technol 51:13545–13567. https://doi.org/10.1021/acs.est.7b04417

CEN: European Committee for Standardization. (2019, April). EN1822-1 High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking.

German Institute for Standardization. (2006). DIN 71460-1 Road vehicles - Air filters for motor passenger compartments - Part 1: Test for particulate filtration.

GRIMM. (2023, Feb). MINI WIDE RANGE AEROSOL SPECTROMETER. Retrieved from https://www.grimm-aerosol.com/products-en/indoor-air-quality/the-wide-range-hybrid/1371/

International Organization for Standardization. (2016). ISO 12103-1:2016 Road vehicles — Test

contaminants for filter evaluation — Part 1: Arizona test dust.

TSI. (2023, Feb). Portable Test Aerosol Generator 3073. Retrieved from https://tsi.com/getmedia/e5d8a77a-7533-4631-a85a-470f11828a1c/5002118_US_3073_Portable%20Test%20Aerosol%20Generator_Web?ext=.pdf

Wei D, Nielsen F, Ekberg L, et al (2020) PM2.5 and ultrafine particles in passenger car cabins in Sweden and northern China—the influence of filter age and pre-ionization. Environ Sci Pollut Res 27:30815–30830. https://doi.org/10.1007/s11356-020-09214-0

Wei D, Nielsen F, Ekberg L, Dalenbäck JO (2022) Size-resolved simulation of particulate matters and CO2 concentration in passenger vehicle cabins. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-19078-1

Wei D, Nielsen F, Karlsson H, et al (2023) Vehicle cabin air quality: influence of air recirculation on energy use, particles, and CO2. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-25219-x

Xu B, Chen X, Xiong J (2016) Air quality inside motor vehicles' cabins: A review. Indoor Built Environ 0:1–14. https://doi.org/10.1177/1420326X16679217

Xu B, Liu J, Ren S, et al (2013) Investigation of the performance of airliner cabin air filters throughout lifetime usage. Aerosol Air Qual Res 13:1544–1551. https://doi.org/10.4209/aaqr.2012.11.0330

Xu B, Liu S, Liu J, Zhu Y (2011) Effects of vehicle cabin filter efficiency on ultrafine particle concentration ratios measured in-cabin and on-roadway. Aerosol Sci Technol 45:215–224. https://doi.org/10.1080/02786826.2010.531792

Zhu Y, Fung DC, Kennedy N, et al (2008) Measurements of ultrafine particles and other vehicular pollutants inside a mobile exposure system on Los Angeles freeways. J Air Waste Manag Assoc 58:424–434. https://doi.org/10.3155/1047-3289.58.3.424