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Energy Efficient Air Quality Solutions for Vehicle Cabins

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Abstract

Maintaining a good air quality level is essential for reducing potential health risks for human beings. Vehicle cabin is one common environment where people spend increasing amount of time in modern societies. It's an environment challenged by elevated pollutants from surrounding traffics, especially small particles like $PM_{2.5}$ and UFP (Ultrafine particles). To efficiently reduce or remove the pollutants from incoming air is one essential focus for development of future vehicles. To achieve that goal with energy efficient solutions would be even more important in the trend of emerging electric vehicles.

The objective of this thesis is to evaluate and propose solutions for improved cabin air quality and energy efficiency, which could be used in the development of vehicle climate system. The work has been conducted through vehicle measurements on road in two different locations, development of an air quality model, modelling of increased recirculation in the climate ventilation strategy, as well as measurements on new prototypes in both rig and road conditions. The purpose of the road measurements is to set the baseline of current air quality levels and evaluate the important influencing factors such as filter age and ventilation settings. The purpose of the model development is to enable a repeatable and comprehensive evaluation environment, which is later used to evaluate the strategy of increased air recirculation under common driving conditions. The purpose of the measurements on prototypes is to evaluate one solution of using EPA (Efficient Particulate Air) or HEPA (high-efficiency particulate air) filters as pre-filters, to prove the concept and the limitations.

The results are showing that cabin particles are highly influenced by the outside particle concentrations, the filter design and status, and to some extent the ventilation settings. Besides the application of pre-ionization assisted filtration was proved valuable. The air quality model, implemented in an existing climate system model, is validated with road measurements. Modelling of increased recirculation results in significant reduction of energy use and particles. In warm climate it's more applicable to avoid fog risks and in all climates the use of high recirculation (for example 70%) should be evaluated based on the number of passengers. One way to achieve that is adding a control based on cabin CO_2 concentration in the climate system. It is also shown feasible to improve air quality using an EPA/HEPA pre-filter. The main limitations come from space and acceptable pressure-drop in the relatively compact environment.

Keywords: vehicle cabin, private car, climate system, air quality, energy use, air filter, filter status, particulate matters, UFP, CO_2, measurements, simulations

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List of publications

Paper I

Wei D, Nielsen F, Ekberg L, et al (2020) $PM_{2.5}$ 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

Paper II

Wei D, Nielsen F, Ekberg L, Dalenbäck JO (2022) Size-resolved simulation of particulate matters and CO_2 concentration in passenger vehicle cabins. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-19078-1

Paper III

Wei D, Nielsen F, Hannes K, et al (2023) Vehicle cabin air quality – influence of air recirculation on energy use, particles and CO_2. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-25219-x

Paper IV

Wei D, Löfvendahl A (2023) HEPA filters to improve vehicle cabin air quality – advantages and limitations. (Abstract accepted by 43rd AIVC)

Author Contribution:

As the first author of all papers, Dixin Wei has conducted the studies including planning, measurements, model development, simulations, data handling, analyses and original draft writing. Main supervisor Jan-Olof Dalenbäck and industrial supervisor Filip Nielsen have supported with supervision, and have, with assistance from co-supervisor Lars Ekberg, and other colleagues, helped with with feed-back and proof-reading, in the writing process. Anders Löfvendahl and Hannes Karlsson have contributed in the vehicle measurement and modelling design.

Abbreviations

AC	Air-Conditioning
EPA	Efficient Particulate Air
HEPA	High-Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air-Conditioning
I/O ratio	Indoor to Outdoor Ratio, value range 0 to 1
MPPS	Most Penetrating Particle Size
OSA	Outside Air
PM	Particulate Matters
$PM_{2.5}$	Particles of aerodynamic diameter less than 2.5µm
PNC	Particle Number Concentration
REC	Recirculation
T0	Cold Ambient Condition
T15	Intermediate Ambient Condition
T27	Warm Ambient Condition
UFP	Ultrafine Particles, which have aerodynamic diameter less than 100nm

Nomenclature

Cbr	Carbon dioxide concentration contained in passenger's exhaled air (ppm)
Cenv	Outside particle count (N/cm^3) or mass concentration($\mu g/m^3$) in one size channel or outside CO_2 (ppm)
Cin	Inside particle count (N/cm^3) or mass concentration($\mu g/m^3$) in one size channel or inside CO_2 (ppm)
N	Number of passengers in the vehicle
Qdep	Deposition flow (m^3/s)
Qinf	Infiltration airflow(m^3/s)
Qoa	Ventilation airflow from outside air (m^3/s)
Qps	Passive ventilation airflow (m^3/s)
Qrec	Ventilation airflow from recirculation (m^3/s)
Vbr	Minute ventilation, the amount of air breathed per minute (L/min)
Vcabin	Cabin volume (m^3)
α	Particle penetration loss coefficient
η	Size-dependent filter efficiency, value range 0 to 1

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1 Introduction

1.1 Background

During the last 50 years we have seen an increased population with increased living standards, followed by an increased number of plants for electricity and heat generation and an ever-growing demand for transports, to a large extent based on fossil fuels. This has led to arising air quality problems, which has received growing focus due to the various potential health effects on human. Examples are allergies, irritation, inflammation, toxicity and cancer (WHO, 2021).

Most common atmospheric pollutants that are harmful to human health are for example: NO_2, SO_2, CO, particulate matters, O_3 (United States Environmental Protection Agency, 2022). They are from extensive sources of industry, traffic, combustion etc. Among others, particulate matter, especially small particles are one of the growing focus areas, as epidemiology studies have shown that high particle concentration influence human health. Gan et al. (2011) stated correlations between exposure to $PM_{2.5}$ (particles of aerodynamic diameter less than 2.5μm) and risks of respiratory and cardiovascular diseases. UFPs (ultrafine particles, which have aerodynamic diameter less than 100nm) can more easily deposit in the lung alveoli (Mitsakou et al. 2007), cause greater inflammatory response and move to other organs (Oberdörster 2000).

Vehicle cabin is one indoor environment associated with elevated risks of pollutant exposure due to the surrounding traffic sources, where elevated particle concentration are likely to exist, and also attributable to UFPs from traffic exposure potentially damage lung function (McCreanor et al. 2007).

Nowadays main protection against outdoor pollutions in vehicles are provided by HVAC (heating, ventilation, and air-conditioning) system, which consumes energy to achieve thermal comfort and good air quality for the passengers. The HVAC filters are commonly used in current vehicles for the incoming air. Main limitations for conventional HVAC filters are the allowed pressure-drop and achievable efficiency in relatively confined space, and efficiency drop over lifetime which influences the service life.

The understanding of air quality levels in transportation context has been growing. Measurements are performed in personal vehicles, trams, buses and taxies, mostly monitoring the particle concentration outdoors and in-cabin, as well as influencing factors. Outside particle concentration and size distribution (Kaur et al. 2005; Knibbs et al. 2009; Knibbs and de Dear 2010; Wang et al. 2015; Jain 2017), as well as filter efficiency have major influence on the cabin particle concentration. The ventilation of vehicle climate system also influence the concentration. Reduced airflow rate (Zhu et al. 2007; Knibbs et al. 2010; Abi-Esber and El-Fadel 2013; Jain 2017; Wei et al. 2020) and the application of recirculation is beneficial in reducing the particles from the outside (Pui et al. 2008; Qiu et al. 2017a).

There are investigations to further reduce the particle levels in the cabin by better HVAC designs. Multi-layer filters and two-step filters exist in different cars. Pre-ionization of particles has been proven to improve the filtration performance in both rigs and cars (Agranovski et al. 2006; Park et al. 2011; Wei et al. 2020).

Despite the research efforts so far, there is a lack of knowledge in several aspects. One example is the correlation of air quality and energy efficiency, which has not been a well-researched area. Climate system is one of the largest auxiliary loads on a vehicle, which can significantly increase the fuel consumption or reduce the range of electric vehicles (Farrington and Rugh 2000; Burgdorf 2011). How to achieve desired air quality in the cabin with limited energy use, as well as considering relevant automotive application requirements etc., is valuable for the corresponding development in the vehicle industry.

There is also a demand to gain knowledge on a comprehensive understanding of the air quality in passenger vehicles. The development of both test and modelling methods are needed to evaluate the air quality levels and other vehicle climate system performance simultaneously.

1.2 Research objectives

The main focus of the project is to increase knowledge on the current vehicle cabin air quality, as well as it's correlation with the energy use of the climate system, in order to propose potential solutions for improvement. The study aims at giving answers to the over-arching research questions:

- What is the current level of vehicle cabin air quality ?
- Which are the major influencing factors?
- What is the correlation between vehicle cabin air quality and climate system energy use?
- Which are the potential improvement solutions, and their performance and limitations?

Corresponding outcomes should be:

Increased knowledge of current air quality level in the vehicle cabin, a systematic vehicle cabin air quality test method, a vehicle cabin air quality simulation model and proposed solutions or new prototypes.

1.3 Research scope

The main scope of this study is on technologies to reduce pollutants coming from the outside environment. Interior material and equipment are also possible sources of pollutants such as VOC (volatile organic compounds) and SVOC (semi-volatile organic compounds) (United States Environmental Protection Agency, 2022), but these are not treated in this study.

1.4 Thesis outline

The thesis comprises 7 chapters. In Chapter 2 the framework for the study is described. Vehicle climate and air quality, measurements and modelling, in parts based on major results from literature studies, are introduced. In Chapter 3 the applied research methods are described and linked to appended papers covering measurements, model development, modelling of air quality and energy use, and evaluation of potential developments. Major results are presented in Chapter 4 with references to the more detailed results described in the papers. Some aspects of particles, filters and climate system control are discussed in Chapter 5. Finally, the work is concluded in relation to the research objectives in Chapter 6 and complemented with some research directions in Chapter 7.

2 Reference framework

In this chapter the relevant theoretical background, concepts and previous research are presented.

2.1 Vehicle climate system

The HVAC (Heating, ventilation, and air conditioning) system has been a part of the vehicle for a long time. In modern vehicles it treats the incoming air to desired temperature and maintain the comfort. Functions of de-frost and de-mist also commonly exist. Moreover, maintaining a good air quality has been an increased focus during the HVAC design, as the desire for clean air grows. This applies to reducing both the pollutants originated from the outside and inside the cabin. An overview of the main components in a common vehicle HVAC system is given in **Figure 1**, with focus on the air handling, i.e. the coolant and refrigerant cycle is not present. In general air is supplied from the outside, possibly mixed with recirculated air from the vehicle cabin, and then filtered, cooled, heated and distributed into the vehicle cabin through different outlets. The operation of all parts in the system is controlled by the climate control software.

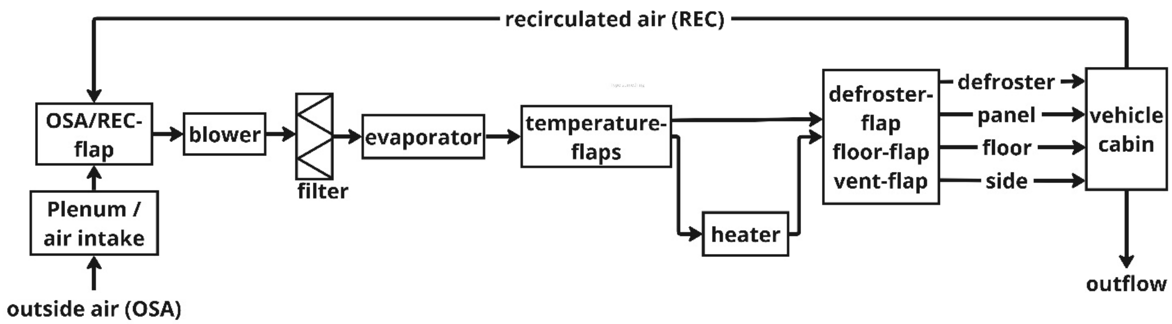


Figure 1 HVAC system overview with focus on the air handling

The climate control software in the vehicle is responsible for ensuring a comfortable cabin climate. The control considers inputs including ambient temperature, sun load, passenger inputs etc. and gives outputs for controlling the HVAC fan, flaps, operation of the heater and cooler etc. A list of main inputs and output is given in **Table 1**. The system could run in automatic mode, where airflow, recirculation, temperatures, air distribution and AC (air-conditioning) system are controlled by the software, or a manual control at different levels.

Table 1: Main input and output parameters of the climate control system

Input	Output
Ambient temperature	Blower level
Passenger compartment temperature	Temperature flap, left and right
Evaporator temperature	Defroster flap
Coolant temperature	Vent/Floor flap
Windscreen temperature	Evaporator set point/AC control signal
Passenger compartment humidity level	Heating/Bypass
Passenger inputs	Outside air/Recirculation flap
AC circuit pressure	Climate coolant circuit pump
Ambient air quality	Cooling

2.2 Vehicle cabin air quality

Pollutants in the vehicle cabin could be various. Common examples are particles, NO and NO_2, CO, VOC and SVOC (Xu et al. 2016). More specifically regarding particles, NOx and CO, the major source would be from the outside, i.e. the incoming air to the vehicle climate system.

2.2.1 Particulate Matter

Atmospheric particulate matters (PM), also known as particulates, atmospheric aerosol particles, refer to microscopic level solid or liquid mixture that suspend in atmospheric environment. They could be composed of sulphates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water etc. The composition varies according to location and origins. $PM_{2.5}$ (also known as fine particles) stands for PM with a diameter lower than 2.5 µm. While UFP normally stands for particulates under 100 nm size.

Both natural formation and anthropogenic productivities generate PM (Pui et al. 2014). Major human activities related sources include combustion process, industry power production from solid fuel, and vehicle engine emission. Industrial mining, construction, manufacturing are origins as well. Besides, secondary particles are generated from NOx (traffic and industry produced), SOx (sulfur-fuel combustion) reacting with other existing compound in air (EPA, United States Environmental Protection Agency, 2022).

Epidemiology studies have shown that high particle concentration influence human health. Symptoms vary from irritation, coughing, asthma trigging, to low body function or even cancer. Gan et al. (2011) stated correlations between exposure to $PM_{2.5}$ (particles of aerodynamic diameter less than 2.5µm) and risks of respiratory and cardiovascular diseases. Exposure to $PM_{2.5}$ also reduces life expectancy. Aphekom project presented comparison study of 25 European cities regarding $PM_{2.5}$ exposure. It is estimated that reduction of annual average atmospheric $PM_{2.5}$ to 10 µg/m^3 increases life length by order of 2 years for persons older than 30 in 25 cities (Aphekom, 2011).

UFPs (ultrafine particles, which have aerodynamic diameter less than 100nm) can more easily deposit in the lung alveoli (Mitsakou et al. 2007), cause greater inflammatory response and move to other organs (Oberdörster 2000). Stölzel et al. (2007) found statistically significant correlations between increased UFP and cardio-respiratory mortality.

When it comes to road environment, vehicle engine emission is an important particle source. Although no strong proofs indicate the specific quantifications of health effects between PM of various composition or origins, combustion-relevant PMs are more evidently hazardous (WHO, Regional Office for Europe, 2007). The exhaust from diesel engine has been defined as category 1 carcinogen by International Agency for Research on Cancer (WHO IARC, 2012). A review from Kittelson (1998), on typical engine exhaust particles pointed out that, most of particle numbers (90%) are found in 0.005-0.05 μm diameter range, which is composed of VOC, sulfur compounds, metals. This adds to the health risk since smaller particles have easier path to pass the respiration system and even translocate to human brains (Oberdorster et al. 2004). It also emphasizes the importance of reducing particles entering the vehicle cabin, when vehicle itself is surrounded with high volume traffic.

2.2.2 Vehicle HVAC filters

To deal with the outside originated pollutants, the current state of art in the automotive industry can be described as the main car manufacturers focusing on common HVAC filters for the incoming air, with the support of subcontractors. The vehicle HVAC system is normally placed in a relatively compact environment. This application context limits what type of filters could be used in vehicles, and how much pressure-drop they could induce. That to large extent defines the efficiency level of these filters.

When it comes to the filter design, polymer filters, often referred to as particle/pollen-filters, are typical on all markets. Premium brands often use electrostatically charged synthetic filters impregnated with different types of active carbon for capacity to remove gases such as NO_2 and SO_2.

There are several limits on these conventional filters:

- The filter dimension is subject to the available space, which is relatively limited in vehicle context compared with other appliances such as buildings. It thus requires a balance between the filter area, volume and the pressure drop, since higher pressure drop means higher fan power, i.e., higher climate system energy use and higher risks of noise, vibration, and harshness (NVH) issue

- The filter is normally electrostatically charged to enhance the filtration performance, while on the other hand ageing problems occur due to the loss of charges. The common solution is to service the filters after a certain interval, which requires experience on the aged filter performance. Relevant indicator for identifying the filter lifetime could be particle and gaseous pollutants removal efficiency, dust holding capacity, microbial growth etc.

- Considering the elevated engine exhaust from surrounding traffics on road or in tunnels, the filter medium should be capable of trapping sub-micron size particles.

While these HVAC filters normally provide lower removal efficiency at the most penetrating particle size around 100-300 nm (Qi et al. 2008; Swanson et al. 2022).

The filter performance could be evaluated by the efficiency. The efficiency of common vehicle HVAC filters have a wide distribution between reported values of 0.2 to 0.9 (Xu et al. 2011). Even for the same filter, the efficiency in real road conditions depends on many factors. Outside particle distribution (Knibbs et al. 2009), pollutant sources (Kaur et al. 2005; Qiu et al. 2017b), filter ageing status, ventilation airflow rate (Abi-Esber and El-Fadel 2013) are among the factors that influence the actual filtration in the vehicle.

To understand and compare the efficiencies, standardized tests (e.g. DIN 71460, Air filters for passenger compartments (German Institute for Standardization, 2006)) have been commonly used as references. Commonly used particles are NaCl, DEHS (Di-Ethyl-Hexyl-Sebacat) and ISO 12103-1 A2 Fine Dust (International Organization for Standardization, 2016).

In this project context, size dependant filtration efficiencies are used in the simulation models. The definition of filtration efficiencies are as in **Equation** (1). *Cout* and *Cin* are count concentrations of particles in certain size channels, before and after filtration. η is the corresponding filtration efficiency of particles in that size channel.

$$\eta = \frac{Cout - Cin}{Cout} \quad (1)$$

When it comes to comparing the $PM_{2.5}$ and UFP concentrations, another common approach used is the indoor to outdoor ratio (I/O ratio), i.e. the ratio of indoor to outdoor concentration. This enables a comparable evaluation on the overall filtration performance of the vehicle climate system, regardless of the outside conditions.

2.3 Vehicle measurements

When it comes to particles inside the cabin, one common approach is the field measurements with portable instruments (Xu et al. 2018). Some studies also measured the particle concentration in the vehicle's surrounding air simultaneously.

Several contemporary vehicle measurements have been performed in different locations, car models and under different climate settings When comparing the cabin $PM_{2.5}$ with the latest WHO guideline of 15 μg/m^3 (WHO, 2021), 12 out of 15 measurements reported higher than guideline results. The details are given in **Table 2**. Furthermore, more measurements were performed on UFP over the past decade. 10 out of 12 studies reported cabin UFPs higher than 10000 p/cm^3, which according to WHO good practice statement is high PNC (particle number concentration) (WHO, 2021).

The results show that there is still a big potential for air quality improvement in the cabin, especially when the outside air is highly polluted, and the filter has relatively low performance.

These vehicle measurements also investigated the major influencing factors, which comprise of the transportation microenvironments (Kaur et al. 2005; Knibbs and de Dear 2010; Huang et al. 2012; Both et al. 2013; Qiu et al. 2017), the ventilation settings (Zhu et al. 2007; Knibbs et al. 2010; Abi-Esber and El-Fadel 2013; Jain 2017), the surrounding traffic (Knibbs et al. 2009), and the measurement methods (Kumar et al. 2018). Moreover, ambient particle concentration and filter ageing have been recognized to have dominant influence on in-cabin particle concentrations, while existing studies seldom compared different filter status and locations. There is also a lack of understanding of how factors including road pollutants distribution influence the in-cabin particle level.

Furthermore, these studies also indicate that standards and guidelines are important for vehicle cabin air quality measurements, which would enable easier comparisons between studies.

Table 2: Summarized measurement results of comparative vehicle studies on $PM_{2.5}$ and UFPs.

$PM_{2.5}$

Reference	Relevant ventilation conditions	$PM_{2.5}$ in cabin ($\mu g/m^3$)	$PM_{2.5}$ I/O	$PM_{2.5}$ outside ($\mu g/m^3$)
(Kaur et al. 2005)	Private car, ventilation as normal	AM = 38.07 ±14.1 (sample N = 29)	/	/
(Knibbs and de Dear 2010)	AC on and cool the cabin, lowest fan speed, no REC	GM: 22.6, AM: 27.3	/	/
(Huang et al. 2012)	taxi's AC on, window closed	31.64±20.77	Median: 0.79 to 1.04	FMS: 35.15 ± 23.97
(Abi-Esber and El-Fadel 2013) (*results presented for mobile tests)*	window closed, AC on OSA, fan medium	79±34	Above 1 (~1.1)	/
	window closed, AC on REC, fan medium	38±28	Below 1 (~0.5)	/
(Both et al. 2013)	private car AC and non-AC	mean(SD) = 91 (38)	/	/
(Qiu et al. 2017a)	window closed, AC on REC	Morning: 10.09 ± 6.63 Afternoon: 8.95 ± 1.08	/	/
	window closed, AC on OSA	Morning: 22.06 ± 3.61 Afternoon: 14.56 ± 10.86	/	/
(Jain 2017)	AC private car	roughly around 80	/	/
(Wei et al. 2020)	Fan on 2nd level, REC off new filter	AM 9.2	AM 0.20	AM 50.6
GOT baseline[a]	Fan on 2nd level, REC off aged filter	AM 35.8	AM 0.60	AM 61.2
(Wei et al. 2020)	Fan on 2nd level, REC off new filter	AM 28.5	AM 0.18	AM 153.3
China baseline[a]	Fan on 2nd level, REC off aged filter	AM 90.5	AM 0.54	AM 166.6

AM: arithmetic mean AC: air conditioning FMS: fixed monitoring site GOT: Gothenburg
GM: gravimetric mean N: number of samples OSA: outside air
REC: recirculation UFP: ultrafine particle SD: standard deviation
[a]: baseline measurements mean test cases without ionization

UFP

Reference	Relevant ventilation conditions [a]	UFP in cabin (× 10^3 p/cm^3)	UFP I/O ratio	UFP outside (×10^3 p/cm^3)
(Kaur et al. 2005)	Private car, ventilation as normal	AM=99.7 range 36.5-151.81 (sample N = 13)	/	/
(Zhu et al. 2007) (*results presented for different locations, newest vehicle model)*	Fan off REC off	9.1± 33 to 150 ±34	~0.15	22 ± 24 to 256 ± 119
	Fan on REC off		~0.3	
	Fan on REC on.		~0.05	
(Knibbs et al. 2009)	Private car driving in a tunnel	/	/	Average:6000 Median:1700
	Private car driving in mixed city routes	/	/	Median: 160
(Knibbs et al. 2010) *(Results presented for 2 vehicles fitted with HVAC and filter, separated with ;)*	REC off, fan lowest, AC full cooling	Mean 282;127	Median 0.66;0.88	/
	REC off, fan 2nd-highest, AC full cooling	Mean 611;257	Median 0.84;0.91	/
	REC on, fan lowest, AC full cooling	Mean 34;40	Median 0.08;0.45	/
(Knibbs and de Dear 2010)	AC on cooling, fan lowest, no RC	GM 75 AM 89	/	/
(Both et al. 2013)	private car AC and non-AC	Median Non-AC:~400 AC:~140	/	/
(Wei et al. 2020)	Fan 2nd low, REC off new filter	AM 5.1	AM 0.24	AM 24.4
GOT baseline [a,b]	Fan 2nd low, REC off aged filter	AM 15.5	AM 0.57	AM 27.9
(Wei et al. 2020)	Fan 2nd low, REC off new filter	AM 6.4	AM 0.25	AM 22.6
China baseline [a,b]	Fan 2nd low, REC off aged filter	AM 15.7	AM 0.57	AM 27.5

AM: arithmetic mean AC: air conditioning GOT: Gothenburg
GM: gravimetric mean N: number of samples OSA: outside air
REC: recirculation UFP: ultrafine particle

[a]: baseline measurements mean test cases without ionization

[b]: UFP size range: 10-100 nm

2.4 Modelling vehicle cabin air quality

Complete vehicle measurements on cabin air quality are relatively straightforward to perform, but they are expensive in terms of time and human resources. Measurements also include some uncontrollable variables, for example the ambient conditions, and measurement uncertainties. Alternatively, a simulation model could be implemented to mitigate the physical limitations of vehicle measurements, and moreover, to investigate scopes that cannot be realized in vehicle testing.

When it comes to in-cabin particle concentration, previous studies were mainly established on mathematical models (Ott et al. 2008; Xu and Zhu 2009; Saber and Bazargan 2011; Lee et al. 2015a; Ding et al. 2016). One-zone mass balance equations were drawn on different sizes of particles as in **Equation** (2). By solving the equations either steady-state or transient cabin concentration could be obtained. The equation is based on the assumption that air in the cabin is well-mixed, i.e. particle concentration is the same in different positions, which has been supported by previous four-point particle measurements in vehicles (Joodatnia et al. 2013).

$$\frac{dCin}{dt} = S - L * Cin \tag{2}$$

The source terms (S) normally contain the incoming particles after HVAC filtration and from potential leakage flows, and loss terms (L) could include depositions of particles on interior surfaces and the outflow. The terms would require definitions of ventilation airflow rates, air recirculation degree, cabin volume, cabin filter efficiency, infiltration airflow etc. They were identified or assumed from available fluid mechanics equations, component or vehicle measurements etc. One challenge has been to define vehicle specific parameters since different car brands and model types could differ significantly from others.

One example is the ventilation airflow rates (m^3/h) or air exchange rates (h^{-1}). Normally this parameter is difficult to obtain since the air distribution is spread at several outlets. In contemporary vehicles the fan level often could be adjusted manually or automatically by the climate control, so as the air distribution to certain area, e.g. chest or foot level. If it's possible to set or control the airflow exiting only limited outlets and fan speed to be constant, the air speed airflow could be measured, which in combination with measurement on the vent outlet dimension, an estimation of the airflow rate could be achieved (Xu and Zhu 2009; Lee et al. 2015b). Another approach is to measure the decay of certain gases (examples are CO, CO_2 ,SF6) and mathematically deduce the air exchange rate or ventilation airflow rate of the vehicles, based on one-zone mass balances (Ott et al. 2008; Gong et al. 2009; Ding et al. 2016; Harik et al. 2017).

There has been few efforts to use the vehicle's own climate control module and obtain the correspondingly airflow rate at any running conditions instead of fixed fan levels (auto or manual), which normally is well-calibrated against measurements in the product development. This is mainly due to the lack of access.

The filter efficiency is one crucial factor when modelling the filtration, the major removal of incoming particles. This is dependent on the filter type, status, the particle size, air speed passing the filter etc (Xu et al. 2011; Shi 2012; Abi-Esber and El-Fadel 2013). If test data exist for the filter to be simulated, the model accuracy could be enhanced. Previously studies however mainly estimate a constant value based on experience or similar studies.

The deposition of particles is primarily influenced by the particle size, interior surface area, material type and ventilation airflow rate, which is relatively hard to estimate. Previous studies have estimated the deposition rate based on field measurements (Gong et al. 2009; Harik et al. 2017). There have been focuses on the estimation of the infiltration flow (the uncontrolled air leakage into the vehicle cabin) through both experimental measurements and modelling analysis (Fletcher and Saunders 1994; Xu et al. 2010; Lee et al. 2015a, b), which relies on the input of vehicle type, driving speed and ventilation airflow.

There are also studies deploying statistical models to estimate the cabin particle concentration. Hudda et al. (2012) generalized UFP I/O ratios using a statistical regression of vehicle type and ages. However the study may be limited to the specific vehicle parameters used and difficult to adapt to other car models.

Overall there appears to be a lack of studies which include important factors like different filter statuses, size-resolved filtration, and a better estimation on the vehicle ventilation parameters like air recirculation degrees, airflow rates. More importantly a connection between air quality and climate energy use modelling is missing, which enables wider usage of the air quality model.

2.5 Potential developments

As mentioned in Chapter 2.2.2, common HVAC filters in contemporary vehicles are facing the problem of loss of efficiency as filters are aged, and low efficiencies around 100-300 nm range. 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.

Besides improved efficiencies, another advantage is that the efficiency normally does not decrease much whilst dust loading. This is mainly due to the material design and 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.

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

Pre-ionization of particles has been proven to increase the filtration performance. Several studies presented improvement of filtration efficiency in test rigs or chambers, by 5-70% -units (Park et al. 2011; Shi 2012). Ionization combined filtration already stands for a large market share of air cleaners in building appliances (Kim et al. 2017). While that application in vehicle environments are not common.

Gas sensors in form of metal oxide sensors have been used by premium automotive brands for almost two decades. These sensors can measure, for example, NO_2, CO and different hydrocarbons which give the system the ability to reduce the amount of outside air, i.e., increase the degree of recirculation when the outside air is polluted. Current sensor development is focused on $PM_{2.5}$ sensors, mainly for visualization of air quality inside and outside the cabin. It is expected that these sensors also can be used for controlling the amount of outside air, similar as the current gas sensor systems.

When it comes to the combined area of cabin air quality and climate energy use, one important factor for the energy use of the climate system is the air flow, i.e. ventilation rate and degree of recirculation (Leung 2015). For many cases increased airflow can increase the energy use considerably. The air quality of the cabin air can both be increased and decreased by increased airflow; large ventilation flows bring larger portion of outdoor air pollution to the inside while a low ventilation flow can increase the concentration of some pollutants generated inside the cabin. Furthermore, air in the cabin can be recirculated to reduce the air conditioning or heating load, which can also both increase and decrease the air quality depending on ambient and cabin conditions (Pui et al. 2008; Atkinson et al. 2017).

When the main source of particles is considered the outdoor environment and the vehicle HVAC system is responsible for removing most of the particles, reduced ventilation airflow and increased air recirculation could be beneficial in reducing the cabin particles. Meanwhile recirculated cabin air could contain CO_2 and humidity from the passengers, which might lead to risks of passenger fatigue and windscreen fogging (Mathur 2016). It is observed in vehicle measurements that even with only 1 passenger, the full recirculation will accumulate CO_2 to 1100 ppm in 5 minutes (Mathur 2008). These different factors should be balanced when applying REC.

While there is still a lack of comprehensive investigation on different REC degrees, i.e. the proportion of ventilation air coming from recirculated cabin air, from 0 to 100%. There is a demand to correlate the air quality performance together with the vehicle climate system performance.

3 Methodology

3.1 Research design

To answer the over-arching research questions in Chapter 1.2, the project was initially designed into five work packages.

1. Literature study for background
2. Measurements in existing vehicles
3. Modell development and system modelling
4. Potential system developments
5. Evaluation of system developments

The first package is a literature study to define the reference framework with focus on defining the air quality scope of the study, the current vehicle cabin air quality, indoor air quality solutions and definitions of good air quality.

In the second package the existing systems are evaluated regarding air quality levels as well as main influencing factors. Meanwhile the climate system energy usage is measured. A systematic vehicle air quality test method is developed. This work package resulted in **Paper I** which describes the results of comprehensive field measurements.

The third work package had the main aim to develop a simulation model of the air quality in the vehicle cabin and the energy use of the climate control system. This, together with measurements, will serve as basis for further evaluation of different solutions. The simulation model provides the possibility to evaluate the climate system and air quality level under controlled, repeatable conditions in an efficient way. This work package resulted in **Papers II** about air quality model development and validation.

The following packages were to evaluate different solutions on different levels. The fourth package investigates available and potential air quality concepts with regards to air quality, energy use and feasibility for automotive use. Data on the performance of different components are obtained by component tests. New technologies or adaptations of building ventilation solutions for automotive use are discussed with subcontractors. Solutions and ideas from other projects are evaluated. Development of control strategies in combination with different air quality solutions. Propose systems for future evaluation in the last work package. This package resulted in **Paper III**, comprising a comprehensive study on REC and climate system energy use. The fifth and last work package includes physical tests of proposed solutions, i.e. road tests. Evaluation of air quality, energy use and other properties such as installation, reliability and functionality in different driving conditions. The last package resulted in **Paper IV** describing an improved HVAC system, including lab and vehicle tests.

3.2 Vehicle baseline measurements

The current levels of air quality and climate system energy use were collected from contemporary vehicles. Two measurement campaigns, one in Gothenburg, Sweden during the summer of 2018 and one in the vicinity of Beijing, China in January 2019 were performed. The intention of two campaigns is to achieve extended data ranges in different ambient air, lightly polluted and highly polluted. Also to extend the ambient meteorological conditions such as temperature, humidity and sun-load. The current air quality level was judged through measuring of particles ($PM_{2.5}$, UFP), CO_2, O_3, NOx, and SO_2 inside and outside the vehicles. Different solutions currently in production were investigated, filters of different age and pre-ionization. Furthermore, the major climate components such as electric heater, blower and compressor power were also measured.

The summer campaign location in Gothenburg is the Lundby Tunnel where the ambient particle level is elevated (average $PM_{2.5}$ 55 μg/m^3 from road measurements) compared with the relatively clean city air (annual average $PM_{2.5}$ 7.7 μg/m^3 (Gothenburg Municipality, 2018)). The test vehicle was standing inside the tunnel with engine and HVAC system on, at an uphill emergency parking spot. This was to maintain long stable measurement periods, compared to driving through the tunnel which takes 2 mins.

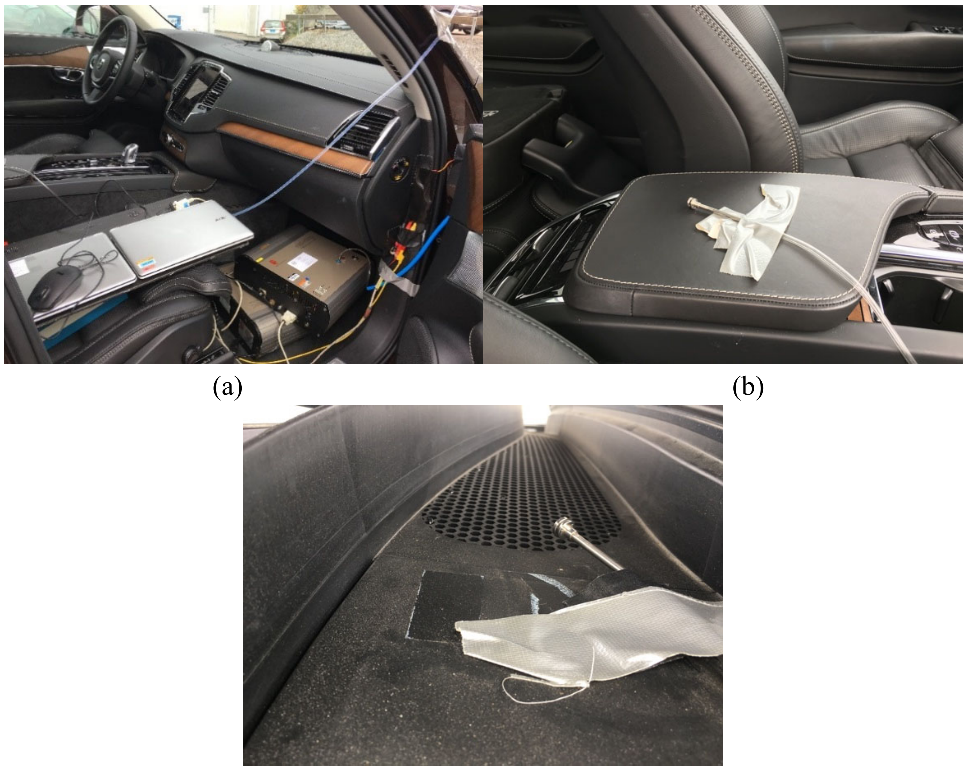
Figure 2 The test route in Northern China, from Linyi to Beijing, passing by Baoding

The winter measurements were performed during driving on freeways and highways, along the relatively polluted 760 km route from Linyi to Beijing, Northern China as in **Figure 2**. Monthly average ambient $PM_{2.5}$ in major cities on the route at that time were Beijing 52, Linyi 114 and Baoding 137 μg/m^3 (CNEMC, January 2019).

3.2.1 Instrumentation and sampling

Particle concentrations were measured with Grimm MiniWRAS (Mini Wide Range Aerosol Spectrometer) model 1.371, with log interval of 1 minute. The instrument measures particles of aerodynamic diameter from 10 nm to 35 μm. Mass and number concentration of all size channels are acquired, as well as $PM_{2.5}$, and UFP counts from 10 nm to 100 nm.

Two inter-calibrated MiniWRAS were measuring simultaneously outside and inside the cabin. Outside sampling tube was placed immediately outside of the HVAC air intake below the wind shield. Inside sampling tube was placed above the middle armrest between the front seats, as in **Figure 3**, as recommended by Abi-Esber and El-Fadel (2013). This position was chosen to measure particle concentration in the well mixed in-cabin air, rather than air samples at HVAC direct outlets.



(a) (b)

(c)

Figure 3 Particle instrument setup at the front row (a), location of sampling tube inside cabin (b) and outside sampling tube at HVAC upstream, under the wind shield, at vehicle front right (c)

In addition, to investigate the possibility of ozone generation from the ionizer, 2B Technologies Model 205 Dual Beam Monitor (UV-absorption principle) was used to monitor the in-cabin ozone concentration, with measurement frequency of 0.5 Hz (2B Technologies). Ozone was measured at the same place as the in-cabin particles.

Temperature, relative humidity (Rotronic Hygroflex HF534) and solar intensity sensors were mounted both inside and outside the cabin. A CO_2 meter Vaisala Darbocap GM70 in the cabin, with the sampling head mounted on the back side of the co-pilot seat pointing to the centre of the cabin, was also used in the cabin. Testing personnel kept distance to all sampling heads throughout the measurement period, to refrain from direct breath influence.

3.2.2 Vehicular parameters

The measurements were carried out in two similar Volvo cars produced in 2018 as shown in **Table 3**. The vehicle used in Gothenburg was a Model Volvo XC90 with its original HVAC system. The vehicle used in China was a Model Volvo S90, with the same type of HVAC system as the XC90 vehicle.

Table 3: Test vehicles correlations and basic information

Measurement Campaign	**Vehicle model**	**Production year**	**HVAC system**	**Cabin filter**	**Cabin volume (m^3)**	**Engine type (Power)**	**Mileage (km)**
Gothenburg, 2018 May-July	Volvo XC90 (5-door SUV)	2018	Volvo original	New and aged synthetic filter	4.1	PHEV Petrol (2.0L 407HP)	1706
China, 2019 January	Volvo S90 (sedan)	2018	Same as above	Same as above	2.9	Diesel (2.0L 245HP)	5054

The filter used in both vehicles was a multi-layer electrostatically charged synthetic filter made of polypropylene and activated carbon. One newly manufactured and one aged filter were installed. The aged filter was aged in an HVAC test rig with ducts connected to outdoor air, in 2018 April at Shanghai for 500 hours, which represents around one-year driving, the recommended filter service interval in China.

Furthermore, both cars were equipped with a pre-ionization unit. It is manufactured to fit the air inlet dimensions and is installed before the water separation unit in front of the HVAC, around 50 cm upstream of the filter.

Several climate parameters were varied and combined. **Table 4** gives a summary of all these varied parameters. Each test case was ensured to be repeated at least three times in different days. Firstly the baseline is measured as: no recirculation (REC), new and aged filters. Furthermore, four ventilation airflows (extra low (Xlow), low, medium, high) and four REC levels (0, 30%, 50%, and 70% of total ventilation air comes from recirculation) were tested. The estimated total ventilation airflow rates (outside and recirculation air) at four airflow levels are around 20, 40, 60, 85 L/s respectively. Adding to the baseline, with ionization was compared.

Other climate settings were windows closed, AC on, desired temperature of 22 °C, as well as constant ratio of airflow at panel and floor vents. Smoking was forbidden, and 2-3 persons sat in the vehicle. When a stable in-cabin air quality was achieved, a data collection interval of around 5-10 minutes started.

All these parameters were controlled by a software connected to the vehicle control unit, to maintain a similar environment in all measurements. Average inside and outside $PM_{2.5}$

concentrations and UFP counts were calculated for each data collection interval firstly, by averaging the 1-min data, and then the general average was calculated for each test case (based on all data collection repetitions). The indoor to outdoor ratio (I/O ratio) of $PM_{2.5}$ mass concentration and UFP counts were calculated, to evaluate the filtration performance regardless of ambient pollution level.

Table 4: Description of varied parameters in all test cases. The baseline case means no ionization.

Filter status	Ventilation airflow level [a]	Recirculation degree (%) [b]	Ionization [c]
new	Xlow	0	off
aged	low	30	on
	medium	50	
	high	70	

[a] Xlow (extra low), medium and high ventilation are only used in combination with 0 recirculation
The estimated total ventilation airflow rates at four airflow levels are around 20, 40, 60, 85 L/s respectively
[b] 30%, 50% and 70% recirculation degree are only used in combination with low airflow
[c] Ionization off test cases mean the baseline cases

3.3 Modelling cabin air quality

A simulation model is developed to predict the cabin air quality and at the same time predict the energy use of the climate system. The work built further on previous work in this area, especially regarding energy use. The model was validated against measurement data gathered in the road measurements (Wei et al. 2020). The vehicles being modelled in this study are the same as in the measurement study, i.e. a Volvo XC90 (model-year 2018) with estimated cabin volume of 4.1 m^3, and a Volvo S90 (model-year 2018) with estimated cabin volume of 2.9 m^3. The two test vehicles share the same HVAC system design and climate control systems.

3.3.1 Climate system model

The air quality model was built into a previous established climate system model, which models the vehicle climate components and control strategies in details (Nielsen et al. 2015). The software GT-SUITE, which solves Navier-Stokes equation in one dimension, was used to simulate the climate systems. This model focused on the energy use of the climate system. The climate control system is also integrated to the model, so it operates as in real production vehicles.

3.3.2 Vehicle cabin air quality model

The air quality model simulates size-dependent particle concentrations, including $PM_{2.5}$ and UFPs as well as CO_2 concentration. Both particle mass and count concentration within 10-2530 nm are simulated. Both the particle and CO_2 levels are simulated based on one-zone mass-balance for the cabin. The key features defining the cabin air quality are simulated in the model, which are sources from outside air, filtration performance at the filter, internal sources from the cabin, and airflows including infiltration airflow. The definition of these parameters are either from available test data, previous developed model or based on experience from relevant studies.

The model also simulates variants such as different filter statuses, application of pre-ionization, different airflow rates and recirculation degrees.

Figure 4 illustrates the basic particle/CO_2 transport in vehicle cabins. For particles, the outside ventilation airflow (*Qoa*) with particle concentration of *Cenv* enters the vehicle cabin through HVAC system, and mixes with the recirculated airflow (*Qrec*) before passing the filter. Besides, the passive ventilation airflow (*Qps*) refers to the air entering HVAC system, which is not induced by the operation of fan, but because of for example vehicle's speed or wind speed. This flow is accounted for in the total ventilation flow in the studied vehicles and it also passes the filter (Ott et al. 2008; Lee et al. 2015b). Thus, it is not considered as infiltration. *Qoa*, *Qps* and *Qrec* together composes the total ventilation airflow.

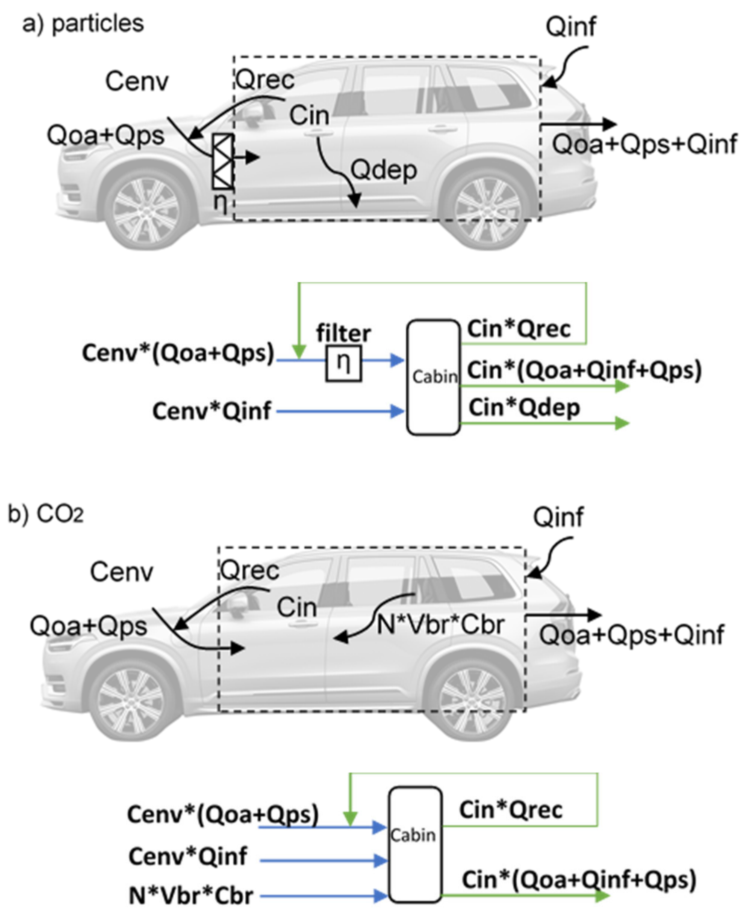


Figure 4 Illustration of a) particle and b) CO_2 transport in vehicle cabins and the corresponding simplified flowcharts where the losses and gains of the cabin are marked green and blue.

The filter removes particles by an efficiency value of η (within 0 to 1), which is size-dependent. The recirculation degree (%) defines the ratio of *Qrec* to *Qrec*+*Qoa*. The infiltration airflow

(*Qinf*) here refers to the uncontrolled air leakage through cracks and leaks on the vehicle envelope, for instance cracks between frame and doors (Xu et al. 2010). The penetration loss coefficient α is accounting for the loss of particles at cracks through which the infiltration flow passes, and an experienced value of 0.6 is utilized (Xu et al. 2010). Particle deposition flow on the interior surfaces like seats and carpets is described as *Qdep*. *Cin* and *Cenv* are inside and outside particle concentrations.

For the CO_2 modelling the transport is similar except that CO_2 is not removed by the HVAC filter, and not depositing on the surfaces. Besides, the internal source from human breath is added, where *N* is number of passengers, *Vbr* is minute ventilation in L/min, *Cbr* is the carbon dioxide concentration contained in the exhaled air. *Cin* and *Cenv* are inside and outside concentrations of CO_2.

Based on the transport mechanisms in **Figure 4**, corresponding size-dependant one zone mass balance equations for the vehicle cabin are given in **Equation** (3) and (4), where the in-cabin concentration (*Cin*) of particle and CO_2 are estimated correspondingly.

$$\frac{dCin}{dt} * Vcabin = ((Qoa + Qps) * (1 - \eta) + Qinf * \alpha) * Cenv - (Qoa + Qps + Qinf + Qdep + Qrec * \eta) * Cin \quad (3)$$

$$\frac{dCin}{dt} * Vcabin = (Qoa + Qps + Qinf) * Cenv + N * Vbr * Cbr - (Qoa + Qps + Qinf) * Cin \quad (4)$$

3.3.3 Definition of parameters

To solve the equations in Equation (3) and (4), the parameters require definitions based on the application conditions. In this study the parameters are defined either from available test data (η, *Cenv* for particles, *N*), previous developed model (*Qoa*, *Qrec*, *Vcabin*) or based on experience from relevant studies (*Qdep*, *Qinf*, *Vbr*, *Cbr*, *Qps*, α, *Cenv* for CO_2). Then the steady-state solution of *Cin* under given conditions can be calculated.

The ventilation airflow (*Qoa*, *Qrec*) are simulated by the previous climate system model based on relevant model inputs, for instance HVAC fan speed, vehicle speed, recirculation degrees, HVAC flap positions, ambient temperatures etc. The passive ventilation airflow *Qps* entering the cabin, has been found linearly related to vehicle driving speed *vspeed* (Ott et al. 2008). Linear regression of the measured passive ventilation data has reported an experience coefficient of 0.21 m^{-1}(Lee et al. 2015a). Thus the *Qps* is calculated as in **Equation** (5) in this study.

$$Qps = 0.21 * vspeed * Vcabin \quad (5)$$

The same filter types used in the validation measurements (**Paper I**), a newly manufactured filter and a 500-h aged (end of service interval) filter of the same type, are used in the simulation model. For the new filter status, the efficiency values were applied from several available supplier component tests. For the 500-h aged status, several component tests data are also available for the same filter model type, however less than the new filter status. Similarly the filter efficiency data with pre-ionization are based on a restricted number of test data, which means the efficiency for aged filter with ionization were partially estimated based on the ionization improvement on the new filters. These tests were mainly performed under the airflow of 288 m^3/h (80L/s) and thus the influence of airflow on filter efficiency is not considered in the initial model. During the simulation, given the filter status and ionization status, the corresponding upper and lower limits of all the available efficiencies are used for η, which can be found in **Table 1** in **Paper II**.

The *Qdep (deposition flow)* in the vehicle cabin could be modelled using the deposition rate β (h^{-1}) as in **Equation** (6). The deposition rate value has been reported to be 0.6-12 h^{-1} for $PM_{2.5}$ by Harik et al. (2017) and 3.2-11.8 h^{-1} on average for UFPs by Gong, Xu, and Zhu (2009). The variation is due to vehicle type, airflow rate and particle size. The infiltration flow was simulated based on previous experience from Lee, Stenstrom, and Zhu (2015a).

$$Qdep = Vcabin * \beta \tag{6}$$

Respiration exhaled CO_2 source is defined by number of passengers (*N*), minute ventilation *Vbr* in L/min and carbon dioxide concentration contained in the passenger exhaled air *Cbr* (ppm). An average *Vbr* of 6.5 L/min is used in this study since passengers sitting in the stand-still car were almost at rest (Levitan, 2015). According to a previous study on carbon dioxide exposure (Scott et al. 2009), *Cbr* is set to 40000 ppm.

The passengers' respiration losses/gains of particles in the cabin are considered negligible compared with losses from filtration and deposition. This assumption is supported by Xu and Zhu (2009), that respiration airflow is nearly zero under driving conditions, and even under extreme idling conditions the deposition losses are 40-210 times higher than respiration losses. Besides, no phase change of particles is included in the model.

3.3.4 Model validation

The model validation uses results from previous vehicle measurement on roads as presented in section 3.2 in **Paper II**. To validate the road measurements, the outside particle concentration, actual HVAC fan speed, flap positions, vehicle speeds, ventilation setup of recirculation degrees and air distribution were read from the test data and input into the air quality model in GT-SUITE, to simulate the measurement conditions. Together with other input parameters as explained in previous sections, the steady-state solution of *Cin*, i.e. the simulated in-cabin particle concentration for each particle size, and CO_2 level could be compared with the actual measurements. When the particle concentrations within certain sizes are summarized, the simulated $PM_{2.5}$ (μg/m^3) and UFP counts (N/cm^3) are obtained and can be compared with the real road measurement.

3.4 Air quality and energy use

3.4.1 Study scope

The ventilation settings affect the particle and CO_2 concentrations in the cabin and would also possibly affect the energy use for climate system in the car. For example, the air recirculation degree could potentially benefit energy use and reduce particle concentration under certain outdoor conditions, since the HVAC treated cabin air is reused. Meanwhile it could also increase CO_2 levels in the relatively condensed cabin, which may cause threat on the driver's performance (Mathur 2016). The climate system model (Nielsen et al. 2015) and the air quality model developed in section 3.3 is used for further investigation of these relationships.

3.4.2 Test cycle development

The cabin air quality level and climate energy use highly depend on the ambient environment and how the climate system operates accordingly. This study aims at achieving a more comparable and representative investigation under different outside conditions. Thus a representative test cycle is developed to simulate scenarios with varying recirculation (REC) degrees of 0, 30%, 50%, 70%. Number of passengers between 1-5 were investigated.

The vehicle climate system could operate in different modes depending on the outside condition. Three outside conditions of temperature and humidity (**Table 5**) are utilized. In brief the conditions are calculated based on the ambient data in 15 largest markets for Volvo Cars, weighted with sales distribution and a common vehicle departure time distribution. In the intermediate and warm climates the vehicle has one hour sun soak before the cycle.

Both the outside particle mass and count concentration could vary significantly in different locations and road conditions. Three outside particle concentrations profiles (between 10 nm and 35 μm) from previous road measurements were selected as Low, Medium, High concentrations (**Table 6**). The corresponding detailed particle mass and count concentrations from 10 nm to 2.5 μm can be found in **Appendix Table 6** in **Paper III.** According to guidelines on European Air quality Index from European Environmental Agency, they lie within the fair, poor and extremely poor air quality levels correspondingly (European Environment Agency, 2013).

Table 5: Ambient conditions of the three climates

	Weight	Temperature (°C)	Dewpoint (°C)	Sun load (W/m^2)
Cold (T0)	0.2	0	-4	0
Intermediate (T15)	0.6	15	7	200
Warm (T27)	0.2	27	17	400
Weighted average		14	7	200

Table 6: Three levels of outside particle concentration profiles used in the simulation, as input to the model

	$PM_{2.5}$ (μg/m^3)	UFP counts (N/cm^3)
Low	18	~7 000
Medium	48	~2 0000
High	128	~3 0000

3.4.3 Vehicle settings

The studied vehicle is a Volvo XC90 (model-year 2018) with estimated cabin volume of 4.1 m^3, which utilizes a high voltage coolant heater (HVCH) and an electric compressor. The vehicle velocity profile is the Worldwide Harmonized Light vehicles Test Procedure (WLTP) class 3 (UNECE, 2014) . The length of the cycle is the length of WLTP, i.e. 30 min. The climate system is running in automatic mode with temperature setting of 22 °C, which means the climate control module controls the system as described in **Table 1**.

But in this study some simplifications and modifications on the climate control are applied in comparison with auto mode in production vehicles, mainly for the purpose of simulation need and achieve fairer comparison in the different cases. Firstly is the REC degree which is controlled manually to different levels. The same applies to the evaporator set point, i.e. the air temperature after evaporator, as well as whether AC is on or off. While in reality these parameters are varied depending on many climate control inputs, such as the environmental and cabin temperatures. Another example is that feedback from an ambient air quality sensor could request for temporary REC to avoid outdoor pollutants, e.g. driving in a tunnel. Similarly manual control of air distribution mode is applied.

Moreover, to achieve a fairer comparison on the climate power, a similar cabin temperature profile should be reached in cold (T0), intermediate (T15), and warm (T27) climate separately. Meanwhile for fairer comparison of particle and CO_2 concentrations, the airflow or the fan speed should be similar between cases. The applied strategy in T0 and T15 cases is that for higher recirculation cases, the maximum allowed heater power is reduced to reach a similar heat-up speed. For T27 cases, the compressor in this study is set to reach the same air temperature after the evaporator (the evaporator set point), thus a self-control ensures the same temperature profile.

The main climate system power of electric heater, blower and compressor power, as well as $PM_{2.5}$, UFP, CO_2 are compared.

3.4.4 CO_2 Feedback control

Furthermore, a feedback control unit is applied in the simulation model to control the REC degree (0-100%) based on the cabin CO_2 concentration. The control target of CO_2 concentration is lower than 1000 ppm. It investigates the strategy of continuously optimizing the REC to reduce the climate energy use and cabin particles, as well as maintain an acceptable CO_2

concentration, in combination with usage of sensors in the vehicle. A PI control unit is used with Proportional Gain of -0.03 and Integral Gain of -0.0003.

3.5 Potential developments

The concept of adding pre-filters prior vehicle HVAC filter is initially investigated. Vehicle measurements are performed both in a test room and on road. Different factors including filtration efficiencies, pressure-drop, space, and practical installation limitations in the vehicles are investigated.

3.5.1 Filter Prototypes

The studied prototypes are listed in **Table 7**. Pictures of filters are shown in **Figure 5**. The pre-filter dimension is designed according to available space in an existing production vehicle. 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. The prototype 2 was loaded with ISO 12103-1 A2 Fine Dust (International Organization for Standardization, 2016) to represent an aged filter status and tested in vehicle as well.

Table 7: 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
Protection filter	Particle filter	400*314* 30 mm	new
Original HVAC filter	Synthetic filter with activated carbon	247*289*40 mm	new

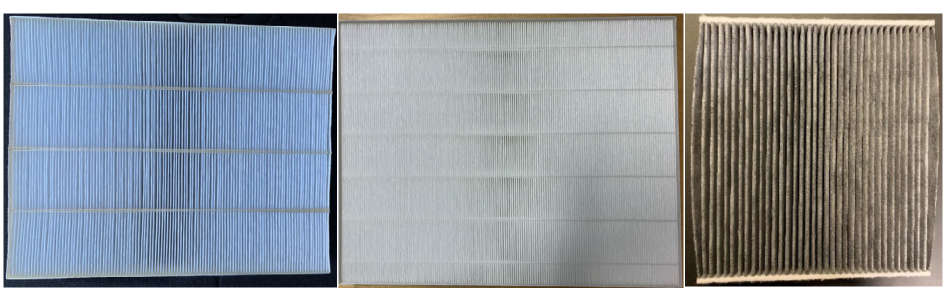


Figure 5 Prototype filters. Left: P1, Middle: P2. Right: original HVAC filter

3.5.2 Vehicle measurement

The prototypes were installed in a production vehicle's thermal bay (VOLVO XC40 BEV model-year 2021) as shown in **Figure 6**. Part of the original storage accessory was removed and replaced with a 3D-printed pre-filter holder, which was connected to the original HVAC system air inlet. The holder is designed to fit in the thermal bay under the hood whilst the hood could be closed as normal.

Vehicle measurements were performed both inside an indoor test room with generated particles of NaCl and DEHS (Di-Ethyl-Hexyl-Sebacat), and also in a road tunnel in Gothenburg (the same as in 3.2). Both the in-cabin and outside particle concentrations were measured with two Grimm MiniWRAS model 1.371. The particle generators are TSI Portable Test Aerosol Generator Model 3073.

The vehicle measurement method is the same as described in 3.2.2. The climate settings during all testing were AC off and desired temperature of 22 °C, as well as constant ratio of airflow at panel and floor vents. 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. The data log starts after steady concentration is reached and lasts at least 10 minutes, with at least 3 repetitions. Different scenarios of filter combination were tested: original HVAC filter alone and pre-filter + original HVAC filter.

Figure 6 Filter prototype installation in an existing production vehicle‘s thermal bay

4 Results

4.1 Vehicle cabin air quality baseline measurements

The key results from the first test campaigns were that although the actual levels of $PM_{2.5}$ and UFP in the cabin could vary drastically depending on outdoor levels, the indoor to outdoor ratio (I/O ratio) of the particles was similar for high pollution and low pollution levels.

As summarized in **Table 8**, baseline (without ionization) and ionization data are compared. The main difference was that outside $PM_{2.5}$ concentrations on average were considerably higher in Northern China (baseline average 160 µg/m^3) than in the road tunnel in Gothenburg (baseline average 55 µg/m^3). Thereby also the inside $PM_{2.5}$ concentrations are on average higher in Northern China (baseline average 58 µg/m^3) than in the road tunnel Gothenburg (baseline average 20 µg/m^3).

Table 8: Summarized overall data of inside and outside $PM_{2.5}$ concentrations, UFP counts and I/O ratio, grouped by location and ionization status

		$PM_{2.5}$ mass concentration (µg/m^3)			**UFP counts (×10^3 particles/cm^3)**		
		In-cabin		**Out. [a]**	**In-cabin**		**Out.**
	N of samples	**AM [b]**	**AM I/O**	**AM**	**AM**	**AM I/O**	**AM**
GOT baseline [c]	40	19.8	0.36	54.9	9.24	0.37	25.8
GOT Ion. [d]	41	9.9	0.20	50.0	4.27	0.18	24.0
China baseline	23	58.1	0.35	159.7	10.8	0.40	25.0
China Ion.	23	30.0	0.15	190.7	6.10	0.20	30.5

[a] Out.: outside [b] AM: arithmetic mean [c] GOT: Gothenburg [d] Ion.: ionization applied cases

Another result from these tests indicated significant improvement of filtration efficiency, i.e., decrease of I/O ratio, with pre-ionization for both new and used filters, in both locations. Results are shown in **Figure 7**.

More importantly, ionization applied to a used filter makes it almost comparable with a new filter without ionization. Four comparisons were made between the I/O ratios of the aged filter with ionization and the new filter without ionization, for two locations and two particle sizes respectively. The comparisons show no significant difference in I/O ratios ($p>0.05$), only except for the comparison of $PM_{2.5}$ I/O ratio in Gothenburg shows significant difference ($p<0.05$). It should however be noted that the standard deviation between the different test cases are larger for aged than for new filters and this could possibly be related to that the aged filter has uneven dust loading.

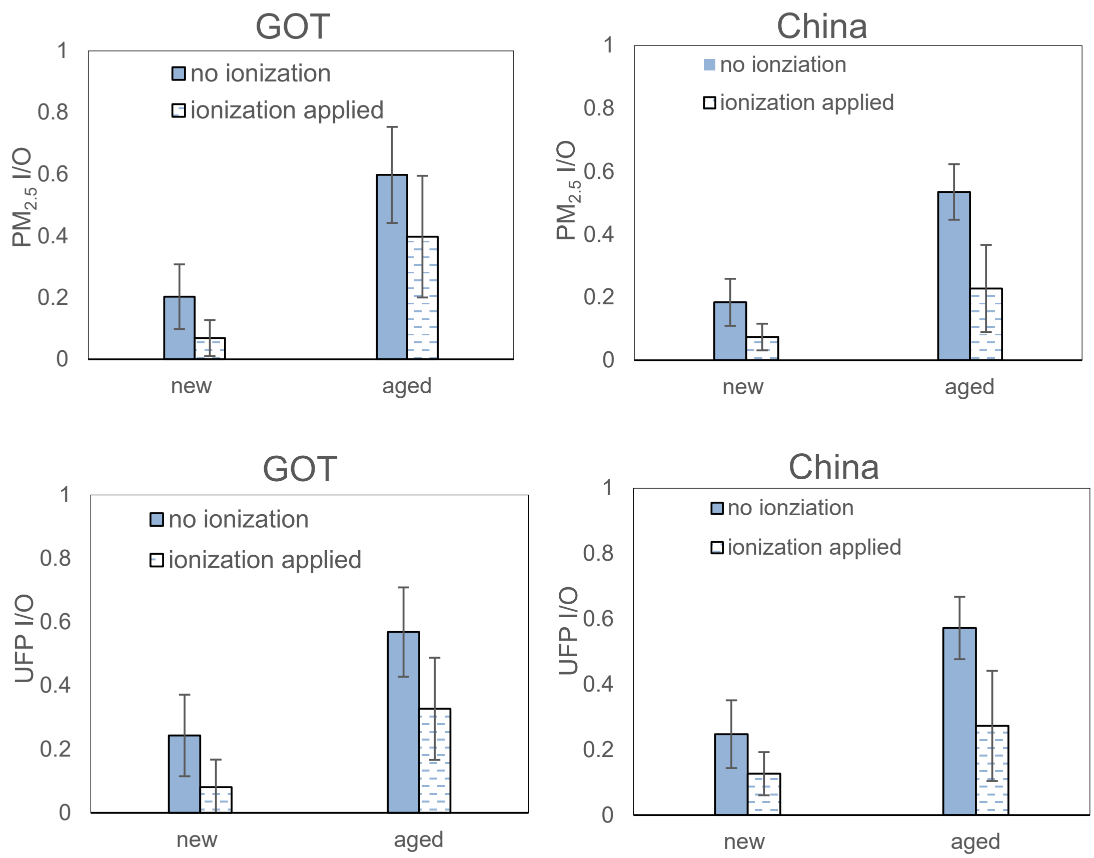


Figure 7 Influence of pre-ionization on in-cabin $PM_{2.5}$, UFP, and I/O ratio in Gothenburg and China, grouped by new and aged filter. Samples include all test cases. Error bars present standard deviation. GOT: Gothenburg

Furthermore, filter age decreased filter performance significantly. The differences of using new and aged filters are also clearly shown in **Figure 8**. The inside $PM_{2.5}$ concentration and the UFP counts are about three times higher using an aged filter in comparison to a new filter. We can notice that the I/O ratios are almost equal across two locations, when the same filter is used, compared to the difference found in $PM_{2.5}$ concentrations and UFP counts. One main reason is that the same filters and HVAC system are used for both locations, and the main protection against particles comes from the HVAC, or specifically the filter.

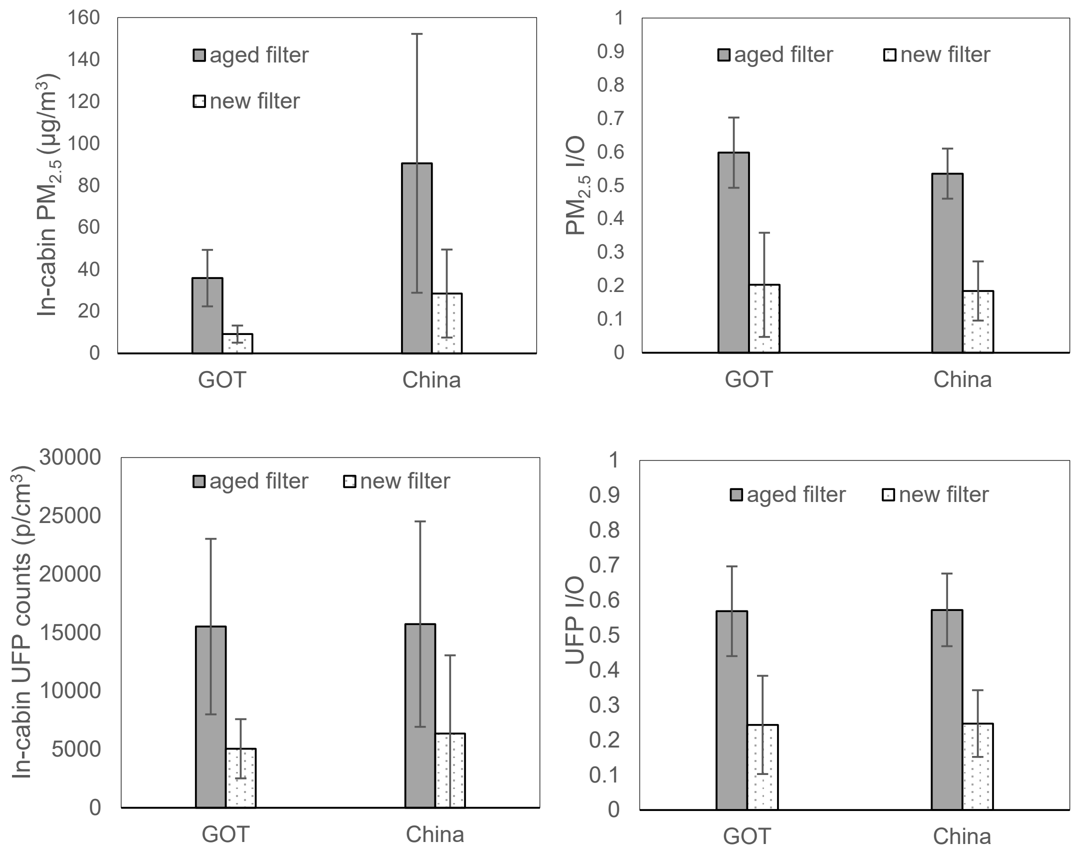
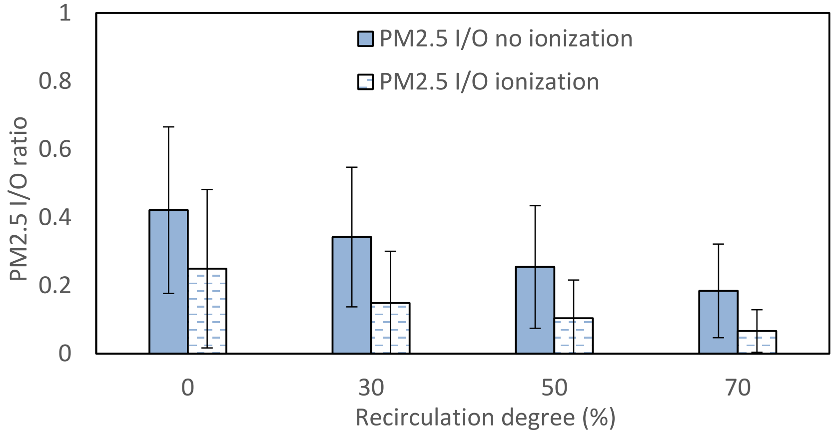


Figure 8 Comparison of all baseline (no ionization) cases in-cabin $PM_{2.5}$ concentration, in-cabin UFP counts, and I/O ratios, grouped by locations, new and aged filter. Error bars present standard deviation. GOT: Gothenburg

Both recirculation of air and total air flow was also investigated, results are indicating that low airflow and high recirculation degrees were beneficial for air quality. For example, 70% recirculation resulted in I/O ratios become less than half compared with no recirculation, which is presented in **Figure 9**. One important reason is that recirculated air from cabin contains less particles than outside air, and is further mixed with outside air, then filtered again.



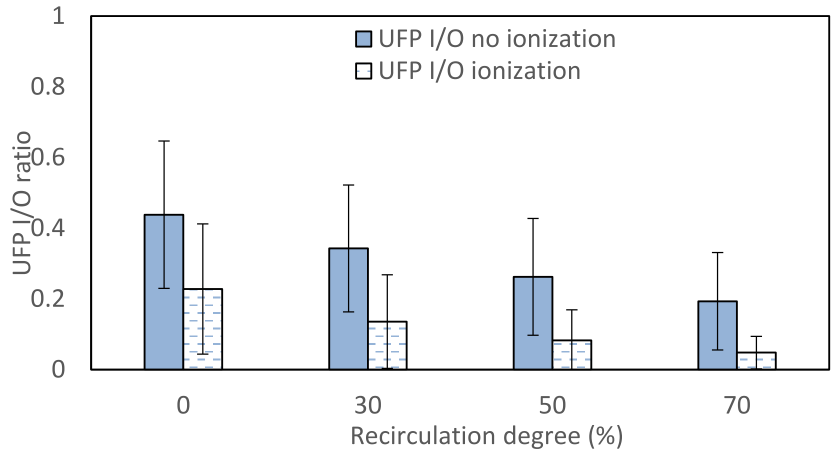


Figure 9 Influence of 4 recirculation degrees on I/O ratio of $PM_{2.5}$, UFP counts. Samples include all Gothenburg measurements (baseline and ionization). Error bars present standard deviation

4.2 Model development

4.2.1 Model validation

The simulated inside $PM_{2.5}$, UFP, were compared with the inside measurements in **Figure 10** of all test cases. Generally, the simulation agrees well with measured data (Person's r 0.89-0.92). For part of the tests in Sweden, when the outdoor air is relatively clean, and the new filter is installed, the inside $PM_{2.5}$ is lower than 10 μg/m^3. At this range the simulation scatters relatively more due to low absolute particle levels.

Similarly, the comparison of CO_2 concentration prediction and measurement is shown in **Figure 11**. The prediction generally agrees well within the measurement range and the Pearson's r is 0.89.

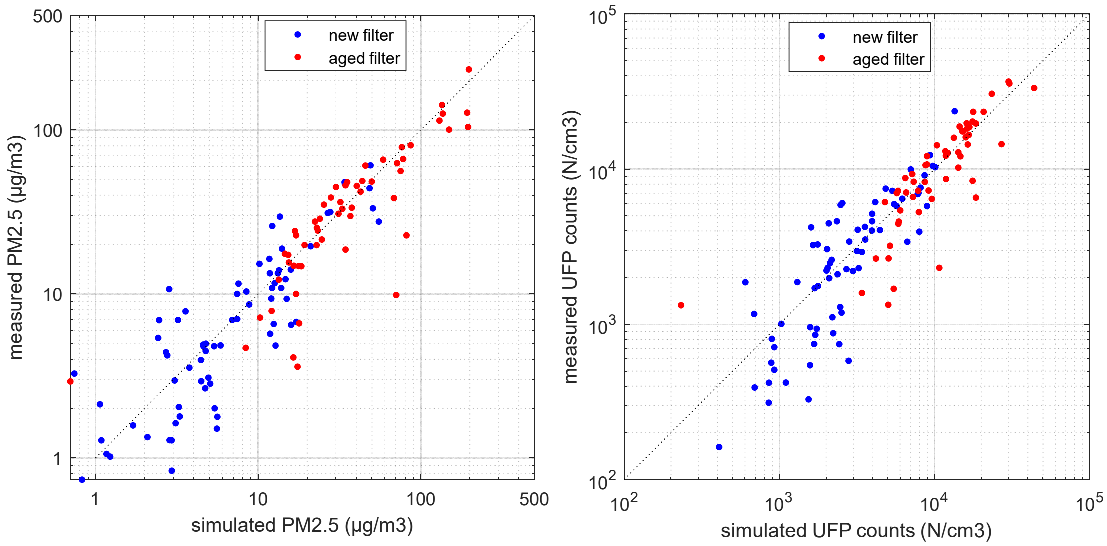


Figure 10 Comparison of simulated and measured in-cabin $PM_{2.5}$ values and UFP counts. Data include all test cases (128 samples), including both new and aged filter statuses, four ventilation airflow rates (total ventilation airflow around 20, 40, 60, 85 L/s respectively)

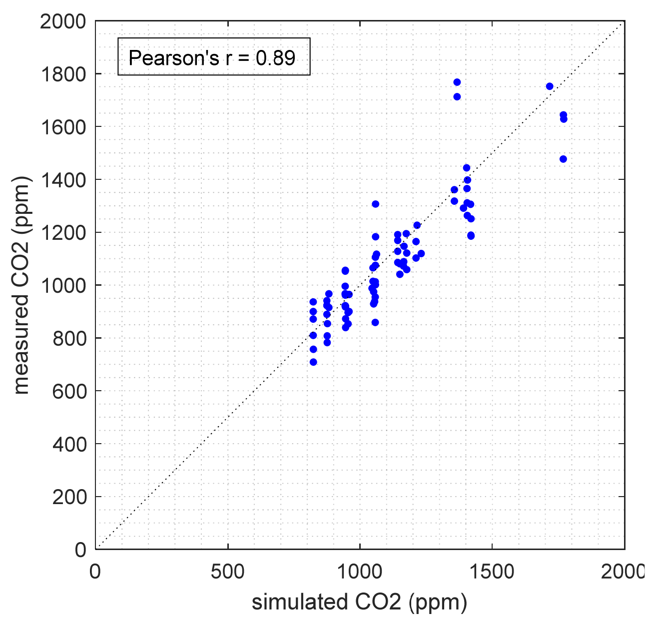


Figure 11 Comparison of simulated and measured steady-state in-cabin CO_2 concentration (ppm). Data include all test cases (81 samples)

The validation also shows that the simulation of aged filter with ionization is showing higher deviation than others. As in **Figure 12 a)**, the simulated and measured average $PM_{2.5}$ I/O ratios of each category are compared. The simulations towards new filters give close average I/O ratios to the measurements (less than 5% difference). On the contrary, the aged filter ionization category showed largest deviation of simulated I/O ratio (31%), and this group also shows larger variance (Std=0.19) of measured I/O ratio compared with others, which is possibly due to the particle accumulation is not even throughout the aged filter surface, and thus possibly more unstable performance. It could also be seen from the graph that the simulation tends to overestimate I/O ratio for the aged filter ionization group, i.e., underestimate the filtration performance.

Furthermore, in graph b), the difference between $PM_{2.5}$ I/O ratio for each sample is calculated, then summarized under the four categories using the box-and-whisker plots. So, each column shows the distribution of simulation and measurement deviation, in the sense of I/O ratio. It confirms the observation from graph a) that the aged filter ionization group has higher simulation deviation, and the I/O ratio difference also lies in a wider range.

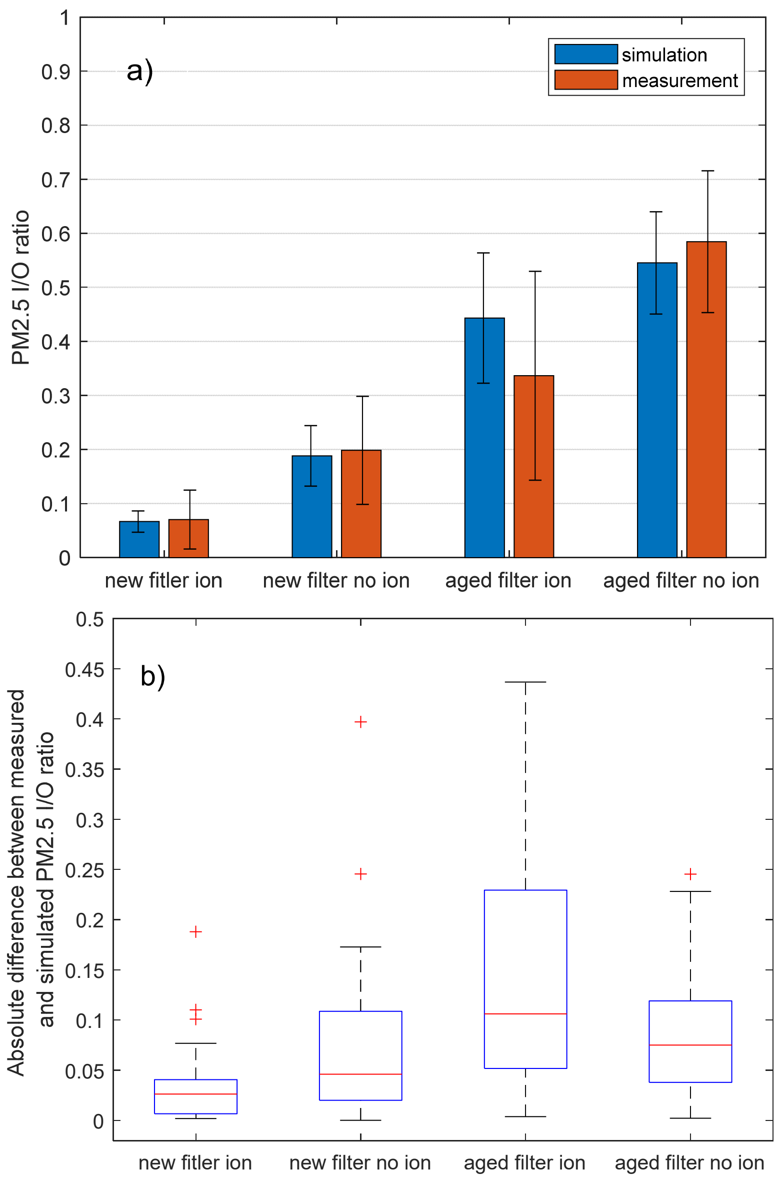


Figure 12 $PM_{2.5}$ Indoor to outdoor ratios (I/O ratios) are compared in different parameter groups: the filter statuses of new and aged, and the ionization status of on and off are combined: a) average simulated and measured I/O ratios are compared, error bars present standard deviation.

b) The absolute difference between simulated and measured I/O ratio of each sample are summarized in box-whisker plots. Data include all test cases (128 samples)

The simulation using medium airflows agrees better than the simulation using other airflows, both lower and higher. The estimated total ventilation airflow rates at four levels are around 20, 40, 60, 85 L/s respectively. 4 paired samples t-tests between the simulated and measured $PM_{2.5}$ I/O ratios in each airflow level are performed, at significance level of 0.05. The corresponding p values are 0.00, 0.05, 0.56, 0.01, which confirms that the Medium airflow category showed no statistically significant difference between simulation and measurement average. The reason for this may be that the filter efficiency data used in the model were mainly obtained at airflow of 288 m^3/h (80 L/s), which is between Medium and High levels in the simulated cars. Since the filter efficiency is influenced by the ventilation airflows in reality (Knibbs et al. 2010; Shi 2012), this estimation could cause the deviation for the other airflows when only efficiencies under one airflow is utilized.

It is also seen that the average of simulation is close to average of measurement in all 4 REC levels and the recirculation estimation is not influencing the simulation performance to a high extent. This agrees with the simulation process since the recirculation is not influencing the estimated filter efficiency.

The simulation is also validated against particle concentration in all size bins. Two examples are shown in **Figure 13**. Overall the size of 100-300 nm were slightly overestimated. The results indicated that among others expanded filter efficiency data as a function of filter ageing and airflow rate would possibly enhance the simulation accuracy.

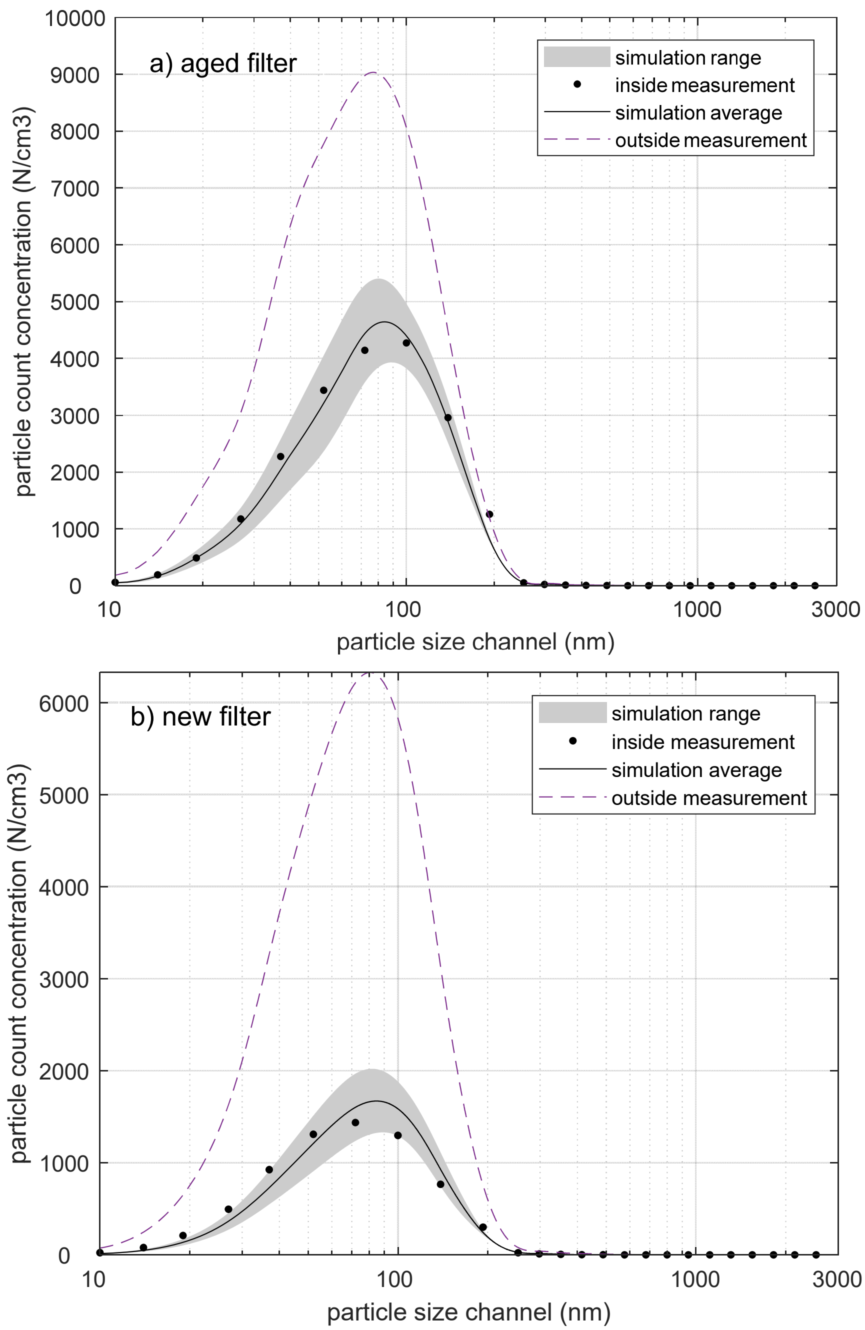


Figure 13 Two example cases are presented regarding measured particle count concentration (inside and outside) and simulated particle count concentration range/average per size channel. The two examples show mean two 5-10 min stabilization measurements under these corresponding settings

4.2.2 Sensitivity analysis

The model performance is expected to be sensitive to filter efficiency estimation, since the efficiencies are relatively dominant in how much particles are removed. The estimated efficiencies in this study are from standardized component test and relatively small deviation are expected especially for new filters. Thus sensitivity analysis was performed by increasing/decreasing the filter efficiencies by 0.05 (efficiency value range 0 to 1) compared to the original values, and the resulting change on $PM_{2.5}$ I/O ratio are summarized in **Figure 14**. All of the simulated cases reported an absolute change in $PM_{2.5}$ I/O ratio smaller than 0.1.

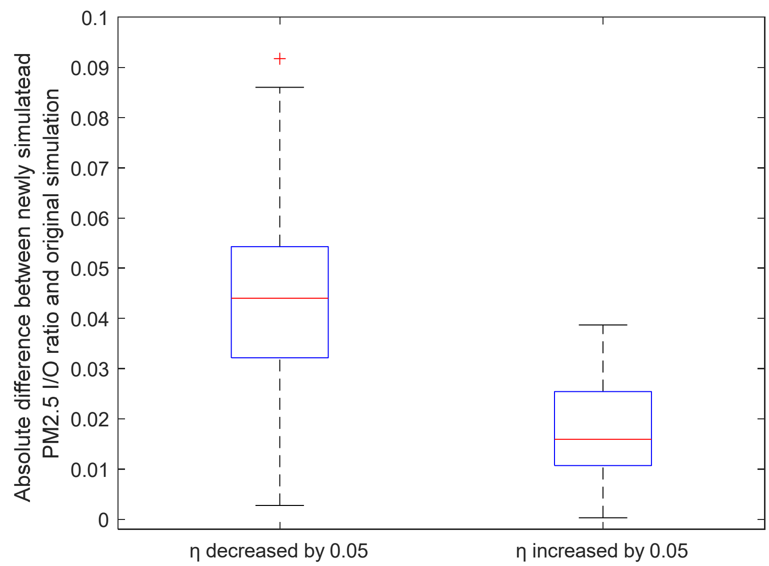


Figure 14 Box-Whisker plot of absolute difference between the altered and the original simulations of the average $PM_{2.5}$ I/O ratios when filter efficiencies were increased and decreased by 0.05. Data include all test cases (128 samples).

Ventilation airflow variation within a common deviation range in this study are not influencing the simulation to a high degree, which is surely relevant to the fact that the influence of airflow on filter efficiency is not considered in the simulation. When the high recirculation and infiltration both happens, the particle simulation results would be more sensitive to the *Qrec* variation.

The infiltration airflow (*Qinf*) was estimated from relevant studies using vehicle characteristic values for the two cars in this study (Lee et al. 2015a). The validation showed that the infiltration values (*Qinf*) were almost all zero in all 128 data samples, except for a few cases that have *Qinf* in the magnitude of 10^{-4} m^3/s. This could be expected since, in general, the newer cars are predicted to have better sealing performance and the measurement cases always have the ventilation fan on, which pressurizes the cabin. The cases with positive *Qinf* are all with high recirculation degrees, where cabin pressurization from outside air (*Qoa*) is less. Further sensitivity study showed that the simulation of infiltration flow would possibly be more sensitive to high speeds conditions, especially when the ventilation flow is low.

The results also showed that deposition has a relatively small contribution and the deposition flow *Qdep* was 30-170 times smaller than ventilation airflow (*Qoa*+*Qrec*).

4.3 Air quality and energy use – influence of recirculation

4.3.1 Particle concentration

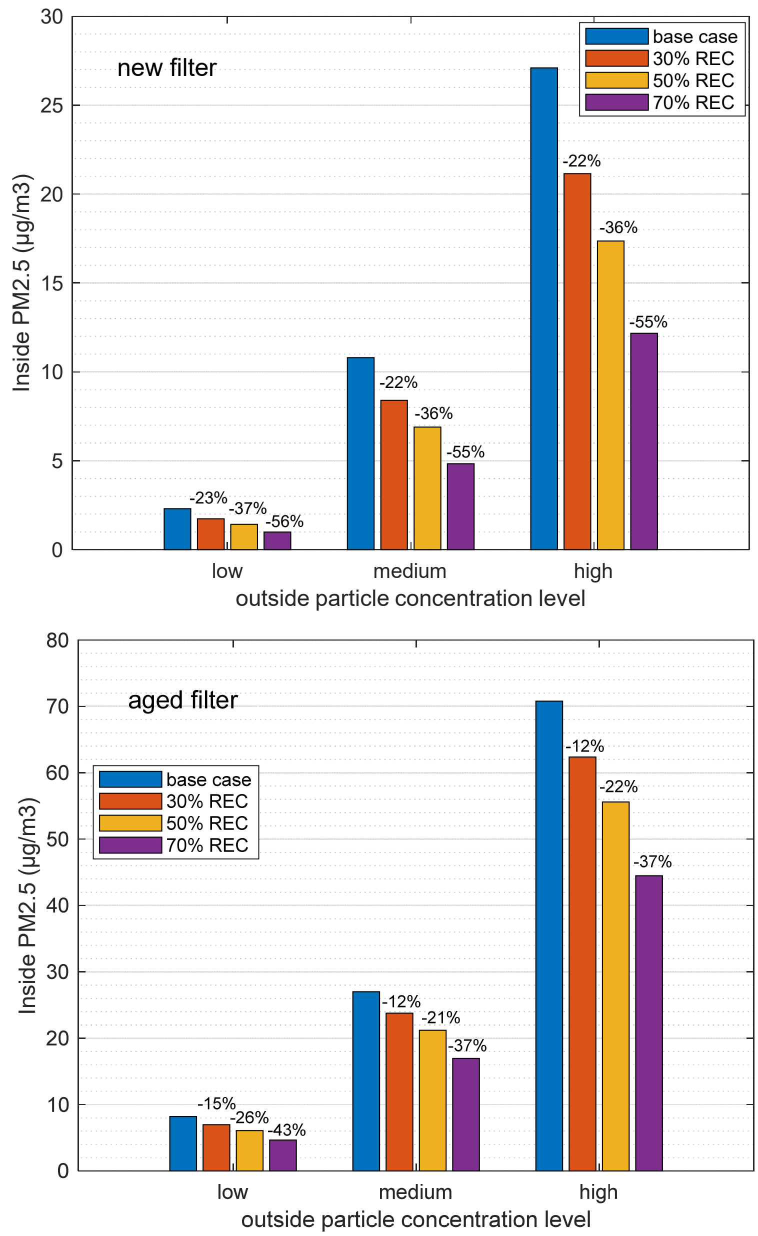


Figure 15 Steady state inside $PM_{2.5}$ concentration at three outside concentration levels, grouped with different recirculation degrees, in comparison with base case. Low, medium, high stands for outside $PM_{2.5}$ concentration, which are 18,48,128 µg/m3 correspondingly. Each bar is the weighted average of cold (T0), intermediate (T15), and warm (T27) climate. 1 passenger is simulated

Significant reduction of $PM_{2.5}$ was achieved with increased levels of recirculation and at the same time the energy use was reduced. The new filter has higher potential compared with aged filter as shown in **Figure 15** . For example with 70% REC and a new filter, when the outside $PM_{2.5}$ is high (128 μg/m^3) the inside $PM_{2.5}$ is below the WHO guideline level of 15 μg/m^3, which means 55% percent reduction is achieved in comparison with base case (27 μg/m^3).

4.3.2 Energy use

The energy use is simulated for a PHEV car with an electric heater, i.e. without heating from the engine. Therefor the energy use is dominated by the heater power as shown in **Figure 16.** It's important to repeat here the applied climate operation in this study, that the AC is off in T15 condition.

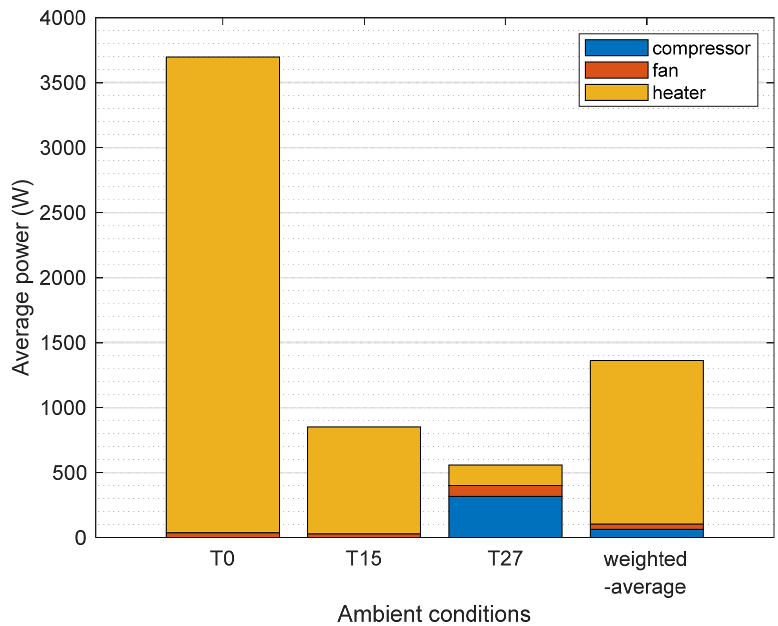


Figure 16 Case average power of compressor, heater, and fan at T0, T15, and T27. Weighted average (weight 0.2, 0.6, and 0.2)

Figure 17 presents the corresponding reduction on weighted-average climate power with increased REC. The reduction is mainly on the heater power. Overall weighted average total power is reduced from 1.4 kW to 1.0 kW at 70% REC, i.e. 27% reduction. For the climate power at T0, T15 and T27 respectively, please refer to **Figure 8** in **Paper III.**

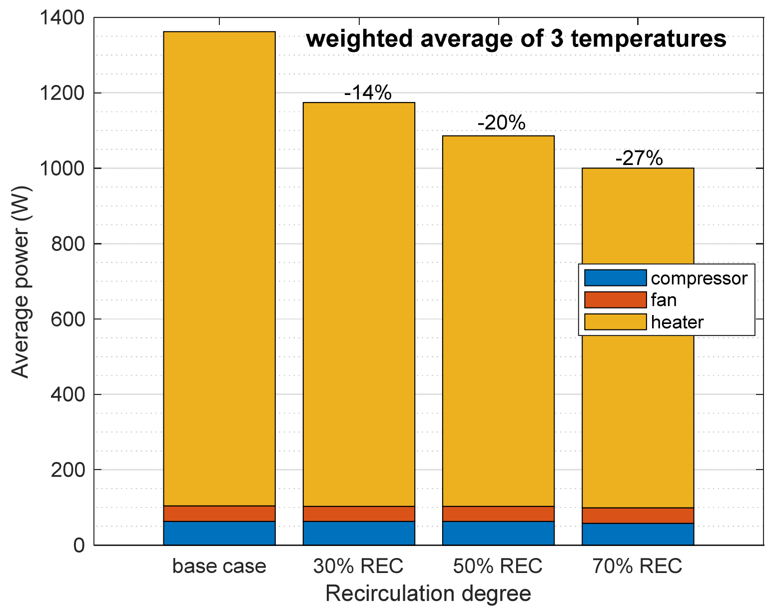
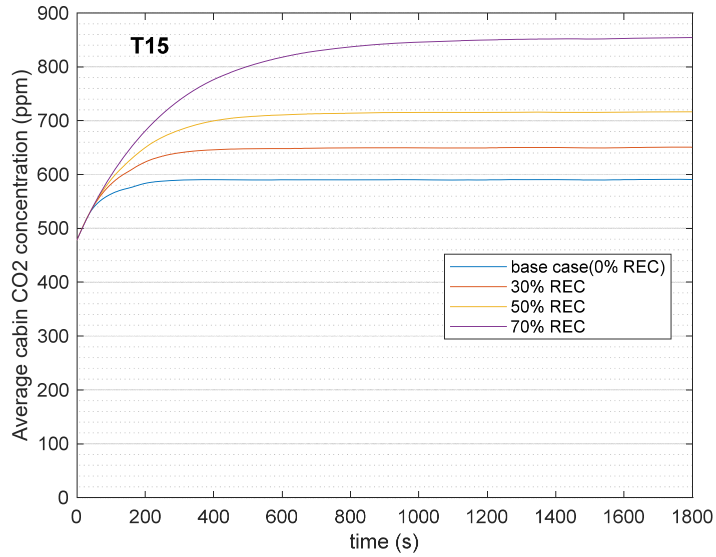


Figure 17 Case average power of compressor, heater, fan at T0, T15 and T27. Weighted average of the three conditions is calculated (weight 0.2, 0.6, 0.2). Results are compared at different recirculation degrees

4.3.3 CO_2 concentration

With increased REC the CO_2 concentration increased in the vehicle cabin and depending on number of passengers this could limit the recirculation degree. However, for 1 passenger, which is the most common number of people in the vehicle (European Environment Agency, 2015), the CO_2-levels were generally low and the potential for recirculation high. As shown in **Figure 18** the CO_2 concentrations are below 1000 ppm, a common indoor guideline level (Lowther et al. 2021), in all climates even at 70% REC. T0 results are not present as very similar toT15, which can be found in **Paper III Figure 3**.

This is a very important result, if we can ensure that the CO_2-level is below different recommended limits, both air quality and energy efficiency improves with increased recirculation. I.e., there is no conflict between the attributes and no balancing required from this perspective.



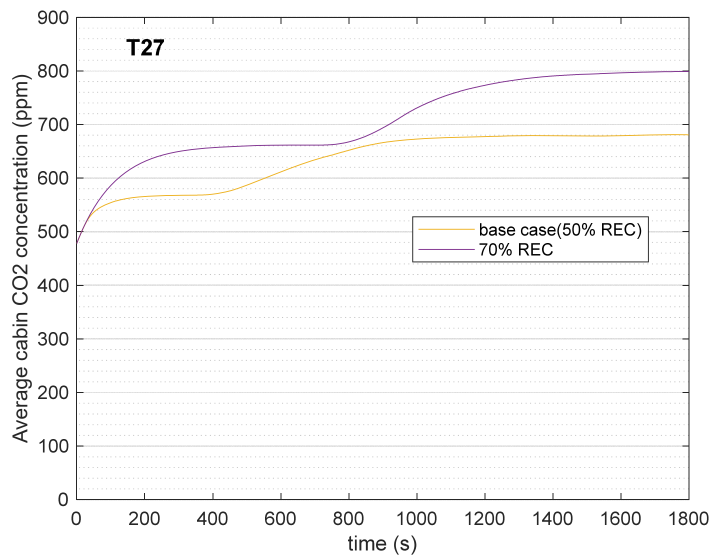


Figure 18 Cabin CO_2 concentration profile T15 and T27, grouped with different recirculation degrees, in comparison with base case. 1 passenger is simulated

When passenger numbers are increased, the CO_2 concentration arise accordingly. As shown in **Figure 19**, results associated with 1 to 5 passengers in three outside conditions are compared. This indicates how much REC is allowed at different conditions. For example at T0 30% REC is not recommended with more than 3 persons.

The above investigation showed that the increased REC is beneficial in reducing particle concentrations in all climates, and in improving energy efficiency in cold, warm climates and in intermediate climate when AC is off (the strategy in this study). In cold climate the potential windscreen fog risks exist, which means increased REC requires more critical judgement. In all climates the accumulation of CO_2 highly depends on the passengers and ventilation airflows. Benefiting from a higher ventilation airflow in the studied T27 cases, higher REC is more likely to implement.

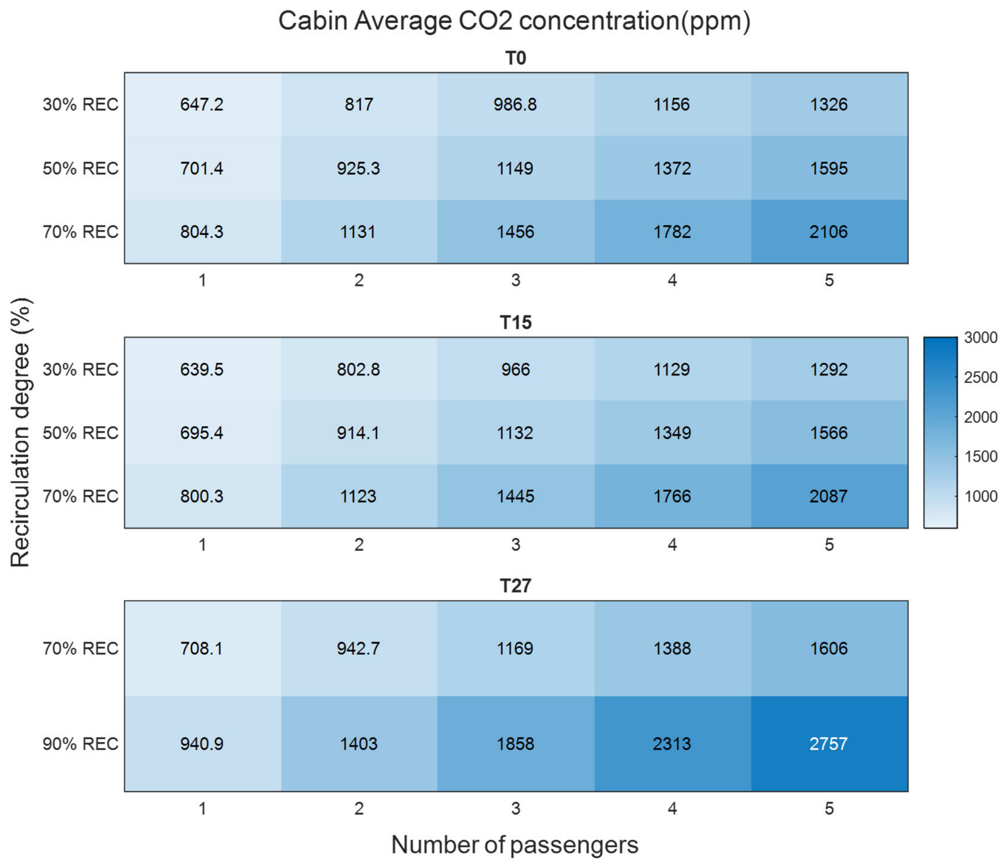


Figure 19 Map of cabin CO_2 concentration (30 min case average) for increased recirculation simulations. Number of passengers are varied from 1 to 5. Ambient condition T0, T15 and T27

4.3.4 CO_2 feedback control

Furthermore, a dynamic control of the recirculation level was also investigated at T27, aiming for a specific CO_2-level (1000ppm). **Figure 20** shows the control results for 1 passenger. The REC starts with 100%, then as CO_2 accumulates the REC dips down and finally stabilizes, which leads to a 30 min-average of 90% REC). With this type of control, the improvement of $PM_{2.5}$ levels and energy use could be even better than the results in **Figure 17** since the REC is continuously optimized. The simulation was also performed on 2 to 5 passengers with the same configuration. The controlled CO_2 concentrations are similar while the results of different REC are shown in **Figure 21**.

The control sample shows the possibility of enhanced climate control. The REC control from CO_2 could be combined with existing control of HVAC fan based on the cabin air temperature and humidity. The input parameters could include cabin CO_2 sensor, outside/inside temperature and humidity sensors, outside air quality sensor, and passenger number to maintain the good air quality and climate comfort level.

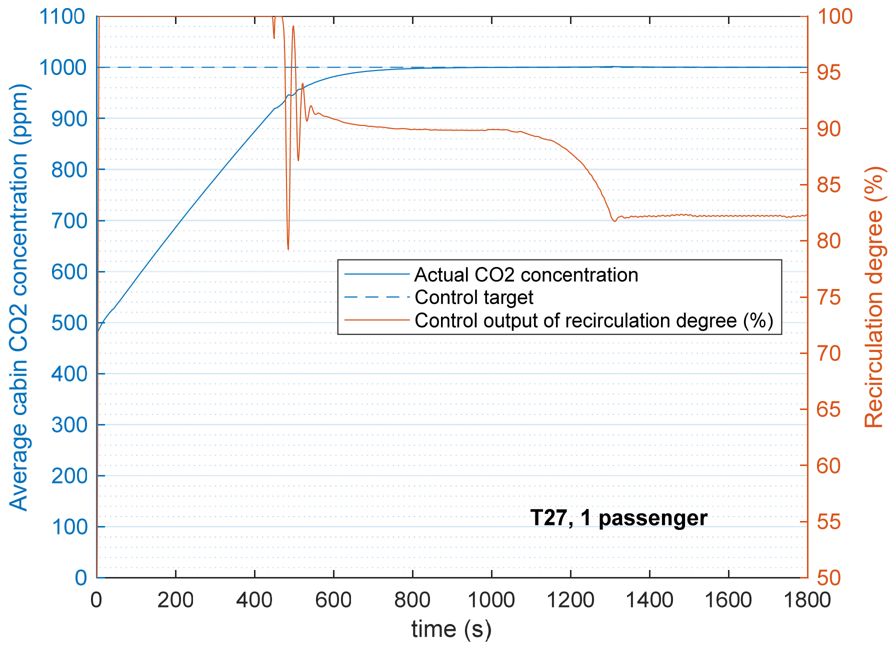


Figure 20 Feedback control of recirculation degree based on the cabin CO_2 concentration. The control target is not higher than 1000 ppm

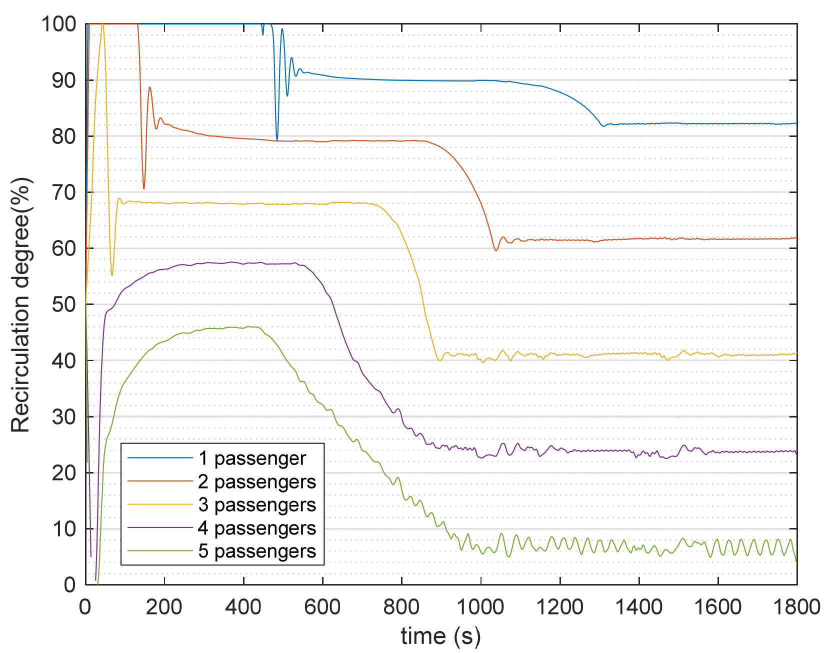


Figure 21 Controlled output of recirculation degrees(%) in the feedback control simulation. Passenger numbers from 1 to 5 are compared. Ambient condition T27

4.4 Potential developments

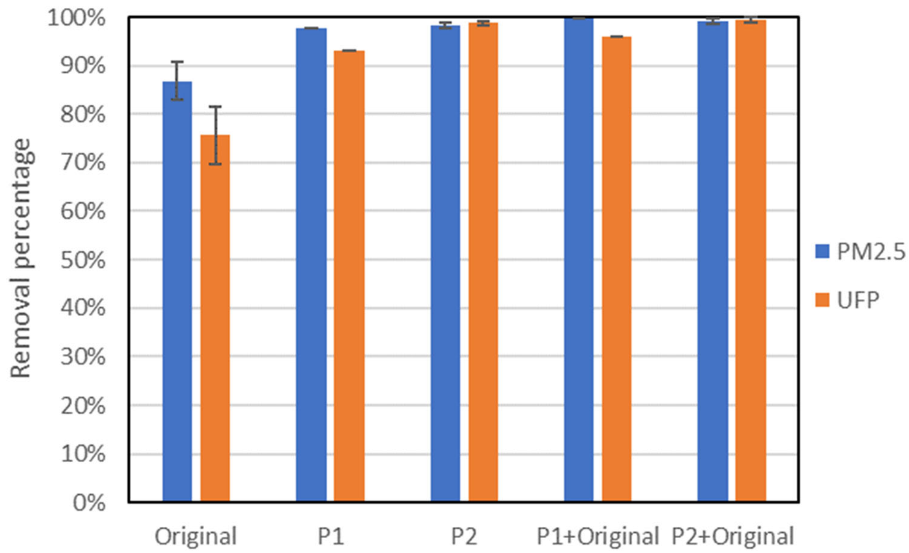


Figure 22 Comparison of in-cabin removal percentage of UFP and $PM_{2.5}$ with different filter combinations. Measurements performed with road particles in Lundby tunnel, Gothenburg, Sweden. Original: the original HVAC filter alone. Airflow Low level (around 40L/s), no recirculation. Error bars present standard deviation.

In **Figure 22** the comparison of particle removal percentage is presented for measurements performed on the road. Different filter combinations are compared. 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 on contrast only removes 76% of UFP and 87% of $PM_{2.5}$. Applying P1 as pre-filter improves the UFP removal up to 96% and $PM_{2.5}$ to 99%.

Both prototypes were tested feasible with regards to achieving better cabin air quality. Also, with an aged P2 filter the performance of 99% $PM_{2.5}$ removal is maintained. It means that the service interval is probably mainly dependent on the pressure-drop increase and other aspects like gas absorption, microbial growth etc.

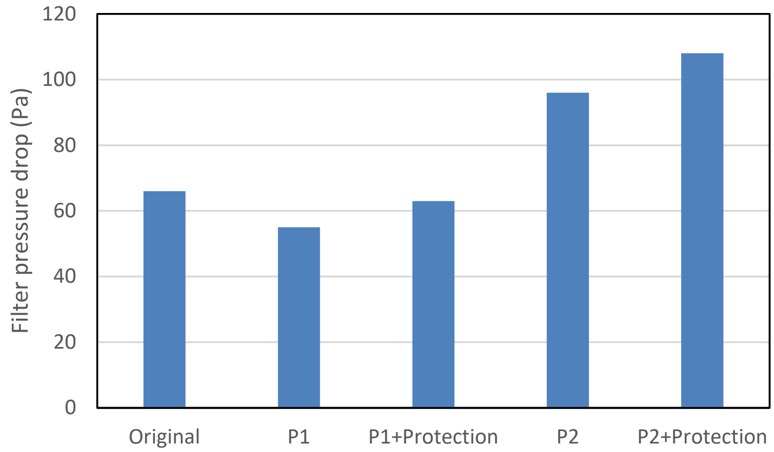


Figure 23 Pressure-drop of filter prototypes measured following standard DIN 71460-1. Test airflow 80L/s. Dimension of Original is smaller than the rest, see **Table 7**

Figure 23 presents the pressure-drop of filter prototypes under airflow 80 L/s measured in certified agency, following the standard DIN 71460-1 (German Institute for Standardization, 2006). 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 7**). P1 has similar level of pressure-drop as the original HVAC filter, which means the application of P1 almost doubles the total pressure-drop from filters.

The choice of filter level in real vehicles would be a balance between cost, filtration efficiency, space, NVH, and energy consumption. 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.

5 Discussions

This study focuses on the topic of vehicle cabin air quality, more specifically the in-cabin particles originated from the outside air. Some research methods and results are now discussed. For instance, either in simulation or measurements, it's important to understand what type of particles are investigated, and also how are the results of particle removal presented. The filter ageing, and the connection with energy use are also discussed.

5.1 Outside particles

In this project several vehicle measurements have been performed in different locations, i.e., in Gothenburg Sweden and Northern China. The difference of $PM_{2.5}$ and UFP concentration could be clearly seen between light and heavily polluted outside air. It was also noticed that the particle size distributions are different, which is due to several factors, e.g. the surrounding traffic conditions, atmospheric particle concentrations, meteorologic parameters etc. (Zhu et al. 2007; Qiu et al. 2019). This indicates the importance of measuring the different sizes, both inside and outside the cabin, especially the nm range where the particles are more harmful to human health.

On the other hand, in this study generated particles in standardized lab tests are used for vehicle measurements as well. In comparison with road particles, they might show different distributions and characteristics (electrostatic charges, deposition in the ducting etc.), which mean different challenges for the vehicle cabin.

Figure 24 presents four examples of different particle size distributions, for generated NaCl and DEHS, road air in Sweden, and in China respectively. All examples have outside $PM_{2.5}$ concentration around 100 $\mu g/m^3$. While from the figure it's observed the particle distribution are quite different. The road particle profiles have two peaks of mass concentration while the generated particles only have one, in agreement with relevant studies (Molnár et al. 2002; Zhu et al. 2008). This is probably due to the multiple source and rapid change of traffic relevant particles.

It should also be noted that road measurements in the figure are only two randomly selected examples, which could not represent a complete profile of various road conditions. In general vehicle test 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 will provide stable and more repeatable conditions. A combination of extensive test methods would be beneficial.

It would also be of interest to investigate if a certain mixture of standard particles or mix of engine emissions could provide results close to real road particles. Again, that would also depend on what road conditions are considered.

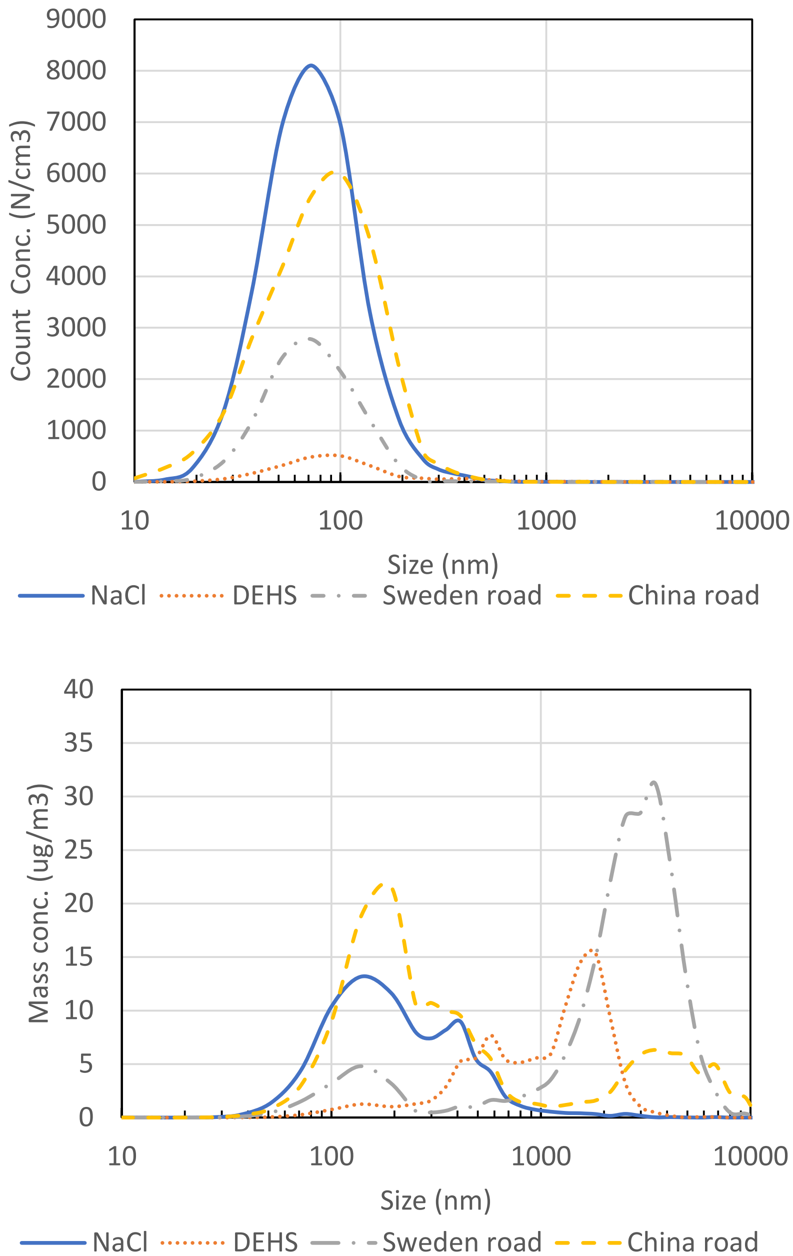


Figure 24 Outside air particle size distribution of count concentration (N/cm^3) and mass concentration(μg/m^3). Examples of the generated dust of DEHS, NaCl, road air in Sweden 2022 and China 2019 are compared. Four examples all have $PM_{2.5}$ concentration around 100 μg/m^3

This is also relevant when modelling the air quality, where the simulations should be designed to be representative of the real vehicle running conditions. In this study the three profiles of outside particle concentration and distributions were selected from the road testing according to the European Air quality Index guidelines (see chapter 3.4.2). It would be possible in future studies to further apply outside profiles from available data, e.g. highway vs. city, thus to extend the knowledge in different road environments.

5.2 I/O ratios and size-resolved efficiencies

In this project I/O ratios and size-resolved efficiencies have been combined when comparing the outside and inside particles: the I/O ratio of total mass or count concentration in a wide range ($PM_{2.5}$, UFP) or the size-resolved efficiency. Another useful measure is to compare the MPPS efficiency, where the comparison is more straightforward in a narrow size range. The combinations of these measures could help draw a complete picture of the particle removal, since the I/O ratio does not reflect the removal of particles with different sizes.

A total removal is influenced by several factors, which sometimes could complex the comparison. As shown in **Figure 24** above, there is obvious difference between different particle types. This would probably result in different removal of particle mass.

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 which has a peak mass concentration at far larger particles where the filter efficiency is high. If one simply compares the total $PM_{2.5}$ I/O ratio, it might hide the size-resolved efficiency for DEHS could be low in the smaller sizes. An example could be found in **Paper IV Figure 5**.

5.3 Filter efficiency and filter age

Filter efficiency is one important topic in this study context, it's not only influenced by the filter type and the operation condition, but also the filter age. Filter ageing happens as the vehicle HVAC system is running. For the conventional synthetic filters with activated carbon, the effect of the electrostatic charges will be reduced as the filter is aged. One common solution is to replace the filter with an appropriate service interval.

To design a proper filter service interval and maintain the efficiency, a good understanding of the ageing effect of the filter is important. One method is to age the same model type with outdoor air from different environments. This ageing method is aiming at achieving as close to real road pollutants conditions as possible, and it naturally includes more variance and makes each aged filter not entirely the same. On the other hand, a better controlled ageing environment, for example with standardized dusts or environmental (temperature and humidity) cycling would be helpful to improve the repeatability. A combination of data from these different sources could be meaningful in creating a comprehensive picture of aged filters.

When it comes to the EPA/HEPA filter applied in **Paper IV**, the efficiency – age relationship is clearly different. As these filters are focusing on the mechanical filtration, the efficiency decrease is less obvious compared with traditional HVAC filters. Thus the main factor for filter change is probably not the efficiency decrease, but the pressure drop increase and possibly odour and microbial growth etc. Relationships among efficiencies, pressure-drop and filter age could be further studied to facilitate the decision on proper filter service interval.

5.4 Air quality and energy use

Automatic climate control in contemporary vehicles is the core of the climate system, it considers inputs from the inside and surroundings, and gives dynamic outputs to how the system should operate. Air quality is only one aspect to consider among others like climate comfort, and more importantly safety. The balance and priority of aspects could be different according to the vehicle running conditions. For example during start-up in winter it would be high importance to heat up the cabin quickly and demist/de-ice if needed. If the vehicle encounters temporary increase of outside pollutants, e.g. tunnel, it would be beneficial to reduce the particles coming in. A good control module would require good inputs and control strategies.

In this project an air quality model based on filter performance was developed as addition to an existing climate system model. This enables evaluation of concepts under various outside conditions and climate system settings. It will also simplify development of future climate control systems as it will be possible to investigate performance, energy use and air quality at the same time. However, the climate system model includes simplifications to be taken into account when evaluating the results in **Paper III**. To implement these investigations in real production vehicles, more comprehensive investigations in different scenarios, for example highly polluted winter condition, would be necessary.

Recirculation of air is in use today in vehicles, mainly for reducing the load on the AC-system during cool downs in warm climate but also to some extent in cold climate to reduce the need for heating. The main limits for increased recirculation in vehicle cabins are risks of accumulated CO_2 especially with more passengers, and window fogging in cold climate. Thus the strategy of increased air recirculation is evaluated in various climate and air quality scenarios with the air quality model. In this study a commonly applied CO_2 level of 1000 ppm, especially in buildings, was used in the evaluation. However, there is a need for further studies to conclude that this level is appropriate under all conditions in a vehicle cabin.

6 Conclusions

This project focuses on the combined area of vehicle cabin air quality and vehicle climate system energy use, a not well-researched area which is receiving increased attention. Four over-arching research questions were raised in Chapter 1.2. The corresponding answers are summarized in the following:

- What is the current level of vehicle cabin air quality ?

The current air quality levels are examined in the contemporary vehicles with focus on air pollutants from outside air (particulate matters). Road measurements reported average in-cabin $PM_{2.5}$ concentration between a wide range of 19.8-58.1 μg/m^3, UFP between 4270 -10800 particles/cm^3(**Paper I**). The variation is mainly due to locations with different outside conditions and filter statuses.

In comparison with the WHO $PM_{2.5}$ guideline of 15 μg/m^3 there is clearly a need of improvement. 12 out of 15 measurements comparative studies in various vehicles and locations also reported levels higher than the guideline (**Table 2**).

- Which are the major influencing factors?

Both from the relevant literatures and measurements in **Paper I**, these major factors are identified as:

1. The outside particle concentration and size distribution, which is further related to the location or transportation microenvironment, pollutant sources and surrounding traffic etc.
2. Filter efficiency and filter ageing status. An aged filter may increase cabin $PM_{2.5}$ to around the double amount, while pre-ionization on the other hand may reduce cabin $PM_{2.5}$ with around 50%.
3. Vehicle climate system settings, mainly ventilation airflow and degree of air recirculation

- What is the correlation between vehicle cabin air quality and climate system energy use?

The climate system energy in studied vehicle is mainly comprising the power for cooling (compressor), for heating (heater) and HVAC fan. One major correlation is that the airflow rate of both outside air and recirculated air would influence cabin air quality and climate energy use. The simulation (**Paper III**) showed that increased recirculation in certain occasions could benefit both. Another relation is that the filter pressure-drop would influence the fan power, but it has a relatively minor influence.

- Which are the potential improvement solutions, and their performance and limitations?

The strategy of increase the air recirculation degree is examined in three climates, three conditions and with different passenger numbers (**Paper III**). The result shows that both the energy use and particles in the vehicle cabin can be reduced significantly with higher levels of recirculation. With 70% REC applied, the $PM_{2.5}$ and climate energy use are reduced by up to 55% and 27% correspondingly. Recirculation will increase the cabin CO_2-levels, however, this project proved that large reduction of energy use and particles are possible while still maintaining CO_2-levels below recommended levels. When only 1 passenger is seated, up to 70% REC still maintains lower than 1000 ppm CO_2. With inputs of acceptable CO_2 concentration in the cabin, passenger numbers, a dynamic control strategy can be applied in the climate system, to ensure an optimum air quality and energy saving.

Implementing of EPA or HEPA filters is proven beneficial in achieving better cabin air quality. One solution with a pre-filter in the thermal bay used for pre-filtration is evaluated feasible (**Paper IV**). The removal of $PM_{2.5}$ and UFP are improved to 99%. More importantly in the range below 100 nm, 97%-99% removal is achieved in all sizes. A balance between filter cost, dimension (space), efficiency, pressure-drop, and NVH in the vehicle is the main challenge of this application.

7 Future Research

The results with largest impact on both air quality and energy use is the effect of air recirculation, i.e., recirculate the cabin air (partial or full) instead of using outside air. In this study several impacts and constraints from increased recirculation are investigated under common user conditions. The next step would naturally be applying it into existing climate control strategies, based on increased inputs of air quality levels (for example from sensors or cloud data), both inside and outside the cabin, to achieve energy efficiency and better air quality. For that implementation the optimization of control strategy is necessary. For instance, there is a need for further studies to conclude that the CO_2 level of 1000 ppm is appropriate under all conditions in a vehicle cabin.

Filtration efficiency of newer types of filters is high and combinations with two filters in serial can achieve very high efficiency with reasonable pressure drop. These systems in combination with recirculation are very promising. Next step would be to further develop and verify the prototypes for production vehicles.

This study is based on vehicle climate system without heat pumps. To expand the current investigations into systems with heat pumps would be of high interest.

There are still many challenges left regarding air quality. One area with new challenges is virus in the cabin, especially in a car sharing context. Other interesting areas would be microbial growth in filters and predictive maintenance, i.e., how long can filters be used before exchanging them.

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