CHALMERS
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Cabin Air-Quality Pollution Detection and Prevention

Master's thesis in Sustainable energy systems

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Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

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Abstract

The purpose of this thesis is to study and test the performance of the current CEVT Air-Purification System for Multiple Air Pollutants, primarily particles but also gases. The tests are designed to reveal differences between traditional air filters and a variety of other air-purification technologies such as an air ionizer, a plasma generator, and an ozone generator.

Furthermore, this research is split into two sections: The first section focuses on experiments conducted in a real car cabin. The measurements in a laboratory test rig make up the second part. The results of the observations made in the two settings are compared and used to evaluate the various air cleaning technologies.

As expected, the efficiency of all filters is higher at lower air flow rates (lower air velocity through the filters) than at higher air flow rates.

The results show that the performance of A/F-3 improved reliability in both car and lab test-rig tests, i.e. new air filters with non-active carbon typically showed slightly higher efficiency values than the other tested filters, followed by A/F-2 new air filters with active carbon coating.

Among the filters with active carbon, it was only the new one that showed any measurable reduction of organic gas.

Keywords: Air filter, filter efficiency, active carbon, air pollution, particulate matter, PM2.5, PM10

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Finally, I would like to dedicate my appreciation to my parents for their love and continuous support during the entire duration of master studies and also I would like to thank my friends for supporting me.

Rakshith Bharadwaj Ramakrishna Subramanya, Gothenburg, 2021

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1

Introduction

In recent years, awareness and mitigation of air pollution has been at the forefront due to serious implications of poor air quality, which is related to human health and well-being. Subsequently, the development in the automotive production industry is met with new challenges every day due to increasing air pollution, which have raised the interest in finding new technologies within the engine development field, which is found to be very necessary for the preservation of human well-being. The rapid progress in this field involves the advancement of air cleaner technology, as well as the development of the best possible means of testing the air quality inside the vehicle cabin.

Air quality in car cabins depends mainly on outside air quality, which tends to be the determining factor for calculating the efficiency of the air filter. Air pollutants are nitrogen oxides (NOx), particulate matter (PM1, PM2.5, PM10), carbon monoxide (CO), ozone (O3) and volatile organic compounds (VOC) present throughout the air. The nature of the time people spent in their cars determines the impact of air pollution on their health. It is therefore necessary to maintain a reasonable air quality inside the car. In climate control system is the most important system impacting the condition of the air inside the car cabin. For this reason, advancement in the climate system is very important for improving the air quality of the vehicle. It is also of great importance to find suitable methods to evaluate/judge the performance of systems and components used to create good car cabin air quality, e.g. air filters.

Health problems from air pollution are serious nowadays. Bad air quality inside the vehicle may lead to increased respiratory disorders like asthma and bronchitis; It even may pose a risk for cancer. By looking at these health issues related to impure air inside the vehicle, it is very important for us to look at how to improve the air quality inside vehicle cabins, by evaluating possible measures to reduce the air pollution inside the vehicle cabin. This is mainly a matter of establishing knowledge about the efficiency of present air filters, and also a matters of searching for technology improvements.

1.1 Aim of this work

The goal of this thesis project is to analyze and evaluate the air cleaning performance of alternative air cleaning devices for various air pollutants, mainly particles, but also selected gases. Another goal is to explore two alternative experimental methods: One where measurements are made in a real vehicle cabin, and the other where measurements are made in a specially designed a laboratory filter-test rig.

1.2 Outline of the present work

This thesis is divided into two sections: A background to the measured air pollutants is given in chapters 2. The tested objects are described in chapter 3 and the measurement methods are summarized in chapter 4.

The first part of chapter 5 shows detailed results from one selected filter-test of each test set-up (car cabin and test-rig). This structure is intended to facilitate the understanding of the methodology used. In the last part of chapter 5 the results from all filter tests are summarized. The full collection of data collected for all test cases is presented in the Appendix.

1.3 Limitations

This thesis work mainly involves testing the filtration efficiency of air filters using air pollutants present in a laboratory setting in Gothenburg. Most of the measurements comprise small airborne particles in so called ultra-fine size range. A large fraction of the particles originate outdoors, and are typically generated by vehicles with combustion engines. However, in order to reach a high enough concentration, test-particles were added to the air by burning candles in the laboratory. SO, the added particles were generated by combustion, just as the naturally occurring particles. This speaks for a clear relevance of the test particles used. Note that generation of test-particles by candle burning is a commonly used procedure in aerosol testing.

However, the test particles used in the lab-tests do not necessarily have the same properties as typically occurring outdoor particles, which in cities typically is dominated by vehicle exhaust. So, the test were made with test particles that in some respects might be different from the particles the filters would be exposed to during real operation of the car.

A final remark is that the single particle property that dominates the filtration efficiency is the particle size. From the experiments the particle size is known, at least to a large extent.

2

Airborne pollutants

Based on the particle size, airborne pollutants may be categorized into various groups, consisting of particles with a dimension of < 10 µm (PM10), small particles with a dimension of < 2.5 µm (PM2.5) and even smaller particles with a dimension of < 0.1 µm (PM0.1). Particles smaller than 0.1 µm are denoted ultrafine particles or nano-particles.

Many studies have determined that contaminants with small dimensions/sizes (ultrafine particles) may be especially harmful and cause health problems for humans. Pollution from automobiles is a primary cause of such airborne pollutants. Also large particles may show negative health effects, such as pollen of various sorts.

Sizewise there is a border around 5 nano-meters (0.005 µm). Above that size the theories of airborne particles, aerosol physics, apply. Below that size, the objects are no longer called particles, they are gases and vapors.

Gases of relevance to outdoor air quality, and consequently of relevance to car-cabin air quality are carbon monoxide (CO), nitrogen dioxide (NO2), various volatile organic compounds (VOC), such as benzene, touene and xylene. VOCs and carbon monoxide is directly generated and emitted by combustion engines. Nitrogen dioxide is typically a secondary pollutant, generated by oxidation of nitrogen monoxide under the influence of ozone (O3). Outdoors, near traffic, O3 is generated by chemical reactions involving VOCs and sunlight.

3

Tested Objects

A number of different air filters and air purifying devices were tested, such as, particle filters without active carbon, particle filters with active carbon, an air ionizer, a plasma generator and an ozone generator.

Table 3.1: Summary of tested air filters.

Air Filters	Type
A/F-1	Active carbon Air Filter used in car for 7500 Kms
A/F-2	NEW Active carbon Air Filter
A/F-3	NEW Air Filter without Active carbon coating
A/F-4	Active carbon Air Filter used in car for 30000 Kms
A/F-5	Active carbon Air Filter used in car for 30000 Kms and Dusty

3.1 Air filter with Active carbon coating

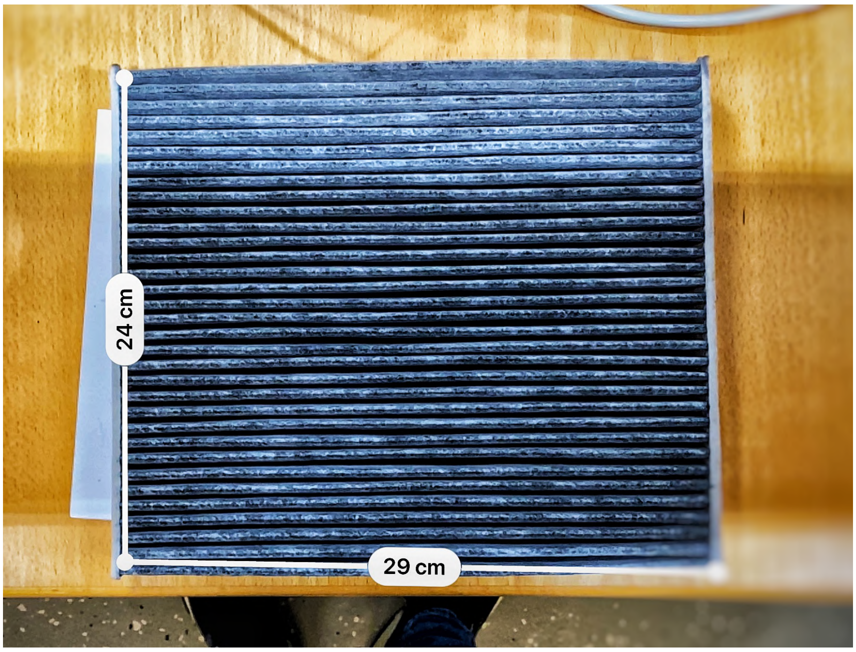

Figure 3.1: Air filter with active carbon coating.

Regular air filters assist with the cleaning of polluted air, such as pollen extraction, dust particles, soot and fresh ventilation inside the cabin. The air-conditioning inside the cabin that removes odours is also maintained by carbon coated air filters. Traditional air filters are strong enough to carry out some of the above operations, but the Active Carbon Air Filter is an even better form of air filter. It's the most common form of air filter that has been used for a long time in many vehicles.

The primary benefit of using active carbon filters is that it not only filters dust particles, it also eliminates odours, helping to keep the vehicle cabin to be a healthy and comfortable environment.

Active carbon coating, with the assistance of the adsorption process, helps to capture potentially harmful gases such as nitrogen dioxide on the carbon coated surface, as the active carbon filter fabric is extremely porous in nature, making it effective in filtering not only particles, but also gases and odours.

The tested filters designated A/F-1, A/F-2, A/F-4 and A/F-5, see Table 3.1, are of this type. Details of the tested filters properties has not been provided by the manufacturer of vendor. Thus, the total filter area, nominal air flow rate, face velocity, rated pressure drop, and the amount of active carbon are unfortunately unknown to the author and cannot be specified in this report.

3.2 Air filter without Active carbon coating

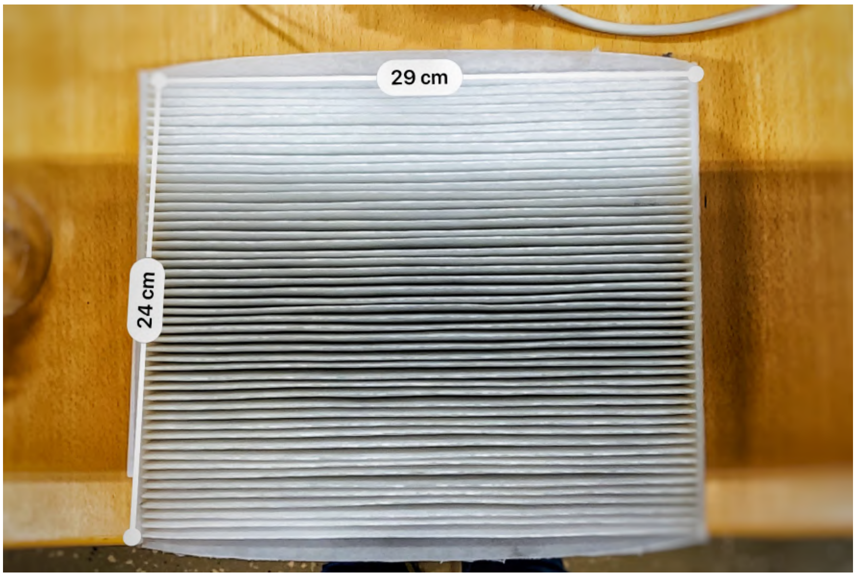

Figure 3.2: Air filter without Active carbon coating Filter designation: A/F-3.

Cabin air filters helps in cleaning contaminated air by filtering pollen, dust particles, soot and provides fresh clean air inside the cabin. Air filter without active carbon coating basically refers to air filter without any active carbon coating on its fabric.

Details of the properties of the tested filter A/F-3 has not been provided by the manufacturer of vendor. Thus, the total filter area, nominal air flow rate, face velocity, rated pressure drop, fiber material and fiber diameter are unfortunately unknown to the author and cannot be specified in this report.

3.3 Air ionizer

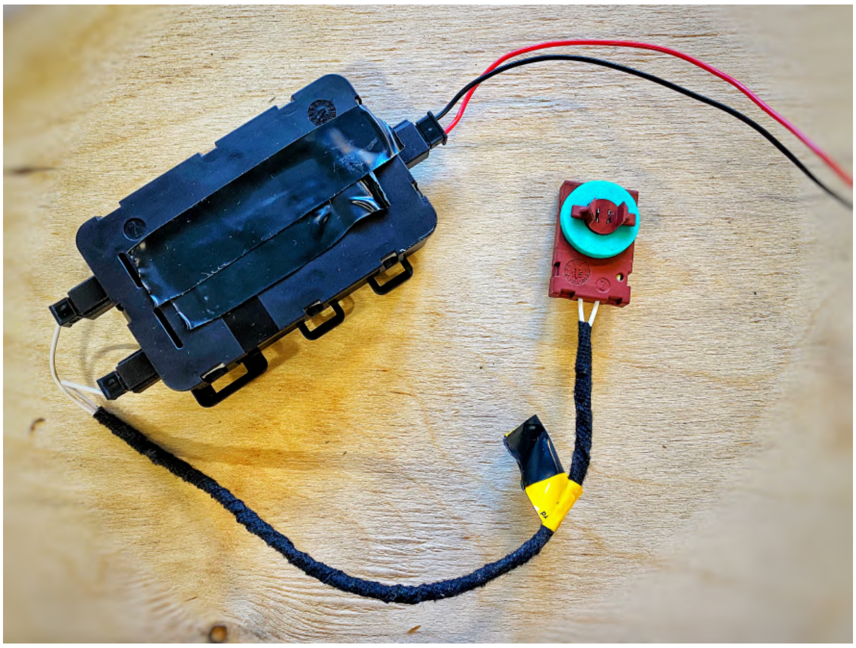

Figure 3.3: Air Ionizer.

The air ionizer is a system used to eliminate particulate matter from indoor conditions. The device is composed of two electrodes at its end, as seen in 3.3, which, as high voltage current is transmitted through the device, produces a discharge between the two electrodes. The discharge leads to airborne particles being electrically charged, which makes them prone to deposit on surrounding surfaces. Thus, the ionization enhances particle removal from the air.

Details of the properties of the tested air ionizer has not been provided by the manufacturer of vendor. Thus, neither the voltage or ionization capacity, nor any other important properties are known to the author and cannot be specified in this report.

3.4 Plasma generator

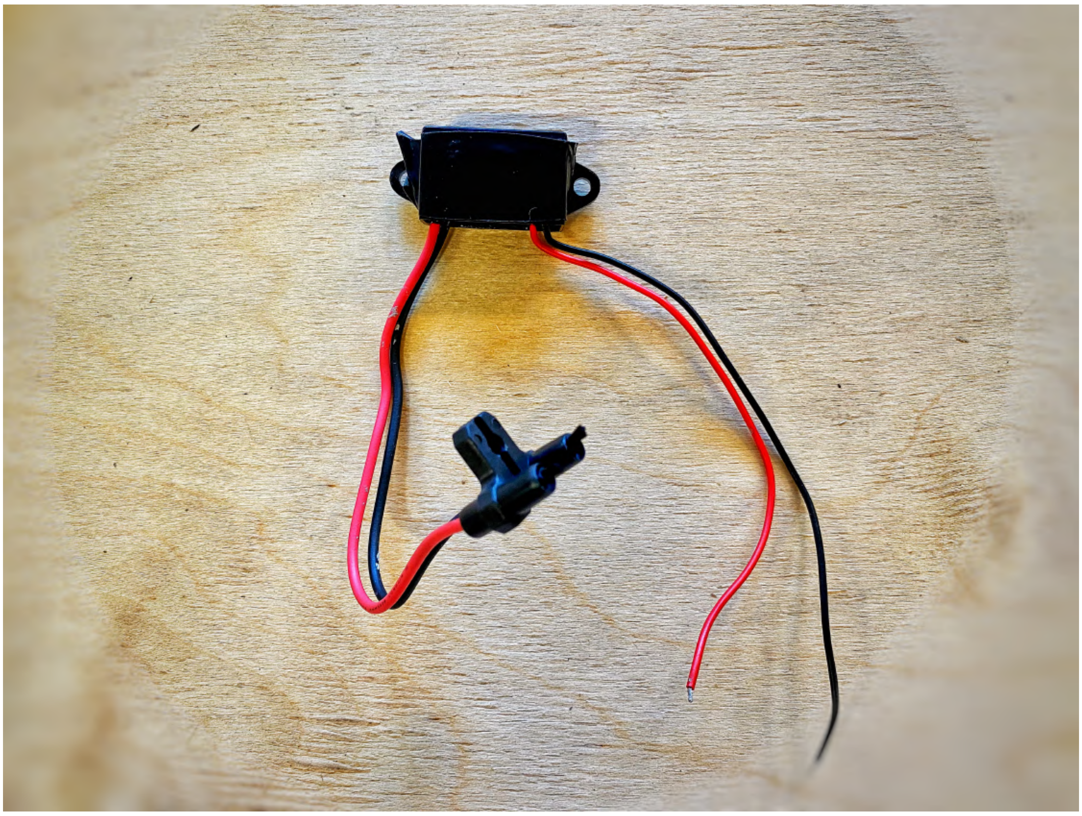

Figure 3.4: Plasma Generator.

Plasma generator is also one of the air purification devices that, with the aid of carbon fiber brushes present at the tip of the device, generate ions (negative and positive charged particles) helping to remove particles in the air and to control foul smells in indoor environments.
Details of the properties of the tested plasma generator has not been provided by the manufacturer of vendor. Thus, neither the voltage or ionization capacity, nor any other important properties are known to the author and cannot be specified in this report.

3.5 Ozone generator

Figure 3.5: Ozone Generator.

The ozone generator is a system developed for the creation of ozone gas. The ozone generator used here has an ozone generation capacity of 10,000 mg per hour and is claimed be able to eliminate bad odours. With the aid of a fan, the ozone is spread throughout the room.

4
Methods

There are two parts to this thesis study, the first part relates to the conduct of experiments to determine the varying efficiency of various air filters using the test car provided by CEVT and the second part is to conduct a related experiment in a laboratory by building a custom test rig with similar conditions as during the test in the car. The time interval for each reading taken in all experiments is one minute each.

In this thesis two new air-filters with and without active carbon coating are tested along with one active carbon air filter used which has run for 7500 kilometers (km) and two old used active carbon air filter used which has run for 30000 km.

4.1 Test set-ups

4.1.1 Method's used for testing in car efficiency

In this process, two types of air filters are used, namely air filter without active carbon coating and air filter with active carbon coating, five separate air filters are considered for measuring efficiency among which 3 air filters used are (old) carbon coated filters and one new air filter with and without carbon coating are used.

The devices used in these procedures are P-Trak for measuring the concentration of particles mainly in the ultra fine size-range, gases such as CO2, VOC and water vapor, etc. In this process, air within the lab hall is used as a concentrate upstream and air from the steel chamber (clean room) flows freely through the lab hall, few candles are constantly burned to produce additional particles within the lab hall as well as in the clean room. Using two P-Trak instruments efficiency of each air filter are calculated at three separate air velocity/flow corresponding to (30.3,60 and 115.2 l/s), corresponding to the car air conditioning fan speed 1-3-7 shall be determined using an air flow measurement system (velocity meter).

The devices used in these procedures are a condensation particle counter, model P-Trak, for measuring the concentration of particles mainly in the ultra fine size-range. Measurements were also made with an IR-spectrometer, model Brüel Kjaer 1302, in order to determine the concentration of gases such as CO2, total concentration of VOCs, aldehydes and water vapor. In this process, air within the lab hall was used, together with an additional supply of particles generated by burning candles in an adjacent test chamber. Air from the test chamber was released close to the air intake to the car cabin.

Using two P-Trak instruments, one was sampling air before the tested filter and the other was sampling after the filter, inside the car. The filtration efficiency of each air filter was calculated at three separate air velocities/airflow rates corresponding to an air supply of 30.3 l/s, 60 l/s and 115.2 l/s. These values correspond to the car air conditioning fan speed 1, 3 and 7, respectively.

As mentioned above measurements were made by positioning the P-Trak instrument at two different positions, before and after the air-filter. The particle measuring position inside the car cabin was in the middle of the front passenger seat (after the air filter measurement point). Outside the car, the sampling was made before the air intake valve (before air filter measurement point).

All values are reported at a time interval of 1 minute for each particular measurement and the average value is taken to know the overall particle count for each different air filter at different air velocity/flow rate. This process is replicated until the findings are reasonably consistent. After calculation of both after and before particle count values using the P-Trak instrument, all values are tabulated, the average value is taken, and the performance of each air filter is calculated. Efficiencies for both new and old air filters are compared at the end and the best air filter is recommended for increased performance.

Apart from this, a further experiment is being carried out with air-ionizer and plasma generator systems to decide the best possible air-purification technology among them. This trial was also carried out with the P-Trak instrument using the same technique inside the car and the findings are tabulated and the correct air purification technology is recommended at the end of the experiment.

Ozone generator is one of the air purification instruments that has been tested inside the car and it is found to be very dangerous to run since it begins to emit ozone at a very high level, which is found to be very harmful to humans, and aside from that, even after the ozone generator has been switched off the ozone generated by the instrument have stayed inside the car for a longer period of time.

Figure 4.1: Car Test setup.

Figure 4.2: Free flow of particles at air Intake.

4.1.2 Method's used for testing Efficiency in LAB

In order to perform the laboratory experiment, a custom test setup is designed consisting of a metal box enclosure with sealants to prevent air leakage and two turbo fans are used to force outside air into the metal box inside which the test specimen (air filters) is mounted.

In this laboratory process, a series of tests were carried out using the P-Trak and the met one particle counters. Experiments are carried out in two parts, first calculating the particle count without an air filter inside the metallic box and then measuring the particle count with an air filter inside the metallic box using the same instruments so that the accuracy is preserved. In this experiment, the measuring point for all the experiments is kept constant, the measurement point is set at the escape point of the test-rig. During the examination, air inside the lab hall is used as an upstream concentration and air from the test chamber flowing freely through the lab hall. Few candles are constantly burned to produce particles within the lab hall as well as in the test chamber.

Using a single P-Trak and Met One particle counter each filter was tested at three air velocities/flow rates corresponding to a face velocity of 1.5 m/s, 2.99 m/s and 5.73 m/s, respectively. The values were measured using a hot-wire anemometer. These air velocities are comparable to the velocity/flow rates used in the car tests of the previous test set-up.

Values were reported with a time interval of 1 minute for each particular measurement and an average value is taken to know the overall particle count for each different air filter at different air velocity/flow rate. This process is replicated until the findings are reasonably consistent. After calculating both with an air filter and without an air filter inside the metallic enclosure, the particle count values are calculated using a single P-Trak instrument, both values are tabulated, the average value is taken and the performance of each air filter is estimated.

Efficiencies in both new and used air filters are compared at the end and the better air filter is recommended for increased performance.

In the laboratory test using the Met One particle counter values, the equivalent performance of each air filter is calculated on the basis of the different particle sizes 0.3 ,0.5, 1.0, 3.0, 5.0 and 10 µm and the results are tabulated.

Measure each filter at three air velocity/flow values equivalent to the velocity/flow rate used in the car tests. But in the lab test no concentration was measured before the filter: Instead, measurements were made without a filter in the box (representing the upstream concentration value). Then measurements were made with the various filters in the box. Adjust the desired air velocity for each filter. Repeat tests until consistent results are obtained. This was made first for one of the speed stages, then for the second, and finally for the third level. The particle measuring position is in the middle of the circular duct after the filter box in the test rig.

Figure 4.3: Lab-Setup (Test Rig)

Figure 4.4: Lab-Setup (Test Rig)

Figure 4.5: Metallic box(Test Rig)

4.2 Measurement instruments

4.2.1 Condensation particule conter (P-Trak)

The P-Trak is a handheld device used to detect airborne particles. The instrument measures particles from about 0.02 µm to 1 µm, but the vast majority of the particles are below 0.1 µm in size (ultrafine), particularly when the particle content of the air is infused by source of combustion.

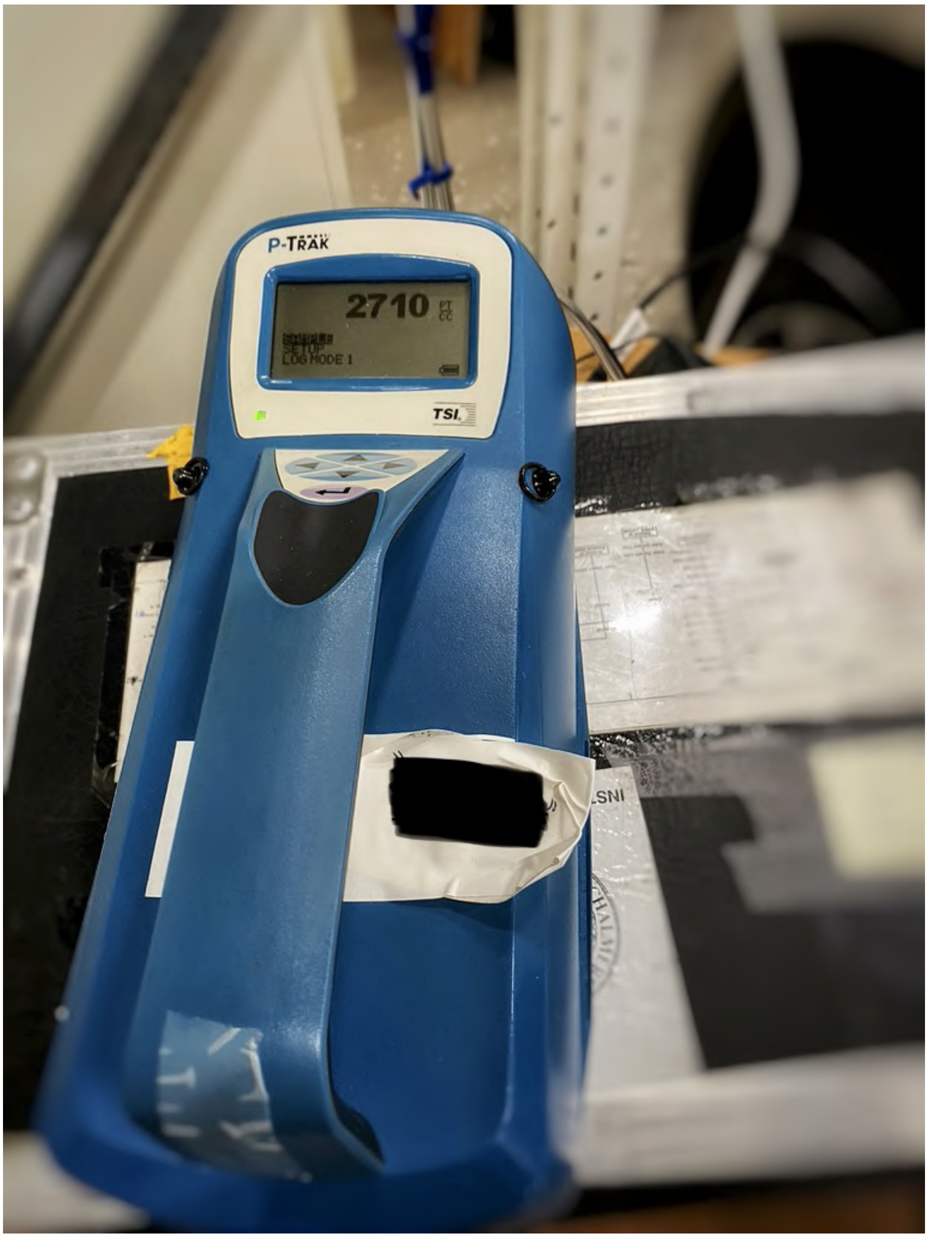

Figure 4.6: Condensation particule conter (P-Trak)

4.2.2 Optical particle counter (Met One)

Met one Particle counter is a portable instrument used to determine particle count based on a wide variety of particle sizes 0.3, 0.5, 1.0, 3.0, 5.0, 10 µm from the emission source. The Met One device is very useful in measuring the efficiency of air filters based on each particle sizes as mentioned above.

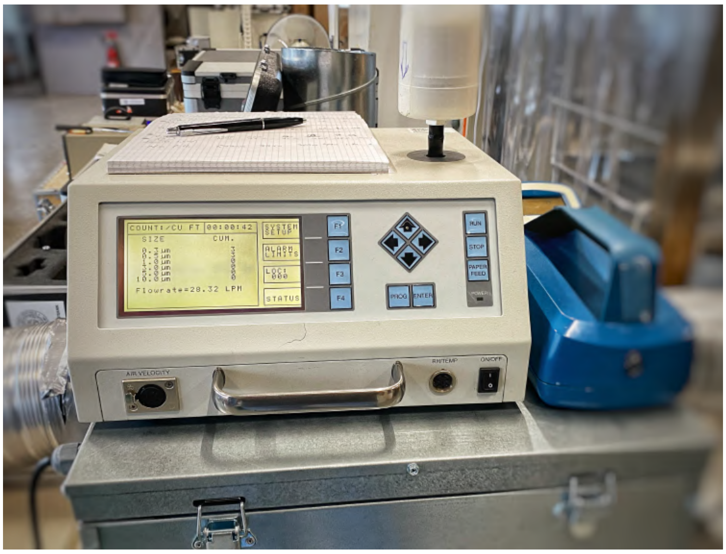

Figure 4.7: Optical particle counter (Met-One)

4.2.3 Gas analyser (Brüel Kjaer)

The Brüel and Kjaer Multi-Gas Detector will simultaneously test different gases in consecutive samples of air taken with a thee interval of approximately 1-2 minutes. Such gases seen by the gas analyser are the total concentration of aldehydes (calibrated for acetaldehyde), carbon dioxide, Total Organic Carbon (TOC) and Water Vapor. In the gas analyser, these gases are represented symbolically as shown in the table 4.1.

Figure 4.8: Gas analyser

Table 4.1: : Gases measured by the Brüel Kjaer 1302 gas analyser.

Symbol	Gas	Unit
A	Acetaldehyde	ppm
D	Carbon dioxide	ppm
E	TOC	ppm
W	Water Vapour	Tdwe

4.2.4 Air velocity and pressure differential instrument (Anemometer)

Swema air 300 is an instrument used to measure the air velocity and pressure differential with separate sensors attached to the instrument. This instrument was used for measurement of the pressure drop and face velocity of the tested filters, as well as the air flow rate in the test duct of the test-rig.

Figure 4.9: Air velocity and pressure differential instrument type Swema Air 300.

5
Results

Results for filtration efficiencies of different air filters and air purification devices are presented, along with input and output data obtained from lab test and in car test.

5.1 Example of results for in-car testing

In this section, test results for air filter A/F-1, obtained from the in-car testing, are presented. Table 5.1 shows the particle count before and after the air filter together with the calculated filtration efficiency. The average efficiency based on five consecutive measurements is presented. The procedure was repeated for a total of three fan speeds, corresponding to three different air flow rates.

The entire procedure described above was repeated three times, each repetition named Trial-1, Trial-2 and Trial-3. The efficiency values from each of the three trials and the grand average are shown in Table 5.2.

The experiments, Trial-1, Trial-2 and Trial-3, were then repeated for all five different air-filters. The final result from all trials and all filters are presented under a separate heading last in this chapter.

Table 5.1: Values taken for air filter A/F-1 in the car - Trial 1 using the P-Trak

Speed	**Average Air flow rate** ($\mathrm{l\,s^{-1}}$)	**Tr No**	**Before A/F**	**After A/F**	**Efficiency**	**Average (%)**
1	30.2	1	3960	888	0.77	74
		2	3690	925	0.74	
		3	3310	879	0.73	
		4	3070	855	0.72	
		5	2910	815	0.71	
3	60	1	3160	982	0.68	65
		2	2930	1080	0.63	
		3	2890	1050	0.63	
		4	3140	1070	0.65	
		5	2890	1030	0.64	
7	115.2	1	3160	1660	0.47	48
		2	3040	1710	0.43	
		3	2990	1650	0.44	
		4	2930	1450	0.50	
		5	2810	1360	0.51	

Table 5.2: Average efficiencies of air filter A/F-1 in the car obtained from all three trials for ultrafine particles using the P-Trak instrument.

Average Airflow Rate ($\mathrm{l\,s^{-1}}$)	**Efficiency (%)**	**Average (%)**
30.2	74.02	74
	70.97	
	76.2	
60	65.2	67
	68.44	
	66.21	
115.2	47.63	51
	52.98	
	53.19	

In addition to particle measurements, the concentration of gases was also measured inside and outside the car. The gases include aldehydes, carbon dioxide, TOC and water vapor. Table 5.3 shows the concentrations measured for filter A/F-1 during Trial-1. Average gas concentrations calculated for all three trials are shown in Table 5.4.

Table 5.3: Measured gas concentrations for air filter A/F-1 during Trial 1.

Symbols	A	D	E	W
Scenario	**Acetaldehyde (ppm)**	**Carbon-dioxide(ppm)**	**TOC (ppm)**	**Water Vapour (Tdwe)**
Outside the Car	0.0024	521	2.65	4.03
	0.0033	521	2.74	3.97
	0.0031	520	2.85	4.02
	0.0030	531	2.97	3.96
	0.0032	524	2.80	4.15
Average	0.0030	523	2.8	4.0
Inside the Car	0.0027	522	2.85	4.04
	0.0030	523	2.91	4.06
	0.0032	527	2.94	3.99
	0.0029	526	2.96	3.95
	0.0032	527	2.92	4.00
Average	0.0030	525	2.92	4.01

Table 5.4: Average gas concentration based on all three trial of filter A/F-1 in the car

Gases	**Outside the car (concentration)**	**Inside the car (concentration)**
Acetaldehyde (ppm)	0.0029	0.0030
Carbon-dioxide (ppm)	539	544
TOC (ppm)	3.25	3.16
Water Vapour (Tdwe)	3.85	3.91

5.2 Example of results from lab-testing

In this section, results from the test-rig measurements are presented. Table 5.5 presents the results obtained when testing filter A/F-1 with respect to ultrafine particles with the P-Trak. Measurements were made with and without the air filter inside the test rig. The efficiency values were determined by comparing these concentrations; the concentration without filter representing the upstream value, and the concentration with the filter representing the downstream value. The measurements were repeated for the three air velocities shown in the table, each representing the same fan speeds as shown in Table 5.1, above.

In the same way, the experiment were done for all five different air-filters, each consisting of 3 sets of Trials named Trial-1, Trial-2 and Trial-3. The results from all trials of filter A/F-1 are shown in table 5.6, which contains the average efficiency values for all three trials and eventually the average efficiency value. The final result from all trials and all filters are presented under a separate heading last in this chapter.

Table 5.5: Values taken in the test-rig for filter A/F-1. Trial 1 using the P-Trak.)

Average Air velocity($\mathrm{m\,s^{-1}}$)	**Tr No**	**Without A/F**	**With A/F**	**Efficiency**	**Average (%)**
1.5	1	55000	14100	0.74	73
	2	53200	14000	0.73	
	3	50000	13500	0.73	
	4	49600	12900	0.73	
	5	48400	12800	0.73	
2.99	1	58500	28300	0.51	56
	2	53400	25100	0.53	
	3	50300	23500	0.53	
	4	47300	20200	0.57	
	5	42500	18300	0.56	
5.73	1	61000	19800	0.67	56
	2	45700	17700	0.61	
	3	35300	15600	0.55	
	4	26900	13400	0.50	
	5	21300	11680	0.45	

Table 5.6: Average efficiencies for ultrafine particles (P-Trak) of air filter A/F-1 in the test-rig. Data from all three trials using.

Average Airflow Rate ($\mathrm{m\,s^{-1}}$)	**Efficiency** (%)	**Average** (%)
1.5	73.72 72.87 73.67	73
2.99	54.43 58.77 55.09	56
5.73	55.99 56.14 54.81	56

5.3 Final efficiency values for ultrafine particles

Table 5.7 shows the final average efficiency results for all five air-filters when tested in the car for ultrafine particles using the P-Trak. Table 5.8 shows the corresponding results for the same filters when tested in the lab test-rig. Table 5.9 shows the difference between the results in the previous tables expressed as efficiency percentage-units (%).

Table 5.7: Final average efficiency results for all five air filters when tested in the car for ultrafine particles using P-Trak

Air flow (l/s)	A/F-1	A/F-2	A/F-3	A/F-4	A/F-5
30.2	74	76	80	79	68
60	67	72	75	76	62
115.2	51	62	61	65	44

Table 5.8: Final average efficiency results for all five air filters when tested in the lab test-rig for ultrafine particles using P-Trak

Air flow (m/s)	A/F-1	A/F-2	A/F-3	A/F-4	A/F-5
1.5	73	84	90	65	62
2.99	56	54	59	60	50
5.73	56	49	53	47	45

Table 5.9: Difference (%) between efficiencies obtained in the car and in the lab test-rig. Results for ultrafine particles measured using P-Trak.

(%)Difference	A/F-1	A/F-2	A/F-3	A/F-4	A/F-5
1	1	-11	-13	18	9
2	16	25	21	21	19
3	-10	21	13	28	-2

5.4 Efficiency values for particles larger than $0.3\,\mu m$

The values obtained from the MetOne particle counter are seen in Table 5.10, 5.11 and this experiment is carried out in the same manner as the previous approach for evaluating the performance of the air filters, i.e. measurements made with an air filter inside the test rig and without an air filter inside the test rig. For each air filter, several samples were taken with and without filter. Figure 5.10 shows the concentration values measured and Table 5.11 shows the calculated filter efficiency values of each particle size for all the various filters. An average efficiency value could be calculated for each filter and each air velocity. However, the table shows only the individual efficiency values determined.

Figure 5.1: Particle concentration measured with the MetOne particle counter for all five filters, at three different air velocities in the lab test -rig. Concentration values presented as particle number per cubic feet (p/ft^3)

Without Filter	A/F-1							With Filter	A/F-1					
Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm		Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm
1.5	262932	28453	10796	243	78	2		1.5	68256	4583	1526	38	0	0
2.99	237936	22781	9285	315	84	2		2.99	141839	8513	1824	35	3	0
2.99	188787	13884	5682	219	72	3		2.99	119575	6347	1381	36	6	0
2.99	171432	10875	4438	185	85	10		2.99	105776	5369	1194	14	6	0
5.73	113337	25508	8108	208	112	29		5.73	56171	11409	2522	52	11	6
5.73	125862	24104	7173	218	84	16		5.73	47922	10324	2162	25	13	2
5.73	129726	23689	7040	196	70	6		5.73	45099	10121	2013	29	7	0

Without Filter	A/F-2							With Filter	A/F-2					
Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm		Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm
1.5	449962	58507	16089	259	72	1		1.5	125350	11996	2554	23	9	0
1.5	346533	41862	11800	198	49	3		1.5	102608	9157	2050	26	7	0
1.5	260625	28825	8675	103	47	0		1.5	84881	7457	1544	27	9	0
2.99	165108	9713	3326	161	60	3		2.99	111323	6447	1598	26	3	0
2.99	154760	8822	3481	222	72	3		2.99	83382	4130	1063	41	11	1
5.73	73711	22100	6554	143	83	4		5.73	47383	10947	1941	22	8	0

Without Filter	A/F-3							With Filter	A/F-3					
Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm		Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm
1.5	357230	25162	7156	322	150	4		1.5	53150	3518	1096	55	16	0
1.5	261569	20851	7392	374	148	9		1.5	43593	2927	954	36	15	2
1.5	207315	17141	7039	448	206	4		1.5	37782	2629	875	37	24	0
2.99	142687	10305	4795	237	102	4		2.99	77912	6539	2295	61	17	0
2.99	129861	8610	3853	205	91	5		2.99	66891	5066	1842	55	15	0
2.99	131432	8726	3653	204	70	3		2.99	58403	3686	1310	43	20	0
5.73	69828	20479	5520	107	54	6		5.73	53997	8166	1589	22	6	3
5.73	68276	19958	5403	94	48	1		5.73	30909	5529	1007	9	3	0

Without Filter	A/F-4							With Filter	A/F-4					
Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm		Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm
1.5	140305	7267	1793	74	24	1		1.5	79074	2944	683	21	20	2
1.5	123453	5859	1542	45	16	2		1.5	69631	2683	620	20	3	0
2.99	154776	9180	3384	198	49	3		2.99	123467	5580	1215	29	7	0
2.99	149009	7762	3144	165	79	5		2.99	114024	4169	887	15	9	0
5.73	67619	13862	4316	120	47	7		5.73	27913	3781	688	37	26	3
5.73	48019	11835	3566	83	53	1		5.73	25194	3430	611	16	3	1
5.73	43110	11387	3288	91	40	7		5.73	24081	3166	574	8	1	0

Without Filter	A/F-5							With Filter	A/F-5					
Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm		Speed (m/s)	0.3 - 0.5 µm	0.5 - 1 µm	1 - 3 µm	3 - 5 µm	5 - 10 µm	>10 µm
1.5	947393	297137	90017	838	140	1		1.5	964866	103729	18597	174	31	3
1.5	1084673	233903	56283	532	113	7		1.5	790611	70712	12650	127	35	1
1.5	1089353	167609	35911	383	88	2		1.5	633329	49954	8996	116	25	0

Table 5.10: Filtration efficiency values determined for the five filters at three different air velocities in the lab test-rig

Filter A/F-1						
Speed (m/s)	**0.3-0.5μm**	**0.5-1μm**	**1-3μm**	**3-5μm**	**5-10μm**	**>10μm**
1.5	74%	84%	86%	84%	100%	100%
2.99	38%	56%	76%	88%	94%	100%
5.73	59%	57%	70%	83%	88%	100%

Filter A/F-2						
Speed (m/s)	**0.3-0.5μm**	**0.5-1μm**	**1-3μm**	**3-5μm**	**5-10μm**	**>10μm**
1.5	70%	77%	83%	84%	85%	100%
2.99	46%	54%	69%	85%	88%	100%
5.73	34%	51%	69%	85%	90%	100%

Filter A/F-3						
Speed (m/s)	**0.3-0.5μm**	**0.5-1μm**	**1-3μm**	**3-5μm**	**5-10μm**	**>10μm**
1.5	83%	86%	86%	88%	89%	100%
2.99	56%	58%	64%	79%	79%	100%
5.73	39%	66%	76%	85%	90%	100%

Filter A/F-4						
Speed (m/s)	**0.3-0.5μm**	**0.5-1μm**	**1-3μm**	**3-5μm**	**5-10μm**	**>10μm**
1.5	44%	57%	61%	64%	81%	100%
2.99	-	-	-	-	-	-
5.73	-	-	-	-	-	-

Filter A/F-5						
Speed (m/s)	**0.3-0.5μm**	**0.5-1μm**	**1-3μm**	**3-5μm**	**5-10μm**	**>10μm**
1.5	-	68%	77%	75%	73%	100%
2.99	-	-	-	-	-	-
5.73	-	-	-	-	-	-

6

Summary and Conclusions

The results and conclusions of the measurements are summarized below:

- As expected, it can be inferred that, at lower air flow rates (low air velocity through the filters), the efficiency of all filters is higher than at higher airflow rates.
- It was found that the new filter with active carbon (A/F-2) reduced organic compounds measured as aldehydes and total organic compounds (TOC) somewhat, while there was no substantial reduction of gasses in any other filter.
- Filter A/F-3 in both scenarios (in-car and lab test-rig tests) showed somewhat higher particle removal efficiency values compared to the other filters. This means that the new/unused air filter without active carbon typically showed somewhat higher particle filtration efficiency values than the used filters and the filters with active carbon.
- Filters A/F-4 and A/F-5, showed lower particle removal than the other filters. These two filters had been in use for about 30,000 km which is substantially longer than the third used filter (A/F-1, 7,500 km).
- The used filters had substantially higher pressure drops than the new filters.
- Air-purification machines such as air-ionizer, plasma generator and ozone generator were tested in the car cabin. There was no added air cleaning effect from these devices, i.e. thy did not contribute to any air quality improvement.
- The tests using the ozone generator in the car cabin showed a substantial increase of the ozone concentration. The ozone concentration remained high for an extended period of time even after the ozone generator had been shut off. Ozone is a known health hazard and should not be generated in spaces for human occupancy.

6.1 Final remarks

The measurements indicate higher performance for the new filters than the used. One of the used filters had quite a low mileage (7,500 km). This filter clearly performed better than the other two used filters, which had substantially higher mileage (30,000 km).

It is suggested that future tests comprise testing of used filters with various mileages fairly evenly distributed over a relevant span. This is needed in order to determine in detail how the performance degrades with increasing mileage.

Among the filters with active carbon, it was only the new one that showed any measurable reduction of organic gases. Thus, there seems to be too little carbon in the filter for any extended gas filtration efficiency. The gas removal performance degrades much faster than the particle removal performance.

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A

Appendix 1

Average Airflow Rate ($\mathrm{l\,s^{-1}}$)	Efficiency (%)	Average (%)
30.2	76.80 75.45 76.64	76.29
60	71.54 73.96 69.94	71.81
115.2	61.90 65.37 58.19	61.82

Table A.1: Average efficiencies of Air filter 2 with Active Carbon (New)

Average Airflow Rate ($\mathrm{l\,s^{-1}}$)	Efficiency (%)	Average (%)
30.2	81.2 83.11 75.93	80.08
60	76.96 75.64 72.83	75.14
115.2	63.37 58.34 60.29	60.67

Table A.2: Average efficiencies of Air filter 3 without Active Carbon (New)

Average Airflow Rate ($\mathrm{l\,s^{-1}}$)	**Efficiency (%)**	**Average (%)**
30.2	82.00 74.54 81.34	79.3
60	81.10 71.54 76.60	76.41
115.2	72.38 56.81 65.39	64.86

Table A.3: Average efficiencies of Air filter 4 with Active Carbon (old-1)

Average Airflow Rate ($\mathrm{l\,s^{-1}}$)	**Efficiency (%)**	**Average (%)**
30.2	79.31 63.11 62.18	68.20
60	68.04 58.69 58.86	61.86
115.2	45.64 45.06 41.62	44.11

Table A.4: Average efficiencies of Air filter 5 with Active Carbon (old-2)

Gases	**Outside the car (concentration)**	**Inside the car (concentration)**
Acetaldehyde (ppm)	0.0029	0.0021
Carbon-dioxide (ppm)	547	557
TOC (ppm)	2.7	2.09
Water Vapour (Tdwe)	6.46	6.46

Table A.5: Average gas concentration for Air filter 2 with Active Carbon (New)

Gases	Outside the car (concentration)	Inside the car (concentration)
Acetaldehyde (ppm)	0.0032	0.0035
Carbon-dioxide (ppm)	598	597
TOC (ppm)	3.40	3.55
Water Vapour (Tdwe)	6.00	5.99

Table A.6: Average gas concentration for Air filter 3 without Active Carbon (New)

Gases	Outside the car (concentration)	Inside the car (concentration)
Acetaldehyde (ppm)	0.0029	0.0027
Carbon-dioxide (ppm)	527	524
TOC (ppm)	3.18	3.32
Water Vapour (Tdwe)	9.31	9.29

Table A.7: Average gas concentration for Air filter 4 with Active Carbon (old-1)

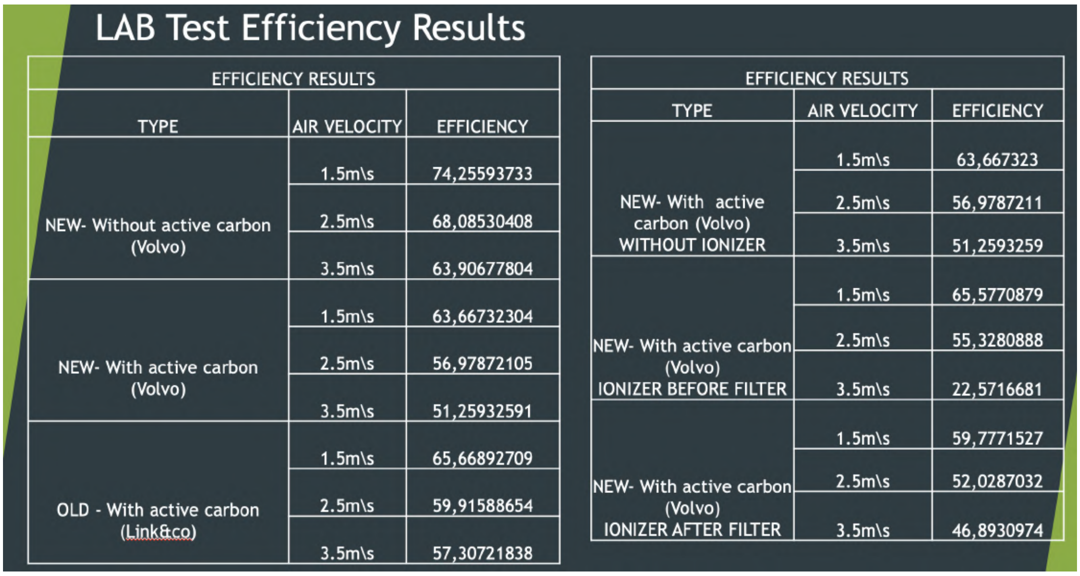
Gases	Outside the car (concentration)	Inside the car (concentration)
Acetaldehyde (ppm)	0.0028	0.0025
Carbon-dioxide (ppm)	593	585
TOC (ppm)	3.71	3.43
Water Vapour (Tdwe)	9.23	8.22

Table A.8: Average gas concentration for Air filter 5 with Active Carbon (old-2)

A.1 Results for Air-Ionizer and Plasma Generator

Test results of Air-ionizer and Plasma generator done in the earlier stages of the thesis with different air flow rate and different efficiency results.

A.2 Efficiency Results for Air-Ionizer and Plasma Generator



EFFICIENCY RESULTS		
TYPE	AIR VELOCITY	EFFICIENCY
NEW- Without active carbon (Volvo)	1.5m\s	74,25593733
	2.5m\s	68,08530408
	3.5m\s	63,90677804
NEW- With active carbon (Volvo)	1.5m\s	63,66732304
	2.5m\s	56,97872105
	3.5m\s	51,25932591
OLD - With active carbon (Link&co)	1.5m\s	65,66892709
	2.5m\s	59,91588654
	3.5m\s	57,30721838

EFFICIENCY RESULTS		
TYPE	AIR VELOCITY	EFFICIENCY
NEW- With active carbon (Volvo) WITHOUT IONIZER	1.5m\s	63,667323
	2.5m\s	56,9787211
	3.5m\s	51,2593259
NEW- With active carbon (Volvo) IONIZER BEFORE FILTER	1.5m\s	65,5770879
	2.5m\s	55,3280888
	3.5m\s	22,5716681
NEW- With active carbon (Volvo) IONIZER AFTER FILTER	1.5m\s	59,7771527
	2.5m\s	52,0287032
	3.5m\s	46,8930974

Figure A.1: Lab test efficiency results

IN CAR CABIN		EFFICIENCY
		88,3082993
Pre Installed Filter		87,66513639
		85,54036352
AIR IONIZER	FRONT	BACK
4.5m\s	88,01273489	84,01155107
6.8m\s	88,21436086	86,14834322
10,7m\s	87,5940689	87,56560385
PLASMA GEN		
4.5m\s	82,23488326	84,66343752
6.8m\s	83,90383061	85,51283328
10,7m\s	84,7830972	85,04668232

Figure A.2: Car test efficiency results

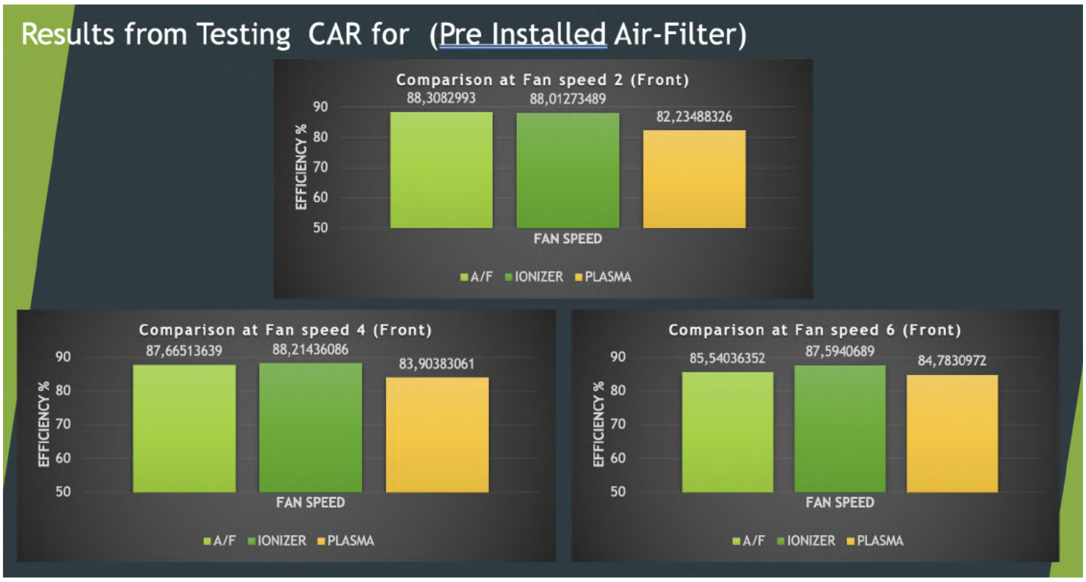


Figure A.3: Different fan speed results

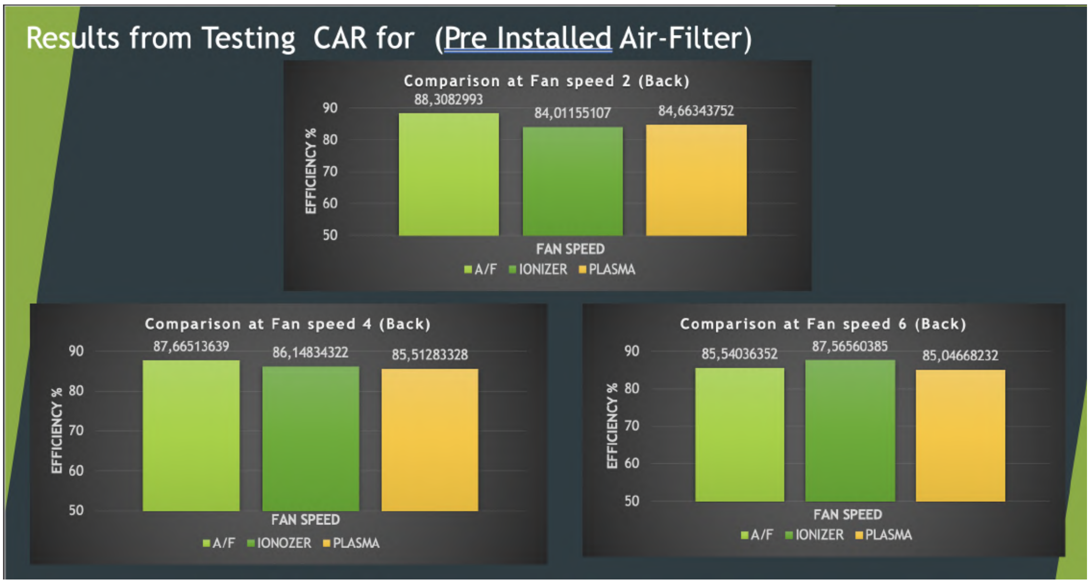


Figure A.4: Different fan speed results

A.3 Air Filters Used

Following Figures shown below are the Air filters used in this Thesis project.

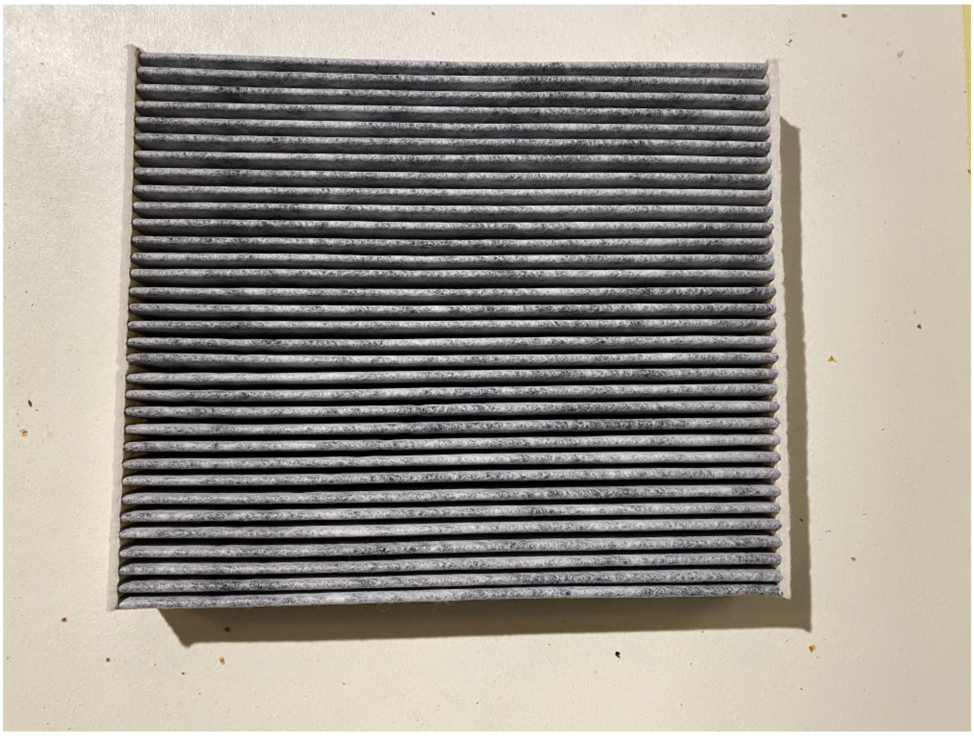


Figure A.5: Air filter 1

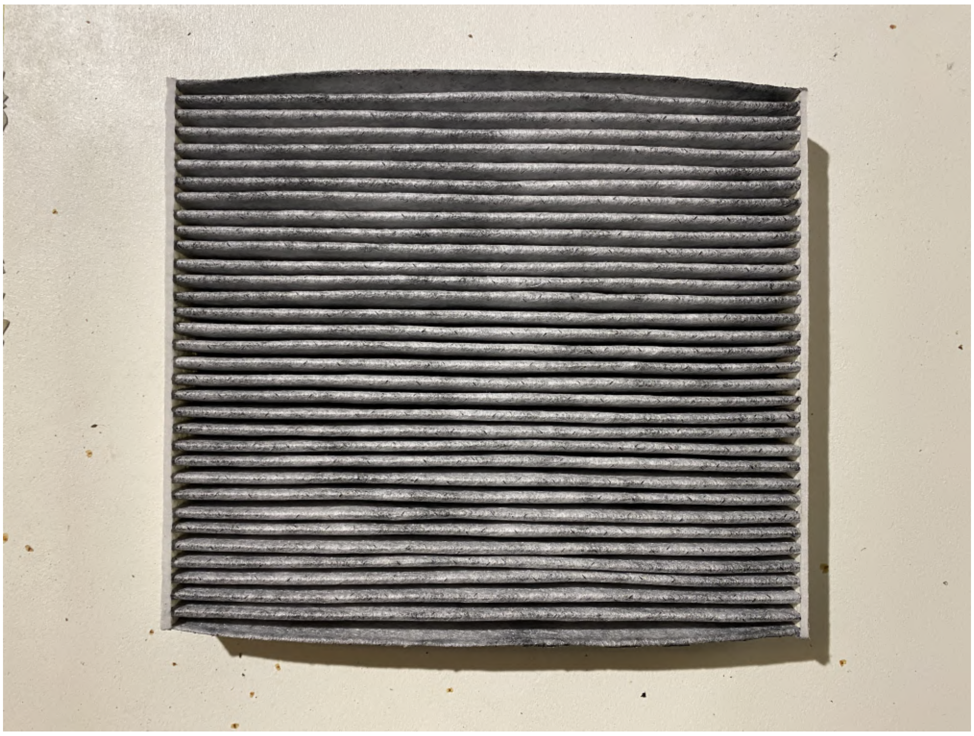


Figure A.6: Air filter 2

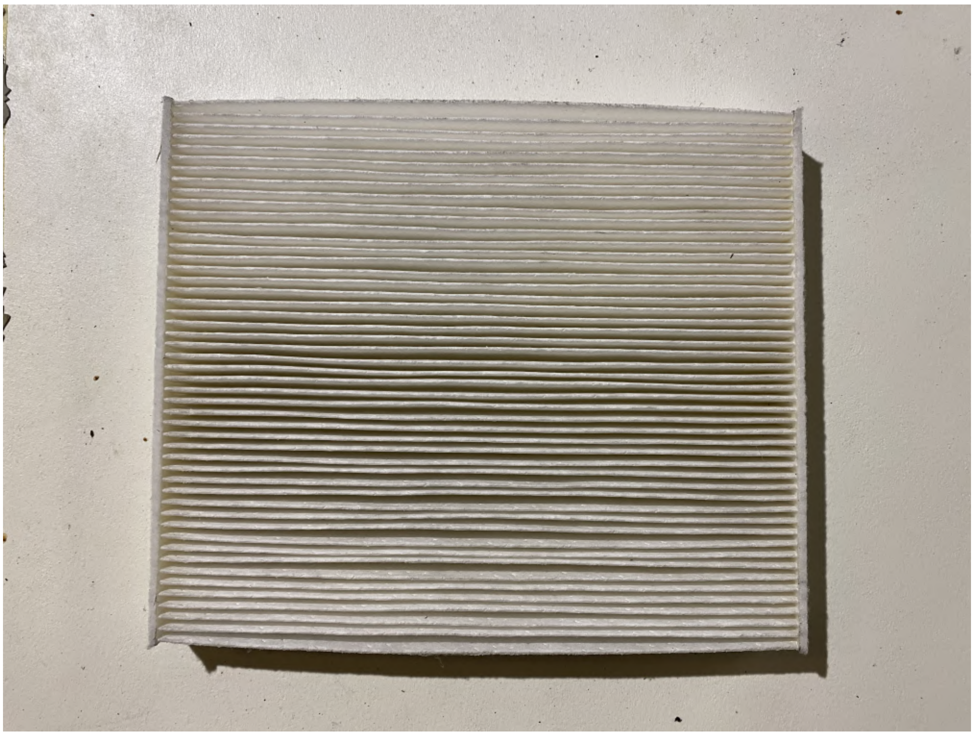


Figure A.7: Air filter 3

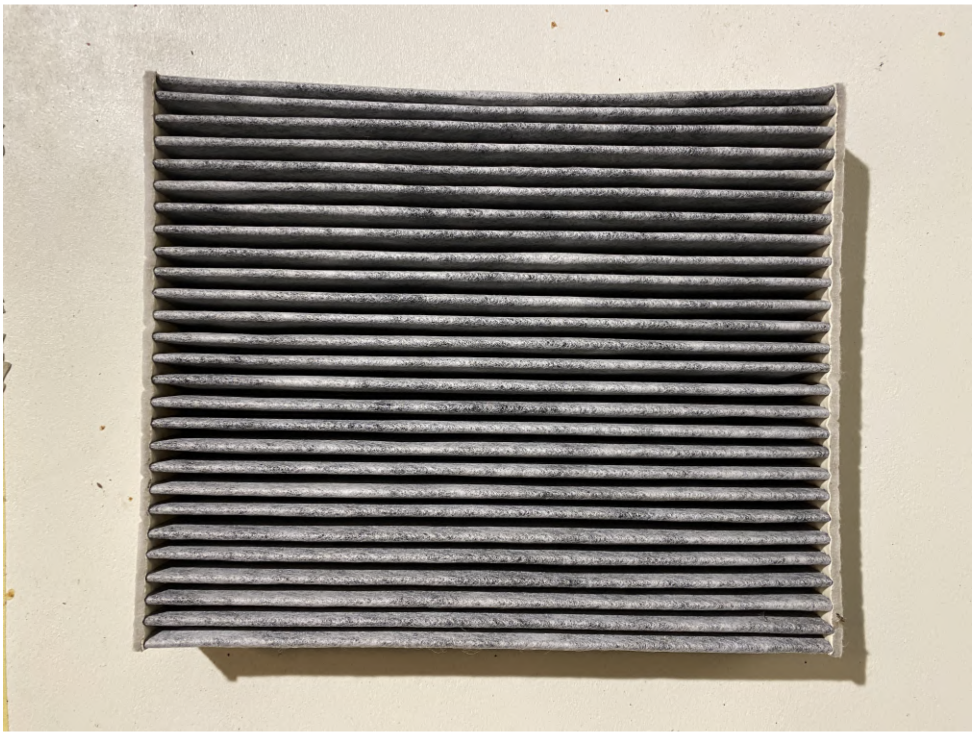


Figure A.8: Air filter 4

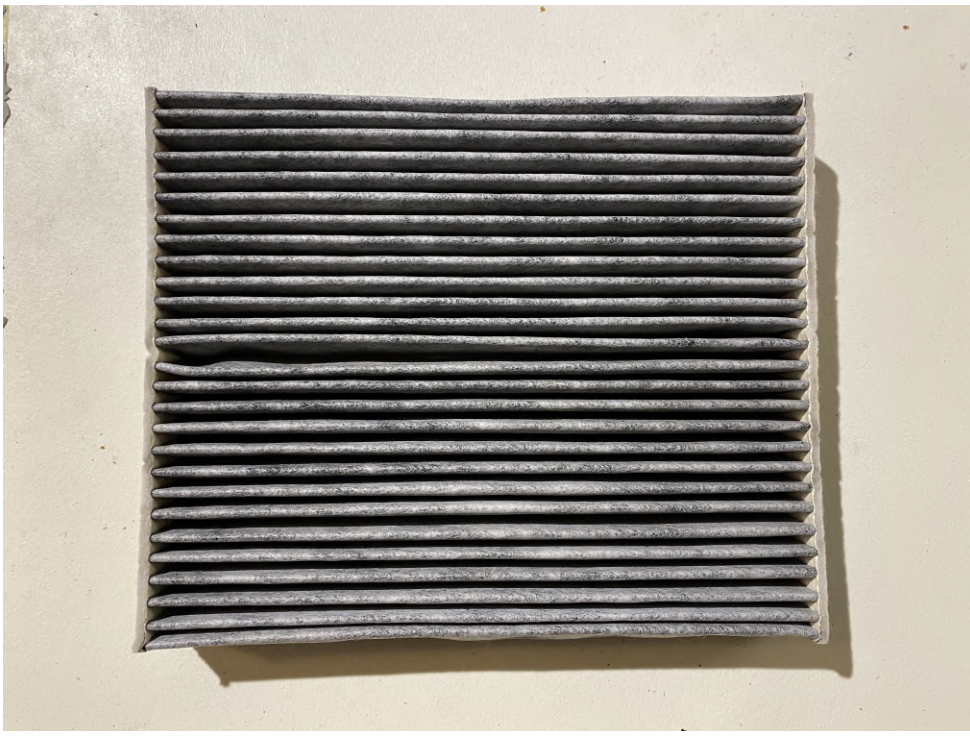


Figure A.9: Air filter 5