

Challenges on  
the development  
of fine dust  
filters for  
vehicle interiors

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## 1. Abstract

Recently, great efforts are being made to develop filter media which fulfill the requirements on a good cabin air quality. Based on the nonwoven technology new media concepts were developed. With the new generation of fine dust cabin air filters it is possible to achieve separation efficiencies of more than 80 % for a test aerosol (NaCl aerosol) at the most penetrating particle size (MPPS) by maintaining other important factors like pressure loss and filter life time. It can be shown that this new filter media concept is able to

better maintain the particle separation efficiency over the filter life time under realistic conditions.

Usually cabin air filter performance is measured according DIN 71460-1 under laboratory conditions. In order to improve the properties of the filter media towards their real-life behavior experiments were conducted with a test car. Here the corresponding particle concentrations in the cabin were measured under varying driving situations and environmental conditions.

## 2. Introduction

Based on the results of research in the last decades the direct link between impacts on health or even premature death and ambient air pollution in terms of PM<sub>2.5</sub> was established<sup>1</sup>. Those findings led to guidelines, regulations and directives on a worldwide basis, setting of limit values and defining actions in order to decrease air pollution. Nevertheless it is reported by European Environment Agency that in 2015 about 10 % of the EU urban population were exposed to concentrations above the limit value for PM<sub>2.5</sub> of 25  $\mu\text{g}/\text{m}^3$  (24-h mean)<sup>2</sup>. If the WHO Air Quality Guidelines limit value of 10  $\mu\text{g}/\text{m}^3$  is applied the exposition is on a level of 85 – 91 %<sup>2,3</sup>.

More and more also the fraction of PM<sub>1</sub> (< 1  $\mu\text{m}$ ) as well as the ultrafine particles (UFP < 0,1  $\mu\text{m}$ ) and their effects on human health are in focus of research<sup>4</sup> as the size range of atmospheric particles extends over a wide range shown in Figure 1. It can be assumed that especially vehicle passen-

gers are exposed to high concentrations of ultrafine particles as the concentrations of those particles were detected on high levels on and close to roadways<sup>5,6</sup>. Furthermore the particle concentration inside vehicles exceeds outdoor concentrations by 3-5 times<sup>5</sup>. The growing knowledge of health related issues induced by fine particulate matter with enhanced exposure to these pollutants especially in fast-growing markets like China and India has led to higher expectations on the air quality also in car cabins. This development is clearly reflected by increased levels of particle separation efficiency requirements (especially for fine particles < 2.5  $\mu\text{m}$ ) in customer specifications.

Thus, the development of a new media generation for cabin air filter applications is offering a great contribution to the convenience and protection of passengers.

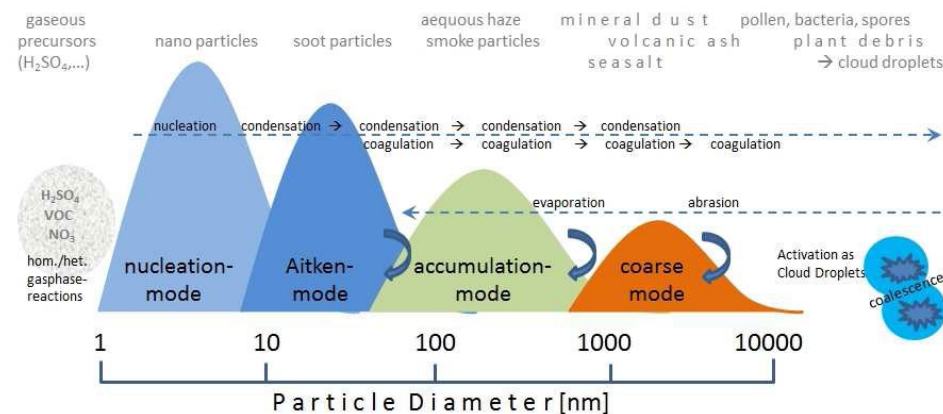


Figure 1: Schematic multimodal particle size distribution with typical transformations and ex-ample particle types within each mode (Source: DWD)<sup>7</sup>

### 3. Cabin Air Filters

Figure 2 shows the main requirements on cabin air filters like differential pressure which is linked to energy needed to transport air through the filter element, the separation efficiency as measure of ability to retain particulate impurities. The filter life time reflects the ability to store particles in the depth of the filter media until a certain “blocking point” is reached. These mentioned requirements can be contradictory in their behaviors so that the challenge in development lies in the finding of the best compromise.

There are several types of cabin air filters with different functionality. Figure 3 shows main types of cabin air filter

elements. Whereas the particle filter removes particulate contaminants the so called combi filter (combination of particle and gas separation) is additionally equipped with a layer of granular activated carbon for the reduction of odour and harmful gases entering the cabin. The biofunctional filter represents the latest stage of development by further adding protection against mould, spores and allergens by special treatment of the filter media<sup>8</sup>. Nevertheless all following statements are focusing on the particle separation function and are valid for all types of cabin air filters.

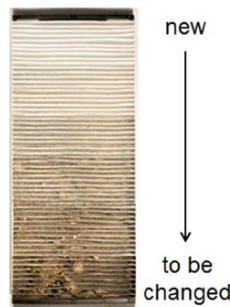
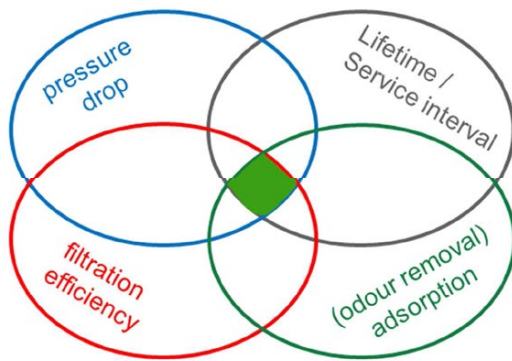


Figure 2: Main requirements on Cabin Air Filters

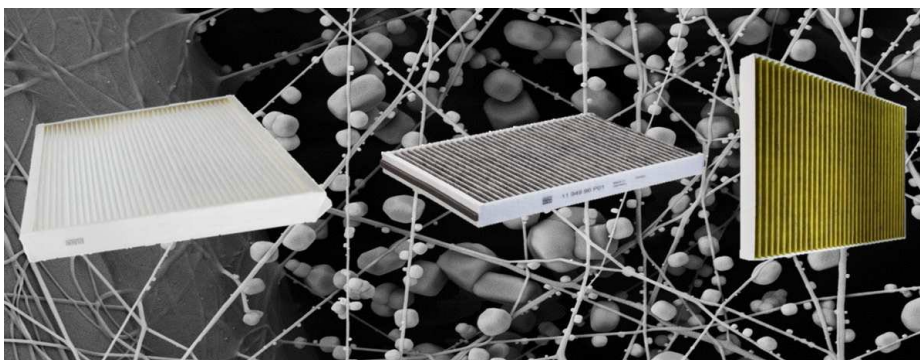


Figure 3: Types of Cabin Air Filters (from left to right particle-, combi- and bio-functional filter)

## 4. New Filtermedia Generation

### 4.1 Filter Media Technology

The main part of each cabin air filter is the filter media itself that is designed to meet the main requirements as described above. Most commonly the market is dominated by so-called electrete filter media, in which the fibers additionally carry a surface charge to offer a further source of attraction to particles. Figure 4 shows different SEM images of possible

media types varying from single layer electrete media to nanofiber coated media and 2-3 layer composite media including their main characteristics.

Typically cabin air filter media rely on different forms of mechanical filtration effects (diffusion, interception, inertial deposition and blocking) plus electrostatic forces for the so-called electrete media as illustrated in Figure 5.

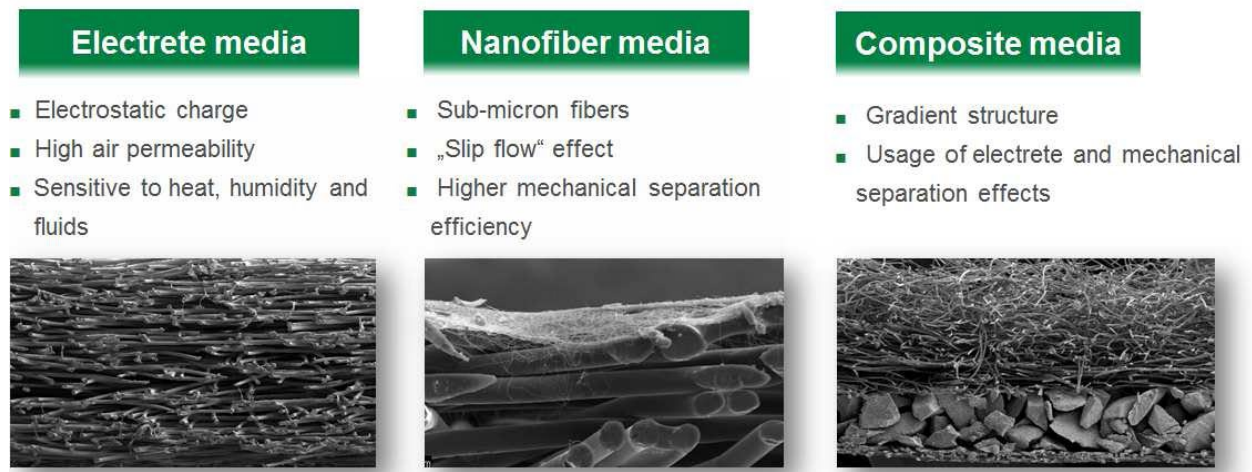


Figure 4: Filter Media Types

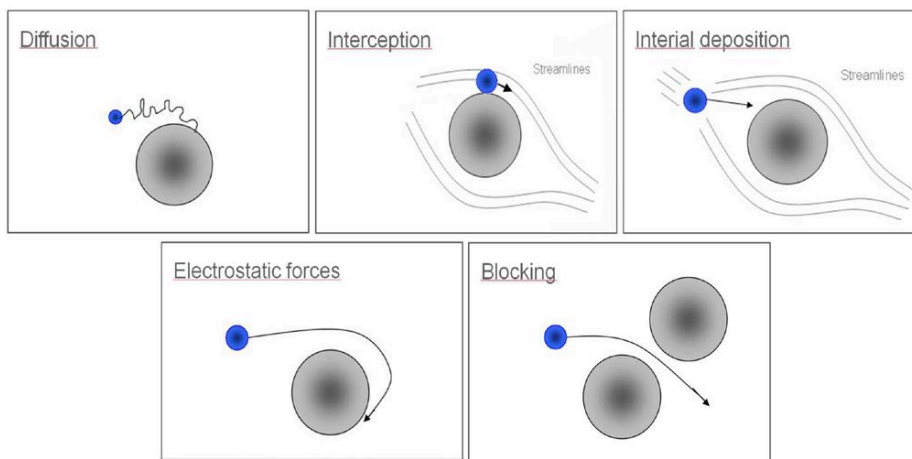


Figure 5: Filtration Mechanism

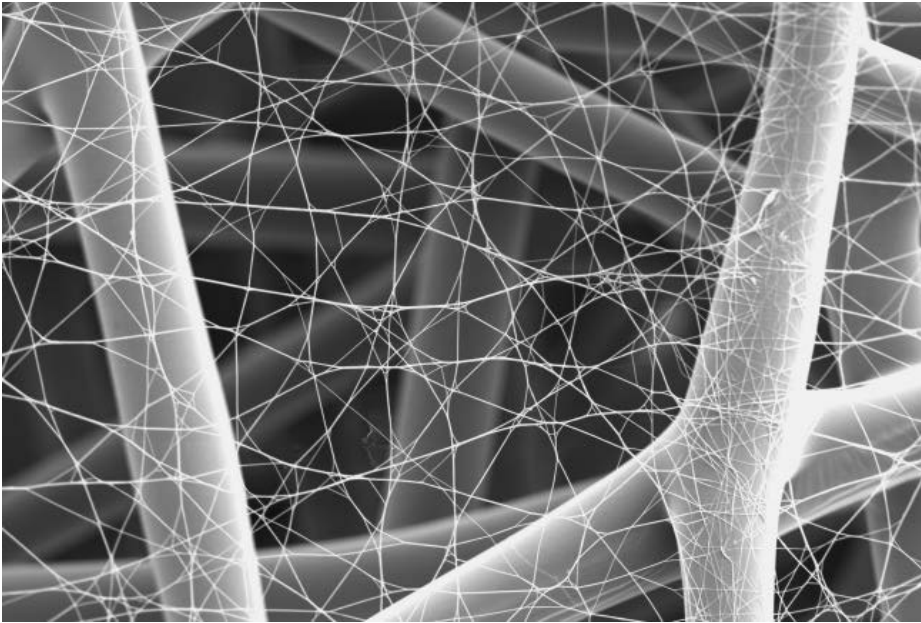


Figure 6: SEM Image  
Nanofiber Media

## 4.2 Nanofiber Media – a new Filter Media Generation

The challenge in the development of filter media meeting the requirements of a higher particle separation efficiency resulting in an enhanced cabin air quality lies in the aforementioned contradicting main characteristics (i.e. differential pressure, particle separation efficiencies and the filter life time). To obtain higher separation efficiencies the most effective method would be to decrease the fiber diameters and thus increase available surface of the fibers inside the filter media. However, as a matter of fact that leads to a higher pressure loss. One approach respecting both requirements makes use of nanofibers. In contrast to microfibers (which are in the range of 1-10  $\mu\text{m}$ ) these nanofibers are defined by having fiber diameters less than 0,5  $\mu\text{m}$ . That leads to the so-called “slip-flow” effect on the surface of the fibers with its positive effects on the flow resistance as the air velocity is not reduced to zero at the fiber surface.<sup>9</sup>

An established technology for producing nanofibers is the electrospinning process in which a polymer solution is pressed through a thin nozzle. This needle also serves as an electrode on which a high voltage in the kV range to a counterelectrode is applied<sup>10</sup>. Usually substrates / carrier layers are coated with a thin layer of a nanofiber web by placing it over the counterelectrode. Figure 6 shows a SEM Image of the finished filter media coated with a nanofiber web. The substrate / carrier layer has to be chosen carefully as there are numerous interactions with the nanofibers and it also influences the function of the overall filtermedia. First of all it brings the mechanical stability to ensure the processability. Moreover it serves as prefilter layer for delivering the appropriate filter life time which could not be achieved by the nanofiber layer alone.

The technology of nanofibers shows functional characteristics superior to a typical state of the art electrete filter media. It provides a more stable and sustainable filtration performance over the whole filter lifetime. This can be achieved by a higher portion of mechanical filtration compared to electrostatic filtration. In the following part the performance and the advantages of that media will be shown.

Like already mentioned cabin air filter elements and their main performance characteristic regarding particle separation behavior is measured according the standard DIN 71460-1 which allows the measurement of the performance under reproducible conditions.

In Table 1 the main characteristic performance values of a typical high performance filter element equipped with electrete media is compared to the performance of the new generation of fine dust filter media measured according DIN 71460-1.

It shows that in initial state the performance of both types are more or less comparable. As this is not reflecting the influence of environmental factors like temperature and humidity variation an ageing of elements is conducted where harsh conditions are simulated (up to 90%rH and 100°C, time

span 312 h). Figure 7 shows the separation efficiency after the ageing treatment of the filter elements. It is obvious that after treatment the performance of the electrete media elements is reduced dramatically whereas the efficiency drop for the new media generation is less pronounced.

It can be concluded that for the electrete media the described storage conditions (high temperature, high humidity) cause a degradation of the fiber charge leading to a reduced ability of attracting particles. As explained for cabin air filters the additional electrostatic forces are added as a further source of particle attraction which can be influenced by environmental influences like temperature, humidity and shielding through already deposited particles on the surface. If that is the case mainly mechanical separation effects remain which leads to a decrease of the overall filtration performance. For the new generation of media the mixture of the mechanical and electrete effects is shifted more towards the mechanical separation effects; leading to a higher tolerance against environmental influences. Based on these results it can be expected that the filtration performance of such media types will stay on a higher level over the filter lifetime.

#### Pressure drop:

Media	Nano fiber	Electrete
@ 300 m <sup>3</sup> /h	85 Pa	78 Pa
<b>Particle efficiency:</b> NaCl @300 m <sup>3</sup> /h:		
0,1 µm	74 %	73 %
0,3 µm	84 %	76 %
0,5 µm	92 %	80 %
ISO fine dust (A2):		
0,5 µm	99 %	98 %
1,0 µm	99 %	99 %
> 3,0 µm	100 %	99 %
> 5,0 µm	100 %	99 %
<b>Dust holding capacity:</b> ISO fine dust (A2):		
+200 Pa	42 g/m <sup>2</sup>	26 g/m <sup>2</sup>

Table 1: Performance Comparison

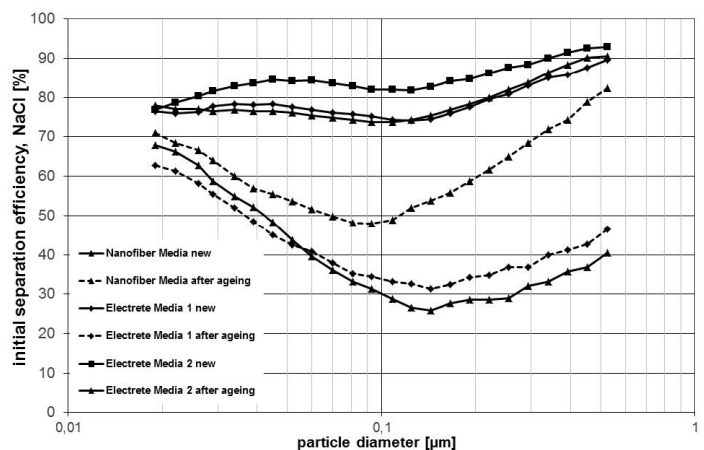


Figure 7: Filter performance after lab ageing

## 5. Particle concentration measurements inside the vehicle

In the previous chapter the performance of the new fine dust filter media generation was shown derived from measurements according DIN 71460-1. However these measurements cannot completely reflect the real time behavior. These filter tests are conducted under controlled and repeatable conditions (e.g. temperature, rel. humidity, aerosol concentration). All in all tests according DIN 71460-1 are a basis to compare different filter elements with an agreed and well established standard in the cabin air filter market. In this chapter the connection to the real time behavior shall be created. Here we

focus on the particle concentrations inside the cabin especially on the PM 2.5 values due to their importance and the available recommendations from the WHO and the Environmental Agencies. Figure 8 shows the general test set-up and the test car used for these tests.

Based on this set-up several measurements were performed to get a first indication on the real time behavior of different filter media types and their capabilities to significantly reduce the fine dust concentration in the vehicle interior.

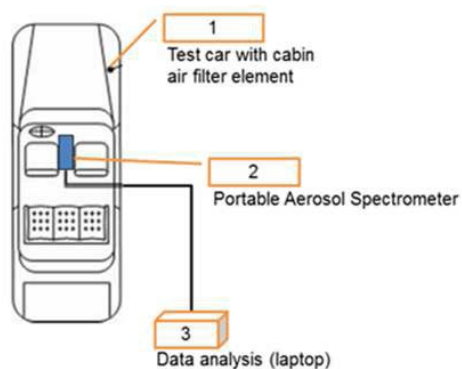


Figure 8: Test Set-Up and Test Car

Figure 9 shows the PM 2.5 concentrations in  $\mu\text{g}/\text{m}^3$  measured inside the vehicle for a complete defined driving cycle in the upper Franconia area. The light grey line represents the driving cycle without installed filter element showing the resulting PM 2.5 concentrations of unfiltered air getting into the cabin whereas the dark grey line represents the cabin air concentration with a filter element installed. Overall it can be observed that in almost all driving situations (highway, city traffic, and country roads) the concentration is around  $20 \mu\text{g}/\text{m}^3$  even if no filter element is installed, which shall be equivalent to the outside concentration. This is reflected in the sequence Ambient PM 2.5 City Traffic. In this sequence the test car is parked close to city traffic, with doors open and the HVAC system switched off leading to assimilation of inside and outside concentration. In the following sequence (Re-Start of HVAC system) the doors are closed and the HVAC system is started again, leading to a quick reduction of

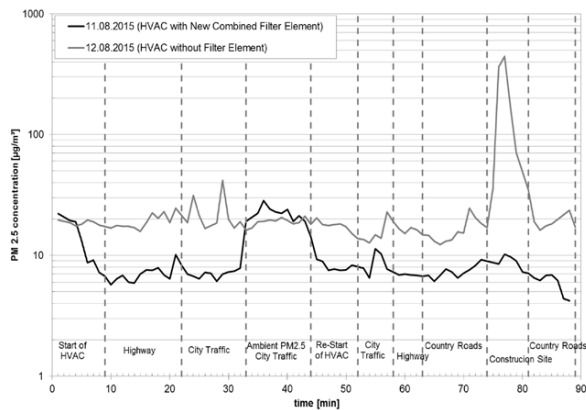


Figure 9: In-Cabin PM 2.5 Concentration of Drive Circle in Upper Franconia Area

the particle concentration in the cabin through the effects of the cabin air filter. Summarizing it can be observed that in all driving situation with cabin air filter in effect the PM 2.5 concentration stays below  $10 \mu\text{g}/\text{m}^3$  (WHO suggestion) even for the heavily polluted construction site where the outside concentration reaches a level of over  $400 \mu\text{g}/\text{m}^3$ .

However as already indicated this only reflects the performance of a new filter element not taking into account the possible decay of the electrostatic charging and its contribution to the overall filtration performance. In Figure 10 the comparison of the filtration performance of a new filter element (dark grey line) and a filter element that was installed in a vehicle for approximately 19.000 km (a typical mileage suggested for many vehicles, (light grey line) is shown. Here the reduction of filtration performance over lifetime for a cabin air filter element that mainly relies on electrostatic filtration effects can be observed.

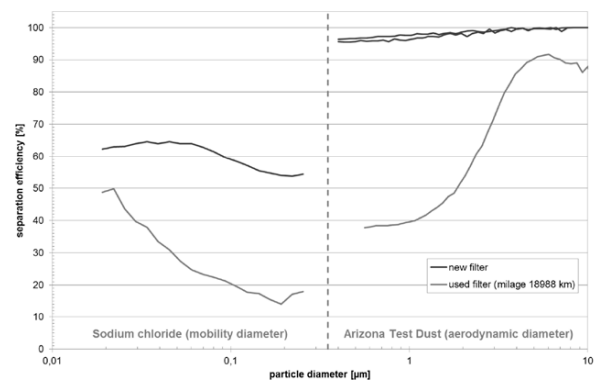


Figure 10: Efficiency decrease of used filter element



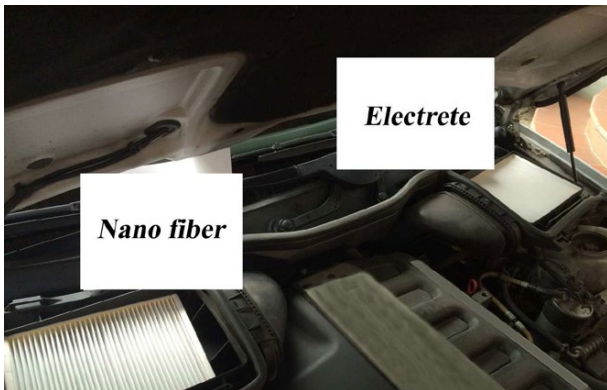


Figure 11: Point of installation field ageing test

Therefore a field study was conducted in which the new nanofiber filter media generation and its advantages of stable filtration performance over the filter lifetime shall be demonstrated. For that reason two identical filter elements in terms of design and initial performance – one with new nanofiber filter media generation and one with typical electrete filter media – were installed into a vehicle with two volute air flow suction. This set-up enables the parallel ageing of two filter elements under realistic conditions. Figure 11 shows the point of installation for the filter elements.

During the experiment both elements were dismantled

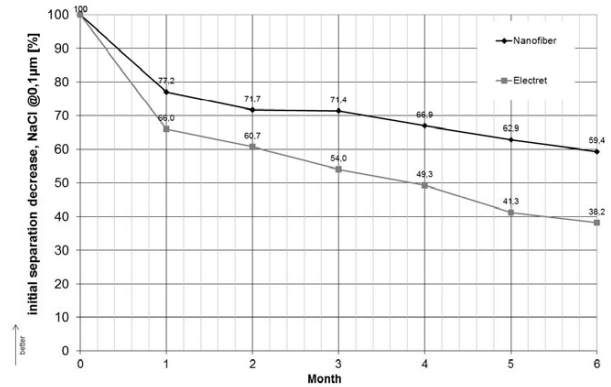


Figure 12: Diagram filtration performance decay after field ageing

every month for measuring the filtration performance in the laboratory. Figure 12 shows the decrease in filtration performance at 0,1 µm particle size for the aged filter elements over the course of 6 months and an overall mileage of approximately 10.000 km.

Those results also show the same tendency as already demonstrated in laboratory tests (see Figure 7) that the decrease of filtration performance of the new filter media generation is less pronounced than for the electrete media leading to higher separation efficiency over the lifetime of the filter element.

## Conclusion

Based on laboratory and field tests the filtration performance of a new filter media generation based on nanofiber technology was evaluated. The conclusions of this study are summarized below:

- » The main characteristics (differential pressure, separation efficiency, dust holding capacity) of the new filter media technology were measured according DIN 71460-1 and compared to a state of the art filter media. It could be shown that the performance in all tested points in new condition is comparable.
- » As the nanofiber filter media technology was expected to show a better ratio in terms of mechanical filtration effect compared to electrostatic filtration effect an ageing routine was applied (climate change test) to measure the filtration performance of an aged filter. The filter elements based on new filter media technology show higher particle separation efficiencies after ageing than the electrostatically charged media.

- » In field tests it could be shown that cabin air filters are able to reduce the PM 2.5 concentration in the cabin to values below the WHO suggested limit of  $10 \mu\text{g}/\text{m}^3$  and with that contribute to the wellbeing of passengers by protecting them from fine dust particles.
- » In further tests (two filter elements were installed in a vehicle to age them under field conditions) it could be shown that the new nanofiber media technology shows a lower decrease of filtration separation efficiency over the whole filter life time also under field conditions.

Cabin air filters contribute to a better air quality inside the vehicle and with that help to protect the passengers from fine dust particles and their negative effects on health. By further development the filter media the protection of passengers can be provided on a more stable level over the filter life time. Further investigations have to be conducted to further confirm the advantages of the new filter nanofiber media generation developed and its positive effects on the air quality inside the cabin.

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