

High air pollution in vehicle cabins due to traffic nanoparticle emission exposure and a solution for in-use vehicles

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Abstract. Vehicles operating in dense traffic take their cabin air from the low diluted exhaust gas cloud produced by other cars or trucks running ahead of them. They usually take it at a low level where the particle concentration and the concentration of heavy gases like NO₂ are still high. Cabin air is thus collecting and storing emission peaks and air pollution in car cabins can therefore be extremely high - often ten times higher than even at roadside. Drivers commuting in big cities, taxi drivers, truckers and school buses might be exposed to this high pollution for several hours per working day, a group put at very high health risk.

Cabin air of today's vehicles usually passes a filter, but these filters are designed for visible road dust and pollen and according to the existing standards filtration of particles < 1 µm is very low. Lung penetration however, only starts < 0.5 µm. In the long run this could be changed by installing different filter systems, but what about the existing fleet? A filter system has been developed to reduce the concentration of ambient ultrafine particles in vehicle cabin air of in-use vehicles to very low levels, which is presented here.

1. Introduction

Health effects of inhaled particles depend to a large effect on particle size, since only particles < 500 nm can penetrate the alveoli, enter the blood stream and are translocated to organs, even to the brain [1,2,3]; Premature mortality due to ultrafine particles is very high, there is epidemiologic evidence for high cardiovascular mortality, cerebrovascular mortality and cancer [7] - they were classified carcinogenic class 1 by IARC/WHO in 2012. Even neurotoxic effects like Parkinson and Alzheimer are suspected since those small particles, if solid and insoluble are entering the brain [4] and there residence time is very long, maybe month or years [5]; whereas larger particles, defined by PM10, which also have some effects in the upper airways, are mainly determined by background particle pollution, the concentration of submicron particles strongly depends on local sources, mainly combustion and in particular combustion engines [6]. Highest levels are therefore found beside busy roads and health of people living close to such roads show particularly high health effects [8].

Official monitoring is usually done at a distance of dense traffic, EPA requires 100 m distance. But if vehicle engines are the main source it is obvious that the hotspot is the road itself, the so-called pollution canyon. This means that people traveling frequently on such roads are exposed to high concentrations of nanoparticles. The exposure may be orders of magnitude higher than at more remote areas, a distance of 2-300 m already brings the pollution level down by an order of magnitude [8].



A study by S. Fruin [9] shows a 15 times increased concentration inside cars compared to the roadside which was confirmed by Airparif-Studies [10]. It was clearly proven that such nanoparticles originated exclusively from vehicle exhaust.

Filters incorporated in present ventilation systems [11,12] remove large particles, for example pollen and visible dust re-entrained from road deposit and also tire wear particles. The filtration standards, actually in force require a high filtration efficiency for particles $> 1\mu\text{m}$, but are usually inefficient for removing very small particles $< 0.5\mu\text{m}$. These standards thus lead to filter media of high porosity and high space velocity - small, low cost, low backpressure solutions. Health effects however, are not taken into account yet.

This is demonstrated by figure 1, where the particle number concentration outside and inside a modern car is plotted during a journey in the vicinity of Zürich. It is obvious that the concentrations inside and outside are more or less identical. All windows were closed during this measurement. Tests with a number of different cars all showed similar results.

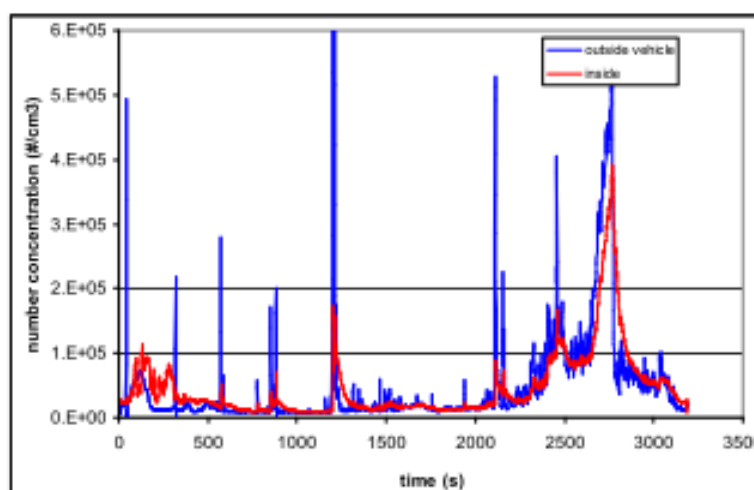


Figure 1. Number concentration of particles inside and outside a car

For all those investigations the particle pollution is measured by particle number counting, following the European PMP-standard [13] and the instruments use the diffusion charging principle [14] which allows to build small size instruments, well suited for in car measurement with low energy requirement but fast response. This type of instruments is now also preferred for real word emission measurements and for periodic technical control of DPF equipped vehicles [15].

Though more efficient filters would be available, these are currently not implemented by the OE car manufacturers, because they cause a higher back pressure, requiring stronger blowers. Manufacturers are aware of this problem but as long as we have no respective regulation they will not improve the filtration [16]. All they do is recommending to shut-off ventilation air, but this does not improve the pollution at all [17,18,19] and on top it leads to a fast increase of CO_2 -concentration in the car atmosphere, a gas which accelerates tiring the driver.

2. The Nanoparticle Filtration System

In this approach we have tried to overcome this problem by filtering only partial intake flows, as will be shown below.

All of currently developed prototypes are retrofit systems. The original car ventilation is not modified, but switched to a recirculation mode. So no fresh air is drawn in from outside via the existing ventilation system. Outside air only enters through an additional filter and a high-performance blower. We have tested a large number (some hundreds) of different types of filters. Test parameters were filter

efficiency, back pressure and capacity. A quartz fiber filter proved to be best and is used in our system. Figure 2 shows the filter efficiency as a function of particle size. In contrast to the filters usually applied in car ventilation systems, this filter has a very high efficiency down to particle sizes of a few nanometers.

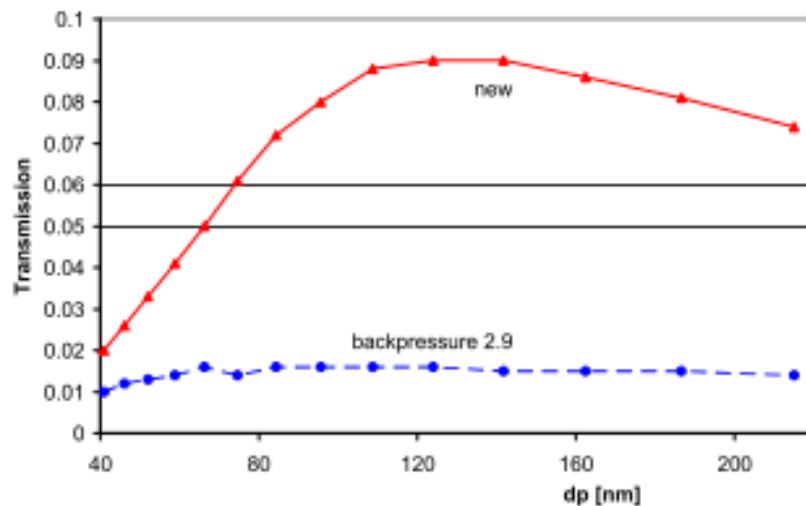


Figure 2. Filter-efficiency: Transmission (Penetration) as function of particle size for the new filter and for the filter loaded to a backpressure of 2.9 mbar. Penetration 0.01 means filtration efficiency of 99%

A prototype of the system is shown in figures 3 and 4. A tube connects an intake location outside the car with the air inlet of the filter system. In the first prototype the blower is directly at the inlet. To increase the lifetime of the high-performance filter it is preceded by a prefilter to remove coarse particles. From there the air reaches the high-performance filter.

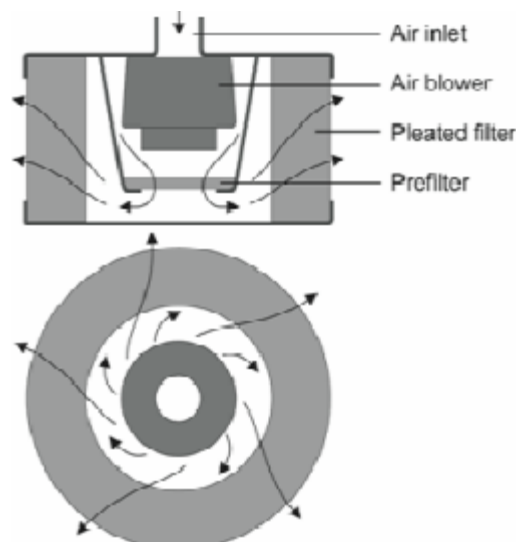


Figure 3. Setup of the filter with integrated pre-filter for coarse particles and blower.

The system is operated at a flow rate of 30 m³/h. The blower can handle back pressures up to 2000 Pa. Importantly, all intake air has to enter through the filter. The size of the filter is strongly influenced by lifetime demands and by the demands for air intake interchange inside the cabin which depends on the number of passengers and the requested CO₂-level. To investigate the lifetime experimentally a filter was placed in a road tunnel of the Zürich downtown highway system together with a particle measurement device for a long term test. Figure 5 shows the back pressure of the filter as a function of the length of time of operation in the tunnel.

Based on these results the filter lifetime has been estimated. The particle concentration in the tunnel is about 10 times higher than average road concentrations. This indicates that under typical operating conditions a filter lifetime of about 10'000 h can be expected, before the backpressure reaches 1000 Pa.

For applications with higher cabin volumes, either several of these filter units can be used in parallel, or larger systems can be devised, as shown in the next section.



Figure 4. Prototype of the filter system. Main filter, prefilter and blower are included. The system is operated by an external control box, containing the drive electronics for the blower and displays for filter backpressure and time meter.

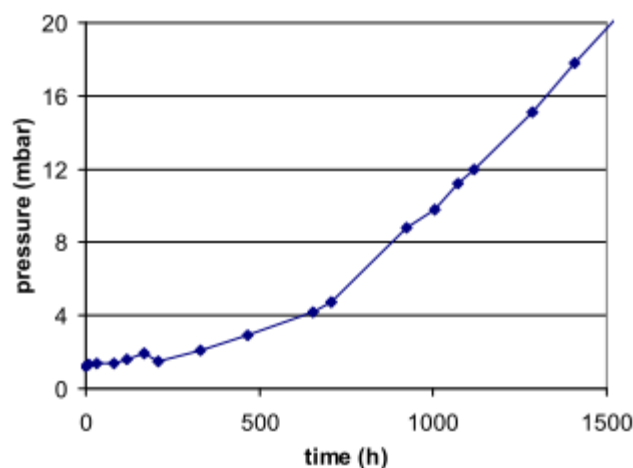


Figure 5. Filter backpressure as function of operating time in a highly polluted road tunnel

Figure 6 shows one possibility to install the filter system in a passenger car. A number of solutions to place the intake air inlet have been investigated. For most of our tests with passenger cars the filter was simply placed on the back seat, together with sensors to measure the particle concentrations (usually two, one sampling outside air and one cabin air) and a notebook for data acquisition (see figure 7).

Diffusion Size Classifiers DiSC (14) were used to monitor the particle number concentration. The DiSC is a new instrument, which allows the measurement of particle number concentration and mean diameter by a very compact, battery operated unit. To make sure that the air exchange remains sufficient, CO₂ concentration in the cabin was also measured using a Li-COR Li-840 CO₂-analyzer.

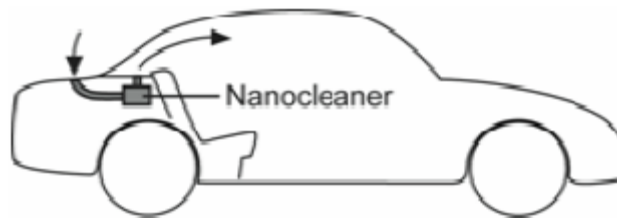


Figure 6. One possible solution to install the filter system



Figure 7. Filter, particle sensor and Notebook for data acquisition during tests

3. Results

The prototypes have been road-tested for extended periods under an extensive variety of traffic conditions, including high-exposure urban and tunnel situations, in cars with the air conditioning in recirculation mode. On start-up, a rapid particle reduction ('clean-down') of 95-99% within 3 minutes is obtained (figure 8). Once cleaned down, the new filter system (air conditioning still in recirculation mode), can maintain a level of nanoparticles in the car at or below 5000 particles/cm³, the equivalent of a typical situation inside a closed office or in woodland, even if external peak counts are (transient) over 1,000,000 particles/cm³ or 250,000 part./cm³ for extended periods (a minute or more). The total nanoparticle count inside the car over the journey is typically ~2% of that encountered outside. Figure 9 shows a typical result. The rapid concentration changes observed outside are hardly visible inside.

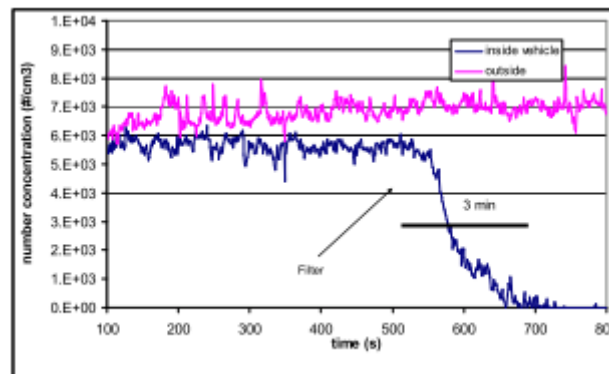


Figure 8. Particle concentration inside and outside the car (passenger car). After turning the filter on, the inside concentration drops to very low levels over about three minutes.

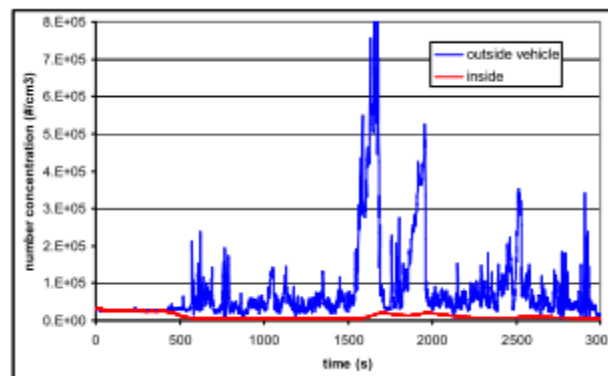


Figure 9. Particle concentration inside and outside a passenger car with the filter turned on. Even when the external concentration is extremely high, in this example while driving through a tunnel, the indoor concentration remains very low.

After tests with a number of passenger cars showed the good performance of the filter system also other vehicles with larger cabin volume were investigated. Figure 10 shows two units mounted in a school bus. To achieve a sufficient air supply both units were equipped with two blowers, leading to a total air flow of 120 m³/h. This was sufficient to obtain results comparable to those with the passenger cars. Similar results were also obtained for larger buses and coaches, as below.

Another series of test has been performed in a truck. Here initially two of the systems developed for passenger cars have been placed in the truck cabin (figure 11). One result of these tests is presented in figure 12. Again, the indoor concentration is significantly lower than outside; however, the result is not quite as good as those obtained for the previous cases. Peaks in the outdoor concentration are still visible inside. This indicates that the cabin of the truck investigated is leakier than that of the passenger cars, and so a slightly larger scaled system is needed.



Figure 10. Two nanocleaner filter systems, installed in a school bus



Figure 11. Nanocleaner placed in a truck cabin. Two units are used for the test measurements.

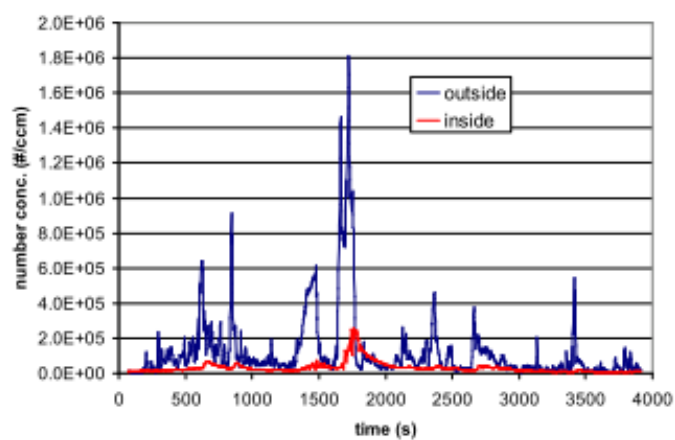


Figure 12. Particle concentration inside and outside of the truck cabin.

A much larger filter system has been installed in the luggage compartment of a 35-seater coach (see figure 13). The coach was fitted with three systems each capable of 180m³/hour airflow, fitted to replace the coach's air conditioning systems, taking air from the luggage compartments, filtering it, and delivering it to the passenger compartment. Again inside and outside particle concentrations are plotted in figure 14.



Figure 13. Filter system for buses, installed in the luggage compartment

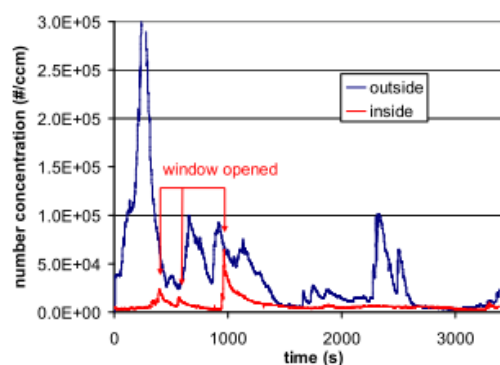


Figure 14. Particle concentration inside and outside a coach. Three times, indicated by the red arrows, a window has been opened. Immediately the indoor concentration rises to approach the outdoor concentration and decreases again after the window is closed.

So far in all applications presented the ventilation system of the vehicle has remained unchanged. As last example we present a case (a BMW 530), where the original filters have been replaced by the prototype nanocleaner. However, the high performance blower has been used (see figure 15) as the sole source of intake air to the cabin. Figures 16 and 17 show the result with normal filter and with the nanocleaner-filter. Again the original filter has no significant effect on the particle concentration in the cabin. If it is replaced by the nanocleaner filter the cabin nanoparticle concentration becomes very low.



Figure 15. The original filter of a BMW 530 has been replaced by high efficiency filters. Air is supplied by a blower which is also placed in the engine compartment.

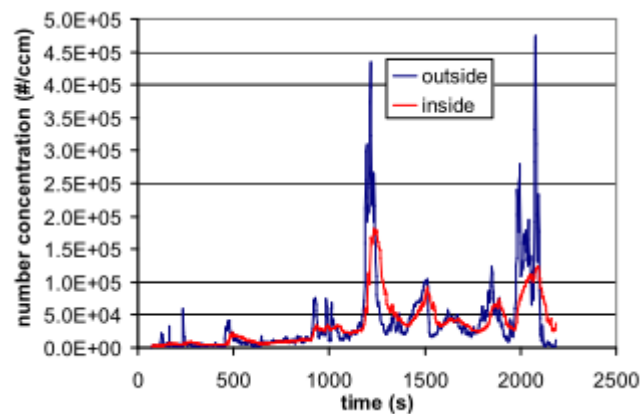


Figure 16: Results with regular ventilation system

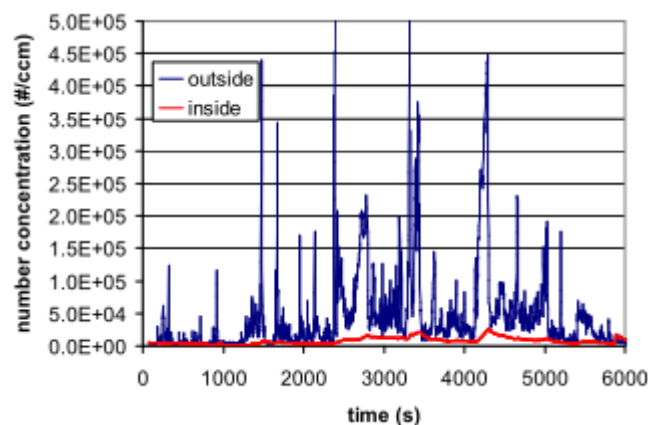


Figure 17. Results using the nanocleaner filter.

4. Conclusions

Air pollution in vehicle cabins is a big threat to a large group of people who are forced to commute in densely populated megacities day by day. They may be exposed to high pollution of ultrafine particles and toxic gases for hours every day. Since vehicles take ventilation air from the emission cloud of the road without much dilution they are cumulating high emission peaks from vehicles running in front of

them. Several investigations from Los Angeles, Paris and Vienna show particle number concentrations as high as 15 times the concentration at roadside.

Filters included in today's cars, trucks or bus ventilation systems usually cannot remove nanoparticles, and so the nanoparticle concentrations outdoor and in the cabin, are more or less identical. The existing standards only require removing pollen and re-entrained road dust with particle sizes $> 1 \mu\text{m}$. For future cars we absolutely need a stringent regulation which requires filtration efficiency $> 99\%$ for solid nanoparticles. This is also valid for e-mobility vehicles.

For taxi drivers, truck drivers etc. this vehicle cabin is their working place and epidemiology has shown that mortality by cancer is very high for this group of people [23]. Consequently, occupational health authorities should require measures to mitigate this health threat. Until now there is no such regulation in any country.

A new filtration element, called Nanocleaner developed by a research team in Switzerland, consists of a very efficient filter and a high-performance blower, reduces of the particle concentration in the cabin by $>98\%$. It can be retrofitted to any vehicle of the in-use fleet and may need filter substrate cleaning or exchange only after 100'000 km of operation. It should be installed in school buses to protect sensitive groups and in all application of long time exposure to dense traffic emissions.

References

- [1] D.W.Dockery, School of Public Health; Lessons from Epidemiologic Studies of Ambient Fine and Ultrafine Particles. 17th ETH-NPC 2013 www.nanoparticles.ethz.ch
- [2] P.Gehr et.al. University of Berne. How ultrafine particles interact with pulmonary cells. 7th ETH-NPC 2003 www.nanoparticles.ethz.ch
- [3] G.Oberdörster et al; University of Rochester; Nanotoxicology; Environmental Health Perspectives 2005
- [4] W.G.Kreyling; Helmholtz Zentrum München; Air-Blood Barrier Translocation ... depends on Particle Size; American Chemical Society J.Heyder, 2014
- [5] J.Heyder et al. GSF, Neuherberg; Long-Term Clearance Kinetics of inhaled Ultrafine Insoluble Particles.....; Inhalation Toxicology
- [6] ETH-Conference on Combustion Generated Nanoparticles; ETH Zürich; annual event; with complete bibliography 1997-2018; www.nanoparticles.ethz.ch
- [7] J.Lelieveld et al; Max Planck Institute Mainz; The contribution of outdoor air pollution sources to premature mortality on a global scale; Nature; 2015
- [8] Hong Chen et al; Institute for Clinical Evaluation, Toronto; Living near major roads and the incidence of dementia, Parkinson's disease and multiple sclerosis; The Lancet 2017
- [9] F Fruin, S.A., Winer, A.M., Rhodes, C.E., 2004. Black carbon concentrations in California vehicles and estimation of invehicle diesel exhaust particulate matter exposures. Atmospheric Environment 38, 4123–4133
- [10] Air Parif; Sept 2007: Mesures dans le flux de circulation; étude exploratoire
- [11] B.Hardeggen, Bundesforschungsanstalt Braunschweig-Völkenrode; Zur Auswahl von Prüfmethode für Luftfilter landwirtschaftlicher Fahrerkabinen; Grundle.Landtechnik 1982
- [12] DIN 24185; SAE J726
- [13] EU-Joint Research Center, 2007; Particle Measurement Programme (PMP)
- [14] M.Fierz et al. FHNW; Field measurement of particle size and number concentration with the diffusion size classifier (disc)" Sae 2008-01-0827

- [15] G.Kadijk, TNO; NPTI-the New Periodic Technical Inspection emission test procedure for behicles with emission control systems; 21.ETH-NPC www.nanoparticles.ethz.ch
- [16] A. Löfvendahl; Volvo Car Corperation; Clean Compartment Concept by Volvo Cars; Volvo Safe & Sound 2004
- [17] TD-Luke et al. Queensland University, Australia ; Effect of Cabin Ventilation Rate on Ultrafine Particle Exposure Inside Automobiles ; Environ.Sci.Technol.2010
- [18] O.Geiss et al : EU-JRC, Ispra ; Exposure to Particulate Matter in Vehicle Cabins of Private Cars; Aerosol and Air Quality Reseach 2010
- [19] C.Sioutas et al ; University of California; Vehicle and driving characteristics that influence in-cabin particle number concentrations : Enviro.Sci & Technology 2011
- [20] H.Burtscher et.al ; FHNW ; Nanoparticle Filtration for Vehicle Cabins ; SAE 2008-01-0827
- [21] A.Mayer et al. ; TTM ; Clean Air in Vehicle Cabins. Ventilation Conference 2012 Paris
- [22] L.Tartakowski; Technion-Israel Insitute of Technology, Haifa; In-vehicle particle air pollution and its mitigation
- [23] J.Pintos et al; Occupational exposure to diesel engine emissions and risk of lung cancer; Occup.Environ.Med. 2012