

Retrospective on the Introduction of Particle Filters to Eliminate Emissions of Nanoparticles from Engine Exhaust Gas

Andreas Mayer*, Max Wyser, Jan Czerwinski, Thomas Lutz, Friedrich Legerer, François Jaussi, and Norbert Heeb

Abstract: The particle filter for most diesels and some petrol categories is now state of the art. The worldwide population is estimated to be >250 million vehicles with filters. The nanoparticle concentration in ambient air is thus reduced in Switzerland to one third of the status of 2005 and worldwide premature deaths by traffic related ambient air is reduced by >2 million cases annually. This success story started in 1995 when SUVA, the Swiss occupation health authority, had to guarantee safety and health in the world's largest railway transalpine tunneling system, NEAT, scheduled to be built from the year 2000. The solution was VERT certified diesel particle filters (DPFs) on all engines without any exceptions. Transfer to other applications and other countries, however, had to overcome serious resistance of industry and politics which delayed the process remarkably until filters became mandatory by the EU-legislation 2011. The decisive element was the introduction of the particle number (PN) limit for solid particles of sizes 10–500 nm in place of particulate matter (PM) mass in 1995. Many vehicles are still waiting for filters worldwide and the effect of this highly effective and cost-efficient tool on health and global warming could be more than tripled.

Keywords: Benefit/cost · Health effects · Nanoparticles · NEAT-VERT-project · Particle filter · Secondary toxics



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deNOx systems, combined DPF-deNOx-systems, and GPFs. For his research on particle filter chemistry, he was awarded the Sandmeyer Prize of the Swiss Chemical Society in 2009. President of the ETH-NPC 2019–2025. Many publications and oral presentations.

1. Introduction

Combustion soot has been known to be carcinogenic since 1775, thanks to P. Pott with his observations of chimney sweeps. In 1962 P. J. Lawther^[1] statistically linked the increase in lung

cancer rates in London and Wales after the first world war to combustion engines. Prior to this, lung cancer was not a notable cause of death in Europe according to oncologist Franco Cavalli (SRF1, Arena 2004). In 1936, the German journal ‘Staub’ called to focus on submicron particles in occupational safety. In 1959, the Johannesburg Conference classified particle risks according to their size down to the alveolar range.^[2] In 1952, 12,000 people died in the London’s SMOG event^[3] – six months earlier, diesel buses had been introduced to replace electric trams. None of this had any policy consequences, and Winston Churchill, Prime Minister, attached no importance to it, according to his memoirs. In 1970, the Clean Air Act (CAA) was passed in the USA, focusing exclusively on petrol engines, and finding its perfect technical solution in 1976 with the three-way catalytic converter developed by John J. Mooney. The CAA did not, in fact, address any health risk from particulate matter (PM), but the first large epidemiological study, the so-called 6-cities study by D. Dockery from Harvard University,^[4] starting 1973 with 15,000 candidates, found 1993 a statistically significant association with mortality only for fine particulate matter, not for PM₁₀, not for sulfur dioxide, aerosol acidity nor for ozone. After the oil crisis and the resulting demand for reduced fleet fuel consumption, an interesting market for passenger car diesel engines emerged in the USA, and the authorities noticed that these engines, which had not previously been subject to any limits, sometimes emitted heavy smoke. The first limit value for diesel cars was introduced in California in 1982 with 0.6 g/mile, and none of the engines could meet this limit. Corning offered cordierite wall-flow filters in 1982. Intense technical competition among all diesel manufacturers began and is documented in the proceedings of the SAE conferences^[5] of the decade. Daimler and VW were the first to receive approval for their filters in 1986, and the market boomed until 1988, when thousands of Daimler engines failed in quick succession because the catalytically coated substrates slowly disintegrated, and the ceramic entered back into the engine *via* the exhaust gas recirculation line. All manufacturers stopped using particle filters, and the industry swore off the filter for good. The shock was profound and continues to reverberate in many places to this day. The actual cause was never published in detail: during periodic temperature peaks (regenerations), this catalyst formed a low-melting ceramic phase with the base material, initially creating pinholes and eventually causing pieces to break off. A shocking sight, as shown by a historical fracture picture in Fig. 1.

The particle filter in vehicles, which had proven its high efficiency in many different designs, had thus died before it was even adolescent. Manufacturers withdrew diesel vehicles from the US market. Limits for particulate emissions as PM mass were gradually introduced in the US and Europe, but remained so modest that filters were not required. The World Health Organization (WHO)’s 1987 statement that diesel soot was ‘probably carcino-



Fig. 1. Left: Fragment of a DB particulate filter from the 1988 damage series. Source VERT; Centre: London SMOG 1952; Right: Soot particles in the lungs of London SMOG victims, source Ref. [3].

genic to humans’ was not incorporated into any emissions policy with the necessary urgency. It was not until 2012 that the WHO’s International Agency for Research on Cancer (IARC) announced the reclassification of diesel exhaust into Group 1 (‘proven to be carcinogenic to humans’).

According to the European Environment Agency, air pollutants caused approximately 5,500 premature deaths in Switzerland. The Swiss Federal Office for the Environment (FOEN) stated: “*Of all the health effects, those on the heart and circulatory system are the most significant. They account for 80% of deaths attributed to air pollution. The remaining 20% of deaths are mainly due to lung cancer and other lung diseases, which are also caused by the effects of fine dust particles.*” (FOEN homepage 17.1.2025)

2. NEAT and VERT

On 2 May 1992, the Transit Agreement of Switzerland with the EU was concluded and approved by Parliament on 16th December 1992. Part of the Transit Agreement was the NEAT concept with three tunnels, including the world’s longest, the Gotthard Base Tunnel, which is 57.1 km long with a diameter of 12 m for high-speed train operation. On 27th September 1992, the Swiss people approved the federal resolution on the construction of the Swiss transalpine railway with 64% voting in favour, after a referendum had been called against it (Fig. 2).

Construction was scheduled to begin in 1999. SUVA, responsible for occupational health and safety, had to ensure that there were no avoidable health risks by then. In 1993, SUVA had already introduced a limit value for ultrafine particles in the air of work places, called DME (diesel motor emissions) of 200 $\mu\text{g}/\text{m}^3$ for total hydrocarbons THC (shortly afterwards redefined to solid, insoluble particles EC <100 $\mu\text{g}/\text{m}^3$) and had listed diesel engine emissions as carcinogenic. This was based on WHO 1987, research of G. Oberdörsters^[32] and U. Heinrich^[33] and others, the DFG-MAK-Standards^[34] and summarized by M. Kasper.^[35]

Initial calculations about the air pollution in tunnelling showed that these limits would probably be exceeded by a factor of >50 during full construction using standard construction machinery. It was therefore urgent to develop solutions in time.

As similar tunnel projects for rapid transit systems were planned in Germany and Austria, the Swiss occupational health authority SUVA joined forces with the relevant organisations, the German Tiefbau-Berufsgenossenschaft TBG and the Austrian occupational health authority AUVA 1995, to launch the common VERT project (Verminderung der Emissionen von Real-Maschinen im Tunnelbau) and a consortium of around 50 creative companies was founded to contribute to pioneering solutions. This group later became the VERT Association.

From the outset, it was clear from an occupational health perspective based on the 1959 Johannesburg Convention, that

insoluble particles smaller than 500 nm were to be considered serious pollutants, and that this was a task for both metrology and limit value setting. PM as a mass metric had to be abandoned, in direct confrontation with the prevailing emissions philosophy. A ‘by-product’ of the VERT project was therefore the establishment of the ETH Nanoparticle Conference (NPC) in 1997 to address this confrontation with science and experts in a global exchange.

This was at a time when automotive circles tended to avoid discussions about the health risks of exhaust gases and the need for exhaust gas aftertreatment. The exhaust gas testing centre AFHB at the University of Applied Sciences in Biel, directed by J. Czerwinski however, was open to environmental concerns and was fortunately already very well equipped for these tasks. Prof. Siegmann’s ETH Institute, with U. Matter, H. Burtscher, and M. Kasper, was also able to support the work with its expertise in aerosol measurement technology, with the condensation nucleus counter (CNC) available from the company TSI since 1976, and later the Scanning Mobility Particle Sizer (SMPS) playing an important role, so that from the outset all possible metric criteria such as PM, EC/OC, PN depending on particle size, solid and volatile, as well as PAH deposits using the ETH developed Photoelectric Particle Sensor (PAS) had been included in this investigation in parallel.

During a two-year experimental phase, a wide range of solutions were tested on engine test benches, but only actual particle filters – from fibre filters and metallic sintered filters to extruded ceramic wall-flow filters – met the requirements in the test bench test. In order to test the additional requirements in practical use, especially the ability to regenerate without leaving any residues or secondary emissions, 10 systems were taken into a two-year field test and tested under the toughest operating conditions on construction machinery with electronic control.

After many development phases, finally all 10 systems passed this rigorous test and were therefore included in the VERT filter list of ‘best available technology’ from 1997. Based on these results, SUVA decided that only diesel engines with VERT-certified filters^[6] could be used underground and no exceptions were tolerated. Regardless of the size, design or age of the engines, an efficiency of >95% had to be demonstrated based on the number of solid particles in the size range of 10–500 nm, without ageing over 2000 hours. This decision was met with massive protests from engine manufacturers, who refused to honour their warranties, but SUVA enforced it without compromise within two years. An episode that took place in the NEAT tunnel in Valais is noteworthy: SUVA wanted to grant some construction machines an exemption in order to meet deadlines. The entire workforce responded with a strike because they did not want to accept such a reckless deterioration in the air quality. The success became apparent after a few years in the ambient air monitoring of a large number of tunnel construction sites (Fig. 3).

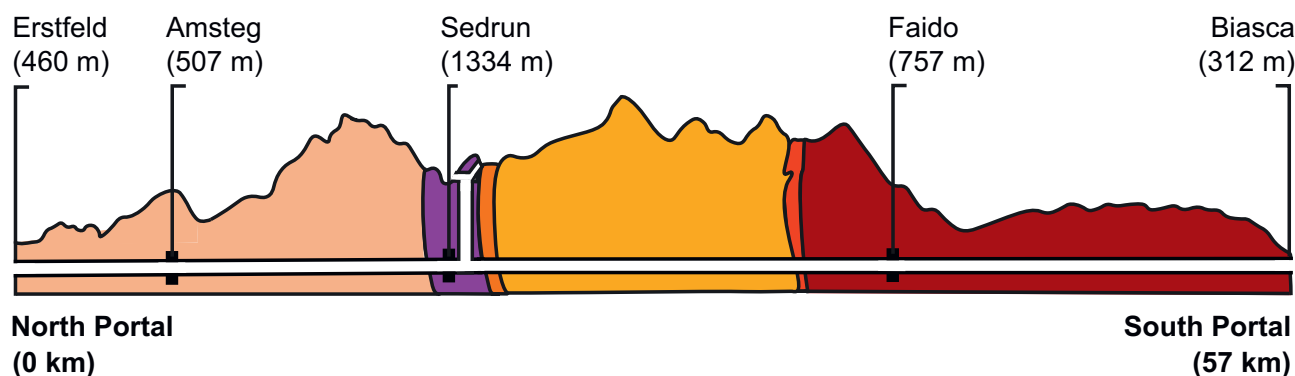
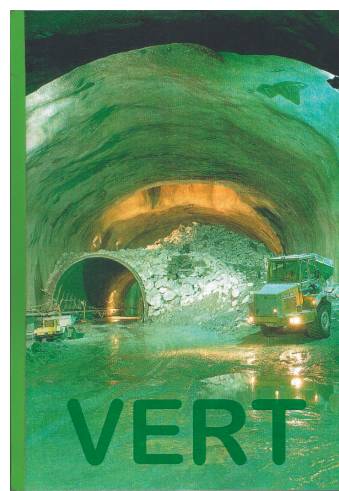
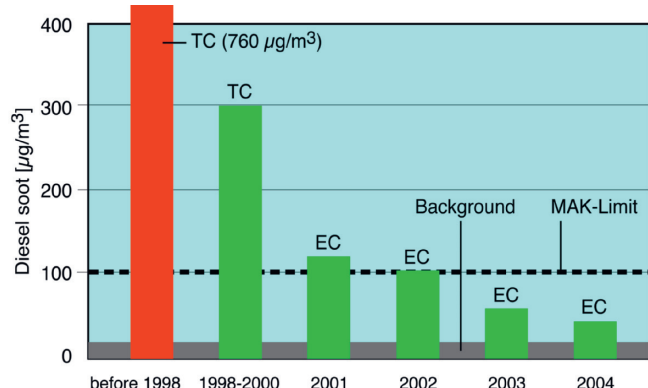


Fig. 2. Gotthard Base Tunnel of the NEAT, source Heeb at ETH-NPC, adapted from Internet 2000.

SUVA:Tunnel-Luftqualität 1998-2004



VERT® Filter List



Fig. 3. Left: Improvement of air quality in tunneling; Right: report A. Mayer VERT-SUVA 2000, VERT Filter List since 1998 with now >80 DPF systems worldwide certified, in addition SCR, GPF and NPPI instruments. Source: VERT.

It should be noted that this development took place at a time when the sulfur content in diesel fuel in Switzerland was still 500 ppm and up to 10,000 ppm in many countries where VERT introduced DPFs, like China and Iran. This result, which summarised the expertise gained over the previous two decades, paved the way for the highly efficient purification of diesel exhaust gases in all types of engines and was taken up in a variety of ways. In Switzerland, this applied to all non-road vehicles - as Switzerland had meanwhile committed itself to the EU emission regulation for road vehicles - and also to all public transport buses, trucks on construction sites, ships on Swiss lakes and stationary engines. The experiences were widely published and taken up in many places, but also triggered massive resistance, including legal proceedings against the protagonists, personal attacks, exclusion from public contracts and more.

3. Number Criterion and Number Measurement

The demand to move away from mass-based assessment and to evaluate particles according to their number concentration, size, and substance, is of course derived from their biological effects. Only insoluble particles < 500 nm enter the alveoli and some spread from there ubiquitously throughout the organism within a few hours.^[7] Soluble particles are quickly diluted at the molecular level in the upper airways and their toxicity is negligible at the given concentrations. Larger particles have more mass, which makes them more significant for a mass criterion and with this for the standard PM_{2.5} based dose-response relationship, but being large is precisely why they have less health effects, not even reaching the alveolar range and being cleared out most effectively by the mucociliary cleaning mechanism.^[2,7,35]

Once the nanoparticles have penetrated the alveolar membranes, they act individually, so to speak, due to their almost inert basic substance, EC, and accumulated toxics, and the more there are, the more places they attack simultaneously. They are neither rendered harmless by agglomeration nor do they dissolve, posing a persistent threat. The important separation between solid and volatile substances was initially achieved by activated carbon absorption, then by evaporation and dilution (Particulate Measurement Programme, PMP)^[8] and, in some cases, by catalytic strippers.

Furthermore, as filtration depends on size, filtration effects of an aerosol ranging from 10 nm to >2500 nm cannot be evaluated based on the accumulated mass, for example to PM_{2.5}, nor can the overall number be used as a valid criterion. With very small particles, diffusion is particularly effective at low speeds, while with very large particles, impaction is particularly effective

at high speeds – a conflict of objectives, and most filters have problems in between.^[9] However, this critical size range is precisely where we find combustion particles, and it is again precisely where penetration from the alveoli into the blood vessels is particularly high,^[2,32] making size-oriented measurement by number a must.

Finally, gravimetric measurement of mass is so insensitive compared to number measurement technology, namely by at least three orders of magnitude, that the quality of the filters cannot be recognised at all by mass nor can mass limit values be used to verify filter quality.^[35]

When UN-ECE finally recognised the importance of the PN-criterion in 2008, the EU accepted it and incorporated it into emission legislation with the following concise wording (EU co-decision procedure, Art. 12 (15)).

“In order to achieve these environmental objectives, it is appropriate to note that particle number limits are likely to reflect the highest performance level of particle filters using the best available technology. The Commission is introducing particle number-based limits at a level appropriate to the technologies actually used”.

The revolutionary need established here to assess the health impact of particles emitted by combustion engines in terms of their number, size, and substance has thus been accepted worldwide as a consequence of the VERT rules for filter assessment 13 years before and has also been recognised for the assessment of particle emissions in Euro 5b vehicle type approval from 2011. In the next step, the number criterion was also recognised for PTI, the periodic inspection of vehicles,^[10] first by the Netherlands, Belgium, Germany, and Switzerland from 2022, later at the European level in the Roadworthiness Directive 2024. Furthermore, in its 2021 recommendations, the WHO recommended number measurement for breathing air, setting a range of 1000 #/cm³ (good) to 10,000 #/cm³ (bad), and the EU extended its AQ Regulation to include number measurement in October 2024.

Irritating however is the fact that in spite of PN emission limits for all vehicles, the resulting health effects are officially still attributed to PM_{2.5} mass in EU-directives (EU 2021/2279 and ReCiPe 2016)^[36] and we regard this as a scandal which hinders air quality improvement worldwide.

4. Proof of Toxicity Reduction and Benefit/Cost

The introduction of a new component like a filter to reduce emissions requires, in the understanding of the authorities and industry, scientific proof of effectiveness and a convincing benefit/cost ratio. Already existing studies, such as epidemiological

statistics of the 6 cities study, pointed to a correlation between mortality and $PM_{2.5}$, and toxicological research, mostly in animal experiments, showed the effects of ultrafine particles, but there was no closed chain of causality to traffic related nanoparticles. So how could the effect of the filters be conclusively proven, and the application defended?

For this purpose, a biological laboratory was set up right next to the engine test benches in the emission lab in Biel, where a triple cell culture with human cells (epithelial cells, macrophages, and dendritic cells) was exposed to exhaust gases in concentrations similar to those found in urban environments. This allowed us to come as close as possible to reality and to examine a large number of influencing factors, such as filters, catalytic converters, fuels and lubricating oils, very sensitively for their biological effects (Fig. 4).

These studies were conducted by the Universities of Bern and Fribourg in three dissertations (L. Müller, S. Steiner, Chr. Bisig) and contributed to this method being adopted in many other places.

For the filter project, it provided evidence that the triggering of inflammation by soot particles, which is commonly regarded as the start of harmful processes, can be entirely avoided by using VERT certified soot filters and also that mutagenic damage (such as from PAH) can be avoided by equipping the system with appropriate catalytic equipment.

The benefit/cost analysis was requested by the Swiss Federal Council prior to the introduction of filters on construction sites in 2003 and resulted in a conservative estimate of 4:1 for retrofitting,^[11] which led to the decision to equip in-use construction machines with filters. Today, with lower costs and increased knowledge about the health effects, this value has exceeded 30:1.

5. Resistance by Industry and Politics, Problems, Goals and Quality Assurance

While SUVA was able to quickly enforce the filter requirement in tunnel construction thanks to the time pressure from the NEAT tunnelling, efforts to introduce filters in the off-road sector met with considerable resistance in Switzerland from the construction industry, equipment manufacturers and their political representatives. Three parliamentary motions, especially the motion by Hutter 2004, herself a construction equipment dealer, shook the Federal Council's decisions, and only a major public campaign by press and TV, trade unions, scientists and medical

doctors was ultimately able to stop this at the very last moment, while the individual filter retrofit protagonists finally had their government consultancy mandates revoked for good.

The manufacturers refused to honour their warranties, and it was only a guideline agreed with the builders' association, which guaranteed them generous compensation for public contracts, that gradually removed the resistance. Exceptions and concessions by the authorities delayed implementation and undermined its effectiveness.

During this phase, VERT took the opposite course, tightened its certification guidelines, raised the limit value to 98% and introduced a 2,000 operation hours endurance test, thereby steadily improving quality requirements and controls.

When filters for road vehicles were subsequently introduced, this resistance from the industry took on adventurous proportions. While Peugeot had launched its perfect FAP system on the market in 2000, those from almost all other manufacturers were so 'primitive' that many problems arose, and vehicle operators were instructed to trigger regeneration by driving fast on the motorway. The aim was most probably intentionally to create widespread resistance to the filters on the political agenda, which almost succeeded.

A special feature of this phase was the introduction of so-called open filters, whose extreme weaknesses VERT was able to comprehensively demonstrate. Invited to in a hearing of the German Bundestag 2008 (Protokoll 16/58, 5.3.2008) VERT was able to stop the political decision to use these open filters, but nevertheless the VERT leaders were inundated by the industry with three lawsuits for threatening competition.

It was not until the diesel scandal of 2015, which was actually triggered by inadequate deNOx technology, that the alarming extent of manipulation of the DPF, at this time already required by law, became apparent. This dramatic attack on public health enabled VERT, again in a government hearing in Berlin (5. Untersuchungsausschuss der 18. Wahlperiode 22. Sept. 2026), to initiate periodic technical inspections based on particle number measurement.^[10] The measurements, which began on a large scale in 2018, showed 10–12% failures, the 'dirty tail' of the fleet, but much higher in cases of some manufacturers such as Ford and Volvo. Now that more than 15 different types of measuring devices have been implemented in test centres and workshops in numbers exceeding 60,000, and this control has thus proven itself in four European countries (NL, B, BRD, CH), it is becoming

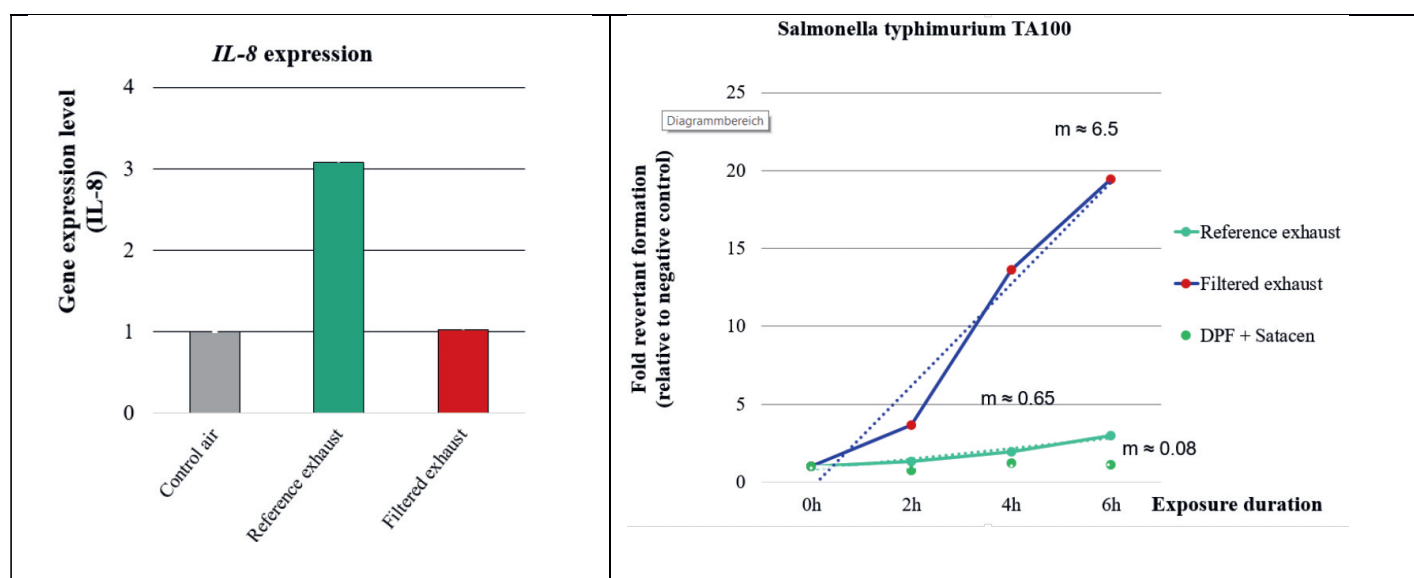


Fig. 4. Left: Filters prevent the development of inflammation; Right: catalysis prevents mutagenicity. Source: Refs. [37–46], University of Fribourg in close cooperation with VERT.

generally binding under the EU Roadworthiness Directive and many other countries are adopting it.

The quality assurance system based on the VERT filter list, which has been in force since 1998, was converted into the Swiss standard SN 277206 in 2011. It focuses on the properties of the filter itself and assumes that, up to a maximum permissible Space Velocity (SV) (volume throughput/filter volume), the filter will have similar properties on every engine. It was also adopted in parts by an UN-ECE directive, the REC Directive, Reg.132, Add.131 215, which, however, has gained little significance because it requires the combined testing of each engine and filter and is therefore unnecessarily complex.

6. State of the Art of Filter Substrates

Of the many approaches, ceramic wall-flow filters have become the standard due to their small specific size and large built-in surface area, their durability, and their low cost. They are available in cell densities of up to 400 cpsi in several materials, primarily cordierite and silicon carbide. An average pore size of 10 μm with a narrow pore size distribution offers optimum low back pressure and high separation rates. The space velocity is usually around 30 1/s. The special feature of this structure is that, macroscopically, the inflow velocity is slowed down by a factor of 500 to the wall flow velocity of a few cm/s and that, microscopically, the pore structure of the wall forms a labyrinth with a large surface area.

With a pore size of 10 μm , it is surprising that particles, being 100 times smaller are separated at all. In fact, despite the very low flow velocities of around 5 cm/sec, which favour diffusion,

the separation efficiency of the clean filter, *i.e.* after each regeneration, is very poor and only reaches the high values of > 98 % after the formation of a soot cake, as shown in Fig. 5 by S. Payne *in statu nascendi*. This was accepted until the introduction of filters for petrol engines, which do not form soot cakes. However, the VERT filter test took this into account by determining the separation efficiency in the driving cycle both at full load and after regeneration. Even during regeneration, the peak emission is monitored and must reach 90% separation efficiency. While the soot and its adsorbates burn without residue during regeneration, ash, which is separated in the same way, remains in the filter, and must be cleaned out at longer intervals (typically 100,000 km) by means of pulsating backflow. These filters do not age; in fact, their separation efficiency increases over time due to the accumulation of ash, and they show very favourable values in life cycle analysis.

7. Catalysis and Secondary Emissions

In addition to soot, the filter absorbs the various educts of engine combustion, can store them and, depending on the driving cycle, provide temperatures that turn the filter into a powerful chemical reactor. This property is further enhanced if the filter has a catalytic coating, or the fuel is enriched with a catalytically active substance (fuel additive). A Swiss regulation issued by the Federal Department for Justice and Police FDJP in 1990, based on the US CAA, therefore allows the retrofit of filters and catalytic converters only if it has been proven that no toxic substances are produced that were not previously present in the exhaust gas, thus going far beyond European regulations. This led to the requirement to test for secondary emissions, often highly toxic trace

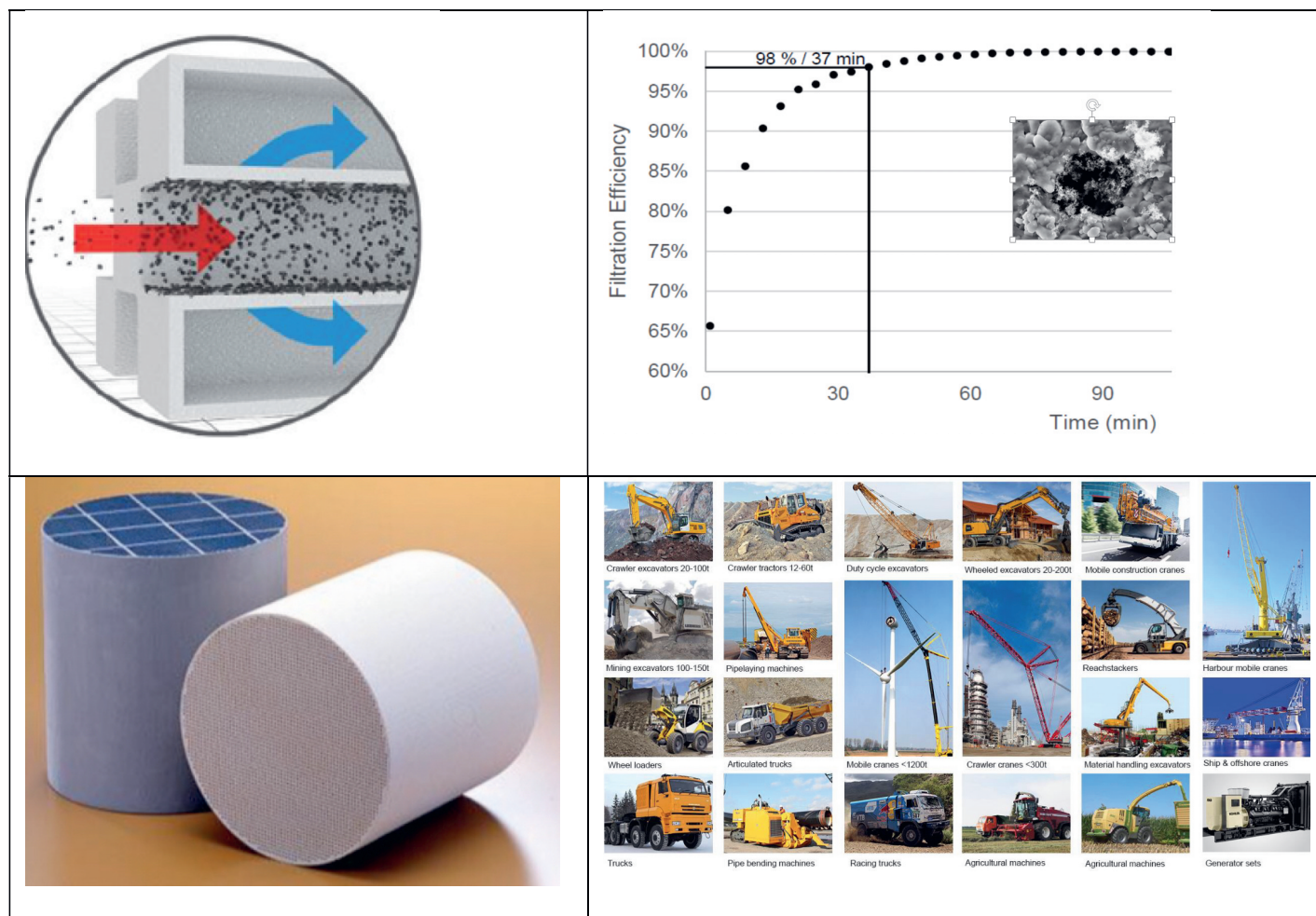


Fig. 5. Top left: the principle of the wall flow cell filter, courtesy CORNING; Top right: these DPFs require a soot layer to become effective. Source VERT research. Microscopy of pore closing mechanism courtesy S. Payne; Bottom left: fine-cell extrudates made of cordierite and SiC; Bottom right: the variety of applications in construction, courtesy LIEBHERR.

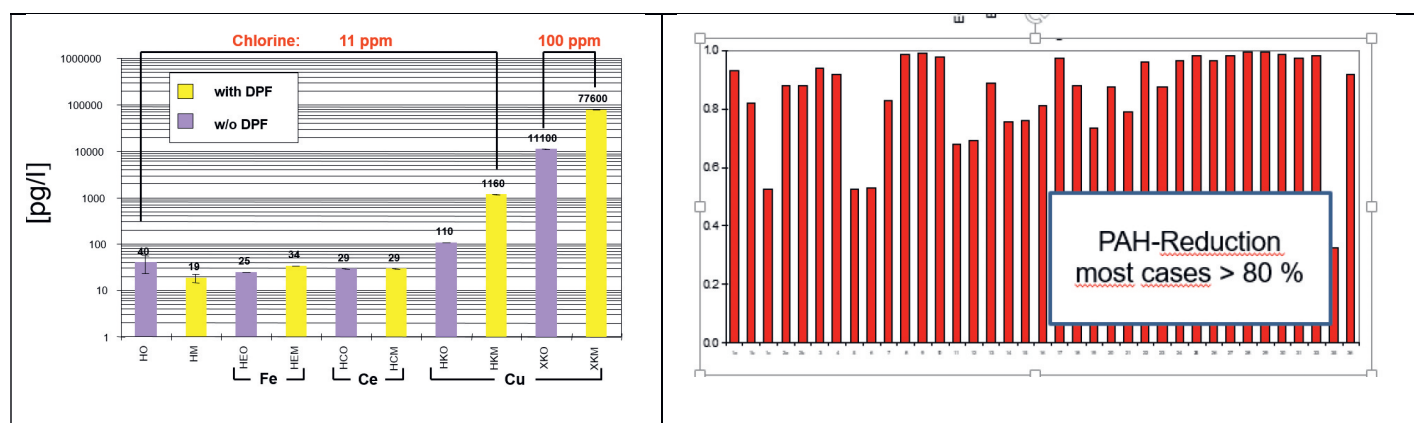


Fig. 6. Left: dioxin emissions with Cu additive; Right: reduction in total PAH emissions, including substances attached to solid particles. Source EMPA Ref. [22].

substances, being introduced into the VERT test and performed by EMPA.^[12]

The fact that this makes perfect sense soon became apparent in 1998 during the investigation of a fuel additive containing copper, which produced dioxins and furans in the corresponding test that exceeded the basic emissions of the engine by 3–4 orders of magnitude, see Fig. 6. The additive was subsequently banned worldwide.

This was followed by several serious cases of extreme toxic secondary emissions, which were eliminated, such as the formation of nitro-PAHs. On the other hand, the filters also demonstrated positive properties in minimising genotoxic PAH emissions, partly during regeneration, but also after desorption through catalysis.

8. Improving Air Quality Thanks to DPFs

In addition to PM_{10} , $PM_{2.5}$ and gaseous pollutants, the Swiss air quality monitoring programme NABEL has been recording the concentration of particle number PN and EC at several locations since 2005. The values for the Härkingen motorway junction, which are likely to be typical of changes in emissions from vehicle engines, are shown in Fig. 7. Similar evaluations are available for central London and Leipzig Low Emission Zones, LEZ. They all show a marked decline in EC and fine particles, which can be attributed to the effect of particle filters in European legislation, an impressive proof of success for the development discussed here.

Of course, this is not yet satisfactory if we take as a basis the Dutch DECOS 2023^[13] requirement for a cancer risk of 4/100,000 in the workplace, which presupposes a BC concentration of 0.1 $\mu\text{g}/\text{m}^3$, or the WHO recommendation to aim for a particle concen-

tration of 1000 $\#/\text{cm}^3$. This should be reached at the workplace of a lorry driver.

9. The Global Effect on Air Cleaning 2025

Nearly all new diesel engines today are equipped with good particle filters. An extrapolation from the production figures of the major manufacturers results in a total of >250 million vehicles,^[47] that today emit 98% fewer nanoparticles than their predecessors. It is estimated that this has reduced the epidemiologically confirmed number of 10 million premature deaths by >2 million per year, which corresponds to a monetary value of 2,000 billion Euros, or 10,000 Euros per filter per year.

However, many commercial vehicles, especially older ones, are not yet equipped with filters, particularly in emerging and developing countries. Their particles travel with weather events, can be detected on the Jungfrauoch and also affect our air quality in Switzerland.

Furthermore, particle filters are not fitted to almost all petrol vehicles, of which there are 4–5 times more than diesel engines. Only the new European DI engines have been required to be equipped with GPFs since 2018, but with 70–80% separation efficiency, they are much less effective than DPFs.

10. Global Warming

1 kg of black fine particles from combustion engines suspended in the atmosphere leads to an increase in the temperature of the Earth's surface that is 2,000 to 7,000 times higher than the effect of one m^3 of CO_2 , thanks to the transfer of radiant energy from the black particle into the ambient air.^[47] BC is therefore the number two global warming substance after CO_2 .

The effect of such particles on ice or snow surfaces is many times greater due to the long-lasting reduction in albedo. This

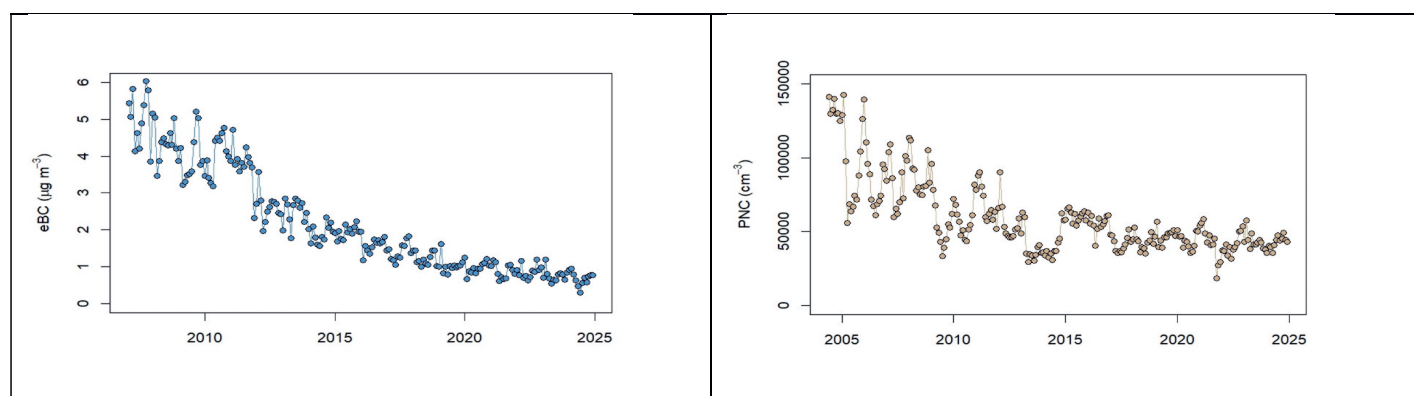


Fig. 7. Reduction in BC and particle numbers at the Härkingen site. Source EMPA, courtesy Chr. Hüglin.

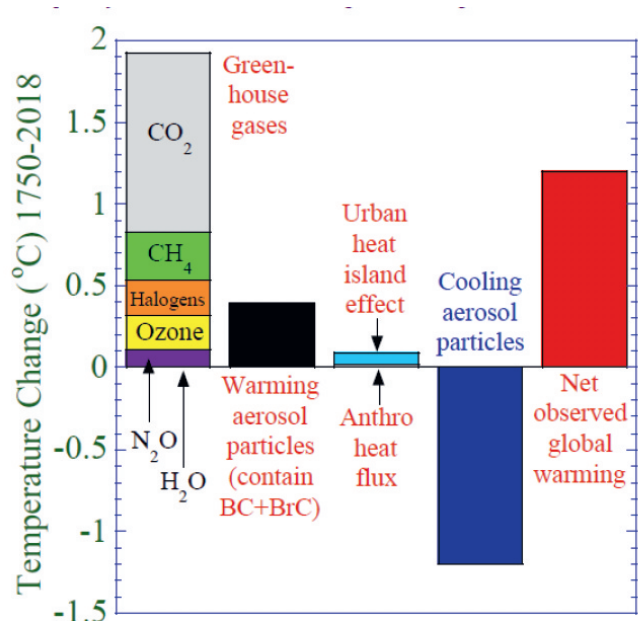


Fig. 8. Global warming due to particle emissions from combustion engines according to M. Z. Jacobson. Source: Ref. [14].

would not actually be necessary if filters were used consistently, also in marine application, a still neglected – rather politically intentionally delayed sector (Fig. 8).

11. Dirty Tail

Only periodic fleet-wide monitoring of particle emissions from diesel and petrol engines using the NPTI method has shown that particle emissions from fleets are very unevenly distributed.^[15] A large part of the fleet is obviously very clean, while 5–10% of vehicles have particle concentrations that are 4–5 orders of magnitude higher. This offers the unique opportunity to achieve a very large air cleaning effect with a relatively small number of retrofits (Fig. 9).^[15]

12. The Long Road to Filters for Petrol Engines

We have always known that the exhaust pipe of a petrol engine is just as black on the inside as that of a diesel engine and that the three-way catalytic converter is completely permeable to

nanoparticles. It is therefore puzzling that no measures were taken anywhere in the world until 2016, when direct injection DI petrol engines were actually introduced, which burn fuel more similar to diesel.

In 2006, M. Mohr^[16] thoroughly investigated this at EMPA, and from 2008 onwards, J. Czerwinski researched and published on the subject.^[17] In 2010, A. Ulrich demonstrated the highly toxic metal emissions from these engines,^[18] and in 2018, N. Heeb and M. Muñoz showed high concentrations of genotoxic substances on the very small particles.^[19] It is unfortunately true that the USA, with their huge fleet of petrol vehicles, are turning a blind eye to all the new findings thanks to a legislation which is still based on particle mass.

So, the impression is growing that the health effects of traffic emissions are largely attributable to petrol engines, and this is a solvable problem.

In 2021, as part of a Horizon project, the EU asked whether older petrol engines could also be retrofitted with filters, and VERT was awarded and carried out the AeroSofld project.^[20]

The results are impressive: new wall flow cellular filters are available^[21] that achieve filtration efficiencies of > 99% under all operating conditions. There are no secondary emissions. The serious problem of residue-free regeneration in diesel engines is solved automatically in petrol engines thanks to their much higher temperatures and oxygen surges during deceleration. The filter usually replaces the silencer and retrofitting can be financed for around 1,000 Euro for a mid-size car. Endurance tests up to 80,000 km have not revealed any problems.

So why is this not being incorporated into the regulations immediately? Because the regulations assess health effects based on mass, and nanoparticles <50 nm have no mass, so to speak. Atmospheric PM_{2.5} only changes in the scattering range, even if all petrol engines have filters. Although we detoxify PM_{2.5} completely by eliminating the traffic related carcinogenic nanoparticles this is not recognized by the authorities since the effect on mass is small.

It is therefore unlikely that the incredible success story of the introduction of particle filters in diesel engines will be repeated, leaving a bitter aftertaste, as described by H. C. Siegmann in the review of his life: “Humans are not capable of reacting to foreseeable risks in time.” (private letter)

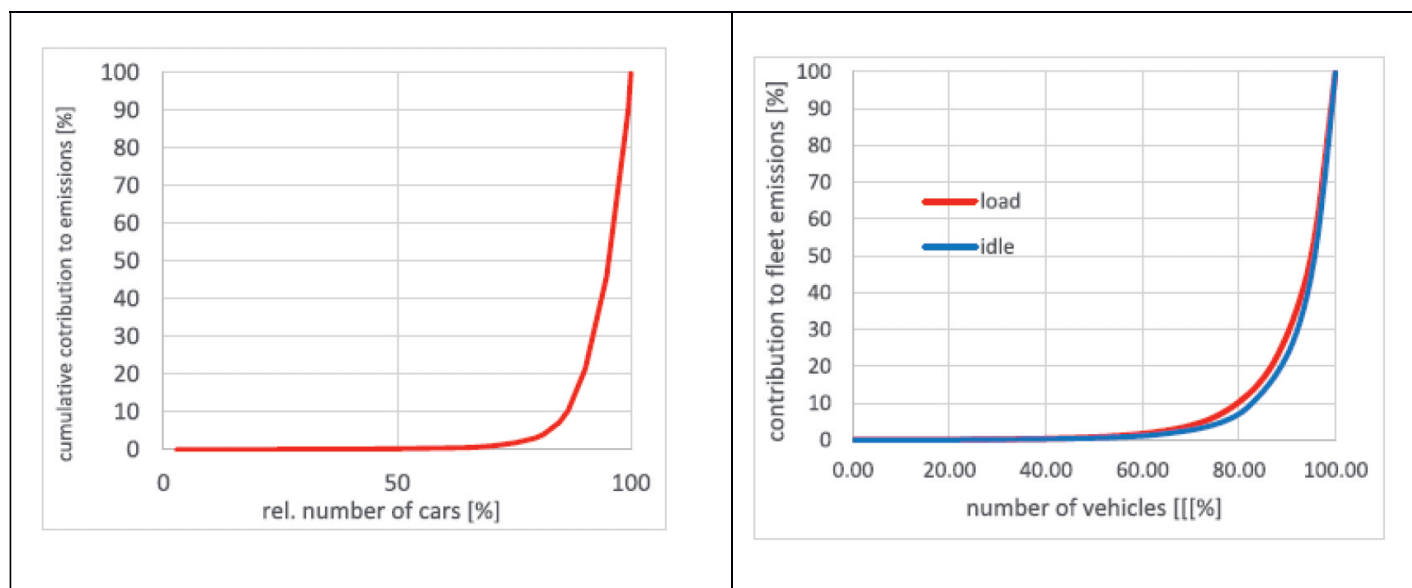


Fig. 9 Fleet emissions generally form a dirty tail. Left: 1000 diesel vehicles with filters in Zurich in 2018; Source B. Gloor; AWEL; Right: 1000 petrol vehicles in Biel in 2024. Source: VERT research within the EU Horizon project AeroSofld.^[15]

13. Technology Consolidation and Developments

DPF-Technology Consolidation

DPFs started with a multitude of technology proposals, from ceramic and metal fibre technologies in different textile formations and sinter technologies to cellular extruded wall flow structures which were already in the race from the beginning of 1982 and finally dominated the market because of their high filtration surface/bulk volume ratio, low cost and long-lasting quality. This interesting part of technical history is mirrored in the SAE emission control conferences.^[5] For educational purposes the authors have published this from 2004 onwards in a sequence of 8 editions of ‘Handbuch Verbrennungsmotor’^[25] and also in the ‘Lexikon Motorentchnik’,^[26] which is still available on the internet^[27] as well as in a series of 3 books on ‘Elimination of Engine Generated Nanoparticles’.^[28–30]

Regeneration of DPFs

An even higher variety of technologies has been developed to solve the complex problem of filter regeneration, meaning the continuous or periodic emission-free combustion of the soot stored in the filter. This was particularly difficult when the sulfur content of fuel was still as high as 500 ppm, and in some countries like China and Iran, where VERT was actively promoting filter technology, even 10,000 ppm. A review provides details on still available solutions,^[6] whilst the physical elements to handle the thermal management of engines for this purpose have also been analysed.^[31]

GPF-Consolidation

While the nanoparticle emissions of gasoline engines have been neglected over decades, the EU-legislation asked for a PN limit for DI petrol engines first in 2016/2017 on the same level as for diesel engines. Manufacturers simply used the existing DPFs which resulted in filtration efficiencies of 70–80% because of the missing soot layer with gasoline engines. A new development only appeared in 2021^[21] with ceramic membranes or hierarchical pore structures.

Combination of DPF and SCR

Today’s series-production engines use multiple SCR units to bring NO_x emissions below the required extremely low limits. Given the fact that health effects due to NO₂ are only observed at concentrations > 400 µg/m³ according to the US EPA, the currently required limits in ambient air and at the exhaust are unnecessarily high and result in benefit/cost ratios < 1. A DPF and SCR unit in a single component would be sufficient, as demonstrated by VERT.^[23]

Oxidation Catalysis in the Outlet Channels of DPFs and GPFs

Secondary emission measurements have shown that highly toxic substances sometimes desorb from the soot deposited in the filter and reach the environment. Oxidation catalysis in the outlet channels of the filters could effectively prevent this.

Filters for Marine Engines

For these engines, especially the large two-stroke engines that are responsible for very high particle emissions there is currently no technical solution. Particularly not for retrofitting and when these engines burn heavy fuel oil. The wall flow cellular filters described here offer a very good option if designed as membrane filters, storing the soot on the surface so that they can be cleaned periodically by pulsed air flushing back.

Non-exhaust Applications

Since viruses have a similar size distribution to soot particles from engine combustion, solutions for infection control were developed during the coronavirus pandemic for critical locations such as hospital beds. Wall flow filters separate > 99.99% of vi-



ruses, and these viruses adhering to the filter walls irreversibly lose their activity within 24 hours. Infection protection reaches 95% and above.^[24]

Acknowledgements

Instead of naming the many participants in the VERT network during this period, a picture of the team is shown here and reference is made to the ETH Nanoparticle Conference archive, which is accessible online at www.nanoparticles.ethz.ch

Abbreviations

AFHB	Abgasprüfstelle der Fachhochschule Biel
AUVA	Allgemeine Unfallversicherungsanstalt AU
BC	Black Carbon
CAA	US-Clean air Act
CNC	Condensation Nucleus Counter
DECOS	Health Council of the Netherlands
DeNOX	NO _x -Emissionen Reduktion
DPF	Diesel particle filter
EC	Elemental carbon
EGR	Exhaust gas recirculation
EMPA	Eidg. Materialprüfungs- und Forschungsanstalt
ETH	Eidgenössische Technische Hochschule
EU	European Union
FDJP	Federal Department for Justice and Police
FOEN	Federal Office for the Environment
GPF	Gasoline particle filter
IARC	International Agency for Research on Cancer
NABEL	Netz der Luftschadstoff-Messstellen Schweiz
NEAT	Neue Eisenbahn-Alpen-Transversale
NPTI	New Periodic Technical Inspection
OC	Organic Carbon
ÖIAZ	Österr. Ingenieur und Architekten Zeitschrift
PAH	Polycyclic-aromatic hydrocarbons
PM	Particle mass
PM10	Particulate Matter of particles < 10 µm
PM2.5	Particulate Matter of particles < 2.5 µm
PN	Particle Number Concentration
PPM	Parts per million
PTI	Periodic Technical Inspection
REC	Retrofit Emission Certification UN-ECE
ReCiPe	Regeln zur Ermittlung der Health Effects
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reaction
SMOG	Mixture of Fog and Smoke
SMPS	Scanning Mobility Particle Sizer
SUVA	Schweiz. Unfall Versicherungs
TBG	Deutsche Tiefbauberufsgenossenschaft
THC	Total hydrocarbons
TSI	Manufacturer of Instruments for UFP
UN ECE	United Nations Economic Comm. for Europe
VERT	Verminderung der Emissionen im Tunnelbau

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