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Particulate Filters for Combustion Engines to Mitigate Global Warming. Estimating the Effects of a Highly Efficient but Underutilized Tool

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Abstract

Particulate filters are state-of-the-art and are used in internal combustion engines worldwide to eliminate carcinogenic nanoparticles. Health studies estimate that this prevents about one million premature deaths annually. What is less known and often neglected is their equally powerful effect on mitigating global warming. This is because these ultrafine particles form stable aerosols in the atmosphere, absorb sunlight, and heat the atmosphere due to their jet-black color. In addition, once deposited on the ground, they reduce albedo especially when deposited on ice or snow. They also thin clouds and reduce their reflectivity. In this paper, we estimate for the first time the cumulative effect of more than 300 million particulate filters currently installed globally on vehicles, showing that, while they reduce ~0.5 Mt of soot per year, their effect on slowing global warming is equivalent to reducing 1 Bt of CO_2 per year or about one-third of the CO_2 emissions of all European Union Member States combined. Despite its strong potential, this highly efficient, proven, and low-cost technology is not yet regarded as a priority in curbing global warming, even though it is possibly the easiest and quickest to implement. If used in retrofitting more diesel and petrol engines worldwide, it could triple the aforementioned effect. While modern internal combustion engines are on track to be replaced with zero-emission vehicles, it is also crucial, and we strongly suggest that, in the interim, all remaining internal fossil fuel combusting engines be fitted with particulate filters. Evidence is presented in this paper that the potential benefits of such retrofit on climate and human health will be impactful and lasting.

Keywords Global warming · Combustion soot particles · Diesel particulate filters · Retrofit of diesel and petrol engines · CO2 equivalence of black carbon · Benefit/cost ratio of DPF-application

Abbreviations

AECC	Association for emission control by catalyst
BC	Black carbon
cc	Cubic centimeter
DI	Direct-injection
DPF	Diesel particle filter
EC	Elemental carbon
EPA	Environment Protection Agency
ETH	Swiss Federal Institute of Technology
ETH-NPC	Nanoparticle Conference at ETH Zurich
EURO 4/IV	Emission limits in the EU
GHG	Greenhouse gases
GPF	Gasoline particle filter
GW	Global warming
GWP	Global warming potential
HDV	Heavy-duty vehicle
ICCT	International Council for Clean Transport
ICE	Internal combustion engines
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LDV	Light-duty vehicle
NRMM	Non-road mobile machinery

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PFI	Port fuel injection
PM	Particle mass
PN	Particle number
SAE	Society of Automotive Engineers
SiC	Silicon carbide
SN	Swiss norm
STRE	Surface temperature response per unit emission
SUVA	Swiss Accident Insurance Institute
UNEP	United Nations Environment Programs
VECC	Vehicle Emission Control Center of the PRC, Beijing
VERT	Verification of emission reduction technology
WHO	World Health Organization

1 Introduction

The natural greenhouse effect is due to the presence of natural water vapor, carbon dioxide (CO_2), methane, nitrous oxide, and other greenhouse gases (GHGs) in the atmosphere. It is caused by the fact that these gases are transparent to most sunlight but absorb the heat re-radiated by the Earth's surface. This greenhouse effect was postulated by Fourier in 1824 [31] and experimentally demonstrated by Newton-Foote in 1856 [30] as well as by John Tyndall in 1859. Global warming is the temperature rise of the Earth's lower atmosphere above and beyond that of the natural greenhouse effect due to anthropogenically emitted greenhouse gases, warming particles, and land-use change. Global warming due to carbon dioxide was first hypothesized by Arrhenius in 1896 [1], who calculated that a doubling of CO_2 in the atmosphere might increase global temperatures by ~5–6°C.

The physical laws of sunlight absorption by suspended soot particles are widely known since the additional experiments of Tyndall and the theoretical calculations of Beer, Lambert, and Mie, with research now focusing mainly on the effects in cloud formation, which in turn, of course, has a significant influence on global warming potential (GWP) [83].

Despite these alarming discoveries, burning fossil fuels, which are largely responsible for both phenomena, have continued ever more intensively to satisfy the unchecked, exponentially growing hunger for energy and prosperity by a growing global population.

Given the continued increase in the world population [65] and the expectation of an unbroken quality of life for people, a return to the natural quasi-equilibrium state (as implied by the term "sustainability") is not possible by political-organizational measures alone. As such, technologies are needed to address the climate problem. Engineers, primarily held responsible for the current situation, are now called upon again to find and implement solutions—and to do so quickly. It still needs to be proven whether this can be done in due time, but every effective effort to slow down the development trend should be taken up immediately.

This paper describes a pragmatic engineering approach to using available technology to rapidly mitigate emissions of black carbon from engine combustion through hot gas filtration. This would provide cost-effective and sustainable abatement of at least one component of global warming, arguably more amenable to an engineering solution than many others.

The fight against ultrafine BC particles, which are produced in technical combustion, was taken up to protect public health after the Big Smog of London in 1952 [48] by exhaust gas laws from 1982 in California and 1990 in the European Union (EU), so that solutions could be developed under the pressure of limit values. The first implementation of Diesel particulate filters in the EU came with the VERT project in occupational health and safety in tunneling in Switzerland from 1995 [20, 117, 126], which already targeted particle size [3, 35, 36, 86, 92], surface area [104], and number [17, 72, 80] and required 98% capture. After metrology was available from 1998 [70] and practicality was proven [117], the concept could be taken up by the UN-ECE [106] and the EU by Euro 5b 2011/13 [26] and has spread rapidly worldwide (Japan 2005, Korea 2010 China 2013, India 2019), so that they are currently state of the art [40] and 20% of all combustion engines worldwide, namely an estimated 300 million, are now equipped with particulate filters.

Switzerland demonstrated the feasibility of using particulate filters in heavy-duty vehicles (HDVs), non-road mobile machinery (NRMM), ships and locomotives [77, 82, 84, 89, 90, 95] and Peugeot with light-duty vehicles (LDVs) starting in 2000 [7, 91, 117]. The World Health Organization (WHO) declared soot particles a class 1 carcinogen in 2012 [115, 125]. About 200 million such filters are now in use worldwide in diesel LDVs alone. Another 100 million filters have been fitted in HDVs, gasoline LDVs, and NRMMs, for a total of over 300 million filters. This has reduced soot particle emissions by 0.5 Mt annually and thereby reduced health risks [75, 78, 79, 112] as well as global warming remarkably [87, 88], as will be shown later in this paper. However, emission inventories for global warming substances [50] have yet to consider this.

The reductions of soot emission could soon become significantly greater than estimated here if policies are put in place worldwide to require retrofitting all internal combustion engines with particulate filters. The technology is proven for all internal combustion engines, the production facilities are available in Europe, Asia, and the USA, and the capacity can be expanded quickly. There is probably no single technical measure to mitigate global warming that can have such a significant impact on both health and climate in a similarly short time at such a low cost.

2 The Heat from Solar Radiation Is Transferred to the Air by Soot Particles

The greenhouse effect is usually attributed to the absorption of the infrared radiation of the earth back into the atmosphere by CO_2 (and further five GHGs, especially methane [22, 33]). In contrast, the finely dispersed jet-black soot particles from engine combustion (whose radiation properties are very close to black carbon particles) are directly heated up by the sun [4, 51, 52], exquisitely transferring the absorbed energy to the atmospheric air by heat conduction and convection, where the heat radiation of soot particles is much lower than the heat conduction fraction. Because of the flaky, also called grape-like, structure of soot particles, this heat transfer from sun radiation to the atmospheric air is extremely effective [107]. This effect ceases only when a particle's morphology changes or its radiation properties change by surface effects like coating or chemical processes.

Even when sedimented, the effect is maintained. The deposited soot reduces the albedo (reflectivity) of light-colored surfaces, which darkens and thus increases the direct heat absorption. This results in the melting of snow and sea ice [41, 42, 54, 58], a process that stops only when the snow layer has completely melted (video experiment [32]) or when the soot particles have lost their absorptivity by sinking into the layer. In the air, soot also becomes incorporated in cloud drops and sits between cloud drops. In both cases, the soot warms the cloud, evaporating it and increasing solar transmission through the cloud in a positive feedback loop [56, 58, 60].

The warming process described depends on very many factors, which atmospheric physics and atmospheric chemistry are still investigating in extensive research [69, 83]. Still, the basic principle of rapid and efficient energy absorption directly from solar radiation to air and ground is widely confirmed by atmospheric physics and chemistry. Water coating can magnify it (magnifying glass effect [100]). It only disappears or reverses when absorption is replaced by reflection, which is entirely possible after prolonged aging and deposition of other matter. Thus, a limited duration of action must be assumed for these soot particles. Particles that do not have a BC-like radiation character, for example, mineral particles or condensate droplets, as they are visible in the contrails after aircraft engines, do not have these properties, of course, and may even contribute to the cooling of the atmosphere, as shown and justified in the comparative summary of the effects of different substances by the IPPC. However, some authors point out that the contribution of BC there is still greatly underestimated [12, 24, 33–35, 58, 81, 94, 99].

Compared with the above-described heat transfer from solar radiation to the Earth's atmosphere or to the ground via soot particles, the direct heat input from fossil fuel combustion is the release of bound chemical energy, in other words, the exhaust gas heat is rather insignificant in this context at 0.03 W/m^2 compared with 1.6 W/m^2 for the overall radiation effect [29, 102].

3 Radiative Forcing Equivalence of Soot Particles and CO_2

To estimate the effect of the total emission of soot particles from engine combustion on global warming, all geographical and meteorological influences have to be considered, which is only possible at sufficient resolution thanks to the calculation power of modern computers. The runtime of such calculations in models with a resolution of about 1 km is still months. One of the most comprehensive studies of this kind was carried out at Stanford University in the 1990s and published in 2001/2 [52–60]. It concluded that the effect of engine combustion soot on the warming of the earth related to the same mass is 360,000–840,000 times that of CO_2 but that the effect of "brown" soot from the combustion of organic substances, e.g., from forest fires, is significantly lower at 120,000–280,000:1 [61]. Continuing the work [54, 58] over a decade, these equivalence factors increased to 1000,000:1 for BC.

Numerous research groups have confirmed these remarkable results [5, 11, 98, 99, 108, 113, 123], and they can be considered scientific state of the art today.

Subsequently, the importance of engine-emitted soot for global warming was the subject of a hearing of the US House of Representatives in 2007 [57]. In conclusion of this hearing, the US administration stated that priority must be given to reducing the impact of motor traffic on global warming, which has led, on the one hand, to great efforts in the electrification of vehicle propulsion systems, but also to a lowering of particulate emission limits of fossil fuel burning ICE to a level that, similar to Europe, should force the introduction of particulate filters even in gasoline engines [10]. The need to concentrate on eliminating soot by using filters has also been explicitly stated by NASA [98] and UNEP [119]. In 2009, this was also one of the reasons for the PR of China to carry out an extensive project with Switzerland and VERT to retrofit construction machinery and heavy road vehicles [124].

4 The Impact of Particle Composition and Morphology

Engine combustion soot is morphologically complex. Primary particles are formed in milliseconds from polycyclic structures during unfavorable combustion conditions in the size range of 5–20 nm; Hydrogene is consumed first and remaining carbon rich hexagonal and pentagonal structures, burning off much more slowly agglomerate in the exhaust tube, as long as the free path lengths are small enough [46, 62]. Specific surface area will become around 200 m^2/g and density around 0.05 g/cm^3. They will reach the atmosphere in loose chains and grape-shaped structures, and because of this structure, they cannot be compared with flat surfaces or spheres of the same mass concerning their radiation behavior. Very detailed studies [107] show that their ability to absorb radiation, transform it into heat, and transmit it to the environment can be 20% higher than expected from the simple spherical model. In addition, the composition of the particles (ash, lubricating oil) and the character of the surface (hydrophobic or hydrophilic) can affect the radiation absorption behavior [5, 39, 101, 120]. In other words, although engine soot is quite black when emitted, it is not pure black carbon (BC) as physically defined or elemental carbon (EC) since, depending on the composition, surface color can change a bit but this takes time, and since we discuss a very limited residence time in the atmosphere this simplification of using BC-properties might be permitted.

5 Atmospheric Effects

A plethora of atmospheric processes that can modify these soot particles have been observed and continue to be intensively researched [6, 69]. These include continued agglomeration, aging and post-oxidation, accumulation of condensates, and internal and external mixing with other aerosols, especially water droplets, sulfates, and nitrates. The interaction with clouds; triggering of condensation, i.e., cloud formation; and the effect in the case of icing within clouds is particularly exciting [83]. All these processes change the properties of soot particles from combustion and can influence their effects, so they must be taken into account in the global impact on atmospheric warming. In our consideration, which is limited to the application, we start from the integral factors of CO_2 equivalence [53], in which these properties were included locally and temporally during the processing of an entire atmospheric model, as far as reliable information was available.

6 The Impact of Time Scale

The time scale over which the impacts of CO_2 and other greenhouse gases are considered is usually selected as either 20 years or 100 years. Since different greenhouse gases have different e-folding lifetimes in the air (defined as the time required for the concentration of a chemical in the air to decrease to $1/e$, or 36.8%, its original value), it is important to pick a common time scale over which to examine the impacts of all warming components together. Black carbon has a very short lifetime (on the order of a week to a few weeks). Methane has a longer lifetime (8–12 years). Carbon dioxide has a much longer lifetime (50–100 years). Nitrous oxide's lifetime is even longer (~ 120 years). The impacts of shorter-lived chemicals (BC and CH_4) over a time scale of 20 years are greater than those over a 100-year time scale. Conversely, the impacts of longer-lived chemicals (CO_2 and N_2O) over 20 years are less than those over 100 years.

Once emitted, the effect of CO_2 on global warming remains for a long time and only ends when it passes from the atmosphere to land through photosynthesis or to the oceans through dissolution. CO_2 is an acid that makes the ocean more acidic (lowers its pH) until the CO_2 converts to rock material in ocean sediment. BC, on the other hand, is removed from the atmosphere primarily by precipitation (rainout and washout) [59]. Although the lifetime of BC is much shorter than that of CO_2, BC in the air causes about 360,000–840,000 times the warming per unit mass as CO_2 [53]. However, accounting for the short lifetime of CO_2, the average warming of the globe, over a 20-year time frame, of continuously emitted BC in fossil fuel soot versus continuously emitted CO_2 is 4500–7200:1. That of BC plus organic matter in fossil soot versus CO_2 is 2400–3800:1, giving an overall range of 2400–7200 [52–60]. Table 1 compares this range with values from other researchers.

For the following estimations, a value of 2000:1 is chosen, which rather follows the very detailed considerations of Jacobson [52–60] and describes the increase of the near-surface temperature by STRE "surface temperature response per unit emission defined as near-surface air temperature change after 20 years per unit continuous emission of BC relative to the same for CO_2." A value at the lower end of

Table 1 Ratio of estimated warming due to continuously emitted engine soot to CO_2 over a 20-year time frame from various sources

	Walsh et al. [123]	Atlantic Research [2]	Mayer (2009)	Jacobson [58] STRE
$BC:CO_2$ warming ratio	1600:1	2200:1	1440:1	2400-7200:1

the given range is chosen to consider the fact that the combustion soot may not quite reach the absorption properties of BC.

7 Filtration Efficiency of Commercial Particulate Filters

For the filtration of particles in the size range 10–500 nm and larger (10–500 nm is the size range that is decisive for lung deposition and translocation [35]) from the hot exhaust gas of internal combustion engines, ceramic cell filters with porous walls have become established, so-called wall-flow filters with a very high active filter area of > 1000 m^2/m^3 filter volume and narrow pore distribution of around 10 µm, which in practice, achieve separation efficiencies of 99% in the entire size range [8, 9, 63, 93, 97], see Fig. 1.

On average, the over 70 diesel particulate filter systems tested by the VERT certification laboratory in accordance with SN 277206 [116] achieve 98.9 % removal of solid particles in the size range 20–300 nm in the stationary ISO 8178 test cycle [93]. The fact that this is also true over many years of practical use and has a correspondingly positive effect on air quality is shown by the investigation at a Swiss freeway intersection over the period of the introduction of the filters for road vehicles (Fig. 2).

The soot trapped in these filters is periodically or continuously burned off to clean the filter and keep backpressure low—a process which is called regeneration. The amount of CO_2 emitted due to combustion of the trapped soot is very small, and for a typical Euro III diesel engine, it might be 0.2 g/kWh compared to 800 g/kWh CO_2 while combusting 250 g/kWh standard diesel fuel.

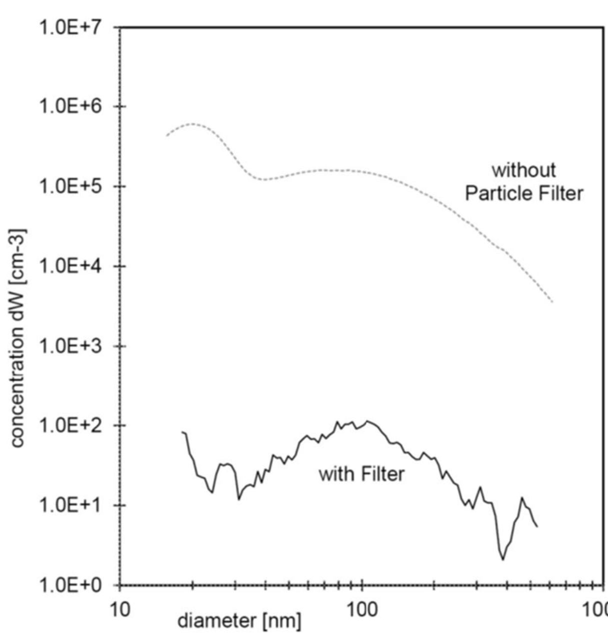

Fig. 1 Typical separation behavior of a modern ceramic diesel wall-flow filter with 200 cells/in^2 Source: [VERT Filter List]

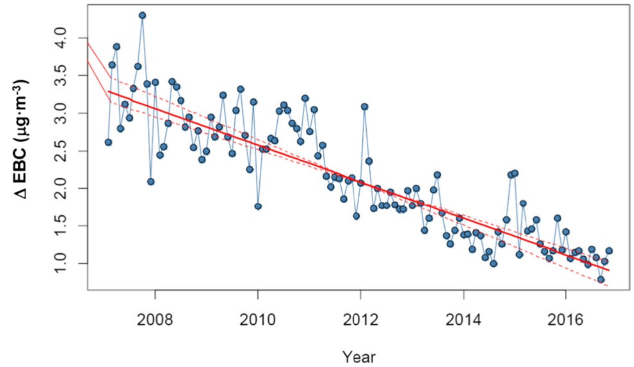

Fig. 2 BC concentration at a freeway junction in Switzerland is a clear sign of the purification of the air breathed by particulate filters [47]. Similar results for central London [43]

8 DPF and GPF Population Worldwide

Figure 3 shows the annual production of diesel engines for vehicles, LDVs, and HDVs in Europe and the USA. The figures from Asian production are not included here. The population of LDV diesel engines in the USA is almost small. The number of HDVs (USA and Europe) is steadily increasing, except for the financial crisis slump and the VW scandal, which eventually involved the whole industry [73]; the diesel share of LDVs in Europe tends to decrease, which, however, is overcompensated by the increased production of gasoline engines, mainly DI, which also must have filters, so-called GPF. According to this, nearly 200 million passenger cars and light-duty vehicles (LDVs) with

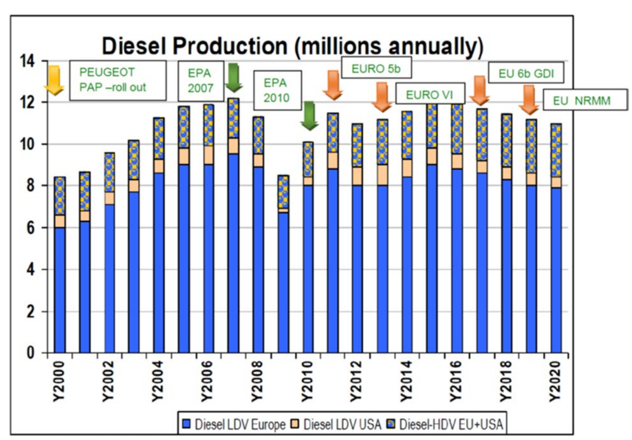

Fig. 3 Diesel vehicle production in Europe and the USA. Source: VERT market research 2015;

diesel engines and about 50 million HDVs were placed on the market in the EU and the USA from 2000–2020. The vehicle production of the world (including diesel, petrol, and natural gas vehicles) is estimated to have been in the range of 100 million per year during this period. The total vehicle population exceeded 1.4 billion in 2023 [German Umweltbundesamt 2023]; the average LDV vehicle age is 15 years in the EU, but higher in many countries, and the overall mileage is still growing.

The important stages of exhaust gas legislation in Europe and the USA, which have had an impact on the introduction of exhaust gas after-treatment, are shown in Fig. 3. It should be emphasized that the introduction of the limit value according to particle number (PN) (#/kWh or #/km) parallel to particulate matter (PM) mass (g/kWh) in Europe virtually forced the introduction of the diesel particulate filter across the board, namely, for all diesel road vehicles and also with a corresponding delay for gasoline vehicles and non-road mobile machinery NRMM, because the two quantities, PN and PM, are not equivalent. The limit value of 6×10^{11} particles/km corresponds to an approximate particle mass of <0.5 mg/km, based on reasonable assumptions made for the mean particle diameter and density of combustion aerosols, while the limit value of PM is 4.5 mg/km. Thus, PN is the much stricter criterion. With PM alone, the use of particulate filters would never have happened.

In the US vehicle emission legislation, on the other hand, which to date has stuck to the particulate matter mass criterion, the decision regarding the use of DPFs has been left to the manufacturer's decisions, and thus, not all HDV and NRMM have DPF. Recently proposed regulation of reduced PM standard of 0.5 mg/mi (0.31 mg/km) for LDVs is projected to result in GPF penetration in the LD gasoline new vehicle fleet starting in MY 2025 [10, 71].

8.1 How Many Particulate Filters Are in Use Today?

In 2015, VERT used production data from its members, which included some of the largest manufacturers, to produce figures showing the uptake of particulate filters in diesel engines—Fig. 4. Notably, the widespread use of particulate filters began long before the relevant legislation came into force. In addition to Switzerland's pioneering efforts with the VERT project from 1994, the reduction of the sulfur content in diesel fuel, the development of a high-strength SiC filter, and the electronic injection technology linked to common rail for perfect control of regeneration were essential conditions for this. Peugeot launched a new engine with DPF very successfully in May 2000 [7] and 4 years later already exceeded a production figure of one million. This has put much more pressure on the competition within the automotive industry than would have been possible due to the growing environmental awareness and slowly developing legislation. The EU legislator was thus able to rely on proven technology from 2011 onwards and thus triggered a worldwide boom without any setbacks. Eight international seminars by Haus der Technik [90]. The ETH nanoparticle conference also played a significant role in this and holds about 2000 scientific documents in its open-access library.

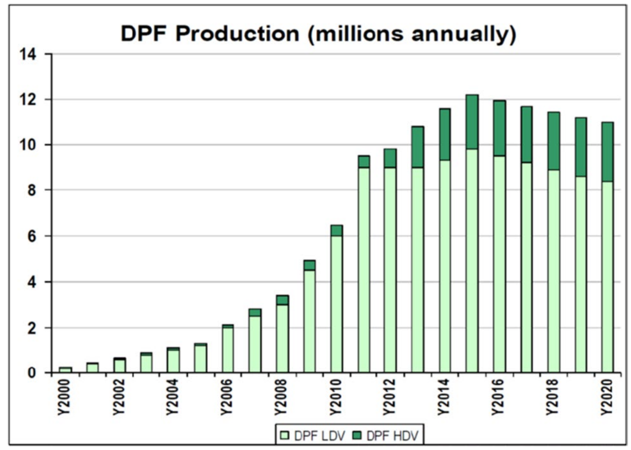

Fig. 4 Particle Filter production of VERT member companies in EU and USA. Source VERT market research; see also [122]

Figure 4 shows the production of about 120 million DPF for LDV diesel and 25 million HDV for the two decades considered. We can expect this figure to double with the additional production figures from other manufacturers and other markets. Add to this the production of GPF (gasoline particle filter), which only started in 2018 but has quickly overtaken DPF production. Thus, we arrive at the following rough estimate of production and fleet numbers by 2023:

- DPF for HDV: 40 million, of which 30 million are in use today
- DPF for LDV diesel: 250 million, of which 200 million are in use today
- DPF for NRMM: 1.2 million, of which 1 million are in use today
- GPF for LDV: 100 million, of which 100 million are in use today

This last figure is particularly uncertain because it is known that many new filter companies have emerged in Korea and China, and many more gasoline engines may have been equipped with filters than we could estimate.

New market research confirms these figures [37].

9 The Amount of Not-Emitted Soot

Today's diesel particulate filters are, therefore, easily capable of reducing emissions of soot and ash particles very efficiently, virtually eliminating them. With professional design and application (VERT Filter List), this applies for the entire lifetime of a filter, which corresponds to the lifetime of the engine; that is, no systematic deterioration due to aging is known. However, it has been shown that in the first generations of some manufacturers, technical problems have arisen due to insufficiently controlled regeneration [76], which has caused damage. In addition, it should be taken into account that due to the interruption of PTI periodic technical control 2013–2023 [26–28], faults and manipulations have not been detected, so statistically, 6–10% of the filters in use today have faults. This should be taken into account here. For NRMM, this value is even higher, with 10–20% [16, 66].

Particulate filters for direct-injection gasoline engines have lower separation rates than DPFs due to the emission policy practiced to date; the calculation takes into account an average value of 80% [19]. This will significantly improve from Euro 7 onwards due to the use of new pore structures [8, 9, 97, 103, 127].

The relevant raw emissions of the engines are based on the Euro 4/IV limits, i.e., the homologation values of new engines. However, to reflect the reality over the entire lifetime of these vehicles in worldwide use, considerable aging effects, deterioration effects, and, in many countries, manipulation of the engines must be taken into account. Thanks to particulate filters, these deteriorations in engine emissions are no longer detected. In addition, when considering the total fleet, the critical share of high emitters [16, 21, 49, 74, 111] must also be taken into account. This has been proven and published within the NPTI project [15, 38, 67], where vehicles with damaged filters showed PN emissions of > 10 million per cc.

For simplicity's sake, the vehicles' lifetime is uniformly assumed to be 10 years, with 200,000 km being calculated for LDVs and 10,000 operating hours for HDVs. This is also a conservative approach since the service lives of passenger cars in many countries already tend toward 15 years, and longer service lives are also frequently observed for the other categories.

Table 2 shows the estimate for a typical vehicle in each of these four categories, with LDV diesel also including light-duty vehicles, which increases the average emission.

Here, the assumptions for LDV petrol and NRMM are particularly uncertain because emission limits for PN were first introduced for gasoline engines in 2015 and for NRMM in 2019. Soot emissions from these two categories have been neglected in the development of emissions legislation in general for more than 25 years; to date, PN limits in the EU for gasoline engines apply only to direct-injection (DI) engines, and port fuel injection (PFI) engines are still not limited concerning particulate emissions. However, it has been demonstrated many times [[18, 44, 96], 2018] that they can emit a lot of PM, which due to very high PAH deposits might have a much higher toxicity compared to diesel. In a study of over 400,000 vehicles in Mexico City [21], 2–5% of the LDV petrol fleet was measured to emit up to 100 million particles/cc (the "dirty tail" of the emission distribution). In the USA, the first step in limiting particulate emissions from LDV petrol came in 2008 at 20 mg/mi and then 10 mg/mi, which was selected as the base for the above emission figure of this category.

In the case of NRMM, i.e., mainly construction and agricultural machinery, the EU legislator's insight also came very late, with the introduction of the PN criterion only with EU Stage V from 2019; that is, it must be assumed that NRMM is still largely used without DPF. The existing construction machines are likely to be on a worldwide average still at the Stage IIIA or lower emission level. In Switzerland, however [117, 126] filters for construction machines had to be used from 2000 for more and more sectors, and therefore, statistical information is available, which can be transferred to other countries of similar industrial structure.

The following Table 3 extrapolates the values to the entire fleet in which DPF/GPF is already in use today. Since the calculation is based on a period of only 10 years, many filters/vehicles put into service before 2003 have probably already been taken out of service, which is why only 200 million are calculated for LDVs, for example, instead of the production figure of 250 million.

The investment in these 331 million filters has thus resulted in a savings of nearly 5 Mt of soot with BC properties during the 10-year deployment period, which otherwise would have continued to warm the atmosphere and the Earth's surface during that time. Another 0.5 Mt of soot will

Table 2 Determination of the soot mass not emitted due to particulate filters for four vehicle categories

	Euro 4/IV emission factors	Realistic emission factors	Average power (kW)	Life	Soot mass emitted per 10 y of life (kg/10-y)	Not-emitted soot mass due to DPF (kg/10-y)	Not emitted soot mass due to DPF (kg/year)
LDV diesel	25 mg/km	50 mg/km	10	200,000 km	10	9	0.9
HDV	30 mg/kWh	100 mg/kWh	100	10,000 h	100	90	9
LDV petrol	10 mg/km	20 mg/km	10	150,000 km	3	2	0.2
NRMM	200 mg/kWh	300 mg/kWh	100	10,000 h	300	255	25

Table 3 The total mass of engine soot not emitted during the last decade due to DPF/GPF is thus almost 5 Mt, or 0.5 Mt/year, on average

	Total fleet size million vehicles	Not-emitted soot mass per vehicle life (kg)	Not-emitted soot mass per vehicle category and life (million tonnes)	Not-emitted soot mass per vehicle category per year (million tonnes/y)	Total soot mass not emitted due to DPF/GPF (million tonnes)	Total soot mass not emitted due to DPF per year (million tonnes/y)
LDV diesel	200	9	1.8	0.18	–	–
HDV	30	90	2.7	0.27	–	–
LDV petrol	100	2	0.2	0.02	–	–
NRMM	1	255	0.255	0.0255	–	–
Total	331				4.96	0.496

be avoided each consecutive year. With additional legislative action, this could be much more.

To date, these filters have not been installed for global warming mitigation. Instead, they have been installed to reduce the extremely high health risks of carcinogens within black carbon aerosols, which according to [14, 25, 79, 105, 112], contribute to 7–10 million premature deaths annually. Approximately one million deaths per year are avoided due to the use of particle filters. The benefit-to-cost ratio for the use of filters in Switzerland was estimated to be 5:1 in 2003 [110] for HDV. Today, this benefit-to-cost ratio is estimated as 30:1 by [23, 25, 105] and 12:1 by [26]. Accounting for the climate benefit increases the overall benefit-to-cost ratio of particulate filters further.

10 Overall CO_2 Equivalence of Soot (BC), Captured by In-Use Particulate Filters

Using the CO_2/soot equivalence criterion of 2000:1 derived above, the total soot mass of 5 Mt not emitted during the entire 10-year operating period thanks to filter technology corresponds to the GWP of 10 Bt of CO_2.

For comparison, the effect achieved per year is more suitable:

- GW mitigation through DPF/GPF is equivalent to 1 Bt of CO_2 annually
- Global emissions of CO_2 currently stand at 36 Bt per year and are continuing to rise
- The CO_2 emission of all member states of the EU is currently 3.1 Bt/year
- The CO_2 emission of Germany is currently 0.7 Bt/year

For one average HDV diesel engine running at 100 kW for over 10,000 h, the total CO_2 emissions (with 800 g CO_2 per kWh) are ~0.8 Mkg, and the soot emissions are ~100 kg. The CO_2 equivalent of the emitted 100 kg of soot is 0.2 Mkg-CO_2. As such, a filter retrofit reduces the total GWP of the engine by ~20%—and is effective immediately. In the case of the LDV diesel, this figure is significantly higher, around 50%. For LDV petrol, it is lower, since CO_2 emissions are higher, but PM emission, is lower.

11 The Potential of Further Immediate Reduction of Soot Emissions

The global vehicle population (with combustion engines) is 1400 million and rising. Of these, about 27 million are currently electric, or 1.9%—the rest are still internal combustion vehicles. Despite major government efforts, the trend toward e-mobility is only weakly progressive. Therefore, the internal combustion engine will continue to dominate urban emissions for a long time [45, 64, 68], and every effort must be made to minimize these emissions, especially CO_2 and soot particles. For CO_2 mitigation, indeed, numerous avenues are being explored, such as the transition to low-carbon fuels like natural gas derivatives, ammonia, synthetic fuels based on the Fischer Tropsch process, or directly hydrogen [13], although it should be noted that all alternative combustion piston engines also produce BC-like lubricating oil particles and therefore need filter [118]. However, all these processes are still at an early stage of development, and their application is costly. In addition, they all come to the market only with new engines.

The filter technology to eliminate GW-active soot for all engines (except marine heavy fuel oil [85]) is available in a market-ready state and can be used for all new vehicles across the board and retrofitted in the existing fleet. A doubling of the filter population from now 20% of the total fleet to 40% would not yet encounter any technical obstacles. Instead, it can be understood as a “copy-paste” state-of-the-art transfer from the EU to the countries that follow the EU emission philosophy anyway, like China and India, and will automatically evolve. But even within the EU, there is still great potential, such as in particular, the retrofitting in the large and important sector of NRMM, for which Switzerland has indeed played a pioneering role [117] to demonstrate feasibility.

That is, we can increase the mitigation of global warming substantially by immediately deploying more particulate filters for new engines and retrofitting existing ones. We also should transfer filter technology to stationary combustion, especially wood burning, which plays an increasing role in heating homes in many countries [34].

12 Financial Tools for Implementation

Finally, there is the question of financing. CO_2 certificate trading was introduced to reduce CO_2 and to reward actions that do so. The price of one tonne of CO_2 is currently around 80 Euros (European Energy Exchange, EEX AG: CO2 2022] and is expected to rise further.

So, if the avoidance of one tonne of CO_2 is worth 80 Euros in the social consensus today, according to the principle of impact equivalence, the avoidance of 1 kg of soot should be worth (80 × 2000)/1000, i.e., 160 Euros. Retrofitting an LDV with filter and operation over 10 years is thus worth 1600 Euros and 16,000 Euros for an HDV. This amount covers the retrofitting of existing vehicles with filters. It even provides an incentive for the operator in target countries such as South America, Africa, India, and many other Asian countries where these vehicles are operated for a much longer time [109]. At the same time, it makes an immense contribution locally to mitigating health risks.

Since the comparative assessment of GHGs needs to be done in any case to reasonably estimate the costs incurred at the sources and their coverage, monetizing the contribution of filters to GWP should be included in this process. This should result in the immediate implementation of more retrofits with filters, since sufficient filters will be available given to their high manufacturing capacity.

13 Conclusions

Internal combustion engines contribute to global warming in two major ways. In addition to their emission of CO_2, they emit soot particles, whose radiative properties are close to black carbon. These black particles not only absorb the energy of the sun and re-emit it as heat to the atmosphere when they are emitted and become a stable aerosol suspended in the air, but they also mix into clouds, causing them to warm and evaporate, increasing sunlight to the surface, and deposit onto snow and sea ice, melting these surfaces to uncover darker surfaces below. The instantaneous warming of 1 kg of soot corresponds to the instantaneous warming of 1 Mkg of CO_2. Taking into account the residence time in the atmosphere, this effect is reduced to about 2000:1. It thus gives soot emitted by combustion engines a very high priority for the assessment and reduction of anthropogenic global warming, especially since combustion engines in LDVs, HDVs, NRMMs, and ships will continue to contribute to urban and global pollution for a long time.

Since these ultrafine soot particles pose a threat to human health, contributing to 10 million premature deaths annually worldwide, particulate filters have been introduced by legislation in EU and USA and other countries for eliminating these soot particles from vehicle exhaust under virtually all operating conditions.

There are now more than 200 million diesel LDVs with such filters in use worldwide, many from more than 10 years ago, and others in HDVs, NRMMs, and gasoline vehicles in a total of 300 million. During this time, they have prevented the emission of about 0.5 Mt of soot annually equivalent to the annual effect of about 1 Bt of CO_2, i.e., 3% of the total global emission of CO_2 or 30% of the emission of all EU member states together.

Today's combustion engines must be replaced as soon as possible with zero-emission vehicles. However, given that many vehicles with traditional combustion engines will remain in operation during this transition [64, 68] it is crucial that we equip them with filters. Even if this is not done entirely, the potential climate benefit of retrofitting even a portion of existing vehicles is large. In addition, the health benefits are immediate and large.

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Compliance with Ethical Standards

Competing Interests The authors declare no competing interests.

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