Nanoparticle Emissions and GPF for MPI Gasoline Cars

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Abstract. Further efforts to reduce the air pollution from traffic are undertaken worldwide and the filtration of exhaust gas will also be increasingly applied on gasoline cars (GPF\textsuperscript{3} ... gasoline particle filter).

In the present paper, some results of investigations of nanoparticles from four MPI gasoline cars are represented. The measurements were performed at vehicle tailpipe and in CVS-tunnel. Moreover, two variants of GPF were investigated on a high-emitting modern vehicle, including analytics of PAH and attempts of soot loading in road application.

The modern MPI vehicles can emit a considerable amount of PN, which in some cases attains the level of Diesel exhaust gas without DPF and can pass over the actual European limit value for GDI ($6.0 \times 10^{11} \, \text{#/km}$). The GPF-technology offers in this respect further potentials to reduce the PN-emissions of traffic. With GPF, in the investigated steady state operation, there is no significant visible nuclei mode and the ultrafine particles concentrations below 10 nm size are insignificant.

1. Introduction

The ultrafine particles (UFP) from combustion processes are invisible, behave like gas and penetrate easily into the human body through the respiratory and olfactory pathways and carry numerous harmful health effects potentials. The nanoaerosol in vehicle exhaust is a complex mixture of different volatile and non-volatile species. It often shows a bimodal particle size distribution with a nucleation mode smaller than 20 nm and a larger accumulation mode that mainly contains aggregates of primary particles. The larger accumulation mode is usually composed of more graphitic soot particles with an elemental carbon (EC) structure, whereas the particles in the nucleation mode are reported to be mainly volatile organics, especially when sulphur is absent from fuel and lubrication oil, [1-5].

However, recent studies detected also low-volatility particle fractions in the ultrafine size range when sampling was carried out according to PMP protocol at 300 °C, [6-8].

The particles in nuclei mode are suspected to be nucleated metal oxides originating from metal additives in lubrication oil or fuels [9-12]. The formation of this particulate fraction was especially observed when the soot content was low as in idle condition of diesel vehicles. These particles mainly appear in the ultrafine size rage <23 nm. While the mass contribution of these ultrafine particles in vehicle emissions is very low, their contribution to the number concentration is significant. Moreover, these ultrafine particles may contribute to the surface composition of the aerosol and have therefore a significant impact on health effects associated with pollution.
Studies for gasoline fueled internal combustion engines pointed out that also this vehicle class can emit remarkable amounts of particles, [13-16]. Especially gasoline direct injection technology (GDI) shows particle number (PN) emissions significantly higher than modern diesel cars equipped with best available DPF technology. Since the trend for gasoline vehicles with GDI technology is increasing, a significant rise in emission is predicted in the near future.

The nanoparticles emissions are produced especially at cold start and warm-up conditions and at a dynamic engine operation, [17-19]. The lube oil contributes to this emission in the sense of number concentrations in nuclei mode and composition, [9-11].

The investigations of morphology of the nanoparticles from gasoline direct injection engine revealed principally graphitic structures, which can store some metal oxides in certain conditions and can be overlapped by condensates, [20, 21].

Car manufacturers and suppliers of exhaust aftertreatment technology offer several mature solutions of GPF for efficient elimination of the nanoparticles from DI SI-engines, [22, 26].

There is also nanoparticles emission of gasoline vehicles with MPI (multipoint port injection). Some of them emitting high amount of PN and PM. In a study of AFHB, [19], an older model with MPI was found to emitting at stationary part load operation up to 4 orders of magnitude more nanoparticles, than a lower emitting GDI car. The main reason for this increased PN-emission was attributed to the increased lube oil consumption. Nevertheless, an inferior quality of mixture preparation cannot be excluded.

The MPI technology has a big share of the worldwide market because of its lower costs and simplicity and in several countries this technology will still stay as primary option for several years to come.

From this perspective and taking account of the progressing exhaust gas legislation aiming an increased care about health and environment protection it is necessary to include the cars with MPI in the efforts to reduce PN & PM.

Investigations in present paper have been performed at AFHB (Laboratories for IC-Engines and Exhaust Emission Control of the Berne University of Applied Sciences, Biel CH) in collaboration with EMPA Analytical Laboratory for analysis of PAH.

This paper presents a comparison between PN-emissions from four MPI gasoline cars and emission reduction potentials of two GPF’s (coated and non-coated).

2. Tested vehicles
Table 1 shows the most important data of the investigated MPI vehicles. It can be remarked that the vehicle ② in this group is the only one with turbocharger and vehicle ④ is equipped with 2 injectors per cylinder intake port.

3. Fuels and lube oils
The gasoline used was from the Swiss market, RON 95, according to SN EN228.

For all vehicles, the lube oils were not changed and not analysed.

4. Test methods and instrumentation
The vehicles were tested on a chassis dynamometer at constant speeds and in the dynamic driving cycles, with cold & warm engine start.

4.1. Chassis dynamometer - following test systems were used:

- roller dynamometer: AFHB GSA 200
- driver conductor system: Tornado, version 3.3.
- CVS dilution system: Horiba CVS-9500T with Roots blower
- air conditioning in the hall automatic (intake- and dilution air).
The driving resistances of the test bench were set according to the legal prescriptions, responding to the horizontal road.

Table 1. Data of investigated MPI vehicle

| Vehicles          | Opel Adam ① | Fiat Panda 4x4 Twin Air ② | Ford KA 1.2i ③ | Suzuki Baleno 1.2 Hybrid④ |
|-------------------|-------------|---------------------------|----------------|--------------------------|
| Number and arrangement of cylinders | 4 / in line | 2 / in line | 4 / in line | 4 / in line |
| Displacement cm³ | 1398        | 875                       | 1242           | 1242                    |
| Power kW          | 64 @ 6000 rpm | 62.5 @ 5500 rpm | 85 @ 5500 rpm | 66 @ 6000 rpm |
| Torque Nm         | 130 @ 4000 rpm | 145 @ 1900 rpm | 102 @ 3000 rpm | 120 @ 4400 rpm |
| Injection type    | MPI         | MPI                       | MPI            | MPI                     |
| Supercharging     | no          | turbo                     | no             | no                      |
| Curb weight kg    | 1195        | 1170                      | 989            | 1010                    |
| Gross vehicle weight kg | 1465     | 1550                      | 1320           | 1405                    |
| Drive wheel       | Front-wheel drive | 4x4                      | Front-wheel drive | Front-wheel drive |
| Gearbox           | m5          | m6                        | m5             | m5                      |
| First registration| 5.3.13      | 2.12.15                   | 30.5.16        | 29.4.16                 |
| Model year km at the beginning | 2013     | 2015                      | 2015           | 2016                    |
| Emission standard | EURO        | EURO                      | EURO           | EURO                    |
| Exh. after-treatment | TWC       | TWC                       | TWC            | TWC + EGR               |

4.2. Nanoparticle analysis

The measurements of NP size distributions were conducted with different SMPS-systems, which enabled different ranges of size analysis at steady state operation:
SMPS: DMA TSI 3081 & CPC TSI 3772 (10 - 429 nm)
nSMPS: nDMA TSI 3085 & CPC TSI 3776 (2 - 64 nm)

For the dilution and sample preparation an ASET system from Matter Aerosol was used, (ASET … aerosol sampling & evaporation tube). This system contains:

- Primary dilution - MD19 tunable rotating disc minidiluter (Matter Eng. MD19-2E)
- Secondary dilution – dilution of the primary diluted and thermally conditioned sample gas on the outlet of evaporative tube.
- Thermoconditioner (TC) - sample heating at 300°C

This sample preparation system fulfills the requirements of PMP and it was used for all measurements. At steady state operation (SSC see next section) this system worked with summary dilution factors DF = V65 to 765.
The estimated accuracy of PN-measurement in the size range of 80-120 nm, with DF = 100 is +/- 6%.

For the measurements of summary PN at transient operation a CPC TSI 3790 (PMP conform) was used.

Figure 1. Set-up of exhaust gas sampling for PN-analysis

In the tests the gas sample for the NP-analysis was taken from the undiluted exhaust gas at tailpipe for stationary operation (SMPS) or from the diluted exhaust gas in CVS-tunnel at transient operation (CPC). The schematic of the general sampling set up is represented in Fig. 1.

4.3. Driving cycles

The steady state cycle (SSC) consists of 20 min-steps at 95, 45 km/h and idling, performed in the sequence from the highest to the lowest speed.

Fig. 2 shows the steady state cycle (SSC) with the resulting tailpipe temperatures ($t_{exh}$) for gasoline vehicle \(\oplus\) (MPI). This gives the magnitude of the temperatures at the particulate sampling point “tailpipe” during steady state measurements (SMPS).

The WLTC (world-wide light duty test cycle) represents typical driving conditions around the world. This cycle (Fig. 3) has been used also in this study. It represents different driving conditions: urban, rural, highway and extra-highway.

Figure 2. Steady State Cycle (SSC) and tailpipe temperature of tested vehicles (MPI)

In the test program with MPI vehicles supplementary cycles RTS 95 and ADAC 130 were used. The RTS95 is a short chassis dynamometer test cycle representing aggressive driving and used for
development purposes as short procedure replacing WLTC. The ADAC 130 cycle represents the highway driving and for the investigated vehicles class requires some full load accelerations.

Fig. 3 shows the time-courses and Table 2 summarizes the most important data of these driving cycles.

![Figure 3. Transient driving cycles WLTC, RTS 95 and ADAC 130](image)

| Cycle      | Duration (s) | Distance (m) | $v_{max}$ (km/h) | $a_{max}$ (m/s$^2$) | $a_{min}$ (m/s$^2$) |
|------------|--------------|--------------|------------------|---------------------|---------------------|
| WLTC       | 1800         | 23’262       | 131              | 1.58                | -1.49               |
| RTS95      | 886          | 12’927       | 134              | 2.61                | -2.63               |
| ADAC130    | 740          | 18’755       | 130              | 6.94                | -5.00               |

4.4. Test Routine

All tests were performed by the same driver. The diluted exhaust gas components were on-line measured and evaluated from the bags after the cycle.

For the cold start the vehicle was conditioned a day before: the conditioning for WLTC cold was another WLTC warm and the conditioning for RTS95 cold was a SSC. The conditioning for “warm” cycles was: 3 min 80 km/h and 1 min idling.

All tests were driven on a 4WD chassis dyno and for the front drive the rear wheels were dragged with the same speed as front wheels.

5. Results

5.1. Four MPI cars at steady state operation (SSC)

Fig. 4 gives an example of the SMPS-particle size distributions (PSD) with the MPI vehicles at 95km/h and at idling. The indicated particle counts concentrations are mostly in the range of ambient background level ($10^2$ to $10^4$ #/cm$^3$). Nevertheless, there are some exceptions such as a clearly higher PN-emission with vehicle ② at 95 km/h and a higher PN-emission with vehicle ③ at idling.
At the highest speed (95 km/h) vehicle 2 causes the particle count concentrations, which are up to 3 ranges of magnitude higher, than with the other vehicles.

There are different interacting processes during mixture preparation, combustion and gas flow in the exhaust system, which sensitively influence the generation of nanoparticle emissions. The following discussion gives some ideas and hypotheses about the reasons of the observed differences of PN-results between the different vehicles:

Important question is the mixture preparation: the ideal mixture preparation should atomize and evaporate all the used fuel and bring it as homogenously premixed, as possible into the combustion chamber.

For MPI there can be, at certain conditions, a portion of fuel deposited on the walls of the intake port, [27, 28, 29], which can, especially at transient operation, arrive in the combustion chamber as liquid non-premixed droplets. A part of this “unprepared” fuel burns heterogeneously and is a source of soot-production. These effects are stronger in DI technology and especially, when the liquid fuel arrives at the wall and, what is also possible, interacts with the lube oil layer, the production of nanoparticles is particularly increased, [30-33].

The chemistry of oil and fuel, their HC-matrix and additive packages have a significant influence on the NP’s.

Further to consider are: the passage of aerosol through the exhaust system, the history of temperature drop, catalysis, chemistry, spontaneous condensation and store/release effects in the exhaust system. All of them have finally influences on “what will be measured at tailpipe”.

The processes influencing NP-production depend on engine operating conditions. With no doubt, the NP-emissions vary with the operating point and are increased at transient operation.

The measurements of all PSD’s at constant speeds were simultaneously performed with two systems SMPS (size range 10-429 nm) and nano-SMPS (size range 2-64 nm).

Figure 4. SMPS particle size distribution at constant speeds with different MPI vehicles

![Graph showing particle size distribution at different speeds and conditions.](image)
Fig. 5 compares the PSD’s measured with SMPS and with nSMPS with the highest emitting vehicle ② and with the lowest emitting vehicle ④ at 95 km/h.

![Figure 5. Particle size distribution of MPI vehicles (min/max emissions)](image)

For vehicle ② there is a very good correlation of results obtained with nSMPS and with SMPS in the common size range (10-64 nm). The particle numbers in the size spectrum below 10nm are zero, or negligible.

For vehicle ④ there is no clearly pronounced size distribution, but random indications of particle counts in the ambient level. There is also a very good accordance of both measuring systems.

5.2. Four MPI cars at transient operation

The legal emission limits are established for the transient operation, which causes higher PN-values. The particle counts are measured as summary of all particle sizes in the diluted exhaust in CVS tunnel, by means of CPC.

Fig. 6 summarizes the integral PN-results of the four MPI vehicles in all transient cycles. It can be remarked that the relationships of emission level are for all vehicles in all driving cycles the same. In the driving cycle with cold start the PN-emissions are higher than with warm start. One of the vehicles would not pass the previous limit value of $6 \times 10^{12}$#/km and three of the vehicles would not pass the actual limit value of $6 \times 10^{11}$#/km.

The following points have to be mentioned:

- in the cycle RTS95 vehicle ② had to be accelerated at full load to follow the driving conductor cycle trace,
- at higher speeds and acceleration there is particularly higher PN-emission with vehicle ②,
- at the ADAC130 high speed cycle none of the vehicles could follow the cycle; all vehicles were fully accelerated; this caused very high CO-emissions - in one case with vehicle ② CO in the bag came in over range,
- vehicle ④ with two injection valves per cylinder yielded the lowest PN-emissions – it can be supposed, that a better mixture preparation and lower portion of liquid fuel film deposited in the intake channels contributed much to this improvement.

![Figure 6. PN results in all driving cycles](image)
Fig. 7 impressively illustrates the residues of particle mass collected on TGA filters of two vehicles in all driving cycles. The thermogravimetric analysis (TGA) was performed on chosen samples and for all vehicles, except for vehicle \( \text{\textcircled{2}} \), the amount of elemental carbon on the measuring filters was below the detection limit of the procedure. For the high-emitting vehicle \( \text{\textcircled{2}} \), there is the highest carbonaceous part of the particle emission.

RTS95, which has higher accelerations than WLTC, produces with cold start the highest amount of black carbon emission. Comparing all four vehicles in WLTC cold an increase of blackness of the filter residue in the sequence: \( V4 < V1 < V3 < V2 \) can be remarked. This is the same sequence, like for the increase of PN-emissions.

5.3. GPF & cGPF on high emitting car

On the highly emitting vehicle \( \text{\textcircled{2}} \), tests with add-on GPF’s were performed. Two GPF’s were mounted after the three-way catalyst with no interference with the original exhaust aftertreatment system. One of the investigated GPF’s was coated (cGPF) and another one was uncoated (GPF). Both filters have different technical specifications of substrates:

- cGPF: commercial high porosity GPF technology, TWC coated, filter size 1.3L
- GPF: commercial medium porosity GPF technology, uncoated, filter size 1.2L

Fig. 8 shows the PN-emissions without GPF and with both GPF’s (coated and uncoated) in the transient driving cycles. It can be remarked that in new state the coated cGPF has mostly a higher filtration efficiency (PCFE). The uncoated GPF in a new state would not fulfill the new limit value in WLTC cold. During the use of this filter the filtration becomes more efficient (see RTS95). In the high-speed cycle ADAC 130 there is (as integral average) no PN-reduction with both GPF’s. The resulting filtration efficiencies in all transient cycles and also at stationary operation (SSC) are summarized in Fig. 9.

In SSC there are very high filtration efficiencies PCFE > 99%.
In the high-speed cycle ADAC 130 the little (downsized) engine of this car is working very much at full load and the filtration efficiency is falling for cGPF to 8% and for GPF to zero. The reason for that are the highest spacial velocities combined with highest temperature of the filter. Fig. 10 shows an example of instantaneous filtration efficiency and of exhaust temperature before GPF in this high-speed cycle. The peak values of $t_{\text{exh}} > 700^\circ\text{C}$ are very high and the loss of diffusion filtration at acceleration events is obvious. Over the cycle duration the temperature increases, while the average filtration efficiency decreases.

**Figure 8.** PN-emissions with add-on cGPF and GPF in different driving cycles

**Figure 9.** Particles Counts Filtration Efficiencies of cGPF and GPF in different driving cycles

**Figure 10.** Instantaneous filtration efficiency and exhaust temperature before GPF in the high-speed driving cycle ADAC130

**Figure 11.** Accumulated emissions with add-on-GPF (uncoated) and cGPF (coated); ADAC 130; V2
The filter was not damaged in this test, as further results with high filtration efficiencies were generated afterwards. The physics of this loss of efficiency is, nevertheless, not fully clarified and it stays as open question for more research.

Observing the accumulated gaseous emissions (measured in diluted gas) with both filters in ADAC 130 cycle, Fig. 11, it can be stated that the uncoated GPF works as thermal reactor and contributes to the partial oxidation of HC. Nevertheless, this also produces CO, so the summary effect of GPF on CO is negligible. The coated cGPF contributes to the reduction of NO\textsubscript{x} due to the non-selective catalytic effect (reduction of NO\textsubscript{x} by means of CO in presence of catalyst). The TWC-coatings containing Rhodium promote this reduction.

Fig. 12 represents some gaseous emissions in three steps of the steady state cycle SSC. It can be remarked that the coated cGPF generally reduces the emissions of CO, HC, NH\textsubscript{3}, HCHO and MeCHO.

The SMPS results, with both: GPF and cGPF in Fig. 13, illustrate that only at higher engine load (95km/h) there is a real particle size distribution (PSD) without GPF and with GPF (or cGPF). At lower speed (45km/h), there are random indications of PN, but no real PSD with GPF and cGPF. The filtration differences between both filters are not visible and the resulting PN-concentrations are mostly below the background (ambient) level.

Figure 12. Gaseous emissions w/o GPF, with cGPF and GPF during steady state operation, SSC
5.4. Soot-loading

Fig. 14 informs about the attempt of using the uncoated GPF over the long distance of real world driving. During the tests GPF was periodically weighed at the same temperature of 280°C (except of the 1st weighing at $t_{amb}$) and no increase of weight over 4100 km could be remarked. For real road driving, a RDE-conform circuit (with urban, rural and highway parts) was used and the maximum temperature before GPF rose up to 670°C.

Except of p/t-datalogging before GPF no other emission measurements were conducted during the real-world driving.

Fig. 15 gives an example of datalogging evaluation of backpressure and temperature before GPF in real road driving. There are events with extremely high temperature which contributes to self-regeneration of GPF. The backpressure mean values and standard deviations stay nearly constant during the whole road trial up to 4100 km.
6. Remarks

Regarding the data of test vehicles in Table 1, it can be remarked, that the vehicle V2 has the smallest engine and the highest vehicle weight. This 2-cylinder, turbocharged engine is equipped with MultiAir valve train system. The specific load of this engine is much higher, than on the other tested cars – all three of them with self-aspirating, 4-cylinder, no downsized engines.

Table 3 represents examples of the specific integrated positive work at the roller in different driving cycles. The engine of vehicle V2 has in average higher specific loads, which are by 56% - 65% higher, than the other engines.

This means, that the fuel amount injected per cylinder is for similar work in this proportion higher and the probability of “unprepared” fuel entering the combustion chamber is increased (see discussion to Fig. 4).

Table 3. Positive specific work at roller during cycle and factor (V2/Vx) representing increased specific engine load of vehicle V2

| Vehicle | WLTC cold V2/Vx | ADAC130 V2/Vx | V2/Vx |
|---------|----------------|---------------|-------|
| V1      | 6264           | 1.65          | 9088  | 1.64 |
| V2      | 10364          | 1.00          | 14873 | 1.00 |
| V3      | 6516           | 1.59          | 9556  | 1.56 |
| V4      | 6413           | 1.62          | 9507  | 1.56 |

Nevertheless, the authors presume that in this highly sophisticated engine, several possibilities could be found to lower the PN-emission, if this would be an objective of the development.

According to the present state of knowledge (January 2018) of the research team the soot loading of GPF will arrive very rarely or not at all, because of much higher exhaust temperatures and much lower soot masses. The externally initiated regeneration (if any) will be very scarce.

The ash loading is logically to expect but after very long operating distances. The fuel penalty, which is to expect for a life time of a GPF-car is most probably significantly lower than for DPF.

For unexpected cases of filter plugging, like due to increased lube oil consumption, or injector damage, the OEM’s apply the precaution strategies in OBD-system.
7. Conclusions

The most important statements of this work can be summarized as follows:

- The present work demonstrated that the modern SI-vehicles with MPI can emit a considerable amount of PN and PM. In an extreme case, the PN-emission was in the range of Diesel car (without DPF).
- With the GPF’s with better filtration quality it is possible to lower the emissions below the actual European limit value of $6.0 \times 10^{11}$#/km.
- The filtration efficiency of GPF can attain 99% but it can also be optimized to lower values – in this respect the requirement of “best available technology for health protection” should be considered.
- With coated cGPF added after 3WC some gaseous emission components are further reduced: CO, HC, NH$_3$, HCHO and MeCHO.
- For the investigated vehicles with gasoline MPI, there is no increase of PC’s in nuclei mode (below 10 nm) at the measured constant speeds, the particle counts below 10 nm are negligible.
- In the real road trial of uncoated GPF no increase of weight or backpressure could be observed up to 4100 km.

The present research on MPI vehicles, showed some tendencies of significantly increased PN-emissions. With this knowledge and taking into consideration the immense multiplication factor of MPI vehicles worldwide the legal PN-limitations for MPI should be quickly progressed and GPF offers excellent potentials of emission reduction.

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References

[1] Packham M S, Finch A and Campbell B 2011 Study of particle number emissions from a turbocharged gasoline direct injection (GDI) engine including data from a fast-response particle size spectrometer SAE Technical Paper 2011-01-1224

[2] Farron C, Matthias N, Andrie M, Krieger R, Najt P, Narayanaswamy K and Solomon A 2011 Particulate characteristics for varying engine operation in a gasoline spark ignited, direct injection engine SAE Technical Paper 2011-01-1220

[3] Ulrich A and Wichser A 2003 Analysis of additive metals in fuel and emission aerosols of diesel vehicles with and without particle traps Analyt. and Bioanalyt.Chem. 377(1) 71-81

[4] Burtscher H 2005 Physical characterization of particulate emissions from diesel engines: a review Journal of Aerosol Science 36(7) 896-932

[5] Sgro L A et al 2012 Investigating the origin of nuclei particles in GDI engine exhausts Combustion and Flame 159(4) 1687-1692

[6] Mayer A, Czerwinski J, Kasper M, Ulrich A and Mooney J J 2012 Metal oxide particle emissions from Diesel and petrol engines SAE Technical Paper 2012-01-0841

[7] Ulrich A et al 2012 Particle and metal emissions of diesel and gasoline engines are particle filters appropriate measures? Proceedings of the 16th ETH Conference on Combustion Generated Nanoparticles

[8] Mayer A, Czerwinski J, Ulrich A and Mooney J J 2010 Metal-oxide particles in combustion engine exhaust SAE Technical Paper 2010-01-0792

[9] Buchholz B A, Dibble R W, Rich D and Cheng A S (Ed) 2003 Quantifying the contribution of lubrication oil carbon to particulate emissions from a diesel engine SAE Technical Paper 2003-01-1987
[10] Sonntag D B, Bailey Ch R, Fulper C R and Baldauf R W 2012 Contribution of lubricating oil to particulate matter emissions from light-duty gasoline vehicles in kansas city Environment Science & Technology 02

[11] Hadler J, Lensch-Franze Ch, Gohl M and Mink T 2015 Emission reduction a solution of lubricant composition, calibration and mechanical development MTZ 09

[12] Yinhui W, Rong Z, Yanhong Q, Jianfei P, Mengren L, Jianrong L, Yusheng W, Min H and Shijin S 2016 The impact of fuel compositions on the particulate emissions of direct injection gasoline engine Elsevier Fuel 166 543-552.

Journal homepage: www.elsevier.com/locate/fuel

[13] Bach C 2007 emissionsvergleich verschiedener Antriebsarten in aktuellen Personenwagen. Untersuchung der Emissionen von aktuellen Personenwagen mit konventionellen und direkteingespritzten Benzinnmotoren, Dieselmotoren mit und ohne Partikelfilter, sowie Erdgasmotoren Empa Final Report for Novatlantis and Bundesamt für Umwelt BAFU Novatlantis

[14] Khalek I A, Bougher Th and Jetter J J 2010 Particle emissions from a 2009 gasoline direct injection engine using different commercially available fuels SAE Technical Paper 2010-01-2117

[15] Zahng Sh and McMahon W 2012 Particulated emissions for LEV II light-duty gasoline direct injection vehicles SAE Technical Paper 2012-01-0442

[16] Bielaczyc P, Szcztoka A and Woodburn J 2013 An overview of particulate matter emissions from modern light duty vehicles Combustion Engines 2/2013 (153) 101-108 ISSN 0138-0346.

[17] Chan T W, Meloche E, Kubsh J, Brezny R, Rosenblatt D and Rideout G 2013 Impact of ambient temperature on gaseous and particle emissions from a direct injection gasoline vehicle and its implications on particle filtration SAE Technical Paper 2013-01-0527

[18] Dimou I, Kar K and Cheng W 2011 Particulate matter emissions from a direct injection spark ignition engine under cold fast idle conditions for ethanol-gasoline blends SAE Technical Paper 2011-01-1305

[19] Czerwinski J, Comte P, Heeb N and Mayer A 2015 Experiences from nanoparticle research on four gasoline cars SAE Technical Paper 2015-01-1079

[20] Mathis U, Kaegi R, Mohr M and Zenobi R 2004 TEM analysis of volatile nanoparticles from particle trap equipped diesel and direct-injection spark-ignition vehicles Atmospheric Environment 38 (2004) 4347-4355

[21] Lee K O, Seong H, Sakai St, Hageman M and Rothamer D 2013 Detailed morphological properties of nanoparticles from gasoline direct injection engine combustion of ethanol blends SAE Technical Paper 2013-24-0185

[22] Saito C, Nakatani T, Miyairi Y, Yuuki K, Makino M, Kurachi H, Heuss W, Kuki T, Furuta Y, Kattouah Ph and Vogt C-D 2011 New particulate filter concept to reduce particle number emissions SAE Technical Paper 2011-01-0814

[23] Königstein A, Fritzsche J, Kettenring K, Ley B, Nolte R and Schaffner P 2015 Alternatives to meet future particle emission standards with a boosted SIDI engine 24th Aachen Colloquium Automobile and Engine Technology 10/2017 1301

[24] Kern B and Kunert S 2015 The potential of comprehensive emission control for gasoline di-engines – a comparison of different exhaust system options and an outlook on future requirements 24th Aachen Colloquium Automobile and Engine Technology 10/ 2015 p. 1267

[25] Rose D, Coulet B, Nicolin P, Boger Th and Kunath F 2016 Field-study and durability evaluations on GDI vehicles equipped with various gasoline particulate filter (GPF) concepts 25th Aachen Colloquium Automobile and Engine Technology

[26] Boger Th, Rose D, Nicolin P and Coulet B 2017 Field experience with gasoline particulate filter
equipped gdi vehicles $MTZ$ Issue 1 28-35
[27] Kendlbacher Ch 1994 Verringerung der schadstoffemissionen im warmlauf durch verbesserung der gemischtbildung bei ottomotoren. 
VDI Fortschritt-Bericht Reihe 12, Nr. 213 ISBN 3-18-321312-5

[28] Meinig U 1997 Reduzierung der schadstoffemissionen von ottomotoren durch einlasskanal-kraftstoffverdampfer FAW-Verlag Bamberg Band 1 ISBN 3-931810-07-0

[29] Bamer F 2003 Kraftstoffzuteilung beim kalten ottomotor im instationären Betrieb mit erweiterter adaptiver Steuerung VDI Fortschritt-Bericht Reihe 12 Nr. 523 ISBN 3-18-352312-4

[30] Winklohofer E, Hopfner W and Kapus, P 2010 Euro VI Partikelgrenzwerte – Entwicklungsmethoden für GDI Motoren AVL List GmbH, Graz, Österreich, 7. Tagung HDT

[31] Dyckmans J, Arndt S, Raatz T, Grzeszik R and Eilts P 2010 Laseroptische Untersuchungen zur Gemischtbildung und Verbrennung in Verbindung mit dem Einsatz von Alkoholen als alternativer Kraftstoff bei der Benzindirekteinspritzung Robert Bosch GmbH Stuttgart TU Braunschweig 7 Tagung HDT

[32] Piock W, Hoffmann G, Berndorfer A, Salemi P and Fusshoecker B 2011 Strategies towards meeting future particulate matter emissions requirements in homogeneous gasoline direct injection engines SAE Technical Paper 2011-01-1212

[33] Whitaker P, Kapus P, Ogris M and Hollerer P 2011 Measures to reduce particulate emissions from gasoline DI engines SAE Technical Paper 2011-01-1212

Definitions/Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| ADAC 130     | ADAC high speed cycle |
| AFHB         | Abgasprüfstelle FH Biel, CH |
| ASET         | Aerosol Sampling & Evaporation Tube |
| BAFU         | Bundesamt für Umwelt, (see FOEN) |
| BP           | boiling point |
| CLA          | chemiluminescent analyzer |
| CPC          | condensation particle counter |
| CVS          | constant volume sampling |
| DF           | dilution factor |
| DI           | Direct Injection |
| DMA          | differential mobility analyzer |
| DPF          | Diesel particle filter |
| EC           | Elemental Carbon European Community |
| EGR          | exhaust gas recirculation |
| EMPA         | Eidgenössische Material Prüf- und Forschungsanstalt |
| fc           | fuel consumption |
| FOEN         | Federal Office for Environment |
| GDI          | gasoline direct injection |
| GPF          | gasoline particle filter |
| GRPE         | EC Groupe Rapporteurs Pollution & Energy |
| HCHO         | Formaldehyde |
| MD           | minidiluter |
| MeCHO        | Acetaldehyde |
| MFS          | mass flow sensor |
| MPI          | multipoint port injection |
| NH3          | Ammonia |
| NP           | nanoparticles < 999 nm |
| nSMPS        | nano SMPS |
| PAH          | polycyclic aromatic hydrocarbons |
| PC           | particle counts (integrated) |
| PM           | particle mass |
| PN           | particle numbers |
| PCFE         | particle counts filtration efficiency |
| PMP          | Particle Measuring Program of the GRPE |
| PSD          | particle size distribution |
| RTS 95       | short research cycle |
| SMPS         | scanning mobility particle sizer |
| SSC          | steady state cycle |
| TC           | thermoconditioner |
| TGA          | thermogravimetric analysis |
| TTM          | Technik Thermische Maschinen |
| TWC          | three way catalyst |
| UFP          | ultrafine particles |
| V            | vehicle |
| VERT         | Verification of Emission |
| WLTC         | Worldwide Light Duty Test Cycle |
| WLTP         | Worldwide Light Duty Test Procedure |