

## Nanoparticle emissions from gasoline vehicles DI & MPI

*The nanoparticles (NP) count concentrations are limited in EU for all Diesel passenger cars since 2013 and for gasoline cars with direct injection (GDI) since 2014. For the particle number (PN) of MPI gasoline cars there are still no legal limitations. In the present paper some results of investigations of nanoparticles from five DI and four MPI gasoline cars are represented. The measurements were performed at vehicle tailpipe and in CVS-tunnel. Moreover, five variants of “vehicle – GPF” were investigated. The PN-emission level of the investigated GDI cars in WLTC without GPF is in the same range of magnitude very near to the actual limit value of  $6.0 \times 10^{12}$  1/km. With the GPF’s with better filtration quality, it is possible to lower the emissions below the future limit value of  $6.0 \times 10^{11}$  1/km. The modern MPI vehicles also emit a considerable amount of PN, which in some cases can attain the level of Diesel exhaust gas without DPF and can pass over the actual limit value for GDI ( $6.0 \times 10^{12}$  1/km). The GPF-technology offers in this respect further potentials to reduce the PN-emissions of traffic.*

Key words: particle number (PN), gasoline direct injection (GDI), multipoint port injection (MPI), gasoline particle filter (GPF)

### 1. Introduction

The invisible nanoparticles (NP) from combustion processes 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 known to be a complex mixture of different volatile and non-volatile species often showing 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 [1–4]. 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 [5–7].

These particles are suspected to be nucleated metal oxides originating from metal additives in lubrication oil or fuels [8–11]. 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 range  $< 23$  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.

Knowledge about the emission level, chemistry and formation mechanisms of these particles is an important objective in order to assess their toxic potential, and to propose effective measures to reduce these emissions.

Studies for gasoline fueled internal combustion engines pointed out that also this vehicle class can emit remarkable amounts of particles [6, 12, 13]. 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 [14]. The lube oil contributes to this emission in the sense of number concentrations in nuclei mode and composition [8–10].

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 [15, 16].

Car manufacturers and suppliers of exhaust aftertreatment technology offer several mature solutions of GPF for efficient elimination of the nanoparticles from DI SI-engines [17, 18].

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.

Some investigations in present paper were performed at AFHB (Laboratories for IC-Engines and Exhaust Emission Control of the Berne University of Applied Sciences, Biel

CH) as a part of the network project GasOMeP, together with the Swiss Research Institutions: EMPA, FHNW and PSI.

This paper presents: comparisons of NP-emissions of five GDI vehicles and four MPI vehicles at steady state (SMPS) and at transient (CPC) operation, as well as the emissions reduction potentials with different gasoline particle filters (GPF's) on some GDI cars.

Table 1a. Data of investigated cars

Vehicles ①②③	Volvo V60 T4F ①	Opel Insignia 1.6 EcoFlex ②	Mitsubishi Carisma 1.8 GDI ③
Number and arrangement of cylinders	4 / in line	4 / in line	4 / in line
Displacement cm <sup>3</sup>	1596	1598	1834
Power kW	132 @ 5700 rpm	125 @ 6000 rpm	90 @ 5500 rpm
Torque Nm	240 @ 1600 rpm	260 @ 1650-3200 rpm	174 @ 3750 rpm
Injection type	DI	DI	DI
Curb weight kg	1554	1701	1315
Gross vehicle weight kg	2110	2120	1750
Drive wheel	Front-wheel drive	Front-wheel drive	Front-wheel drive
Gearbox	a6	m6	m5
First registration	27.01.2012	2014	05.2001
Exhaust	EURO 5a	EURO 5b+	EURO 3
Aftertreatment	TWC	TWC	TWC/Ox.Cat

Table 1b. Data of investigated cars

Vehicles ④⑤⑥	Opel Zafira Tourer ④	VW Golf Plus ⑤	Diesel Peugeot 4008 1.6HDi STT ⑥
Number and arrangement of cylinders	4 / in line	4 / in line	4 / in line
Displacement cm <sup>3</sup>	1598	1390	1560
Power kW	125 @ 6000 rpm	118 @ 5800 rpm	84 @ 3600 rpm
Torque Nm	260 @ 1650 - 3200 rpm	240 @ 1500 rpm	270 @ 1750 rpm
Injection type	DI	DI	DI
Curb weight kg	1678	1348 - 1362	1462
Gross vehicle weight kg	2360	1960 - 1980	2060
Drive wheel	Front-wheel drive	Front-wheel drive	Front-wheel drive
Gearbox	m6	m6	m6
First registration	22.07.2014	01.02.2010	12.04.2013
Exhaust	EURO 5b+	EURO 4	EURO 5b
Aftertreatment	TWC	TWC	DPF

## 2. Tested vehicles

Table 1 summarizes the most important GDI vehicle data. As a reference of the best available technology, concerning the reduction or elimination of PM- and PN-emissions a modern Diesel passenger car with a high-quality DPF was included in the tests (vehicle ⑥).

Table 2 shows the most important data of the investigated MPI vehicles. It can be remarked that the vehicle ⑧ in this group is the only one with turbocharger and vehicle ⑩ is equipped with 2 injectors per cylinder intake port.

Table 2. Data of investigated MPI vehicle

Vehicles ⑦⑧⑨⑩	Opel Adam ⑦	Fiat Panda 4x4 Twin Air ⑧	Ford KA 1.2i ⑨	Suzuki Baleno 1.2 Hybrid ⑩
Number and arrangement of cylinders	4 / in line	2 / in line	4 / in line	4 / in line
Displacement cm <sup>3</sup>	1398	875	1242	1242
Power kW	64 @ 6000 min <sup>-1</sup>	62.5 @ 5500 min <sup>-1</sup>	85 @ 5500 min <sup>-1</sup>	66 @ 6000 min <sup>-1</sup>
Torque Nm	130 @ 4000 min <sup>-1</sup>	145 @ 1900 min <sup>-1</sup>	102 @ 3000 min <sup>-1</sup>	120 @ 4400 min <sup>-1</sup>
Injection type	MPI	MPI	MPI	MPI
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
Exhaust	EURO 5b	EURO 6b	EURO 6b	EURO 6b
After-treatment	TWC	TWC	TWC	TWC + EGR

## 3. Fuels and lube oils

The gasoline used was from the Swiss market, RON 95, according to SN EN228. A bigger charge of gasoline was purchased for the project and it was analysed at INTERTEC Laboratory. The most important data are given in Table 3.

The lube oils for GDI-vehicles were also analysed at EMPA Laboratory, Table 4, which shows the 9 most prominent metals and the sums of all analysed 21 metals. For all GDI-vehicles, except of vehicle ②, the same lube oil was applied.

For the Diesel car as well as for the MPI cars the lube oils were not changed and not analysed.

Table 3. Data of gasoline

Property	Unit	Result
Density (at 15°C)	kg/m <sup>3</sup>	736.1
Vapor pressure (at 37.8°C)	kPa	67.3
Research Octan Number (RON)	–	95.6
Oxygen content	% (m/m)	1.0
Sulfur content	mg/kg	<1.0
Pb Lead	mg/L	<1.0
Ca Calcium	mg/kg	<1.0
Fe Iron	mg/kg	<1.0
Mg Magnesium	mg/kg	<1.0
Mn Manganese	mg/kg	<1.0
P Phosphorus	mg/kg	<1.0
Zn Zink	mg/kg	<1.0
Na Natrium	mg/kg	<1.0
K Potassium	mg/kg	<1.0
Distillation (at 101.3 kPa)		
• start	°C	34
• 10% Vol	°C	48
• 50% Vol	°C	75
• 90% Vol	°C	142
• end	°C	174

Table 4. Data of the utilized lube oils (\* analysis, others: specifications)

Property (typical value)	Vehicles ①③④⑤	Vehicles ②	Unit
	Castrol Magnatec	dexos 2	
Viscosity kin 40°C	72.0	72.0	mm <sup>2</sup> /s
Viscosity kin 100°C	12.2	12.1	mm <sup>2</sup> /s
Viscosity index	166	165	(–)
Density 15°C	852	854	kg/m <sup>3</sup>
Pour point	–39	–36	°C
Flash point (PMCC)	207	>201	°C
Total Base Number TBN		7.5	mg KOH/g
Sulphated ash	0.8	0.8	%wt
Na *	4.7	434	µg/g
Mg *	17	9.2	µg/g
Al *	32	5.4	µg/g
Ca *	2240	2300	µg/g
Mn *	0.20	24	µg/g
Fe *	17	34	µg/g
Cu *	0.07	27	µg/g
Zn *	760	630	µg/g
Mo *	36	0.81	µg/g
Sum metals	3109.56	3481.48	µg/g

#### 4. Test methods and instrumentation

The vehicles were tested on a chassis dynamometer at constant speeds and in the dynamic driving cycles WLTC, 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.

##### 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 mini-diluter (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 = 100 to 500.

The estimated accuracy of PN-measurement in the size range of 80–120 nm, with DF = 100 is ±6%.

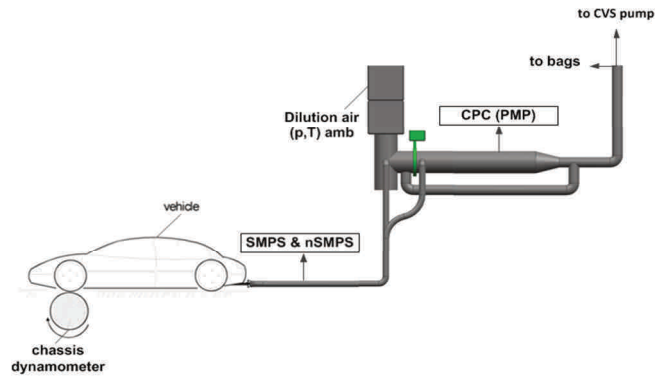


Fig. 1. Set-up of exhaust gas sampling for PN-analysis

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

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 vehicles were tested on a chassis dynamometer at constant speeds (SSC) and in the dynamic 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 ⑦ (MPI). This gives the magnitude of the temperatures at the particulate sampling point “tailpipe” during steady state measurements (SMPS).

The approach to find a homogenized world-wide driving cycle was successfully finished with the development of the homogenized WLTP world-wide light duty test procedure. 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.

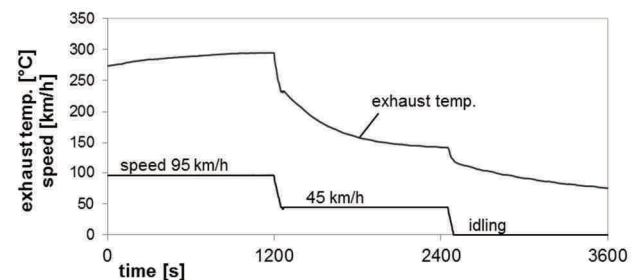


Fig. 2. Steady State Cycle (SSC) and tailpipe temperature of vehicle 7 (MPI)

In the test program with MPI vehicles the 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 high-way

driving and for the investigated vehicles class requires some full load accelerations.

Fig. 3 shows the time-courses and Table 5 summarizes the most important data of these driving cycles.

Table 5. Data of the driving cycles

Cycle	Duration s	Distance m	$V_{\max}$ km/h	$a_{\max}$ m/s <sup>2</sup>	$a_{\min}$ m/s <sup>2</sup>
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

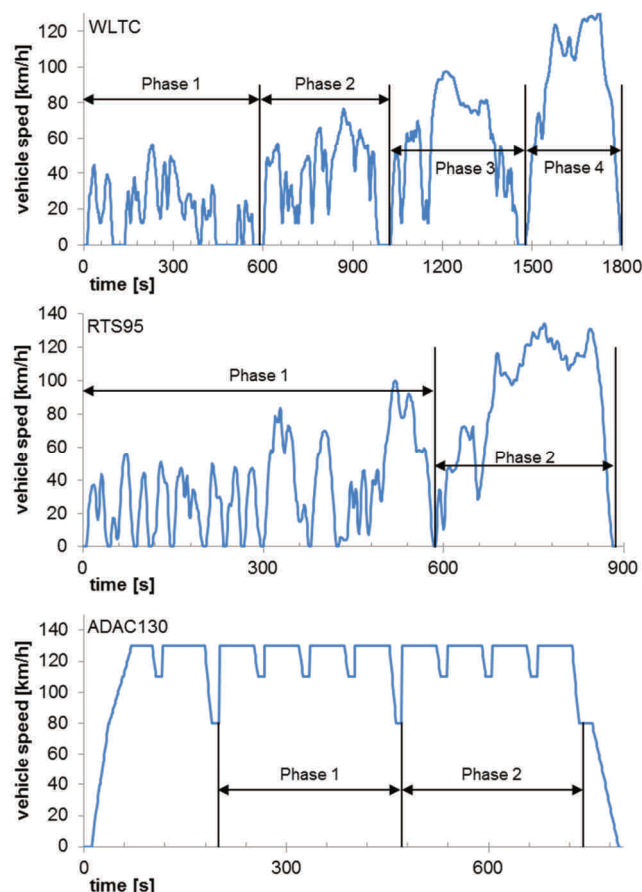


Fig. 3. Transient driving cycles WLTC, RTS 95 and ADAC 130

## 5. Results with GDI vehicles

### 5.1. Steady state operation (SSC)

The considerations of particle size distributions at steady state operation give a basic view on the PN-concentrations at tailpipe and allow some reflections about the nanoparticle production. Nevertheless, this is not a legal measuring procedure and therefore the results do not have to be compared with the legal PN limit values.

Fig. 4 represents exemplary the SMPS particle size distributions (PSD) of all tested vehicles (V1 to V5) at tailpipe without GPF at the same constant speeds and idling.

At 95 and 45 km/h the maxima of PSD's show in certain cases the particle counts concentrations (PC) in the range of  $10^6$  to  $10^7$  1/cm<sup>3</sup>, which is similar as for Diesel engines (without DPF). At idling, the PC values are roughly one order of magnitude lower.

For vehicle ③, strong fluctuations of the PC-concentration during the period of scanning (over the size range) are visible. During the constant speed operation of this vehicle (at 95 and 45 km/h), periodic fluctuations of gaseous emissions (CO, HC, NO<sub>x</sub>) were observed (not represented here) and confirmed a continuous switching of the operation between lean and rich. This means that for this vehicle, changing between the stratified, or homogeneous (lean) and homogeneous (rich) operating strategies, it also implies the switching of parameters, like ignition timing, injection timing, injection quantity and eventually EGR. This can have the influences on NP-emissions as demonstrated.

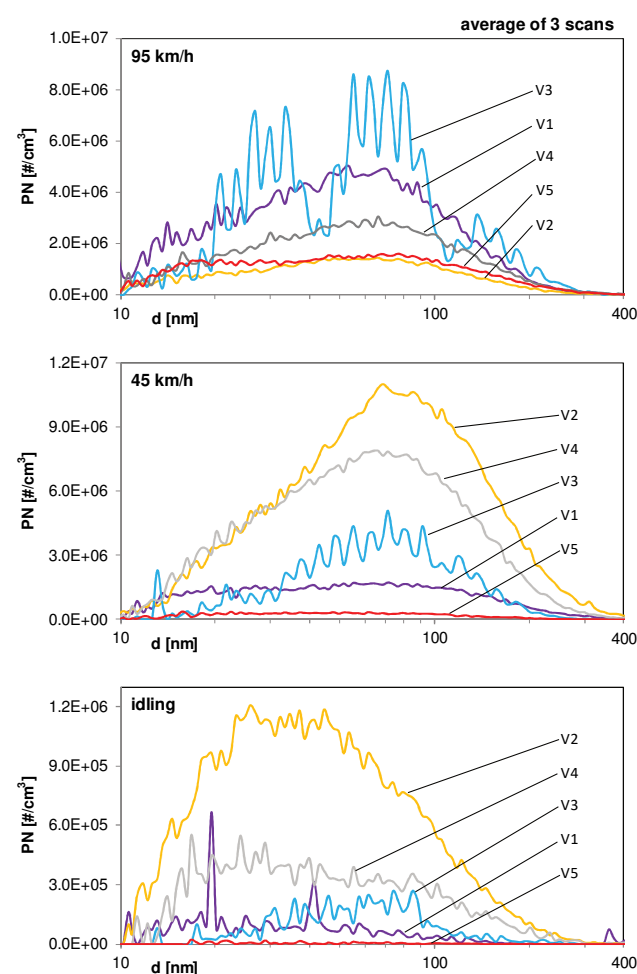


Fig. 4. SMPS particle size distributions at constant speeds with different GDI vehicles (w/o GPF)

The relationships of NP-emissions between different vehicles can vary depending on operating condition. As example: vehicle ② has at 95 km/h the lowest and at 45 km/h and idling the highest particle counts concentrations. This is also visible in the summary representation of integral PN-emissions at all tested constant speeds, Fig. 5.

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.



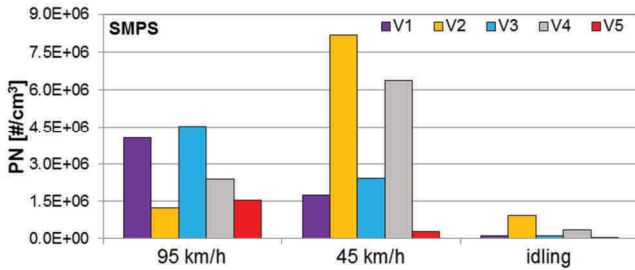


Fig. 5. Integral PN emissions at constant speeds with different GDI vehicles (w/o GPF)

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

For MPI there is usually a portion of fuel deposited on the walls of the intake port, 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 [20, 21].

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).

Fig. 6 shows, as example, the particle size distributions measured with SMPS and with nSMPS for the higher (vehicle ④) and for the lower (vehicle ②) emitting vehicles at 95 km/h.

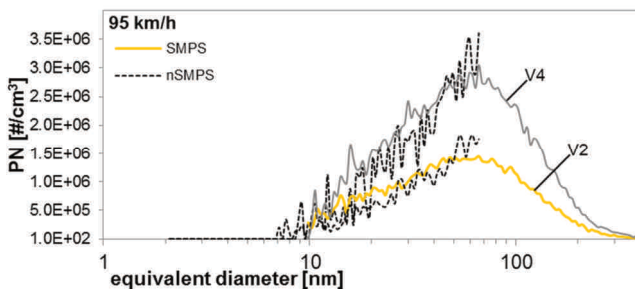


Fig. 6. SMPS & nSMPS particle size distributions at 95 km/h with GDI V2 & V4 (w/o GPF)

There are no PC in the sizes below 6 nm and the PC in the size range 6 to 10 nm can be considered as negligible.

Generally there is a very good accordance of PSD's measured with both systems SMPS and nSMPS in the common size range (10–64 nm).

Fig. 7 shows an example of scans with and without GPF. It confirms the excellent accordance of scans with both systems, it also confirms very good particle count filtration efficiency (PCFE) of the tested GPF and it particularly shows the total elimination of nanoparticles with sizes below 30 nm.

The opinion of the authors, resulting from these tests as well as from previous experiences with GDI-vehicles [19], is that additional research, or discussions about NP's with sub-10 nm-sizes and more restrictions of the legislation for sub-23nm-sizes, are not necessary.

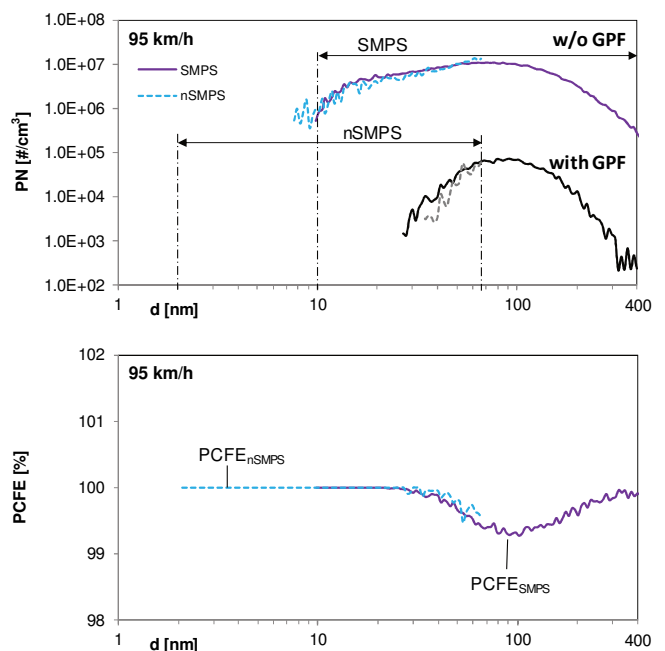


Fig. 7. Example of PSD's with SMPS & nSMPS and particle counts filtration efficiency (PCFE) with V1, GPF 1 at 95 km/h

Five variants “vehicle – GPF” were tested. The GPF's were randomly obtained for the tests and they were mounted in the exhaust systems of the cars approximately 60 cm downstream of the TWC. They were neither developed, nor optimized for this application. The specific data of the GPF's are not available.

Fig. 8 summarizes the filtration efficiencies (PCFE) obtained at the constant speeds. The PCFE-values are between 91% and 100%. GPF3 and GPF4 represent clearly lower filtration efficiency than GPF1 and GPF2. This result indicates that the filtration efficiencies can be adapted by optimizing the substrate to fulfil different objectives or requirements.

In comparison, the quality requirements for DPF retrofitting are: for the Swiss Confederation OAPC  $PCFE \geq 97\%$  and of the VERT Association  $PCFE \geq 99\%$ . This is in the sense of “best available technology for health protection”.

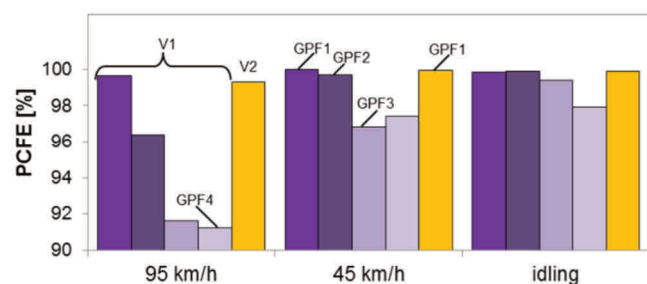


Fig. 8. Filtration efficiencies PCFE at constant speeds with different GPF's (SMPS data)

## 5.2. Transient operation

The results at transient operation are obtained with CPC (according to PMP) at the end of CVS-dilution tunnel. These results can be compared with the legal PN limit values.

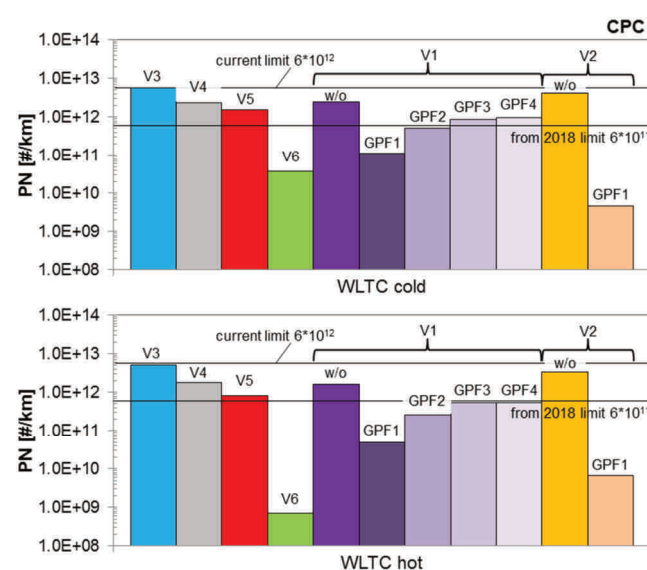


Fig. 9. Comparison of PN-emissions in WLTC cold and hot for different vehicles

All mechanisms influencing the NP-production in combustion chambers and in the exhaust system are at transient operation variable and mostly overlapping each other. A known and accepted fact is that the peak values of NP-emissions coincide with the acceleration, or deceleration events in the driving cycle.

Fig. 9 summarizes the average PN emissions in WLTC cold and hot. The emission level of “hot” cycles is generally lower than the emission level of “cold” cycles. Vehicles which are equipped with GPF have, as expected, lower PN-emissions. Vehicle ⑥ is a Diesel car with original DPF of a very good quality; it sets a quality level, which is only roughly attained by the vehicle ② with GPF1.

From all variants with GPF's the GPF3 and GPF4 have the highest emissions. These two filters also have the lowest average filtration efficiencies, Fig. 10.

Finally, it can be concluded that the PN-emission level of the investigated GDI cars in WLTC without GPF is in the same range of magnitude very near to the actual limit value of  $6.0 \times 10^{12}$  1/km. With the GPF's with better filtra-

tion quality it is possible to lower the emissions below the future limit value of  $6.0 \times 10^{11}$  1/km.

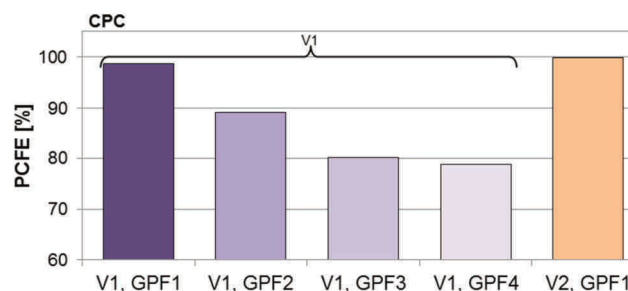


Fig. 10. PCFE's of the investigated GPF's in WLTC hot

## 6. Results with MPI vehicles

### 6.1. Steady state operation (SSC)

Fig. 11 gives an example of the SMPS-particle size distributions (PSD) with the MPI vehicles at 95 km/h and at idling. The indicated particle counts concentrations are mostly in the range of ambient background level ( $10^2$  to  $10^4$  1/cm<sup>3</sup>). Nevertheless, there are some exceptions such as a clearly higher PN-emission with vehicle ⑧ at 95 km/h and a higher PN-emission with vehicle ⑨ at idling.

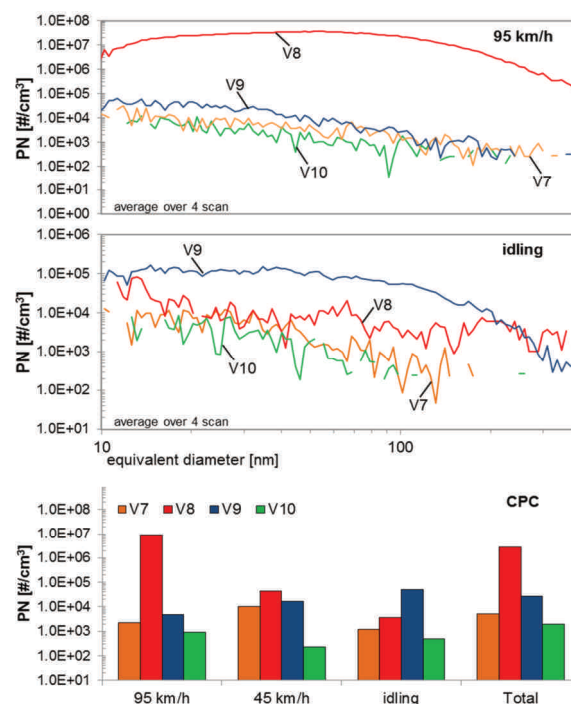


Fig. 11. SMPS particle size distribution at constant speeds with different MPI vehicles

At the highest speed (95 km/h) vehicle ⑧ causes the particle count concentrations, which are up to 3 ranges of magnitude higher, then with the other vehicles.

Fig. 12 compares the PSD's measured with SMPS and with nSMPS with the highest emitting vehicle ⑧ and with the lowest emitting vehicle ⑩ at 95 km/h.

For vehicle ⑧ 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 10 nm are zero, or negligible.

For vehicle ⑩ 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.

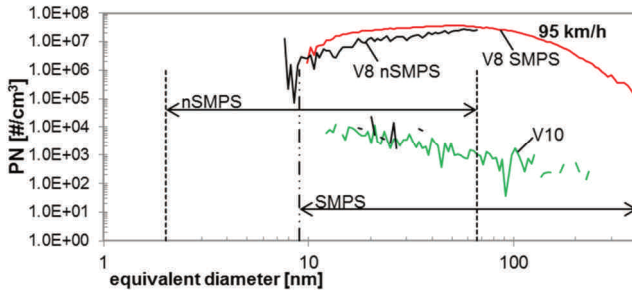


Fig. 12. Particle size distribution of MPI vehicles (min/max emissions)

## 6.2. 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. 13 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 present limit value of  $6 \times 10^{12}$  1/km and three of the vehicles would not pass the future limit value of  $6 \times 10^{11}$  1/km.

The following points have to be mentioned:

- in the cycle RTS95 vehicle ⑧ 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 ⑧,
- 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 ⑧ CO in the bag came in over range,
- vehicle ⑩ 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.

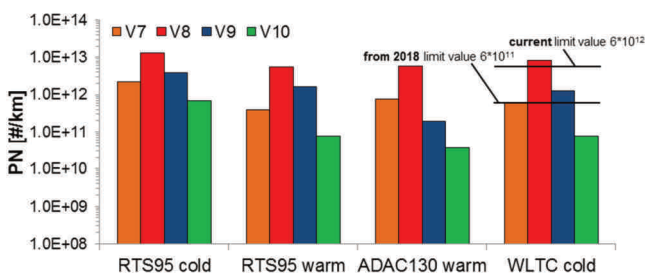


Fig. 13. PN results in all driving cycles

Fig. 14 impressively illustrates the residues on PM-measuring filters of two vehicles in all driving cycles. There is a high carbonaceous part of the particle emission of the high-emitting vehicle ⑧.

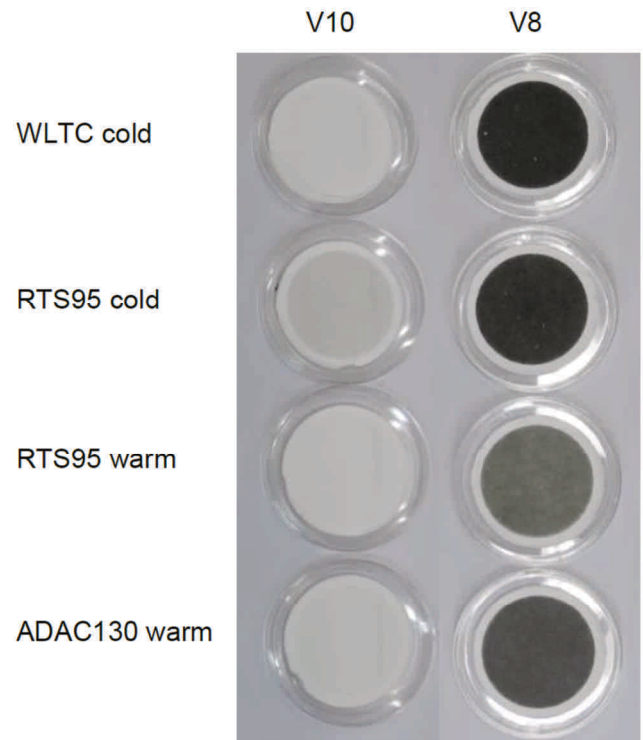


Fig. 14. PM-results of the lowest & highest emitting vehicles in different transient cycles

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:  $V10 < V7 < V9 < V8$  can be remarked. This is the same sequence, like for the increase of PN-emissions.

## 7. Conclusions

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

- The PN-emission level of the investigated GDI cars in WLTC without GPF is in the same range of magnitude and very near to the actual limit value of  $6.0 \times 10^{12}$  1/km.
- With the GPF's with better filtration quality it is possible to lower the emissions below the future limit value of  $6.0 \times 10^{11}$  1/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.
- The present work demonstrated that the modern SI-vehicles with MPI also emit a considerable amount of PN and PM. In an extreme case the PN-emission was in the range of Diesel car (without DPF).
- The relationships of NP-emissions between different vehicles can vary depending on operating conditions.

- Generally there is a very good accordance of PSD's measured with both systems SMPS and nSMPS in the common size range (10–64 nm).
- For the investigated vehicles with gasoline DI and 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.
- Due to the electronic regulation of the engine the NP-emission of some vehicles (here vehicle ③) are periodically fluctuating. The present paper focuses solely on solid nanoparticle emissions. The tested GDI cars, except of vehicle ③, were with homogenous combustion concept and all of them (GDI & MPI) represented a modern TWC technology. According to that the emissions of gaseous legislated components (CO, HC, NO<sub>x</sub>) were very low.

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.

The present high filtration quality of Diesel vehicles (DPF) set's high requirements on the filtration quality in the gasoline sector (GPF).

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### Nomenclature

AFHB	Abgasprüfstelle FH Biel, CH	MD	minidiluter
ASET	aerosol sampling & evaporation tube	MFS	mass flow sensor
BAFU	Bundesamt für Umwelt, (see FOEN)	MPI	multipoint port injection
CLA	chemiluminescent analyzer	NP	nanoparticles < 999 nm
CPC	condensation particle counter	nSMPS	nano SMPS
CVS	constant volume sampling	OAPC	CH: Ordinance of Air Protection Control
DF	dilution factor	PC	particle counts (integrated)
DI	direct injection	PM	particle mass
DMA	differential mobility analyzer	PN	particle numbers
DPF	diesel particle filter	PMP	Particle Measuring Program of the GRPE
EC	elemental carbon European Community	PSD	particle size distribution
EGR	exhaust gas recirculation	PSI	Paul Scherrer Institute
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt	SMPS	scanning mobility particle sizer
FHNW	Fachhochschule Nord-West Schweiz	SSC	steady state cycle
FOEN	Federal Office for Environment	TC	thermoconditioner
GasOMeP	gasoline organic & metal particles	TTM	Technik Thermische Maschinen
GDI	gasoline direct injection	TWC	three way catalyst
GPF	gasoline particle filter	V	vehicle
GRPE	EC Groupe Rapporteurs Pollution & Energy	VERT	verification of emission reduction technologies
		WLTC	worldwide light duty test cycle

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