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PN-EMISSIONS WITH INCREASED LUBE OIL CONSUMPTION OF GDI CAR WITH/WITHOUT GPF

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Abstract

The particle number (PN) emissions are increasingly considered in the progressing exhaust gas legislation for on- and off- road vehicles. The invisible nanoparticles penetrate like a gas into the living organisms and cause several health hazards.

The present paper shows how the PN- and gaseous emissions of a modern GDI (Abbreviations see at the end of this paper) vehicle change, when there is an in-creased lube oil consumption. What are the potentials of a gasoline particle filter to reduce the emissions?

The lube oil consumption was simulated by mixing 2% vol. lube oil into the fuel. A non-coated GPF was mounted at tailpipe, so only the filtration effects were indicated.

The tests were performed at transient (WLTC) and at stationary (SSC) operating conditions.

It has been shown that the increased lube oil consumption significantly increases the PN-emissions and the applied high quality GPF eliminates these emissions very efficiently.

Keywords: *PN-emissions of road transport, combustion engines, air pollution, environmental protection*

1. Introduction

The nanoparticles (NP)*[)] count concentrations are limited in EU for Diesel passenger cars since 2013 and for gasoline cars with direct injection (GDI) since 2014. The limit for GDI was temporary extended to 6 x 10^{12} #/km (regulation No. 459/2012/EU) and will be lowered back to the level of Diesel cars (6x10^{11} #/km) in 2017.

The nanoaerosol in vehicle exhaust is known to be a complex mixture of different volatile and non-volatile species often showing a bi-modal 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 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 sur-face composition of the aerosol and have therefore a significant impact on health effects associated with pollution.

Studies for gasoline fuelled 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 in-creasing, 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].

The investigations in present paper were per-formed 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.

The objectives were to demonstrate the influences of increased lube oil consumption on the emissions, to show the effect of high quality exhaust gas filtration and to state if the different characteristics of lube oil will show measurable effects?

2. Test vehicle, fuel and lubricants

2.1 Test vehicle data

The tests on gasoline vehicle (GDI) were performed with a Seat Leon 1.4 TSI. This vehicle was operated with gasoline, in original condition (3WC) and with lube oil blended to the fuel, which simulated the increased lube oil consumption.

The vehicle is presented in Fig. 1 and Tab. 1.

Fig. 1. Seat Leon 1.4 TSI ST

Tab. 1. Technical data of tested vehicle

Model and year	**Seat Leon 1.4 TSI ST/ 2015**
Type of engine	CZEA
Number and arrangement of cylinders	4 / in line
Displacement	1395 cm^3
Power	110 kW @ 6000 min^{-1}
Torque	250 Nm @ 1500 min^{-1}
Injection	Gasoline / DI
Turbocharging	Yes
Curb weight	1287 kg
Gross vehicle weight	1830 kg
Drive wheel	Front-wheel drive
Gearbox	m6
First registration / mileage	13.11.2014 / 27880 km
Exhaust standard	EURO 6b
Exhaust aftertreatment system	O_2-Sonde, TWC

2.2 Fuel

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 Tab. 2.

2.3 Lubricants

In the present tests, the lube oil of the engine was not changed and analysed – it was the lube oil recommended by the manufacturer Vapoil SAE 5W-30.

Tab. 2. Data of gasoline

Property	**Unit**	**Result**
Density (at 15°C)	kg/m^3	736.1
Vapour pressure (at 37.8°C)	kPa	67.3
Research Octan Number (RON)	-	95.6
Oxygen content	% (m/m)	1.0
Sulphur 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

For the simulation of increased oil consumption by adding it to the fuel two other lube oils, manufactured and analysed at Motorex, CH, were used. See Tab. 3 for the results of analysis.

These lube oils were selected in order to enable the testing with high "H" (≤ 1.2%) or with low "L" (≤ 0.5%) content of ashes and metals. They have a unified HC-matrix (hydrocrack) and equal viscosity. This choice makes the influence of ashes and metals on the PN more visible.

Tab. 3. Analysis data of the used lube oils

Property	**"L" ACEA C4 SAE 5W/30**	**"H" ACEA A3/B4 SAE 5W/30**	
Viscosity kin 40°C	68.5	69.7	mm^2/s
Viscosity kin 100°C	11.96	11.90	mm^2/s
Viscosity index	172.5	168.0	(--)
Density 20°C	852.4	855.0	kg/m^3
Flamepoint	≥ 200	≥ 200	°C
Total Base Number TBN	7.4	10.2	mg KOH/g
Sulphur ashes	400	1200	mg/kg
Sulphur	1770	3376	mg/kg
Mg	21	66	mg/kg
Zn	517	1117	mg/kg
Ca	1219	3106	mg/kg
P	458	926	mg/kg
Sum S to P	3985	8591	mg/kg

3. Test Methods and instrumentation

The vehicle was tested on a chassis dynamometer at constant speeds and in the dynamic driving cycles WLTC, with cold & warm engine.

The test series were:
- state of origin (gasoline, 3WC),
- addition of 2% lube oil "H" to fuel,
- addition of 2% lube oil "H" to fuel + GPF,
- addition of 2% lube oil "L" to fuel.

3.1 Chassis dynamometer – following test systems were used:
- roller dynamometer: Schenk 500 GS 60,
- 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 ac-cording to the legal prescriptions, responding to the horizontal road.

3.2 Test equipment for regulated exhaust gas emissions

This equipment fulfils the requirements of the Swiss and European exhaust gas legislation:
- gaseous components: exhaust gas measuring system Horiba MEXA-9400H:

  CO, CO_2 – infrared analysers (IR),
  HCIR ... only for idling,
  HCFID ... flame ionisation detector for total hydrocarbons,
  NO/NO_x ... chemoluminescence analyser (CLA) –not heated, only for diluted gas,
  O_2 ... Magnos.

The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO_2-analysis.

3.3 FTIR

FTIR (Fourier Transform Infrared) Spectrometer (AVL SESAM) offers the possibility of simultaneous, time-resolved measurement of approx. 30 emission components – among others: NO, NO_2, NO_x, NH_3, N_2O, HCN, HNCO, HCHO.

3.4 Nanoparticle analysis

The measurements of NP size distributions were con-ducted with different SMPS-systems, which enabled different ranges of size analysis:

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

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).

3.5 Driving cycles

The steady state cycle (SSC) consists of 20 min-steps at 95, 61, 45, 26 km/h and idling, performed in the sequence from the highest to the lowest speed.

The approach to find a homogenized worldwide driving cycle was successfully finished with the development of the homogenized WLTP worldwide light duty test procedure. The WLTC (worldwide light duty test cycle) represents typical driving conditions around the world.

This cycle (Fig. 2) has been used also in this study. It represents different driving conditions: urban, rural, highway and extra-highway.

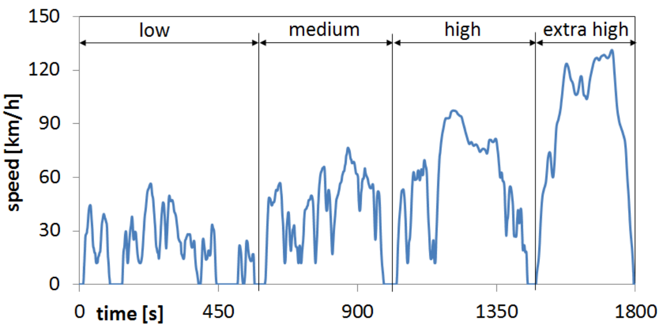

Fig. 2. WLTC driving cycle

4. Results

Figure 3 represents the comparison of limited gaseous emissions CO, HC, and NO_x in WLTC warm (averages of 3 cycles). The average emission levels with fuels containing lube oil are generally higher than the reference (gasoline). This is to explain with the higher content of heavy

HC, their influence on chemistry of exhaust gases and on the Lambda regulation. There are, nevertheless, significant differences of CO- and HC − values between "2% H" and "2% H + GPF". The questions arise: how repetitive are the CO peak values in WLTC? Can the GPF be responsible for the observed effects?

With this configuration (2% "H" + GPF) 30 WLTC with 3 cold starts were performed in the frame of another project. This gave the opportunity to consider the above questions. In Fig. 4 the peak CO − values, which were attained in the successive WLTC's are represented. The values "cold start" are at the beginning of the cycles "1", but the other peak values happen usually in the high speed / high acceleration periods of the cycle that means they are not dependent on the "cold start". Also, the "cold start" value from the 2nd day, which is represented in Fig. 4, seems to be exceptional. Finally, it can be stated, that the extreme CO − values are not connected to the GPF and they represent some coincidental and random states of the system (mixture preparation, λ-regulation, OBD-control, state of catalyst) of this vehicle. The influence of driver is unlikely, but cannot be excluded.

The results in SSC (not presented in this paper) confirm the highest CO & HC values with lube oil "H".

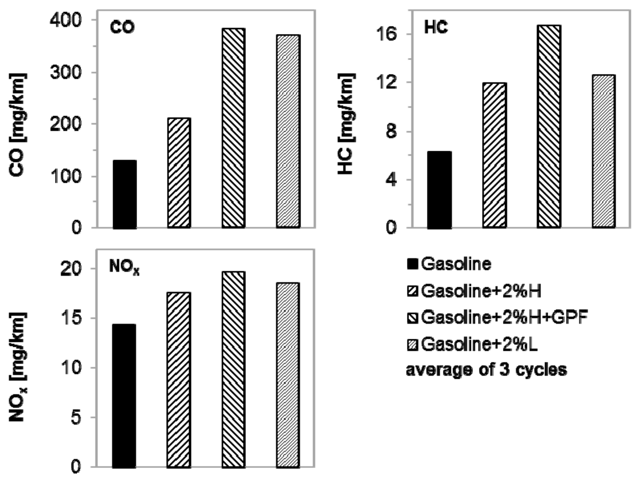

Fig. 3. Limited gaseous exhaust emissions in WLTC warm

Figure 5 compares the integral average values of non-legislated gaseous components in a single WLTC warm. There is a clear increase of NH_3 with fuels containing lube oil. This is a result from both influences: oil chemistry and impact of the oil on the Lambda regulation (more Lambda rich "excursions" provokes more NH_3).

The emissions of NO_2, N_2O, HCHO and MeCHO are negligible.

In previous research of NH_3 emissions on gasoline vehicles, [19], was found that certain NH_3-peaks in the repeated transient cycle (WLTC) appear randomly, while the NH_3-peaks connected with the acceleration events in the high-speed part of the cycle appear regularly, but of course with an extremely varying intensity. This means that the NH_3-emissions are irregular even in the repeating operating conditions. Additionally to the rich Lambda, excursions and high exhaust temperatures further reasons for the NH_3-fluctuations are the store/release effect of NH_3 and NH_3 precursor substances in the exhaust system and especially in the catalyst.

Considering this together with the emission variability represented in Fig. 4 the authors presume, that the NH_3 values in Fig. 5 are generally overlapped by the emission fluctuation.

Figure 6 represents the average PN-emission (WLTC averages of 3 cycles, SSC single cycle). It is demonstrated in this figure that the fuel variant "2% H" in-creases the nanoparticle emissions a little bit more than the fuel variant "2% L". The applied, non-catalytic gasoline particle filter (GPF) eliminates very efficiently the nanoparticle counts.

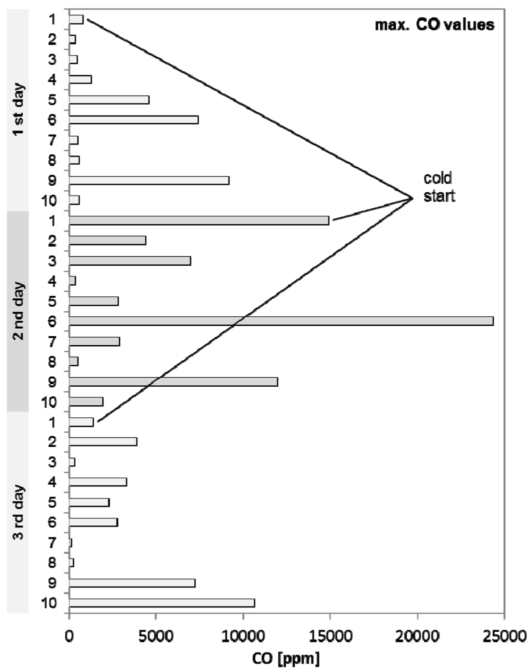

Fig. 4. Chronological comparison of CO peaks during 30 WLTC driving cycles. Fuel: gasoline + 2% oil H; with GPF

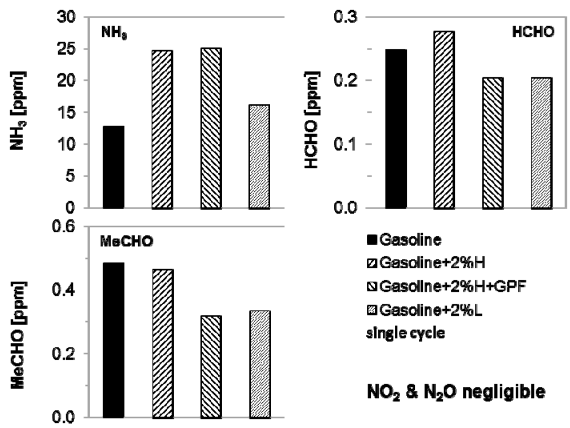

Fig. 5. Non-legislated gaseous emissions in WLTC warm

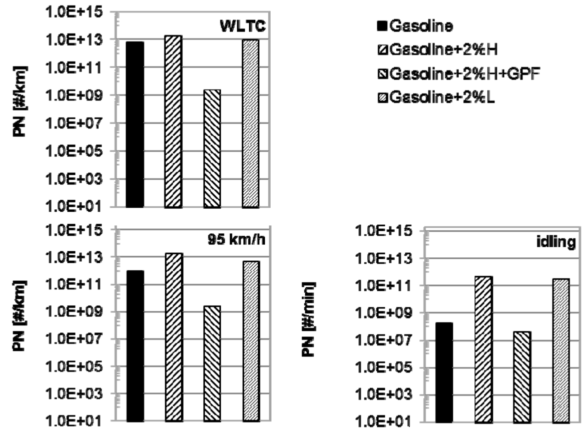

Fig. 6. PN emissions during WLTC (3 cycles) and SSC (single) driving cycles warm

Figure 7 gives an exemplary comparison of SMPS particle size distribution (PSD) with the three fuel variants (gasoline, "H" and "L").

SMPS size spectra with 2% lube oil "H" have maxima, which are by 1-2 orders of magnitude higher than in "state of reference" and these maxima are at lower sizes: example at 95 km/h maximum of PSD at 20 nm, reference at 70 nm. These are typical signs of nanoparticles originating from the lube oil, which was added to the fuel, like in the 2-stroke engines with lost oil lubrication.

Comparing the fuel variants "L" and "H" – there are tendencies of higher nuclei mode and lower sizes with lube oil "L" at 95 km/h. At 45 km/h and idling, there are slightly lower peak values and lower median diameters. All that indicates the differences between the two-lube oils "L" and "H".

The progress of spontaneous condensation, which determinates the nuclei mode, depends on the condensing substances, but also on the availability of condensation kernels. With the lube oil, containing high amount of metals the probability of triggering the condensation is higher and bigger particle sizes can be developed.

At the bottom of Fig. 7 the total particle, number (TPN) emissions in WLTC (averages of 3 cycles) are represented. This confirms the previous remarks that the lube oil "L" increases the PN-emissions less than the lube oil "H".

Figure 8 demonstrates an impressing reduction of particle count concentrations (SMPS at two chosen stationary operating points) and of TPN (in WLTC warm) by means of GPF. This reduction is by approximately 4 orders of magnitude and sets the particle count concentrations down to or below the ambient level.

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).

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). Figure 9 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. In the whole test program, 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.

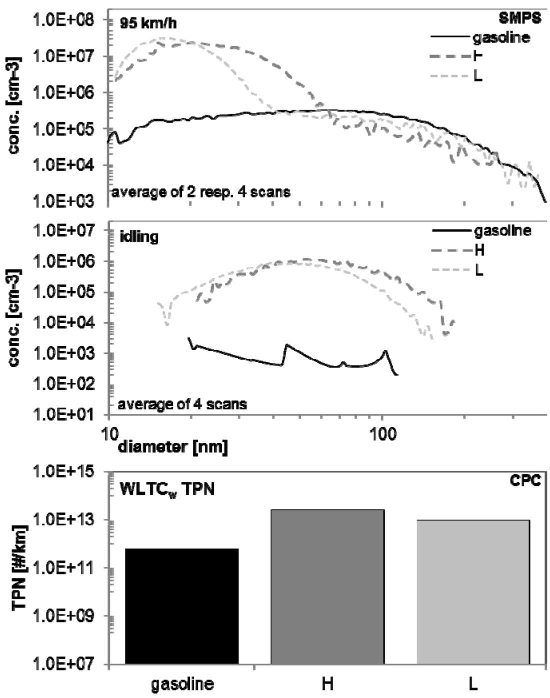

Fig. 7. Effect of increased lube consumption fuel: gasoline & gas. + 2% oil H… «high», L… «low» metals & ashes in lube oil

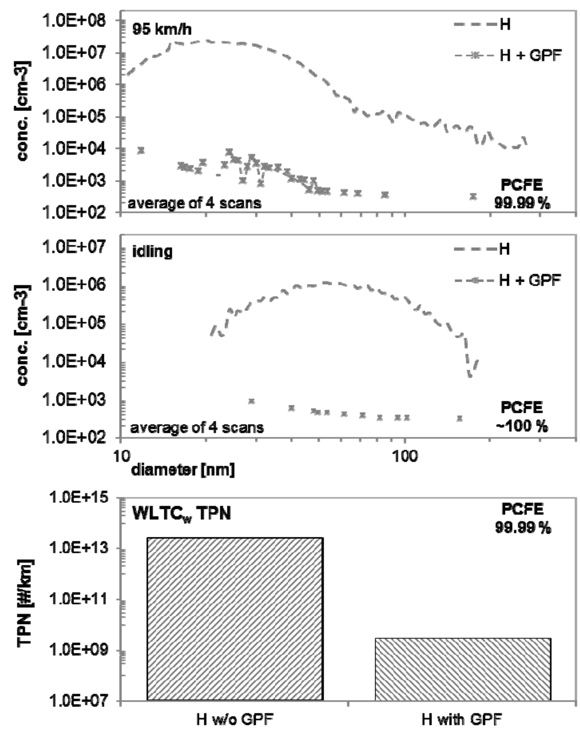

Fig. 8. Effect of GPF with increased lube oil consumption, fuel: gasoline + 2% oil H; with & w/o GPF

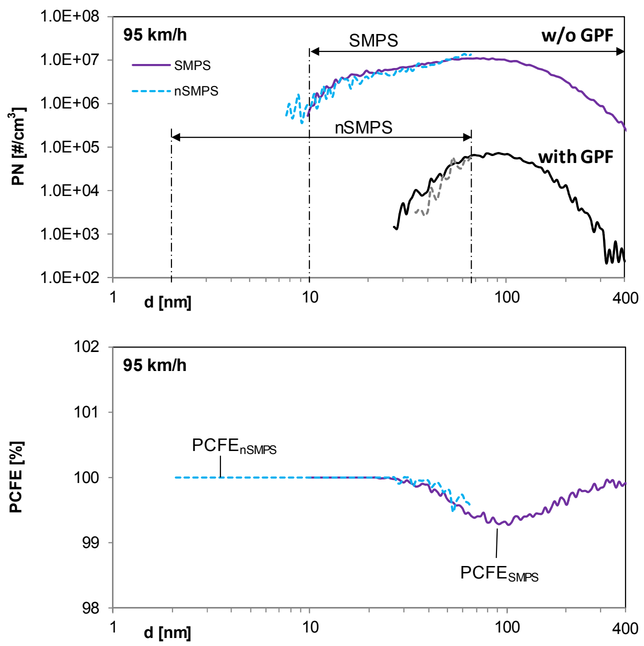

Fig. 9. Example of PSD's with SMPS & nSMPS and particle counts filtration efficiency (PCFE)

5. Conclusions

The obtained results allow following summarizing statements:

- the increased lube oil consumption increases emissions of CO and HC, it can have impact on Lambda regulation and contributes to increased NH_3 – values,
- with all fuels: gasoline, gasoline +"H" and gasoline +"L" there are no emissions of nitric dioxide NO_2, of nitrous oxide N_2O and negligible emissions (<1 ppm) of aldehyde HCHO and of acetaldehyde MeOH,

- with increasing constant speed the NP-emissions increase for the investigated car; at idling there is the lowest NP-emission (1-2 orders of magnitude lower than with engine load),
- with addition of lube oil to the fuel (simulating the increased lube oil consumption) there is an increase of PN-emissions by approximately 2 orders of magnitude,
  - lube oil "H" increases PN by 2 orders of
  - magnitude,
  - lube oil "L" increases PN a little less (1 to 1.5 orders of magnitude),
- the lube oil composition (HC-matrix and content of metals) influences slightly the particle size distributions,
- an efficient GPF eliminates the nanoparticles and lowers PN by 4 orders of magnitude.

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Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
ASET	Aerosol Sampling & Evaporation Tube
BAFU	Bundesamt für Umwelt, (see FOEN)
CLA	chemiluminescent analyzer
CPC	condensation particle counter
CVS	constant volume sampling
DF	dilution factor
DI	Direct Injection
DMA	differential mobility analyzer
EGR	exhaust gas recirculation
EMPA	Eidgenössische Material Prüf − und Forschungsanstalt
FHNW	Fachhochschule Nord-West Schweiz
FOEN	Federal Office for Environment
GasOMeP	Gasoline Organic & Metal Particles
GDI	gasoline direct injection
GPF	gasoline particle filter
„H"	high (ash/metal content)
HCHO	Formaldehyde
„L"	low (ash/metal content)
MD	minidiluter
MeCHO	Acetaldehyde
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NH_3	Ammonia
NO_x	nitric oxides
NP	nanoparticles < 999 nm
nSMPS	nano SMPS
PC	particle counts (integrated)
PCFE	particle counts filtration efficiency
PM	particle mass
PN	particle numbers

PSD	particle size distribution
PSI	Paul Scherrer Institute
SMPS	scanning mobility particle sizer
TC	thermoconditioner
TPN	total particle numbers
TTM	Technik Thermische Maschinen
TWC	three way catalyst
VERT	Verification of Emission Reduction Technologies (VERT Association)
WLTC	Worldwide Light Duty Test Cycle
3WC	three way catalyst

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