Influences of Oil, Fuel & Catalyst on Particle Emissions of a DI 2-Stroke Scooter

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1. Abstract

Limited and nonlimited emissions of scooters were analysed during several annual research programs of the Swiss Federal Office of Environment Forests and Landscape (FOEFL)*).

Small scooters, which are very much used in the congested centers of several cities are a remarkable source of air pollution. Therefore every effort to reduce the emissions is an important contribution to improve the air quality in urban centers.

In the present work detailed investigations of particle emissions of a Peugeot scooter with TSDI (Two Stroke Direct Injection) were performed.

The nanoparticulate emissions with different lube oils and fuels were measured by means of SMPS, (CPC) and NanoMet *). Also the particle mass emission (PM) was measured with the same method as for Diesel engines.

It can be stated, that the oil and fuel quality have a considerable influence on the particle emissions, which are mainly oil condensates. Not all influences can be explained and more detailed knowledge about the oil composition and about the used additive packages is necessary.

The use of non active catalyst leads to strongly increased particle emissions values, both mass and counts.

Since the particulate emission of the 2-S consists mainly of lube oil condensates the minimization of oil consumption stays still an important goal.

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*) Abbreviations see chap. 10
**) References see chap. 9

2. Introduction and objectives

The growing number of 2-wheelers became ever more urgent question in the last years. Particularly in several cities where the scooters and low-power motorcycles are used for individual transportation, the emissions components of this vehicle group have to be minimized.
Several research works and technical improvements have been performed, [1, 2, 3], **), nevertheless further efforts are necessary.

The Laboratory for Exhaust Gas Control of the University of Applied Sciences, Biel-Bienne, CH was mandated by the Swiss EPA (BUWAL) to investigate several topics concerning the emissions of 2-wheelers, [4, 5, 6, 7, 8, 9, 10, 11].

During the last four years the particulate mass- and counts emissions of 2-stroke engines were investigated. These emissions reach the level of diesel engines and cannot be neglected in the context of the present discussions, while the diesel exhaust gases are cleaned by means of the particle filters.

Objective of the present work was to show what is the influence of lube oil, fuels and catalytic activity on the emissions, and especially on the (nano) particulates.

It is important to remark that the results from single vehicles and single measurements cannot be generalized and further research in this domain is necessary.

3. Investigated Scooter

The investigated scooter was:

Peugeot Looxor TSDI (see table 1)

model year	2002
transmission no. of gears	variomat
km at beginning	1250
engine: type displacement cm^3 number of cylinders	 2 stroke 50 1
cooling	air
rated power kW rated speed rpm idling speed rpm	3.6 7250 1700
max vehicle speed km/h	45
weight empty kg	94
mixture preparation	direct injection
catalyst	yes

Table 1: Data of the scooter Peugeot Looxor TSDI

Fig. 1 shows this scooter on the chassis dynamometer.

The Peugeot TSDI-System, Fig. 2, uses crankshaft driven air compressor.

Gasoline is injected in the pressurised air of the feed rail where the premixing of air and fuel takes place. The air injector controls the admission of the rich mixture in the combustion chamber. The lubrication oil is dosed in the intake air of the engine by means of the oil pump.

Fig. 1: Investigated scooter Peugeot Looxor TSDI on the chassis dynamometer

Peugeot-Two Stoke Direct Injection System (TSDI)

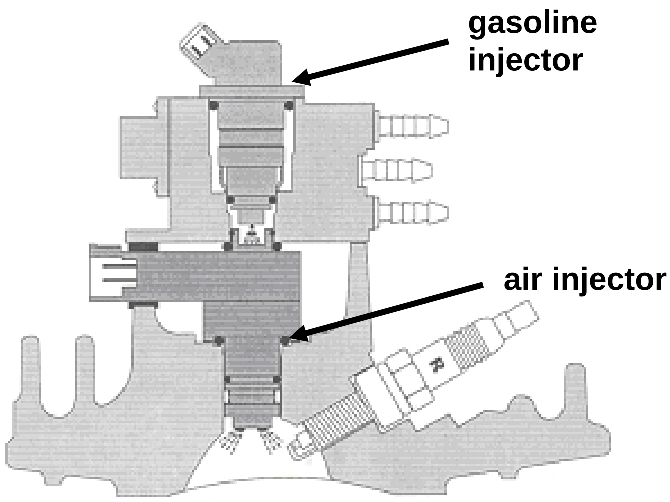


Fig. 2: TSDI – system

4. Measuring apparatus

4.1. Chassis dynamometer

- roller dynamometer:
  Schenk 500 G5 60
- driver conductor system: Zöllner FLG 2 Typ. RP 0927-3d, Progr. Version 1.4
- CVS dilution system: Horiba CVS 9500T with Roots blower
- air conditioning in the hall (intake- and dilution air) automatic
  temperature: 20 - 30 ^oC
  humidity: 5.5 – 12.2. g/kg

4.2 Test equipment for regulated exhaust gas emissions

This equipment fulfils the requirements of the Swiss and European exhaust gas legislation – 70/220/EWG 98/69/EG.

- gaseous components:
  exhaust gas measuring system Horiba MEXA-9400H
  CO, CO_2 – infrared analysers (IR)
  HC_{IR}... only for idling
  HC_{FID}... flame ionization detector for total hydrocarbons
  NO/NO_X... chemoluminescence analyser (CLA)
  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.
- measurement of the particulate mass (PM):
  sampling from the full-flow dilution tunnel
  filter temperature $\leq 52\ ^oC$
  conditioning of filter: 8 - 24 h (20^oC, rel. humidity 50%)
  scale: Mettler, accuracy $\pm 1\ \mu g$

4.3. Particle size analysis

In addition to the gravimetric measurement of particulate mass, the particle size and counts distributions were analysed with following apparatus:

- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3071, CPC TSI 3025 A)
- NanoMet – System consisting of:
  PAS – Photoelectric Aerosol Sensor (Eco Chem PAS 2000)
  DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC)
  MD19 tunable minidiluter (Matter Eng. MD19-2E, see Fig. 1).

A detailed description of those systems can be found in the manufacturers informations. The sampling and measuring set-up during the tests shows Fig. 3. The nanoparticulates measurements were performed during cold acceleration to a constant speed and a following warm-up period with CPC and NanoMet and at the constant speed (warm) with SMPS and NanoMet, (see chap. 5).

5. Measuring procedure

The on-line nanoparticles measurements were performed with CPC (SMPS w/o DMA) and NanoMet at following driving pattern:

- cold start – acceleration to 30 km/h – constant speed.

The first 4 min including cold start were considered as a warm-up period. The following 4 min were used for the preparation of the measuring apparatus for the subsequent stationary measurement, which took also about 4 min. In the 1st and 3rd 4 min period the exhaust gases bag-values and the particle mass PM were sampled.

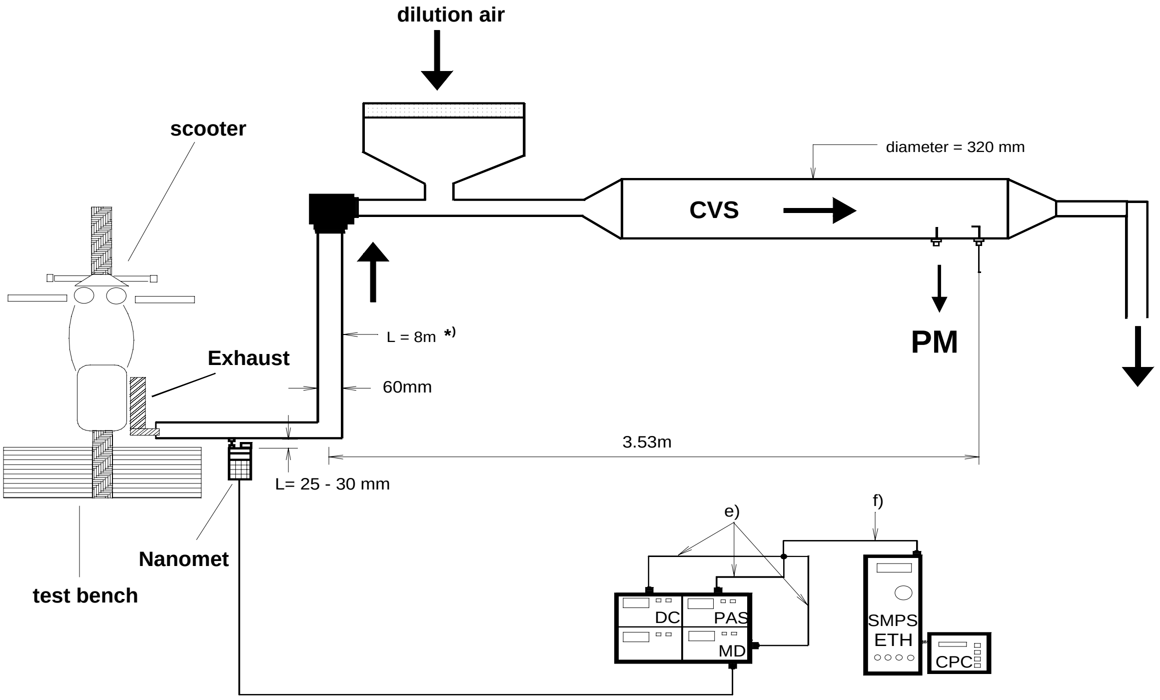


Fig. 3: Sampling and measuring set-up for nanoparticulates analysis of the scooters

The CPC (condensation particles counter) is a part of SMPS, which allows a dynamic measurement of all particle sizes simultaneously. The scanning of particle size distribution with DMA (differential mobility analyser) needs time and makes sense only at stationary emission source (here at 30 km/h warm).

At constant speed warm two or more samples of SMPS particle size distributions were taken.

In the first part with v = const = 30 km/h (cold) there is mostly the influence of the temperature (warm up) to be observed. The second part v=const=30 km/h (warm) represents the stationary operating conditions.

The sampling of the gas probe for the nanoparticulates analysis was at the tailpipe trough the heated NanoMet MD19 minidiluter (see Fig. 1 and Fig. 3).

After measurement of a given configuration there was a change of the configuration (oil, fuel, catalyst), a conditioning period of about 10 min and cooling down with blower during at least 30 min.

The measured configurations of oil, fuel and catalyst are summarized in the table 2.

name	cat.	fuel	oil type	oil sulphur	oil dosage
V1	yes	stand.	original	2790 ppm	original
V2	yes	stand.	Panaolin TS	6250 ppm	original
V3	yes	stand.	Panaolin TS	6250 ppm	**mini: -33%**
V4	yes	stand.	Panaolin TS	6250 ppm	**maxi: x2**
V5	fictitious	stand.	Panaolin TS	6250 ppm	original
V6	yes	stand.	Panaolin Synth	450 ppm	original
V7	yes	stand.	Pan. Synth Aqua	0 ppm	original
V8	yes	stand.	Nycolube	350 ppm	original
V9	yes	stand.	DEA	0 ppm	original
V10	yes	**Aspen**	DEA	0 ppm	original
V11	yes	**Aspen**	Pan. Synth Aqua	0 ppm	original
V12	yes	stand.	original	2790 ppm	original

Table 2: Measurements of scooter Peugeot TSDI with nanoparticle analysis

To vary the activity of the catalyst an identical exhaust pipe with geometrically the same, but noncoated catalyst was used.

The driving resistances of the test bench were set according to the Swiss exhaust gas legislation for motorcycles.

5.1. Used lube oils and fuels

The data of used lube oils are represented in table 3.

		Original	Panolin TS	Panolin 2-S Synth.
Property	Unit			
Viscosity kin 40°C	mm^2/s		90	103
Viscosity kin 100°C	mm^2/s		11.2	8.2
Density 15°C	kg/m^3		882	925
Pourpoint	°C		-27	-40
Flamepoint	°C		> 150	> 150
Total Base Number TBN	mg KOH/g		3	3
Sulfur	ppm	2790	6250	450
Fe	ppm	0	0	5
Mo	ppm	0	1	0
Mg	ppm	26	2	3
Zn	ppm	20	105	18
Ca	ppm	287	617	458
P	ppm	30	90	36

		Panolin Synth. Aqua	Nycolube	DEA
Property	Unit			
Viscosity kin 40°C	mm^2/s	95.0		95.6
Viscosity kin 100°C	mm^2/s	6.3	7.9	13.5
Density 15°C	kg/m^3	946		882
Pourpoint	°C	-28		-27
Flamepoint	°C	> 150		> 210
Total Base Number TBN	mg KOH/g	2.5		
Sulfur	ppm	0	350	0
Fe	ppm	2	1	0
Mo	ppm	0	0	0
Mg	ppm	1	2	1
Zn	ppm	0	0	0
Ca	ppm	11	322	0
P	ppm	16	6	0

Table 3: Data of the used lube oils

The oils: "original, Panolin TS & Nycolube" are semi-synthetic. DEA is a research, non-market oil without additives, a mixture of paraffinic hydrocarbons between C12 and C26

Two fuels were used during the measurements: standard market gasoline and an Aspen gasoline, which is almost aromats-free (aromats < 0,1 Vol %, benzol < 0,01 Vol %). The sulfur content of both gasolines was analysed and no sulfur was found.

6. Results

Fig. 4 shows an example of the NanoMet- and CPC-signals during acceleration with cold engine until 30 km/h, followed by a constant speed until light off of the catalyst.

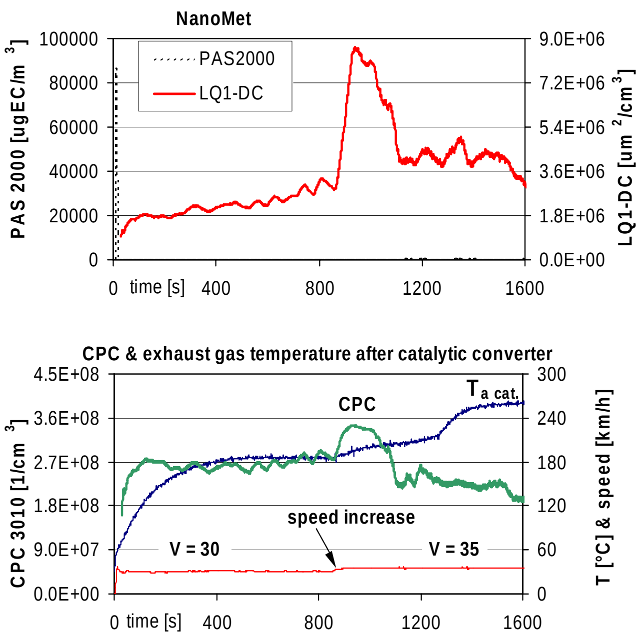


Fig. 4: NanoMet- and CPC-signals at cold start and v=const, Oil: Panolin TS (V2)

PAS (photoelectric aerosol sensor) is sensitive to the surface of particulates and to the chemical properties of the surface. It indicates the solid particles.

DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties. It indicates the solids and the condensates.

At cold start and acceleration until v=const there is a spike of nanoparticle count concentration. At the beginning the solid particles PAS are visible, after they generally disappear being enveloped by the condensates DC (oil droplets, SOF). Some repetition measurements, which were performed, showed a measuring dispersion of the results, but a very good coherence between DC and CPC, i.e. the DC-signal represents very well the total nanoparticle emissions and can be used for the interpretation of the results instead of the CPC-signal.

After about 880 s (Fig. 4) the speed was increased to provoke a quicker catalyst light off. This change of speed is very sensitively indicated by the signals DC & CPC. The light off of the catalyst is visible later (after approx. 1300 s) as a quicker increase of the $T_{after\ cat}$.

Several repetition measurements were performed to state, if there is an influence of the light off on the NP-signals? Another example is illustrated in Fig. 5. The light off of the catalyst is visible also as a decrease of CO & O_2 (not represented in this plot) after catalyst.

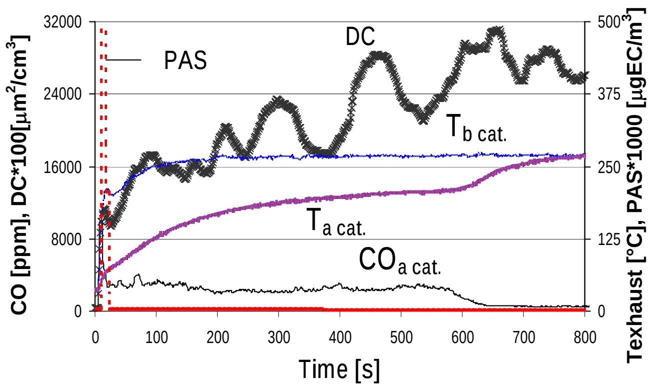


Fig. 5: Exhaust gas and gas temperature before and after catalytic converter and NanoMet signals
Oil : Panolin Synth Aqua (V7); cold start & 30 km/h

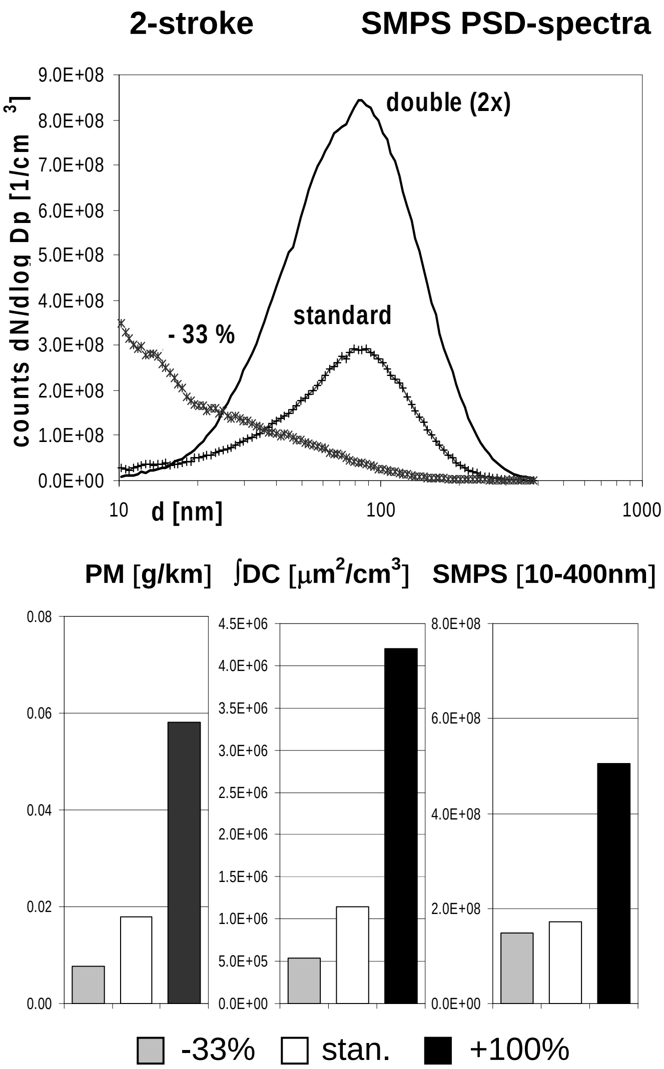


Fig. 6: Particle mass and nanoparticles at 30 km/h warm with different lube oil dosing
Oil: Panolin TS; (V3; V2; V4)

The DC-signals (and CPC) have generally a fluctuating character even at constant speed, which reflects as a principal reason the periodic store-release phenomena of the oil-aerosol in the engine and in the exhaust system. Differently to the scooters with carburator, for these investigated scooters with direct injection almost no manual regulation with accelerator at constant speed is necessary.

The fluctuations of DC cannot be attributed to the catalyst light off.

During some repetition measurements after about 2 months, it was remarked, that the light off at the same starting and operating conditions was remarkably retarded.

Oil dosing

The oil dosing, as already stated in previous works, has a strong influence on particle mass and nanoparticles emissions because the aerosol consists almost totally (approx. 98%) of oil droplets. Fig. 6 shows the SMPS particle size distribution spectra (PSD) and the integral values of PM, DC & SMPS [10 – 400 nm].
The sampling for SMPS was always with the heated minidiluter (150 °C) at tail pipe. The represented spectra are averages of three samples.

All PSD in this work, except the one with -33% oil, are normal distributions with the maximum count concentration values 2 – 10 x 10^8 [1/cm^3] (which is above the diesel engine out concentrations). The maxima are in the size spectrum of 60 – 100 nm.
In the measurement with the minimum oil dosing only the nuclei mode is visible.

With increasing lube oil dosing the particle counts in the accumulation mode increase; with decreasing the lube oil dosing the accumulation mode (40 – 300 nm) disappears and the spontaneous condensates in the nuclei (< 40 nm) increase strongly (no condensation seeds cause spontaneous condensates).

The particle mass PM and the summary surface of particles DC correlate very well with the higher NP-counts concentrations (in accumulation mode, or as integral values).

The plots in Fig. 7 confirm the lowest DC- and CPC-values with the lowest lube oil dosing. Again an impressive sensitivity of the DC-signal by speed increase is demonstrated. The traces of temperatures after catalyst indicate the moment of increasing the driving speed.

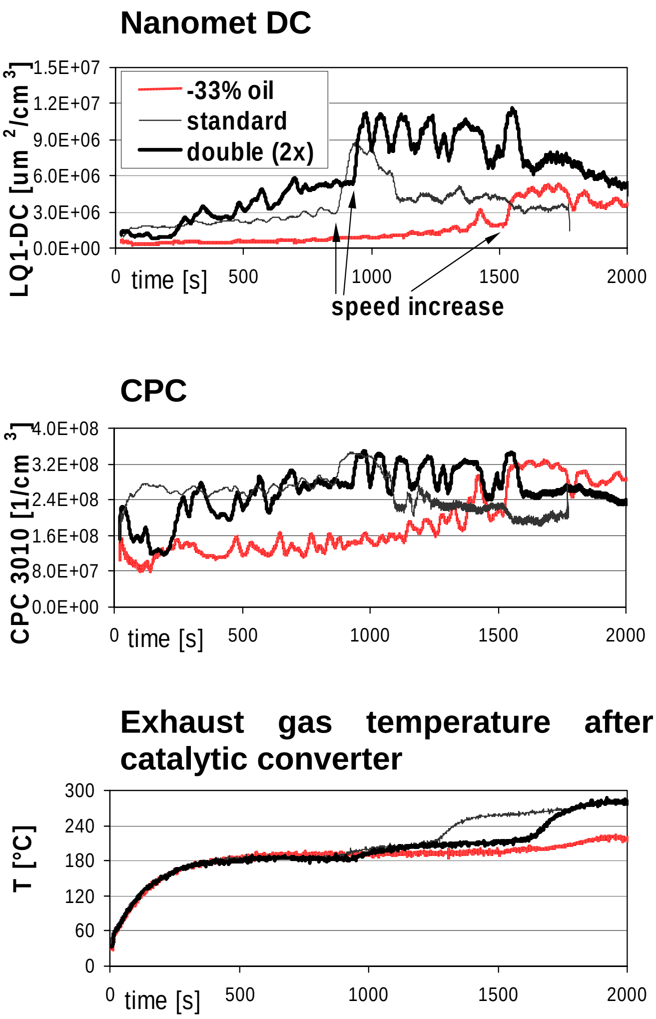


Fig. 7: Variation of lube oil dosing on Peugeot Looxor 50 cm^3 by acceleration with cold engine until 30 km/h followed by a constant speed until light off of catalytic converter
Oil : Panolin TS; dosing : -33%; standard; +100% Oil (V3; V2; V4)

For the variant with the lowest oil content the speed increase was at the latest moment (approx. 1500 s) and therefore the light off didn't occur in the measured time period.

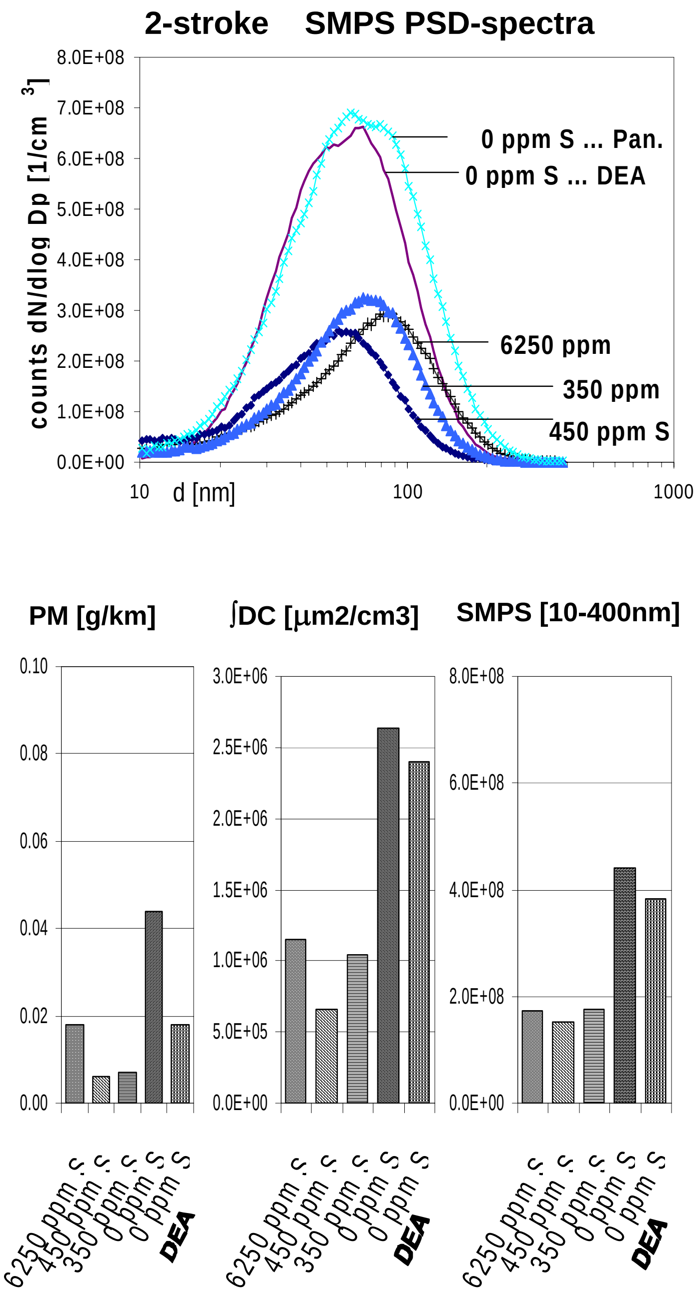


Fig. 8: Particle mass and nanoparticles at 30 km/h warm with different lube oils (V2; V6; V8; V7; V9)

The question about influences of oil dosing on the ageing of the catalyst and on its light off behaviour appeared, but it couldn't be dealt with it more in the present work. This question stays to be answered in the further investigations.

Oil quality

The results of PM and NP's at 30 km/h warm with different oils, the same oil dosing and the same fuel, are represented in Fig. 8.

Decreasing the sulphur content in the lube oil from 6250 ppm to 350 – 450 ppm first the PM, DC & SMPS decrease, but further reduction of sulphur until 0 ppm increases again those values; with 0 ppm S there are the highest particle emissions PM, DC & SMPS.

How can the sulphur content affect the amount of spontaneous condensates in the opposite manner to the expected? Sulphuric acid droplets can be coated by organic compounds, which usually hinders the hygroscopic H_2O-admission, [12]. By absence of the sulphatic condensation kernels there is more spontaneous condensation of SOF. Additionally to that different hydro-carbons have different speed of spon-taneous condensation in nuclei mode, due to the water solubility and surface tension, [13].

This is a possible hypothese, because it shall be noticed, that the temperatures after catalyst light off (250 °C - 270 °C) are not sufficient for an intensive production of sulphates.

It is most probably, that with the oils with 0 ppm S there is a higher speed of growth of the droplets, but on the other hand it is clear, that also the HC-composition of the oil, the additive packages used and the fuel quality play an important role in this respect. Those influences must be suggested regarding some comparisons of chosen oils, here for example Panolin Synth. Aqua and DEA, both with 0 ppm S.
The oil compositions and their additive packages were not known in these investigations, so these questions stay unanswered for later.

It was also remarked, that the area of purely oil aerosols is quite different from the diesel-typical aerosols and a further research and eventually further development of sampling methods is necessary.

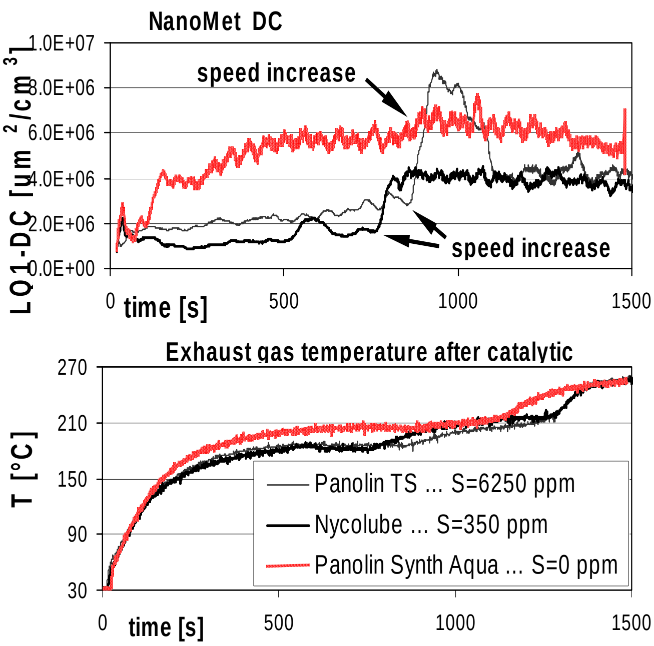


Fig. 9: Acceleration with cold engine until 30 km/h followed by a constant speed until light off of catalytic converter with different S-content in lube oil on Peugeot Looxor 50 cm3
Oil : Panolin TS; Nycolube; Panolin Synth Aqua (V2; V8; V7)

Fig. 9 shows the plots of DC signal and temperature after catalyst with three chosen oils. The highest DC-values with 0 ppm S, as well as the sensitivity of DC-signal by speed increase are confirmed.

The relationship of results between Nycolube (semi-synthetic) and Panolin Synth. Aqua contradicts (at least at TSDI) the general opinion about synthetic oils being better for lowering the particle emission.

Fuel

Comparing the integral results of respective measuring series with standard fuel and with Aspen (like comparisons V7-V11, or V9-V10, see annex) it can be remarked, that there is very little influence of the fuel quality on the limited emissions CO, HC and NOx and on the particle emission at cold start and warm up.

At the warm operation, in contrary, Aspen provokes lower CO-, HC- and NOx-emissions, but also higher particle counts emissions with both investigated oils: Panolin Synth Aqua and DEA.

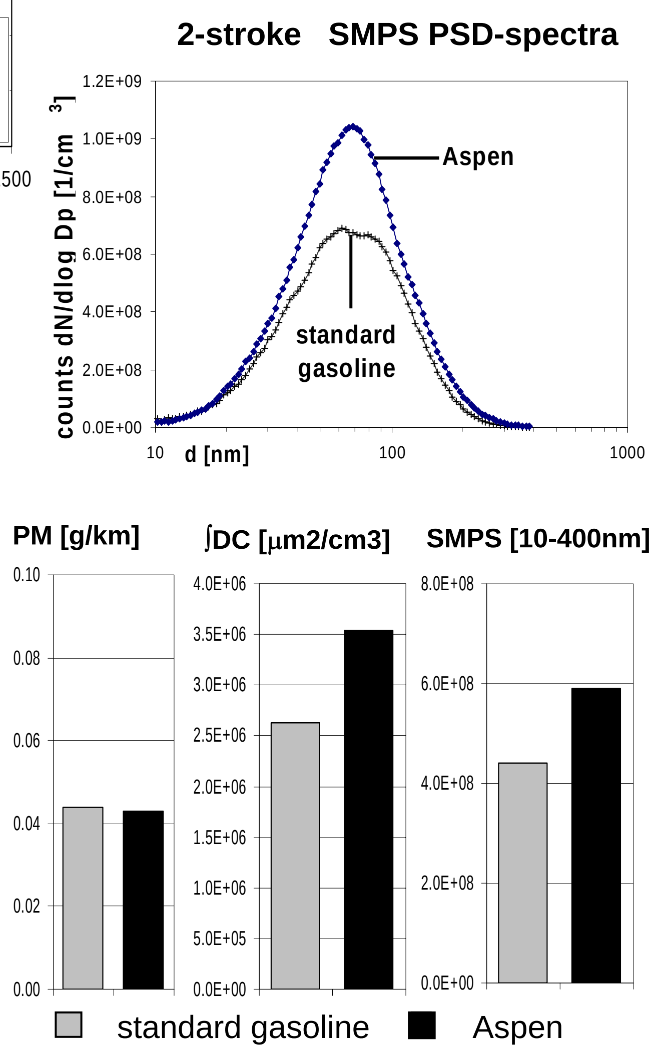


Fig. 10: Particle mass and nanoparticles at 30 km/h warm with different fuels
Oil: Panolin Synth Aqua (V7;V11)

An example of particle mass and nanoparticles with one oil quality is represented in Fig. 10. Higher particle counts and the same particle mass for Aspen suggest, that there are less particles of higher sizes.

It was remarked, that Aspen produces in each test shorter light off times of the catalyst, Fig. 11.

In some previous research with Aspen different influences were stated:

- on a chain saw (2S - SI engine), with $t_{Exhaust}$ ~ 550 - 650°C, w/o catalyst Aspen clearly reduced the nanoparticle count concentrations, [14],
- on a small 4S - SI engine, with $t_{Exhaust}$ ~ 500 - 800°C Aspen didn't show clear influences on the nanoparticles (i.e. at some operating points increase and at some other points reduction), [15].

How does the fuel quality influence the processes of condensation of oil vapors and coagulation of oil droplets in the exhaust gas of the engine? Following explanations can be given:

In the investigated mixture-lubricated 2S engine the lube oil is injected in the intake air of the engine and the majority of it takes part on the combustion. Certainly a part of oil & fuel passes the engine with the scavenging losses and another little part is not completely burned mainly because of the extinction of the flame at the combustion chamber walls.

During the combustion the HC-molecules are cracked and dehydrated, so when the combustion stops the unburned components create a HC-spectrum, which can be quite different from the original one.

If the combustion with different fuels has different time- & space - histories,(which is most probably the case regarding the NOx at cold operation – with no influence of catalyst, see annex 1) than it can produce more or less different HC-spectra from the same initial lube oil composition. A certain co-influence of the hydrocarbons and additive packages from the fuels must be also assumed at this stage.

In the exhaust pipe the combustion gases and the scavenging gases meet and continue their flow to the catalyst.

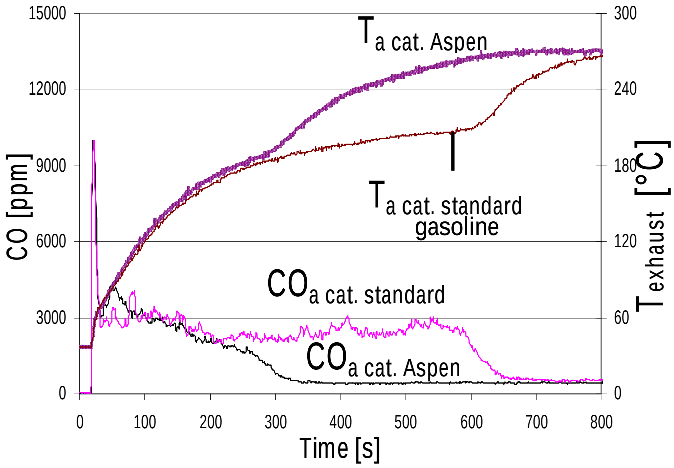


Fig. 11: Light off of the catalyst with different fuels
Oil: Panolin Synth Aqua (V7;V11)

Different hydrocarbons have different light off temperatures in the same catalyst, so it is not astonishing, that the differences appear with both investigated fuels. Due to the quicker light off with Aspen the lower CO- and HC-values are explained.

The postoxidation of heavy hydrocarbons in the oxidation catalyst is only partial one and the composition of HC is again modified on this occasion.

As a result it appears, that the fuel quality, which acts in the combustion chamber and in the catalyst influences the compositions of the unburned hydrocarbons also from the lube oil.

This has consequences for the speed of condensation and coagulation and it explains the measured differences of nanoparticles concentrations.

It cannot be definitely clarified in the present investigation what are the principal, most important influences for the higher count concentrations of oil condensates. For this purpose a further basic research, like measurements before catalyst, differential analytics of HC and special investigations of catalyst light off, would be necessary.

Catalyst

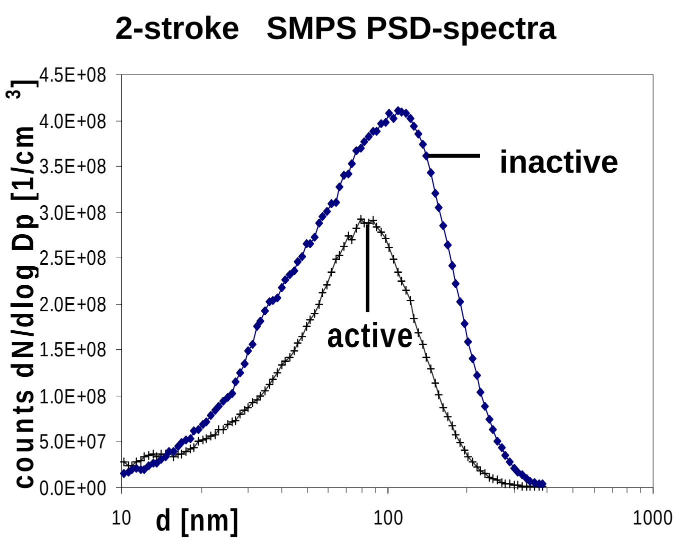
Fig. 12 shows the comparison of particle results with active and inactive catalyst.

To keep exactly the same geometry of the exhaust gas system, which usually influences very much the 2S engine operation, an identical catalyst, but without catalytic wash-coat was used.

It appears clearly, that there are: less condensates (DC), lower particle counts (SMPS) and lower particle mass (PM) with the active catalyst, which converts a part of the HC precursor substances.

Also at cold operation (cold start and warm up) there is a clear reduction of DC and PM with active catalyst (see annex 2).

The active catalyst is at cold start still inactive from the point of view of limited emissions, but it has most probably influence on the coagulation process, provoking less condensates with bigger size and less summary surface and it can also promote a partial low-temperature oxidation of SOF. The release of solids form the coated catalyst is more intense.



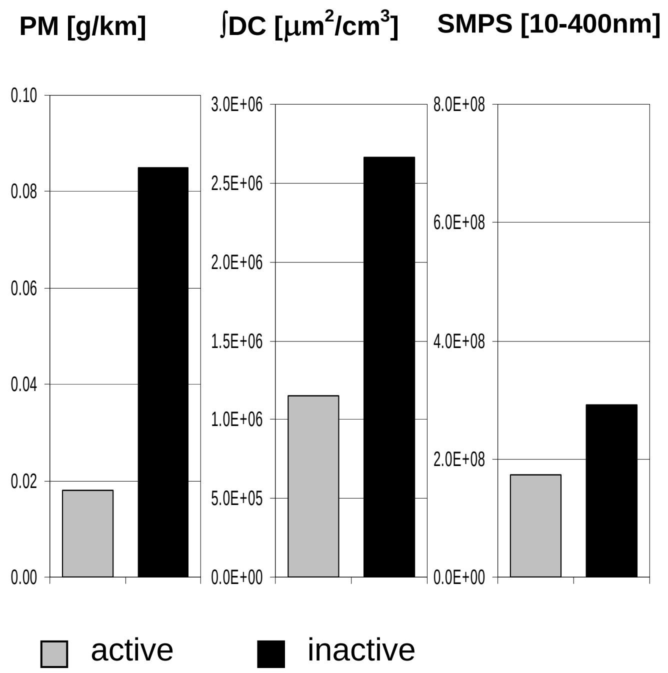


Fig. 12: Particle mass and nanoparticles at 30 km/h warm with active and inactive catalyst
Oil : Panolin TS; (V2; V5)

7. Conclusions

Following conclusions can be pointed out:

- 2-stroke engine has generally higher nanoparticulates (NP) emission than 4-stroke
- the particulates of 2-stroke consist mostly of soluble fraction (higher DC-values)

- at cold start and acceleration until v=const there is a spike of nano-particle count concentration. On the beginning the solid particles PAS are visible, after they generally disappear being enveloped by the condensates DC (oil droplets, SOF)
- the DC-signal represents very well the total nanoparticle emissions and can be used for the interpretation of the results instead of the CPC-signal
- the DC-signals (and CPC) have generally a fluctuating character even at constant speed, which reflects as a principal reason the periodic store-release phenomena of the oil-aerosol in the engine and in the exhaust system
- the fluctuations of DC are independent of the catalyst light off
- increased lube oil dosing causes a higher particle mass PM and higher particle counts (SMPS, CPC, DC)
- the use of non coated catalyst, or absence of catalyst leads to strongly increased particle emissions values, both mass and counts
- reduction of S-content in the lube oil (to approx. 400 ppm) reduces at first the particle emissions, but the further reduction (until S = 0 ppm) increases the particle emissions strongly. It can be stated that the S-content is not the only parameter influencing the droplet formation and condensation processes and there are co-influences of the HC-composition and additive packages of the oil (subjects for further research).
- the aromats-free Aspen fuel causes higher particle emissions (mass, counts and condensates), quicker light off of the catalyst and no solid particles at cold start. Since this fuel was used only with the S-free oils it cannot be stated to what extend the influences on the particle emissions are due to the oil, to the fuel, or to both of them. Here also further investigations are necessary.

Most of the represented results are form single measurements, which is not enough to be generalized. Certain influences are also difficult to see, because of fluctuations of the very sensitive signals and the measuring dispersion. This problem can be resolved by measuring more vehicles and establishing the statistical results.

On the other hand several fields for new research appeared:

- physical behaviour of the aerosols consisting of oil droplets, which are not the same as diesel aerosols consisting of soot, SOF and other substances,
- new consideration of sampling methods (thermodiluter, thermodesorber) and measuring equipment,
- research of the impact of the composition and additizing of the lube oils on the particle emissions,
- research of fuel quality versus particle emissions,
- research of catalyst light off and ageing.

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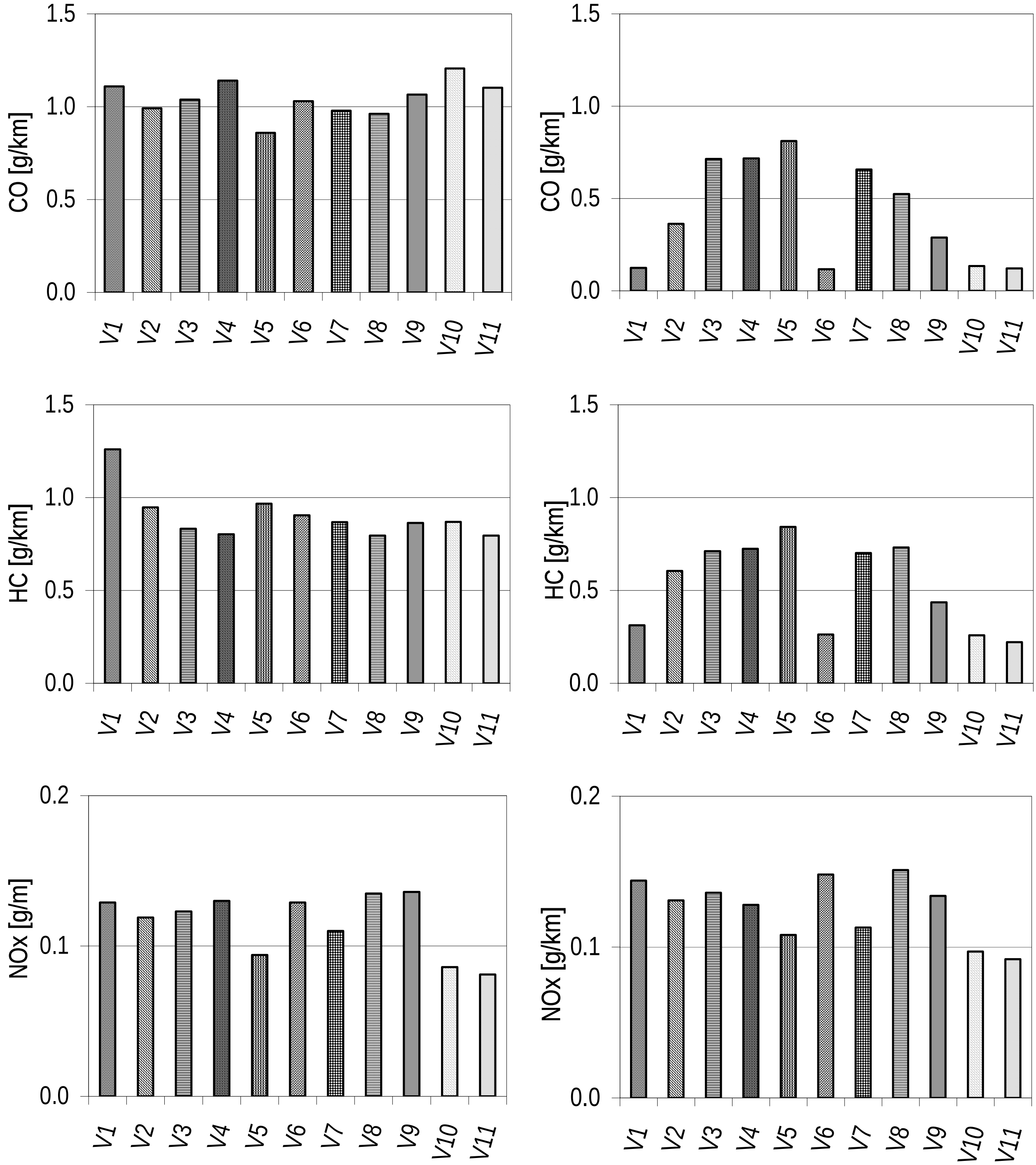
10. Abbreviations

AFHB	Abgasprüfstelle der Fachhochschule, Biel CH (Lab. For Exhaust Gas Control, Univ. of Appl. Sciences, Biel-Bienne, Switzerland)
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Swiss EPA, FOEFL)
CPC	condensation particle counter
CVS	constant volume sampling
DC	diffusion charging sensor
DEA	Deutsche Erdöl AG – experimental oil w/o any additive packages
DMA	differential mobility analyzer
EPA	Environmental Protection Agency
ETHZ	Eidgenössische Technische Hochschule Zürich
FOEFL	Federal Office for Environment, Forests and Landscape (Swiss EPA, BUWAL)
NanoMet	minidiluter + PAS + DC
NP	nanoparticulates
Pan	Panolin (Swiss lube oil manufacturer)
PAS	photoelectric aerosol sensor
PM	particulate matter, particulate mass
PN	particles number
PSD	particles size distribution
SMPS	scanning mobility particles sizer
SOF	soluble organic fractions
TSDI	Two Stroke Direct Injection

Comparison of limited emissions of different configurations with the Peugeot scooter

bag values approx. 4 min

cold **warm**



Comparison of nonlimited emissions of different configurations with the Peugeot scooter

integral average values of approx. 4 min

cold **warm**