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Particle Mass and Nanoparticulates of a Scooter with 2-Stroke Direct Injection (TSDI)

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1. Abstract

Analysis of limited and nonlimited emissions of scooters was performed during several research programs of the Swiss Federal Office of Environment Forests and Landscape (FOEFL) - and as a contribution to the European project ARTEMIS *).

Small scooters, which are very much used in the congested centers of the European 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 a Peugeot scooter with TSDI (Two Stroke Direct Injection) were performed and the emissions were compared to the other 2-S & 4-S scooters.

As nonlimited emissions the nanoparticulate emissions at cold and warm operating conditions were measured by means of SMPS, ELPI and NanoMet *). The measurements were both: at steady state and at transient operating conditions.

It can be stated, that the TSDI-technology offers advantages of lower gaseous and particulate emissions. It reaches about the level of 4-S vehicles.

Since the particulate emission of the 2-S consists mainly of lube oil condensates the minimization of oil consumption stays still an important goal. Further improvements of oil & fuel quality, as well as optimisation of catalysts can also contribute to a reduction of particulate matter and particle counts.

2. Introduction and objectives

Reduction of emissions of 2-wheelers became ever more urgent question in the last years. Particularly the scooters and low-power motorcycles, which in several cities are used for individual transportation, even in the winter time, have to be carefully regarded.

Several research works and technical improvements have been performed, [1, 2, 3, 4, 5, 6, 7], **), nevertheless further efforts are necessary.

Important activities on the international level are among others:

- the preparation of new universal legal measuring procedures the Worlwide Motorcycle Test Cycle (WMTC) of the UN-GRPE,
- European project ARTEMIS about the emissions of transport, modelling and inventory with an extensive subprogram about 2-wheelers.

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

In an international Emission Factors Program of the Swiss and German Federal Offices of Environment, beginning of 90-ties, a large data base of about 40 two-wheelers was established. The procedures and results of the project, which concerned also cars and trucks, are given in the report N° 255 of the Swiss EPA (BUWAL), [8], [9].

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, [10,11, 12, 13, 14, 15, 16].

The most important objectives of the past investigations were:

- complementing the inventory of emissions factors,
- establishing and research of the real-world driving cycles (with the scope of emission factors),
- research of the summer cold start,
- research of particulate emissions,
- participation at Swiss works for WMTC.

The particulate mass- and counts emissions of 2-stroke engines reach the level of diesel engines and cannot be neglected in the context of the present discussions.

Objective of the present work was to show what is the influence of the new 2-stroke technology (TSDI) on the emissions, and especially on the (nano) particulates. The results are compared to the other investigated scooters.

It is important to remark that the results from single vehicles cannot be generalized and that the field of 2 stroke particulate emissions, as well as the field of all small engines particulate emissions remains relatively unknown and has to be more widely and deeply explored.

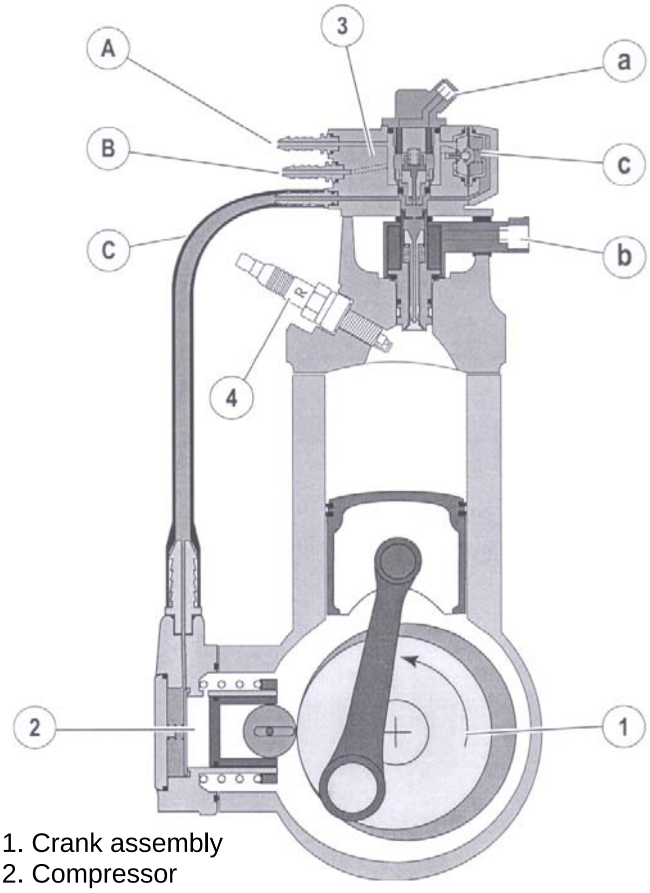
3. Investigated Scooters

The investigated scooter was:

Peugeot Looxor TSDI

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

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



1. Crank assembly
2. Compressor
3. Feed rail
   a) petrol injector
   b) air injector
   c) petrol pressure regulator

A. Fuel inlet
B: Fuel return
C. Pressurized air inlet

Fig. 2: TSDI – system components & functioning

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.

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^{o}C, rel. humidity 50%)
  scale: Mettler, accuracy $\pm$ 1 μg

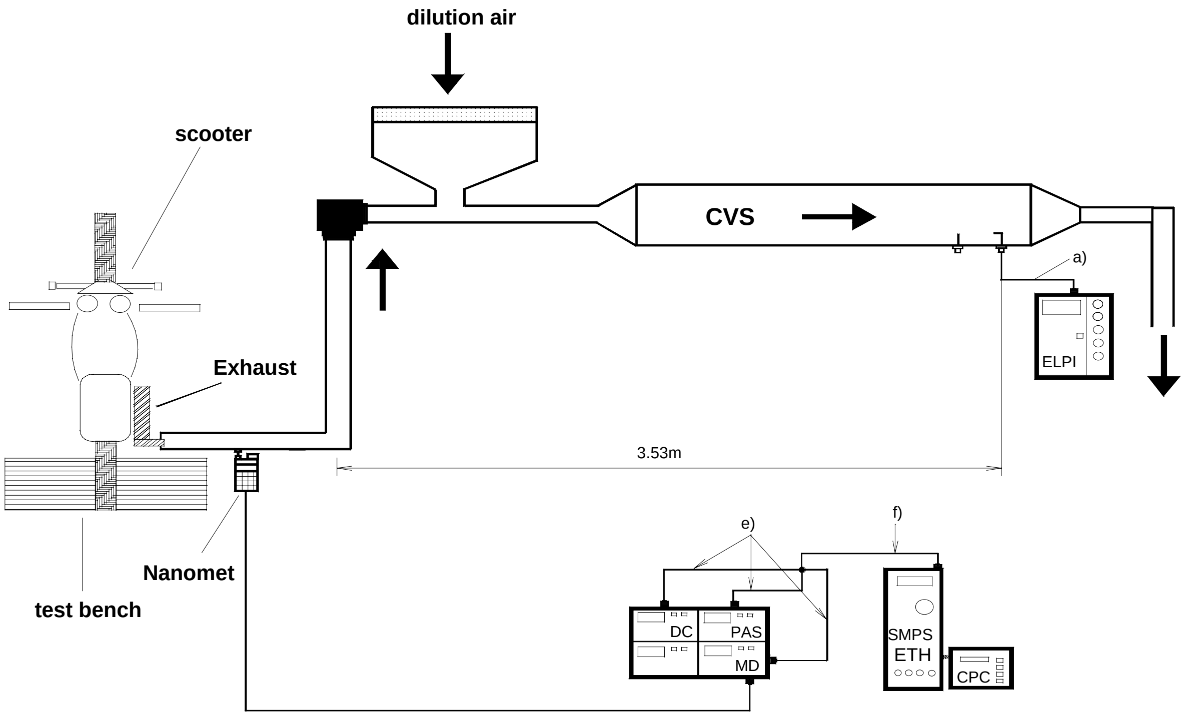
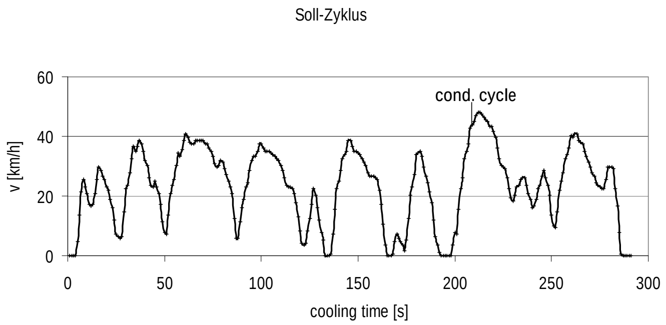


Fig. 3: Sampling and measuring set-up for nanoparticulates analysis of the scooters



Characteristic parameters of the driving cycle (ZUS 98) (cond. ...conducting cycle)

cycle	t	s	v=0		v=const	
[-]	[s]	[m]	[s]	[%]	[s]	[%]
cond	291	1888.2	24	8.2	65	22.3

stab v	stab a	v mean	a+	a-
[m/s]	[m/s^2]	[m/s]	[m/s^2]	[m/s^2]
12.592	0.872	23.36	1.062	-0.777

Fig. 4: Driving cycle for warm-up after the cold start and for nanoparticulates analysis

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)
- ELPI – Electrical Low Pressure Impactor, DEKATI
- 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 at stationary and at transient engine operation.

5. Measuring procedures

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

- cold start – acceleration to 30 km/h constant speed
- warm cycle (Fig. 4) – bag sampling, PM
- cooling down during 30 min
- cold cycle (Fig. 4) – bag sampling, PM.

In the first part with v = const = 30 km/h there is mostly the influence of the temperature to be observed. In the second part there are effects of dynamic driving and in the third part there is a superposition of warm-up and transient operation.

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).

The sampling of the gas probe for the nanoparticulates analysis was at the tailpipe trough the NanoMet MD19 minidiluter (see Fig. 1), except of ELPI, which got the sample from the CVS-dilution tunnel (see Fig. 3).

The used driving cycle was created from the cycle "city center" from [10] by leaving the parts with zero-speed and with the highest speed. This cycle is depicted in Fig. 4.

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

6. Results

Nanoparticles of TSDI

Fig. 5 shows the plots of nanoparticulate emissions during the cold start, acceleration to 30 km/h and continuation at this constant speed.

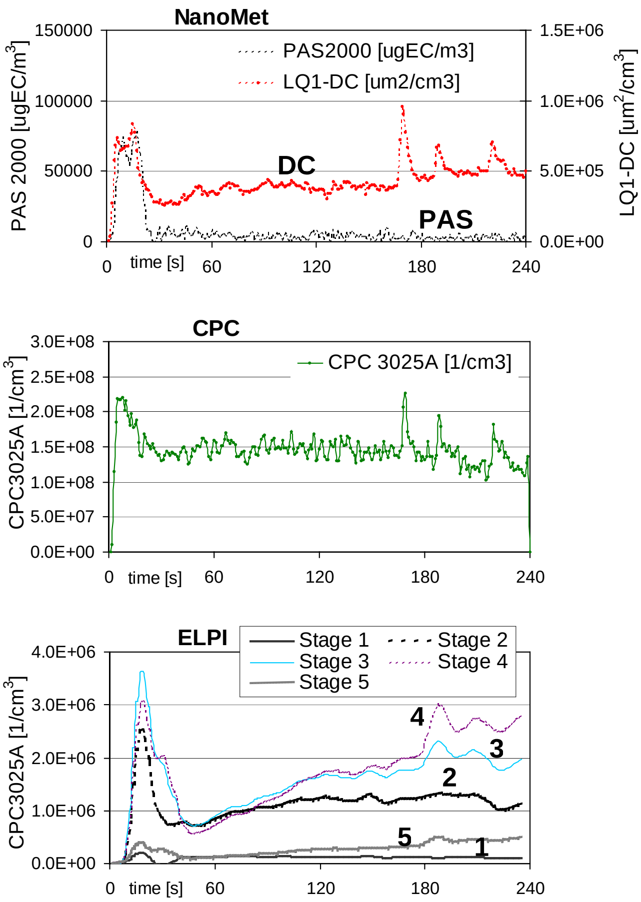


Fig. 5: Nanoparticulates at v = 30 km/h, with cold start, Peugeot Looxor TSDI with catalyst

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

DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties, i.e. it measures the sum of solids and condensates.

The SMPS (DMA + CPC) was used only for constant speed warm, for the transient measurements the summary particles counts (without size distribution analysis) were measured with CPC.

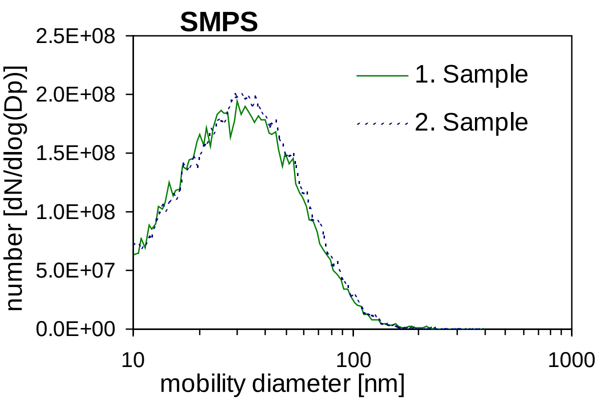
The ELPI has following stages:

Stage	1	2	3	4	5	6
D µm	0.043	0.083	0.137	0.215	0.330	0.516
Stage	7	8	9	10	11	12
D µm	0.818	1.300	2.042	3.208	5.177	8.099

In the time-plots the first 5 stages are represented.

It can be remarked, that:

- there are higher peak values of particle emissions (solids PAS, condensates DC & total CPC) after the cold start
- there is clearly a higher level of soluble particles (DC)
- after the warm-up period of about 160s some peaks of condensates (DC) occur, which are also visible on the CPC- & ELPI-signals.



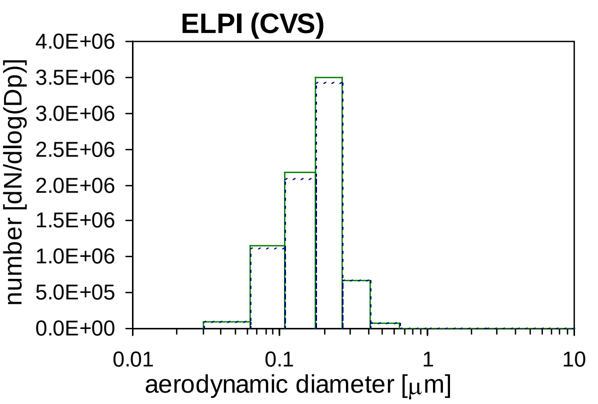


Fig. 6: SMPS- & ELPI-particle size distribution spectra at v=30 km/h, engine warm

From the stationary measurements of the SMPS- & ELPI size distribution spectra, Fig. 6, it is to see, that:

- the SMPS-spectra for 2-stroke have a maximum number concentration as high (or higher) as the diesel engines, this maximum is placed mostly at the sizes of 30 ÷ 40 nm (for diesel usually 90 ÷ 100 nm)
- compared to the SMPS-spectra the ELPI-spectra are generally shifted to the bigger sizes and lower counts concentrations – this is explained with: the coagulation effects in the exhaust gas line between tail pipe sampling (SMPS) and CVS-tunnel-sampling (ELPI) (a distance of approx. 8 m.), the diffusion losses on the walls of the exhaust gas line and condensation/evaporation-effects of the volatiles in the gas line and in the ELPI.

These effects explain the fact, that while the CPC-total PN during the warm-up (Fig. 5) stays constant, the ELPI-stages 3 & 4 increase the PN-concentration.

Fig. 7 gives an example of NP-emissions during the transient cycle with cold start:

- in the transient driving cycles the peaks of NP-emissions coincide generally with the accelerations and with the maxima of driving speed
- the NanoMet-signals show the peak of solid particles (PAS) at cold start (most probably particle blow-out of the cold catalyst) and the increase of condensates (DC) after the warm-up (approx. 200 s); these condensates are also visible on the ELPI-stages 3 & 4 and additionally to the lube oil they can be caused also by the formation of sulphates in the hot catalyst
- the emissions of solids (PAS) is usually near to zero for 2-S engines (except for the cold start); with the appearance of condensates, which envelope usually the solid particles,

the solids cannot be recognized any more by the PAS.

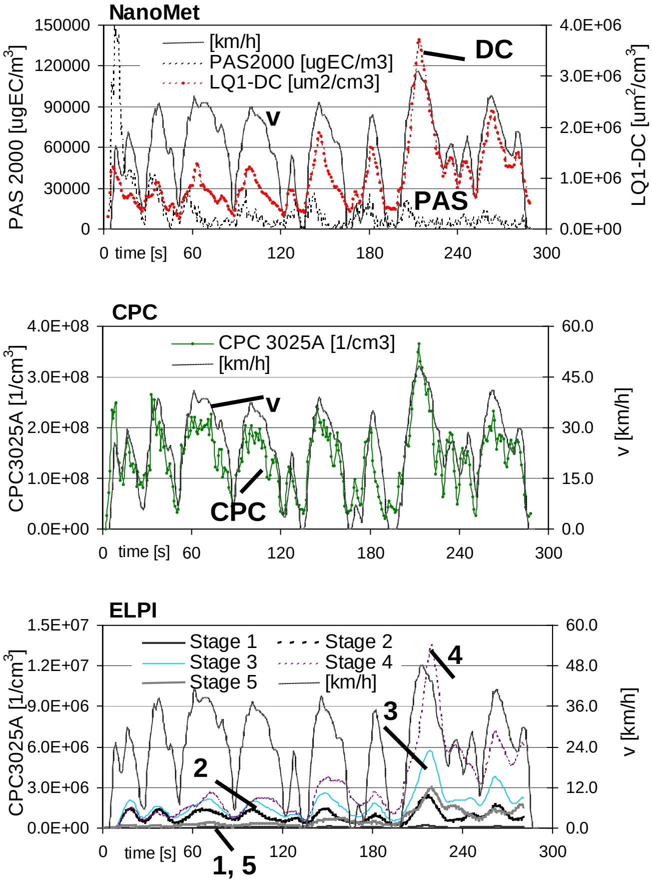


Fig. 7: Nanoparticulates at transient cycle, with cold start, Peugeot Looxor TSDI with catalyst

The direct comparison of the time-plots of different signals at different operating conditions is limited by the measuring dispersion and by the measuring lag. The consideration of time-averaged values, which eliminates these difficulties by a big part, can be very helpful.

Fig. 8 represents the time average values of all parameters characterizing the particle emissions at all investigated operating conditions. It can be remarked:

- the hot operation and particularly hot & dynamic operation increases the PM; this increase is due to the condensates (DC) (the condensates originate mainly from the lube oil; but the influence of sulphates must also be supposed)
- the cold operation increases the average emission of solid nano-particulates (PAS), which still remains on a very low level (the observed results of PAS are influenced by different effects: engine out emissions, catalyst blow-out & envelop of condensates).

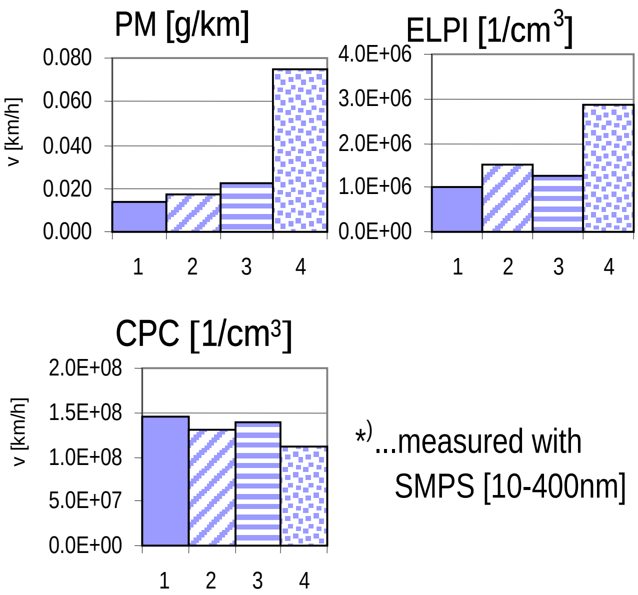


Fig. 8a: Particle mass & time average nanoparticulates at different driving conditions

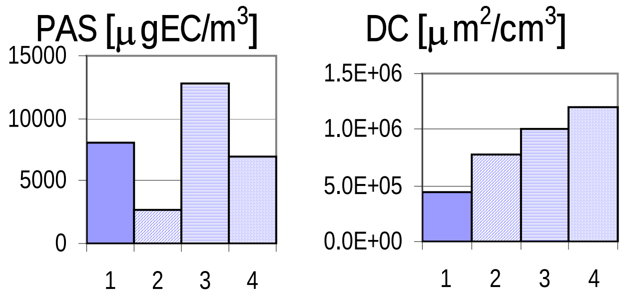


Fig. 8b: Average NanoMet values at different driving conditions

PEUGEOT Looxor TSDI

1... v = 30 km/h cold start | 2... v = 30 km/h

3... driving cycle cold*) | 4... driving cycle

*) cooling time 30 min

Comparison with other scooters

Following scooters, which were investigated in [13] & [16] at identical driving conditions with the same apparatus, can be an interesting base of comparison with the TSDI-technology:

Yamaha EW50 Slider

- 2-stroke, displacement 50 cc, air cooling
- max. power 2,5 kW, at 6800 rpm, variomat, max. speed 60 km/h (with cat.)
- weight empty: 81 kg
- construction year: 2000 (22 km at beginning of measurements)
- non regulated oxidation catalyst

Aprilia Leonardo 15

- 4-stroke, displacement 125 cc, water cooling
- max. power 8,5 kW, at 9000 rpm, variomat, max. speed 95 km/h (w/o cat.)
- weight empty: 136 kg
- construction year: 1999 (33 km at beginning of measurements)

Piaggio Vespa ET4

- 4-stroke, displacement 50 cc, air cooling
- max. power 3,2 kW, at 8500 rpm, variomat, max. speed 45 km/h (w/o cat.)
- weight empty: 96 kg
- construction year: 2002 (100 km at beginning of measurements)

It is known, that a comparison of results, which were taken a long time apart to each other, must be regarded with certain tolerance.

It is also important to underline, that the results from single vehicles cannot be generalized and that the field of 2 stroke particulate emissions, as well as the field of all small engines particulate emissions remains relatively unknown and has to be more widely and deeply explored.

Nevertheless the look on Figures 9, 10 & 11 is very interesting and it confirms the advantages of the TSDI-technology (Peugeot).

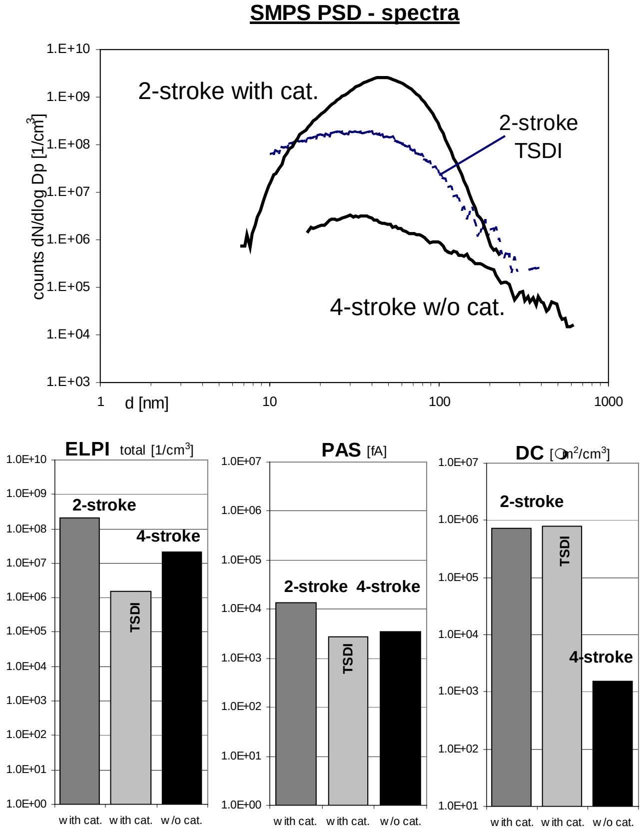


Fig. 9: Nanoparticulates at v = 30 km/h, with warm engine for 2-stroke with & 4-stroke without catalyst (2-S: Yamaha 50, Peugeot TSDI; 4-S: Aprilia 125)

Fig. 9 shows the NP-emissions of Peugeot TSDI in relationship to the other vehicles from [13] at constant speed. This representation confirms the lower NP-emissions of the TSDI except of condensates (DC), which are also influenced by the oxidation catalyst.

Comparing with the 2-stroke with carburator (Yamaha) the Peugeot with TSDI has leaner engine tuning, less CO, HC and more NOx, Fig. 10.

The PM-emissions of Peugeot with TSDI reach the level of the 4-stroke engines, Fig. 11. This is confirmed by the ELPI-values. The TSDI shows the highest values of condensates (DC).

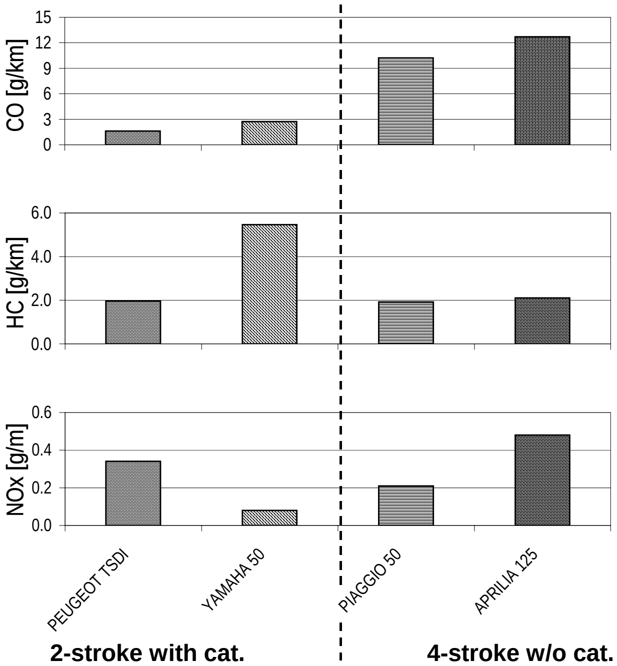


Fig. 10: Comparison of gaseous emissions of different scooters in the driving cycle (ZUS 98) cold

At hot operation the PM-values of TSDI are strongly increased by the condensates, which are developed particularly at the transient cycle and confirmed by the DC-values. Additionally to the lube oil these condensates originate usually by a part from the sulphates and depend on the used oil & fuel, as well as on the used catalyst and its working conditions, like temperature and spatial velocity.

Another reason for the increased production of condensates is the near stoichiometric operation with higher average temperature level of combustion.
All those influences couldn't be investigated in the presented work and are a matter for further investigations. It shall be precised, that the condensates have nothing to do directly with the TSDI technology.

7. Conclusions

Following conclusions can be pointed out:

- 2-stroke engine has generally higher particle mass (PM) and nanoparticulates (NP) emission than the 4-stroke engine
- the particulates of 2-stroke consist mostly of soluble fraction (higher DC-values)
- the engine with TSDI has leaner mixture tuning as the conventional 2-stroke with carburtor and it offers clear advantages of lower gaseous and particulate emissions
- at hot and particularly hot & transient operation there is an increase of PM caused by the increase of condensates
- the cold operation increases the average emission of solid nanoparticulates (PAS)
- with cold start there is a tendency of less condensates (DC)

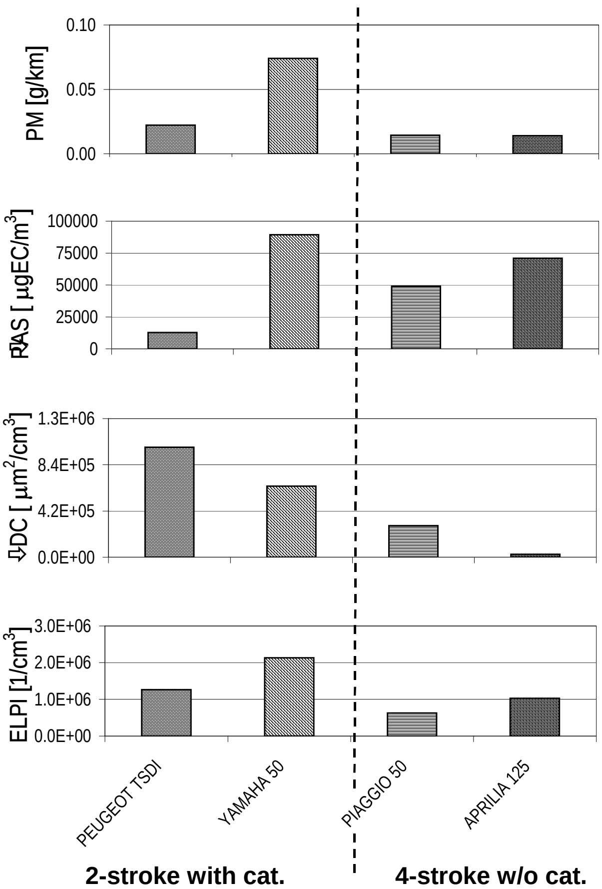


Fig. 11: Comparison of particle of different scooters in the driving cycle (ZUS 98) cold

Further improvements can be reached by reducing the lube oil consumption and by optimising the quality of oil, fuel and catalyst.

8. Acknowledgment

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10. Abbreviations

AFHB	Abgasprüfstelle der Fachhochschule, Biel CH (Lab. For Exhaust Gas Control, Univ. of Appl. Sciences, Biel-Bienne, Switzerland)
ARTEMIS	assessment and reliability of transport emission models and inventory systems
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Swiss EPA, FOEFL)
CPC	condensation particle counter
CVS	constant volume sampling
DMA	differential mobility analyzer
DC	diffusion charging sensor
ELPI	electrical low pressure impactor
EPA	Environmental Protection Agency
ETHZ	Eidgenössische Technische Hochschule Zürich
FOEFL	Federal Office for Environment, Forests and Landscape (Swiss EPA, BUWAL)
GRPE	Groupe Rapporteurs Polution et Energie
NanoMet	minidiluter + PAS + DC
NP	nanoparticulates
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
UN	United Nations
WMTC	Worldwide Motorcycle Test Cycle