PARTICLES EMISSIONS OF COMMERCIALLY AVAILABLE SMALL HANDHELD EQUIPMENT

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INTRODUCTION

Small gasoline-powered handheld equipment such as chainsaws, brush-cutters, or leaf blowers may not contribute prominently to the EU-wide pollutant emissions inventory but their exhaust emissions cannot be neglected when considering the health of their operators, be they private or professional users. In Europe, emissions of such handheld tools are regulated by the Non-Road Mobile Machinery (NRMM) Directive 1997/68/EC, which defines emissions limits for HC, CO and NOx gaseous emissions. Particulate Matter (PM) emissions of small NRMM spark ignited engines are not regulated though; neither in mass nor in number. The Association for Emissions Control by Catalyst (AECC) conducted a test program in an independent lab to investigate gaseous and particulate exhaust emissions of this type of applications.

SELECTION OF TEST DEVICES

Since small handheld equipment engine technologies are very diverse, six different engines/machines were chosen, being representative of the European and US market, with engine capacities ranging from 22 to 72 cm³ and power outputs of between 0.6 and 4 kW as described in the table below. A low-cost Asian model was included in the engines selection (#4).

#	Engine specification					Oil/fuel mixture		Catalyst
	Working principle	Displacement [cm³]	Power [W]	Max speed [rpm]	Idle speed [rpm]	Preparation	Ratio	
1	4S dry sump lubricated	25	740	11000	2800	Carburetor	Separated lubrication 10W30	No
2	4S	28.4	960	10200	2800	Carburetor	Synthetic oil 1:50	No
3	2S	22	620	9000	2800	Carburetor	Synthetic oil 1:50	Wire-mesh
4	2S	45	1410	8000	2800	Carburetor	Synthetic oil 1:40	Wire-mesh
5	2S stratified scavenging	59	3400	13000	2800	Carburetor	Synthetic oil 1:50	No
6	2S	72.2	4030	10100	2500	Fuel Injection	Synthetic oil 1:50	No

TEST SET-UP AND EMISSIONS MEASUREMENT

For the engine bench tests, a flexible test rig was designed to be able to carry different types of power tools. In this configuration the open end of the crankshaft with its original flywheel clutch was connected to a flexible clutch, followed by an intermediate shaft and a torque measurement flange that is screwed to the shaft of an electric brake. The actuation of the throttle plate was done by a stepper motor. Exhaust gas was collected by an open CVS system. By using such an open setup, backpressure effects on the engine behaviour can be avoided; this mimics as much as possible in-field engine operation.

Emissions were measured over the regulatory test cycle G3. Cycle G3 is made of two steady-state engine points: wide-open throttle (WOT) and idle. In addition to regulatory gaseous emissions, PM mass and number were measured according to the UNECE light-duty PMP protocol. Gaseous emissions were weighted as required in the NRMM directive, emissions at WOT accounting for 85% and emissions at idle for 15%. The same approach was taken for PM mass and number emissions. Finally, collected particulate matter samples were subjected to a Thermo Gravimetric Analysis (TGA) to identify the mass fraction of organic and elemental carbon. A PM size distribution analysis was performed, using an SMPS instrument on two of the selected engines and finally, the impact of using OEM-recommended mineral oil on PM mass and number emissions were evaluated on the low-cost tool, in comparison with synthetic oil.

All engines except #1 were lubricated by an oil/fuel mixture; therefore some influence on particulate matter measurement was expected from the sampling method, especially in terms of oil droplets possibly counted as particles. In absence of specific regulatory procedure to measure particle emissions from hand-held tools, the PMP protocol was used. The temperature of the heated tube used to remove volatiles adsorbed on particles is set to 350°C in the light-duty UN Regulation 83; this means a gas temperature of about 200°C. The impact of pre-heating on the particulate number measured was evaluated by comparing different temperatures of the evaporation tube. The maximum technically achievable temperature was 500°C (i.e. 300°C gas). Within this range (350-500°C), no significant impact on particle numbers was measured. Tests were therefore conducted using the regulatory 350°C.

ENGINE OPERATION

All tested engines operated under rich conditions both at WOT and at idle. The rich tuning of engines aims at increasing the power output and managing thermal stress at WOT and at enhancing stability at idle. The low-cost 2-stroke (#4) showed the richest combustion at WOT (~λ=0.7), followed by the 2S engine with stratified scavenging (#5) below λ=0.8. The other engines showed comparable λ-values at WOT, between 0.8 and 0.9. A higher variability of the air-fuel ratio was observed on the low-cost engine #4, indicating a less-well controlled combustion.

PM MASS EMISSIONS RESULTS

Particulate mass measurements were repeatable and showed big differences for the various engine working principles. The dry sump lubricated 4-stroke (#1) produces the lowest amount by far (18 mg/kWh); this may be explained by the separation of fuel and oil. Next in line are the 2-strokes with exhaust gas aftertreatment (#3 and 4 around 100 mg/kWh) which indicates a certain reduction of particles - or of the more heavy volatiles adsorbed onto PM - in the catalyst. Finally, all the engines with mixture lubrication produced much higher PM emissions (around 250 mg/kW for #2 and #5 and 410 mg/kWh for #6).

PM NUMBER EMISSIONS RESULTS

PM number emissions varied from $2x10^{12}$ to $5x10^{14}$/kWh, depending on the engine working principle. These levels are of the order of magnitude of non-DPF equipped diesel engines. Engine #1 produced the lowest number of particles. This value was one order of magnitude lower than for the second-best engine #3. Despite similar PM mass to engine #3, the low-cost engine (#4) produced almost the same number of particles (> 10^{14}/kWh) as engines #2 and #6 which are not equipped with a catalyst. Engine #5 with stratified scavenging emitted a lower PM number, at similar level to the catalyst-equipped engine #3 (~ 10^{13}/kWh).

Engine #4 was tested with fully synthetic oil and with mineral oil. Using mineral oil almost doubled the PM mass, but the already high PM number remained identical. Oil may be mainly influencing the size of particles.

PM SIZE DISTRIBUTION

As they differ in working principle and exhaust gas aftertreatment, engines #2 and #3 were chosen for the evaluation of their particles size distribution using a Scanning Mobility Particle Sizer (SMPS). Particles emitted during idle were smaller than during WOT operation for both engines whereas the difference was much bigger for engine #3. Generally, particles emitted by the mixture lubricated 4-stroke (#2) were bigger than the ones emitted by the 2-stroke with catalyst (#3). However, there was no clear evidence whether the difference in mean particle size relates to the different combustion process or to the catalytic oxidation.

PM COMPOSITION

The PM composition analysis by TGA showed that elemental carbon weight shares were only about 10-20 % at idle and 10% at WOT for all six engines. This can result from the high amount of unburned fuel in the exhaust gas due to comparatively poor combustion or from the oil coming from the mixture lubrication. However, the dry sump lubricated engine (#1) showed a similar behaviour. Using the mineral oil increased the content of organic carbon compared to synthetic oil.

CONCLUSION

PM mass and number results were high due to the rich operation of the small handheld equipment engines. The separation of fuel and oil as in the 4-stroke engine #1 with dry sump lubrication strongly helps reducing both PM mass and number. In general, PM mass and number results were equivalent or higher than for typical diesel engines without DPF. One of the main challenge fur future engine development activities in the field of NRMM will be the control of particulate matter emissions, provided future legislation tackles the issue.

With regard to the oil and unburned fuel in the exhaust gas it can be assumed that measurement results would be influenced by the sampling method (evaporation and heating). The tests reported here were conducted as close as possible to existing automotive PMP standards.

The high shares of organic carbon in the particulate matter (between 70% and 90%) are an indicator of the influence of oil and unburned fuel in the exhaust gas. Further analysis to evaluate the content of oil in the OC fraction could be of interest.

Particles Emissions of Commercially Available Small Handheld Equipment

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Technology for exhaust emissions control for cars, buses and commercial vehicles, and an increasing number of non-road mobile machinery applications and motorcycles.

Introduction

- Small Hand-Held (SHH) equipment is regulated through the Non-Road Mobile Machinery (NRMM) Directive 97/68/EC (chainsaws, leaf blowers, etc.)
- Contribution to air pollution inventory may not be predominant but occupational health is of primary concern with hand-held Non-Road Mobile Machinery.
- Objective of AECC test program: demonstrate emission levels of Small Hand-Held state-of-the art equipment available in Europe, including low-cost import from Asia.

Test Plan and Selection of Engines

- Evaluate state-of-the-art engines used in SHH applications.
- Regulated pollutants (HC, CO, NOx) according to Directive 97/68/EC.
- PM mass and particles number according to Light-duty PMP protocol.
- PM size distribution by SMPS on engines N°2 and 3.

		Specifications		rpm		rpm certification	Mixture preparation	Oil/Fuel mixture ratio		Catalyst
1	**4 stroke** dry sump lubricated without catalyst	Engine displ. [cm^3]	25.0	max	11000	7000	carburetor	separated lubrication 10W30		NO
		Power rating [kW]	0.74	idle	2800					
2	**4 stroke** fuel/oil mixture lubricated without catalyst	Engine displ. [cm^3]	28.4	max	10200	8000	carburetor	synthetic oil 1:50		NO
		Power rating [kW]	0.96	idle	2800					
3	**2 stroke** fuel/oil mixture lubricated with catalyst	Engine displ. [cm^3]	22.0	max	9000	7900	carburetor	synthetic oil 1:50		wiremesh catalyst
		Power rating [kW]	0.62	idle	2800					
4	**2 stroke** fuel/oil mixture lubricated with catalyst	Engine displ. [cm^3]	45	max	8000	8000	carburetor	synthetic oil	1:50	wiremesh catalyst
		Power rating [kW]	1.41	idle	2800			mineral oil	1:40	
5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst	Engine displ. [cm^3]	59.0	max	13000	10000	carburetor	synthetic oil 1:50		NO
		Power rating [kW]	3.4	idle	2800					
6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst	Engine displ. [cm^3]	72.2	max	10100	9500	fuel injection	synthetic oil 1:50		NO
		Power rating[kW]	4.03	idle	2500					

Directive 97/68/EC as amended

Class/category	Displacement (cubic cm)
Hand-held engines Class SH:1	< 20
Class SH:2	≥ 20 < 50
Class SH:3	≥ 50
Non-hand-held engines Class SN:1	< 66
Class SN:2	≥ 66 < 100
Class SN:3	≥ 100 < 225
Class SN:4	≥ 225

1 2 3 4
5 6

4. TYPE-APPROVALS STAGE II

Member States shall refuse to grant type-approval for an engine type or engine family and to issue the documents as described in Annex VII, and shall refuse to grant any other type-approval for non-road mobile machinery in which an engine is installed:

after 1 August 2004 for engine classes SN:1 and SN:2

after 1 August 2006 for engine class SN:4

after 1 August 2007 for engine classes SH:1, SH:2 and SN:3

after 1 August 2008 for engine class SH:3,

if the engine fails to meet the requirements specified in this Directive and where the emissions of gaseous pollutants from the engine do not comply with the limit values as set out in the table in section 4.2.2.2 of

Notwithstanding the first subparagraph, an extension of the derogation period is granted until 31 July 2013, within the category of top handle machines, for professional use, multi-positional, hand-held hedge trimmers and top handle tree service chainsaws in which engines of classes SH:2 and SH:3 are installed.

Stage II (*)

Class	Carbon monoxide (CO) (g/kWh)	Sum of hydrocarbons and oxides of nitrogen (g/kWh) HC + NO_x
SH:1	805	50
SH:2	805	50
SH:3	603	72
SN:1	610	50,0
SN:2	610	40,0
SN:3	610	16,1
SN:4	610	12,1

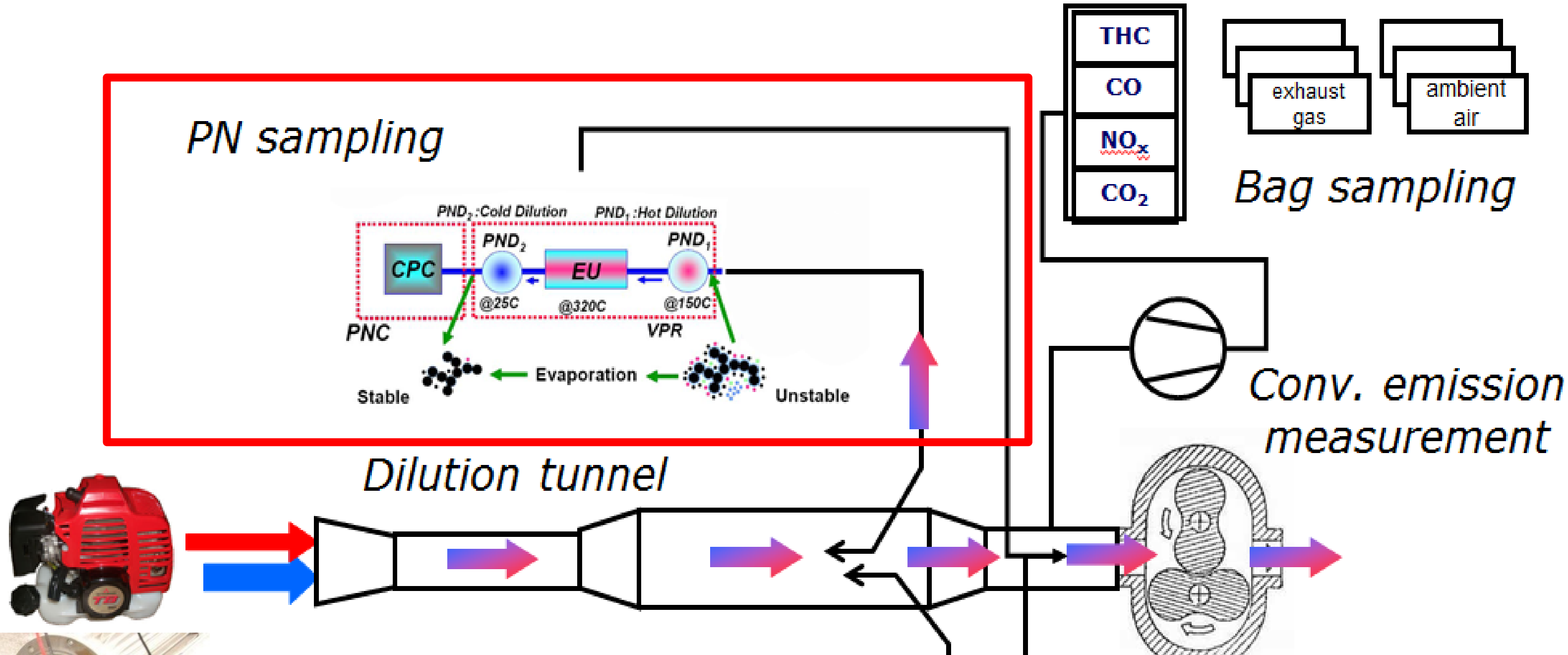
(*) See Annex 4, Appendix 4: deterioration factors included.

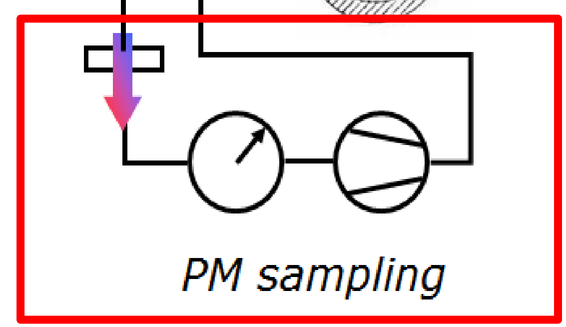
The NO_x emissions for all engine classes must not exceed 10 g/kWh.

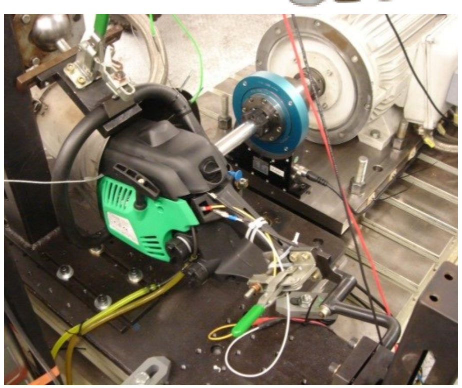
Cycle G3

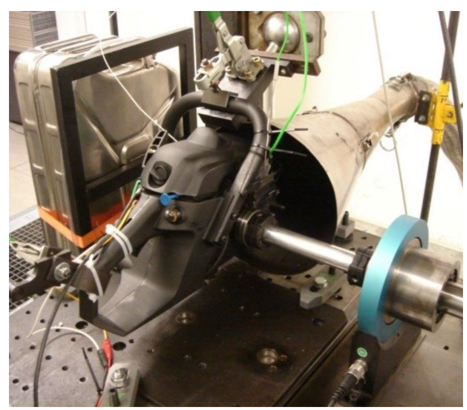
Mode number	1										2
Engine speed	Rated speed						Intermediate Speed				Low-idle speed
Load %	100										0
Weighting factor	0,85 (*)										0,15 (*)

Test Bench Set-up

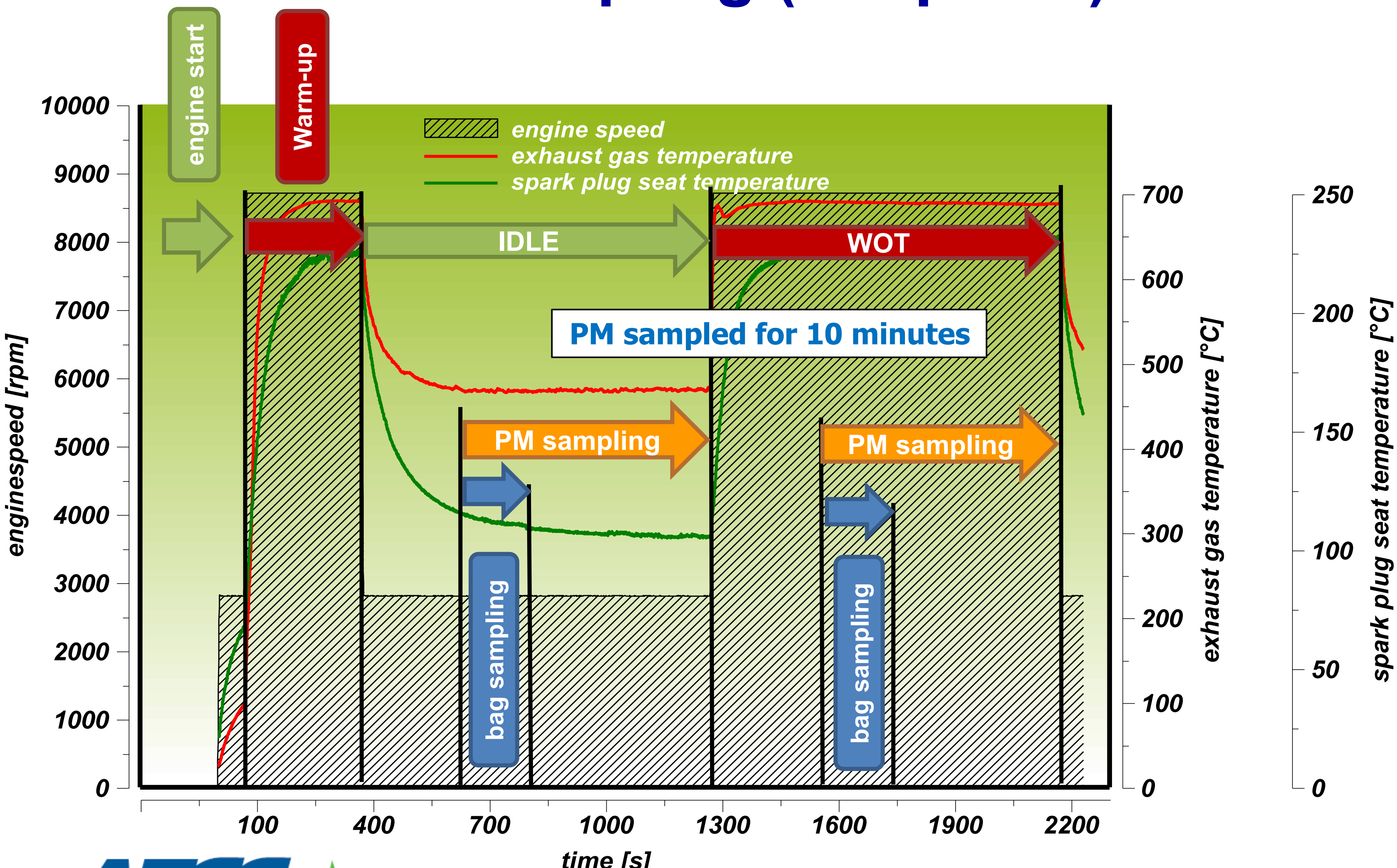








Measurement Procedure adapted for PM Sampling (3 repeats)



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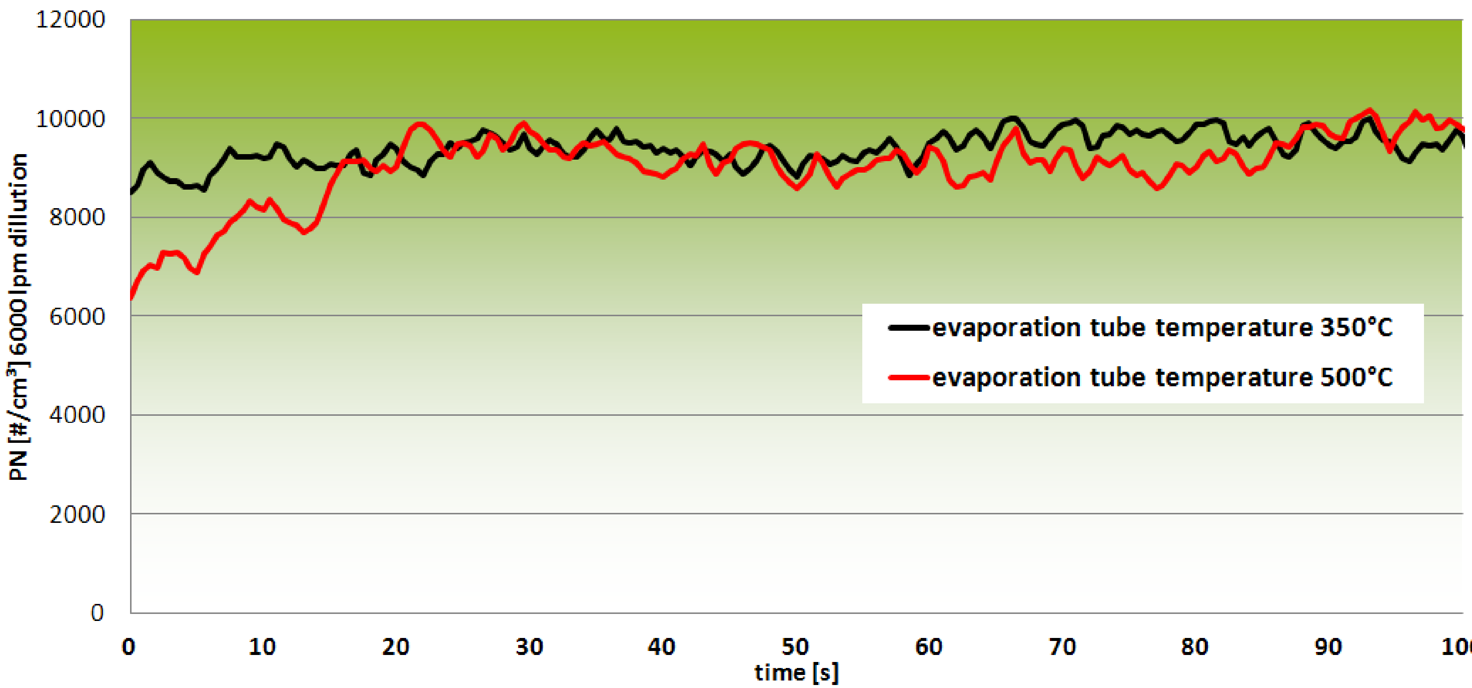
Evaporation Tube Temperature Impact

- Because of high quantity of volatiles adsorbed to PM, particles number was measured in 2 configurations of the evaporation tube: 350°C (Light-duty PMP procedure) and 500°C.
- Gas temperature was 220°C and 300°C respectively

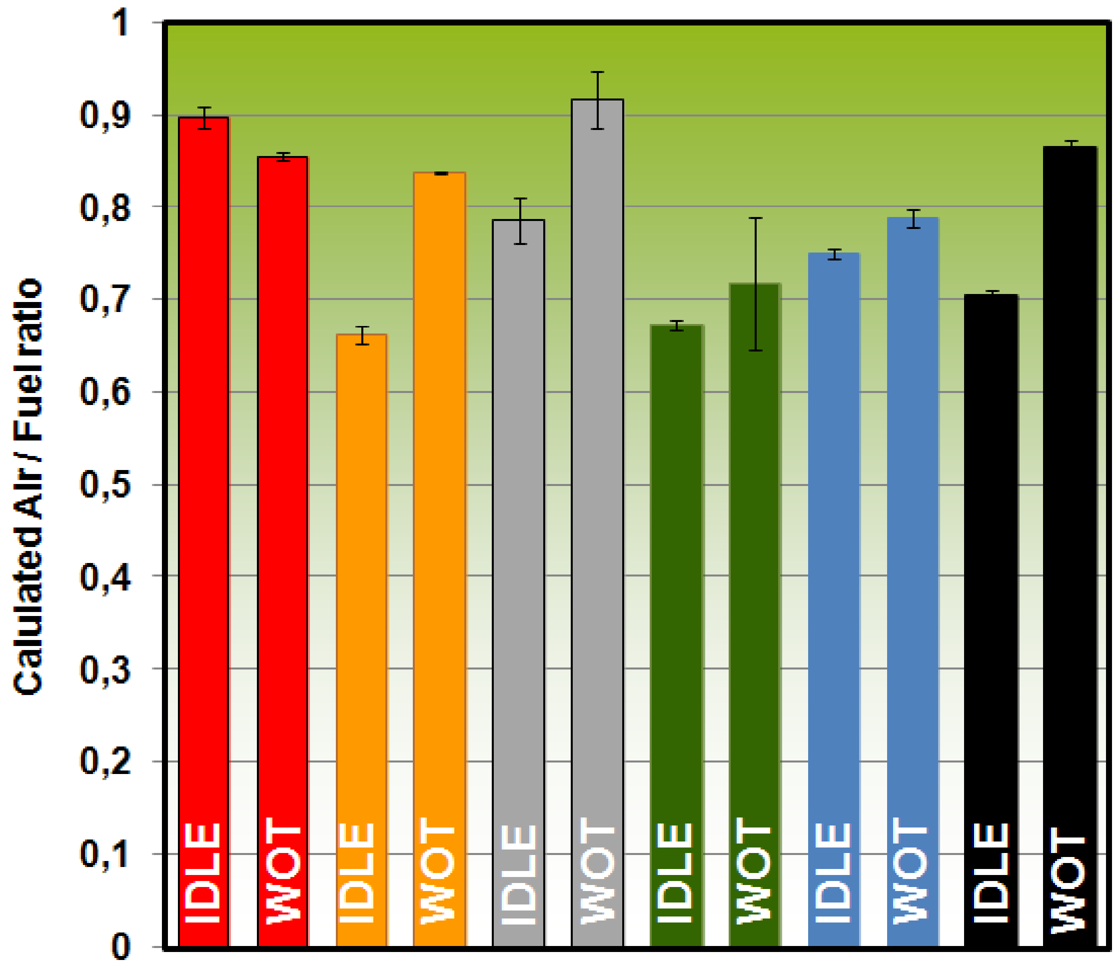


- No impact on PM number measured.

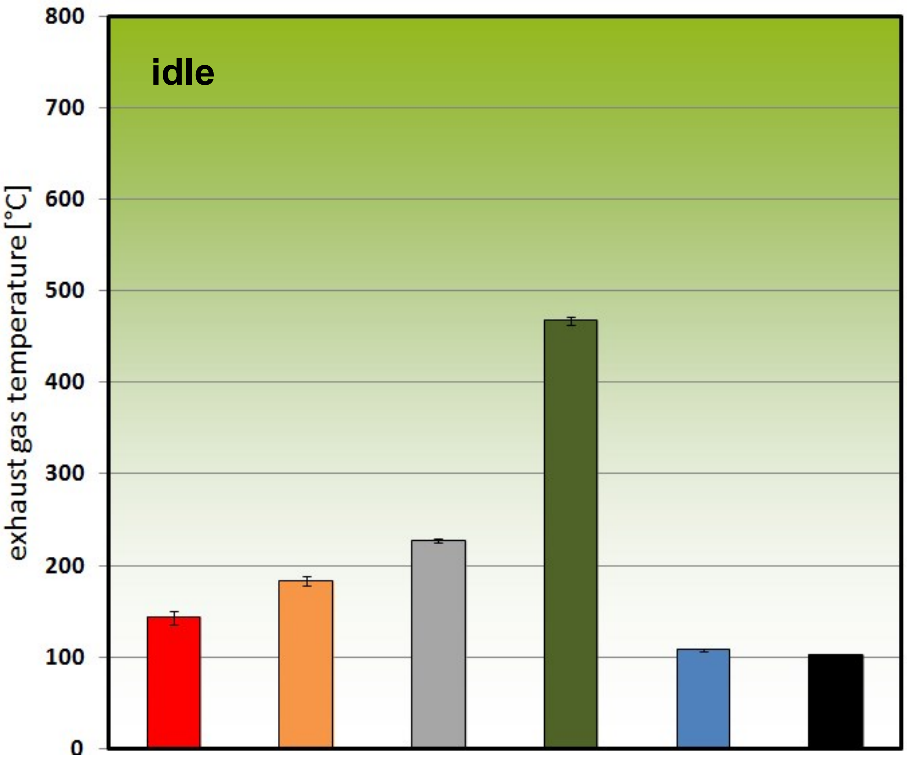
Tests Results: calculated Air-Fuel Ratio

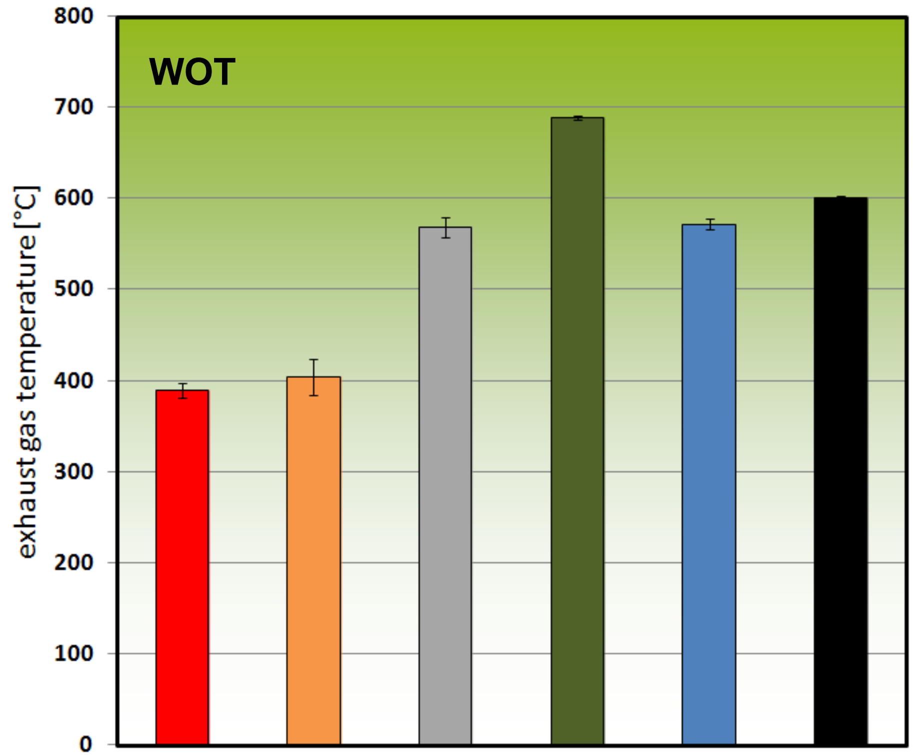
- All engines run rich, between 0.7 and 0.9 λ.
- A/F ratio of the low-cost engine is the richer and the less controlled (larger error bar).

1	**4 stroke** dry sump lubricated without catalyst
2	**4 stroke** fuel/oil mixture lubricated without catalyst
3	**2 stroke** fuel/oil mixture lubricated with catalyst
4	**2 stroke** fuel/oil mixture lubricated with catalyst
5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst
6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst



Tests Results: Exhaust Gas Temperature





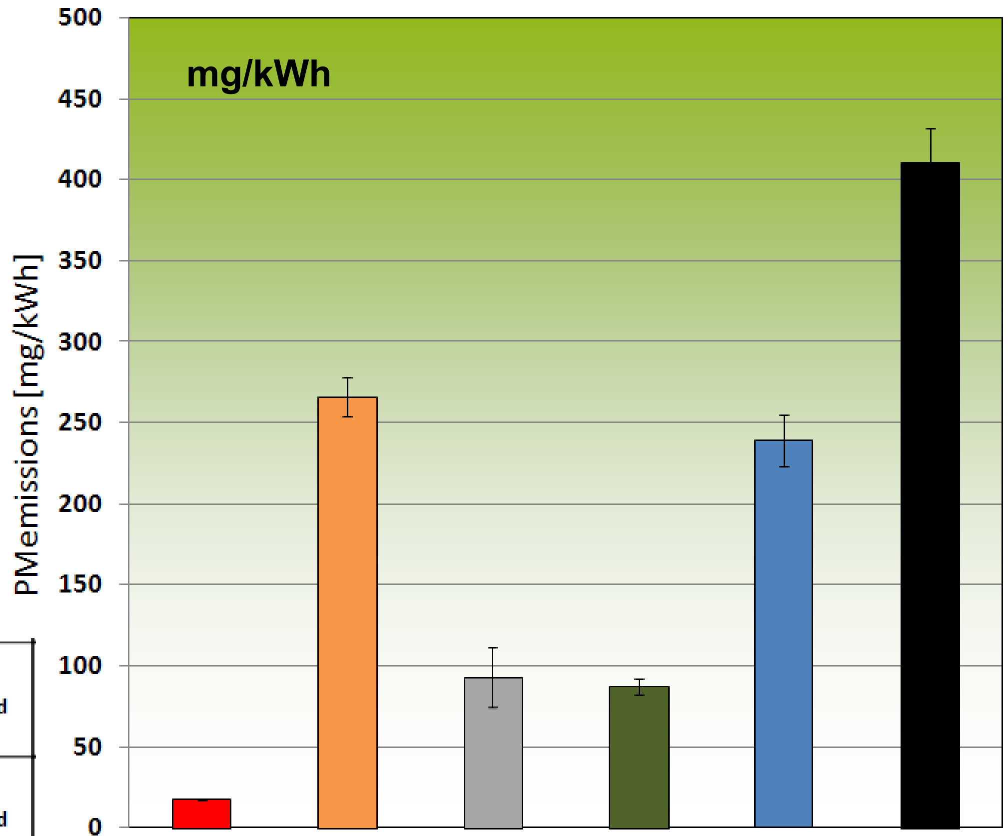
1	**4 stroke** dry sump lubricated without catalyst
2	**4 stroke** fuel/oil mixture lubricated without catalyst

3	**2 stroke** fuel/oil mixture lubricated with catalyst
4	**2 stroke** fuel/oil mixture lubricated with catalyst

5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst
6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst

Tests Results: PM Mass Emissions

- PM mass results are repeatable.
- PM mass level depends on engine working principle.
- PM vary from 18 to 410 mg/kWh
- Presence of catalyst on 2-stroke engines (n°3 & 4) reduces PM mass.



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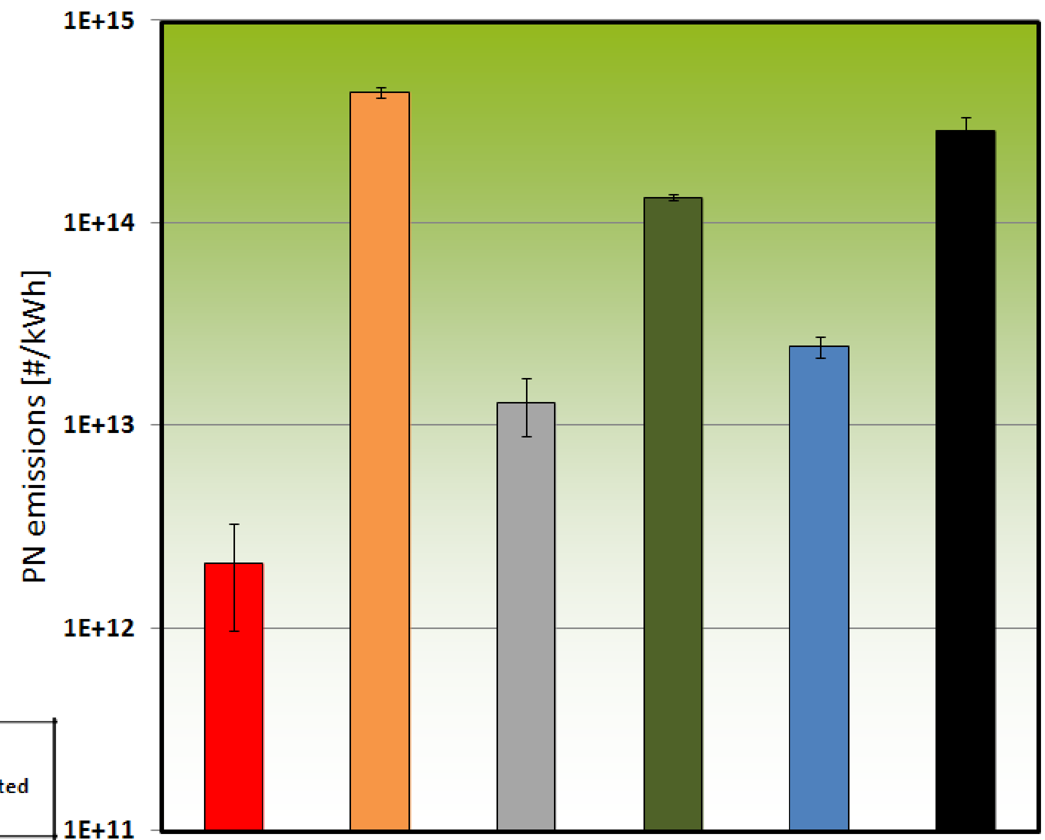
3	**2 stroke** fuel/oil mixture lubricated with catalyst
4	**2 stroke** fuel/oil mixture lubricated with catalyst
5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst
6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst

Tests Results: Particle Number Emissions

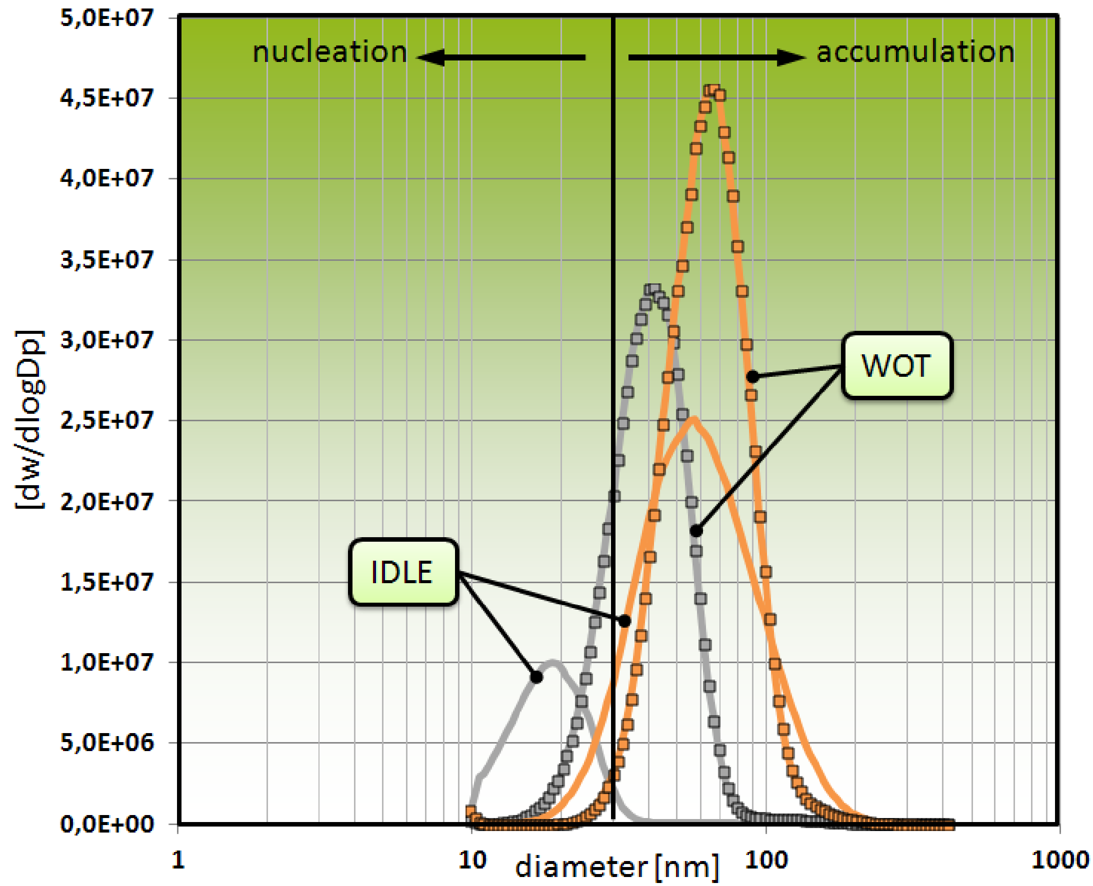
- PN vary from $2x10^{12}$ to $5x10^{14}$/kWh.
- PN emissions level depends on engine working principle.
- PN levels are of the order of magnitude of non-DPF equipped diesel engines.
- Presence of catalyst on 2S engine can reduce PN.



1	**4 stroke** dry sump lubricated without catalyst	4	**2 stroke** fuel/oil mixture lubricated with catalyst
2	**4 stroke** fuel/oil mixture lubricated without catalyst	5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst
3	**2 stroke** fuel/oil mixture lubricated with catalyst	6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst

PM Size Distribution

- Size distribution of PM emissions from engines n°2 and 3 were evaluated with an SMPS. Particles were sampled directly from the CVS.
- Particles emitted at idle are smaller than those emitted at full load.
- There is no clear evidence if the difference in mean particle size is based on the different combustion process or on the oxidation of SOF by the catalyst

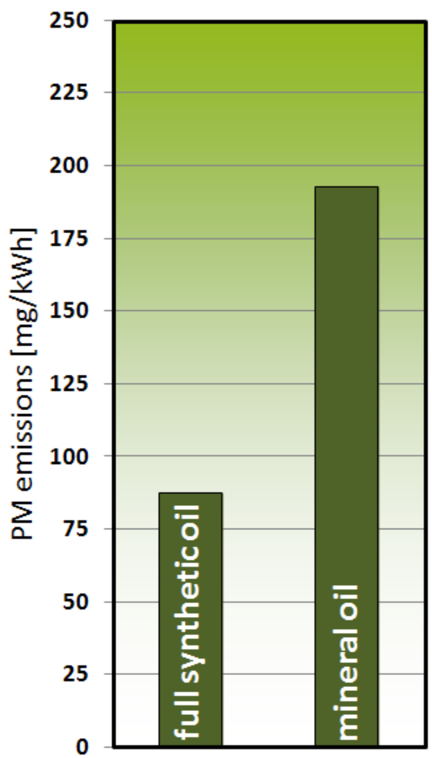


2	**4 stroke** fuel/oil mixture lubricated without catalyst
3	**2 stroke** fuel/oil mixture lubricated with catalyst

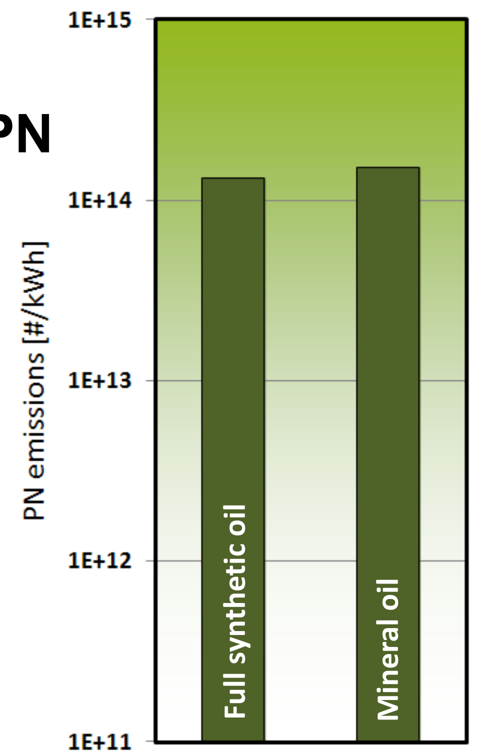
Effect of Oil on PM/PN Emissions

- The low-cost 2S engine was tested also with mineral oil (OEM recommendation).
- Compared to synthetic oil, PM mass doubled but Particles Number was stable when mineral oil was used.

PM



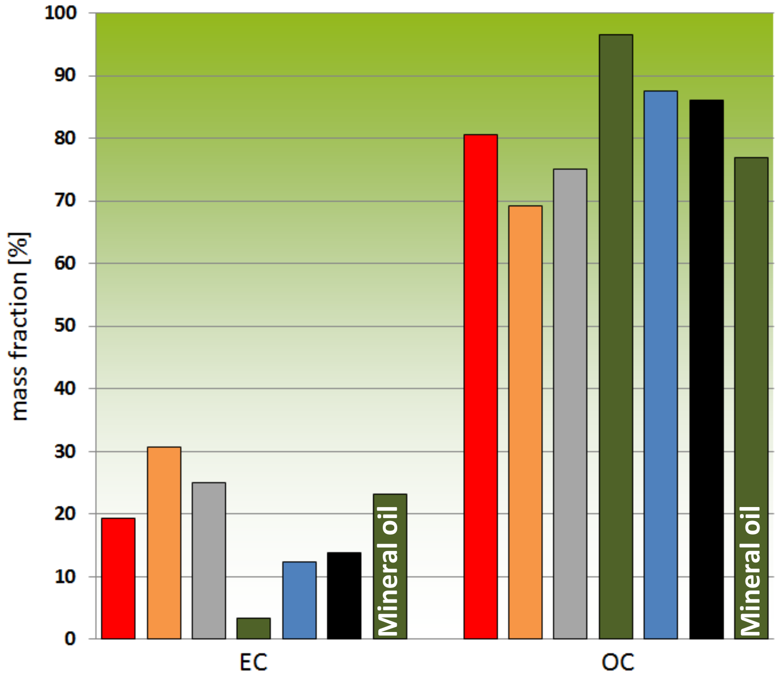
PN



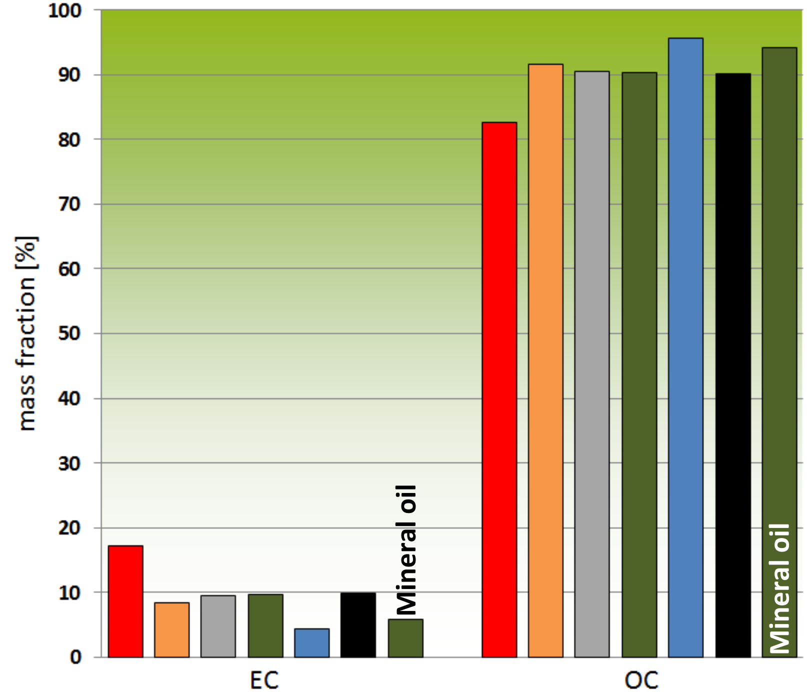
PM Chemical Composition

- Elemental Carbon (EC) and Organic Carbon (OC) fractions measured by Thermo-Gravimetric Analysis

Idle



WOT



1	**4 stroke** dry sump lubricated without catalyst
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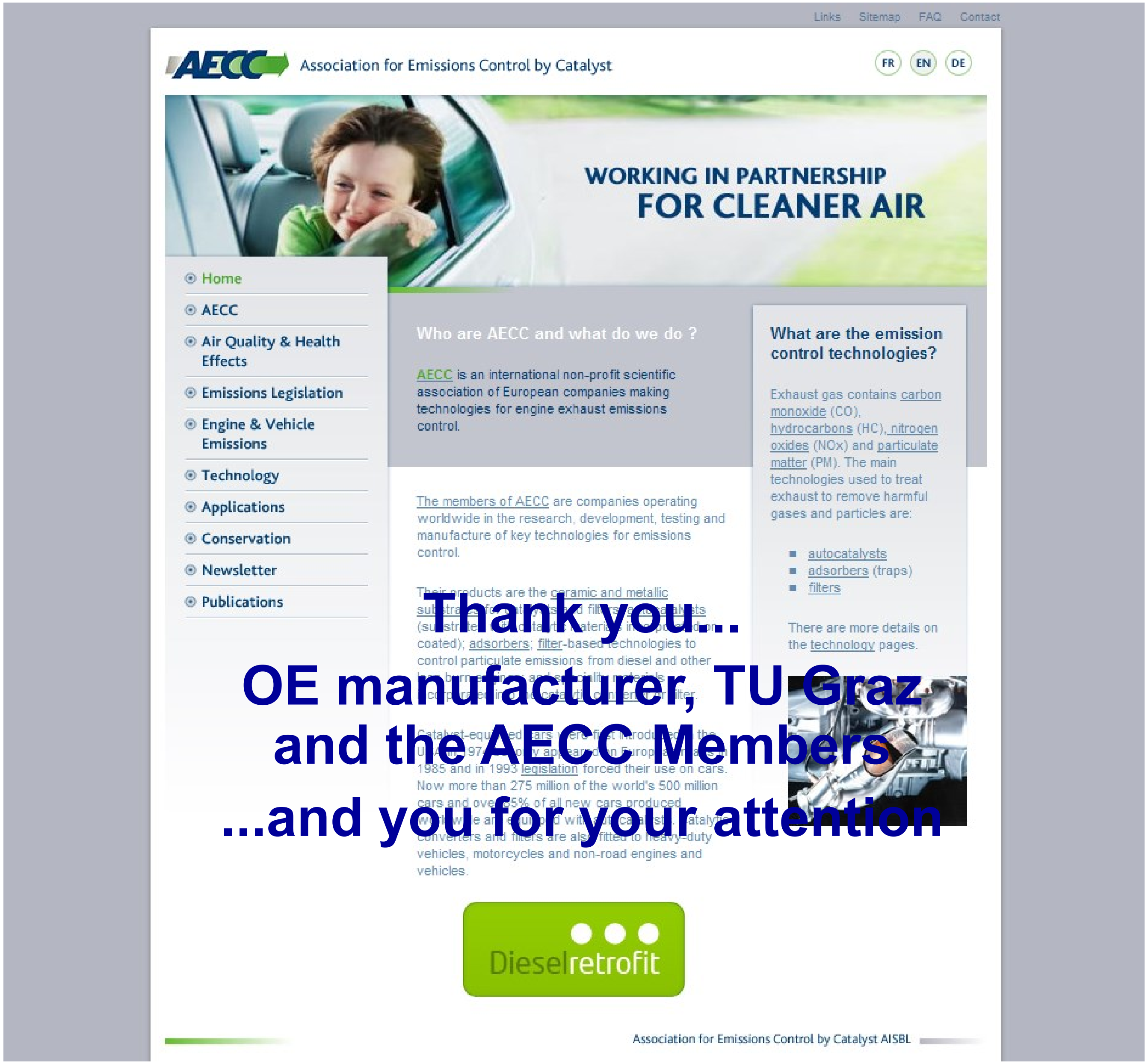
3	**2 stroke** fuel/oil mixture lubricated with catalyst
4	**2 stroke** fuel/oil mixture lubricated with catalyst

5	**2 stroke** fuel/oil mixture lubricated stratified scavening without catalyst
6	**2 stroke** fuel/oil mixture lubricated fuel injection system without catalyst

Conclusions

- 6 state-of-the-art engines of Small Hand-Held equipment available in EU have been evaluated.
- Adapted emissions measurement method, based on PMP automotive standards, provided repeatable results for PM and PN.
- PM and PN emissions depend on working principle and on lubrication method and oil quality. Separation of fuel and oil strongly helps reducing both PM and PN.
- PM and PN were high due to the rich operation of the engines. Results were equivalent or higher than for typical diesel engines without a DPF.
- Particles emitted at idle were smaller than at full load.
- For all engines and operating points, less than 20% of PM was elemental carbon.



Thank you...

OE manufacturer, TU Graz and the AECC Members

...and you for your attention