STRATEGIES FOR PARTICLE EMISSION CONTROL FROM GAS FUELLED HEAVY-DUTY ENGINES: POTENTIALITY OF FILTER TECHNOLOGY

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CONTENTS

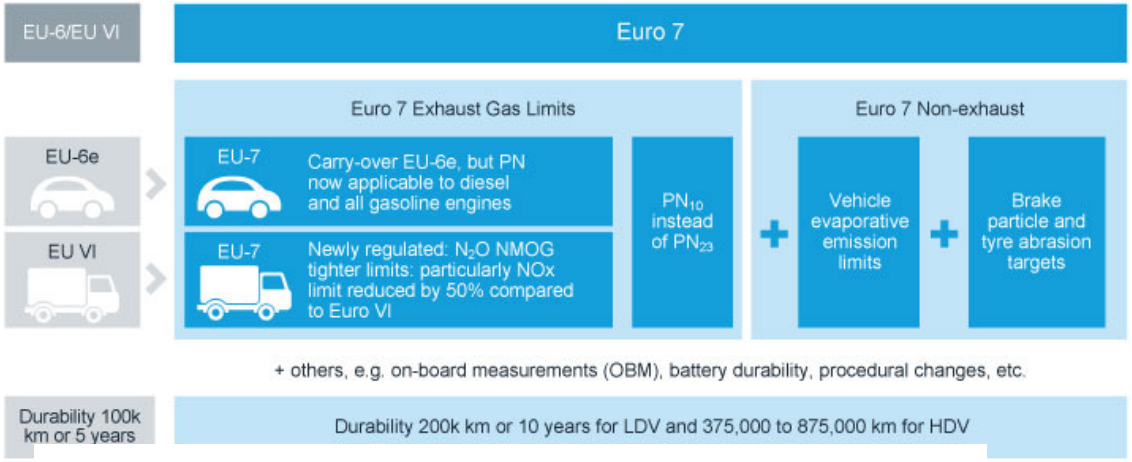
SCENARIO

ICE is expected to be the powertrain of choice for heavy-duty engine category for many years to come, since HD vehicles are more challenging to electrify than smaller engines category.

Gas fuelled engines represents a valid solution toward decarbonization target, mainly if low or zero-carbon fuels are considered (like biomethane or H_2).

As a result, next Euro 7 regulations (approved on April the 12th, 2024) will drive substantial changes and bring new technologies to the market.

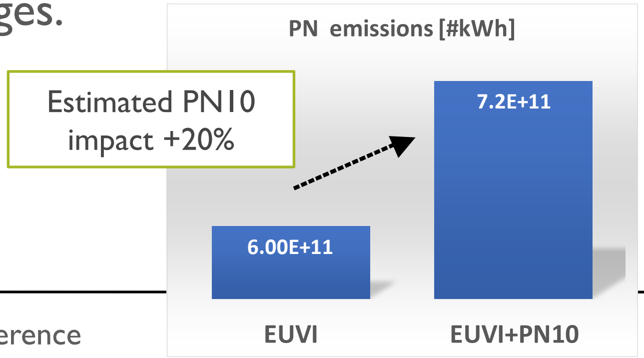
Meeting the severe PN limits will be one of the biggest challenges.



Current and future heavy-duty emissions regulations

Emission limits (mg/kWh unless noted)	Euro VI petrol	Euro VI diesel	
	Euro VI Transient testing	Euro VI Transient testing	Euro VI Steady-state testing
NOx	460	460	400
PM	10	10	10
PN_{23nm} (#/kWh)	6.0×10^{11}	6.0×10^{11}	8.0×10^{11}
CO	4000	4000	1500
THC	–	160	130
NMHC	160	–	–
NH_3 (ppm)	10	10	10
CH_4	500	–	–

Emission limits (mg/kWh unless noted)	Euro 7	
	WHSC & W[illegible] (C[illegible]	RDE
NOx	[illegible]	260
PM	[illegible]	–
PN_{10nm} (#k/Wh)	6×10^{11}	9×10^{11}
CO	1500	1950
NMOG	80	105
NH_3 (ppm)	60	85
CH_4	500	650
N_2O	200	260

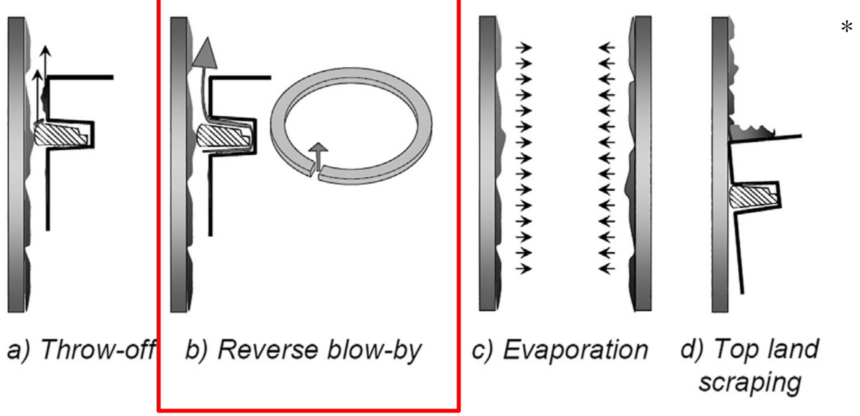


PN FROM GAS FUELLED HEAVY-DUTY ENGINES

Lubricant oil combustion is the main source of PN emission from gas engines

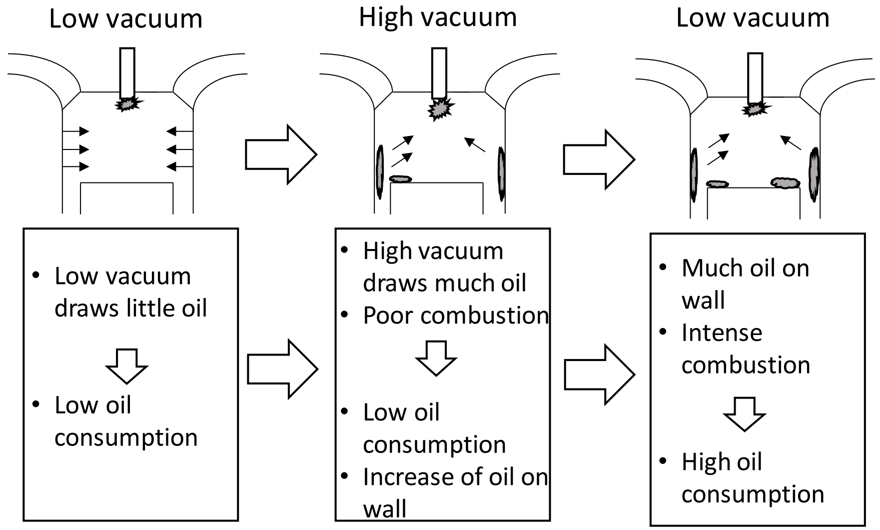
Four major sources of oil consumption in engines:

- through the piston rings
- crankcase ventilation
- valve stem seals
- turbocharger leakages



<u>Main mechanism: Reverse blow-by</u>

Gas-containing **oil is pushed into the combustion chamber** by the pressure difference during high vacuum conditions between the cc (lower p) and the crankcase (higher p).



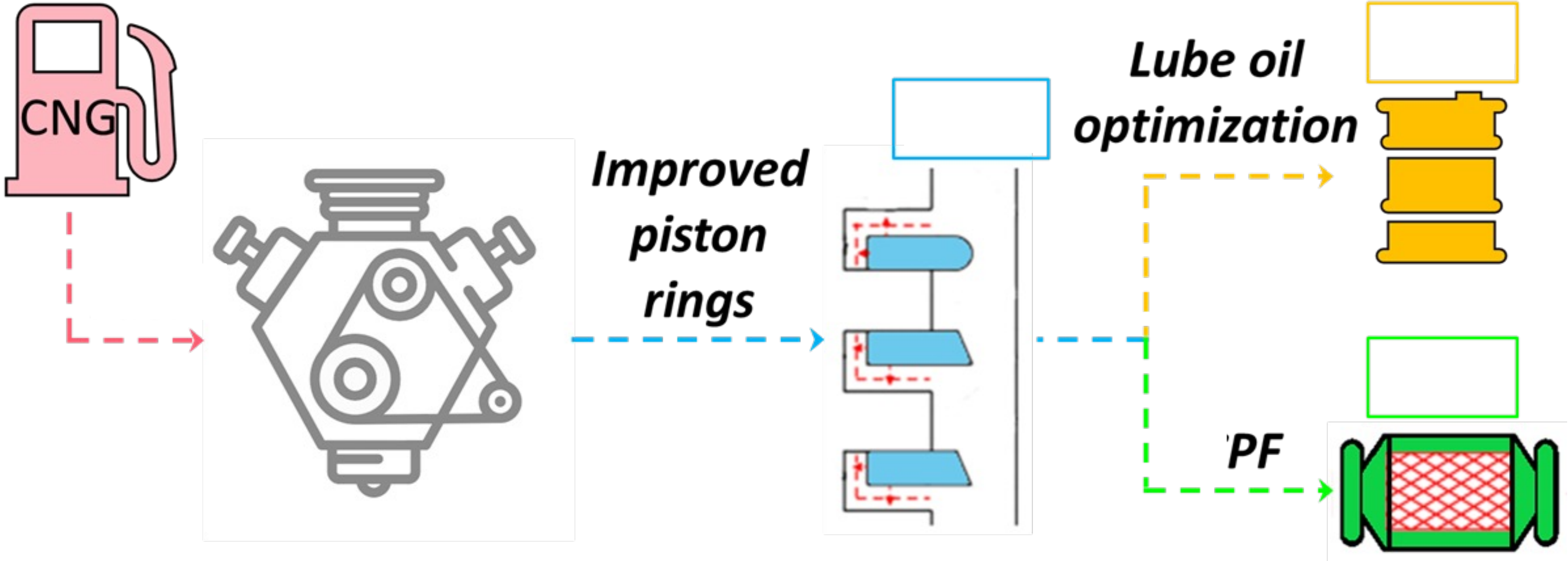
Reverse blow-by phenomenon scheme

* Froelund K. SAE Technical Paper 2000-01-2876. https://doi.org/10.4271/2000-01-2876.

APPROACHES FOR PARTICLE EMISSION CONTROL

Authors experience in particle emission control from NG engines:

- ❑ Improvement of engine ring-pack design
- ❑ Optimization of oil formulation
- ❑ Particulate Filters



- *Guido C, et al. Energy 231 (2021) 120748, https://doi.org/10.1016/j.energy.2021.120748*
- *Napolitano, P. et al. Atmosphere (2022), 13, 1919. https://doi.org/10.3390/atmos13111919*
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- *Napolitano P. et al. Journal of Environmental Management 331 (2023) 117204*

EXPERIMENTAL SETUP AND TESTING PROCEDURE

TAILPIPE MEASUREMENTS

Engine specifications

Engine type	6 cylinders in line
Certification	Euro VI
Displacement	$5883\ cm^3$
Valves per cylinder	2
Rated power and torque	$150\ kW\ @\ 2700\ rpm$ $750\ Nm\ @\ 1500\ rpm$
Compression ratio	$10:1$

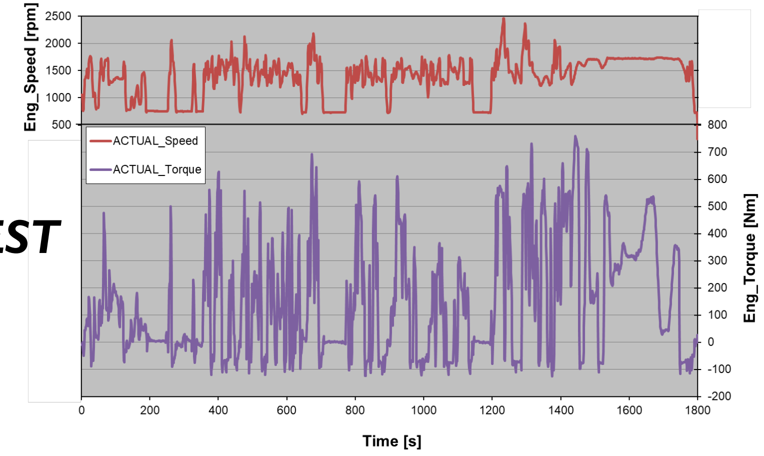
DMS500
PSDF/PN

Micro Soot Sensor:
Soot concentration

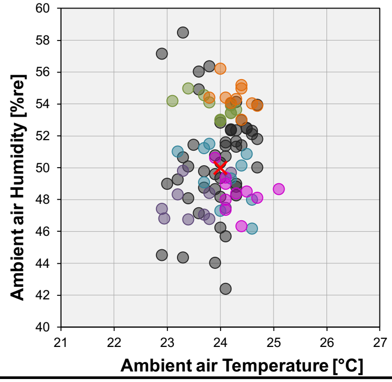
APC:
PN10

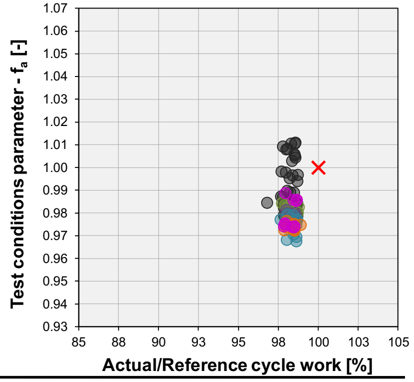
Definition and validation of a robust methodology

WHTC TEST CYCLE



- Cold and hot start WHTC conditions
- Post-processing examination, comparing the target and the recorded values of engine speed, load and power (regulation procedure).
- Fixed limits on intake air T, humidity, fuel T and p.

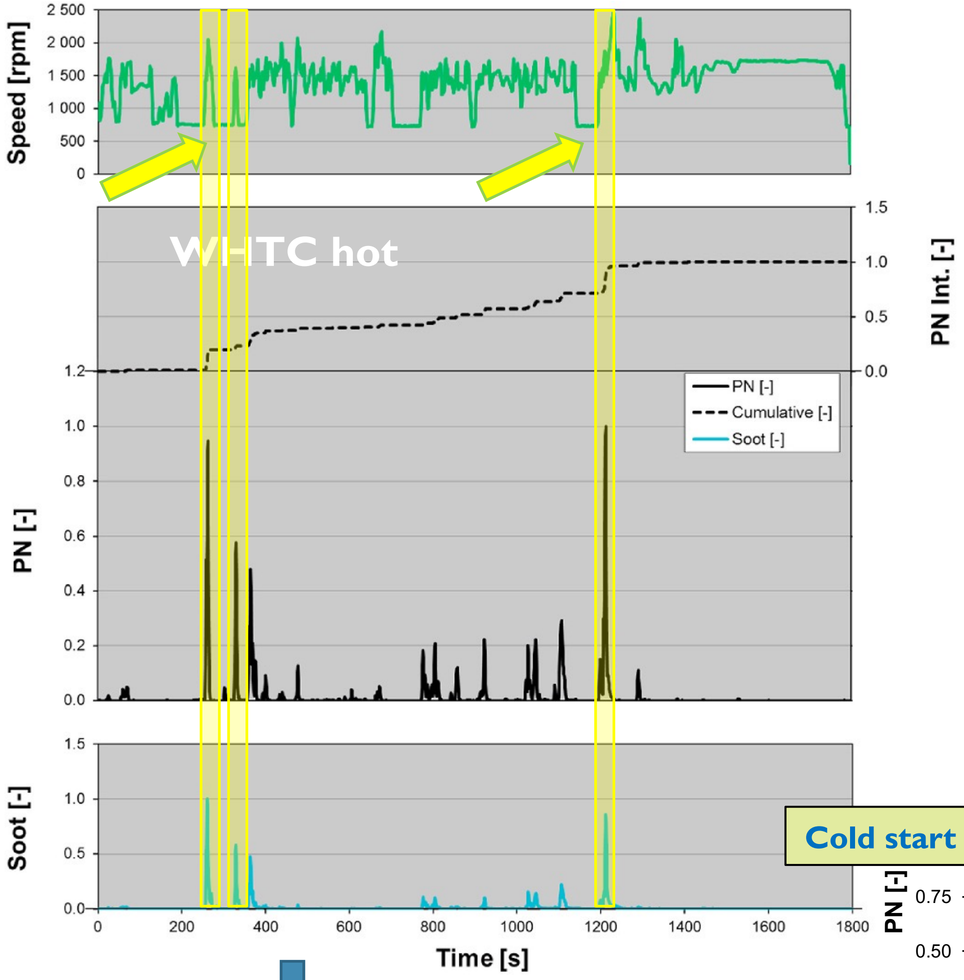




PN EMISSION EVOLUTION - INSIGHTS

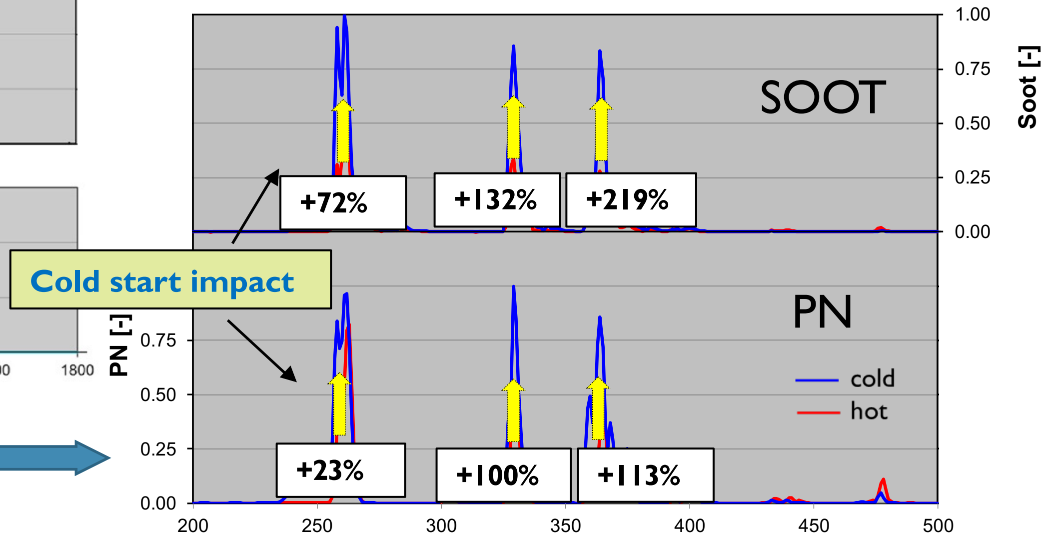
EFFECT OF CYCLE EVOLUTION

- Emissions spikes in correspondence of the transition from engine idle to acceleration phases.
- Very low emissions in other driving conditions → emissions spikes are main contribution to the total soot and PN.
- Source → lube oil leakage, favored by long idle phases.

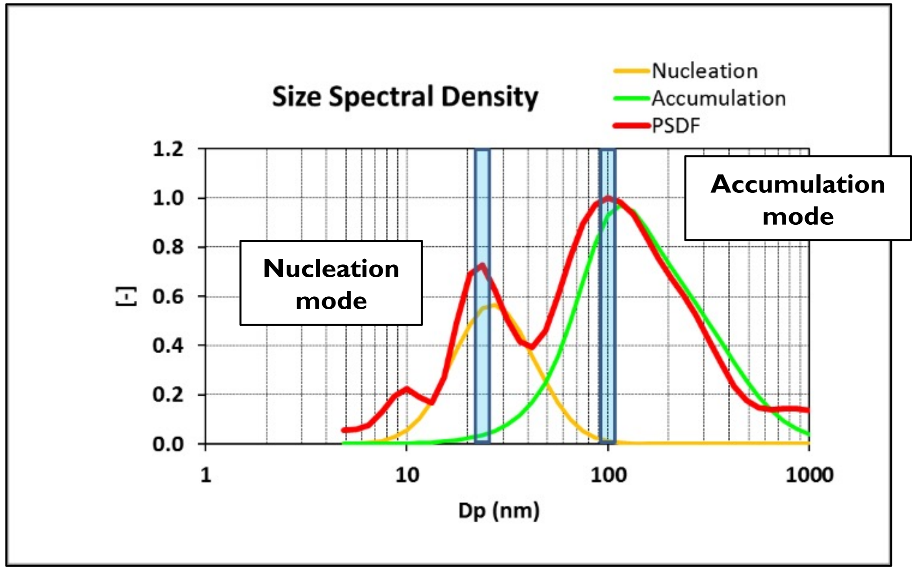


EFFECT OF STARTING CONDITION

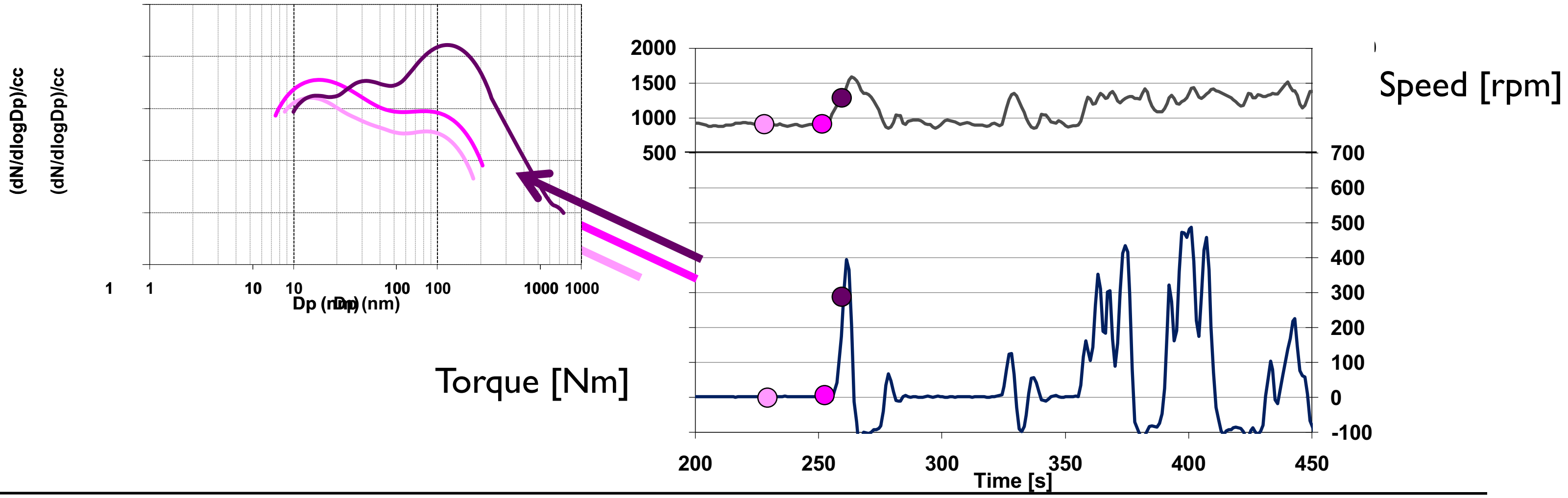
- In the first 500s both PN and soot emissions are higher in Cold conditions
- Two possible reasons: the simultaneous increase of gas-phase pollutants (lower ATS efficiency in the initial low operation temperatures); higher contribution of hydrocarbons derived from the oil leakage and condensed along the exhaust line.



PN EMISSION EVOLUTION - INSIGHTS



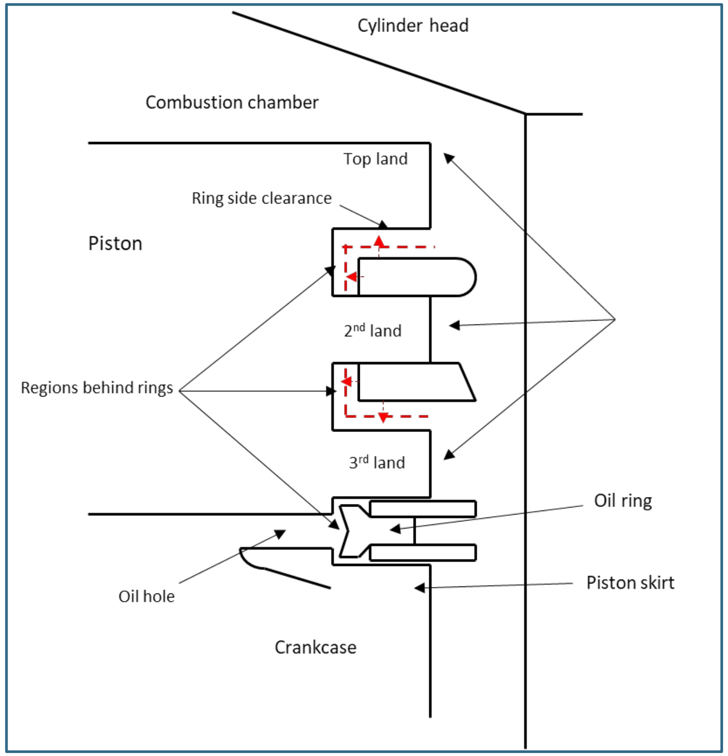
- Particle size distribution curve is "bimodal" with two main peaks at about 25 nm and 100 nm.
- The presence of particles with different sizes is due to the well known nucleation and accumulation phenomena which dominate the formation of respectively small and large particles.
- Same distribution curve shape for gasoline and natural gas engines; depending on the investigated application, the peaks may slightly vary.



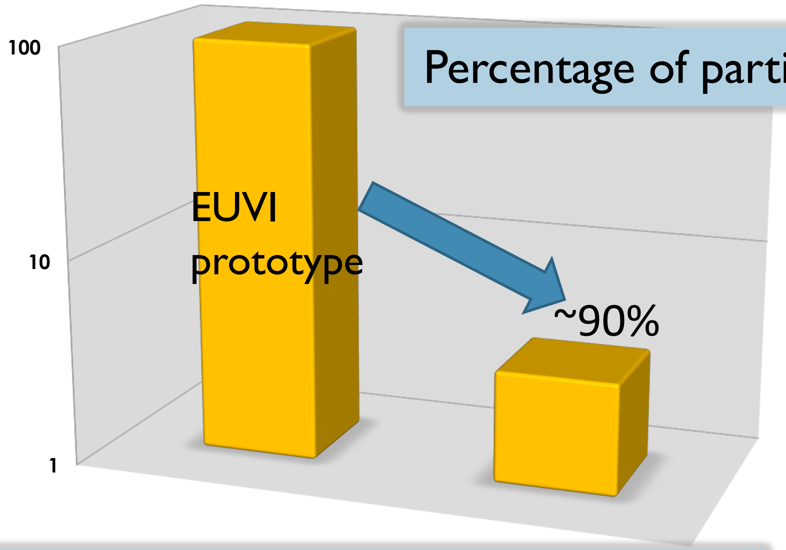
EFFECT OF RING PACK DESIGN OPTIMIZATION

The design of the whole ring pack greatly affects in-cylinder oil consumption and also the reverse blow-by phenomena.

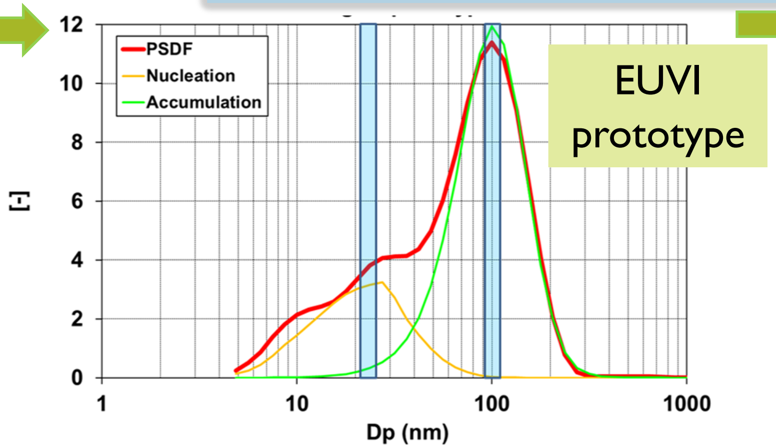
The compression ring design was improved working on the reduction of the side clearance and volume behind the rings:

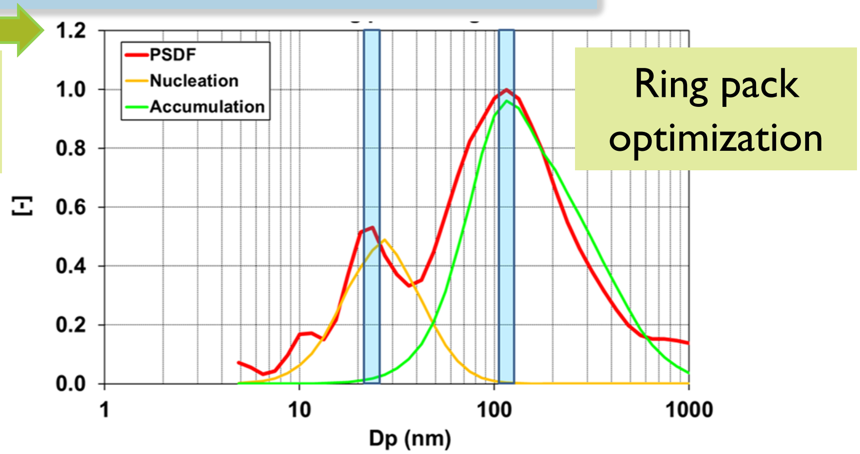


Percentage of particle reduction



Drop of particle concentration over the whole spectrum





EFFECT OF LUBE OIL FORMULATION

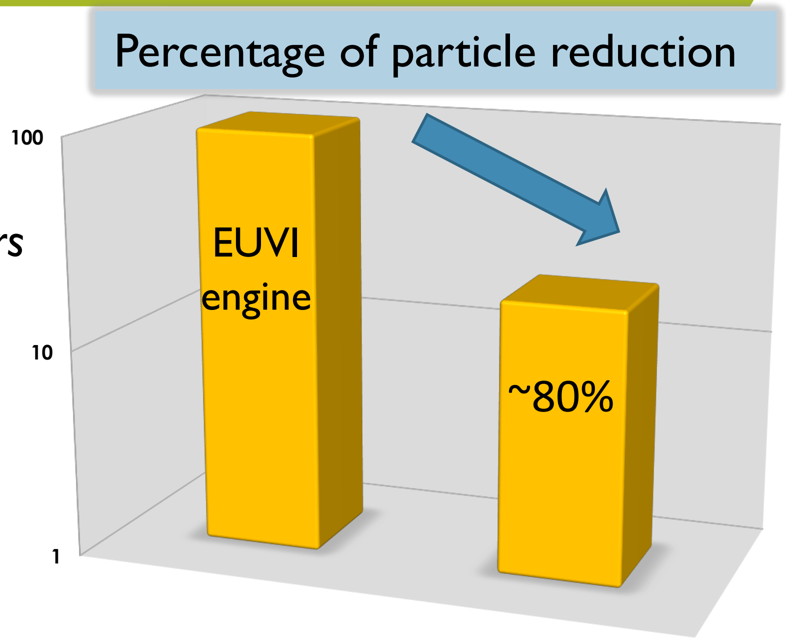
	REF	OIL 1	OIL 2	OIL 3	OIL 4	OIL 5
Oil grade	10W-40	10W-40	0W-30	5W-30	5W-30	0W-40
% package/REF	1	0.5	1	1	1	1
KV100 (cSt)	13.49	13.8	9.601	9.747	9.499	13.53
Base oil viscosity (mm^2/s)	6	8	4	4	4.5	0.5
Base oil group	III	III	IV	IV	V(75%) + IV(25%)	III

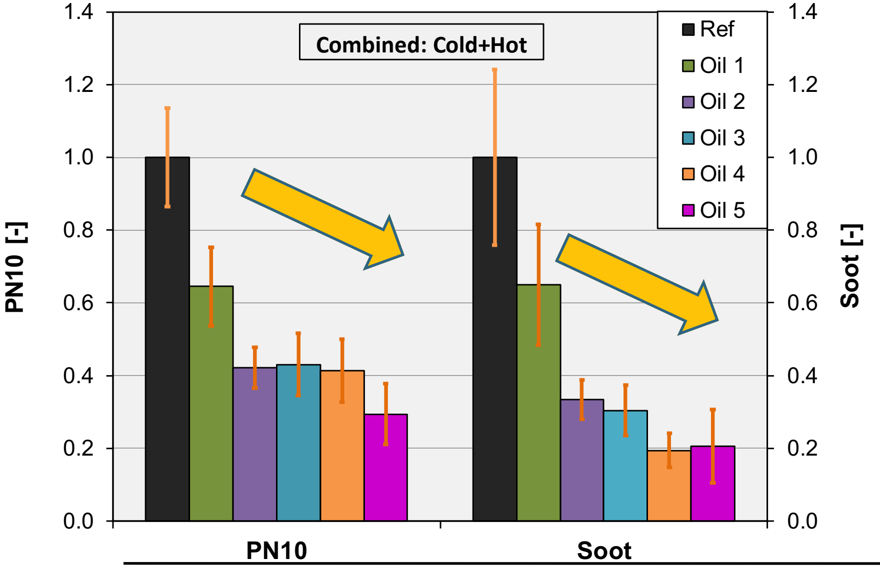
Reference oil: commercial SAE 10W-40

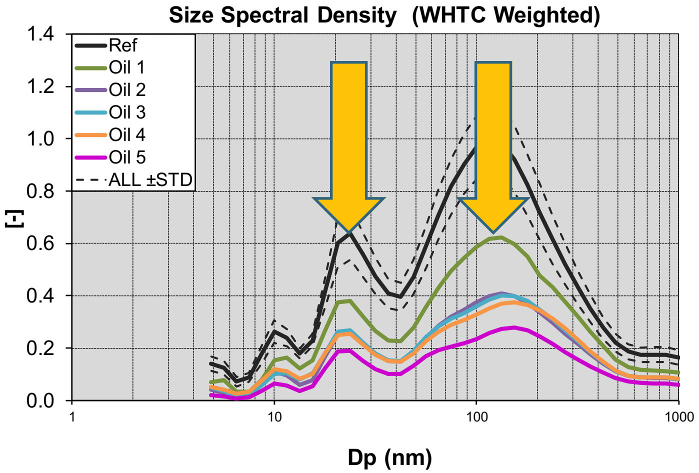
Ash content

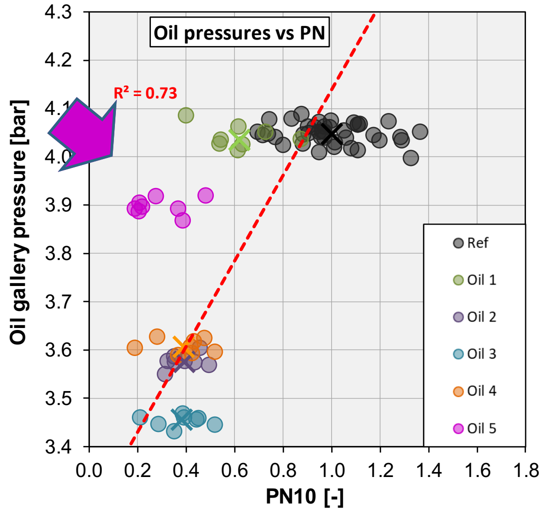
Base oil group

Base oil viscosity + polymers









Oil 5 is «out of tendency», showing the lowest PN and a relatively high pressure.

POTENTIALITY OF FILTER TECHNOLOGY

- Same substrate material and size
- Similar mean Pore size (MPS) for all samples
- Two different wall thickness and porosity
- Different cell structure → Symmetric vs. Asymmetric structure
- Impact of catalyst coating with same filter structure and porosity
- Impact of a hierarchical microstructure (modified surface porosity)

	TWC	CPF 1	CPF 2	CPF 3	CPF4
Wall Thickness (mil)	4	8	8	12	8
Cell Density (cpsi)	400	200	200	200	200
Cell Geometry		Symmetric	Symmetric	Asymmetric	Symmetric
Porosity (%)	-	≧ 55%	≧ 55%	40÷50%	45÷55%
MPS (μm)	-	10÷15μm	10÷15μm	10÷15μm	10÷16μm
Catalyst Coating	✓	-	✓	-	-
Hierarchical microstructure					✓

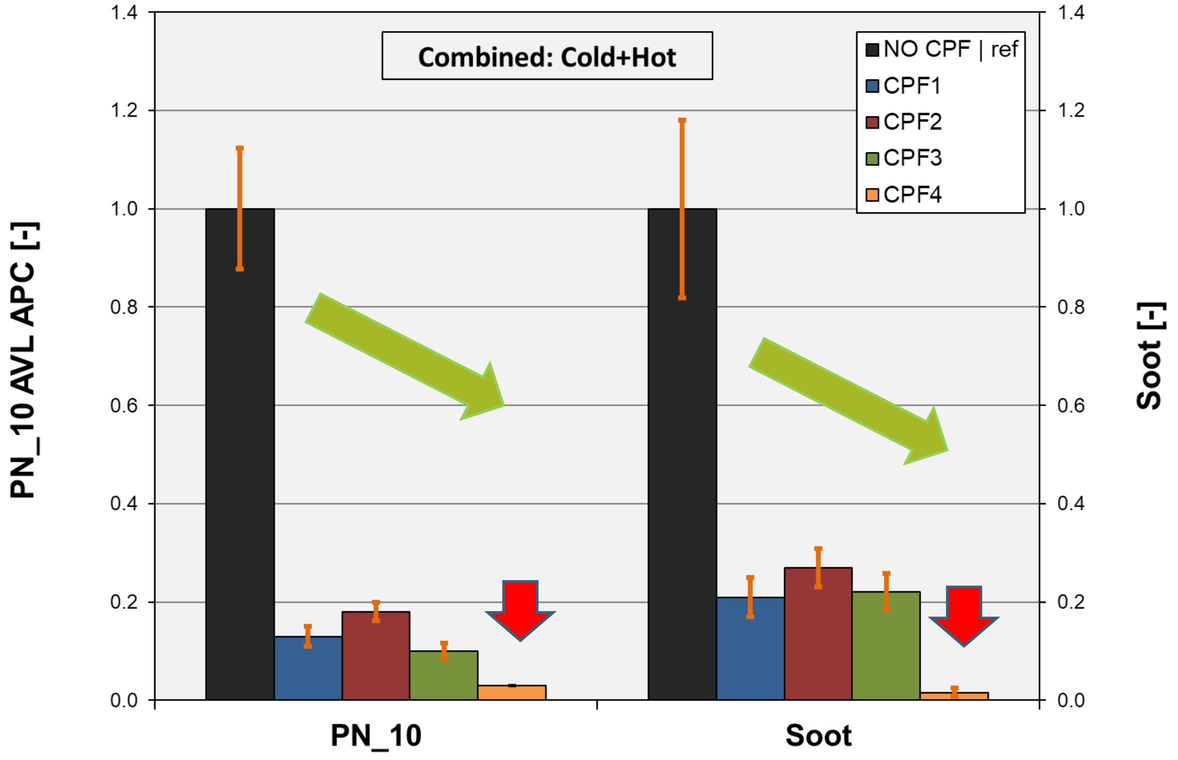
1mil = 0.0254 mm

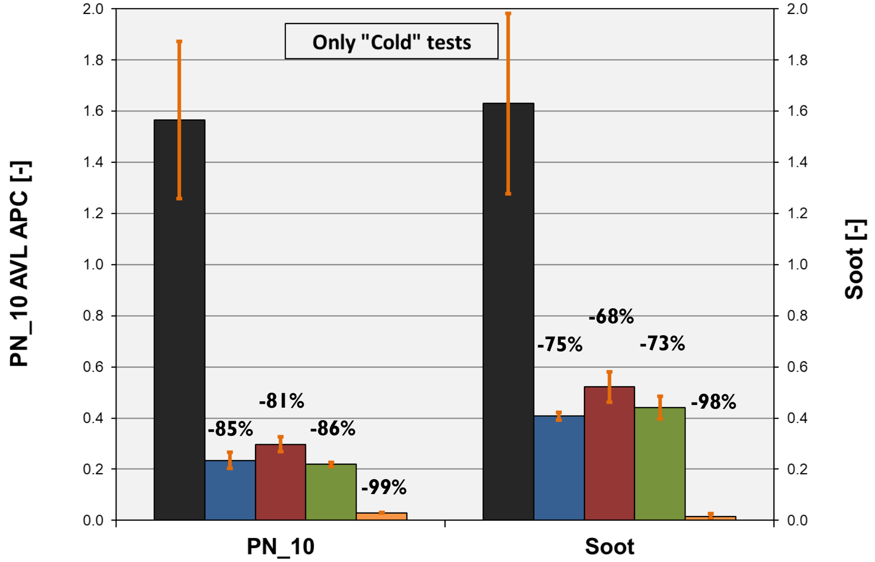
Cpsi = cells per square inch

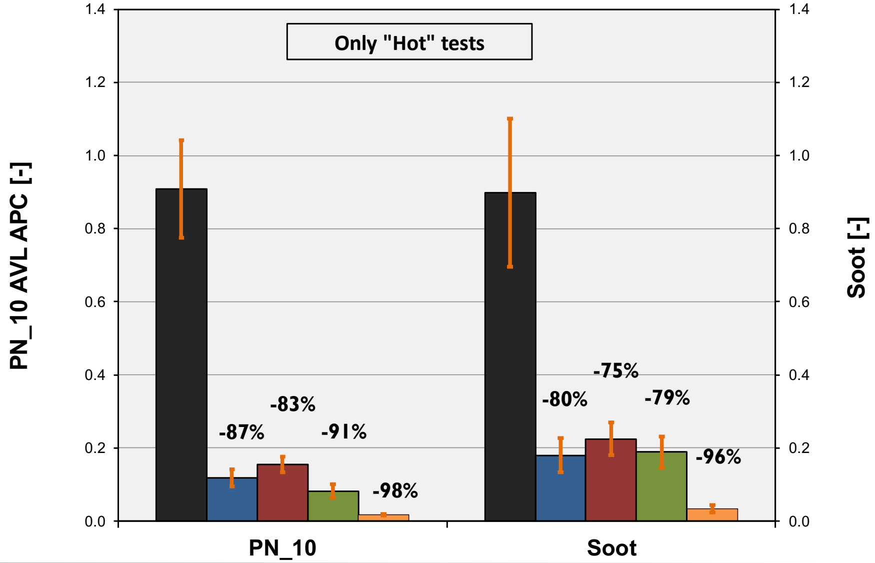
MPS = mean pore size

POTENTIALITY OF FILTER TECHNOLOGY

PN and soot filtration efficiency – Impact of start condition





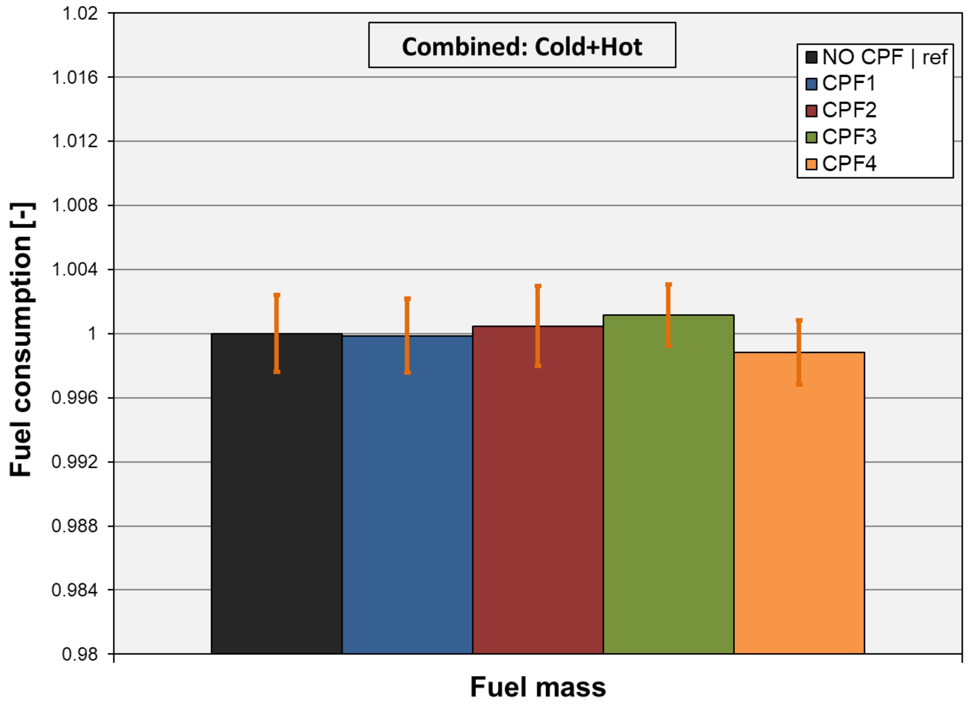


- PN and soot reduction over combined, hot and cold WHTC with different CPFs.
- PN reduction is similar regardless test conditions; despite higher raw PN in cold WHTC, overall PN performance are comparable.
- Slightly larger difference can be observed on soot reduction even if overall performances are still within tolerance band.

POTENTIALITY OF FILTER TECHNOLOGY

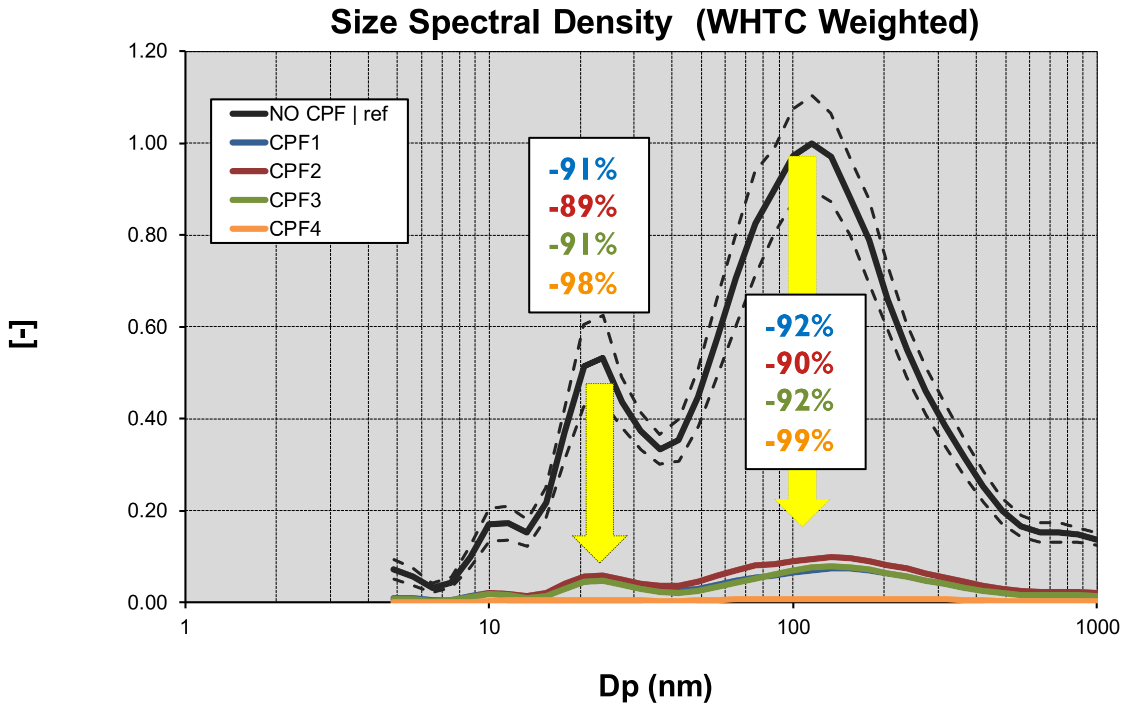
Filter back pressure impact on Fuel Consumption

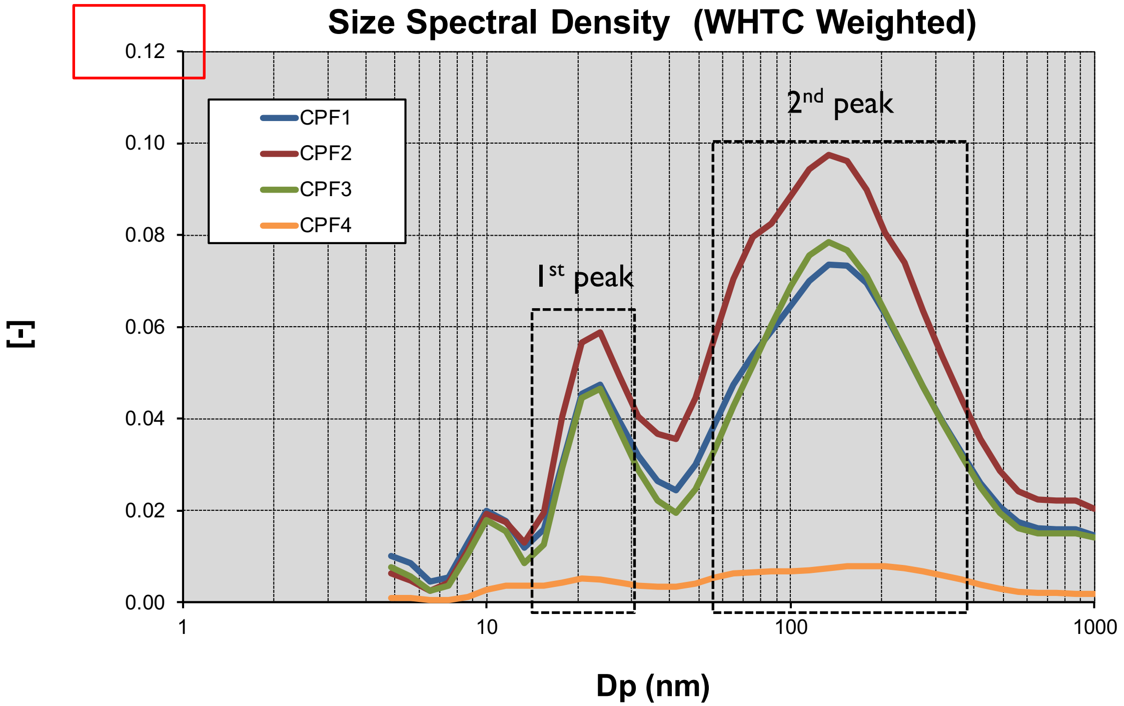
- Despite different filter configurations, no significant variations in terms of Fuel consumption over WHTC.
- Fuel penalty variation in the range of +/-0,25%.
- To be further investigated ash accumulation impact on back pressure behaviour → Asymmetric structure could provide benefit in long term accumulation.



POTENTIALITY OF FILTER TECHNOLOGY

PN efficiency as function of particle size

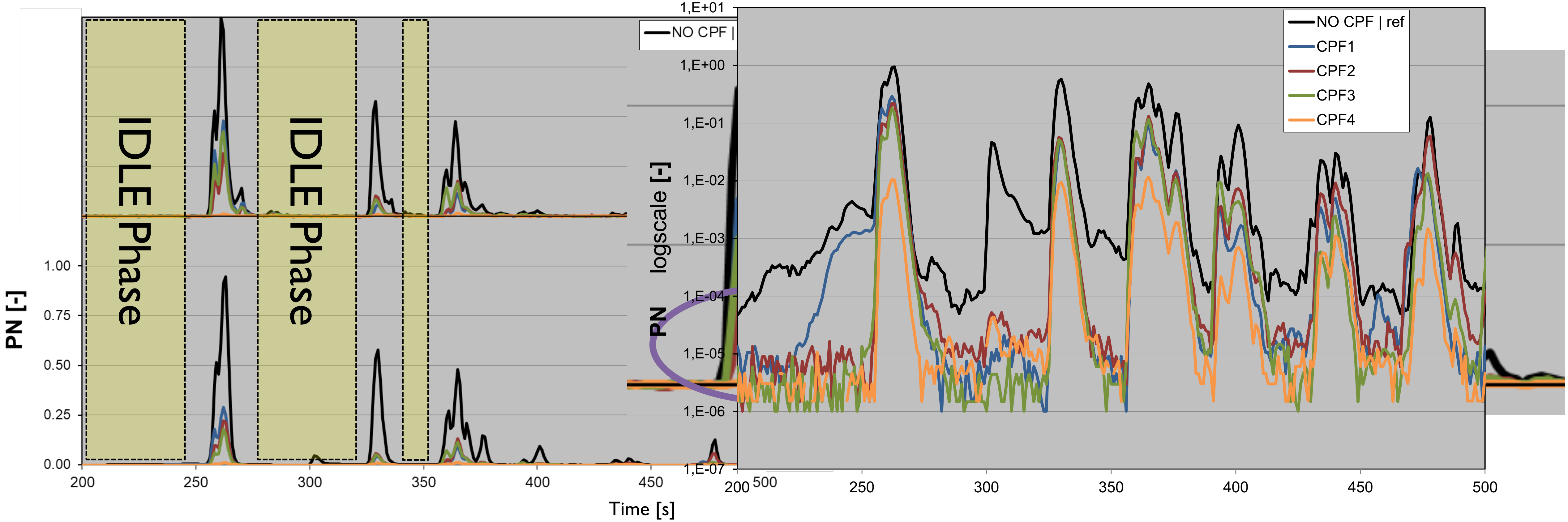




- Particle size distribution traces show bimodal shape.
- All filters show similar filtration efficiency on both particle size ranges (~25nm and ~130nm); despite the smaller size current available filters are capable to effectively trap the particles.
- Uncoated CPF1 and CPF3 have almost identical performances on both peaks.
- Coated CPF2 shows slightly lower performance probably due to MPS/porosity modification impacting trapping mechanism.
- CPF4 confirmed as the most efficient in all the size interval.

POTENTIALITY OF FILTER TECHNOLOGY

Dynamic PN and soot filtration behavior



- PN emissions is reduced in all the phases of WHTC: both during peak and when the emissions are low, i.e., when engine operation in terms of speed and load is quasi-steady state. This evidence further supports the hypothesis of a continuous filtration mechanism and particle oxidation in which no discontinuous regeneration event of the filter takes place.

POTENTIALITY OF FILTER TECHNOLOGY

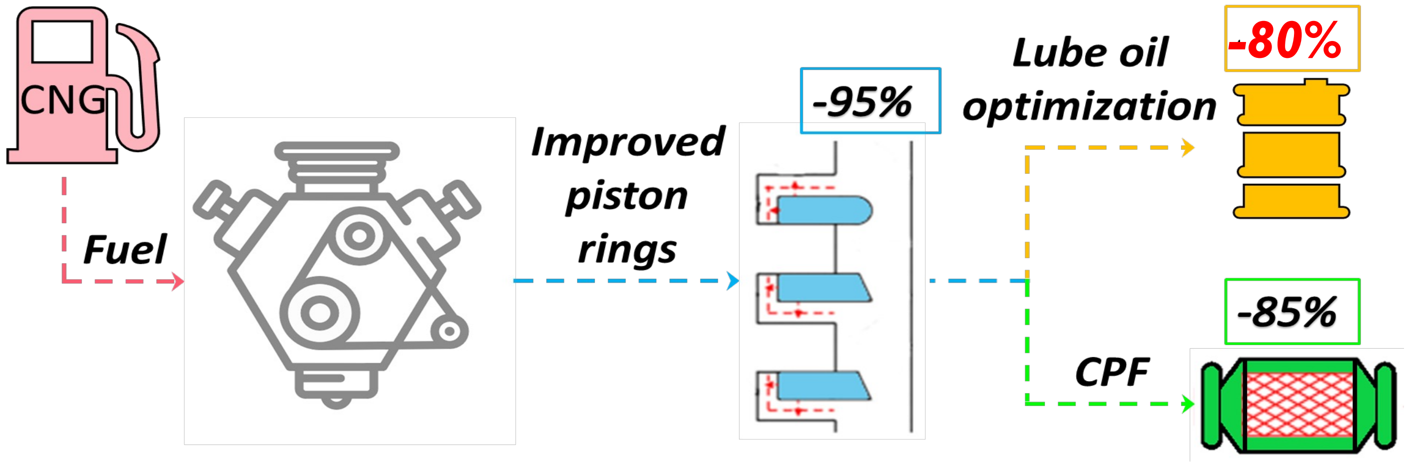
PN and soot filtration efficiency – Impact of CPF characteristics

- Overall best filtration efficiency performance measured on CPF4 linked to the layer presence.
- Good performance for CPF3 probably due to high wall thickness which maximise deep bed filtration capability.
- CPF1 and CPF2 have same substrate characteristics, but the presence of catalytic coating on CPF2 seems to negatively impacting PN filtration efficiency compared to CPF1.
- Possible hypotheses to explain CPF2 result are the following:
  - ✓ Non-uniform distribution catalyst washcoat within the pores would lead to local high gas flow velocity resulting in higher PN release.
  - ✓ Catalytic coating could produce faster particles oxidation modifying particulate trapping mechanism since soot can promote the competing process of condensation and adsorption instead of nucleation.

	TWC	CPF 1	CPF 2	CPF 3	CPF4
Wall Thickness (mil)	4	8	8	12	8
Cell Density (cpsi)	400	200	200	200	200
Cell Geometry		Symmetric	Symmetric	Asymmetric	Symmetric
Porosity (%)	-	≧ 55%	≧ 55%	40÷50%	45÷55%
MPS (µm)	-	10÷15µm	10÷15µm	10÷15µm	10÷16µm
Catalyst Coating	✓	-	✓	-	-
Hierarchical microstructure					✓
PN reduction		87%	82%	90%	98%

MAIN REMARKS

- ✓ Particle emission from gas fuelled engines represents an aspect to be considered in view of next regulation compliance.
- ✓ All the investigated strategies revealed effective in particle emission control:



Guidelines for PN control in case of decarbonized fuels, like hydrogen.

- ✓ The use of a diesel particulate filters on Euro VI Heavy-Duty NG engine generate considerable benefits in terms of PN emission revealing very interesting opportunities in view of the future emissions regulations.

- ✓ Although experimental results are very promising, further improvements on filter materials and coating technology are probably required to increase safety margin and take into account wider testing conditions (e.g. real driving cycles in extended environmental conditions).

Thank for your attention

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