Particle number characterization from a spark ignition direct injection engine with a gasoline particulate filter

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It is now well documented that the particulate number is a more relevant information than the total particulate mass regarding the adverse effect on human health[a]. Thus, the future European regulation Euro 6c will limit the maximum particle number emitted by vehicle powered with gasoline direct injection engines at 6.10^{+11} part/km in 2017, with a preliminary step Euro 6b at $6.10+^{12}$ part/km starting from 2014[b]. The more stringent could be reached whether by improvement on fuel injection system and calibration or by implementing an emission control system like a particulate filter. The latter was considered in this publication.

In this study, particulate number was measured at the exhaust of a commercial euro 5, 4 cylinder, 1.6 L, stoichiometric gasoline direct injection (GDI) engine. This engine had a prototype exhaust line, comprising a state-of-the-art three way catalyst and a non-catalyzed gasoline particulate filter (GPF). Measurements were done at different locations of the exhaust line in steady state conditions with three different measurement devices: a SMPS with a nano-DMA and a CPC 3775 from TSI, a SMPS + E from Grimm and a DMS500 from Cambustion. Then, the covered particle diameter range was 2 nm - 1000 nm. Sampling and dilution of the 2 SMPSs were performed behind a FPS4000 diluter from Dekati (Figure 1) while DMS500 used its own dilution system.

The 3-way catalyst is able to abate particulate from 66% to 99% depending on the analyzers, especially on the nucleation mode. On the other hand, the efficiency of the GPF is superior to 80% in the range 8 – 1000 nm, whatever the operating conditions and the particle analyzer used. If the measurement devices show a good consistency in the range 23 nm - 1000 nm, this is not always the case under this limit: in the range 8 - 23 nm, the differences could be attributed to the sampling and the dilution stage, with possible nucleation of volatile particles. In the range 2 – 8 nm, the PN concentration is even more scattered, because of the cumulative effect of the sampling and dilution stage and the poorer sensibility of the detectors at the very low particulate diameters.

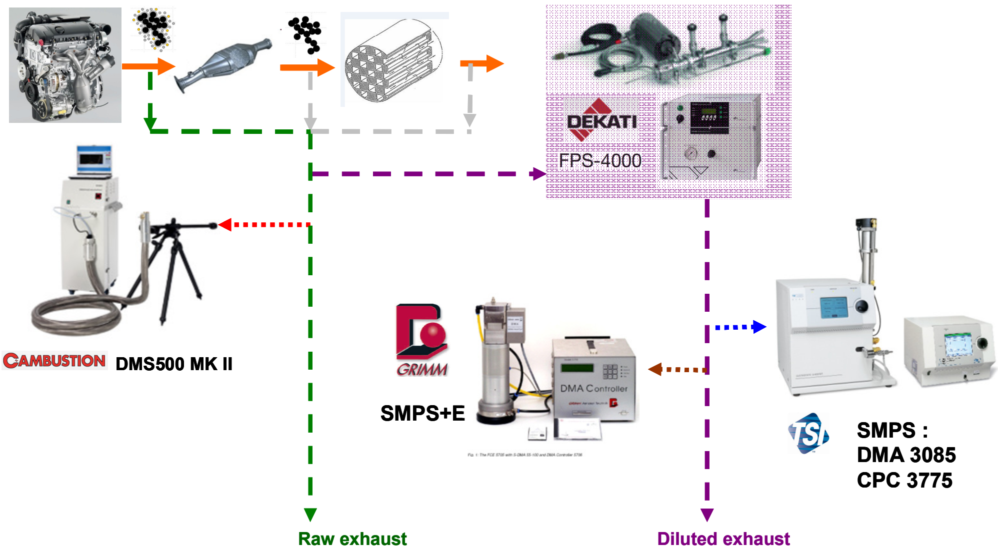

Figure 1 : Experimental setup for the GDI engine particles characterisation with DMS500, SMPS TSI and SMPS+E Grimm

In addition to the steady-state tests, transient tests were performed on a hot NEDC cycle at the engine test bench in order to evaluate the efficiency of the 3-way catalyst and the GPF regarding the particulate number abatement. Only the DMS 500 was used for this evaluation (Figure 2). Particulate number cut-off was about 94% with the 3 way catalyst, especially in the size range [5 – 20 nm]. However, the estimated particulate level remained above the future Euro 6c limit. The GPF offered a complementary reduction of 96%, mainly in the range [20 nm – 200 nm], that allows to reach estimated particulate number compliant with the future Euro 6c regulation. This result was obtained while keeping the backpressure of the GPF as low as 20 mbar.

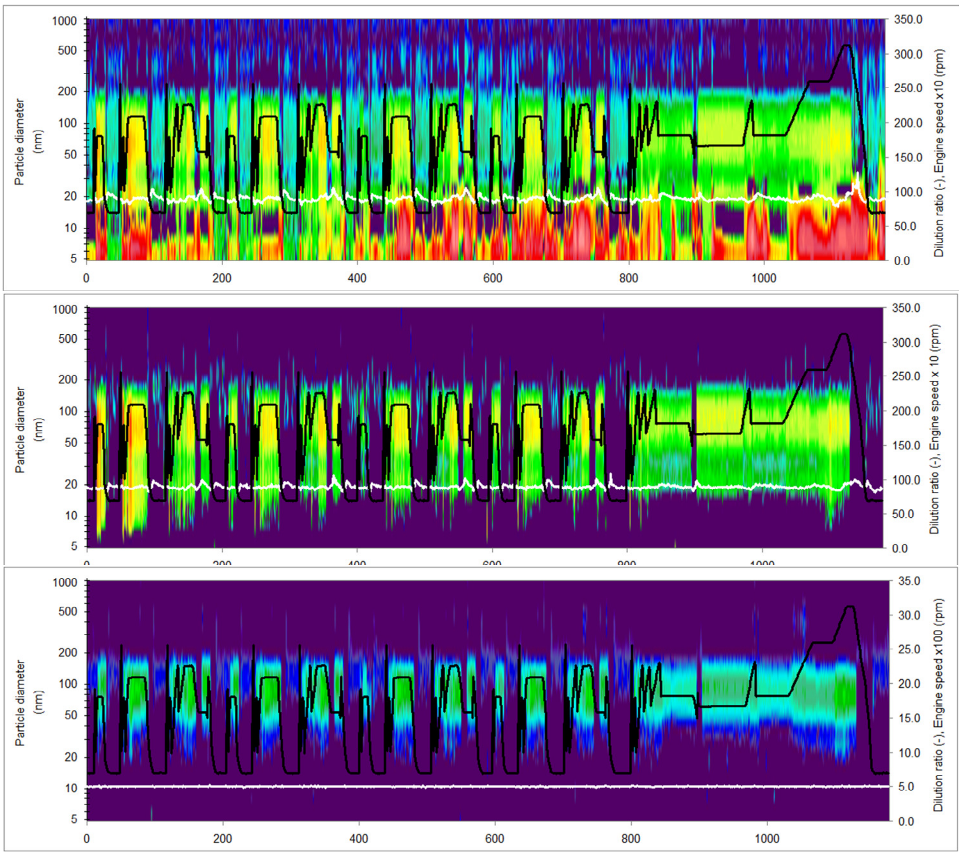

Figure 2 : DMS500 spectra for 3WC upstream (1), 3WC downstream (2) and GPF downstream (3) positions for a convertional vehicle

Finally, the impact of vehicle hybridization on particle emissions was considered. A hardware-in-the-loop approach was chosen: a virtual parallel hybrid vehicle was simulated, using the real GDI engine at the test bench. The tests were done on a hot NEDC cycle and the particle number was measured with the DMS500 device (Figure 3). Even if the thermal engine was run less than 30% of the cycle time, the average load was significantly higher. Finally, the emitted particle number is 2.5 times higher in the hybrid case than in the conventional case, but this result must be nuanced because no specific work was done on the engine to adapt it to the hybrid running mode. Whatever, mounting a GPF on this hybrid vehicle also allows to make the estimated particulate number compliant with the future Euro 6c regulation.

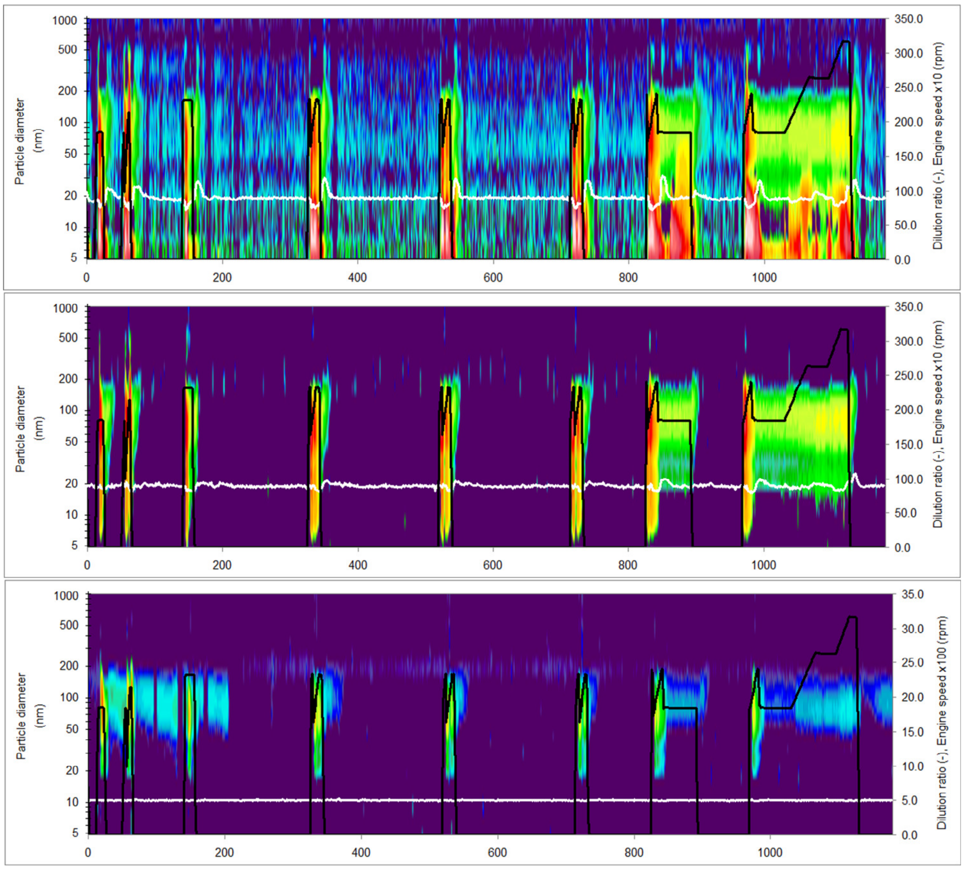

Figure 3: DMS500 spectra for 3WC upstream (1), 3WC downstream (2) and GPF downstream (3) positions for a convertional vehicle

Acknowledgements

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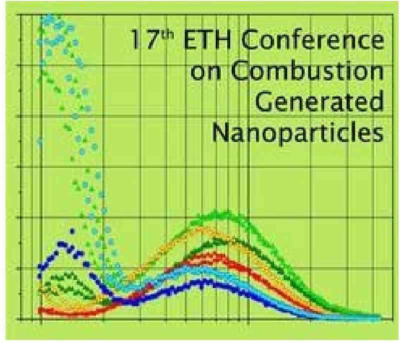
References

[a] : WHO (2005). Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide Global Update 2005.World Health Organization Copenhagen, Denmark.

[b]: UNECE, regulation n°89 for light-duty vehicle

Particles number characterization from a SIDI engine with a gasoline particulate filter



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Particles number characterization from a SIDI engine with a gasoline particulate filter

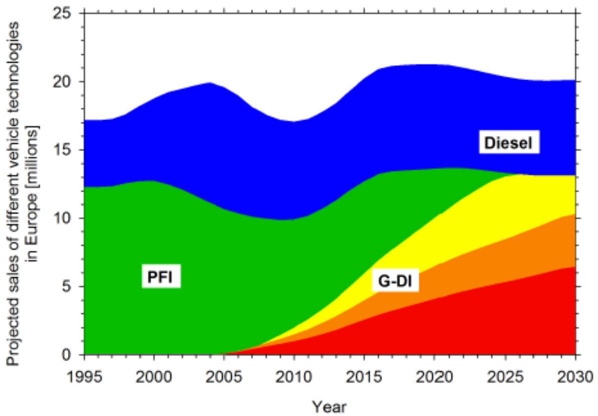
Agenda

- Context and future regulations
- Particles characterization on steady state conditions
- Particles characterization on transient conditions and impact of vehicle hybridization on particulate emissions
- Conclusions

Context and future regulations

- Increasing market share of GDI vehicles in Europe in the next decade.

source : JRC



- Future regulations :

Euro 6b
PN limit (GDI) = 6.10^{+12} part/km

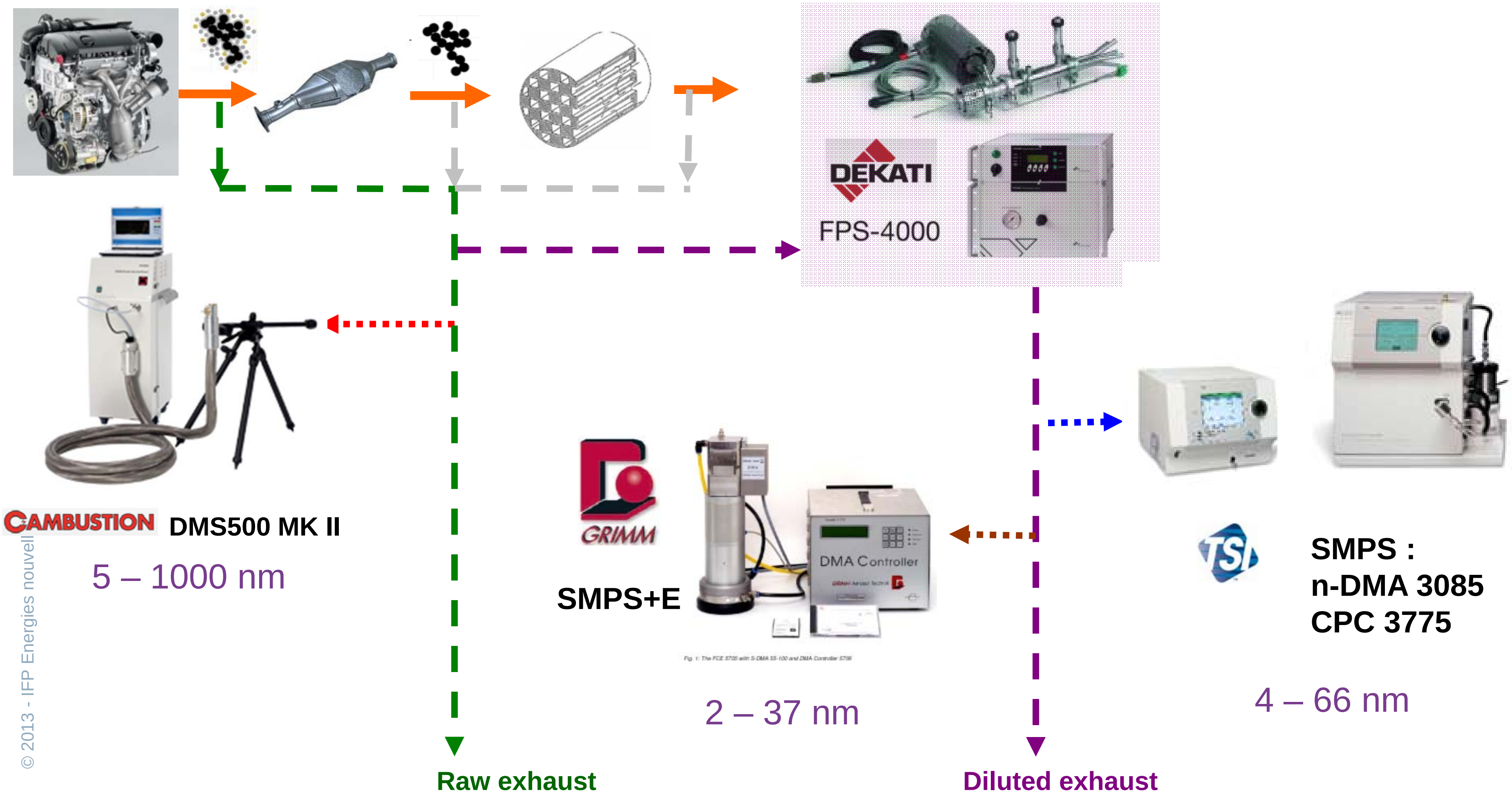
Euro 6c
PN limit (GDI) = 6.10^{+11} #/km

Euro 7?
PN limit to be defined

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

- 66th GRPE - 3-7 June 2013
  - Work on emission of particles below 23 nm from light duty vehicles
    → need to revise the d50 cut-off of the PMP ?

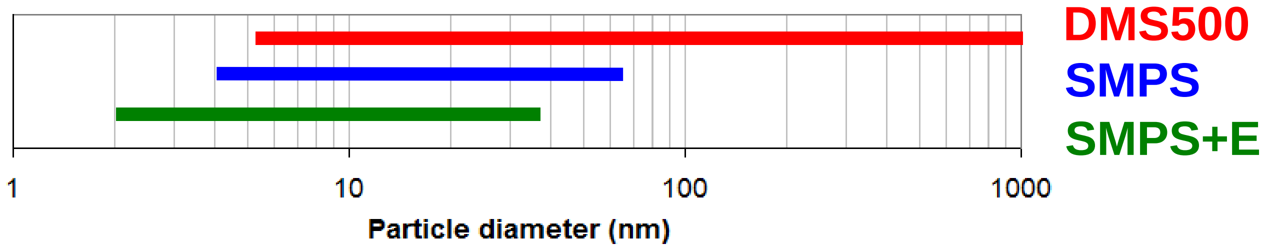
Particles characterization on steady state conditions: experimental setup



Particles characterization on steady state conditions:

Objectives of the tests

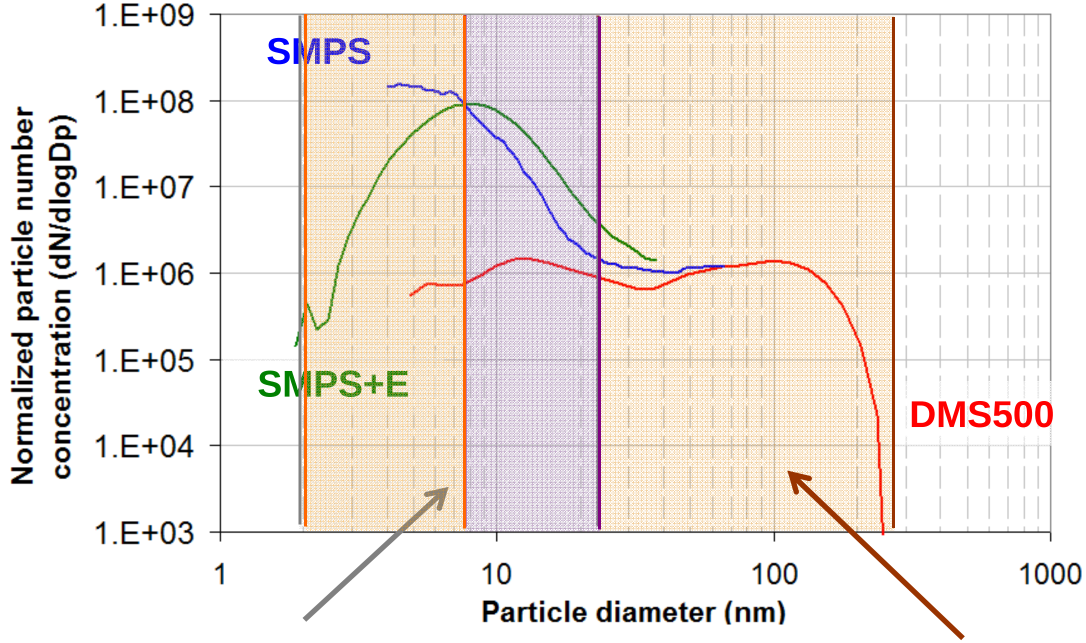
- Determine the granulometric spectrum on the range 2 – 1000 nm for the 3 sample locations



- Compare the results between the analyzers on the overlapped particle diameters

- Evaluate the PN abatement done by the 3WC and the GPF

Particles characterization on steady state conditions: Engine out @ 1500 rpm – 5 bar



THC ~ 2000 ppmC

Nucleation mode : 2 - 23 nm

Accumulation mode : 23 – 250 nm

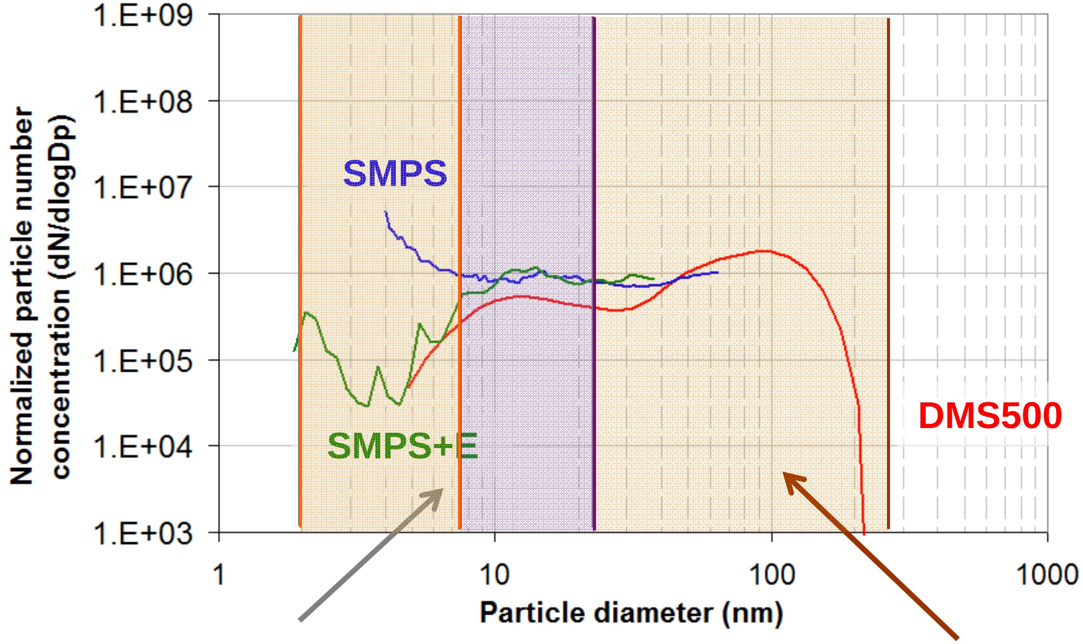
Nucleation mode 8 - 23 nm

- Same dilution for SMPS and SMPS+E
- DMS500 sampling and measurement @ 250 mbar

Nucleation mode 2 - 8 nm

- Idem + poorer sensibility of the detectors for small particles

Particles characterization on steady state conditions: 3WC out @ 1500 rpm – 5 bar



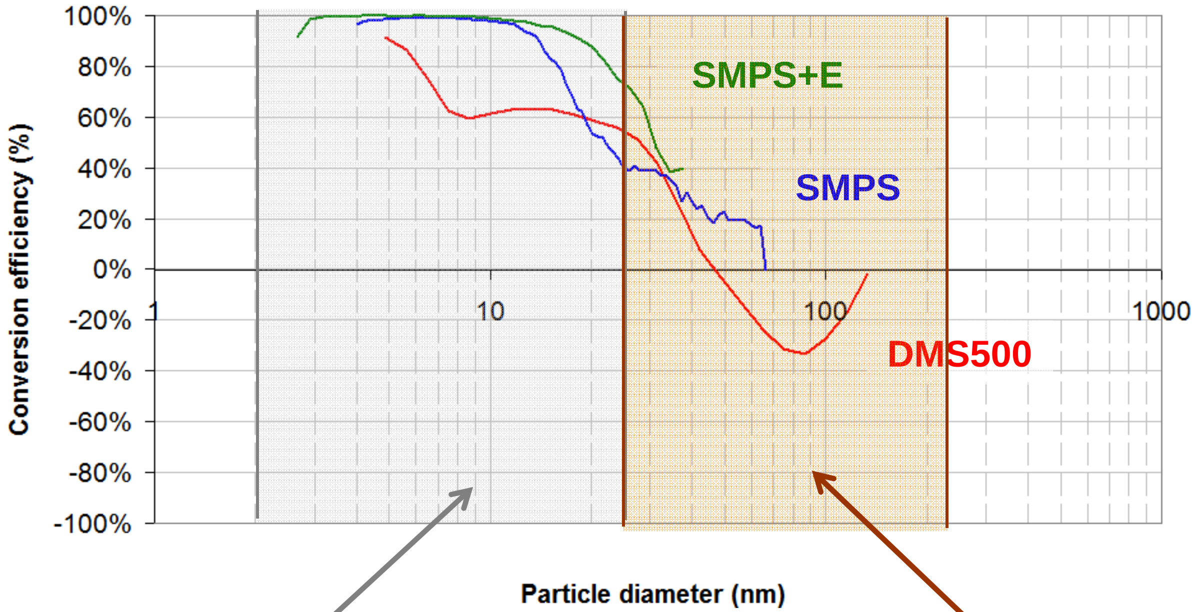
THC ~ 30 ppmC

Nucleation mode : 2 - 23 nm

Accumulation mode : 23 – 250 nm

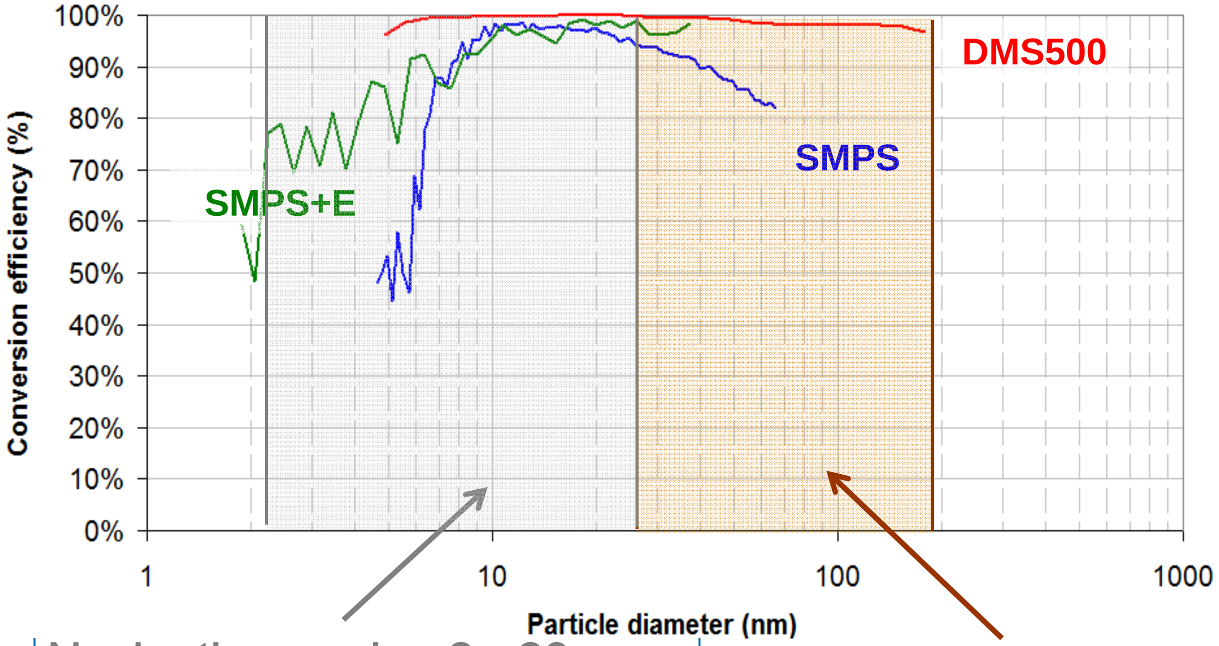
- no more effet of volatile fractions...
- ... but poorer sensibility of the detectors for small particles remains for Dp < 8 nm

Particles characterization on steady state conditions: 3WC PN efficiency



3WC PN efficiency	Nucleation mode : 2 - 23 nm	Accumulation mode : 23 – 250 nm
DMS500	66%	0 %
SMPS	98%	-
SMPS+E	99%	-

Particles characterization on steady state conditions: GPF PN efficiency

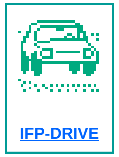


GPF PN efficiency	Nucleation mode : 2 - 23 nm	Accumulation mode : 23 – 250 nm
DMS500	99.7 %	98 %
SMPS	82 %	-
SMPS+E	87 %	-

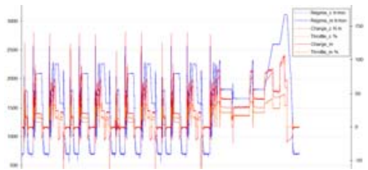
Particles characterization on transient conditions
Impact of vehicle hybridization on PN emissions

Hardware in the Loop approach

- Building of 2 AMESim Drive simulators :
  - 1 conventional vehicle + 1 hybrid vehicle

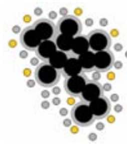


- Generation of engine speed + load profiles



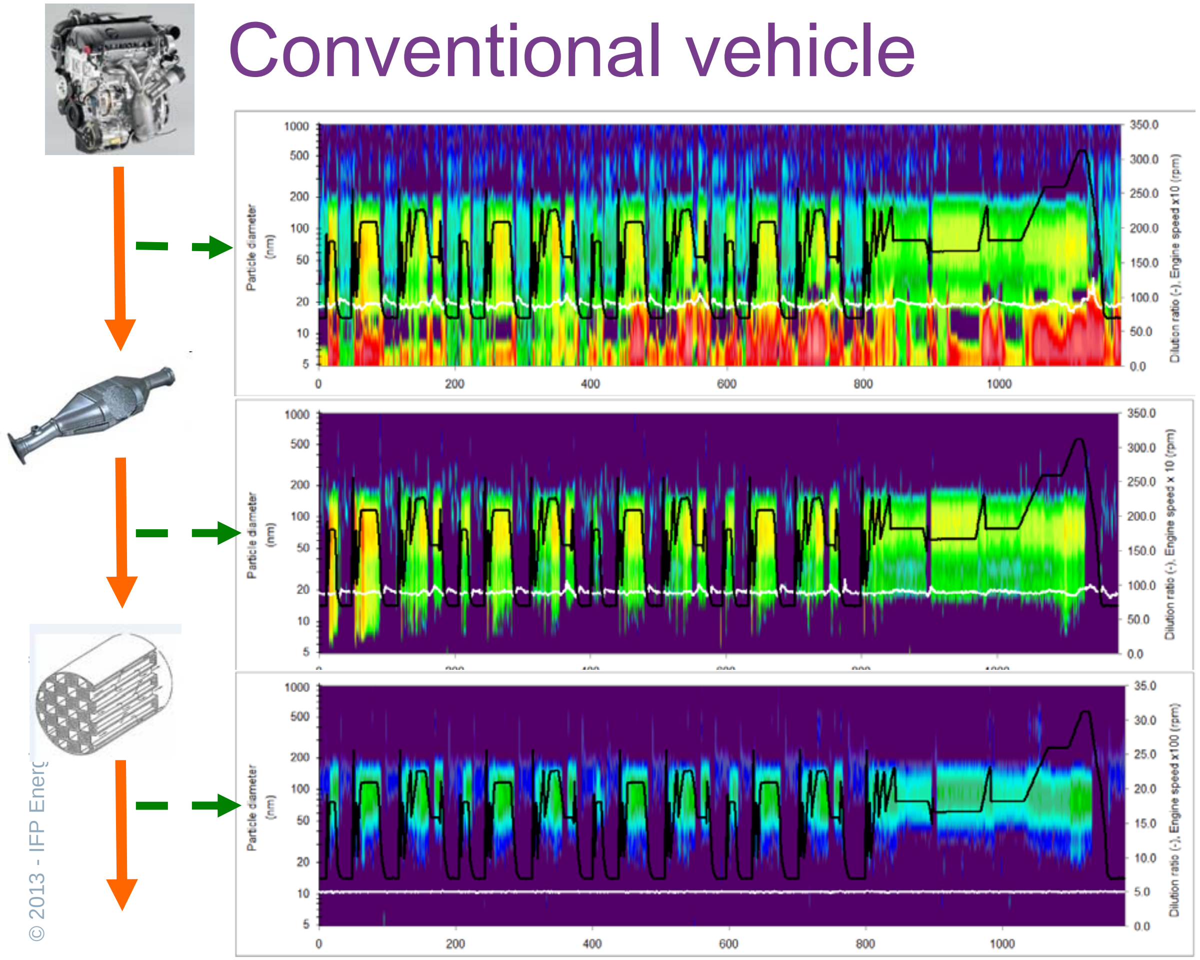
- Test bench monitoring with Morphée 2

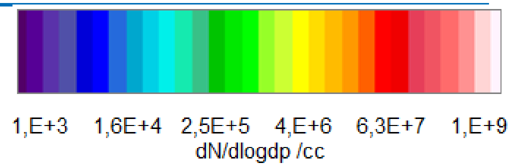
- PN exhaust measurement



Results in transient tests

Conventional vehicle



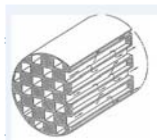


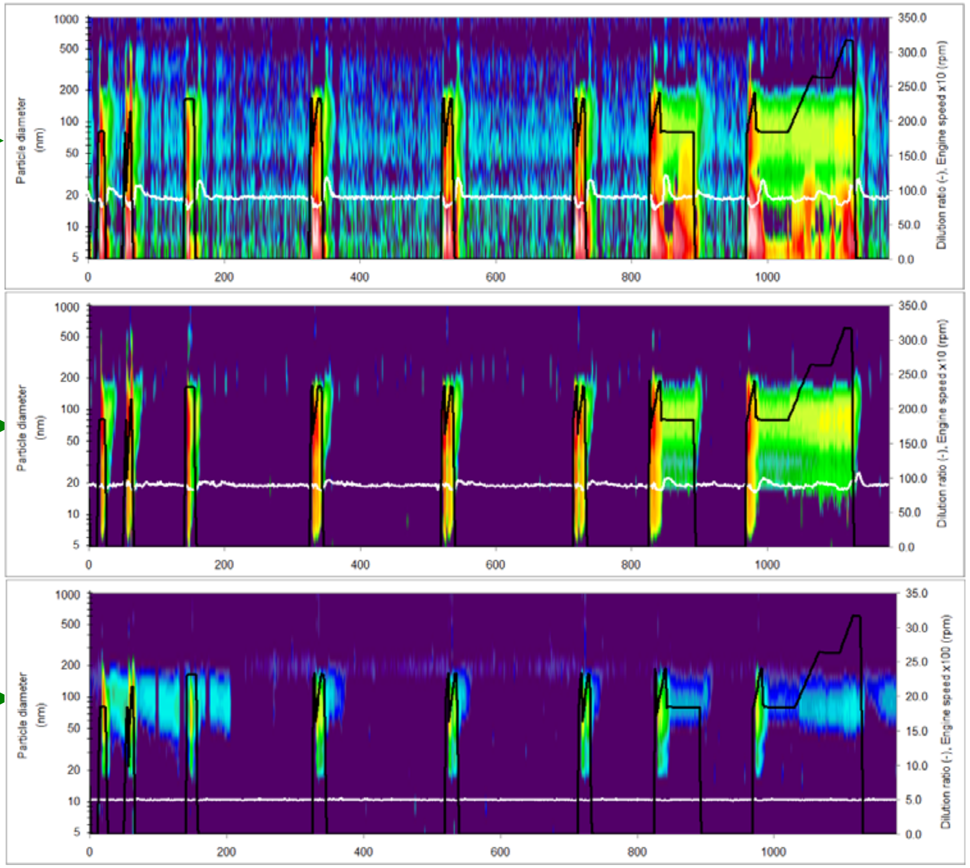
3WC effi: 94%

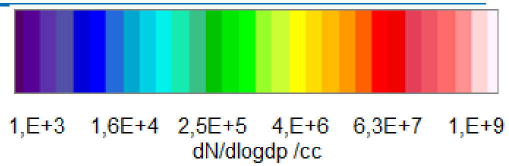
GPF effi: 96%

Results in transient tests

Hybrid vehicle





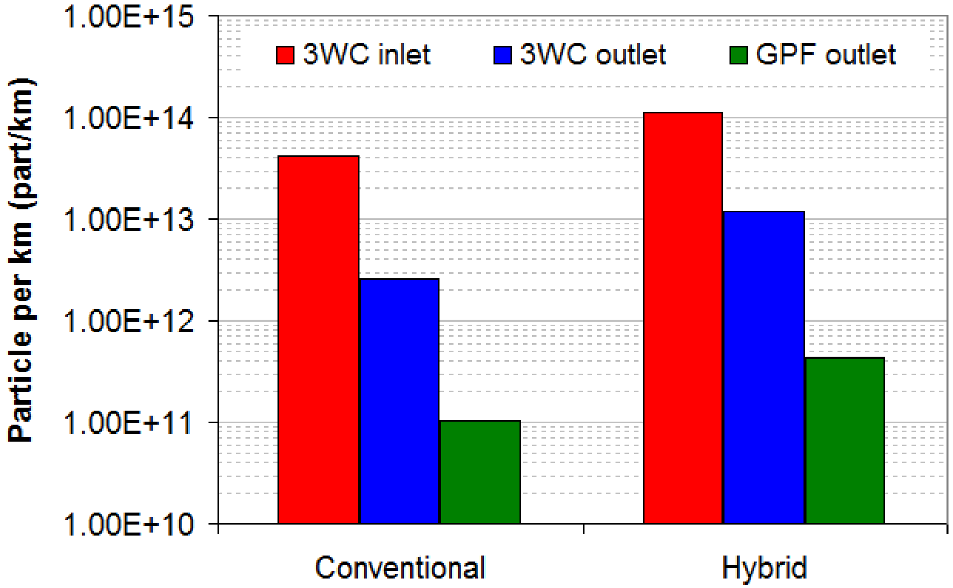


3WC effi: 89%

GPF effi: 96%

Impact of hybridization on PN emissions

- Results from the test bench :

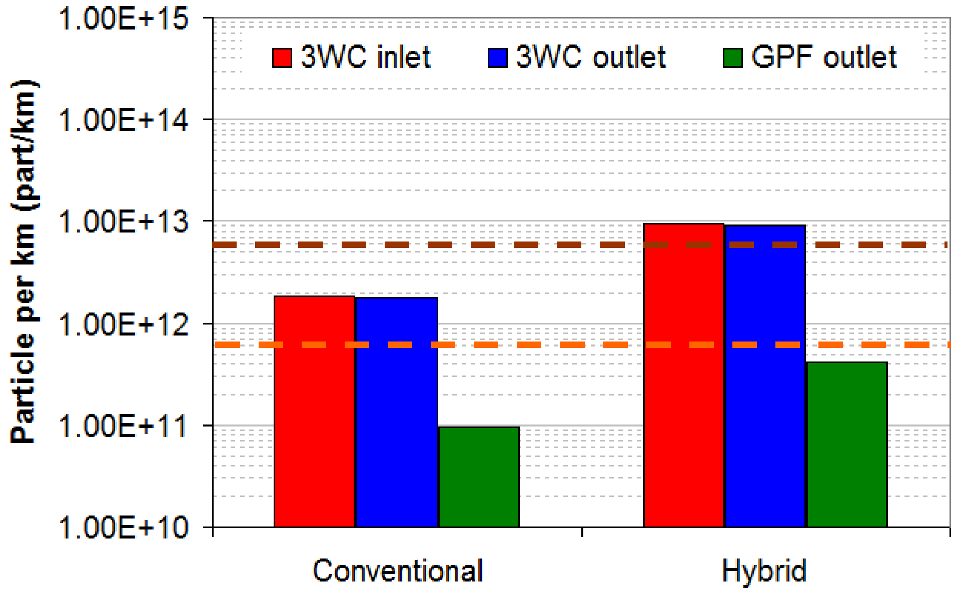


Range 5 – 1000 nm

- ➢ **2.5 times more PN in hybrid mode (after 3WC) ...**
- ➢ **... but no specific work to adapt the engine to the hybridization**
- ➢ **Possible to increase PN score (energy management, thermal engine starting strategy, ...)**

Impact of hybridization on PN emissions

- Results from the test bench :



Range 23 – 1000 nm
« pseudo PMP »

Euro 6b limit : 6.10^{+12} part/km

Euro 6c limit : 6.10^{+11} part/km

- **Conventional vehicle with 3WC only would be compliant with the Euro 6b limit, but hybrid vehicle does not.**
- **GPF is an efficient way to respect the Euro 6c step, both in conv. and hybrid modes**

Conclusions

Particulate characterization

- Satisfactory consistency and good repeatability for the 3 particulate analyzers used, excepted on the nucleation phase because of different dilution and counting systems.
- Nucleation remained present, even after hot dilution, because chosen dilution ratio was a trade-off between [PN], temperature, and condensates
- Outlook: the « ideal dilutor » would be a device able:
  - to adjust temperature to analyzers capabilities
  - to remove water and volatile fraction from the gas...
  - ...without reducing the particulate concentration and without any particulate losses

Conclusions

Exhaust emission control system

- 3WC has a good efficiency regarding small particulates in the nucleation mode
- GPF is an efficient way to remove solid particulate in steady state and in transient operations
  - efficiency > 96% on the range 5 – 1000 nm
  - low backpressure (<20 mbar on NEDC cycle)
  - the particulate concentration at the exhaust of the GPF is about 6.10^{+4} part/cm^3 – comparable to ambient air concentration

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Thank you for your attention!

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