

Performance evaluation of an iPEMS: intercomparisons and implications for road-side inspection, fleet screening, and road worthiness

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Outline

- Introduction to Periodic Technical Inspection (PTI)
- The impact of particulate composition on PN from PTI equipment
- Emissions measurement system error margins
- The parSYNC iPEMS solution
- Test Program
- Results
- Conclusions





Periodic Technical Inspection (PTI) Today

- The European Union methods of inspection and maintenance, Periodic Technical Inspection (PTI) for exhaust emissions are mostly regulated by Directive 2014/45/EU:
 - Correct status of complex exhaust after-treatment systems are verified only by visual inspection
 - Requires different emission tests based on vehicle engine type:
 - Positive ignition engine emissions use a certified exhaust gas analyzer to determine:
 - Gaseous emissions (CO, CO₂, O₂, HC) do not exceed OEM/vehicle type specified thresholds,
 - Lambda coefficient not outside OEM specified range, or if not specified not outside 1 ± 0.03 ,
 - OBD read-out does not indicate significant malfunction.
 - Compression ignition engine emissions use certified opacity meter and protocol to determine:
 - Opacity does not exceed OEM/vehicle type specified thresholds.
- Directive 2014/45/EU is out of date:
 - No check for relevant pollutants such as NO_x and PN,
 - There are concerns around the sensitivity of the smoke opacity method to detect particulate emission issues from vehicles fitted with particulate filters.





- European PTI emission measurement is progressing:
 - A methodology that seems to be efficient for detecting tampered or malfunctioning particulate filters in diesel vehicles is the solid particle number (SPN) measurement at idling,
 - Some member states are introducing new PTI regulations upfront of EU regulation
 - EU regulates OBM CO₂ monitoring for new vehicles from 2021, with PTI procedures to be defined,
 - Work is ongoing to develop a NOx PTI protocol.
- But there is much progress yet to be made:
 - Particulate (PN) protocol, measurement & threshold to be finalized,
 - NOx protocol, measurement & threshold to be agreed,
 - CO and CO₂ protocol, measurement & threshold to be developed.
- Existing PTI equipment won't likely be of use in the future. New equipment must still be:
 - Robust enough for the garage environment,
 - Simple in operation for non-expert staff,
 - Low cost,
 - Sensitive enough for purpose.





The impact of particulate composition on PN readings from PTI equipment

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- Melas et al (2021) found high sub-23nm fractions and volatile fractions from testing of different vehicles,
- Solid sub-23nm fractions (SPN10 – SPN23)/SPN23 ranged from 5% to 775%.
 - Volatile fractions (TPN10 – SPN10)/SPN10 ranged from 6% to 47%.
 - Sub-23nm volatile fractions (TPN10 – SPN23)/SPN23 ranged from 45% to 1025%.

Vehicle	Comment	SPN23 (#/cm3)	SPN10 (#/cm3)	Sub-23 nm Fraction	TPN10 (#/cm3)	Volatiles Fraction	Sub-23 and volatiles fraction
V1	DPF (high sub-23)	4.00E+04	3.50E+05	775%	4.50E+05	29%	1025%
V2	DPF (after regen.)	4.80E+04	5.00E+04	4%			
V3	DPF (old)	3.80E+05	1.70E+06	347%			
V4	DPF (bypass)	2.70E+05	7.00E+05	159%	1.10E+06	57%	307%
V5	GDI (no filter)	7.60E+04	1.00E+05	32%	1.10E+05	10%	45%
V6	No DPF	8.90E+06	1.40E+07	57%			

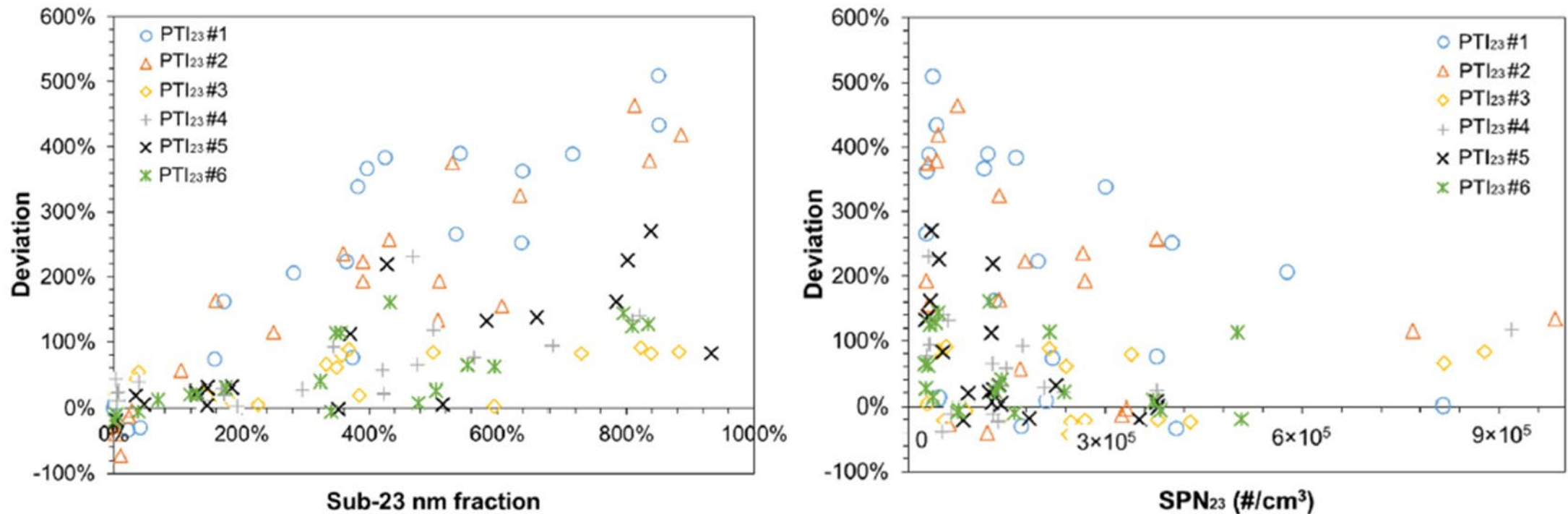
Melas, A.; Selleri, T.; Suarez-Bertoa, R.; Giechaskiel, B. Evaluation of Solid Particle Number Sensors for Periodic Technical Inspection of Passenger Cars. *Sensors* 2021, 21, 8325. <https://doi.org/10.3390/s21248325>



The impact of particulate composition on PN from PTI equipment

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- Melas et al (2021) found that the sub 23nm fraction causes deviation of existing PN PTI equipment from PMP-type systems (23nm cut-off, VPR).



- One would expect even greater deviations from PN equipment without the 23nm cut-off (or a VPR).

Melas, A.; Selli, T.; Suarez-Bertoa, R.; Giechaskiel, B. Evaluation of Solid Particle Number Sensors for Periodic Technical Inspection of Passenger Cars. *Sensors* 2021, 21, 8325. <https://doi.org/10.3390/s21248325>



A note on emissions measurement system error margins

- The EU outlines the permissible error margins for PEMS equipment compared to standard laboratory equipment. They are presented as a mass emission difference and a percentage difference, with the larger of the two taken as the threshold.
- When comparing two PEMS devices directly, it is logical to combine the uncertainties that each can have with regard to the laboratory references, according to standard error propagation rules;

$$\delta_{total} = \sqrt{\delta_{PEMS1}^2 + \delta_{PEMS2}^2},$$

- Therefore, between two PEMS we infer larger permissible error margins.
- Note that these error margins are not currently required of PTI equipment.

	PEMS vs Lab		PEMS vs PEMS	
	Mass Emissions	Percentage difference	Mass Emissions	Percentage difference
CO ₂	10 g/km	10%	14.12 g/km	14.10%
CO	150 mg/km	15%	212.13 mg/km	21.20%
NO _x	15 mg/km	15%	21.21 mg/km	21.20%
PN	1E11 #/km	50%	1.41E11 #/km	70.70%





Test Program





Aims and Objectives

- Study the performance of emissions measurement systems for new PTI testing,
 - Compare the measured mass emission values and linearity between the iPEMS and regulatory PEMS/Lab equipment,
 - Study the drift and rise response characteristics of the iPEMS.
- Investigate the impact of a 23nm cut-off and volatile particle removal on measured PN values,
 - Calculate the sub-23nm and volatiles fractions on PN from a diesel vehicle,
 - Compare the readings between different equipment setups (23nm vs 10nm cut-off diameters, VPR vs non-VPR).





Device used - The parSYNC iPEMS

➤ Lightweight & Easy To Use

- Total System Weight: 6.7 kg (22.1 lb)
 - parSYNC® Weight: 4.1 kg (13.7 lb)
 - CUBE™ Weight (with one battery): 2.6 kg (8.4 lb)

➤ Battery Life

- 4-5 hours typically

➤ Tier 1 GasMOD™ Sensor Cartridge

- Electrochemical: NO (0-5000ppm) & NO₂ (0-300ppm)
- NDIR: CO₂ (0-20%), CO (0-15%)

➤ Tier 1 Particulates Sensor Cartridge

- PN/PM (10 to 10,000nm = 0.01 to 10µm)



No 23nm cut-off for this system

A volatile particle remover (VPR) was tested in this trial
– VPR was a heated evaporation tube operating at 400C





The new parSYNC **FLEX** iPEMS

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Gases – CO, CO₂, NO, NO₂ + **HC and O₂**

Particulates - Ionization,
Scattering, and Opacity,
**with advanced
temperature control**

**Enhanced chiller and
volatile particle removal**

**Hot-swap Milwaukee Li-Ion
batteries for full-day of
testing**

**Onboard display and data
storage + WiFi Access-point**

**Full CAN + support for
external sensors**

**Integrated GPS and Ambient
Pressure, Temperature,
Humidity**

**Integrated wireless OBD
reader for LD and HD**

*... and still light-weight
(10 kg) and installs in
minutes*





Test Vehicles, Cycles and Equipment

Vehicle	Model Year	Euro Standard	Fuel	Injection	Aftertreatment	Powertrain
V1	2020	Euro 6D-TEMP	Gasoline	Direct Injection	TWC, GPF	Plug-in Hybrid
V2	2017	Euro 6-TEMP	Diesel	Direct Injection	SCR, DPF	ICE

Test	Cycle	Vehicle	Equipment
1	On-road dynamic drive <i>outside</i> RDE boundary (<u>2 repeats</u>)	V1	parSYNC with and without VPR, Horiba OBS-ONE
2	WLTC	V1	parSYNC with VPR, AVL AMAi60 Analyzer, AVL Particle Counter
3	Steady state – low idle	V2	parSYNC with and without VPR, AVL Particle Counter both with 10nm and 23nm cut-off diameters

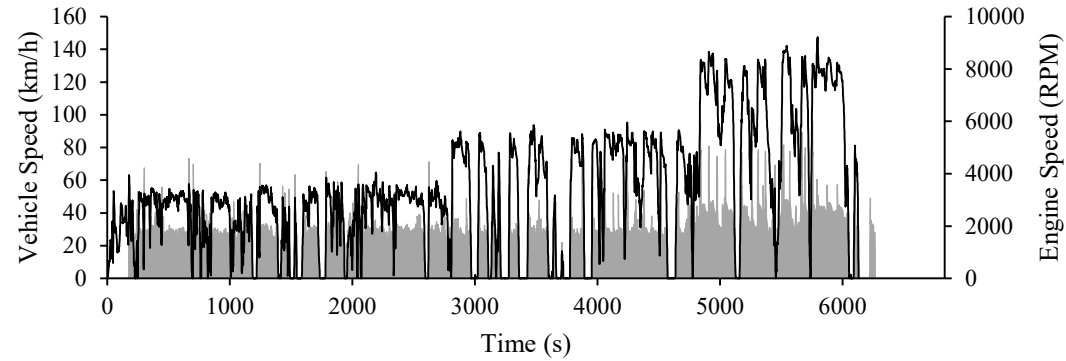
All tests were performed at the European Commission's Joint research facility by JRC personnel





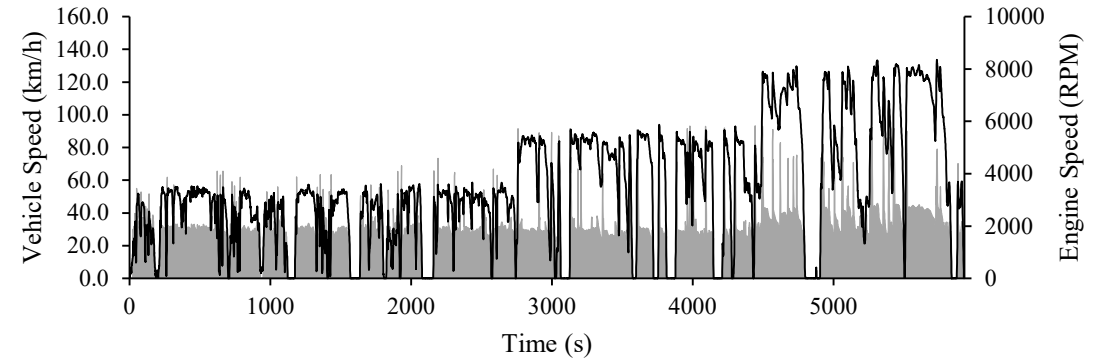
Test Vehicles, Cycles and Equipment

Test 1a



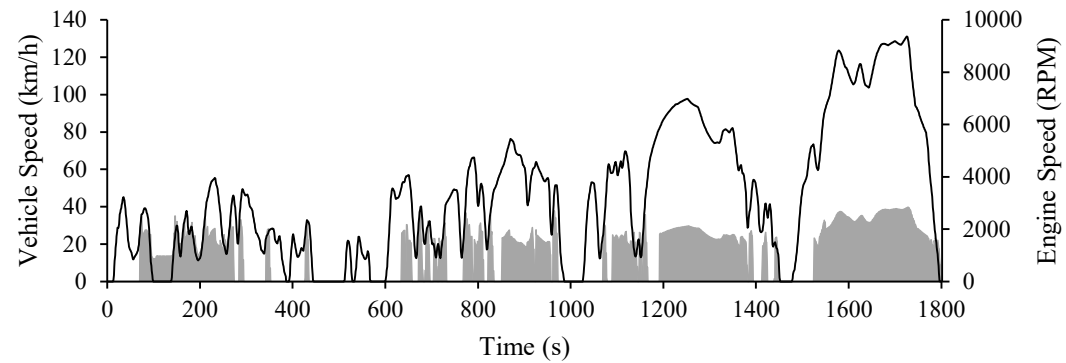
Engine speed ECU [rpm] Vehicle speed GPS [km/h]

Test 1b



Engine speed ECU [rpm] Vehicle speed GPS [km/h]

Test 2



EngineRPM_ dyno - Speed [km/h]



Results



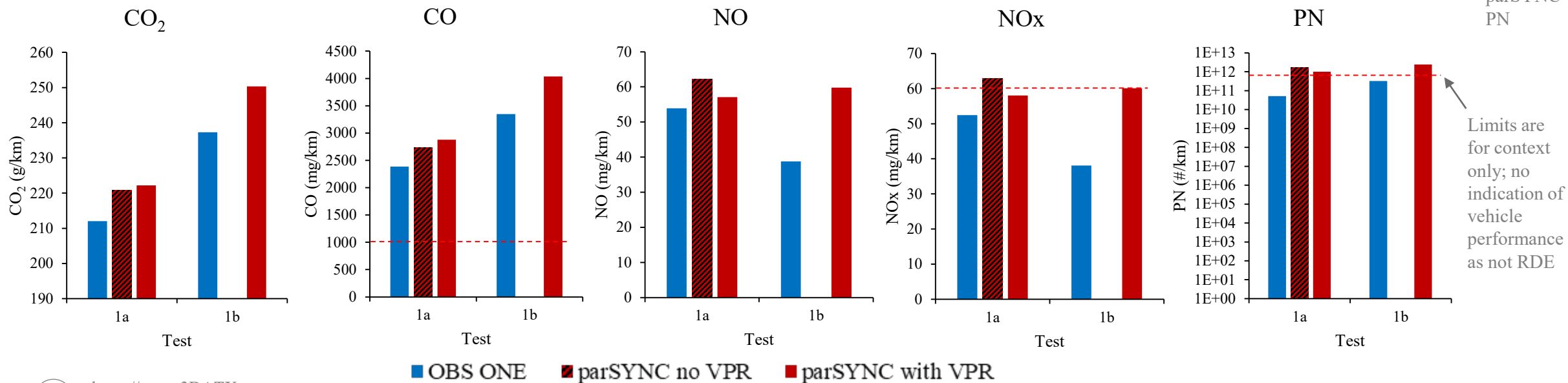


2020 Euro-6D-TEMP GDI On-road Dynamic Drive Results

	Absolute difference between parSYNC and Horiba OBS ONE, per kilometer*	Percentage difference between parSYNC and Horiba OBS ONE	Correlation coefficient
CO ₂	11 ± 1 g/km ← 14 g/km permissible	5 ± 0.4 % ← 14 % permissible	0.99 ± 0.03
CO	500 ± 100 mg/km ← 212 mg/km permissible	17 ± 2 % ← 21 % permissible	0.94 ± 0.1
NO	21 ± 6 mg/km ← No specific limit	10 ± 3 % ← No specific limit	0.88 ± 0.1
NO _x	22 ± 8 mg/km ← 21 mg/km permissible	14 ± 3 % ← 21 % permissible	0.87 ± 0.03
PN	2x10 ¹² #/km ← 1.4x10 ¹¹ #/km permissible	152 % ← 70.7 % permissible	0.11

*All mass emissions calculated via GPS speed for distance and Horiba OBS ONE for exhaust flow rate

N.B. no 23nm cut-off for parSYNC PN



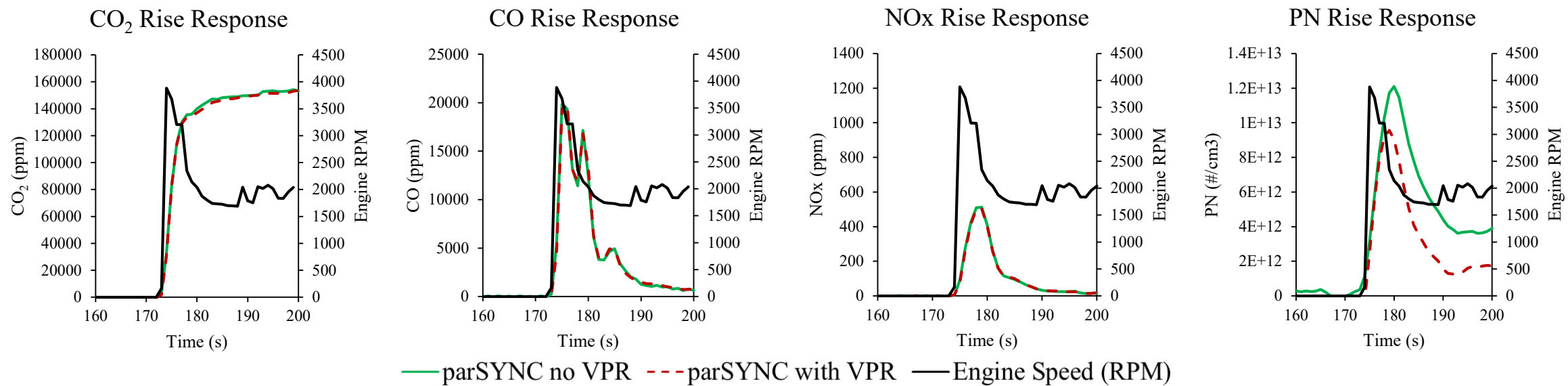
Limits are for context only; no indication of vehicle performance as not RDE



2020 Euro-6D-TEMP GDI On-road Dynamic Drive Results

Drift between parSYNC start and end of test (from ambient readings)

CO ₂	110.9 ppm ← RDE zero drift limit: 2000 ppm
CO	6.5 ppm ← RDE zero drift limit: : 75 ppm
NO	4.9 ppm ← No specific RDE zero drift limit
NO _x	5.0 ppm ← RDE zero drift limit: : 5 ppm
PN	4.67x10 ⁵ #/cm ³ ← No specific RDE zero drift limit



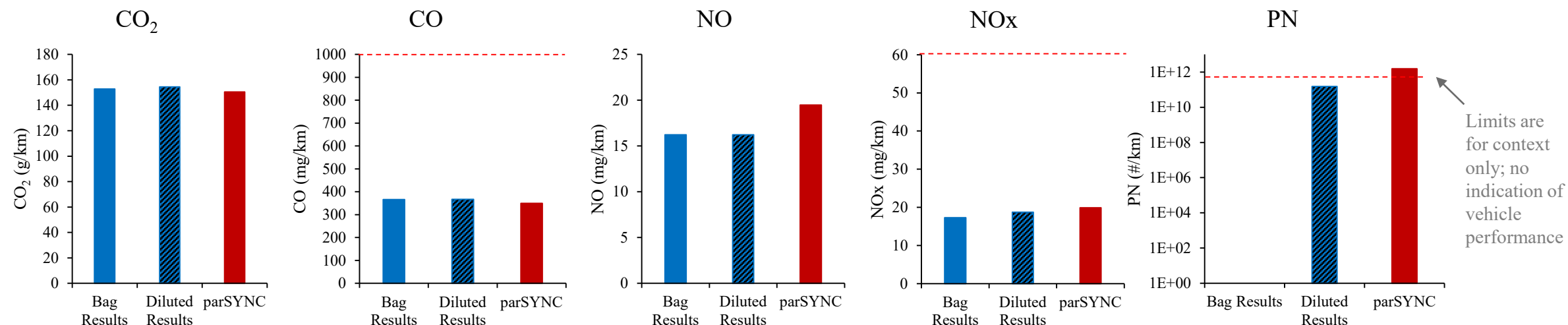


2020 Euro-6D-TEMP GDI WLTC Results

	Absolute difference between parSYNC and Lab values, per kilometer*	Percent difference between parSYNC and Lab values	Correlation coefficient
CO ₂	2.4 g/km ← 10 g/km permissible	1.6 % ← 10 % permissible	1.002
CO	16.6 mg/km ← 150 mg/km permissible	5 % ← 15 % permissible	0.39
NO	3.3 mg/km ← No specific limit	18 % ← No specific limit	0.75
NO _x	2.6 mg/km ← 15 mg/km permissible	14 % ← 15% permissible	0.74
PN	1.4x10 ¹² #/km ← 1x10 ¹¹ #/km permissible	164 % ← 50 % permissible	1.58

*All mass emissions calculated via GPS speed for distance and Horiba OBS ONE for exhaust flow rate

N.B. no 23nm cut-off for parSYNC PN



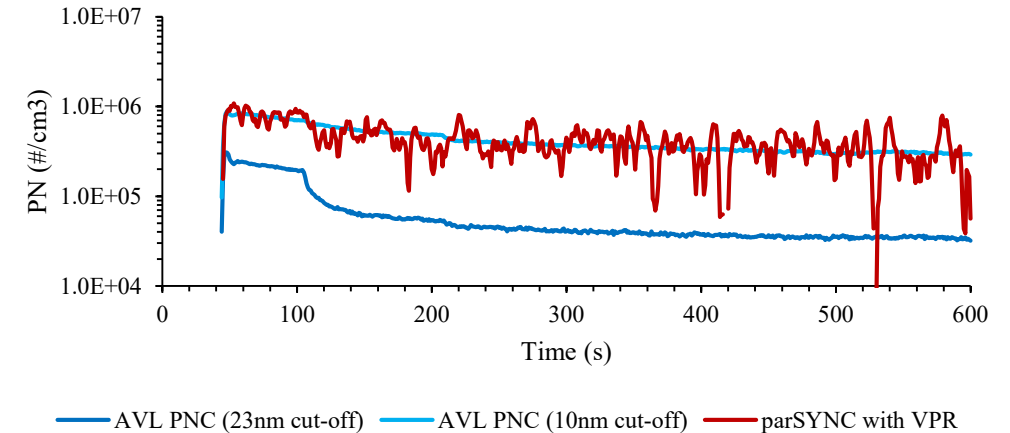
(Diluted results are the transient emission values sampled from within the CVS system, corrected for dilution)



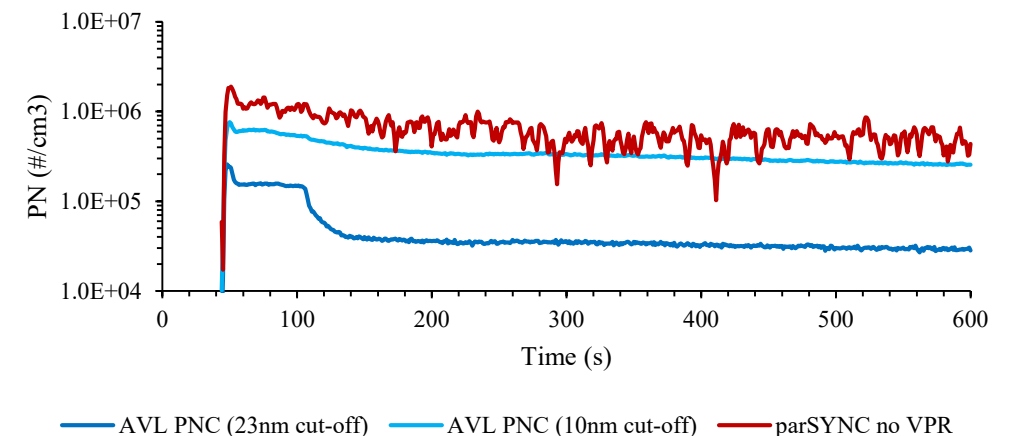
2017 Euro-6-TEMP Diesel Steady State Low Idle Results

- All previous PN results presented compare parSYNC with no cut-off against a regulated PEMS/lab system with 23nm cut-off, so are not valid comparisons.
- For a more meaningful comparison the parSYNC with and without VPR (separate tests performed for each) was compared against the AVL Particle Counter with 23nm and 10nm cut-offs.
- *N.B. A zero drift was corrected on VPR parSYNC test data during processing.*
- From the two tests performed, the sub-23nm fraction was 590 ± 40 %.
- The volatile fraction appears to be approximately 50% from comparison of two separate tests, in agreement with the findings of Melas et al (2021).

Transient PN values - parSYNC with VPR Test



Transient PN values - parSYNC without VPR Test





2017 Euro-6-TEMP Diesel Steady State Low Idle Results

parSYNC VPR?	APC cut-off	Percentage difference between parSYNC and Lab values
<u>VPR</u>	23nm	~148% ← 50 % permissible
	<u>10nm</u>	<u>~1.1% ← 50 % permissible</u>
No VPR	23nm	~172% ← 50 % permissible
	10nm	~59% ← 50 % permissible

- The 10nm APC readings were much closer to the parSYNC PN values than the 23nm APC readings on both (VPR and non-VPR) tests; The parSYNC VPR brought PN readings closer to those of the APC.
- The parSYNC with VPR was closest to the APC with 10nm cut-off, and well within the permissible tolerance for percent difference between a PEMS and lab values,
 - One would expect this difference to decrease further if the cut-off for the APC was reduced (e.g. to 4nm).
- A substantial reduction of measured PN values results from a 23nm cut-off and volatiles removal.
- If PTI is to tackle air quality health concerns, these <23nm particles should also be limited. Type approval Euro standards should incorporate particles smaller than 23nm, with PTI following suite.





Conclusions





Conclusions

- The gaseous emissions from the parSYNC tests were generally within the permissible tolerances applicable to regulatory PEMS / laboratory equipment.
- The parSYNC instrument drift from PTI testing was within the tolerance set for regulatory PEMS equipment during RDE testing.
- An APC with 10nm cut-off approached the values of the parSYNC with VPR (and no cut-off)
- A large fraction of sub-23nm diameter particles and volatile particles arise from idle engine testing, supporting a reduction in PN cut-off diameter (for both type approval and PTI) if air quality concerns are to be addressed.
- These tests show that equipment designed for PTI use can perform reasonably well against regulatory lab equipment. The upgraded parSYNC device (parSYNC FLEX) will improve the system further.





Thank you for listening

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