# 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, $CO_2$, $O_2$, 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- Directive 2014/45/EU is out of date: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 NOx and PN,
  - There are concerns around the sensitivity of the smoke opacity method to detect particulate emission issues from vehicles fitted with particulate filters.

# PTI Tomorrow

- 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 $CO_2$ 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 $CO_2$ 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

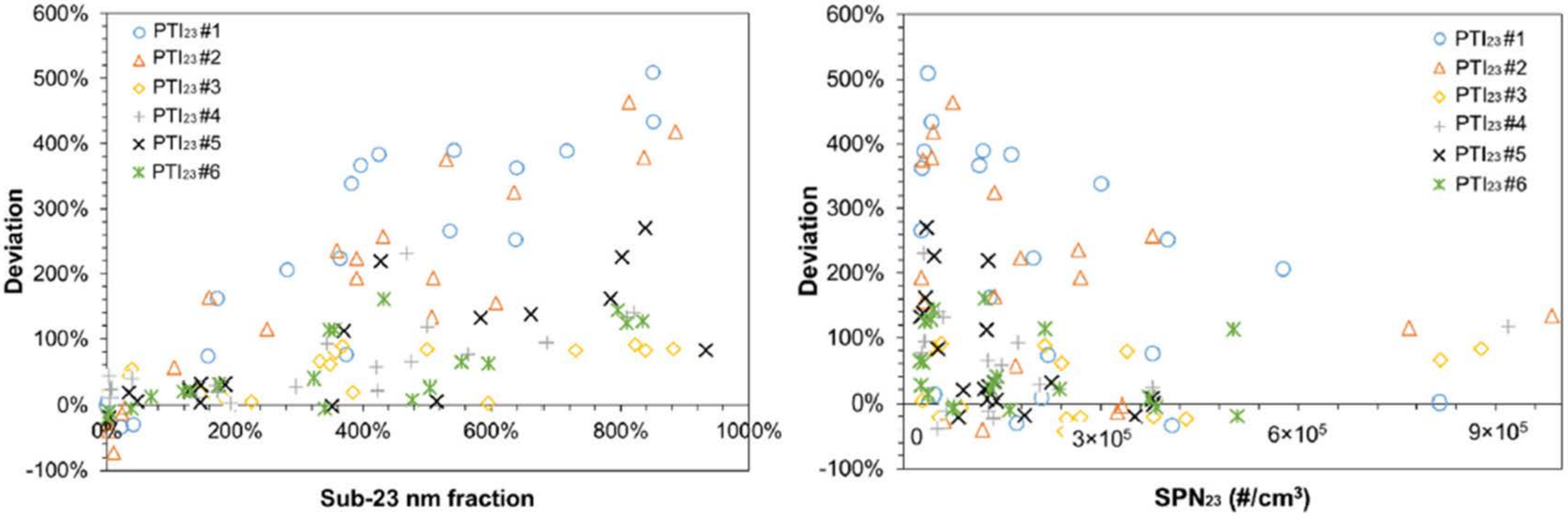
- Melas et al (2021) found high sub-23nm fractions and volatile fractions from testing of different vehicles,
  - Solid sub-23nm fractions (SPN10 – SPN23)/SPN23 ranged from 5% to 775%.
  - Volatile fractions (TPN10 – SPN10)/SPN10 ranged from 6% to 47%.
  - Sub-23nm volatile fractions (TPN10 – SPN23)/SPN23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

- ➢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.; 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

# 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;

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

- 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% |
| NOx | 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) & $NO_2$ (0-300ppm)
  - NDIR: $CO_2$ (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

Full CAN + support for external sensors

Gases – CO, $CO_2$, NO, $NO_2$ + **HC and $O_2$**

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


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

**Enhanced chiller and volatile particle removal**

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

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

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

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

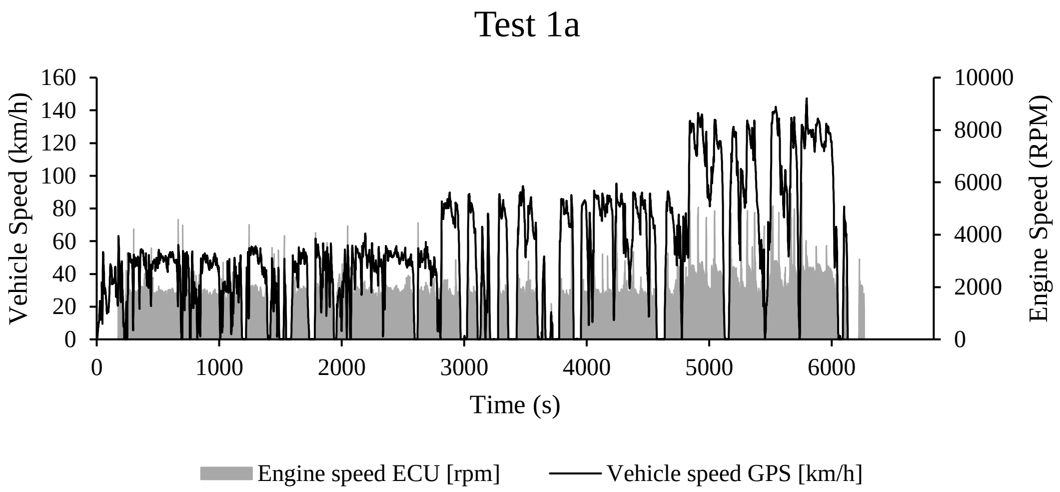
# Test Vehicles, Cycles and Equipment

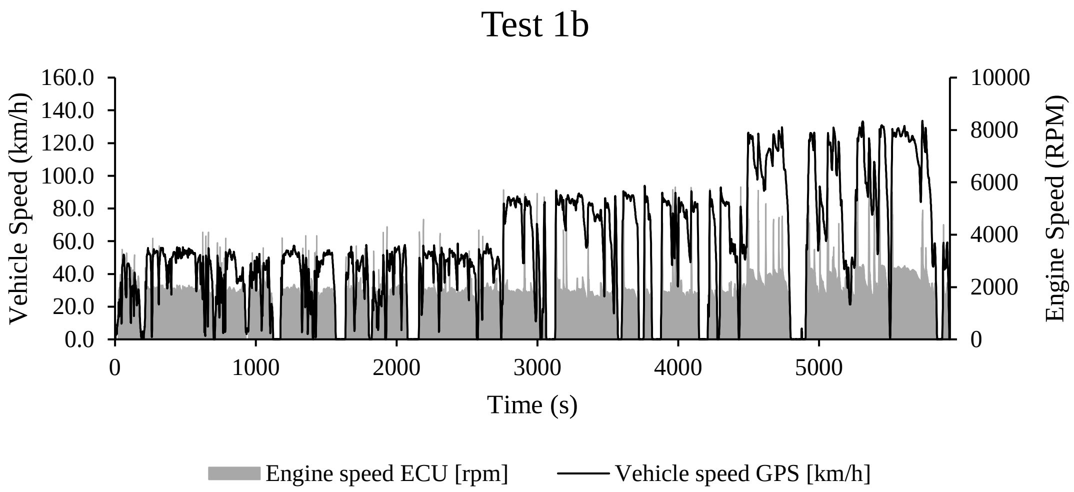
| Vehicle | Model Year | Euro Standard | Fuel | Injection | Aftertreatment | Powertrain |
|---|---|---|---|---|---|---|
| V1 | 2020 | Euro 6D-TEMP | Gasoline | Direct Injection | TWC, GPF | Plug-in Hybrid |
| V2 | 2017 | Euro 6-TEMP | Diesel | Direct Injection | SCR, DPF | ICE |

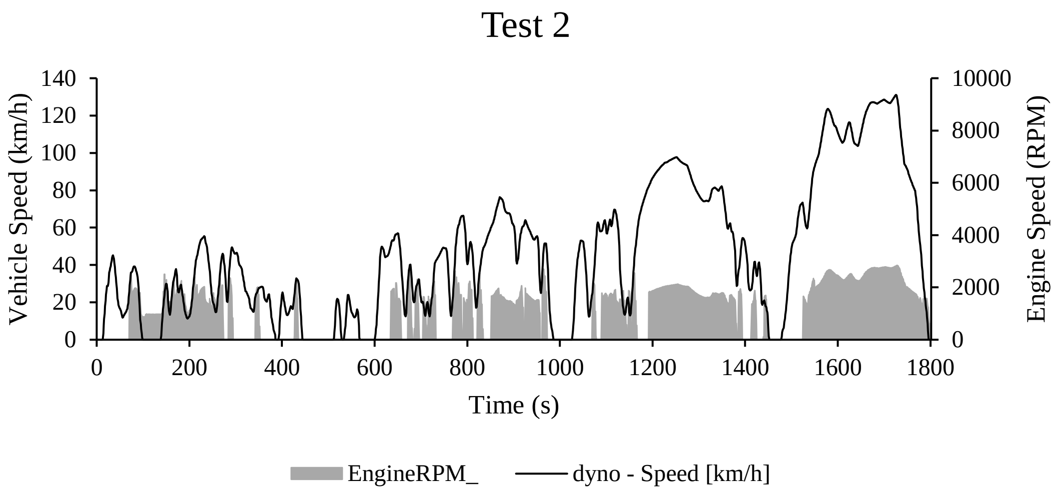
| Test | Cycle | Vehicle | Equipment |
|---|---|---|---|
| 1 | On-road dynamic drive *outside* RDE boundary (2 repeats) | V1 | parSYNC with and without VPR, Horiba OBS-ONE |
| 2 | WLTC | V1 | parSYNC with VPR, AVL AMAi60 Analyzer, AVL Particle Counter |
| 3 | Steady state – low idle | V2 | parSYNC with 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



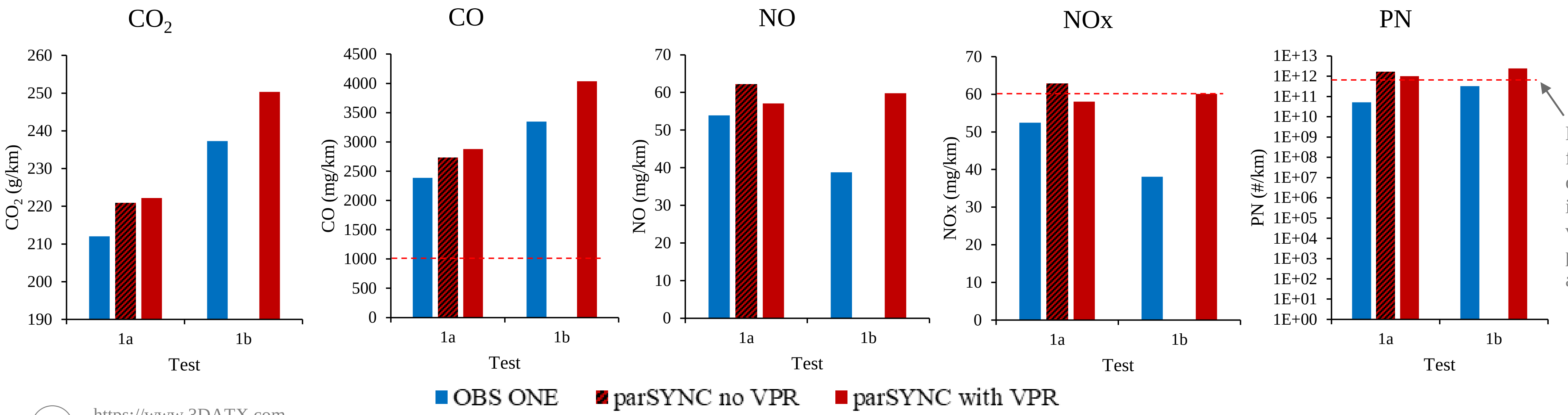
# Results

# 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 |
| NOx | 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

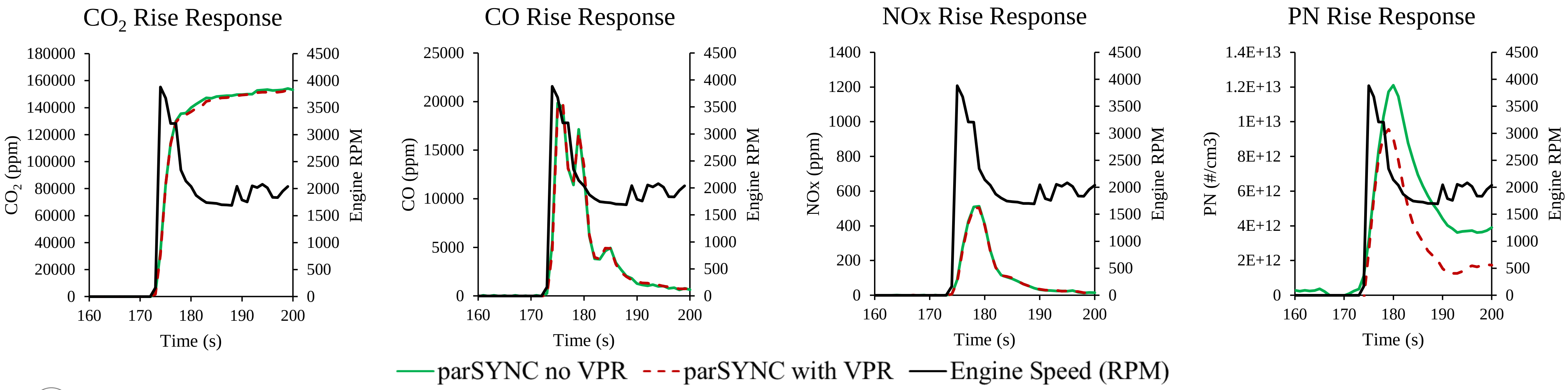
N.B. no 23nm cut-off for parSYNC PN




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 |
| NOx | 5.0 ppm ← RDE zero drift limit: : 5 ppm |
| PN | $4.67 \times 10^5$ #/cm3 ← No specific RDE zero drift limit |

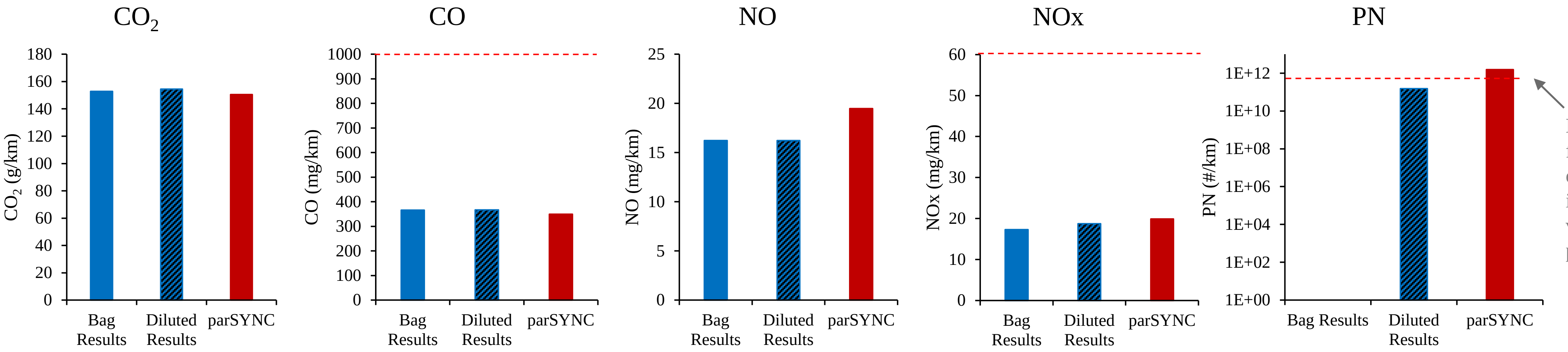


# 2020 Euro-6D-TEMP GDI WLTC Results

| | 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 |
| NOx | 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

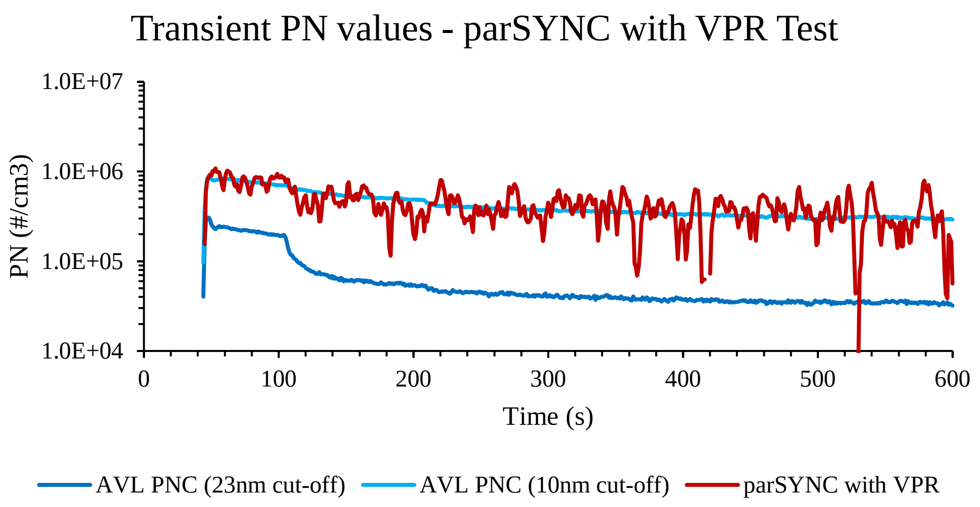


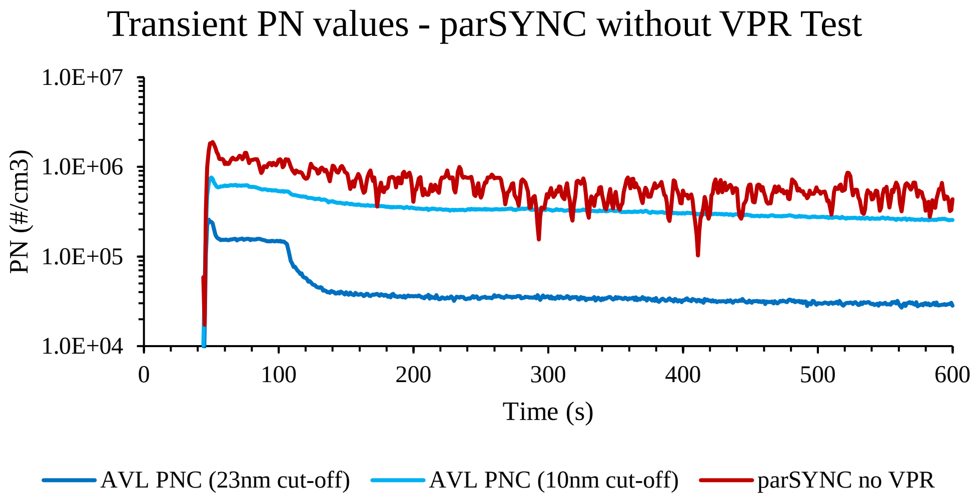

Limits are for context only; no indication of vehicle performance

(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).



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

| parSYNC VPR? | APC cut-off | Percentage difference between parSYNC and Lab values |
|---|---|---|
| VPR | 23nm | ~148% ← 50 % permissible |
| | **10nm** | **~1.1% ← 50 % permissible** |
| 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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## Acknowledgement

The authors would like to thank the Joint Research Centre (JRC) for conducting the test campaign