Particle Measurement Programme

Final Heavy-duty Inter-laboratory Validation Exercise Results

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Outline of Presentation

- Programme Outline
- Emissions Characteristics
- Particulate Mass Measurements
- Particle Number Measurements
- Investigations into PM and PN Results
- Conclusions

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- **Programme Outline**
- Preconditioning and Emissions Characteristics
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What's the PMP All About?

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- Inter-governmental research programme under the auspices of UNECE GRPE to develop new vehicle exhaust particle measurement procedures for regulatory use
- Set up due to health concerns over nanoparticles…
- …and concerns over the ability of the current particulate mass measurement method to enable the forced adoption of technologies which effectively control their emissions
- Mandate was to develop techniques to replace or complement the particulate mass measurement method
  - must be applicable to Light Duty Vehicle & Heavy Duty Engine type approval testing
- PMP also to
  - provide data on the performance of different vehicle and engine technologies according to the new measurement procedures
  - demonstrate the viability of developed measurement approaches and test the written procedures in validation exercises
  - fine-tune the written procedures ready for regulatory use
- Light-duty procedures validated and ready for regulation in Euro 5b/Euro 6
- Heavy-duty procedure validation reported here

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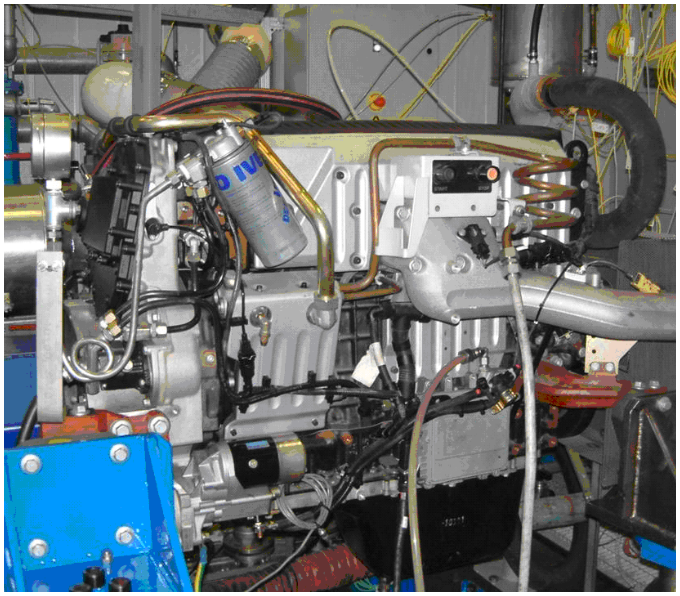
Engine and Test Cycles

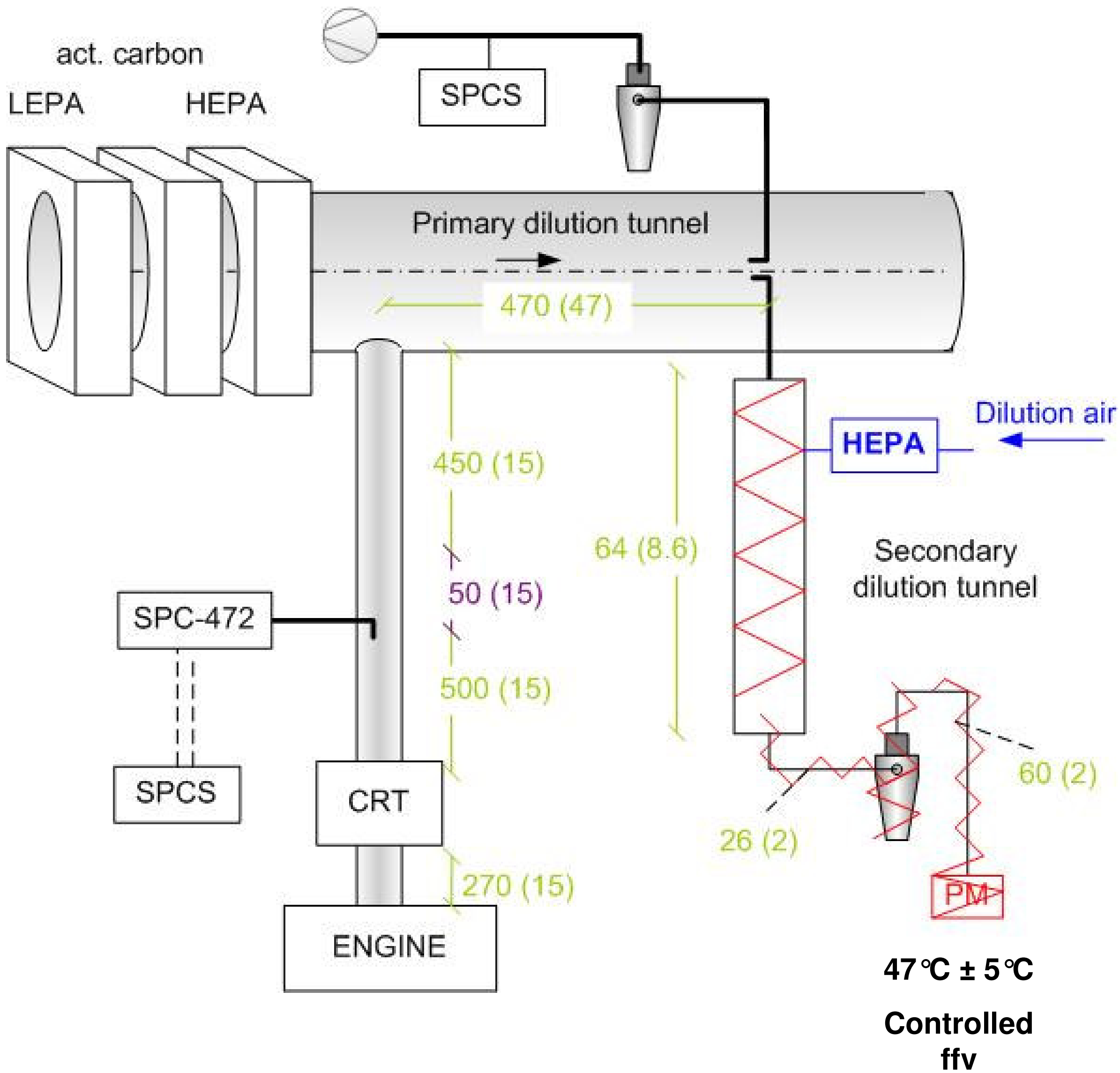


Previous lab	Day 0	Days 1-7	Day 8
	oil change	IFV	IFV
	2h ESC Mode 10	cold WHTC	cold WHTC
	3 x ETC	10 minute soak	10 minute soak
		hot WHTC	hot WHTC
		10 minutes at WHSC mode 9	10 minutes at WHSC mode 9
		WHSC	WHSC
		CP	CP
		ETC	ETC
		CP	CP
		ESC	ESC
*2 hours at ESC Mode 10	Precon	Precon	*2 hours at ESC Mode 10

ESC - European Steady State Cycle for emissions measurement [30 min]
ETC - European Transient Cycle for emissions measurement [30 min]
WHTC - World Harmonised Steady State Cycle for emissions measurement [30 min]
WHTC - World Harmonised Transient Cycle for emissions measurement [30 min]
IFV - Instrument Functional Verification
CP - Continuity Protocol
Precon - 15 miuntes ESC mode 10, 30 minutes ESC mode 7
* DPF regeneration only required if oil change and conditioning not performed

- 7.8 lt – 6 cylinder **Euro III IVECO Cursor 8**
- **Retrofit DPF**
  - CRT: Pt-based oxidation catalyst (4.25 lt) & cordierite wall flow filter (~24 lt)
- **Reference Fuel**
  - RF06-03 fuel (<10 ppm S)
- **OEM Lubricant**
  - BP Vanellus E8 fully synthetic 5W/30 lubricant (<0.2% S)
- Test Matrix addressed replicate European and World Cycles
  - **ETC, ESC, WHTC, WHSC**
- At least **8 repetitions** of each test cycle at each lab
- 5 labs, one (JRC) testing twice = **6 sets**

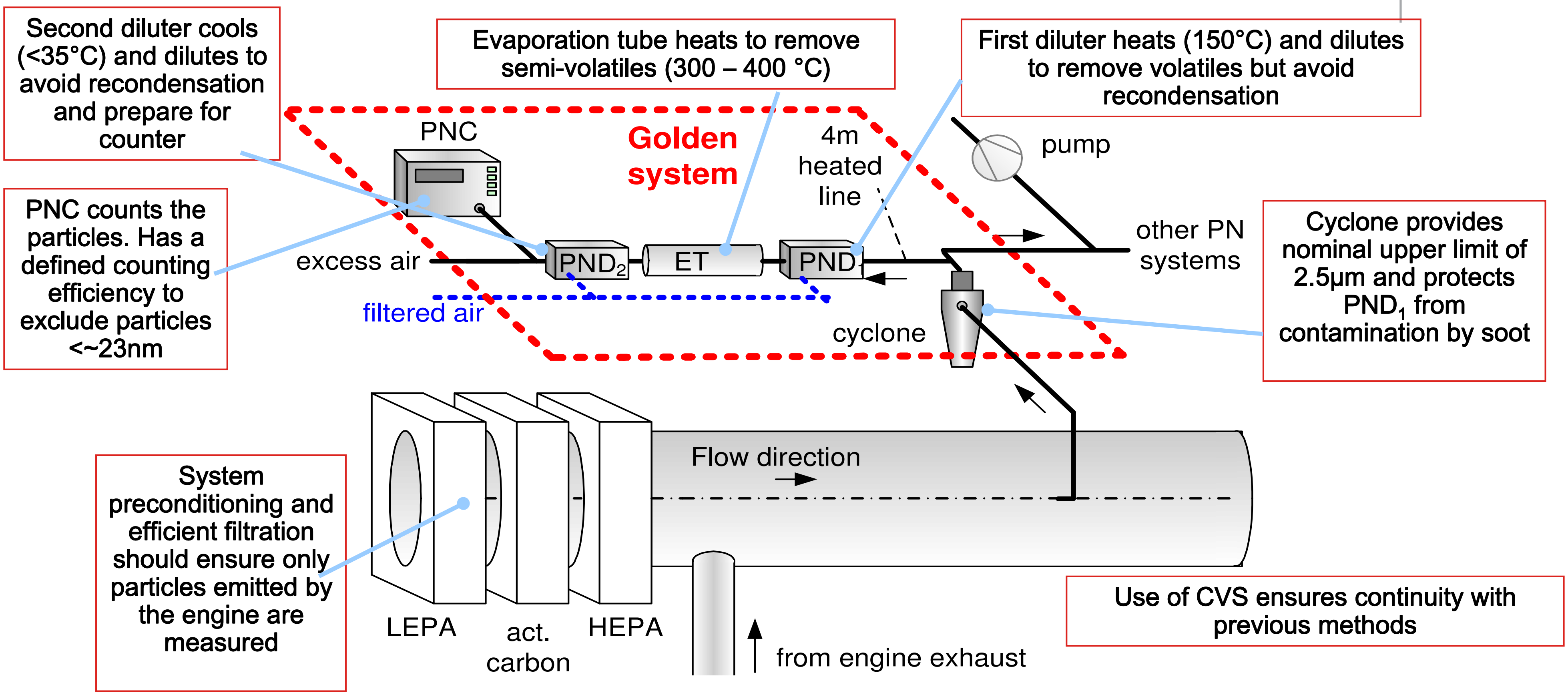
Typical measurement setup (JRC Example)



- Two Golden Particle Measurement Systems (Horiba SPCS). One at CVS and one at the Partial Flow System.

- Additional instrumentation (for experiments at JRC)
  - VPR systems
    - APC
    - Nanomet
    - Dual Ejector & Evaporating Tube
    - Thermodenuder
  - TSI's SMPS
  - EEPS
  - Soot Sensor
  - DMM

Particle Number Measurement Approach



- Measurement employs a condensation nucleus counter, but uses sample pre-conditioning to eliminate the most volatile particles which may contribute significantly to variability
- Solid particles defined by the measurement equipment
  - ~23nm to 2.5µm and surviving evaporation at (or above) 300℃
  - Analogous to heated FID hydrocarbon method

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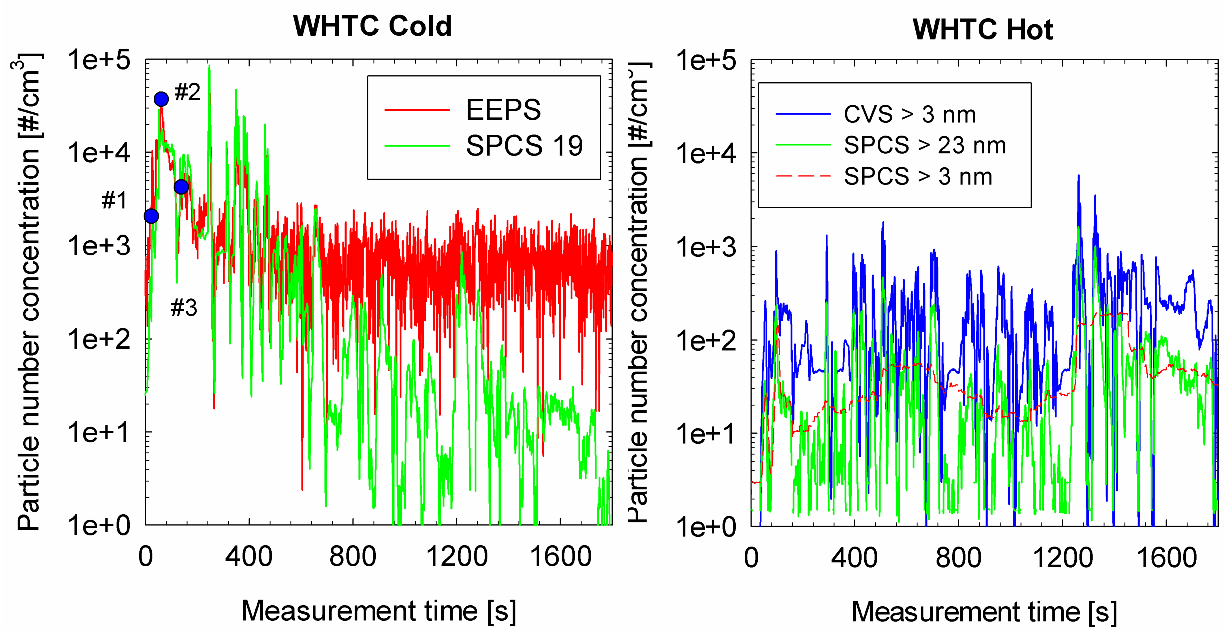
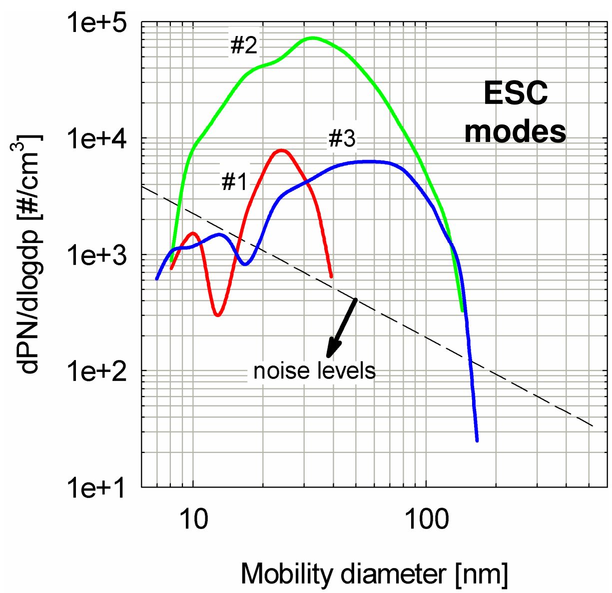
Real Time PN emissions





- High cold start emissions
  - Elemental carbon
- ~100x lower emissions over the hot start cycles
  - Robust and stable soot cake
- High emissions at high temperature steady state modes
  - Passive regeneration, carbon breakthrough
  - Semi-volatile release leading to nucleation mode

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PM Can be Influenced by Sampling Approach

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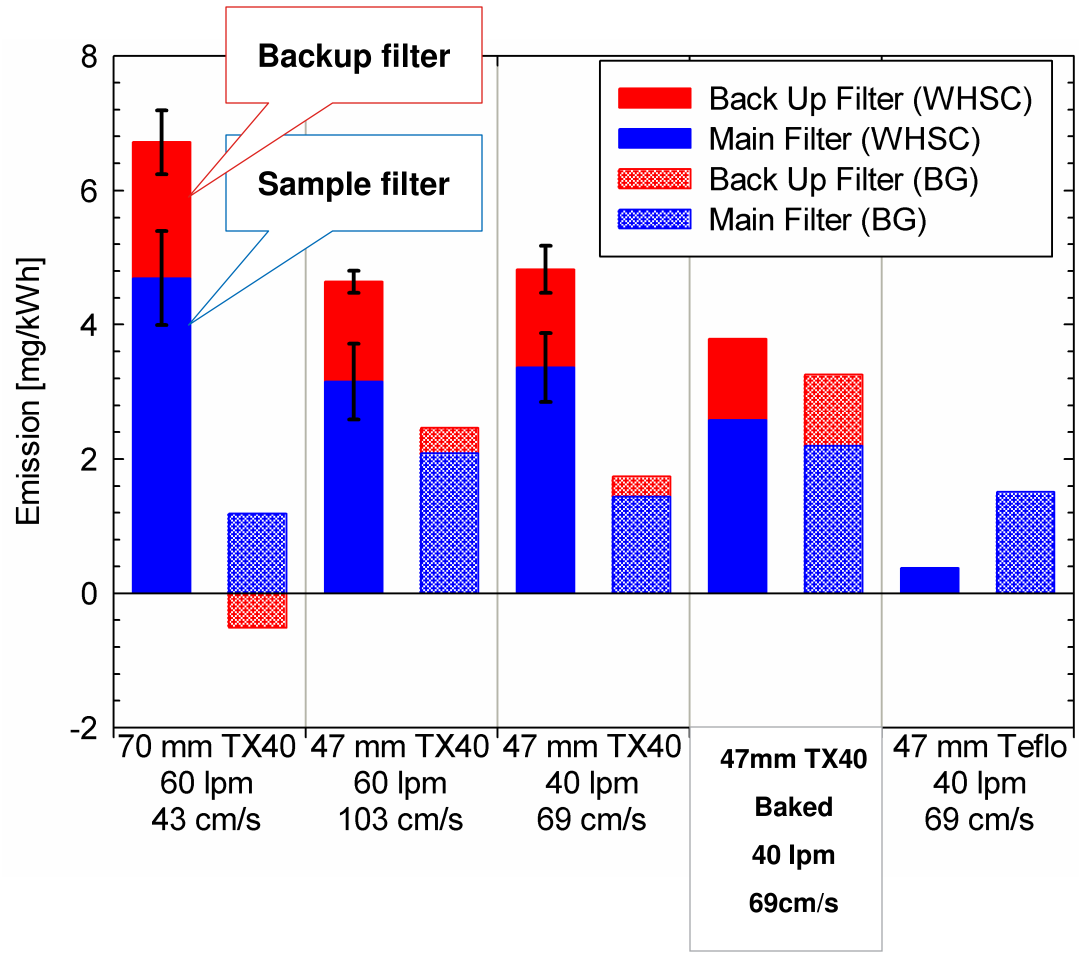
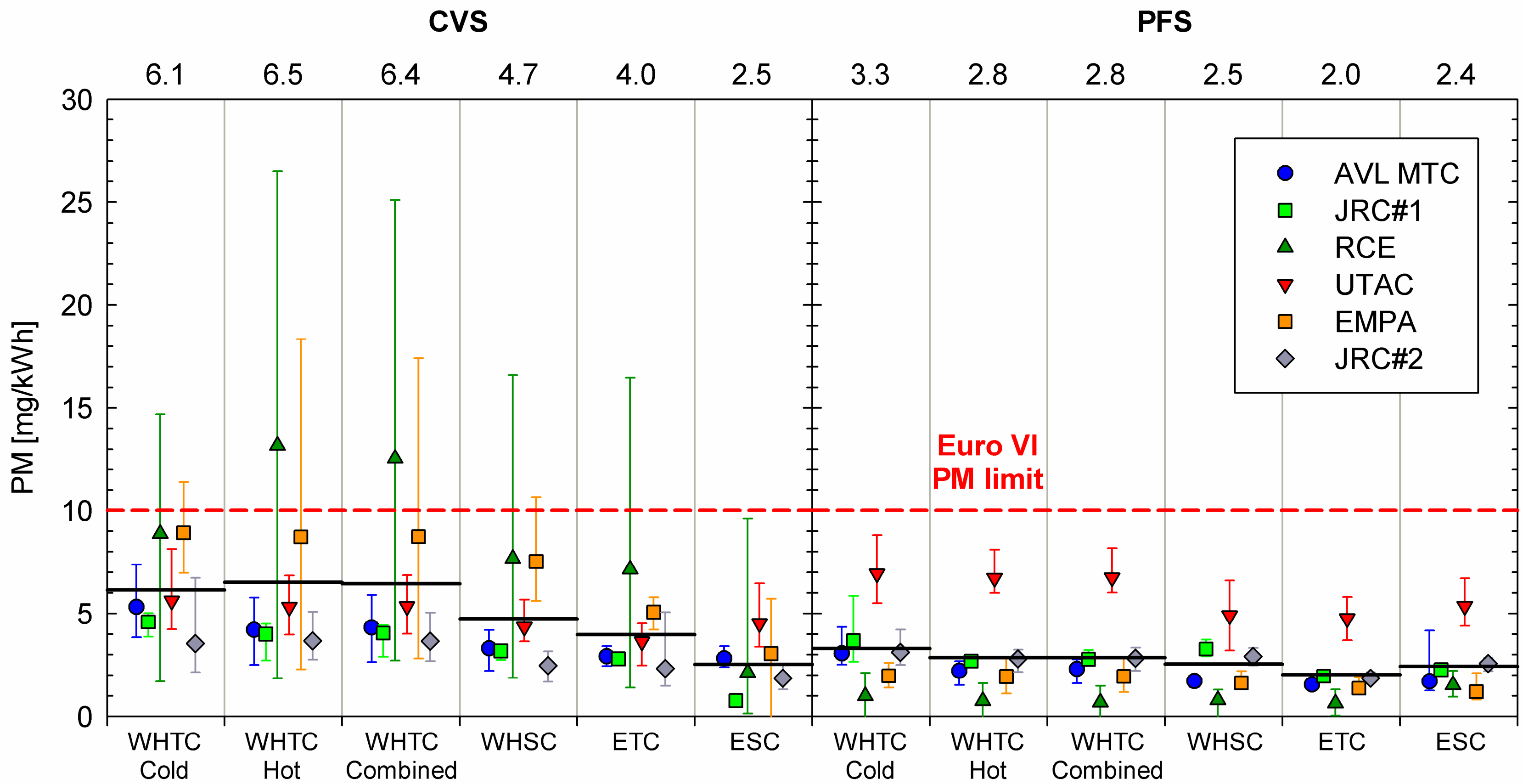


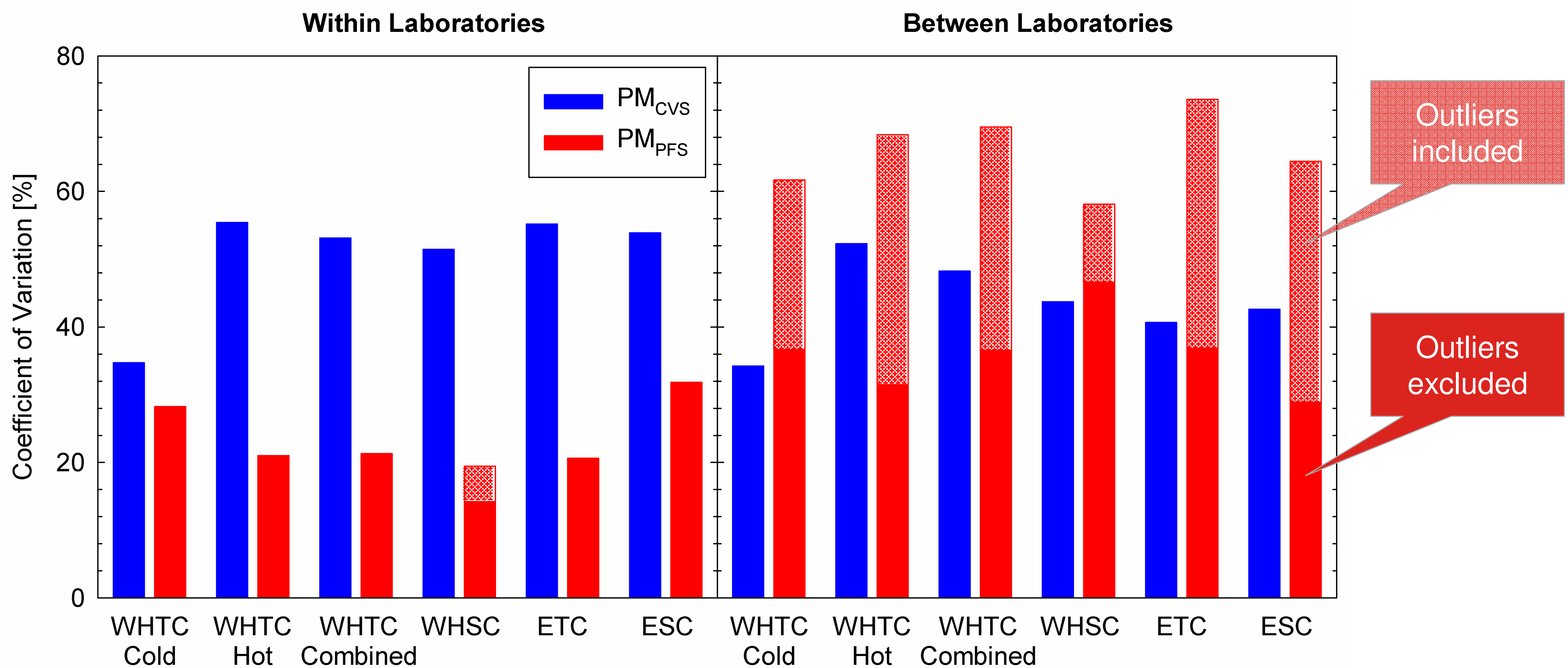
- PM emissions may be slightly higher than background levels
- Higher masses on 70mm filters than 47mm filters, other parameters matched
- Repeatability improves for filter face velocities in the ~70 to 100 cm/s range
- Pre-baking of filters has no beneficial effect
  - No significant residual HCs
- Back-up filters collect ~30% of primary filter mass
- Less mass collected on Teflo filters
  - on average 63% to 81% lower from Teflo filters than from TX40 filters
  - Volatile artefact

PM Emission Levels Generally Well below 10mg/kWh



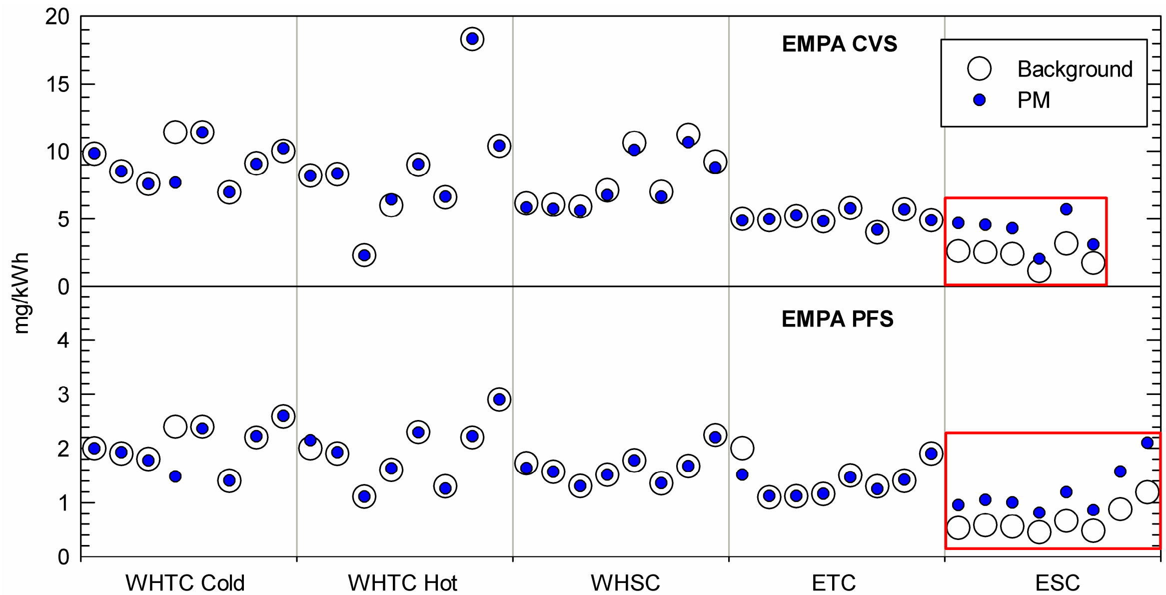
- PM levels were generally < 6 mg/kWh, with no obvious difference between cold and hot tests.
- High and variable background levels in the CVS tunnel of RCE and EMPA led to elevated PM

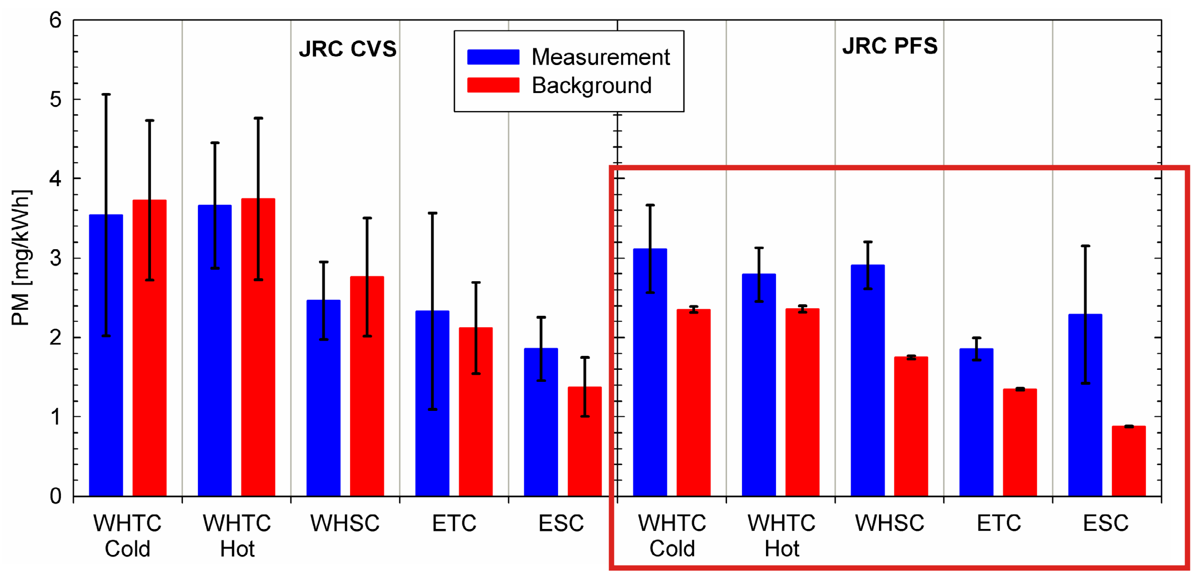
PM Repeatability & Reproducibility Similar



- PM measured at PFS were more repeatable from those determined from the CVS (~20% compared to 50%).
- Reproducibility at ~40% from both systems after excluding outliers (PFS results from UTAC)

Hard to Resolve Sample Masses from Background PM





- In most cases PM background was at the same levels as samples
- CVS results show no discrimination of PM from background
  - Except EMPA over ESC (low volatility HCs and sample time effects)
- PFS system results at JRC suggest that it is just possible to resolve PM emissions from background in a new, very clean PFS
  - Because the background is very low and repeatably so

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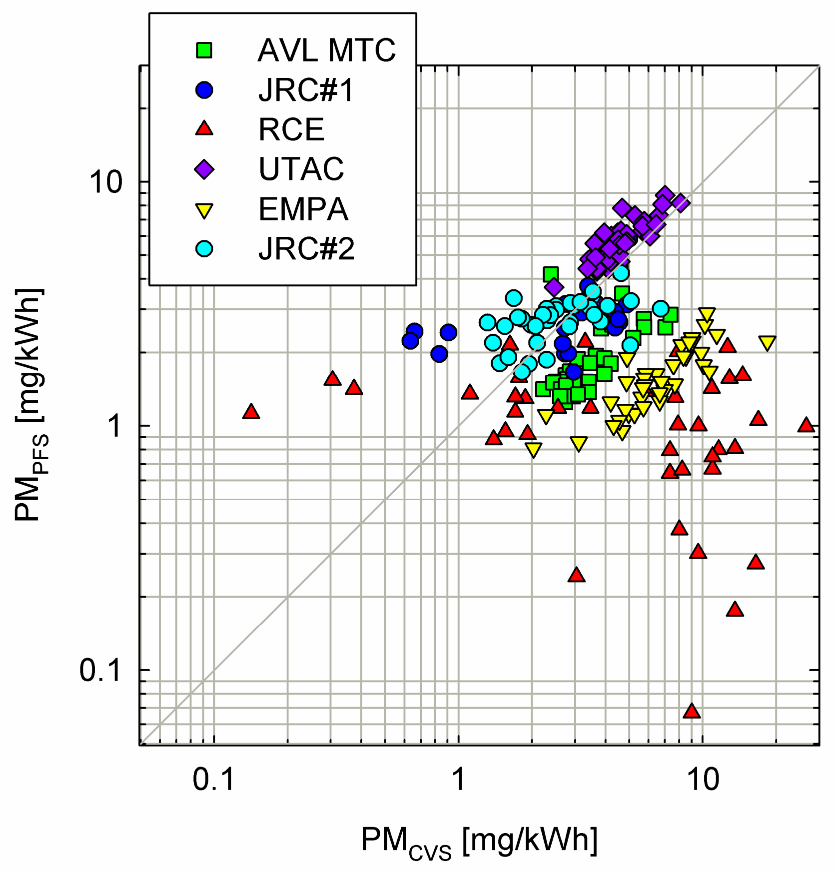
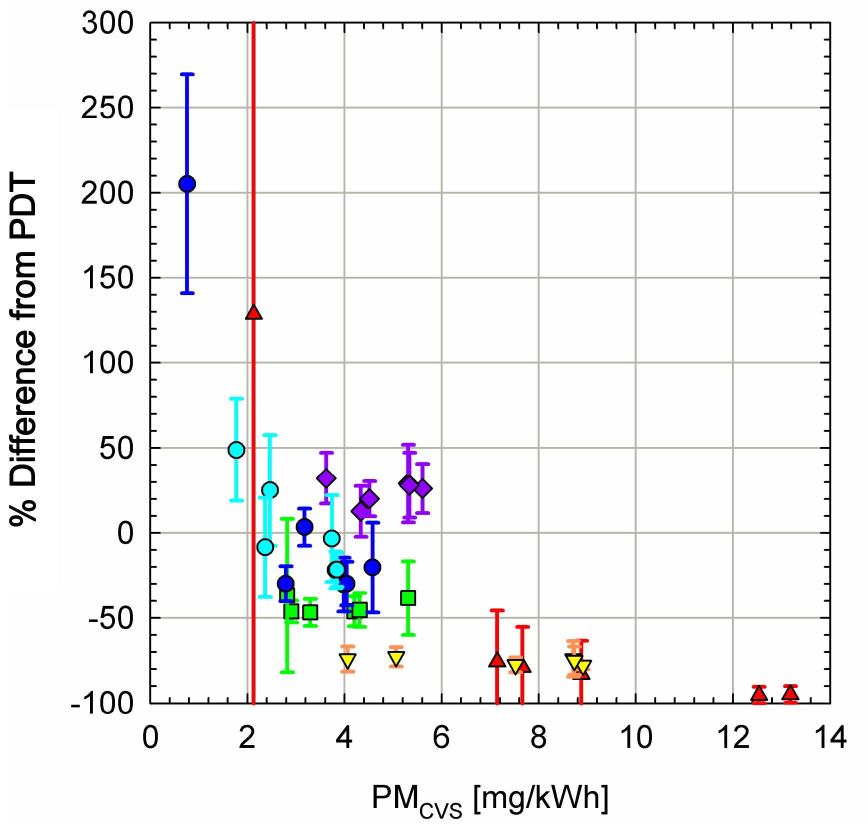
Comparison of PM Measurement systems shows similar levels from CVS and PFS when background is low





- PM levels broadly similar (±50%) for labs with low background
  - This probably demonstrates similarity between background levels
- Mass system suitable for indicating engine emissions are below 10mg/kWh limit

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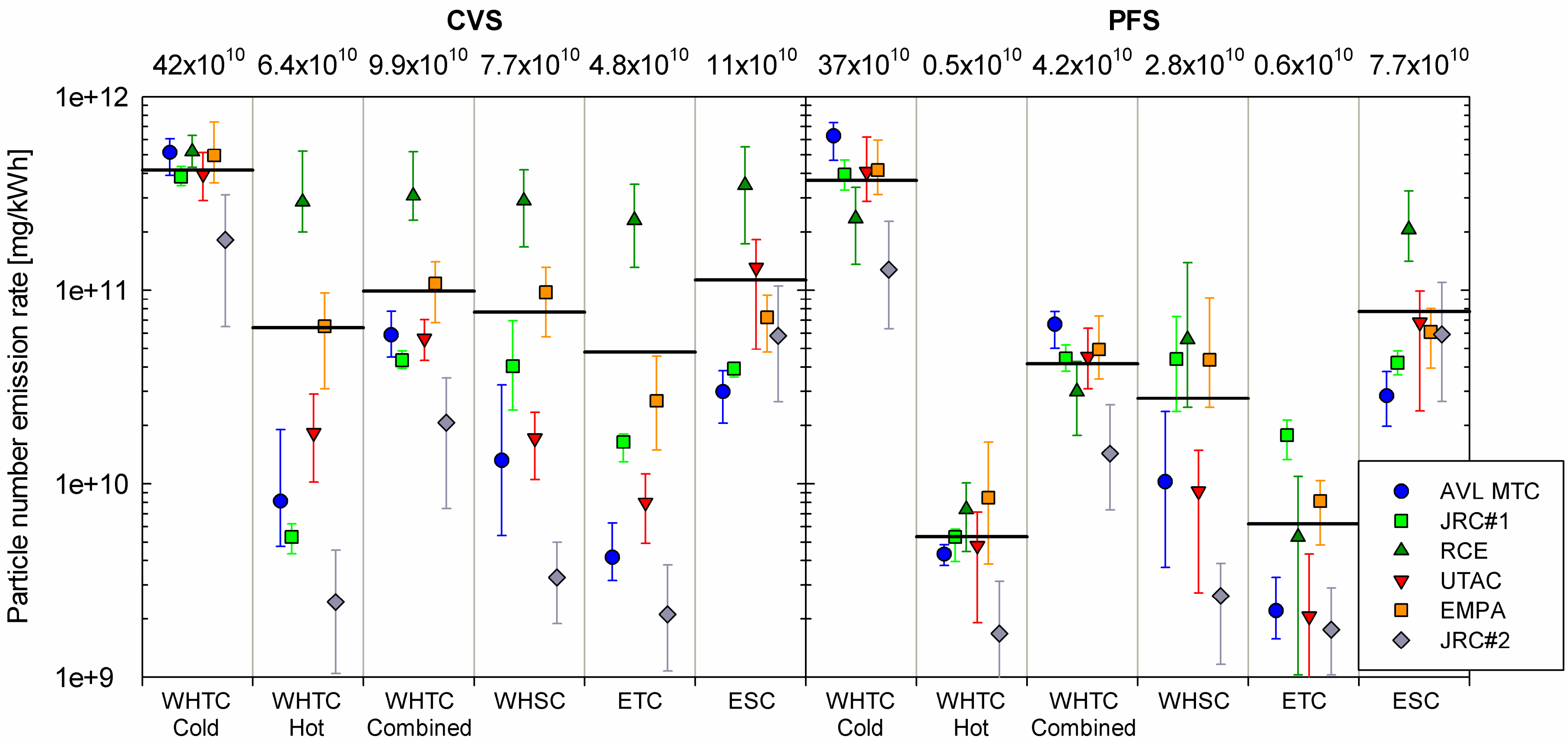
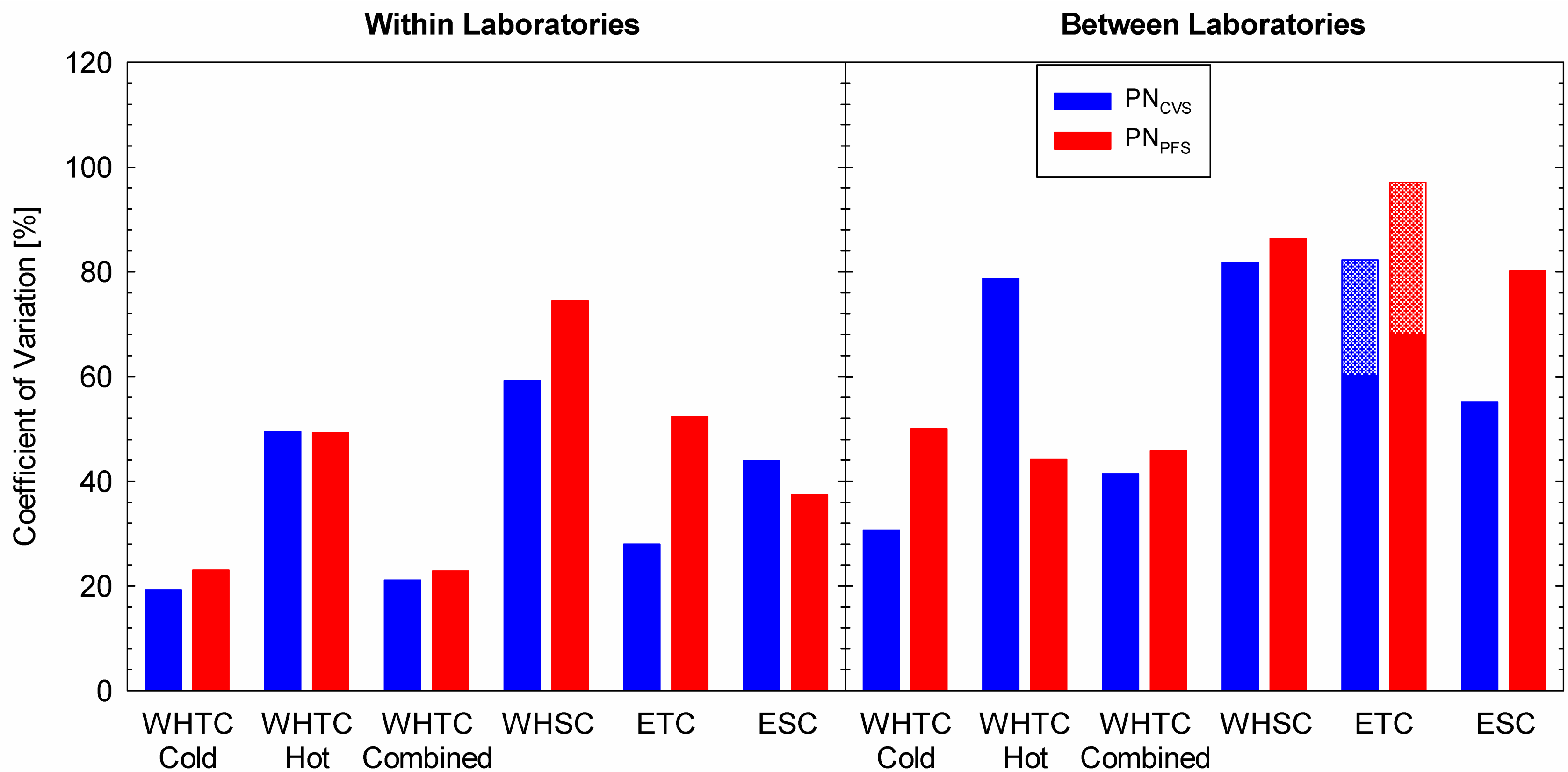
Greater Confidence in PN Emission Levels Comparability from PFS – due to high background CVS systems



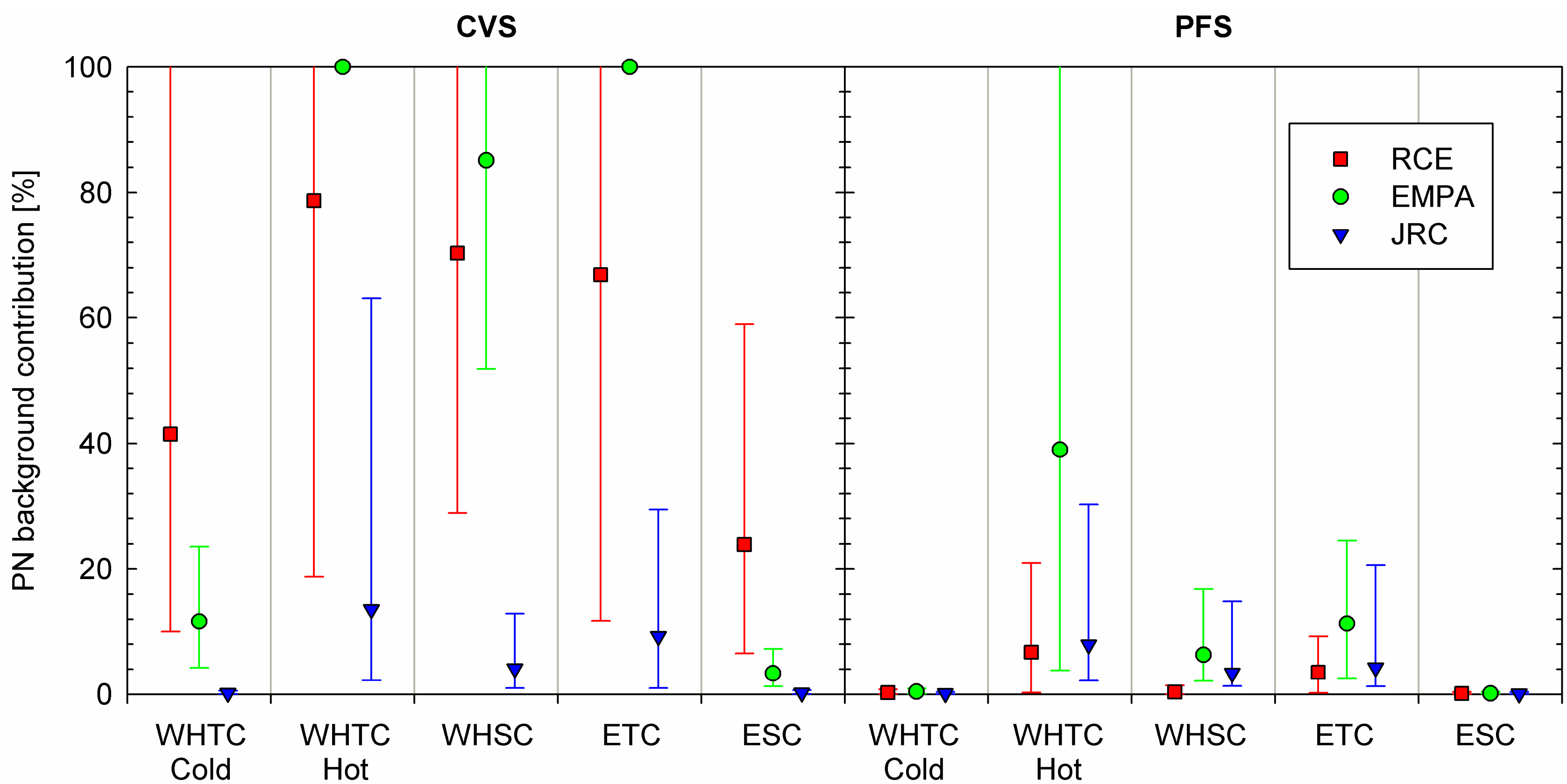
- ~4×10^{11} #/kWh over cold start WHTC
- Lowest emissions over the test cycles that do not have substantial periods of passive regeneration (WHTC hot - ETC)
- Higher levels and increased variability of results from ESC and WHSC due to passive regeneration. But: emission levels below 4×10^{11} #/kWh

PN Repeatability - Reproducibility



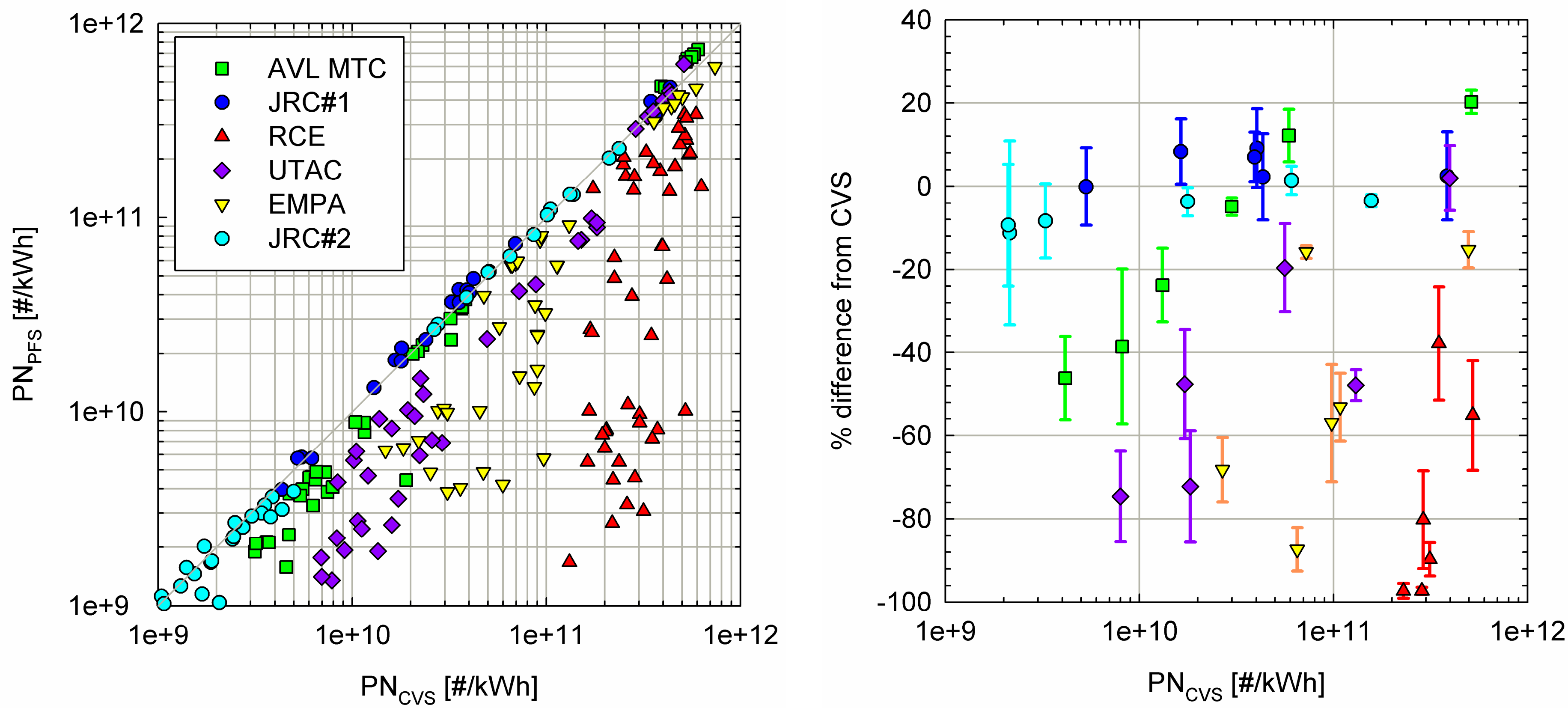
- Repeatability ranged between ~20% (over the high emission cold WHTC) and ~60% (over the high temperature WHSC) for both CVS and PFS after removing outliers
- Reproducibility ranged between ~40% (cold WHTC) and 80% (WHSC).

Background PN Masked Some CVS Results Except for WHTC and ESC



- Some labs (EMPA and RCE) suffered from high PN background levels in the CVS but this was low compared to WHTC cold and ESC emissions levels
- The contribution of background in PFS systems was lower than 20%

Good Agreement of PN from CVS and PFS



- Agreement was better than ±20% at emission levels above the background.

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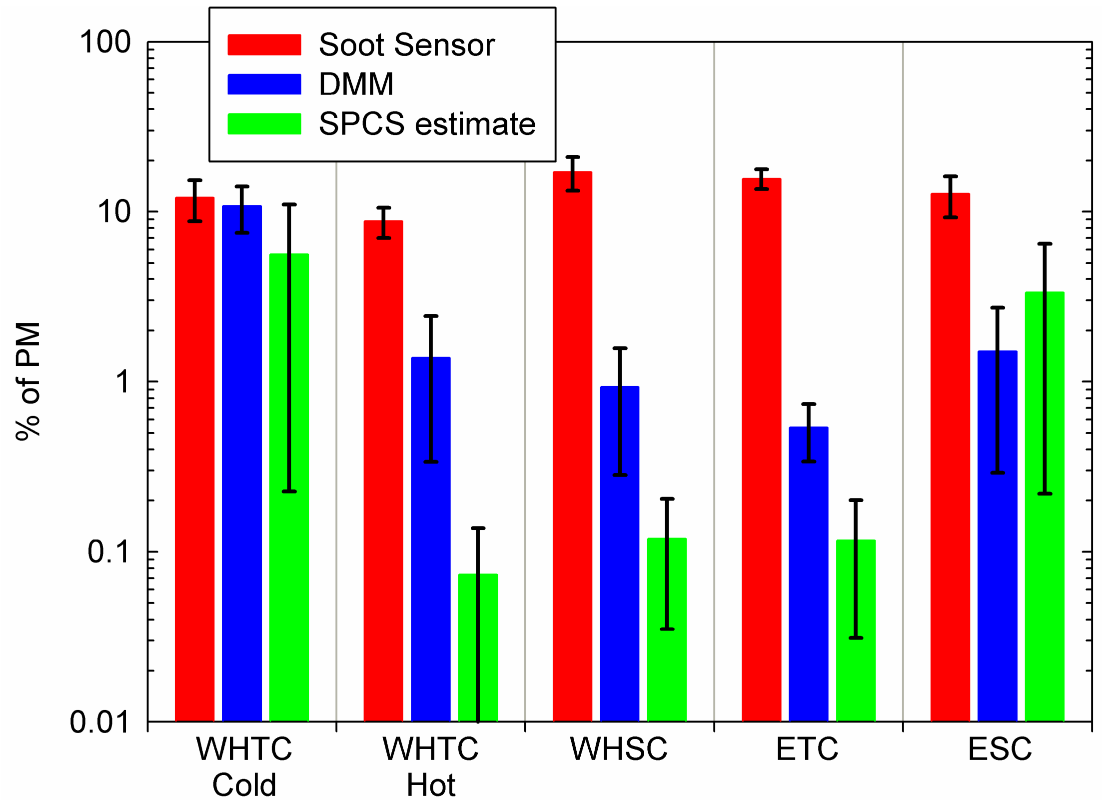
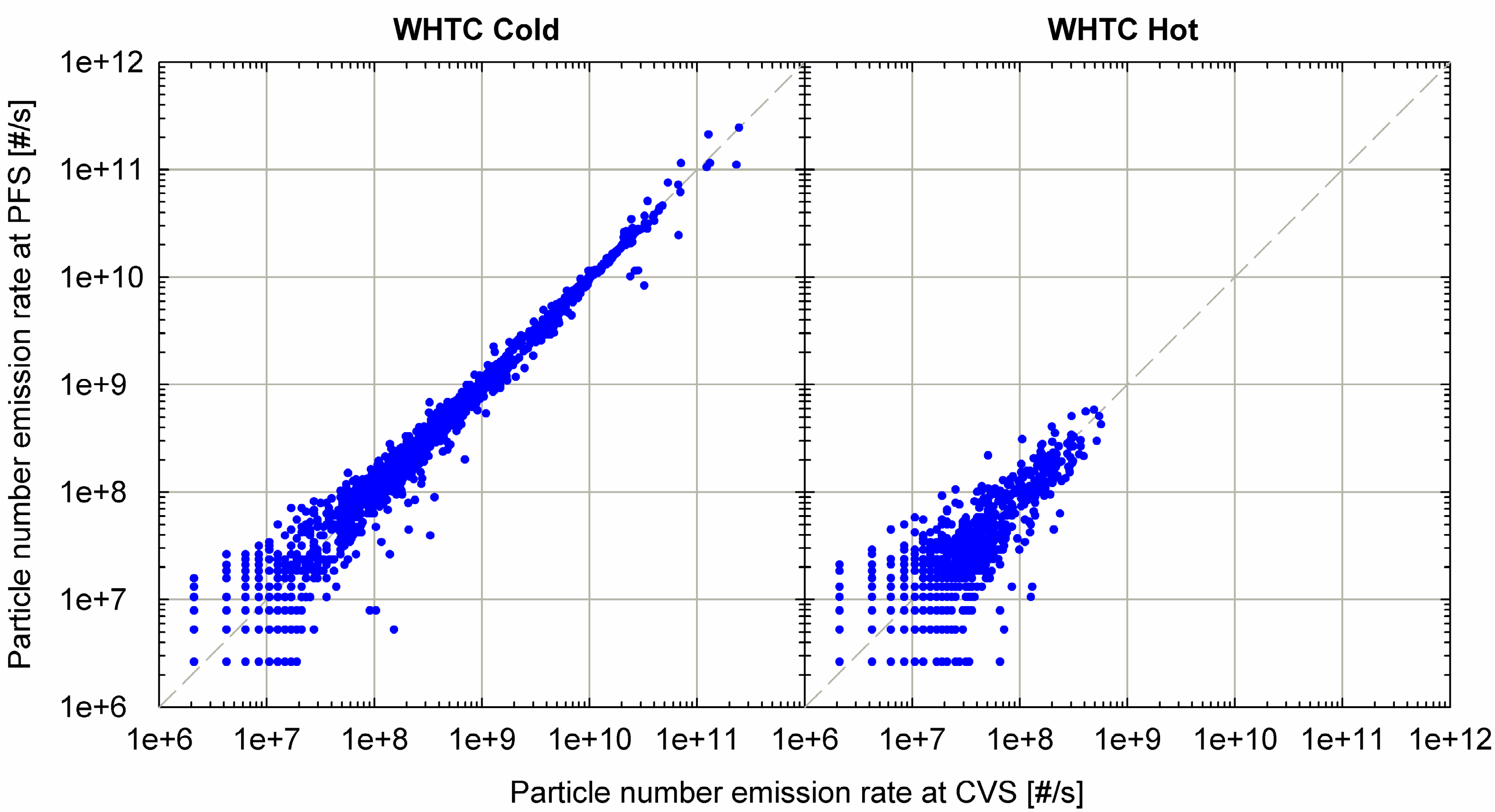
Mass contributed by soot & particles never >20% of PM: Majority of PM is not solid or semi-volatile



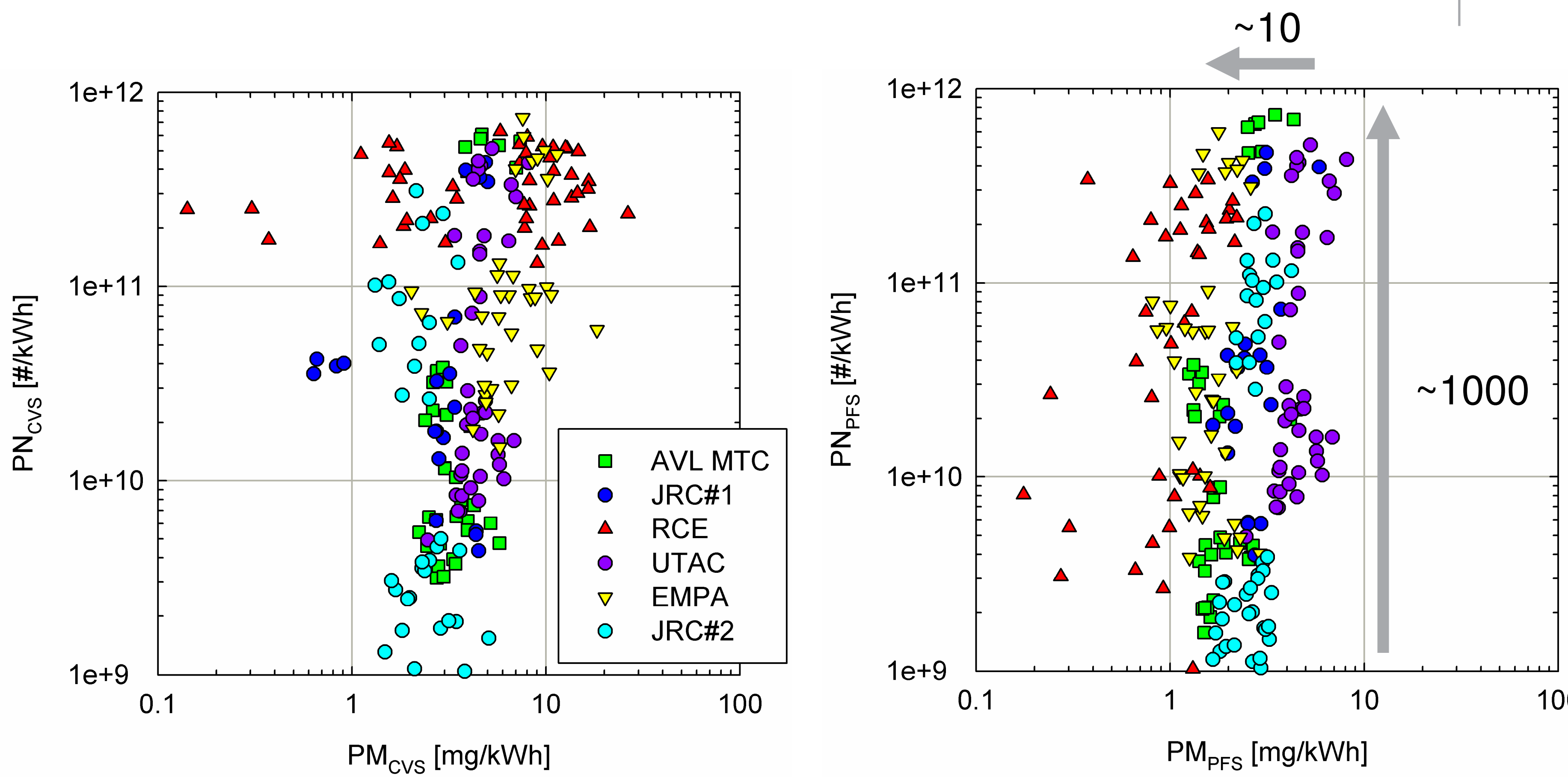
- SPCS estimation assumptions:
  - d_g=70 nm, σ_g=1.8
  - DF=2.3 – 3
  - ρ_0=1.6 - 2 g/cm^3
  - d_{B0}=20 nm
- Data corrected for particle losses
  - in TD, SPCS
- Majority of PM mass is not particles
- Both TX40 and Teflon filters show substantial artefacts
- **AVL soot sensor may have an interference at low emissions levels**

Real time correlations CVS vs PFS: Excellent – In Low Background System



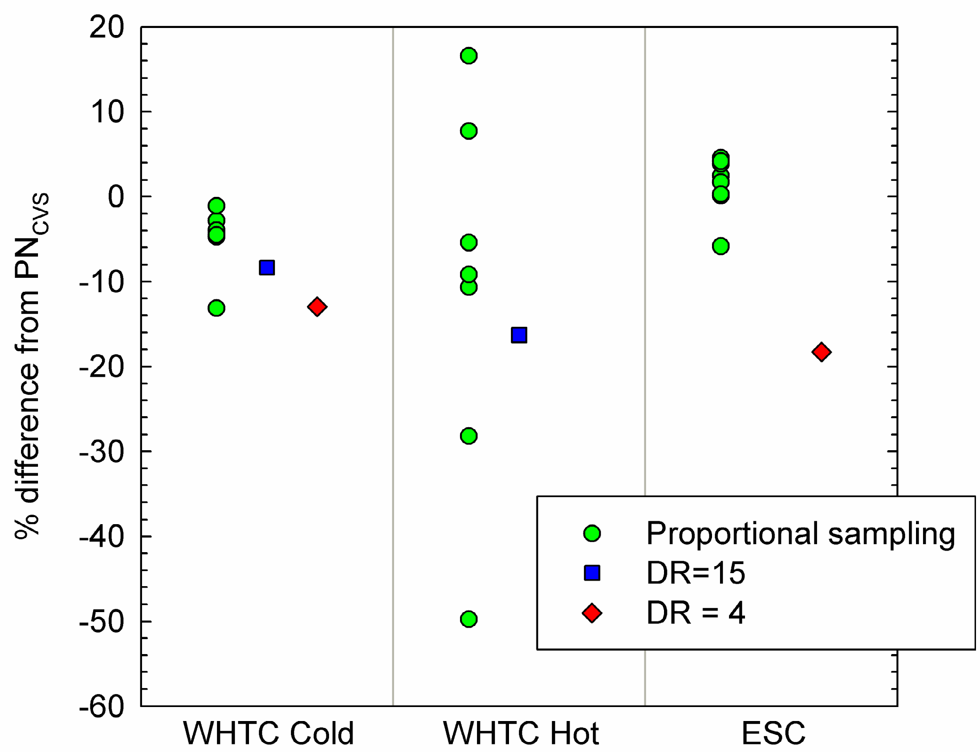
- Real time responses of the PFS and CVS also correlate very well over 5 orders of magnitude
- The deterioration of the correlation at the lowest levels is due to counting statistics (concentration levels over WHTC hot were below 5 #/cm^3)

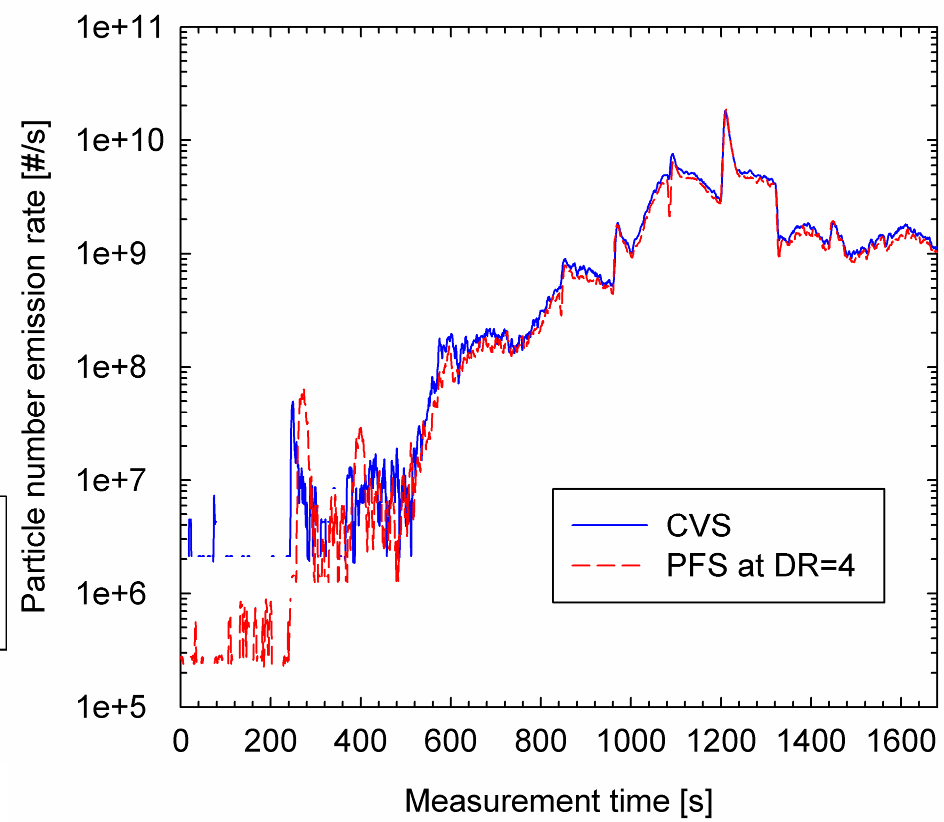
No Correlation between PN & PM in any Test Facility



- PM does not correlate with PN from either CVS or PFS
- PN method much more sensitive
  - PN levels vary over three orders of magnitude
  - PM varies by less than 1 order of magnitude, even for clean dilution systems

A Cheap Approach to PN? PFS at constant DR gives similar results to proportional sampling





- Limited data available suggests acceptable accuracy (better than ~15%) with the use of constant DR even at extreme settings (DR=4).
- The real-time emissions are also reproduced accurately.

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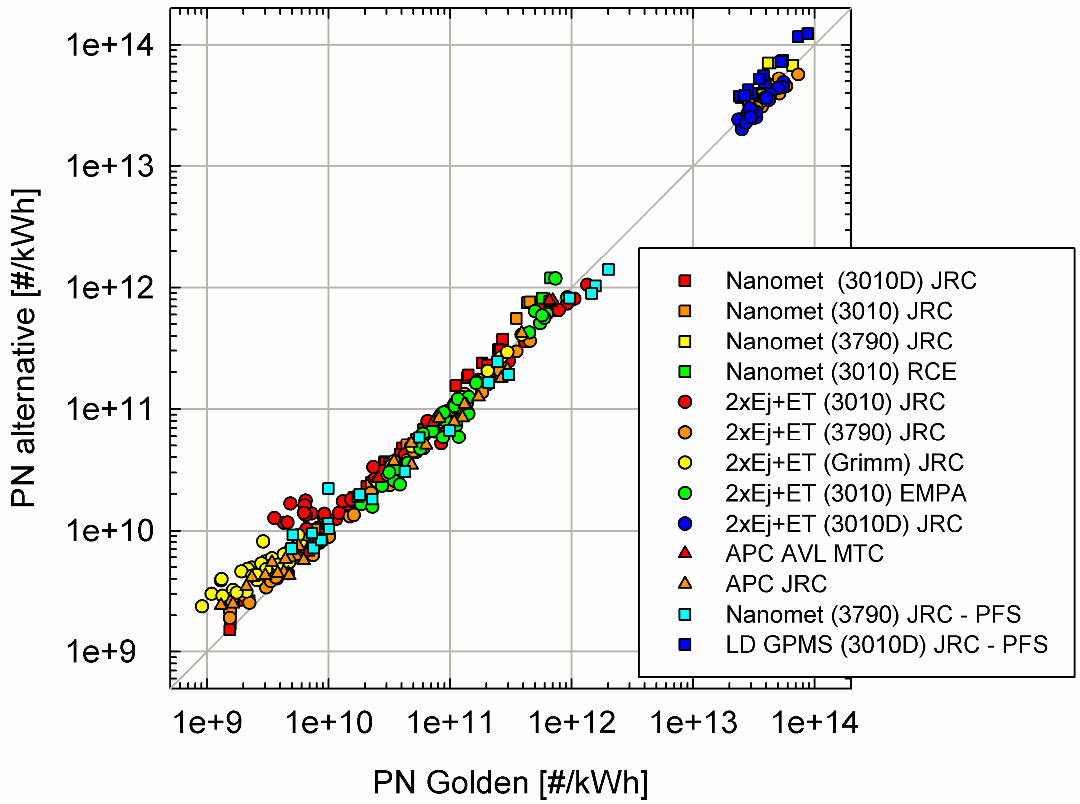
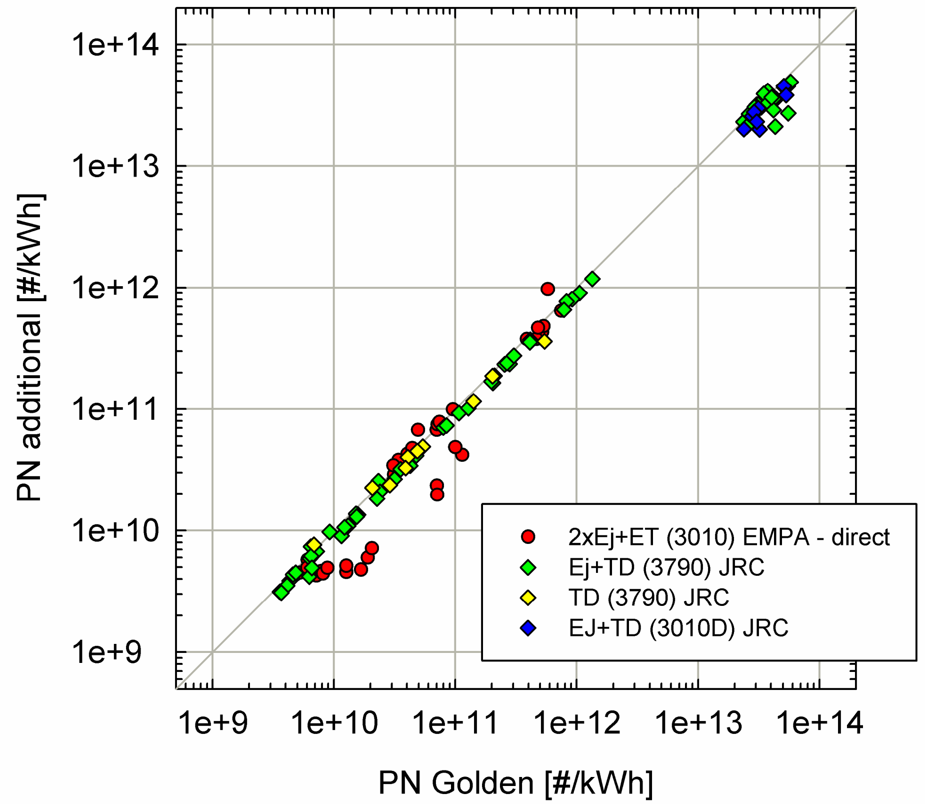
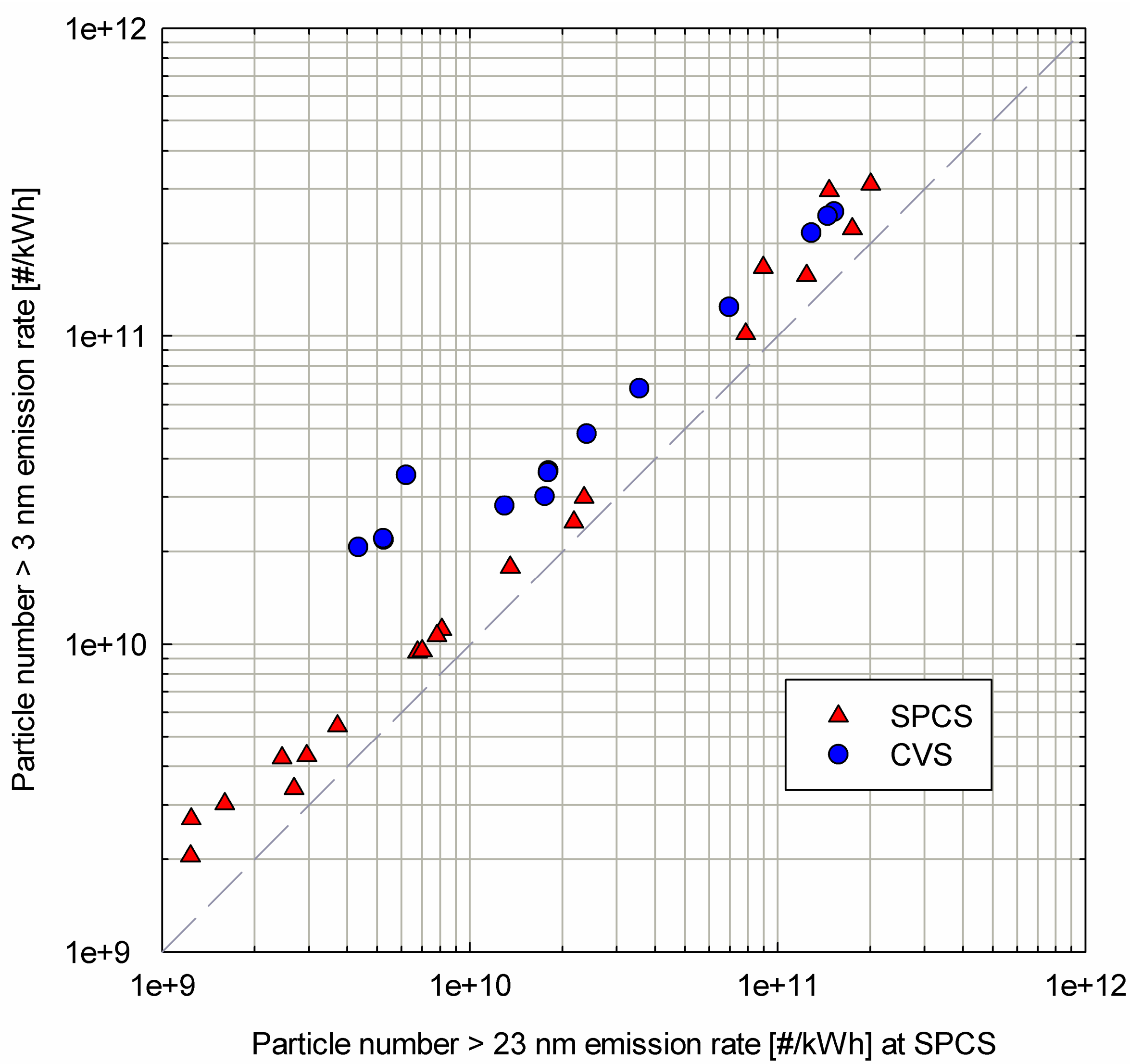
Alternative & Additional PN systems agree to +/-15% with GPMS (with PCRF retrospectively applied)





- Calibrated alternative VPR systems generally agreed with GPMS within ±15%.
- The agreement holds over a range of 5 orders of magnitude but weakens at low concentrations due to background effects.

Fewer particles 3-23 nm than 23nm - 2.5µm



- Total particle number > 3 nm is approximately 80% larger than the "non-volatile" particle number >23 nm.
- "Non-volatile" number concentrations > 3 nm are approximately 40% higher than "non-volatile" number concentrations > 23 nm
- Significant interest from the Commission in the possibility of high levels of <23nm from catalysed DPFs
- CARB considering including <23nm particles in future regulations

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Conclusions #1

- PM:
  - PM emissions were generally <6 mg/kWh.
  - However, background levels were equivalent to drive cycle emissions levels.
  - The majority of PM mass is gaseous/volatiles, which contribute from 10% (cold WHTC) to 99.9% (hot start cycles) of the total mass.
- Particle number:
  - PN emission levels over cold WHTC were determined to be $\sim 4\times10^{11}$ #/kWh with both CVS and PFS systems. At these emission levels, the background effect is insignificant.
  - PN emission levels over hot start WHTC and ETC cycles were $<2\times10^{10}$ #/kWh. Passive regeneration occurring over the WHSC and ESC cycles results in an increase of the emissions up to 6×10^{10} #/kWh
    - Background in some labs was a substantial influence from these cycles

Conclusions #2

- Particle Number#2:
  - Repeatability and reproducibility levels for the CVS and PFS were similar, ranging from:
    - ~20% and ~40%, respectively, over cold WHTC
    - ~70% and ~80%, respectively, over WHSC, due to passive regeneration related emissions.
  - PFS systems showed lower backgrounds than CVS systems, but when the two systems had similar backgrounds, the correlation between PN emission levels was excellent.
  - Particle number emissions do not correlate with PM results, as the later are almost entirely volatile material.

Conclusions #3

- Alternative Systems:
  - The majority of the alternative systems correlated closely with the GPMS, the difference being on average smaller than ±15% after accounting for the PCRF values and the slopes of the CPCs.
  - The observed differences hold for emission levels spanning over ~5 orders of magnitude as well as when different CPC units are employed. This points towards inaccuracies in the determination of the PCRF values or even differences in the PCRF curves.
  - Simplified approaches such as the use of VPR systems sampling directly from the tailpipe or the partial flow operating at constant DR resulted in similar levels of agreement (<15%).

Further Work

- Background:
  - Correction
  - Possibilities to reduce PFS background making PM resolvable
  - Dilution air filtration of alternative systems (HEPA or ULPA?)
- VPR calibration
- VPR systems sampling directly from exhaust
- <23nm particles

Thank you

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