

# **Particle Measurement Programme (PMP) Heavy-duty Inter-laboratory Correlation Exercise (ILCE\_HD) Final Report**

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## CONTENTS

<b>1.</b>	<b>INTRODUCTION</b> .....	<b>10</b>
<b>2.</b>	<b>OBJECTIVES</b> .....	<b>11</b>
<b>3.</b>	<b>NATURE AND SCOPE OF THE ILCE_HD</b> .....	<b>11</b>
3.1	Background to the PMP .....	11
3.2	PMP Phase 3 Inter-laboratory Exercise for Light-duty Vehicles .....	12
3.3	Brief Overview of the Inter-laboratory Correlation Exercises for Heavy-duty Engines .....	13
3.4	Test Engine and Emissions Control System .....	15
3.4.1	CRT: Pt-based Oxidation Catalyst and Wall-flow DPF .....	18
3.5	Fuel and Lubricant .....	18
3.6	Gaseous Emissions Measurement Systems .....	19
3.7	Dilution Approaches .....	20
3.7.1	Principles of the Dilution Systems .....	20
3.8	Particulate Mass Measurements .....	23
3.8.1	Full Flow Measurements .....	23
3.8.2	Partial flow Measurements .....	24
3.9	Particle Number Measurement Systems .....	25
3.9.1	Principles of the Measurement System .....	25
3.9.2	Golden Particle Measurement Systems .....	25
3.9.3	Alternative Systems .....	27
3.9.4	Additional instrumentation .....	28
3.10	Test Programme .....	28
3.10.1	Participating Laboratories .....	28
3.10.2	Summary of Preliminary Experiments .....	29
3.10.3	Daily Protocol .....	38
<b>4.</b>	<b>STATISTICAL ANALYSES</b> .....	<b>39</b>
4.1	Definitions .....	40
4.1.1	Basic statistical concepts .....	40
4.1.2	Intra- And Inter-Laboratory Variance Estimators .....	41
4.1.3	Statistical outliers .....	41
<b>5.</b>	<b>CALIBRATION AND VALIDATION</b> .....	<b>43</b>
5.1	Mass systems .....	43
5.2	Number systems .....	43
<b>6.</b>	<b>EMISSIONS RESULTS</b> .....	<b>44</b>
6.1	Full Flow and Partial Flow PM .....	44
6.1.1	PM - Repeatability .....	44
6.1.2	PM - Reproducibility .....	46
6.1.3	PM – Filter Weights, Background Levels and Background Subtraction .....	47
6.1.4	PM – Emissions Levels .....	52
6.1.5	PM – Daily Trends .....	55
6.1.6	Overview of PM Results .....	56
6.2	Full Flow and Partial Flow PN .....	57

6.2.1	PN – Background Levels .....	57
6.2.2	PN - Repeatability .....	59
6.2.3	PN - Reproducibility.....	72
6.2.4	PN – Emissions Levels.....	73
6.3	Gaseous Emissions.....	81
6.4	Long-term trends in engine operation .....	82
6.4.1	Regulated Gases.....	82
6.4.2	Particle Number Emissions .....	87
<b>7.</b>	<b>ADDITIONAL TESTWORK OVERVIEW .....</b>	<b>89</b>
7.1	Mass Contributed by EC and by Particles.....	89
7.2	Further Filter Media Evaluations .....	92
7.3	Particle Number Measurements from PDT at Constant Dilution Factors.....	94
<b>8.</b>	<b>COMPARISONS OF MEASUREMENT SYSTEMS .....</b>	<b>97</b>
8.1	Comparison of Particle Number Measurements from CVS and PDT .....	97
8.2	Comparison of Particulate Mass Systems.....	100
8.3	Mass vs. Number full flow .....	102
8.4	Mass vs. number partial flow .....	103
8.5	Comparisons Of Alternative And Additional Systems.....	105
8.5.1	Alternative and Additional Systems .....	105
8.5.2	Particle Losses.....	106
8.6	Results from Golden Engine equipped with DPF .....	108
8.6.1	Alternative systems .....	108
8.6.2	Additional systems .....	111
8.7	Engine out and open flow emission levels .....	112
8.8	Raw and dilute gases .....	116
<b>9.</b>	<b>DISCUSSION AND OVERVIEW.....</b>	<b>116</b>
9.1	Particulate Measurements .....	116
9.1.1	Recommended Filter Loading.....	116
9.1.2	Validation Exercises .....	116
9.1.3	Background Mass Levels - CVS.....	116
9.1.4	Background Mass Levels - PDT .....	117
9.1.5	Emissions Levels.....	118
9.1.6	Background Subtraction .....	118
9.1.7	Partial Flow or Full Dilution.....	118
9.2	Particle Number Measurements.....	119
9.2.1	Golden Systems – PCRF Correction .....	119
9.2.2	Particle Number Backgrounds.....	119
9.2.3	Real-time Particle Emissions Elevated at Cold Start.....	119
9.2.4	PN Emissions Levels Compared with Backgrounds .....	120
9.2.5	PN Emissions levels.....	120
9.3	Repeatability and Reproducibility.....	121
9.3.1	PM and PN – Repeatability .....	121
9.3.2	PM and PN – Reproducibility.....	122
9.3.3	Repeatability and Reproducibility Overview.....	122

9.4	Elemental carbon and non-volatile particle contributions to PM .....	122
9.5	Filter Media Effects.....	123
9.6	Alternative Systems.....	123
9.7	Should Solid Particles <23nm be Considered for European PN Legislation? .....	124
9.8	Euro VI Certification.....	125
9.9	Achievable PN Limit for this Engine .....	125
9.10	Simulation of RR with alternative systems .....	125
9.11	An Economical Approach to Legislative PN Measurements.....	125
<b>10.</b>	<b>CONCLUSIONS (<i>To be refined</i>).....</b>	<b>126</b>
10.1	Engine Operation.....	126
10.2	Measurement Systems .....	126
10.3	PM Emissions.....	126
	10.3.1 Levels.....	126
	10.3.2 Repeatability / Reproducibility .....	127
10.4	PN Emissions .....	127
	10.4.1 Levels.....	127
	10.4.2 Repeatability / Reproducibility .....	128
10.5	Relationships Between Measurement Approaches.....	128
	10.5.1 Full Vs Partial Flow Mass .....	128
	10.5.2 Full Vs Partial Flow Number .....	128
	10.5.3 Mass Vs Number.....	129
	10.5.4 Number Vs Number.....	129
10.6	Alternative Systems.....	129
10.7	General Conclusions .....	129
<b>11.</b>	<b>RECOMMENDATIONS .....</b>	<b>130</b>

## List of Figures

Figure 1: Typical Engine and Emissions Control System Installations .....	15
Figure 2: Schematic of Exhaust and Emissions Control System Layout .....	17
Figure 3: Schematic of Full Flow, Double Dilution System for PM Measurements .....	20
Figure 4: Schematic of Partial Flow Dilution System for PM Measurements .....	20
Figure 5: PDT – Principle of Dilution .....	22
Figure 6: Flow schematic of the prototype SPCS.....	27
Figure 7: PM Sampling Set-up for Experiment 1 .....	31
Figure 8: Experiment 1 - Background and Sampling Parameters for PM .....	31
Figure 9: Minimal Impact of Heated Line on PN Results.....	33
Figure 10: Minimal Impact of Cyclone on PN.....	33
Figure 11: DPF Preconditioning –Regeneration (Mode 10) and Fill (Mode 7) .....	36
Figure 12: Stable Mode 7 Selected for the Continuity Protocol .....	36
Figure 13: Particle Number Emissions <23nm.....	37
Figure 14: Repeatability of the CVS PM Method.....	45
Figure 15: Repeatability of the PDT PM Method.....	46
Figure 16: Reproducibility of PM Methods .....	47
Figure 17: Sampled Filter Masses – Various Cycles, Both Measurement Systems.....	48
Figure 18: Filter Masses - Samples and Backgrounds Compared .....	49
Figure 19: Background and Sample PM levels - CVS.....	50
Figure 20: Background and Sample PM levels - PDT .....	51
Figure 21: Maximum and Minimum Ranges of Emissions – CVS PM .....	54
Figure 22: Maximum and Minimum Ranges of Emissions – PDT PM .....	54
Figure 23: CVS PM Emissions through the Test Sequence – All labs.....	55
Figure 24: PDT PM Emissions through the Test Sequence – All labs.....	56
Figure 25: Background Impacts PN Results – CVS Systems at 3 Labs .....	58
Figure 26: Background Effect on PN Results Minimal– PDT Systems at 3 Labs.....	58
Figure 27: Particle Number Backgrounds – 3 Labs; CVS and PDT Facilities.....	59
Figure 28: Real-time Data – Cycle-to-cycle Repeatability, Cold WHTC .....	62
Figure 29: Real-time Data – Cycle-to-cycle Repeatability, Hot WHTC .....	64
Figure 30: Real-time Data – Cycle-to-cycle Repeatability, Hot WHSC.....	66
Figure 31: Passive Regeneration During the WHSC.....	68
Figure 32: Real-time Data – Cycle-to-cycle Repeatability, Hot ESC .....	69
Figure 33: Repeatability of Particle Number Measurement Systems .....	72
Figure 34: Reproducibility of Particle Number Measurement Systems.....	73
Figure 35: Maximum and Minimum Ranges for CVS-measured PN .....	75
Figure 36: CVS PN Results – Effect of Eliminating Outliers .....	76
Figure 37: Maximum and Minimum Ranges for PDT-measured PN.....	79
Figure 38: All Labs' Mean of Means PN Results - PDT Systems .....	80
Figure 39: CO <sub>2</sub> – Consistency Across The Validation Exercise.....	83
Figure 40: NO <sub>x</sub> – Consistency Across The Validation Exercise .....	85
Figure 41: PN from cold-WHTC: Consistency Through The Test Programme .....	87
Figure 42: Real time PN Production from the CVS- Cold WHTC (JRC#1) .....	89
Figure 43: Real time PN Production from the CVS- Cold WHTC (JRC#2) .....	89
Figure 44: Fraction of PM Mass Contributed by Solid Particles (>300°C) .....	91
Figure 45: Fraction of Mass Contributed by EC .....	91
Figure 46: PM results obtained using TX40 and TEFLO filters – JRC CVS .....	93
Figure 47: PM results obtained using TX40 and TEFLO filters – JRC PDT.....	94
Figure 48: Cycle Averaged PN Results: Proportional Vs. Constant Dilution.....	95
Figure 49: PN from Proportional and Constant Dilution Sampling Compared .....	96
Figure 50: Correlation of PN from Proportional and Constant Dilution Sampling.....	96
Figure 51: PM Sampled From Proportional Dilution and Constant Dilution .....	97
Figure 52: Correlations between PN Measured from CVS and PDT Systems.....	98

Figure 53: Correlations between Real-time PN from CVS and PDT Systems .....	99
Figure 54: Percentage Differences in PDT Emissions Compared to CVS – All Labs .	100
Figure 55: Correlations between PM Measured from CVS and PDT Systems .....	101
Figure 56: PDT PM results: % Difference to CVS PM Data .....	102
Figure 57: Relationship between Mass and Number Measurements (CVS).....	103
Figure 58: Relationship between Mass and Number Measurements (PDT).....	104
Figure 59: No Correlation Exists PM & PN Even in a Very Low Emissions PDT .....	105
Figure 60: Correlation between the alternative and the GPMS systems .....	109
Figure 61: Comparison of real time particle number concentrations in the CVS tunnel determined with the GPMS and a dual ejector plus ET system over WHTC Cold and WHTC Hot .....	111
Figure 62: Correlation between the additional and the GPMS systems.....	112
Figure 63: Correlation between the alternative and the GPMS systems at engine out emission levels .....	113
Figure 64: Correlation between the alternative and the GPMS systems at engine out emission levels .....	114

#### List of TABLES

Table 1: Test Engine and Specification.....	15
Table 2: Exhaust System Installation Variability at the Test Laboratories .....	17
Table 3: Fuel specifications .....	18
Table 4: Lubricant Properties.....	18
Table 5: Principal Differences Between CVS Systems – Test Labs .....	24
Table 6: Principal Differences Between PDT Systems – Test Labs .....	25
Table 7: Test Laboratories and Timeline.....	28
Table 8: Matrix for Emissions Testing .....	39
Table 9: Limits of Detection – PM Methods at JRC and EMPA .....	51
Table 10: Maximum and Minimum Ranges for CVS-measured PN.....	74
Table 11: Maximum and Minimum Ranges for PDT-measured PN.....	77
Table 12: Contribution of soot and solid airborne particles on the PM collected on filters as determined by the Soot Sensor and the DMM, respectively .....	90
Table 13: Particle penetrations through the various alternative – additional systems used in the PMP HD validation exercise. ....	107
Table 14: Percentage difference between the different CPCs employed and the Golden CPC of SPCS19. ....	107
Table 15: Percentage differences in the number concentrations measured with the alternative – additional systems and the GPMSs.....	115

# TITLE

## Executive Summary

### 1. INTRODUCTION

The effect of exhaust emissions from road vehicles on public health has long been a concern. Legislation limiting the pollutant emissions of new vehicles is well established in many regions of the world. One emission of special concern is particulate matter. In vehicle exhaust this consists of tiny solid particles and liquid droplets ranging in size from a few nanometres to up to around one micrometre in diameter. Current legislative emissions standards regulate particle emissions in terms of the total mass of particulate matter emitted per kilometre travelled. This is effective at controlling emissions of larger size particles, but particles at the smaller end of the size range contribute little to the total mass of particulate matter emitted.

There is a growing consensus amongst health experts that particles in the ultrafine (<100nm diameter) size range may be those which are having the greatest adverse effect on human health. The main driver behind Particle Measurement Programme (PMP) is the impact of particles on human health. The PMP has no medical expertise and does not seek to pre-judge the advice that may emerge from medical experts with respect to the most crucial particle characteristics affecting human health. Nonetheless, current medical opinion suggests that reductions in particle emissions will lead to improved air quality and health and the PMP has therefore moved forward on the basis of the precautionary principle. This and the potential limitations of current regulatory procedures at forcing technology that would control these particle emissions led to the setting up of the PMP as a Working Group of the UN-ECE GRPE. PMP is essentially a collaborative programme of Government sponsored research projects. However the Working Group, chaired by the UK, exists to co-ordinate the research and ensures that the programme is open to contributions from a wider audience. National Governments, individual laboratories, exhaust aftertreatment, automotive industry and fuel industry representatives have all provided significant input to the programme.

The mandate given to the PMP Working Group by GRPE was to develop new particle measurement techniques to complement or replace the existing particulate mass measurement, with special consideration to measuring particle emissions at very low levels. These techniques should include a detailed specification of test procedures and equipment, be suitable for Light Duty Vehicle and Heavy Duty Engine type approval testing and be suitable for use in transient testing. Since, within the EU, type approval testing to demonstrate compliance with emissions standards involves a limited number of tests which could take place at one of many laboratories, good repeatability and reproducibility from laboratory-to-laboratory are key requirements for regulatory measurement techniques. PMP has therefore sought to demonstrate the repeatability and reproducibility of the proposed techniques. PMP was also tasked with accumulating data on the performance of a range of engine/vehicle technologies when tested according to the proposed procedures.

## **2. OBJECTIVES**

## **3. NATURE AND SCOPE OF THE ILCE\_HD**

### **3.1 Background to the PMP**

In 2001, the French, German, Netherlands, Swedish and United Kingdom Governments agreed to a collaborative programme aimed at developing new methods and procedures to facilitate the control of ultrafine particles within a regulatory framework. This programme was designed to deliver a regulatory procedure that would either replace or complement the existing procedure used for particulate mass measurement.

The resulting Particle Measurement Programme (PMP) working group, chaired by the United Kingdom's Department for Transport, operates under the auspices of the UNECE, where the government of Switzerland joined the consortium. Japanese and Korean governments have also contributed.

The PMP working group devised a three-phased approach to the PMP Programme.

In the first two phases of the programme, a wide range of measurement instruments and sampling systems were assessed over standard regulatory tests:

In the PMP Phase 1 study, measurement systems addressing several key particle properties including mass, number, active surface and chemistry were evaluated along with appropriate dilution methods, sample conditioning and consideration of cost and logistical aspects.

Phase 2 subjected the best performing systems from Phase 1 to more rigorous evaluations. Aims were to confirm the results of Phase 1 and determine fundamental levels of repeatability within a single laboratory during a variety of steady state and transient tests with both engine-out and post-DPF exhaust aerosols. The testing from Phase 2 enabled the conclusions that a revised filter mass measurement method and a particle number method both, based upon sampling from a standard dilution system, best met the original objectives of the programme. The two recommended systems were:

- A filter method based broadly upon those currently used in Europe and the US and that proposed for the US for 2007 type approvals
- A particle number method using a Particle Counter, a selected size range and sample pre-conditioning to eliminate volatile particles

Draft revised versions of the light-duty vehicle (DR83 [1]) and heavy-duty engine (DR49 [2]) particulate regulatory sampling annexes were prepared from the existing regulatory documents: R83 [3] and R49 [4].

The new documents integrated the PMP particulate and particle number approaches into the existing regulatory framework and also formed the bases for two test protocol documents written as laboratory guides for testing. The PMP Phase 3 "Inter-Laboratory Correlation Exercises" (ILCE) for light-duty vehicles (ILCE\_LD) and heavy-duty engines (ILCE\_HD) then commenced with the light duty vehicles' exercise.

### **3.2 PMP Phase 3 Inter-laboratory Exercise for Light-duty Vehicles**

The light duty vehicles' exercise circulated a Euro 4 light-duty Diesel vehicle equipped with an OEM fit Diesel Particulate Filter (DPF) plus a reference "Golden" particle

measurement system (GPMS) between laboratories. In addition, each lab was invited to employ other particle measurement systems constructed to meet the design criteria of the GPMS, and to test other Euro 4 vehicles. Testing followed the procedures described in the inter-laboratory guide for light-duty vehicles (ILG\_LD) [5] and comprised the measurement of regulated gaseous emissions, particulate mass and particle number from repeat NEDC tests. To ensure maximum consistency of testing between laboratories, the Golden Engineer and project manager visited the participating labs to advise on facility modifications, how to undertake the test protocols and installation and operation of the GPMS. Low sulphur fuel and lubricant from the same batches were also used at all labs.

The ILCE\_LD has now completed, with the final report published in June 2007 [6] and extended data analyses published in the scientific literature [7], [8].

The general conclusions of the ILCE\_LD are presented below:

- The revised PMP mass method provides repeatable measurements at well below 2.5 mg/km, but the method collects a large gaseous volatile fraction that may be 20 times the mass of the solid particles collected.
- Both mass and number measurement approaches appear to have detection limits low enough to discriminate between a highly efficient wall-flow DPF equipped Diesel and non-DPF equipped Diesel vehicles. In this testing, the mass method proved unable to discriminate a porous wall-flow DPF from a more efficient one.
- The PMP Particle Number method proved to be less variable than the PMP mass method for Euro-4 non-DPF diesel cars, with repeatability levels from 6 vehicles at  $\geq 5\%$ .
- Comparing the lowest emissions of the non-DPF Diesels and the highest emissions of the efficient wall-flow DPF equipped Diesels, the number method showed a difference of >300 times and the mass method a difference of ~18 times. This can be expressed as a difference in discriminating power approximately 20 times greater for the number method than for the mass method.
- Mass and number measurement equipment presented no significant functional challenges during the 2 year programme. Minor maintenance issues did occur but these were dealt with as normal service issues.
- The PMP number method presents improvements over the PMP mass method in terms of limit of detection, accuracy, discrimination power and variability when measuring a stable particle source. For these reasons, the number method is a superior alternative to the existing or a revised mass method for future regulatory procedures.

The conclusions of the final report, and consultations with stakeholder groups including national Governments, the European Commission, the automotive industry, Tier 1 suppliers and the test houses were used to finalise a new Annex for the R83 which introduced the particle number procedure for certification testing. Modifications to the particulate mass measurement procedure were also integrated. The new procedures came into force with the official publication of the procedures during February 2009<sup>9</sup>.

### 3.3 Brief Overview of the Inter-laboratory Correlation Exercises for Heavy-duty Engines

Following the successful completion of the ILCE\_LD, the PMP working group determined the scope of the heavy-duty exercise. This essentially comprises 3 parts:

- Investigative work to develop and finalise a robust inter-laboratory guide for heavy-duty engines testing. Experiments included identifying background PM and PN levels, effects of different filter media, impacts of filter face velocity changes, exhaust and engine preconditioning effects, comparisons of different particle number systems and investigation of the golden instruments. A full report of the experimental work has been published previously [<sup>10</sup>, <sup>11</sup>] and an overview is given in Section 3.10.2. The final inter-laboratory guide [<sup>12</sup>] is included in this report as Appendix 1.
- The validation exercise: analogous to the ILCE\_LD, this programme investigated particle number repeatability and reproducibility by transporting a Golden engine to each test laboratory in turn. Along with the engine, two Golden Particle Measurement Systems (GPMS) were shipped to permit particle number measurements to be made simultaneously from both full flow constant volume sampler (CVS) dilution and partial flow dilution (PDT) systems. As in the ILCE\_LD, participating laboratories were also invited to test their own particle measurement systems, or other commercially available particle numbers systems. PM and gaseous emissions were also measured. The Golden Engineer and the project manager ensured that participating labs correctly followed the measurement protocols defined in the inter-laboratory guide. Low sulphur fuel and lubricant from the same batches were used at all labs. The participating labs were JRC (Ipsra, Italy), AVL\_MTC (Sweden), Ricardo (UK), UTAC (France), and EMPA (Switzerland). Each test laboratory was funded by its respective national government. JRC undertook duplicate measurement campaigns – at the start and end of testing - to monitor consistency of emissions through the programme. Testing in the validation exercise completed at JRC in October 2009.
- The round robin exercise: adhering to the principles of an automotive industry round-robin exercise, this programme is complementary to the validation exercise, but subtly different. Its objective is purely the evaluation of particle number repeatability and reproducibility using different measurement systems. In the round robin, a reference engine is circulated, but each lab uses its own particle number systems from full flow dilution tunnels. Optionally, particle number measurements will also be made from partial flow systems at some participating laboratories. All labs will use fuel and lubricant of the same types (but not necessarily from the same batches). PM and regulated gaseous emissions will also be measured. Laboratories from the EU, Japan, Korea and Canada have expressed interest in participating in the programme. While testing in the round-robin exercise has completed at several laboratories, work is ongoing, with completion anticipated during 2011.

This report describes the procedures, results and conclusions of the PMP Phase 3 validation exercise in detail. Once it has completed, the round-robin exercise will be reported separately.

### 3.4 Test Engine and Emissions Control System

The engine employed in the test programme was a series production IVECO Cursor 8 engine in EU III specification; a modern 7.8 litre, 6-cylinder engine used in heavy-duty vehicle and bus applications. Further details can be found in Table 1.

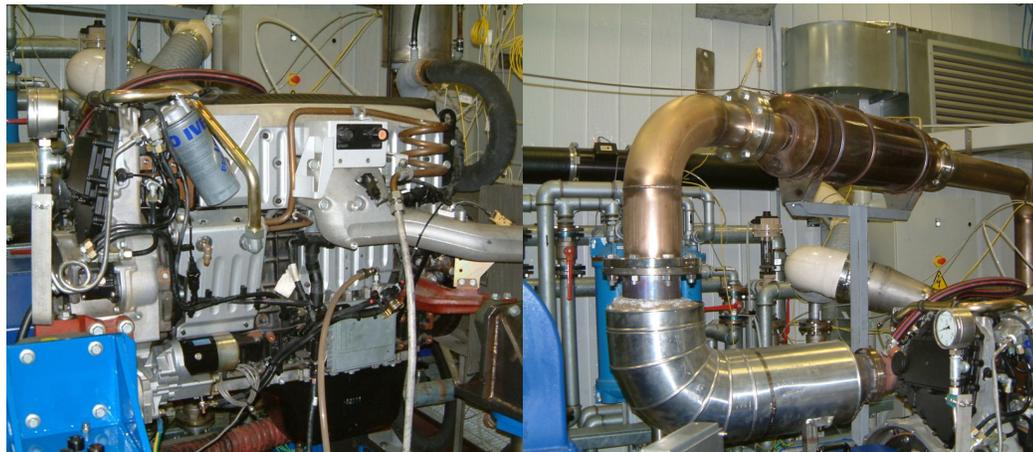
**Table 1: Test Engine and Specification**

IVECO Cursor 8 (Euro 3)	
Details	7.8 l, 6 cylinder, 4 valves/cylinder
Compression ratio	17:1
Maximum power	295 kW @ 1900 to 2400 rpm
Maximum torque	1280 Nm @ 1000 to 1900 rpm
After-treatment	Continuous Regenerating Trap (CRT)
Oxicat	Pt-based: 10.5x3" catalyst section; approx 4.25 litres.
DPF	Wall-flow DPF: 11.25x14"; approx 24 litres

Figure 1 (below left) illustrates a typical installation of the engine, in this case the first test laboratory, JRC. The right-hand part of Figure 1 illustrates the exhaust system layout at JRC which was used to devise a set of benchmark dimensions for installations at all the other test laboratories.

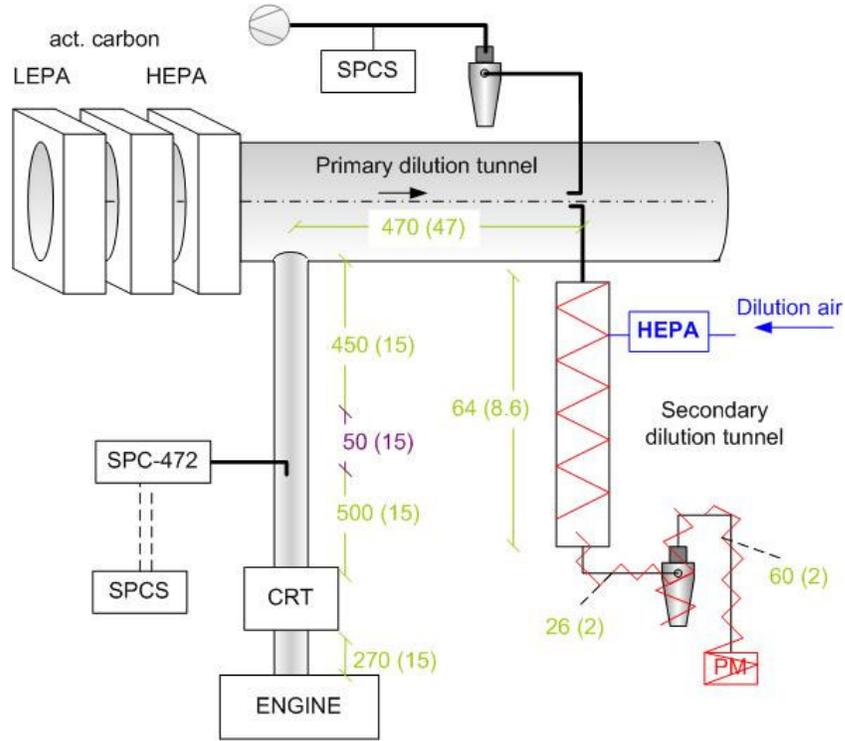
A guide to installation and commissioning was supplied with the test engine and a support engineer visited each test laboratory to facilitate these processes. After testing at JRC this guide was updated to include the exhaust system layout and sampling positions for the PDT, raw gas analysers and temperature and pressure sensors. A schematic representation of the engine and exhaust layout is given in Figure 2.

**Figure 1: Typical Engine and Emissions Control System Installations**



A degree of variability, due to the constraints of test cell size and orientation, was expected during engine, exhaust system and PM / PN measurement system installations. Differences are summarised in Table 2. Generally, differences between labs were small and are not expected to have impacted results.

**Figure 2: Schematic of Exhaust and Emissions Control System Layout**



**Table 2: Exhaust System Installation Variability at the Test Laboratories**

Sampling Dimensions [cm]	AVL MTC	JRC	Ricardo	UTAC	EMPA
Engine-CRT	250 (15)	270 (15)	165 (15)	100 (15)	299 (10)
CRT-PFS	700 (15)	500 (15)	395 (15)	350 (15)	934 (12.5)
CRT-CVS	1100 (15)	950 (15)	930 (15)	750 (15)	1469 (12.5)
CRT-CVS Insulated	1100 (15)	600 (15)	200 (15)	450 (15)	1045 (12.5)
PFS-SPCS20	150	150	400	150	320
CVS sampling point – CVS mixing point	500 (50)	470 (47)	500 (45)	575 (45)	470
CVS-SPCS19	400	400	360*	400	202

\* Ricardo used a heated line at 47°C to extend the 1m Horiba sampling line to ~4m.

### 3.4.1 CRT: Pt-based Oxidation Catalyst and Wall-flow DPF

The DPF employed in the test programme was a cordierite wallflow filter of approximately 24 litres volume and originally supplied by Johnson-Matthey. The ratio of DPF volume to engine size is therefore approximately 3, which is larger than the 1.5 to 2.5 typically employed in current HD applications.

The DPF is preceded in the exhaust system by a close-canned Pt-based oxidation catalyst (Eminox) of approximately 4.25 litres volume.

### 3.5 Fuel and Lubricant

Fuel and lubricant were supplied to the PMP programme by members of Concawe.

The test fuel was provided by Total, who isolated a large batch of the certification reference fuel RF06-03 and nominated it RF06-03-PMP. Participating labs purchased quantities of this batch directly from the supplier. This fuel fully complies with Annexes 3 and 4 of Directive 2003/17/EC describing fuel specifications to be employed after 1<sup>st</sup> January 2009 (i.e. sulphur content of < 10 ppm). Selected properties are given in Table 2 and the detailed specifications can be found in Appendix 2.

**Table 3: Fuel specifications**

Properties	Units	Value
Cetane Number	[-]	53.1
Density	[kg/m <sup>3</sup> ]	834.9
Sulphur	[ppm] or [mg/kg]	7
Polycyclic aromatics	[%] by mass	5.1

The test lubricant (Table 4: Lubricant Properties) was a BP Vanellus E8 fully synthetic, 5W/30 PAO (polyalphaolefin) based oil with <0.2% sulphur content. Defined oil change and conditioning procedures were employed at each laboratory to standardise oil conditioning and eliminate this as a source of variability in the results.

**Table 4: Lubricant Properties**

Density @ 15 °C	0.860kg/litre
Kinematic viscosity @100 °C	12.03mm <sup>2</sup> /s
Viscosity Index	163
Viscosity CCS @ -30 °C	5260 CP
Total Base Number	15.9 mg KOH/g
Sulphated Ash	0.19%

### 3.6 Gaseous Emissions Measurement Systems

During emissions tests at all laboratories selected gaseous emissions were measured on a continuous basis from both raw and diluted exhaust. In addition, some laboratories supplied cumulative 'bagged' sample results.

Raw exhaust samples were drawn directly from the exhaust line, while diluted samples and bagged analyses were made from the full-flow dilution system.

Regulated exhaust gases and their methods of analysis are given below:

- Total hydrocarbons (THC): performed using a heated Flame Ionisation Detector (FID)
- Oxides of Nitrogen (NO<sub>x</sub>): conducted using a Chemiluminescence Analyser (CLA). CLA detects photons that are emitted by excited NO<sub>2</sub> molecules generated in the instrument reaction chamber from NO. Excited NO<sub>2</sub> emits photons of a specific wavelength. The light generated in the reaction is proportional to the NO present in the sample. All the NO<sub>2</sub> in the sample gas is reduced to NO prior to the reaction chamber. The combined concentration of

NO+NO<sub>2</sub> is measured. As most oxides of nitrogen are generally in one of these two forms, this measurement is expressed as NO<sub>x</sub>

- Carbon Monoxide (CO) using a Non-Dispersive Infra-red (NDIR) instrument
- Though currently unregulated, carbon dioxide emissions were also measured: using a Non-Dispersive Infra-red (NDIR) instrument.

During the validation exercise, instrumentation provided by the following analyser suppliers was used for gaseous emissions analysis:

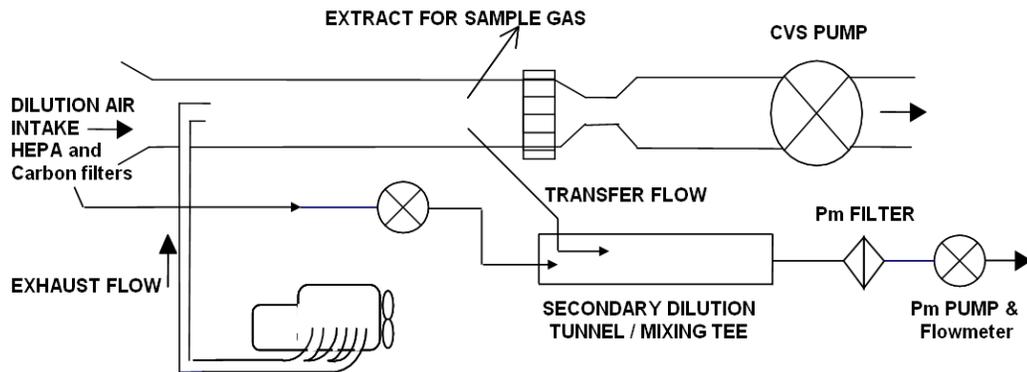
- Horiba
- AVL (both own branded and Pierburg)

### 3.7 Dilution Approaches

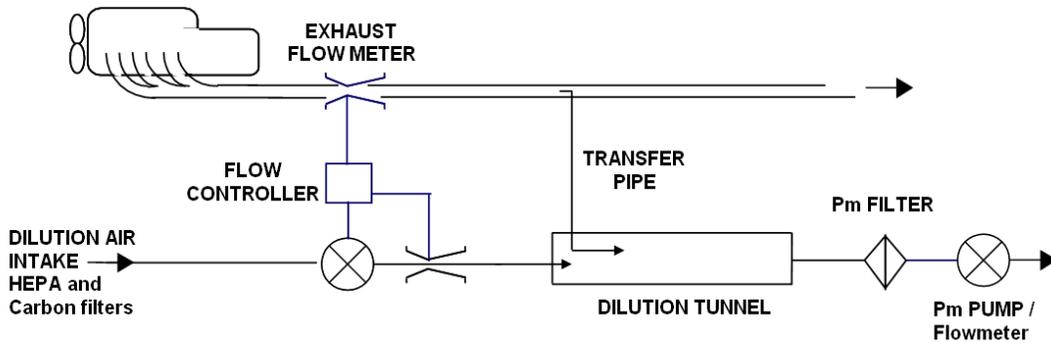
#### 3.7.1 Principles of the Dilution Systems

In Europe since the implementation of Euro IV legislation, two dilution approaches have been considered equivalent for the measurement of particulate mass during certification testing. These full and partial flow dilution approaches are shown in schematic form in Figure 3 and Figure 4 respectively.

**Figure 3: Schematic of Full Flow, Double Dilution System for PM Measurements**



**Figure 4: Schematic of Partial Flow Dilution System for PM Measurements**



### *Full flow dilution*

In a full flow dilution system, the entire exhaust is sampled and diluted but the total flow through the dilution system is maintained at a constant level. This is known as constant volume sampling and the dilution tunnel is often referred to as the constant volume sampler (CVS). Since the exhaust flow varies with engine operation but the total flow through the CVS is fixed, the dilution ratio varies during a test.

Heavy-duty dilution systems in Europe tend to be twin stage systems with a small secondary dilution system in series from the main CVS. This secondary dilution system takes a fixed proportion of the flow from the CVS and dilutes it by a preselected ratio. The main aim of this step is to reduce the temperature of the diluted exhaust.

Diluted exhaust is drawn from the secondary dilution system through a filter. The sampled flow rate must be virtually constant and, by definition, proportional to the total flow through the CVS.

In the validation exercise, all the full-flow dilution systems were employed with secondary dilution systems for mass measurements, but particle number measurements were drawn directly from the primary CVS.

The main issues with CVS dilution systems are:

- The transfer time between engine emission and measurement of real time diluted gases in the CVS makes the identification of real time emissions effects complex
- Hydrocarbons and PM are known to deposit and release from the transfer system between the exhaust manifold and CVS
- Finally, the full flow CVS is a large, often ceiling-mounted, tube which is difficult to remove and consequently to clean. Carryover of PM emissions from previous tests may result in high background levels

Full flow dilution systems provided by Horiba and AVL were tested in this work.

### *Partial Flow dilution*

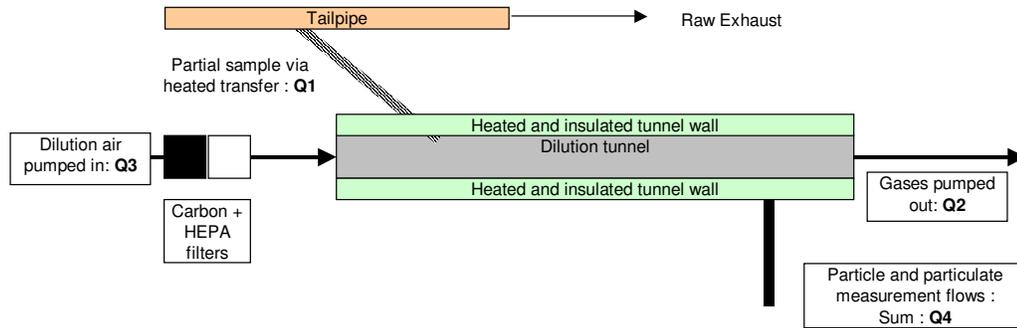
Partial flow dilution systems (PDT) are simpler, more compact and less expensive than CVS.

In a PDT, a fraction of the raw exhaust (a partial flow) is sampled and diluted. However, the transfer flow from exhaust to tunnel must be proportional to the total flow through the exhaust: In Figure 5;  $Q_1$  must constantly change during the transient cycle and this is achieved by varying the flow of dilution air that is added ( $Q_3$ ). As in the CVS, the total flow,  $Q_2$ , remains constant, but unlike the CVS the entire tunnel flow is drawn through the PM filter.

If an additional flow ( $Q_4$ ) is drawn for further mass or number measurements, an identical increase in the transfer flow,  $Q_1$  occurs. This reduces the dilution ratio in the tunnel and would increase the measured PM, so an equivalent flow to  $Q_4$  must either be added back upstream of the flow measurement device (which is positioned downstream of the PM filter) or the changes in dilution corrected automatically by the software.

During preliminary work for this programme, JRC performed a comparison of PN measurements from partial flow systems which had both physical correction for the removal of Q4 (i.e. the flow was replaced) and software correction for the removal of Q4<sup>11</sup>. These two approaches were shown to give equivalent results, but during the actual test programme only the software correction approach was employed.

**Figure 5: PDT – Principle of Dilution**



To facilitate the changes in exhaust flow rate and dilution flow (Q3), real-time fast flow measurement and rapid changes in flow rate are required.

The main challenge for partial flow dilution systems is maintaining proportionality with the exhaust flow rate. Measurement procedures for particulate emissions using partial flow dilution systems and of gaseous emissions from raw exhaust gases under transient test conditions are defined in an International Standards Organisation publication ISO16183:2002 [13].

Partial flow dilution systems provided by Horiba [14], AVL [15] and Control Systems [16] were tested in this work. A PDT system is also available from Sierra [17].

All these systems are fully compliant with ISO16183:2002 and in principle operate almost identically. The main differences between systems are the methods by which flow is measured and controlled.

### 3.8 Particulate Mass Measurements

#### 3.8.1 Full Flow Measurements

In the PMP ILCE\_LD the filter-based method was employed as the reference method, and for conventional Diesels a similar approach has been shown to give results consistent with the current European method [18].

The development philosophy of the particulate mass measurement system was to adapt the practically achievable elements of the mass method proposed for heavy-duty approvals in the US for 2007, along with selected amendments to improve data quality, to create an enhanced European light-duty procedure. Consequently, the approach developed for light-duty vehicles in the ILCE\_LD was considered directly transferrable to heavy-duty engines' full flow dilution system sampling and the main additions to the standard European method are described in the following sections.

- Application of highly efficient dilution air filters for particles and hydrocarbons that reduces mass contributions from the dilution air to near zero
- The application of a cyclone pre-classifier with a 50% cut-size at between 2.5µm and 10µm to limit the contribution of re-entrained and wear materials to the filter mass
- External heating of the filter holder and transfer tubing to permit aerosol stabilisation of >0.2s at 47°C +/-5°C prior to sampling and to ensure close control of the filter face temperature to 47°C +/-5°C. External heating was achieved by either direct surface heating (most labs) or by situating the cyclone, transfer tubing and filter holder in an enclosed vessel. In the second case, the sample probe in the CVS was also heated.
- The use of a single 47mm filter rather than primary and back-up filters to eliminate weighing errors and the back-up filter as a source of volatile artefact
- The filter medium provides at least 99% filtration efficiency for 0.3µm particles at 35l/min (~50cm/s filter face velocity).
- Controlled filter face velocity range (50cm/s to 80cm/s) to improve reproducibility

#### Definition of PMP Particulate Mass

Despite the changes introduced to the method, the PM definition remains broadly unchanged from that used previously: all materials sampled from a dilution tunnel using the prescribed method on to a single filter at between 42°C and 52°C.

#### Test Facilities

*This section is incomplete*

**Table 5: Principal Differences Between CVS Systems – Test Labs**

	AVL MTC	JRC	Ricardo	UTAC	EMPA
CVS flowrate [Nm <sup>3</sup> /min]	72	80	60	80	80
CVS length [cm]	500	470	450	575	470
CVS diameter [cm]	50	47	45	45	47
CVS Heat exchanger	No	Yes	Yes	Yes	Yes
Preclassifier cutpoint [µm]	2.5	2.5	2.5	2.5	2.5
Secondary tunnel flowrate [lpm]	50	50	60	50	40
Secondary tunnel DR	2:1	2:1	2:1	2:1	2:1
Secondary tunnel length [cm]	30	64	100	30	200
Secondary tunnel diameter [cm]	8	8.6	10	8	1.4

#### 3.8.2 Partial flow Measurements

Partial flow dilution measurements of PM were not undertaken in the ILCE\_LD, but development work was undertaken to refine the procedure in the working group that developed the ISO standard [13]. This procedure has many parallels with the PMP full flow method:

- Efficient dilution air filtration
- Filter face temperature control is permissible
- 47mm filters are permitted
- The same filter media are mandated

On these bases, it was considered wise to conduct partial flow testing according to the requirements of ISO16183, but to align sampling parameters where possible with the full flow method. Parameters to be matched were prescribed in the inter-laboratory guide, but these included: filter face velocity, filter medium, filter diameter and dilution air quality.

The definition of PM sampled from a partial flow dilution system: all materials sampled from a dilution tunnel using the prescribed method on to a single filter at  $\leq 52^{\circ}\text{C}$ .

#### *Test Facilities*

***This section is incomplete***

**Table 6: Principal Differences Between PDT Systems – Test Labs**

	AVL MTC	JRC	Ricardo	UTAC	EMPA
System	Smart Sampler	Smart Sampler & PSS-20	Horiba Mini Dilution Tunnel	PSS-20	Smart Sampler
PM flowrate [g/s]	1.08	1.08	1.205	1.08	0.86
Split ratio	0.06%	0.06%	0.09%	0.06%	0.06%

### **3.9 Particle Number Measurement Systems**

#### *3.9.1 Principles of the Measurement System*

Description and diagram of PMP particle number measurement system: elements and function. Touch upon PCRF and dilution factor-based systems.

#### *3.9.2 Golden Particle Measurement Systems*

Two nominally identical particle number measurement systems were circulated across the participating laboratories for the concurrent determination of the particle number emissions from a full flow CVS tunnel and a partial flow system. These are referred to as Golden Particle Number Systems (GPMS), as they served as an internal standard providing a link between testing at the various laboratories.

The GPMSs selected for this study were two prototype Solid Particle Counting Systems (SPCS) developed by Horiba (REF). The selection of this particular system was not based on its performance in terms of the criteria specified in DR83, but rather on the intention to evaluate alternative candidate systems from the GPMS employed in the PMP Light Duty Interlaboratory Correlation Exercise (REF).

### *SPCS description*

The SPCS unit consists of a hot-diluter (PND1), an evaporation tube (ET), a cold diluter (PND2) and a condensation particle counter (PNC). A flow schematic of the SPCS unit is shown in Figure 6. The aerosol first enters a temperature controlled cabinet where it is diverged into a bypass flow, the sole purpose of which is the decrease of the residence time in the sampling line, and the sample flow. The sample mass flowrate is measured in real time by an orifice flowmeter (CFO), taking into account the temperature and the pressure of the sample as determined with a thermocouple and a pressure transducer, respectively. The sample is then diluted in a temperature controlled mixer (HD) with heated – filter dilution air supplied at an adjustable flowrate by means of a mass flow controller (MFC1).

A small fraction of the diluted aerosol exiting the PND1 passes through an orifice flowmeter and then enters an externally heated evaporation tube (EU) whose wall temperature is controlled in the range of 300 to 400 °C. During the ~0.5 s residence of the aerosol inside the EU, the volatile particles are vaporized to gas phase. Immediately after exiting the EU the thermally treated aerosol enters a mixer (CD) where it is cooled by filtered-dilution air supplied at an adjustable flowrate by means of another mass flow controller (MFC3). The concentration of the aerosol exiting this secondary diluter is then measured in real time in a TSI's 3010D condensation particle counter (CPC).

The excess flow from the two dilution stages is sampled with a pump. The dilution ratio of the two diluters is kept constant by supplying make-up air in the two excess lines. Two mass flow controllers (MFC2 and MFC4) continuously adjust the make up air to account for small fluctuations of the sample flowrates measured in real time with the two flowmeters.

### *Operating parameters*

All labs participated in this study operated the two Golden SPCS units at the same settings. The temperatures at the units were set at:

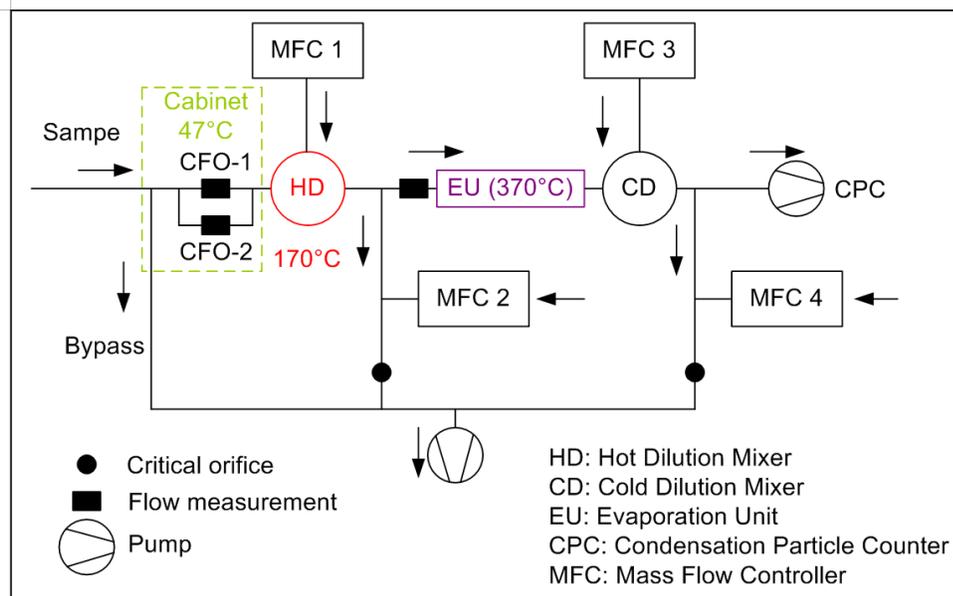
- Cabinet temperature: 47 °C
- Hot dilution air temperature for PND1: 170 °C
- Mixer temperature (HD): 170 °C
- Evaporation unit (EU): 350 °C

In these prototype units, the user has to specify the desired dilution ratio of each diluter as well as the dilution air flowrates and the bypass flow. The values employed in the campaign were:

- Primary dilution ratio (PND1): 10
- Primary dilution air flowrate (MFC1): 11.5 lpm
- Secondary dilution ratio (PND2): 15
- Secondary dilution air flowrate (MFC3): 10.5 lpm
- Bypass flowrate: 2 lpm

These values were selected after preliminary experiments conducted at JRC. The dilution ratios fulfill the specifications laid down in DR83 and the resulting sample flowrate (~1.3 lpm) is high enough for pressure fluctuations to have an insignificant effect on the stability of the achieved dilution ratios.

**Figure 6: Flow schematic of the prototype SPCS**



### 3.9.3 Alternative Systems

A number of alternative candidate systems have also been used in parallel from the participating labs. These are briefly described below.

*This section is incomplete*

*Nanomet*

*APC*

*Dekati's dual ejector and evaporating tube system*

*EMPA's*

### 3.9.4 Additional instrumentation

In addition to the aforementioned PMP compliant systems, the participating laboratories have also employed additional aerosol instrumentation in order to get a better insight in the characteristics of the emitted particles. These included:

- EEPS
- Dekati's Mass Monitor
- AVL's Soot Sensor
- TSI's SMPS
- TSI's 3025 CPC

## 3.10 Test Programme

### 3.10.1 Participating Laboratories

Four laboratories in EC member states, and one in Switzerland, were participants in the test programme. The test labs, timing and final test order are given in Table 7. JRC also conducted additional experiments prior to and following the formal testing. Preliminary

experiments, undertaken to refine the inter-laboratory guide are discussed in the next section.

**Table 7: Test Laboratories and Timeline**

Dates	Test Laboratory	Location	Testing
Jan – Feb 2008	JRC	Ispra, Italy	Preliminary Experiments
Mar-Apr 2008	AVL-MTC	Sweden	Formal Testing Lab#1
May – Jun 2008	JRC	Ispra, Italy	Formal Testing Lab#2
Dec 2008 – Jan 2009	Ricardo	UK	Formal Testing Lab#3
Feb - Apr 2009	UTAC	France	Formal Testing Lab#4
Apr – Aug 2009	EMPA	Switzerland	Formal Testing Lab#5
Aug– Oct 2009	JRC	Ispra, Italy	Formal Testing Lab#2rpt
Nov-09	JRC	Ispra, Italy	Additional Experiments

### 3.10.2 Summary of Preliminary Experiments

A number of experiments were conducted in order to better define the measurement approaches described in the inter-laboratory guide. These were based upon concerns regarding the possible differences in emissions between the light duty vehicles that the measurement procedures were developed for, and the heavy-duty engines to be the subject of the next phase of PMP work. Further details can be found elsewhere [10]. In particular, the differences in PM chemistry, the aftertreatment devices to be used, characteristics of different dilution systems and possible differences in the nature of particles: their sizes and origins, were of concern. These experiments can be classified into four groups as follows:

- Expt 1 - Background and filter tests

These experiments considered the CVS and partial flow systems' background levels for mass and the effect of the filter medium and filter face velocity (ffv) on the PM emissions

- Expt 2 - Sampling parameters

These experiments considered the impact and necessity of using a pre-cyclone with the Horiba SPCS systems. In addition, the two SPCS systems supplied by Horiba had different transfer lines lengths (1m insulated, 4m heated). The impact of these lines on the PN results was determined.

- Expt 3 - Pre-conditioning and continuity protocol

In the ILCE\_LD, it was determined that to improve the repeatability of particle number results a purge of pre-existing particles from the exhaust system and a standardised DPF fill-state was required. Experiments were undertaken to determine the minimum required pre-conditioning for the exhaust and after treatment for repeatable measurements.

- Expt 4 - Real time PN emissions

Concerns have been raised in the US<sup>19</sup> that high levels of solid particles may be present, in the exhaust from HD Diesel engines, in the size range below the PMP cut-off

(d50) of ~23nm. Measurements were undertaken to determine the presence and magnitude of <23nm solid and <23nm volatile particles from the golden engine.

All experiments were conducted on the golden engine and emissions control system and using the fuel and lubricant described in Section 3.5.

#### *Experiment 1 - Background and Sampling Parameters for PM*

A schematic of the sampling system used in these experiments is shown in Figure 7.

Evaluations of filter media and face velocity effects were undertaken during repeat WHSC testing. In all cases tests were conducted using a primary and back-up filter to enable the magnitude of volatile 'slippage' from the primary filter to the secondary filter to be quantified. The following measurements were made from the CVS, with results shown in Figure 8.

(a)

- One background (BG) PM measurement followed by 3 hot WHSC repeats
- 70mm TX40 filters, PM sample flow of 60l/min (ffv = 43cm/s)

(b)

- One background PM measurement followed by 3 hot WHSC repeats
- 47mm TX40 filters, PM sample flow of 60l/min (ffv = 103cm/s)

(c)

- One background PM measurement followed by 3 hot WHSC repeats
- 47mm TX40 filters, PM sample flow of 40l/min (ffv = 69cm/s)

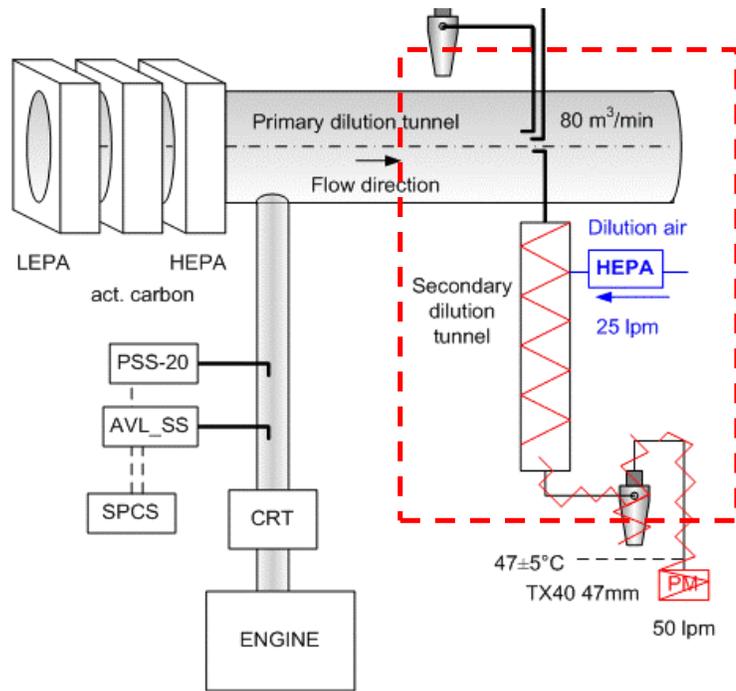
(d)

- One background PM measurement followed by 1 hot WHSC
- 47mm TX40 filters, PM sample flow of 40l/min (ffv = 69cm/s)
- PM filters baked in an oven at 47 °C for 3 hours to remove residual volatiles

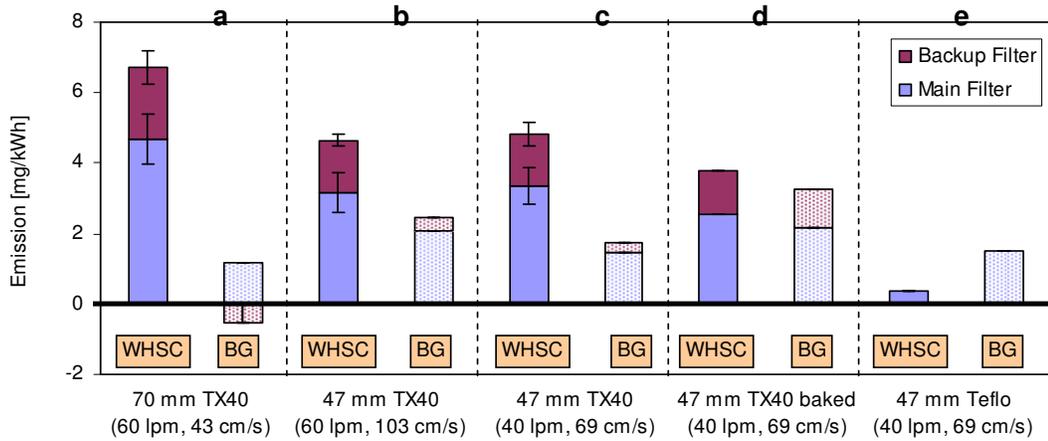
(e)

- One background PM measurement followed by 1 hot WHSC
- 47mm Teflon membrane filters, PM sample flow of 40l/min (ffv = 69cm/s)

**Figure 7: PM Sampling Set-up for Experiment 1**



**Figure 8: Experiment 1 - Background and Sampling Parameters for PM**



The conclusions of these experiments were:

- PM emissions were slightly higher than background levels
- Highest PM mass was collected on 70mm filters with a sample flow of 60l/min (ffv of ~40cm/s)

- Similar masses were collected on 47mm filters at ffvs of ~70 to 100cm/s (40 to 60l/min)
- Baking TX40 filters has no beneficial effect
- Teflo filters appear to collect less mass than 47mm filters
- Secondary (backup filters) collect ~ 30% of primary filter mass from sample filters

#### Contributions to test protocol

- No substantive changes to light-duty PM protocol
- Employ 50 l/min flow rate for PMP tests (for full flow and partial flow systems with 47 mm TX40 filters).

#### *Experiment 2 – PN Sampling Parameters*

In these experiments 2 SPCS systems were used in parallel during various periods of transient engine operation.

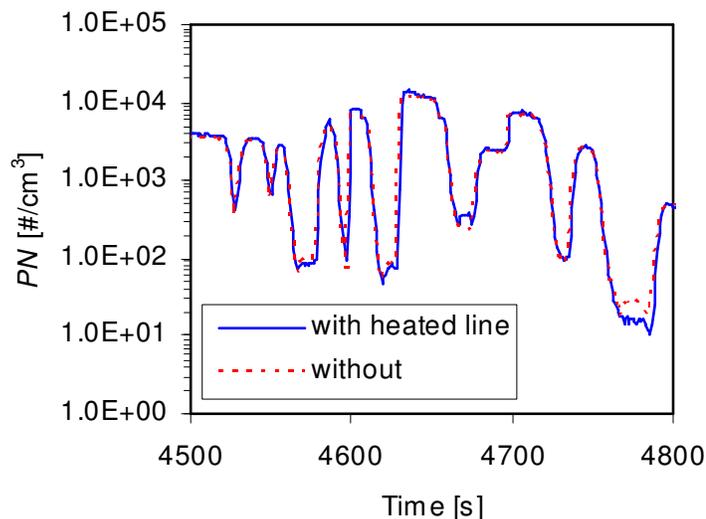
#### (f) Transfer line effects (Figure 9)

- One SPCS sampling directly from the CVS with a 1m insulated line
- One SPCS sampling directly from the CVS with a 4m heated line

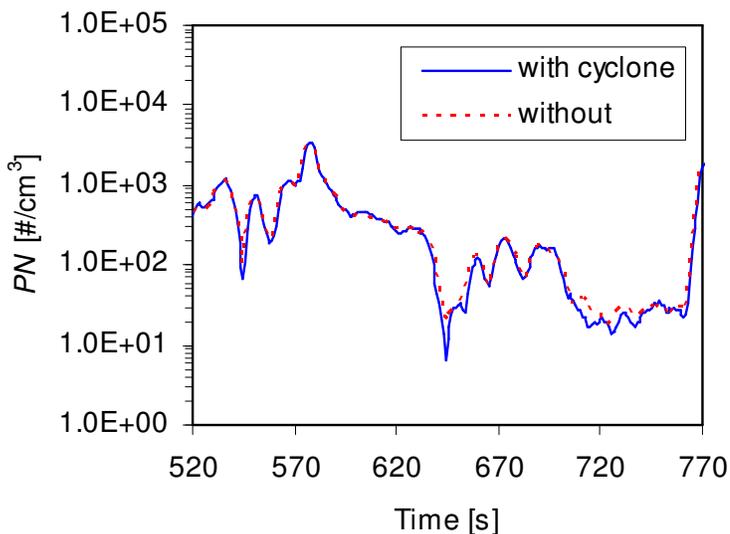
#### (g) Cyclone effects (Figure 10)

- One SPCS sampling directly from the CVS with a 1m insulated line
- One SPCS with 4m heated line sampling from the CVS via a cyclone operating with a 4 $\mu$ m cut

**Figure 9: Minimal Impact of Heated Line on PN Results**



**Figure 10: Minimal Impact of Cyclone on PN**



The conclusions of these experiments were:

- The 4 m heated line (at 47°C) had a minimal effect on PN emissions (<5%). This means that one SPCS can be connected to the CVS through 4 m line (heated at 47°C), while the other SPCS can be connected to the partial flow system with a short (insulated) line without adjustment of results for transport losses.
- The cyclone had a negligible effect on the particle number emissions, so for number measurements it is not necessary. However, it is recommended to use one in order to protect instruments' primary diluters from contamination through

deposition of larger particles. Insulation of the cyclone and transfer tubes is required to limit thermophoretic losses during high temperature operation.

#### Contributions to Test Protocol

- Cyclone mandatory for CVS sampling
- Cyclone optional for partial flow sampling
- Insulation of cyclone and external sampling system to limit thermophoretic losses
- Dedicated SPCS (Serial no. 19) for full flow sampling (with heated line)
- Dedicated SPCS (Serial no. 20) for partial flow sampling (with 1m insulated line)

#### *Experiment 3 – Preconditioning Protocols*

A daily preconditioning protocol was required that first used a high exhaust temperature steady state (~600°C) to passively regenerate the DPF, and then used a lower temperature non-regenerating condition to add a standardised quantity of soot to the DPF. This protocol was used at the end of each day to re-baseline the loading state of the DPF prior to the next day's run-through of the test matrix. To avoid very long test days, it was desirable that the entire process was shorter than 2 hours.

- 15 minutes at mode 10 was determined as the suitable engine operation and minimum time required to passively regenerate the DPF, eliminating the stored soot. This was determined by running ESC 10 and monitoring how long it took for post DPF solid particle emissions to stabilise (Figure 11, green line, 400s to 900s).

Mode 10 operation for 30 minutes showed particle number levels consistent with those seen during the 2 hours of mode 10 running used to condition the lubricating oil, thus indicating that the DPF was indeed 'emptied' by the 30 minutes period (Figure 11, red and blue lines).

- ESC Mode 7 has a stabilised exhaust temperature of well below 300°C, so passive regeneration at this temperature, even with an oxidation catalyst, is minimal. 30 minutes of operation was chosen to add soot to the DPF (Figure 11, green line, 1500s to 3300s)

The daily test matrix comprised both cold and hot start tests and it was desirable that each lab tested the cycles with the exhaust and emissions control system at the comparable temperatures. This would lead to more repeatable gaseous emissions and particle results. To ensure this, cycles without regulatory defined warm-ups were preceded by the continuity protocol.

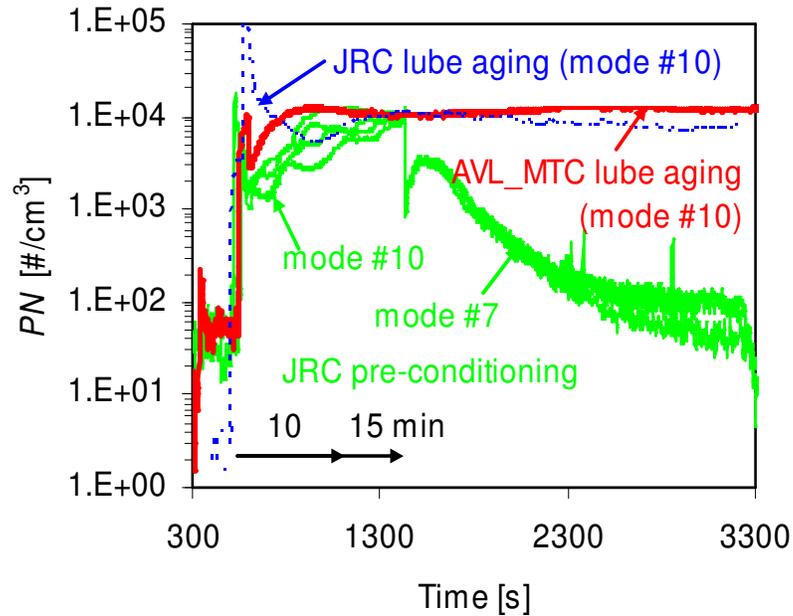
The hot WHTC was preceded only by the cold WHTC and a 10 minute soak while the WHSC, was preceded by the hot WHTC and the mandatory 10 mins at WHSC Mode 9. No continuity protocols were required for these cycles.

The continuity protocol comprised 5 min at Mode 7 of the ESC and 3 min at idle. Mode 7 was selected after repeat size distribution measurements at this condition showed no evolution in magnitude or size – indicating stability of both volatile and

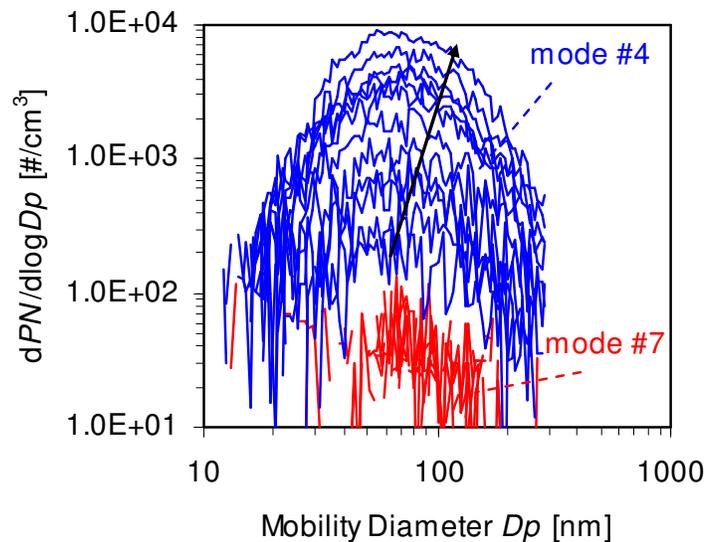
solid particles (Figure 12). By comparison a slightly hotter steady state, ESC Mode 4 showed obvious evolution, related to some passive regeneration.

Idle followed the Mode 7 operation to permit preparation of the exhaust emissions analysers and to limit emissions and fuel consumption without stopping the engine.

**Figure 11: DPF Preconditioning –Regeneration (Mode 10) and Fill (Mode 7)**



**Figure 12: Stable Mode 7 Selected for the Continuity Protocol**



Contributions to test Protocol

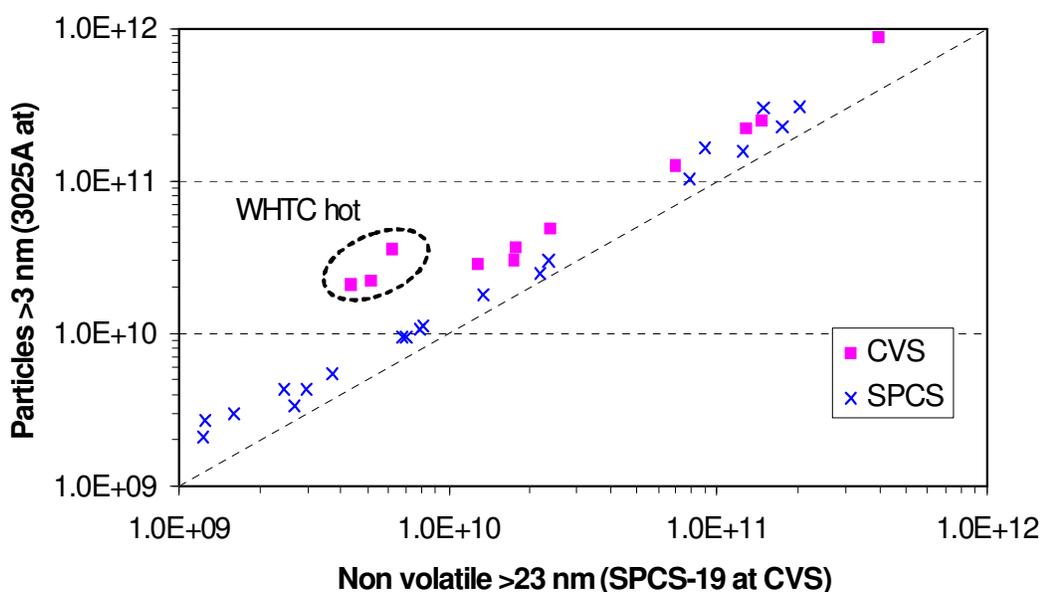
- 15 mins ESC Mode 10 plus 30 mins ESC Mode 7 for the daily preconditioning

- 5 mins ESC Mode 7 plus 3 mins at idle for the continuity protocol

#### Experiment 4 – Real-time PN Emissions

A variety of steady state and transient emissions tests were performed measuring solid particles from the CVS with an SPCS system equipped with both a TSI 3010D CPC (measuring particles >23nm) and a TSI 3025A CPC (measuring particles >3nm). The difference between the results of these two particle counters indicated the presence of solid particles in the size range 3nm to 23nm. In addition, the same 3025A CPC was used to measure particles directly from the CVS. This permitted the number of volatile particles smaller than 23nm to be determined. Results are summarised in Figure 13.

**Figure 13: Particle Number Emissions <23nm**



The implications of this figure can be summarised as follows:

- For the cycles examined, the concentration of total particles >3 nm was 50-95% higher than the non-volatile particles (300% for the hot WHTC).
- For the cycles examined the concentration of the non-volatile particles <23 nm was 15-45% higher than the non-volatile particles >23 nm (85% for the cold WHTC).

#### Contributions to test Protocol

- While there was some evidence that solid particles <23nm were present, the levels seen were not consistent with the orders of magnitude increases relative to >23nm particles reported from US engines. On this basis, it was considered reasonable to retain the size and volatility range of particles measured in the ILCE\_LD.

### 3.10.3 Daily Protocol

Following the completion of the preliminary experiments, the test protocol for the inter-laboratory exercise was finalised and used to update the ILG\_HD. The baseline test matrix comprised at least 8 repeats of each of the following tests:

- Cold WHTC
- Hot WHTC
- WHSC
- ETC
- ESC

Test order followed the defined matrix (Table 8), with preconditioning for each cycle set as the regulatory requirement or the continuity protocol if no regulatory requirement exists.

**Table 8: Matrix for Emissions Testing**

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 minutes ESC mode 10, 30 minutes ESC mode 7			
* DPF regeneration only required if oil change and conditioning not performed			

## 4. STATISTICAL ANALYSES

The variability of the results collected in the PMP Heavy Duty Validation Exercise was quantified using the “random effects analysis of variance” model (REF). This analysis provides the means for a separate quantification of the repeatability and reproducibility of the measurements.

On the other hand, the equivalency between the results (PM and particle number) obtained from the CVS tunnel, the partial flow system and the alternative particle number systems employed, was investigated by means of calculating the average value and the standard deviation of the percentage differences of each individual result. It has been decided not to employ paired t-tests for this type of checks as the particular methodology is prone to identifying statistically significant differences when in fact the result are practically equivalent (REF), with the ability to discriminate between statistically and practically significant differences strongly affected by the sample size.

## 4.1 Definitions

### 4.1.1 Basic statistical concepts

Before describing the statistical analysis used for the evaluation of the PMP methodology it is important to distinguish between the statistical concepts of accuracy, precision and trueness.

Accuracy represents the degree of agreement between the results obtained from a test method and the true or 'accepted' true value. On the other hand, precision refers to how closely the independent measurements agree with each other, while trueness refers to the closeness of agreement between the arithmetic mean of a large number of test results and the "accepted" reference value. In most cases, however, the true value is unknown and therefore only precision statements can be developed. Precision is a qualitative concept which can be expressed numerically only in terms of its opposite, that is the variance or standard deviation.

The variance in the results obtained from a test method is due to some random variations of the properties being measured but also due to the fluctuation of some factors affecting the outcome of the test method. These factors are generally the equipment used, the calibration of the equipment, the operators using the equipment and the environmental variables.

When the test method is performed in one laboratory in the shortest practical period of time, by the same operators, using the same equipment on – ideally – materials taken from a single quantity of homogeneous material, then the aforementioned factors remain reasonably constant and the variance in the results is referred to as the within laboratory (intra-laboratory) variability ( $\sigma^2$ ). However, when the test method is performed at different laboratories these factors vary considerably, leading to even greater variability. The variability induced because of performing the tests in different physical environments is the between laboratories (inter-laboratory) variability.

The results obtained from one laboratory are said to be satisfactory if they are both repeatable and reproducible. Repeatability is ensured when the above mentioned factors remain reasonably constant. This would be reflected where inter-laboratory variance was similar to intra-laboratory variance. Furthermore, the results obtained from one laboratory are said to be reproducible if the divergence of their mean value is not significantly greater than the variability range which would be expected on the basis of the inter-laboratory variability.

### 4.1.2 Intra- And Inter-Laboratory Variance Estimators

The random effects analysis of variance model provides the means for the quantification of the intra-laboratory and inter-laboratories variances  $\sigma^2$  and  $\sigma_r^2$ , respectively. If  $y_{ij}$  represents the  $j^{\text{th}}$  result obtained from the  $i^{\text{th}}$  laboratory participating in an interlaboratory correlation exercise (also known as round robin) conducted at  $p$  different laboratories, and  $n_i$  is the number of results provided from the  $i^{\text{th}}$  laboratory then the estimators of  $\sigma$  and  $\sigma_r^2$  are (REF):

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^p \sum_{j=1}^{n_i} y_{ij}^2 - \sum_{i=1}^p \frac{y_{i.}^2}{n_i}}{N - p}$$

$$\hat{\sigma}_\tau^2 = \frac{\left( \sum_{i=1}^p \frac{y_{i.}^2}{n_i} - \frac{y_{..}^2}{N} \right) / (p-1) - \hat{\sigma}^2}{\frac{1}{p-1} \left[ N - \frac{\sum_{i=1}^p n_i^2}{N} \right]}$$

Where:

$$N = \sum_{i=1}^p n_i, \quad y_{i.} = \sum_{j=1}^{n_i} y_{ij} \quad \text{and} \quad y_{..} = \sum_{i=1}^p \sum_{j=1}^{n_i} y_{ij}$$

#### 4.1.3 Statistical outliers

One of the basic assumptions of the analysis of variance model is that the results obtained from each laboratory are equally variable (an situation known as homogeneity of variance). If the variability in one particular laboratory is significantly different from the rest of the laboratories the particular laboratory is said to have repeatability problems and can be characterized as an outlier. The ASTM 691-99 and the ISO 5725-2:1994 standards provide the means for identifying the laboratories having repeatability problems, by utilizing the repeatability index (k). The k statistic for the results obtained from a laboratory z is defined as

$$k_z = \frac{s_z}{\sigma}$$

where  $s_z$  represents the standard deviation of the results obtained from laboratory z, while  $\sigma$  is the intra-laboratory standard deviation (square root of  $\sigma^2$ ).

Furthermore, the two standards suggest the use of the reproducibility index (h) in order to identify laboratories measuring significantly higher or lower results. The h statistic for the results obtained from laboratory z is defined as:

$$h_z = \frac{\bar{x}_z - \mu}{\sigma_0}$$

where  $\bar{x}_z$  represents the average value of the results obtained from laboratory z,  $\mu$  is the pooled mean value from all labs and  $\sigma_0$  represents the range where the difference  $\bar{x}_z - \mu$  is expected to vary due to the intra and inter-laboratory variabilities ( $\sigma^2$  and  $\sigma_\tau^2$ , respectively).

The statistical analysis underlying the definition of these two statistics is the hypothesis testing of two variances and two means respectively, and therefore some critical  $h^*$  and  $k^*$  values can be derived by assuming a type-I error ( $\alpha$ ). Any h or k value greater or equal to the corresponding critical  $h^*$  or  $k^*$  is indicative of reproducibility or repeatability problems, respectively. There are also additional patterns indicating problems like one lab having positive (or negative) h values and all the rest negative (or positive), or one lab having too high or too low k values for all tests compared to the rest of the labs.

The two aforementioned standards provide the equations and critical values for the case of balanced samples (equal number of results from each lab). In the more general case of unbalanced samples the following equations apply (REF):

$$k_z = \frac{\sqrt{\frac{\sum_{j=1}^{n_z} \left( y_{zj} - \frac{y_{z.}}{n_z} \right)^2}{(n_z - 1)}}}{\sqrt{\hat{\sigma}^2}}$$

$$h_z = \frac{\bar{x}_z - \frac{\sum_{i=1}^p \bar{x}_i}{p}}{\sqrt{\frac{\sum_{i=1}^p \left( \frac{y_{i.}}{n_i} - \frac{y_{..}}{N} \right)^2}{p-1}}}$$

$$k_z^* = \frac{1}{\sqrt{\frac{n_z - 1}{\sum_{i=1}^p (n_i - p)} + \frac{1 - \frac{(n_z - 1)}{\left( \sum_{i=1}^p n_i - p \right)}}{F}}}}$$

$$h_z^* = \frac{(p-1)t}{\sqrt{p(p-2+t^2)}}$$

where t is the  $\alpha/2$  percentage point of the Student's t-distribution with p-2 degrees of freedom, and F the  $\alpha$  percentage point of the F-distribution for  $n_z-1$  degrees of freedom for the numerator and  $[N-p-(n_z-1)]$  degrees of freedom for the denominator.

Following the recommendations of the ISO standard, the critical h and k statistics were calculated at a significance level ( $\alpha$ ) of 1 %.

## 5. CALIBRATION AND VALIDATION

### 5.1 Mass systems

#### *This section is incomplete*

- No substantive issues were observed with the weighing procedures of the HD\_ILG at any of the test labs during the programme
- It is possible that occasionally reference filter variability (47mm TX40) increases such that  $\pm 10\mu\text{g}$  range could be required instead of the  $\pm 5\mu\text{g}$  used in the R83

### 5.2 Number systems

#### *This section is incomplete*

- No substantive issues were observed with the PN validation procedures of the HD\_ILG at any of the test labs during the programme. This included zero checks of the PNC and SPCS systems and flow checks of the PNC.

## 6. EMISSIONS RESULTS

### 6.1 Full Flow and Partial Flow PM

Particulate mass data from full and partial flow dilution systems are discussed in this section.

#### 6.1.1 PM - Repeatability

Repeatability levels for all labs are expressed as single CoV values that express overall intra-lab variability for each emissions cycle (see Section **Error! Reference source not found.**).

Figure 14 shows the repeatability of the 5 test matrix cycles and the composite weighted WHTC result for the CVS-based PM method.

Three results are shown for each cycle, and these include:

- PMCVS1: All data from all labs (excepting tests excluded for technical reasons)
- PMCVS2: Outlier analysis iteration 1
- PMCVS3: Outlier analysis iteration 2

Outlier analyses found no substantive exclusions.

The best repeatability of ~34% was seen from the cold start WHTC cycle, with all other cycles showing between 50% and 56%. Filters from emissions tests revealed that the cold start WHTC showed both the highest sample masses and visible grey staining indicating the presence of some elemental carbon. Other cycles' filters did not show the same discoloration.

**Figure 14: Repeatability of the CVS PM Method**

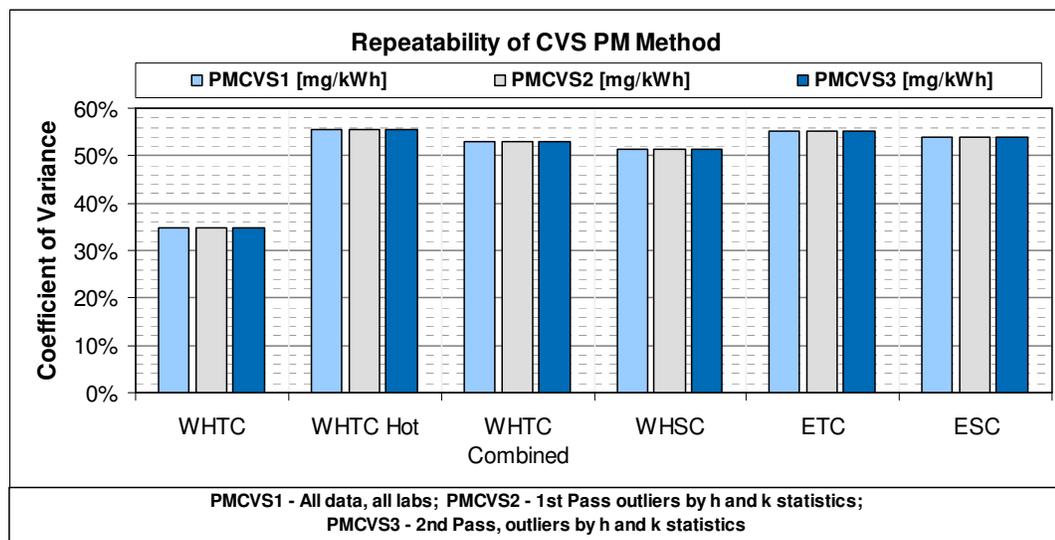


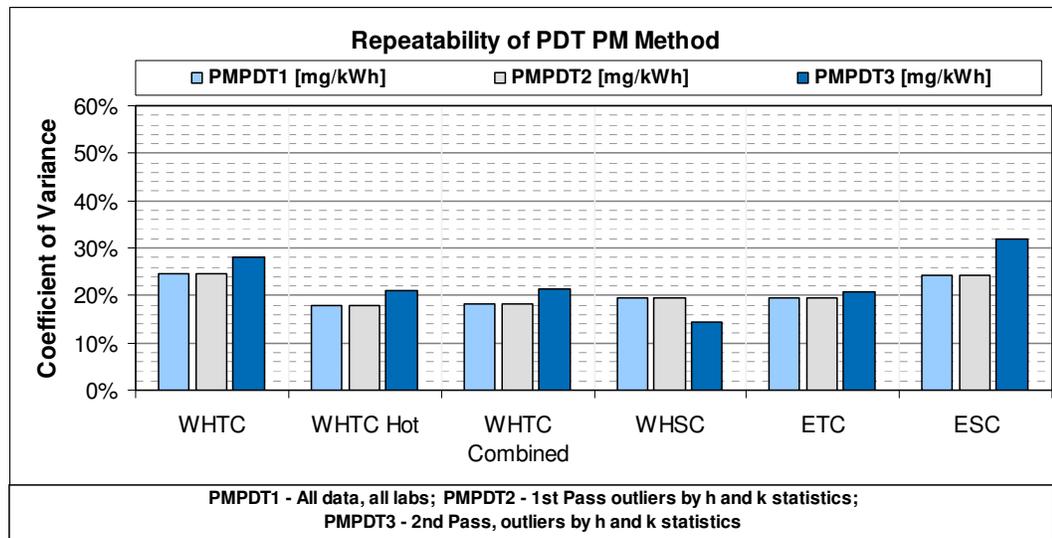
Figure 15 shows the repeatability of the 5 test matrix cycles and the composite weighted WHTC result for the PDT-based PM method.

Three results are shown for each cycle, and these include:

- PMCVS1: All data from all labs (excepting tests excluded for technical reasons)
- PMCVS2: Outlier analysis iteration 1
- PMCVS3: Outlier analysis iteration 2

Outlier analyses led to the exclusion of all PM results from UTAC which showed PM levels significantly higher than PDT results from any other lab. Interestingly, this lab's PDT results showed very similar levels to its CVS-measured results. Following this analysis, the resulting repeatability levels were typically 20% to 30% across all emissions cycles.

**Figure 15: Repeatability of the PDT PM Method**



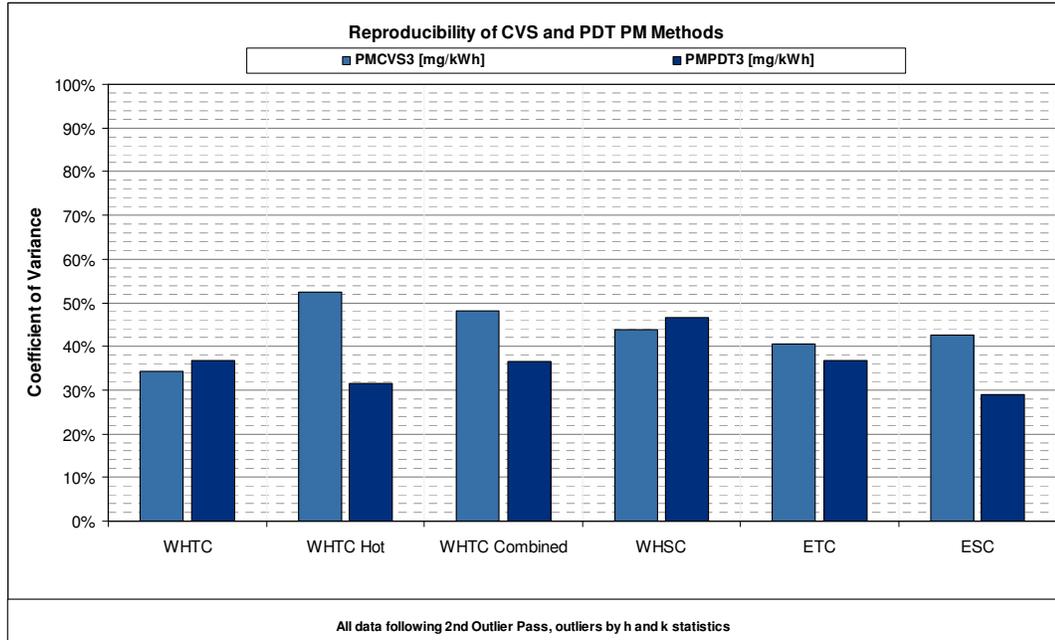
### 6.1.2 PM - Reproducibility

Reproducibilities are given as single CoV values that express overall inter-lab variability for each emissions cycle (see Section **Error! Reference source not found.**). Reproducibility levels for the CVS and PDT PM methods are shown in Figure 16. Data generated following two round of outlier iterations are shown.

CVS PM reproducibility levels were typically in the range 35% to 55%, averaging 42.7% for the 5 emissions cycles in the test matrix. PDT PM reproducibility levels ranged from ~30% to ~45%, averaging 36.1%.

The lower CoVs from the PDT systems probably reflect the greater consistency of background levels in the partial flow system compared to the CVS.

**Figure 16: Reproducibility of PM Methods**



**6.1.3 PM – Filter Weights, Background Levels and Background Subtraction**

Testing at Ricardo included both CVS and PDT PM measurements, and a comparison has been made of the filter masses collected from background and cycle testing.

*Filter Weights*

In all cases filter masses proved to be higher from the CVS than from the partial flow system (Figure 17). The greatest differential between measurement systems proved to be from the WHTC cycles, with results between the systems closest from the ESC cycle.

Filter loadings seldom exceeded 50µg with partial flow sampling (collected masses ranged from a high of 59µg (ESC) to a low of zero (also ESC)). CVS levels were both higher and covered a wider range: from 346µg over one cold WHTC down to 31µg (ESC).

**Figure 17: Sampled Filter Masses – Various Cycles, Both Measurement Systems**

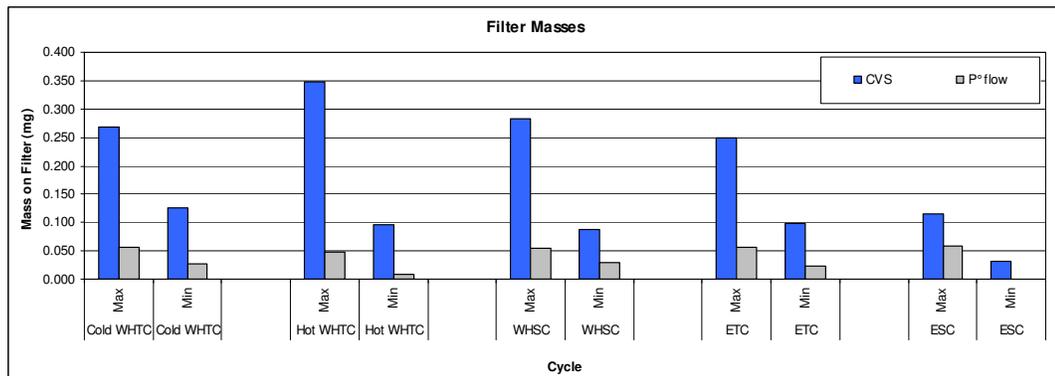


Figure 18 puts measured filter masses into context of the background filter levels recorded:

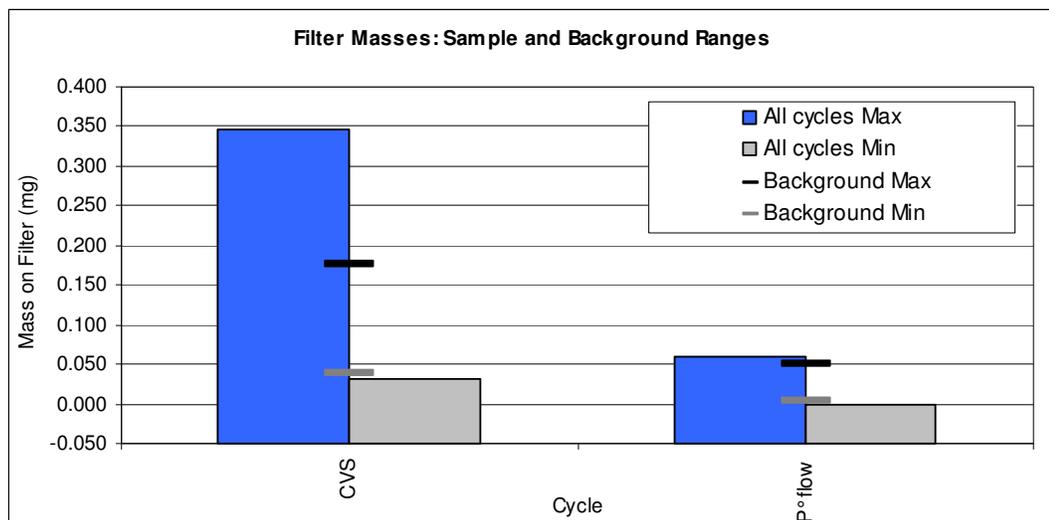
- It is clear that from the CVS, the highest sample mass is higher than the highest background, but the lowest sample mass is lower than the lowest background.
- From the partial flow system, the highest and lowest sample masses are roughly equivalent to the highest and lowest background masses.

These observations indicate the following:

- Mass emissions measured by the partial flow system may be indistinguishable from the system background. In this case, mass emissions from all cycles are effectively zero.
- Mass emissions measured by the CVS system may be higher than the background levels, but it is also possible that the CVS background may be unrepresentative.

If the first observation and comment (all mass emissions measured by the partial flow system are effectively zero) is true, and the partial flow results are valid, then the highest CVS results must be seeing a greater background contribution during the test than from the pre-test measurement.

**Figure 18: Filter Masses - Samples and Backgrounds Compared**



Blank subtraction of filter masses from partial flow and a substantial number of full flow tests is likely to give nett PM results of 0 mg/km. This may be a true indication of the mass emissions of this engine with DPF when the resolution of the mass method is considered.

Background PM was also frequently measured at EMPA and JRC.

Background PM filters were drawn prior to the cold start WHTC emissions test each day. The mass on each background filter was then treated as a cycle emissions result (masses were adjusted for differences in sample times between cycles) and the

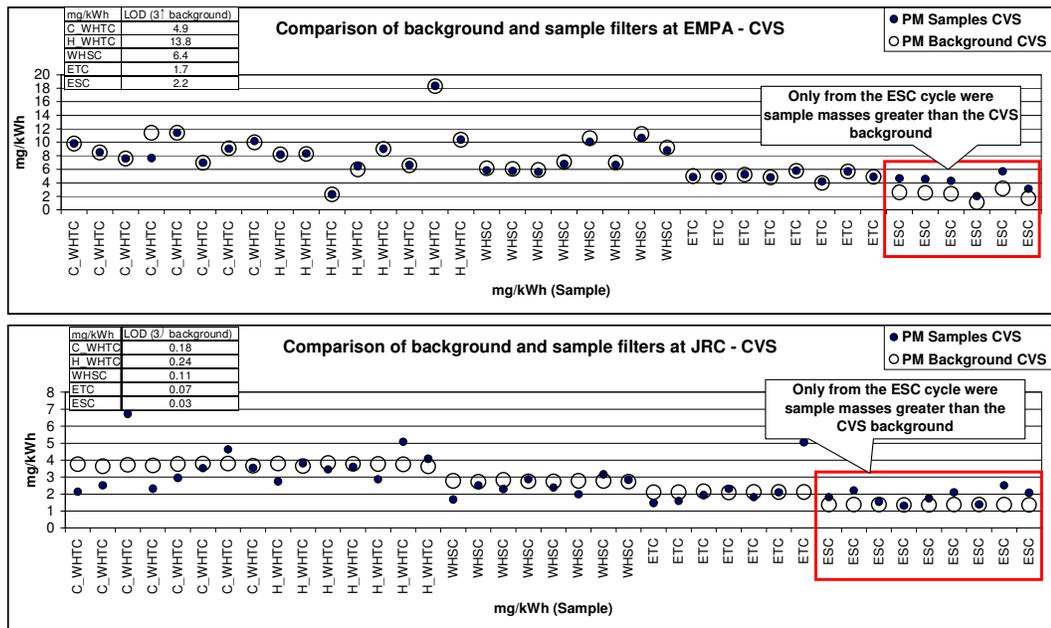
corresponding mg/kWh emissions figure calculated using engine data from that day's emissions tests.

### CVS PM Background

As Figure 19 shows for CVS-sampled PM data from both EMPA and JRC, only measurements from ESC cycles were above background levels. The ESC cycle has a substantial period of operation at high exhaust temperatures and this may lead to emissions of low volatility compounds that are efficiently collected and then retained by the filter. Filters from other cycles collect higher volatility materials from the exhaust and dilution air, but these can be released following acquisition through volatilisation or through a washing effect as further aerosol is drawn through the filter.

It is worth noting that except for hot start WHTC measurements at EMPA, both samples and background results were above the limits of detection (3 standard deviations of the blank measurement) for the various cycles.

**Figure 19: Background and Sample PM levels - CVS**



These data suggest that the CVS PM method is capable of resolving PM emissions from ESC tests from background levels. Results from other cycles, including the cold WHTC are subject to high uncertainty and would reduce to zero if background subtraction was undertaken.

### PDT PM Background

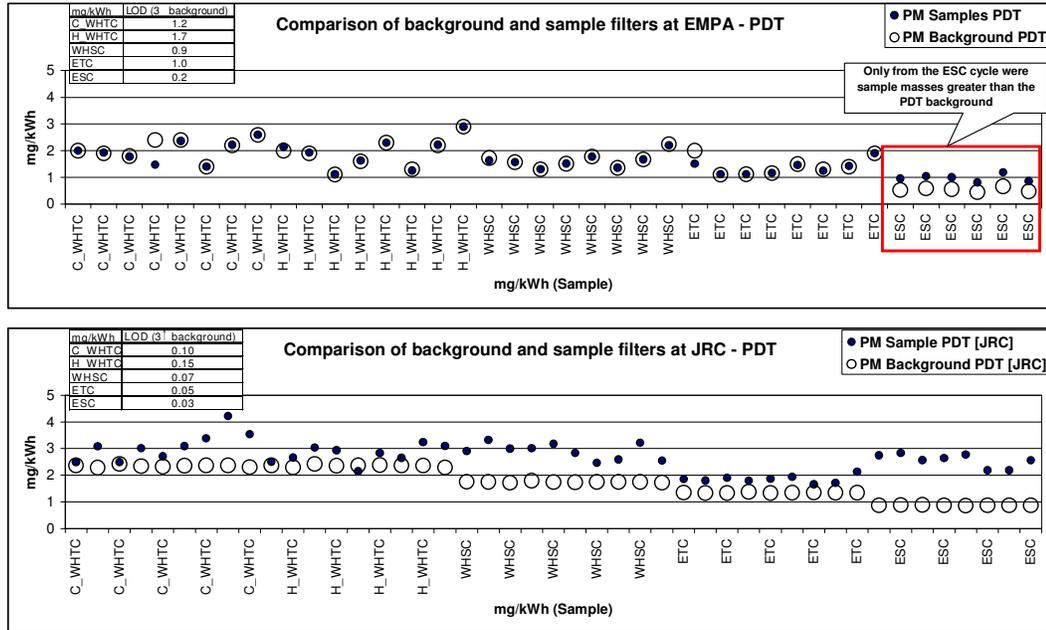
Background and sample filter comparisons were also made from partial flow dilution systems at JRC and EMPA (Figure 20).

EMPA results reflected the CVS results, where all cycles' data except ESC were similar to the background levels.

JRC results, conversely, showed that it is possible to discriminate PM samples from the background, but this discrimination is poorest from the hot and cold WHTC cycles.

Background correction of the JRC PDT results would reduce the emissions levels from cold start WHTC to (generally) <1mg/kWh, hot start WHTC to 0.5g/kWh or less, WHSC to ~1.2g/kWh, ETC to 0.5g/kWh or less and ESC to <2mg/kWh.

**Figure 20: Background and Sample PM levels - PDT**



*Limits of Detection (LOD) for Mass Methods –CVS and PDT*

LOD from tests at EMPA and JRC show that for the hot-start WHTC at EMPA, the limit of detection was above the Euro V limit (10mg/kWh) for the weighted WHTC cycle. However LOD for partial flow systems were always below 2mg/kWh.

**Table 9: Limits of Detection – PM Methods at JRC and EMPA**

	EMPA CVS	EMPA PDT	JRC CVS	JRC PDT
C_WHTC	4.9	1.2	0.18	0.10
H_WHTC	13.8	1.7	0.24	0.15
WHSC	6.4	0.9	0.11	0.07
ETC	1.7	1.0	0.07	0.05
ESC	2.2	0.2	0.03	0.03

**6.1.4 PM – Emissions Levels**

Figure 21 (CVS) and Figure 22 (PDT) show the maximum to minimum ranges of Particulate Matter emissions levels seen from each emissions cycle at each laboratory. Ranges are shown as error bars above and below the mean values. These data are not corrected for backgrounds.

### *PM emissions from CVS Systems*

Emissions levels from the CVS (Figure 21) showed the largest ranges from Ricardo and EMPA, where background levels were substantially higher than other laboratories. These laboratories also showed some of the lowest emissions values as well as some of the highest, but were sampled according to the prescribed protocols using compliant equipment and thus cannot be eliminated as outliers by simple statistical techniques.

The contribution of high and variable background Pm to the results from EMPA and Ricardo is believed to be responsible for the variable PM results from these two labs and this may be related to the recent test history of the facility. In particular, Ricardo had undertaken testing on high bio-content fuels, active regeneration strategies for DPF regeneration and undertaken substantial amounts of non-DPF testing on low NOx calibration engines. All these types of testing would be expected to contribute substantially to both volatile and carbonaceous CVS backgrounds.

The test protocols were designed to help purge the CVS system of residual backgrounds, but it is clear that in some cases extreme measures may be required to eliminate historical PM from full flow dilution systems. For this reason it may be necessary to permit the subtraction of a tunnel, rather than dilution air, background for regulatory PM purposes.

Background levels of PM in other laboratories were very low (typically <1mg/kWh).

Generally speaking, and excepting some results from Ricardo and EMPA which were higher, PM emissions from all cycles were <6mg/kWh, with no obvious difference in emissions between the cold and hot start WHTC cycles. These levels are substantially below the 10mg/kWh limits set for the weighted WHTC and WHSC at Euro V and expected for Euro VI.

Tunnel background correction of the PM results from Ricardo<sup>20</sup> (which showed the highest emissions of all labs) brought them in line with other labs: reducing Cold WHTC results to ~8mg/kWh, hot WHTC results to ~7mg/kWh, WHSC to ~4mg/kWh, ETC to ~1mg/kWh and ESC to <1mg/kWh.

### *PM Emissions from PDT Systems*

PM emissions measured by PDTs (Figure 22) showed narrower ranges than those measured from CVS systems.

Statistical analyses identified PM results from UTAC as systematically higher, with mean values from all cycles at between 4mg/kWh and 7mg/kWh. It is possible that the PDT used by UTAC had been employed for non-DPF testing and was contributing particles during emissions tests. This is analogous to the high background PM levels observed by Ricardo from their CVS.

By contrast, PDT emissions levels from other laboratories, and considering all emissions cycles, rarely exceeded 4mg/kWh.

As seen in the CVS PM data, the emissions levels from cold and hot start WHTC do not appear to differ.

Comparisons between CVS and PDT mass data are discussed in Section 8.5, but emissions from the same engine measured simultaneously from CVS and PDT appear, in general, to be lower from the PDT. This is likely to be related to the fact that almost

all the PDTs tested were relatively new and one, tested at Ricardo, had never been used before. Newer dilution systems are less likely to have been exposed to old technology higher PM engines. Background contributions to PM are therefore likely to be low.

It is widely assumed that dilution systems reach a deposition and entrainment equilibrium where losses to the dilution tunnel walls are balanced by resuspension. This follows a period where particle deposition to tunnel walls is favoured. 'Clean' systems may be within the deposition-dominated phase and this may explain the directionally lower PM results seen with the PDT data from Ricardo.

Figure 21: Maximum and Minimum Ranges of Emissions – CVS PM

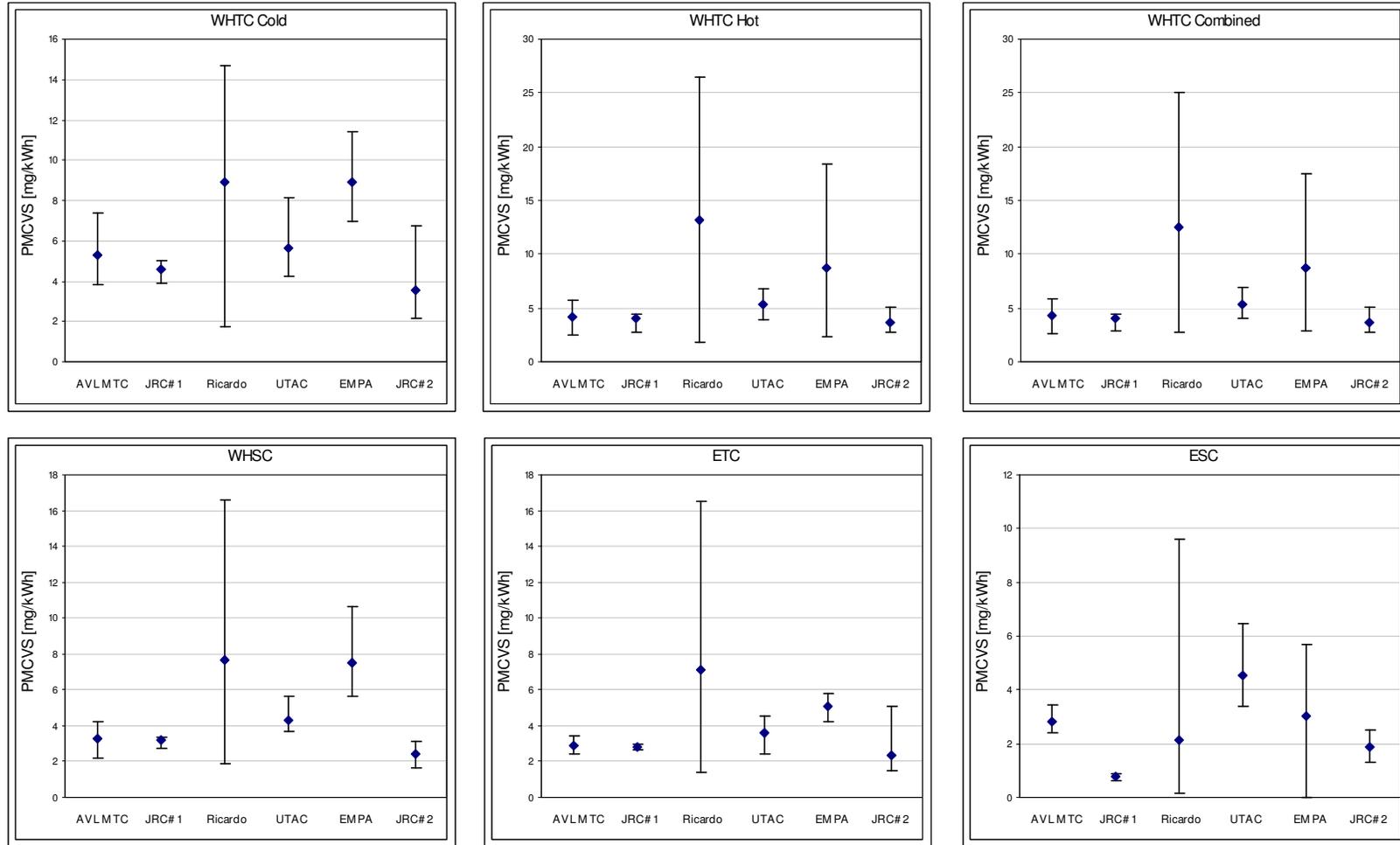
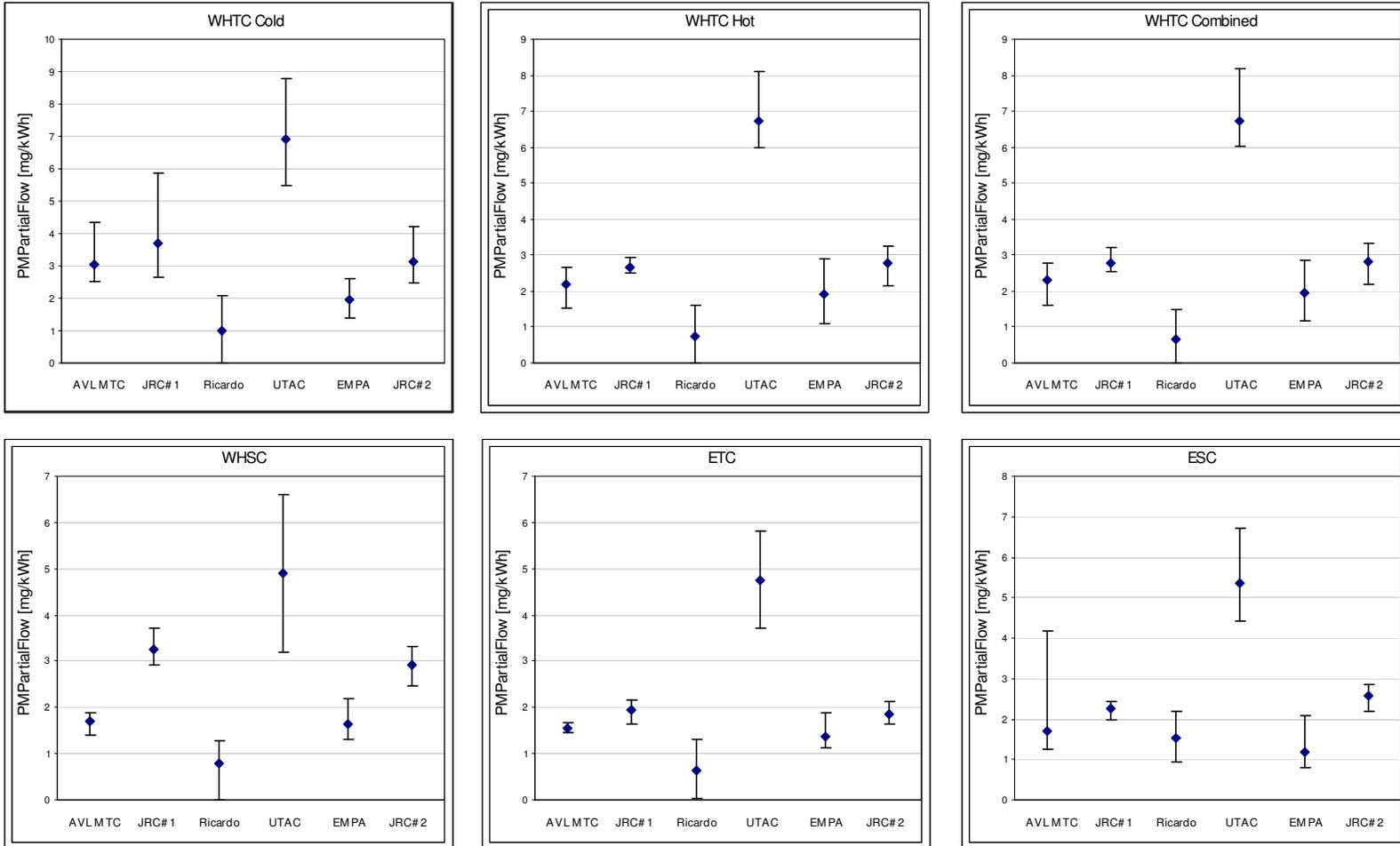


Figure 22: Maximum and Minimum Ranges of Emissions – PDT PM

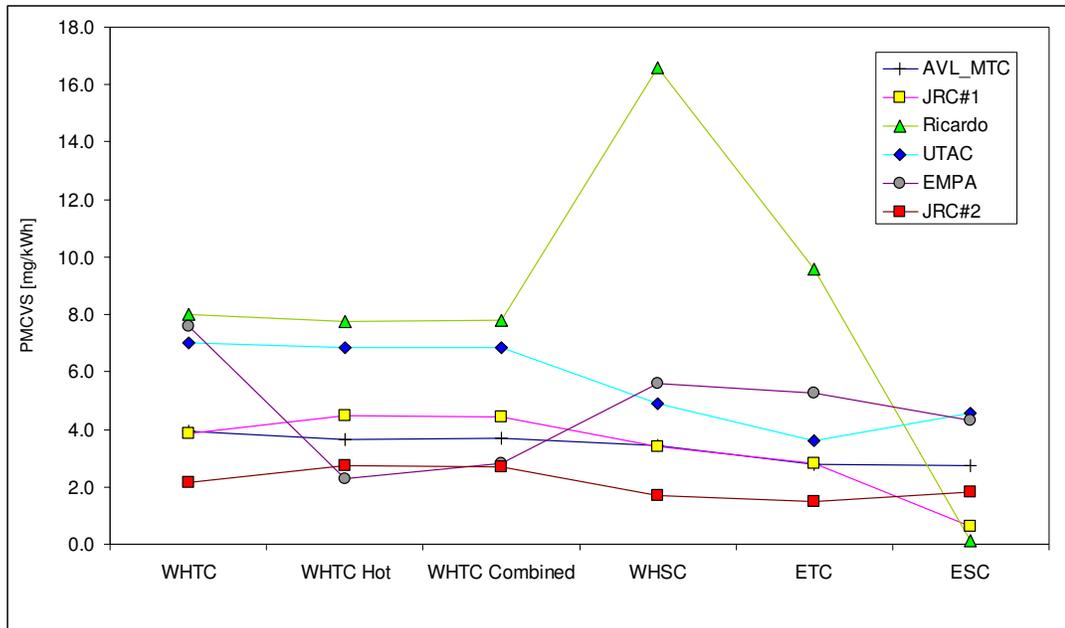


### 6.1.5 PM – Daily Trends

The trends in PM emissions across the day's test sequence are shown for CVS PM in Figure 23 and for PDT PM in Figure 24. Data are shown from all test labs, with concurrently sampled data from the CVS and PDT shown.

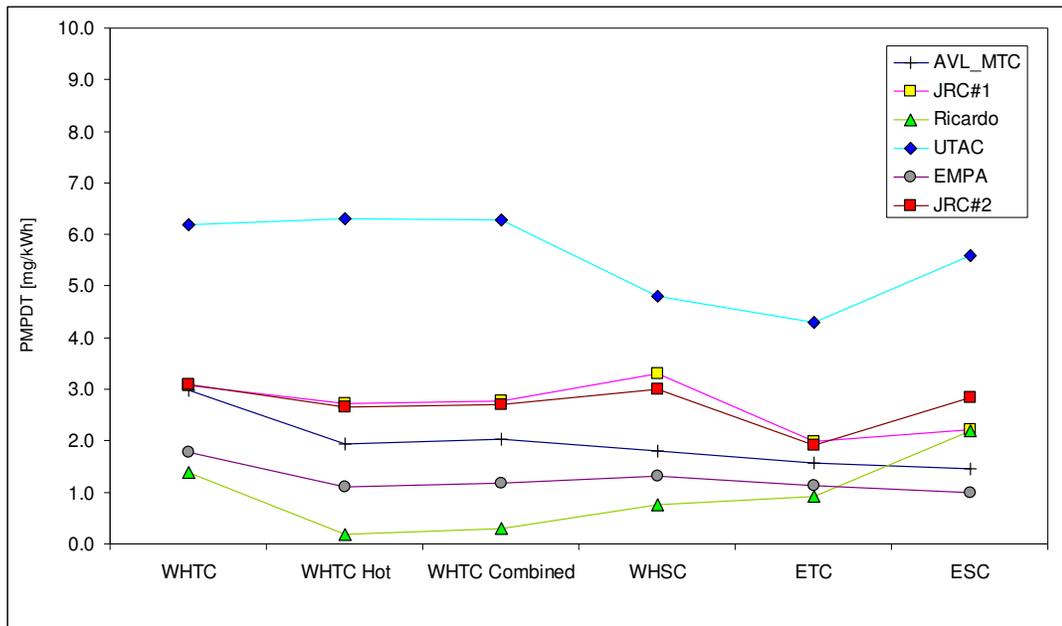
From the CVS (Figure 23), profiles from the JRC, UTAC and AVL-MTC tests are relatively similar, with PM levels remaining relatively flat through the test sequence. The labs with the high backgrounds show different profiles. These results indicate that if any changes in emissions levels occur due to cycle-to-cycle variations or changes to DPF fill state occur with passive regeneration within individual cycles, CVS PM is insensitive to them. Alternatively, any effects that do occur are masked by background levels even in the labs with low emissions.

**Figure 23: CVS PM Emissions through the Test Sequence – All labs**



From the partial flow system (Figure 24), PM levels were relatively consistent through the test sequence from all labs except UTAC where the background levels were higher. It is possible that the PM method detects a reduction in cycle PM between the cold and hot WHTC cycles, but as with the CVS data, the PDT PM method is either insufficiently sensitive to detect changes in DPF fill state through the day's test sequence, or effects are masked by background levels.

**Figure 24: PDT PM Emissions through the Test Sequence – All labs**



### 6.1.6 Overview of PM Results

- CVS PM results, after elimination of the high background labs data, showed emissions levels of <6mg/kWh across all cycles
- Emissions levels from the PDTs were generally lower at 4mg/kWh or less from all cycles, with the exception of UTAC's results which were in the range 4mg/kWh to 7mg/kWh. This may have been due to a higher PDT background than other labs, but there is insufficient data to draw a firm conclusion
- CVS PM backgrounds were generally at the same level as samples except from ESC cycles, as ESC PM contains low volatility HCs which, once collected, remain on the filter. As a consequence, the CVS PM method is only capable of resolving engine emissions from the background from ESC tests.
- Background PM levels in PDT systems were at the low end of levels seen from CVS systems. Even so in only one of 3 systems, in which background levels were determined, was it possible to discriminate data from any more cycles than the ESC.
- In the one PDT system that enabled discrimination between background and sample levels, emissions from all cycles were <2mg/kWh and specifically ~1.2mg/kWh from the WHSC and <1mg/kWh from the weighted WHTC.

*This section is incomplete*

## 6.2 Full Flow and Partial Flow PN

### 6.2.1 PN – Background Levels

PN background levels appear to vary substantially between CVS systems in different laboratories, but appear highly similar between partial flow systems. While data are not

available for backgrounds in all labs, comparisons of hot transient cycle results from different labs, where particle emissions are low, clearly shows the offsets due to backgrounds.

As Figure 25 shows, particle number emissions measured from the CVS from different labs across the hot WHTC can vary by a factor of 100 or more. In contrast (Figure 29), particle number emissions from PDTs sampled simultaneously to the CVS data appear to overlay.

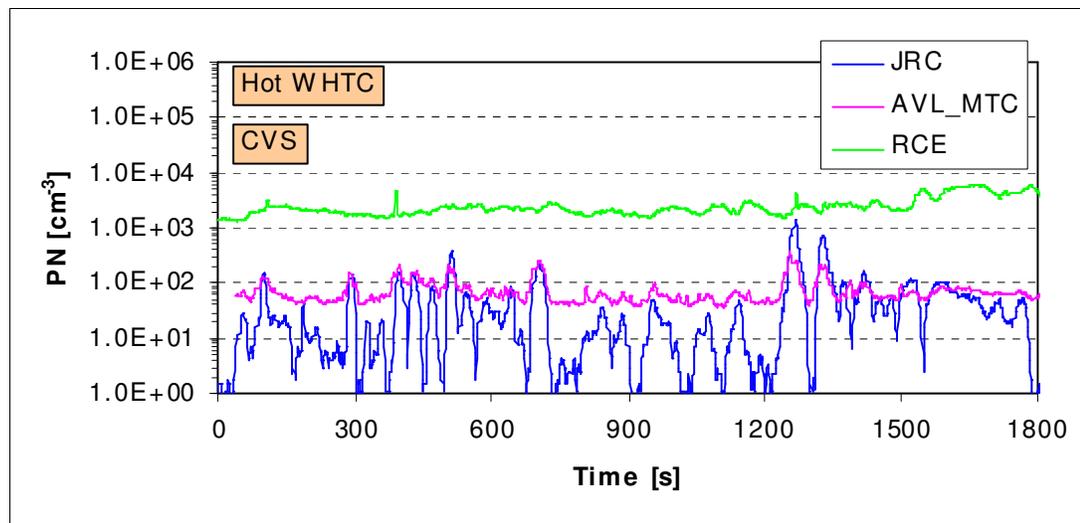
JRC, AVL and Ricardo (RCE) also supplied particle number data from 30 minutes dilution system background acquisitions taken prior to the cold start WHTC on each test day. A typical background from each of the PDT and CVS facilities at these labs was calculated to particles/kWh and the values obtained were compared. These data are shown in Figure 26.

The CVS background at Ricardo was  $>4 \times 10^{10}$ /kWh. This was ~60 times higher than the CVS background at AVL-MTC and ~140 times higher than the CVS background at JRC. These differences are in line with the differences in emissions levels seen from the hot start transient test shown in Figure 25, and indicate that from Ricardo and to a lesser extent AVL, the background predominates in the particle numbers measured.

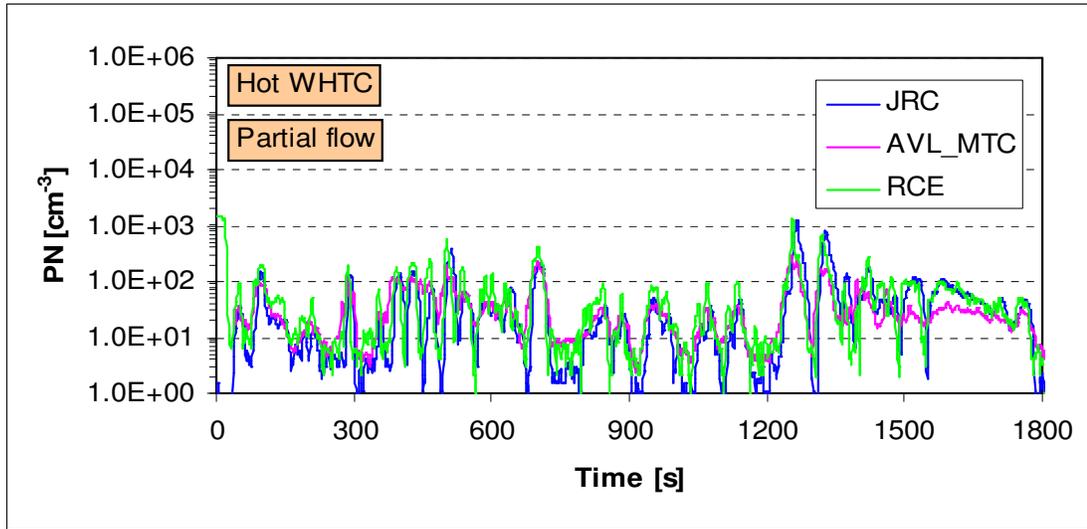
The background levels from the 3 PDT systems are almost identical: at  $<3 \times 10^8$ /kWh. This indicates that the small variations in particle number levels seen in Figure 26 are probably related to real engine or DPF variability rather than background contributions.

As noted in Section 6.1.4, where PM background was discussed, the Ricardo facility is a working facility which had recently experienced testing on high bio-content fuels, work on active regeneration strategies for DPF regeneration and substantial amounts of non-DPF testing on low NOx calibration engines. An elevated PM background was seen from this lab and it is apparent the background also contributes substantially to PN.

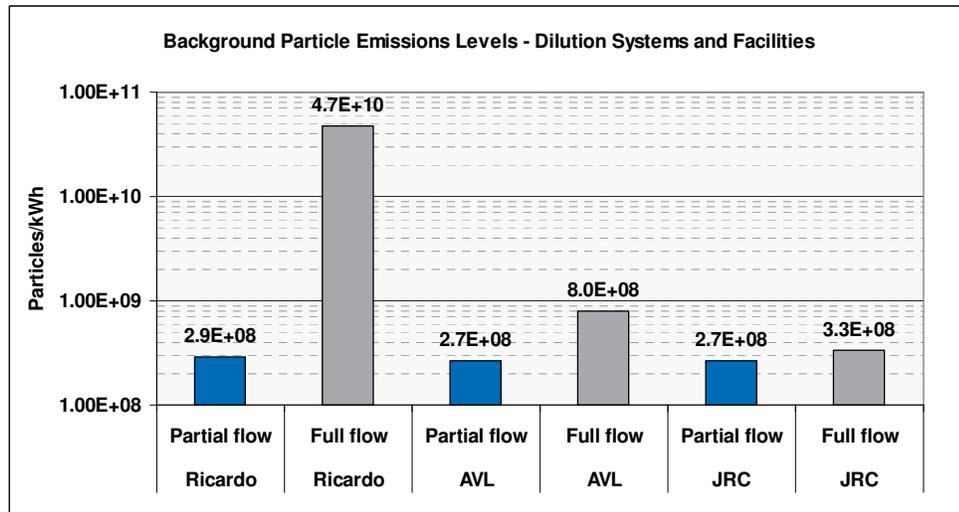
**Figure 25: Background Impacts PN Results – CVS Systems at 3 Labs**



**Figure 26: Background Effect on PN Results Minimal– PDT Systems at 3 Labs**



**Figure 27: Particle Number Backgrounds – 3 Labs; CVS and PDT Facilities**



6.2.2 PN - Repeatability

*Transient Particle Production*

Figure 28 to Figure 32 inclusive show real-time repeatability traces for cold WHTC, hot WHTC, WHSC and ESC tests. Each figure shows PN results from a lab with the highest CVS particle number background (upper), results from the lab with the lowest CVS PN background (middle) and typical results from a partial flow system (lower). The bottom and middle charts' data are drawn from the same test laboratory.

Data from the cold start WHTCs shown in Figure 28 (upper) covers approximately two orders of magnitude, but the range seen in the middle and lower figures covers more than 4 orders of magnitude. It is also clear that data in the top figure shows little similarity to the engine speed after the first 700s, but the middle and lower figures reflect changes in engine operation throughout the emissions cycle.

The high levels of background seen in the CVS (Figure 28, upper) do not have a substantial effect on repeatability, because the overall emissions levels from the cycle are dominated by those of the first 700s. Repeatability levels from the data shown, based upon mean cycle results, would be relatively similar to those seen for Figure 28, middle and lower.

The contrast between the upper and middle parts of Figure 28 is clear: while the profiles of emissions coincide at the peaks, the less transient parts of the emissions cycles can be masked if the background is high. Results from the lower figure are highly similar to those of the middle figure, indicating that there are not fundamental differences in either emissions levels or transient measurements from full and partial flow systems as long as background levels are similar.

The sensitivity of the measurement is obviously affected by the background, but as mentioned above, the dominance of the peaks seen in the first 700s makes even a high background almost irrelevant to results from the cold WHTC emissions cycle.

Results from the hot start WHTC (Figure 29) were substantially affected by the high CVS background. A comparison between high (upper figure) and low (middle figure) background CVS facilities shows that the transient traces from the high background lab bear little or no relationship to the transient events of the cycle and span less than a factor of 10. Conversely, the emissions of the low background CVS (middle figure) and from the partial flow system (lower figure) indicate transient events corresponding to engine operation and emissions ranges that span 2 to 3 orders of magnitude. Once again, results from the flow background CVS and partial flow systems appear very similar.

Peak emissions levels from the partial flow system (and low background CVS) were ~ 1000 times lower than the peaks from the cold start WHTC, but in the high background CVS, cold WHTC emissions only appeared to be 10 times higher than the hot start WHTC. Clearly, the hot WHTC repeatability from the high background CVS system reflects little more than the repeatability of the background levels.

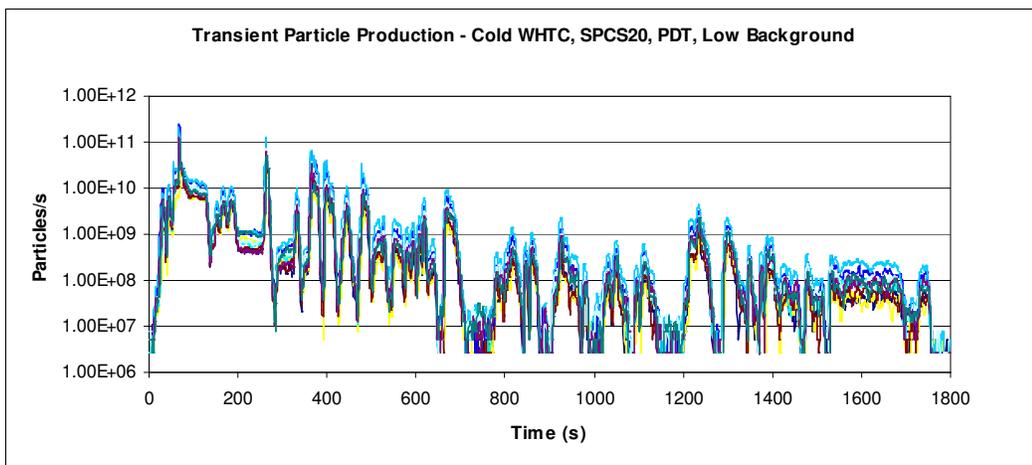
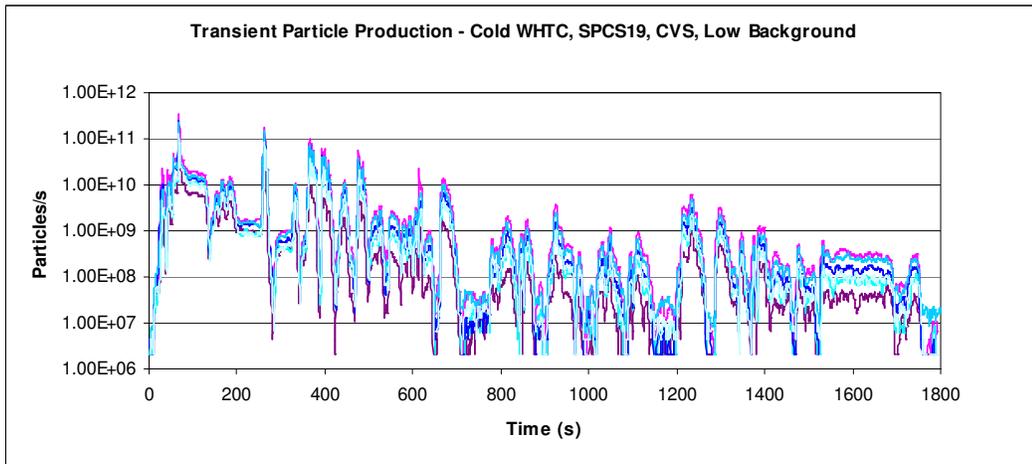
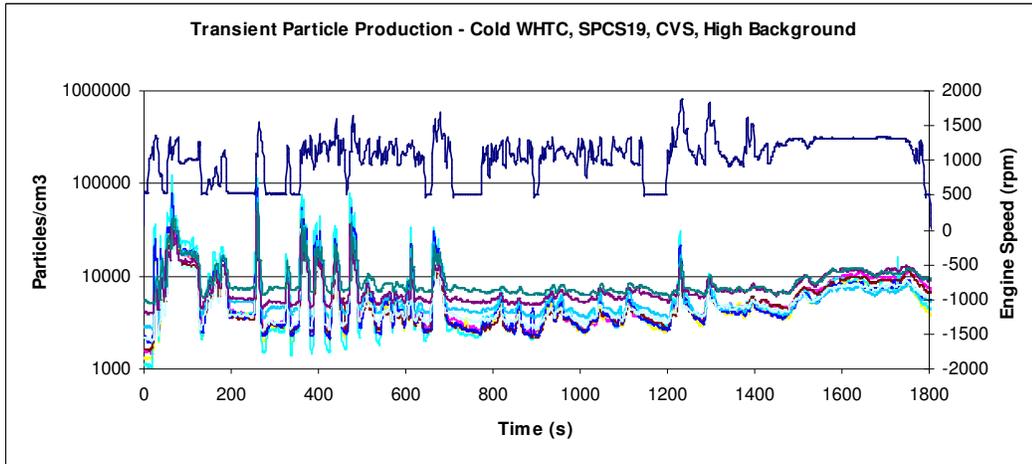
Emissions from the WHSC cycle (Figure 30) were at a similar level to those seen from the hot WHTC (Figure 29), but the emissions profile from the high background CVS (upper figure) tracks the engine speed trace well. This suggests that the background is less significant during this cycle than in the hot WHTC, so running the previous two cycles in the test matrix may have had a 'cleaning' effect on the CVS.

From all three dilution tunnels, it appears that particle number emissions are very low from the WHSC until ~1200s. The exhaust temperature of the WHSC is sufficient to enable passive regeneration (where NO<sub>2</sub> reacts with soot on the DPF to produce N<sub>2</sub> and CO<sub>2</sub>) during ~60% of the emissions cycle (Figure 31, left).

It is possible that after ~1200s of the WHSC, the soot loading of the DPF has reduced sufficiently to have a substantial impact on filtration efficiency. The exhaust temperature has also increased to ~450°C at this point in the cycle (Figure 31, right) and this might lead to the thermal release of low volatility components from the exhaust system. Both these mechanisms could increase particle number emissions and variability.

The ETC cycle is tested following the WHSC in the test sequence. Results, emissions levels and repeatability from this cycle were very similar to those from the hot WHTC. The ETC runs at relatively low exhaust temperatures, so during this cycle additional soot is added to the DPF following passive regeneration in the WHSC. This may have the effect of increasing filtration efficiency for the start of the ESC.

**Figure 28: Real-time Data – Cycle-to-cycle Repeatability, Cold WHTC**



**Figure 29: Real-time Data – Cycle-to-cycle Repeatability, Hot WHTC**

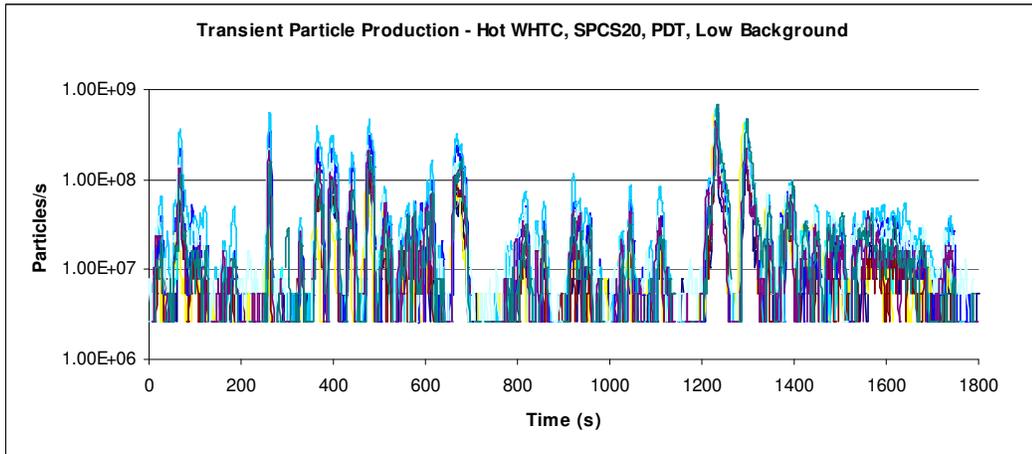
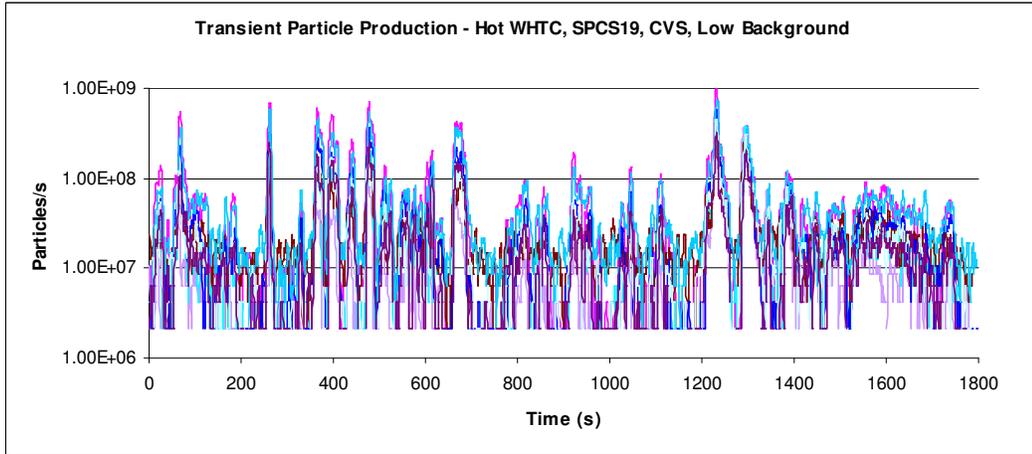
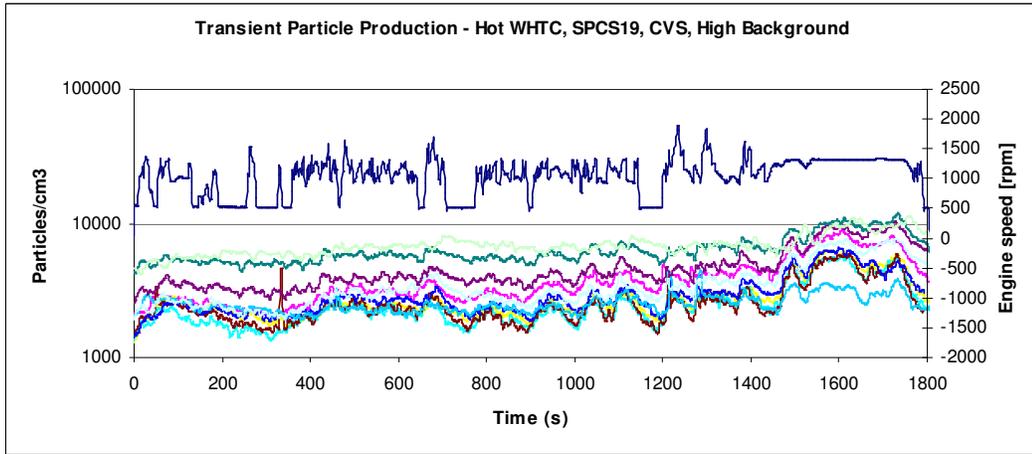
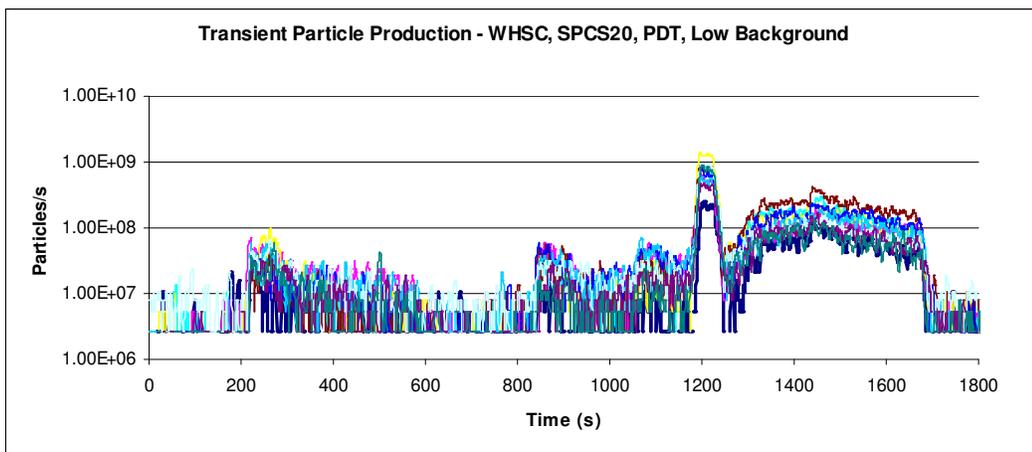
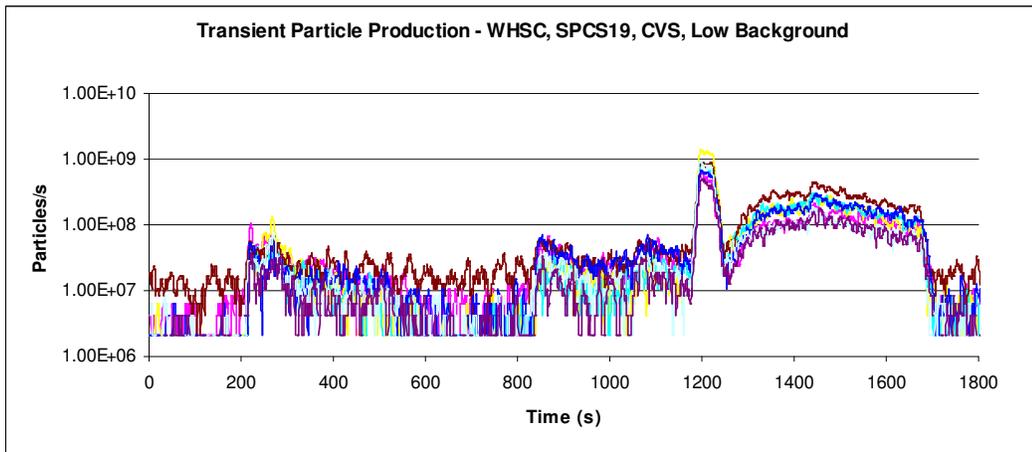
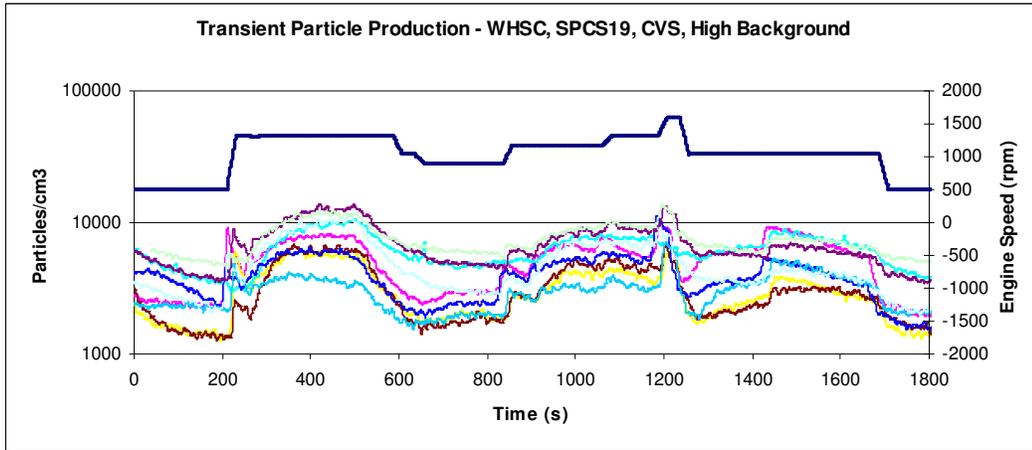
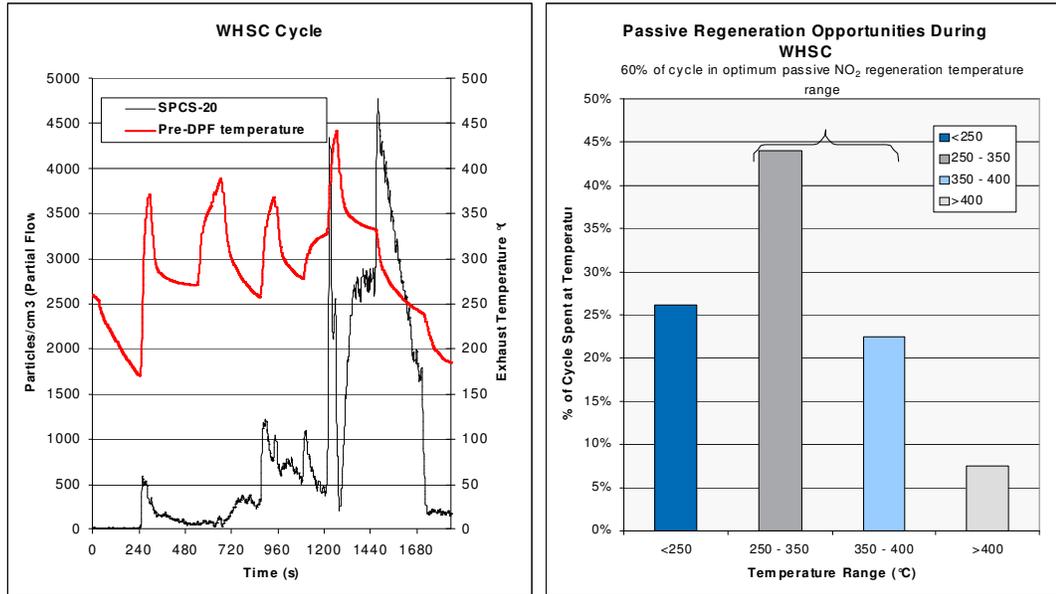


Figure 30: Real-time Data – Cycle-to-cycle Repeatability, Hot WHSC



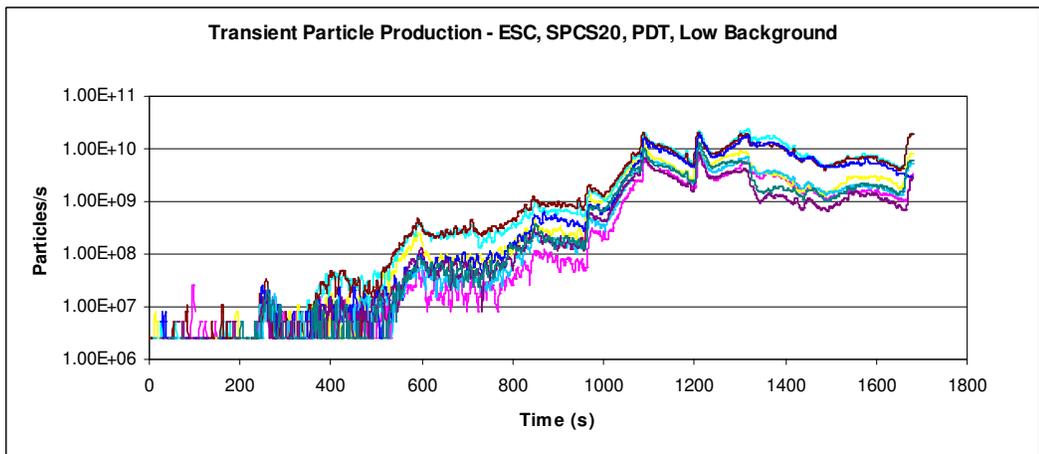
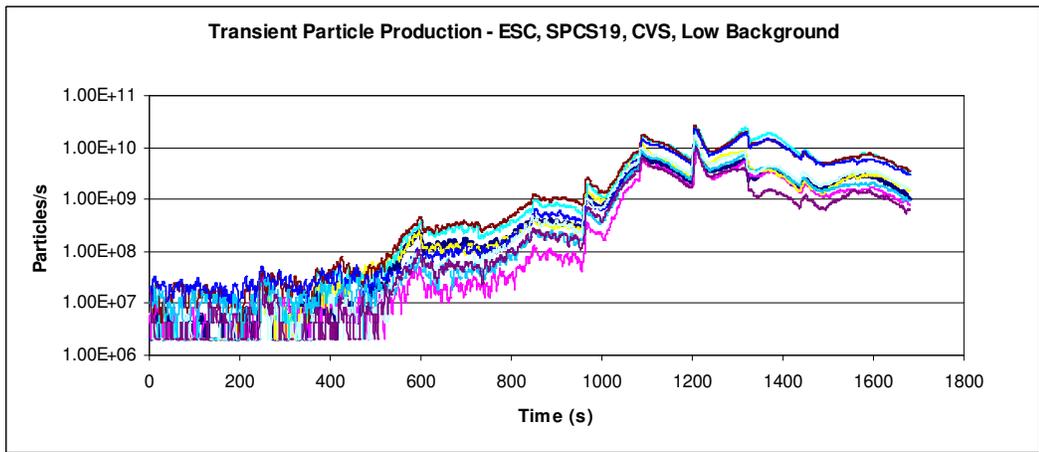
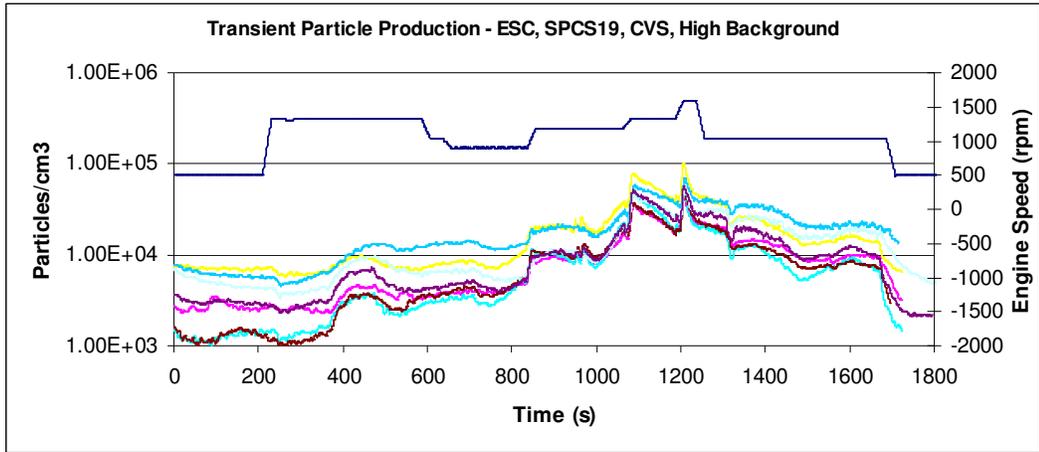
**Figure 31: Passive Regeneration During the WHSC**



Emissions during the 4 minutes of idle at the start of ESC cycle (Figure 32 upper, middle and lower) were very low and probably indistinguishable from background in all dilution systems. As with the WHSC cycle, most of the modal transitions of the ESC are visible even in the high background data (upper figure), but the range of emissions seen in this system (~100 from low to high) compares poorly with the 4 orders of magnitude from the low background CVS and PDT and indicates lowered sensitivity of this measurement system.

The ESC shows the highest variability levels on a cycle-to-cycle basis, and these appear to worsen after 1000s of the cycle: at this point exhaust temperatures rise substantially, reaching >600°C after ~1300s. Passive regeneration in this cycle may eliminate the soot replaced during the ETC cycle and further eliminate soot from the DPF. Any variations in initial soot loading during the previous night's preconditioning may manifest as variability in the ESC.

Figure 32: Real-time Data – Cycle-to-cycle Repeatability, Hot ESC



### *Repeatability as CoV*

Repeatability levels for all labs are given as single CoV values that express overall intra-lab variability for each emissions cycle (see Section **Error! Reference source not found.**).

Figure 33 shows the repeatability of the 5 test matrix cycles and the composite weighted WHTC result for the CVS-based and PDT-based PN methods.

Three results are shown for each cycle, and these include:

- PMCVS1: All data from all labs (excepting tests excluded for technical reasons)
- PMCVS2: Outlier analysis iteration 1
- PMCVS3: Outlier analysis iteration 2

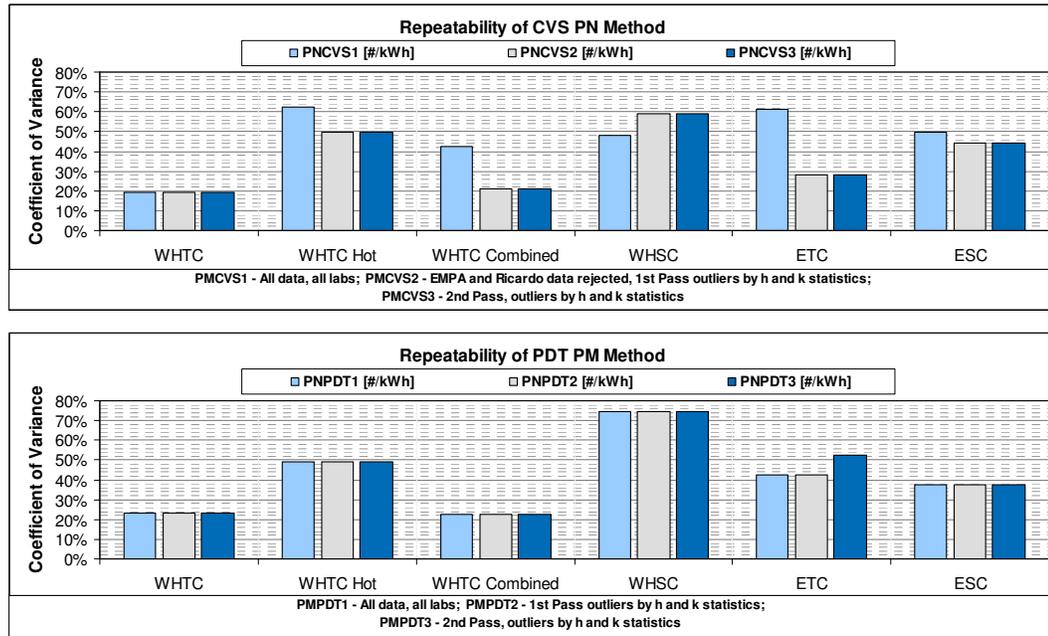
Outlier analyses excluded the CVS PN results from both Ricardo and EMPA on the first pass iteration excepting: cold WHTC data from both labs and ESC data from EMPA.

On the second pass analysis, the ETC data from the first batch of tests at JRC were excluded.

Considering all cycles (Figure 24), and following the outlier iterations, repeatability levels were broadly similar: CVS CoVs ranged from ~20% to ~60% and PDT CoVs from ~20% to ~70%.

Focusing on the Euro VI legislative cycles in isolation shows that the CVS approach has better repeatability over the weighted WHTC (21.1% Vs. 22.8%) and over the WHSC (59.2% Vs. 74.4%) than the PDT approach.

Figure 33: Repeatability of Particle Number Measurement Systems



### 6.2.3 PN - Reproducibility

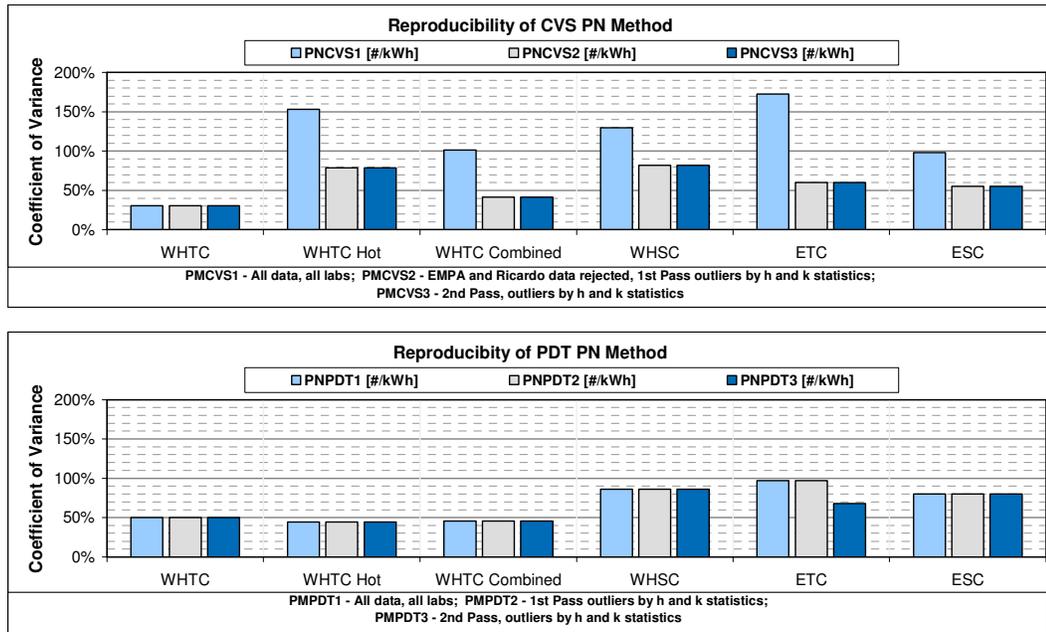
Reproducibility levels for all labs are given as single CoV values that express overall inter-lab variability from each emissions cycle (see Section **Error! Reference source not found.**).

Figure 34 shows the reproducibility of the 5 test matrix cycles and the composite weighted WHTC result for the CVS-based and PDT-based PN methods.

The outlier analysis has a substantial effect on reducing the variability of the CVS system's results (Figure 34 upper), but has little impact on the PDT results, except in the ETC where the first results from JRC were eliminated from the dataset.

Considering just the Euro VI legislative cycles shows that the CVS approach has better reproducibility over the weighted WHTC (41.4% Vs. 45.8%) and over the WHSC (81.7% Vs. 86.3%) than the PDT approach.

**Figure 34: Reproducibility of Particle Number Measurement Systems**



#### 6.2.4 PN – Emissions Levels

Particle number emissions from the various test cycles are shown for CVS measurements in Table 10 and Figure 35 and for PDT measurements in Table 11 and Figure 37.

##### *PN Emissions from CVS Systems*

Particle number emissions from the cold WHTC cycle ranged by approximately an order of magnitude across all laboratories – from  $\sim 6 \times 10^{10}/\text{kWh}$  to  $\sim 7 \times 10^{11}/\text{kWh}$  with the all-labs mean at  $\sim 4 \times 10^{11}/\text{kWh}$ .

Hot WHTC results ranged from  $10^9/\text{kWh}$  (JRC 2<sup>nd</sup> campaign) up to  $\sim 5 \times 10^{11}/\text{kWh}$  at Ricardo, a difference from low to high of 500 times. The all labs mean, at  $\sim 6 \times 10^{10}/\text{kWh}$ , was substantially impacted by the labs with high emissions levels.

**Table 10: Maximum and Minimum Ranges for CVS-measured PN**

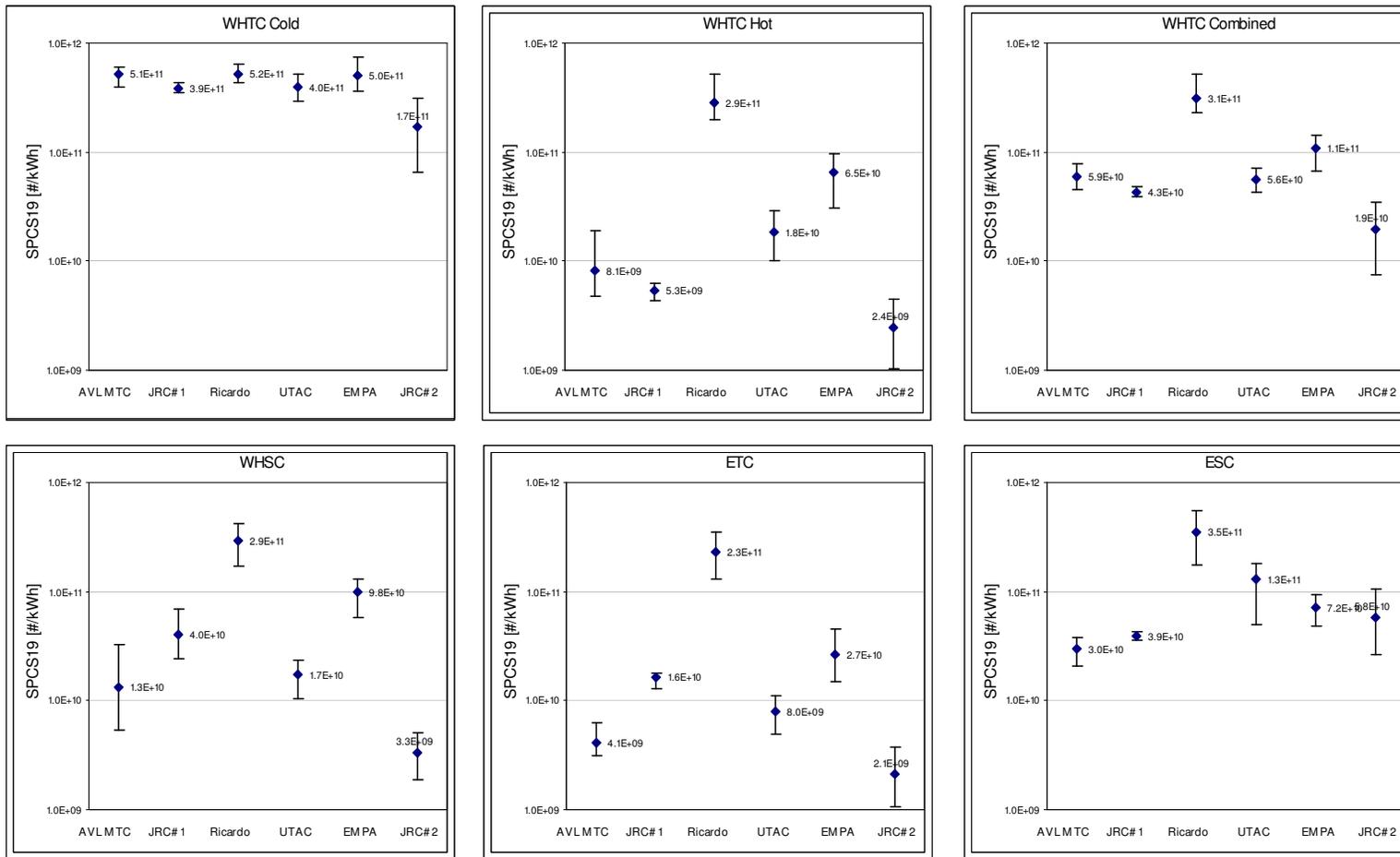
		WHTC Cold	WHTC Hot	WHTC Combined	WHSC	ETC	ESC
AVL MTC	Average	5.1E+11	8.1E+09	5.9E+10	1.3E+10	4.1E+09	3.0E+10
	Maximum	6.1E+11	1.9E+10	7.8E+10	3.2E+10	6.3E+09	3.8E+10
	Minimum	3.9E+11	4.7E+09	4.5E+10	5.4E+09	3.2E+09	2.1E+10
JRC #1	Average	3.9E+11	5.3E+09	4.3E+10	4.0E+10	1.6E+10	3.9E+10
	Maximum	4.3E+11	6.2E+09	4.8E+10	6.9E+10	1.8E+10	4.2E+10
	Minimum	3.5E+11	4.3E+09	3.9E+10	2.4E+10	1.3E+10	3.6E+10
Ricardo	Average	5.2E+11	2.9E+11	3.1E+11	2.9E+11	2.3E+11	3.5E+11
	Maximum	6.3E+11	5.2E+11	5.2E+11	4.2E+11	3.5E+11	5.5E+11
	Minimum	4.3E+11	2.0E+11	2.3E+11	1.7E+11	1.3E+11	1.7E+11
UTAC	Average	4.0E+11	1.8E+10	5.6E+10	1.7E+10	8.0E+09	1.3E+11
	Maximum	5.1E+11	2.9E+10	7.0E+10	2.3E+10	1.1E+10	1.8E+11
	Minimum	2.9E+11	1.0E+10	4.3E+10	1.1E+10	4.9E+09	5.0E+10
EMPA	Average	5.0E+11	6.5E+10	1.1E+11	9.8E+10	2.7E+10	7.2E+10
	Maximum	7.4E+11	9.7E+10	1.4E+11	1.3E+11	4.5E+10	9.4E+10
	Minimum	3.6E+11	3.1E+10	6.8E+10	5.7E+10	1.5E+10	4.8E+10
JRC #2	Average	1.7E+11	2.4E+09	1.9E+10	3.3E+09	2.1E+09	5.8E+10
	Maximum	3.1E+11	4.5E+09	3.5E+10	5.0E+09	3.8E+09	1.1E+11
	Minimum	6.5E+10	1.0E+09	7.4E+09	1.9E+09	1.1E+09	2.6E+10
	All Min	7.4E+11	5.2E+11	5.2E+11	4.2E+11	3.5E+11	5.5E+11
	All Max	6.5E+10	1.0E+09	7.4E+09	1.9E+09	1.1E+09	2.1E+10
All data	Mean of means	4.1E+11	6.4E+10	9.9E+10	7.7E+10	4.8E+10	1.1E+11
	Range Factor	11.4	500.8	69.7	221.4	327.3	26.8
Outlier labs excluded	Mean of means	4.1E+11	8.6E+09	4.9E+10	1.8E+10	7.6E+09	6.6E+10

Weighted WHTC results, based upon the cold and hot WHTC data providing 10% and 90% contributions respectively, ranged from  $\sim 7 \times 10^9$ /kWh to  $\sim 5 \times 10^{11}$ /kWh with an all labs mean of  $\sim 10^{11}$ /kWh.

WHSC and ETC results reflected the results of the hot WHTC, with lowest emissions levels at JRC and highest at Ricardo. WHSC emissions levels ranged by more than 200 times: from  $2 \times 10^9$ /kWh up to  $\sim 4 \times 10^{11}$ /kWh and ETC ranged by a factor of >300, from  $\sim 10^9$ /kWh up to  $\sim 3.5 \times 10^{11}$ /kWh.

ESC results showed a narrower range than any of the emissions cycles except the Cold WHTC. Low to high range covered a factor of <30, from  $\sim 2 \times 10^{10}$ /kWh up to  $\sim 5.5 \times 10^{11}$ /kWh.

Figure 35: Maximum and Minimum Ranges for CVS-measured PN

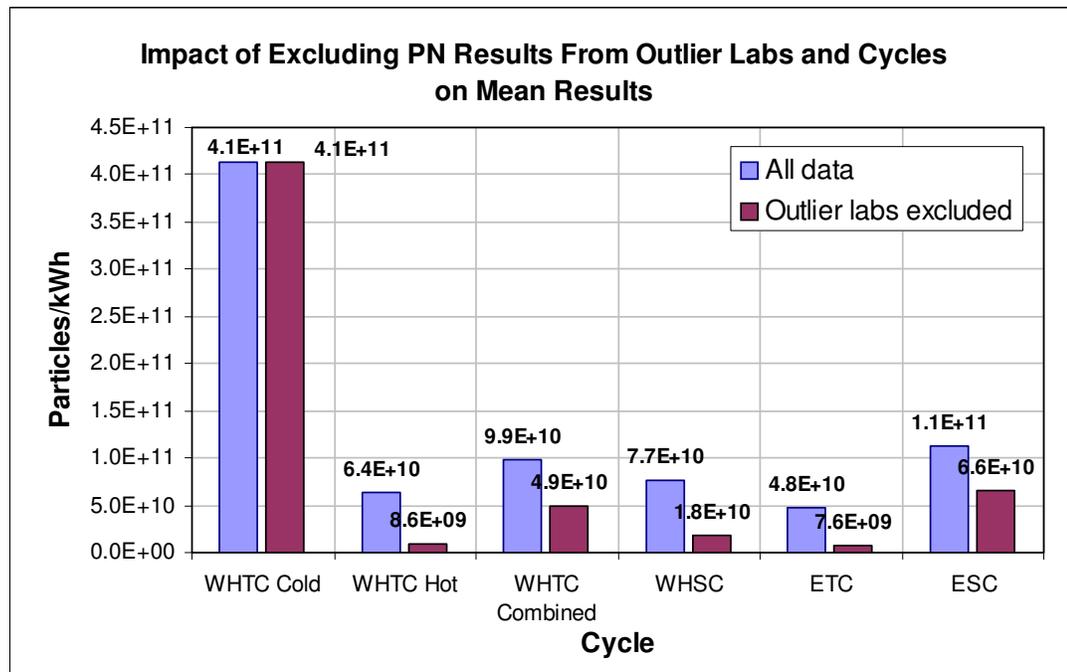


As described in Section **Error! Reference source not found.**, statistical methods were used to eliminate individual PN data and a majority of data from several cycles at two specific laboratories in the dataset. Excluded data are:

- Ricardo CVS data from WHTC Hot, WHSC, ETC, ESC
- EMPA CVS data from WHTC Hot, WHSC, ETC
- ETC data from the first set of tests at JRC

The effects on the mean of means (the average PN emissions across all labs) of eliminating the outlier data is shown in Figure 36. The Cold WHTC data are unaffected since no data are excluded, but the hot WHTC result is substantially reduced, resulting in a weighted WHTC reduction of >50% to  $\sim 5 \times 10^{10}$ /kWh. The WHSC result drops to  $< 2 \times 10^{10}$ /kWh, the ETC to below  $10^{10}$ /kWh and the ESC to  $< 7 \times 10^{10}$ /kWh.

**Figure 36: CVS PN Results – Effect of Eliminating Outliers**



*PN Emissions from PDT Systems*

Particle number emissions from the cold WHTC cycle ranged by approximately an order of magnitude across all laboratories – from  $\sim 6 \times 10^{10}$ /kWh to  $\sim 7 \times 10^{11}$ /kWh with the all-labs mean at  $\sim 3.7 \times 10^{11}$ /kWh. From the PDTs, cold WHTC emissions levels were substantially higher than from any other cycles.

**Table 11: Maximum and Minimum Ranges for PDT-measured PN**

		WHTC Cold	WHTC Hot	WHTC Combined	WHSC	ETC	ESC
AVL MTC	Average	6.3E+11	4.3E+09	6.7E+10	1.0E+10	2.2E+09	2.8E+10
	Maximum	7.3E+11	4.9E+09	7.7E+10	2.4E+10	3.3E+09	3.8E+10
	Minimum	4.7E+11	3.8E+09	5.0E+10	3.7E+09	1.6E+09	2.0E+10
JRC #1	Average	4.0E+11	5.3E+09	4.4E+10	4.4E+10	1.8E+10	4.2E+10
	Maximum	4.7E+11	5.8E+09	5.2E+10	7.3E+10	2.1E+10	4.8E+10
	Minimum	3.3E+11	4.0E+09	3.8E+10	2.4E+10	1.3E+10	3.6E+10
Ricardo	Average	2.3E+11	7.4E+09	3.0E+10	5.6E+10	5.3E+09	2.1E+11
	Maximum	3.4E+11	1.0E+10	4.3E+10	1.4E+11	1.1E+10	3.3E+11
	Minimum	1.4E+11	4.5E+09	1.8E+10	2.5E+10	1.0E+09	1.4E+11
UTAC	Average	4.1E+11	4.8E+09	4.5E+10	9.1E+09	2.1E+09	6.8E+10
	Maximum	6.2E+11	7.1E+09	6.4E+10	1.5E+10	4.3E+09	9.9E+10
	Minimum	2.9E+11	1.9E+09	3.1E+10	2.7E+09	9.5E+08	2.4E+10
EMPA	Average	4.2E+11	8.5E+09	4.9E+10	4.4E+10	8.1E+09	6.1E+10
	Maximum	6.0E+11	1.6E+10	7.3E+10	9.1E+10	1.0E+10	8.0E+10
	Minimum	3.1E+11	3.8E+09	3.5E+10	2.5E+10	4.8E+09	3.9E+10
JRC #2	Average	1.3E+11	1.7E+09	1.4E+10	2.6E+09	1.8E+09	5.9E+10
	Maximum	2.3E+11	3.1E+09	2.5E+10	3.9E+09	2.9E+09	1.1E+11
	Minimum	6.3E+10	8.9E+08	7.3E+09	1.2E+09	1.0E+09	2.6E+10
	All Min	7.3E+11	1.6E+10	7.7E+10	1.4E+11	2.1E+10	3.3E+11
	All Max	6.3E+10	8.9E+08	7.3E+09	1.2E+09	9.5E+08	2.0E+10
	Mean of means	3.7E+11	5.3E+09	4.2E+10	2.8E+10	6.2E+09	7.7E+10
	Range Factor	11.6	18.4	10.6	119.2	22.4	16.4

Hot WHTC results ranged from  $<10^9$ /kWh (JRC 2<sup>nd</sup> campaign) up to  $\sim 1.6 \times 10^{10}$ /kWh, a difference from low to high of less than 20 times. The all labs mean was  $\sim 5 \times 10^9$ /kWh, almost 2 orders of magnitude lower than the cold start emissions.

The low emissions levels measured from PDTs during the hot WHTC cycle resulted in a substantial reduction in the weighted WHTC result relative to the cold start cycle. Emission ranged from  $\sim 7 \times 10^9$ /kWh to  $\sim 8 \times 10^{10}$ /kWh with the all labs mean at  $\sim 4.2 \times 10^{10}$ .

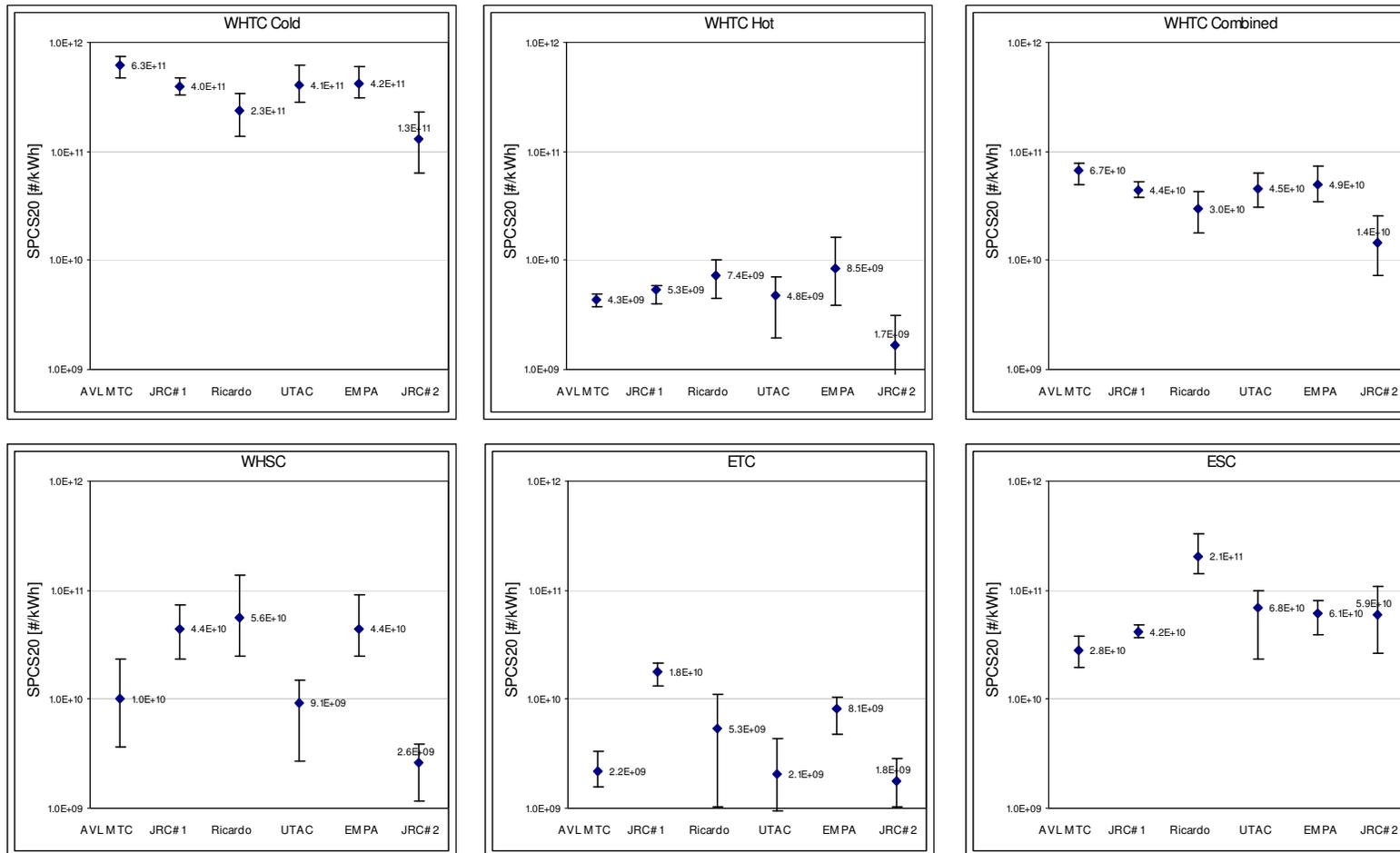
Emissions from the WHSC showed the greatest range, a factor of  $\sim 120$ , which reflects the substantial period of operation spent in passive regeneration during this cycle and the influence that has on DPF fill-state and filtration efficiency. Low-end emissions levels were close to  $10^9$ /kWh increasing to  $1.4 \times 10^{11}$ /kWh.

The range and absolute emissions levels from the ETC were similar to those seen from the hot WHTC:  $\sim 10^9$ /kWh up to  $\sim 2 \times 10^{10}$ /kWh with the all labs mean at  $\sim 6 \times 10^9$ /kWh.

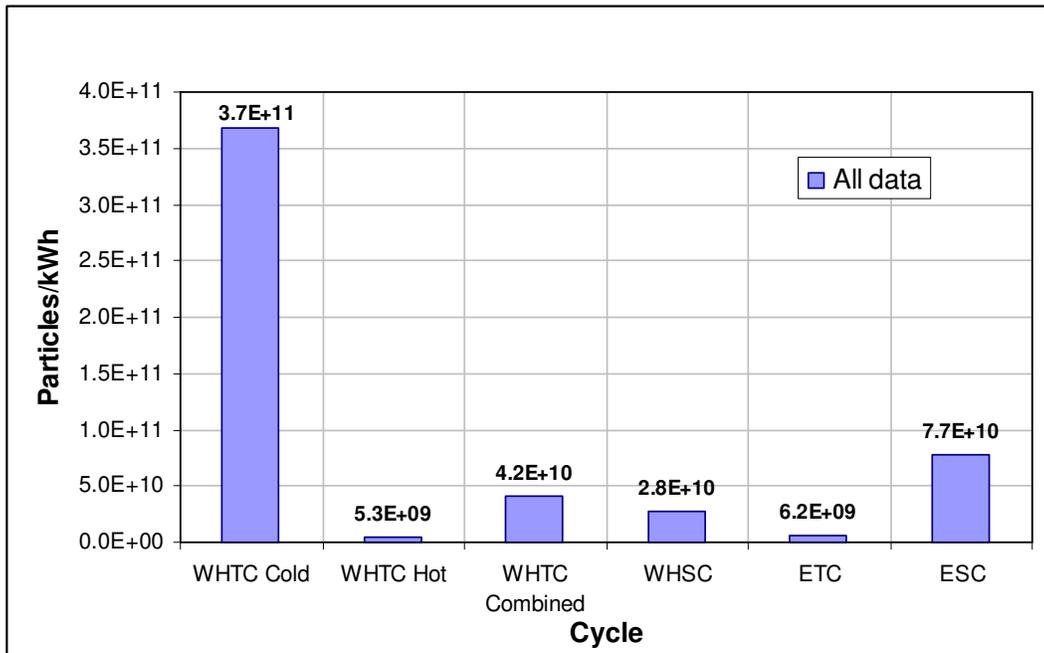
ESC data from Ricardo were highest of all the labs, but not identified as an outlier. Emissions ranged from  $\sim 2 \times 10^{10}$  to  $\sim 3 \times 10^{11}$ /kWh with the all labs mean at just below  $8 \times 10^{10}$ /kWh.

Figure 38 shows the mean of all labs PN emissions from PDT systems. Data are shown for all emissions cycles.

Figure 37: Maximum and Minimum Ranges for PDT-measured PN



**Figure 38: All Labs' Mean of Means PN Results - PDT Systems**



*PN Emissions Levels Overview*

In both CVS and PDT cases, and considering mean of means data, emissions were highest from the cold start WHTC at  $\sim 4 \times 10^{11}$ /kWh. At this level of emissions, contributions from the background, even from labs with very high backgrounds, do not have a substantial impact on emissions.

Lowest emissions were observed from hot cycles which do not have substantial periods of passive regeneration: hot WHTC and ETC. These cycles showed emissions levels of  $5 - 6 \times 10^9$ /kWh from the PDT and  $8 - 9 \times 10^9$ /kWh from the CVS once outlier laboratories were excluded. Laboratories considered to be outliers reported emissions levels from these cycles substantially above  $10^{11}$ /kWh.

Weighted WHTC results were of the order  $4 - 5 \times 10^{10}$ /kWh from the PDT and CVS (outliers excluded) and  $\sim 10^{11}$ /kWh from the CVS when all labs data were considered.

ESC and WHSC cycles results were generally more variable than the hot start ETC and WHTC due to the presence of passive regeneration during these cycles. Passive regeneration may reduce filtration efficiency by reducing or removing the filter cake but high temperatures may also liberate low volatility HCs which contribute to solid particles: both of these result in higher PN emissions from the ESC and WHSC than from the ETC and hot WHTC. The ESC cycle, which has a 2 minutes period of operation at full load, and other modes with very high exhaust temperatures, sees a higher contribution of low volatility HC 'solid particles' than the lower temperature WHSC. Emissions from the WHSC were around  $2-3 \times 10^{10}$ /kWh from PDT and CVS (outliers excluded) and  $6 - 8 \times 10^{10}$ /kWh from the ESC with outliers excluded from the CVS data.

### *Euro VI Certification*

Certification testing for Euro VI will include both WHTC and WHSC. From the emissions levels seen in this study a limit set mandating PDT and excluding CVS could be lower than a limit set that permits either dilution system. If either dilution system is permitted, the test laboratory or OEM would face substantially higher risk of non-compliance when using a full flow system, unless that CVS was well characterised beforehand.

### *Achievable PN Limit for this Engine*

Across this test programme the highest single PN emissions result seen from any cycle across all labs was  $7.4 \times 10^{11}$ /kWh from a cold WHTC. If this engine and its DPF are considered to have representative PN emissions and both CVS and PDT dilution approaches are used, a PN limit of  $8 \times 10^{11}$ /kWh would be achievable for all emissions cycles tested.

## **6.3 Gaseous Emissions**

### **This section is incomplete**

#### **All raw emissions**

- CO<sub>2</sub> emissions differences across the labs: best cycle 6%, worst cycle 13%
- CO emissions differences across the labs: best cycle 63%, worst cycle 91%. CO emissions range from 13mg/kWh to 400mg/kWh
- NO<sub>x</sub> emissions differences across the labs: best cycle 26%, worst cycle 38%
- HC emissions differences across the labs: best cycle 68%, worst cycle 82%. Emissions range from 6 to 120mg/kWh
- Cycle work differences across the labs: best cycle 2.5%, worst cycle 12.8%

Reproducibility acceptable but some results show higher than expected variation.

## **6.4 Long-term trends in engine operation**

### **This section is incomplete**

#### *6.4.1 Regulated Gases*

No obvious progressive trends in gaseous emissions across the test programme e.g.CO<sub>2</sub> (Figure 39) and NO<sub>x</sub> (Figure 40) rather step changes associated with different labs.

Gaseous emissions data from JRC was generally similar between the two measurement campaigns.

**Figure 39: CO<sub>2</sub> – Consistency Across The Validation Exercise**

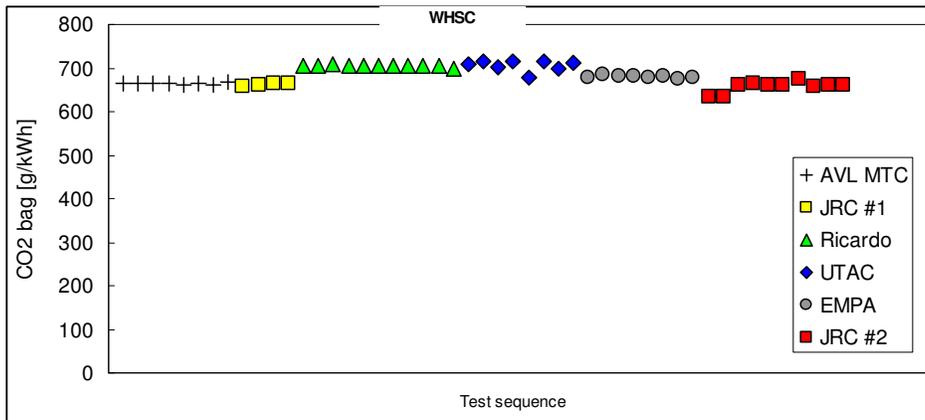
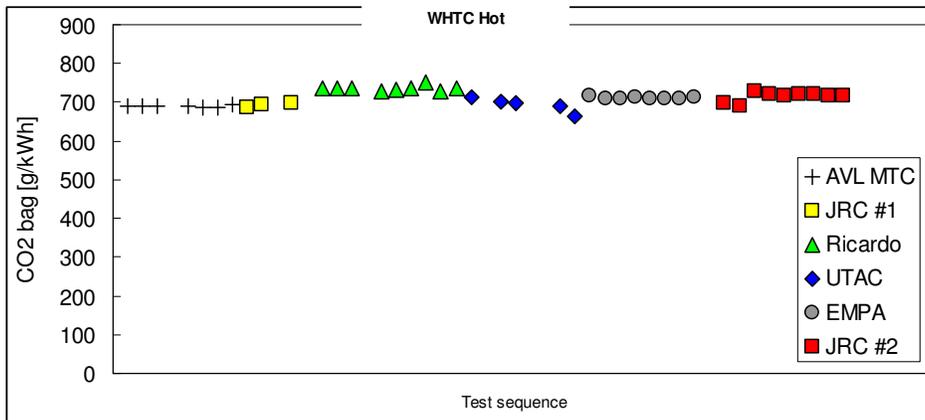
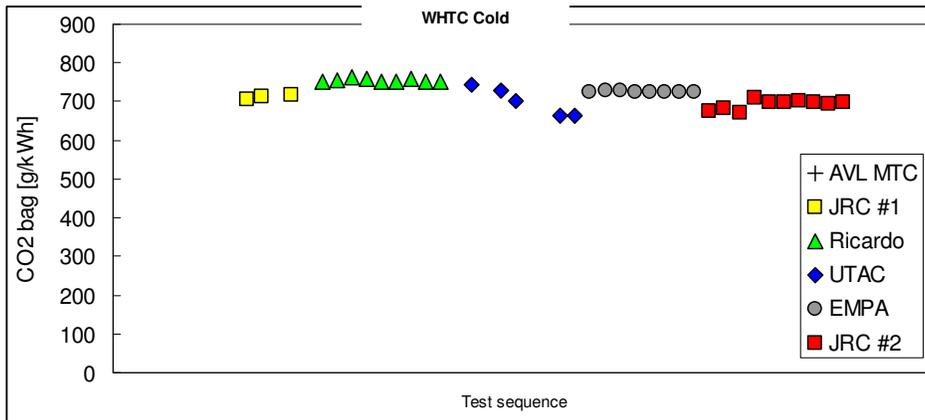
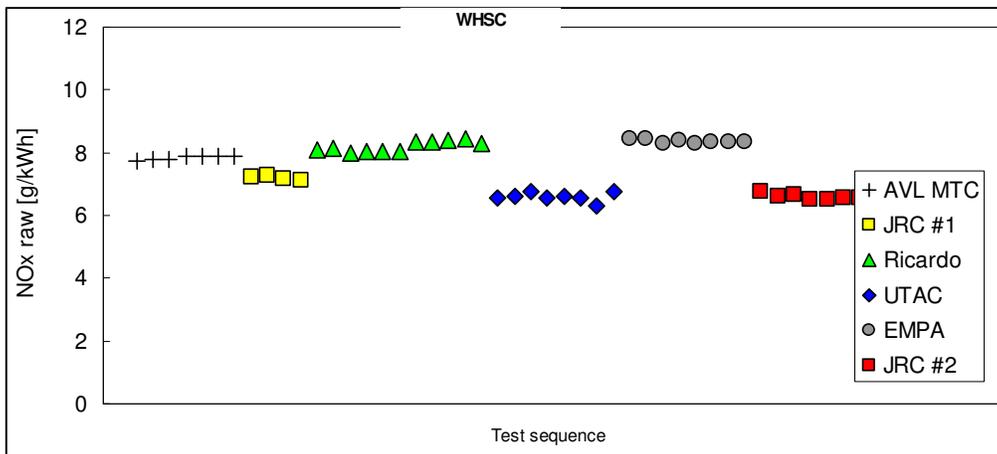
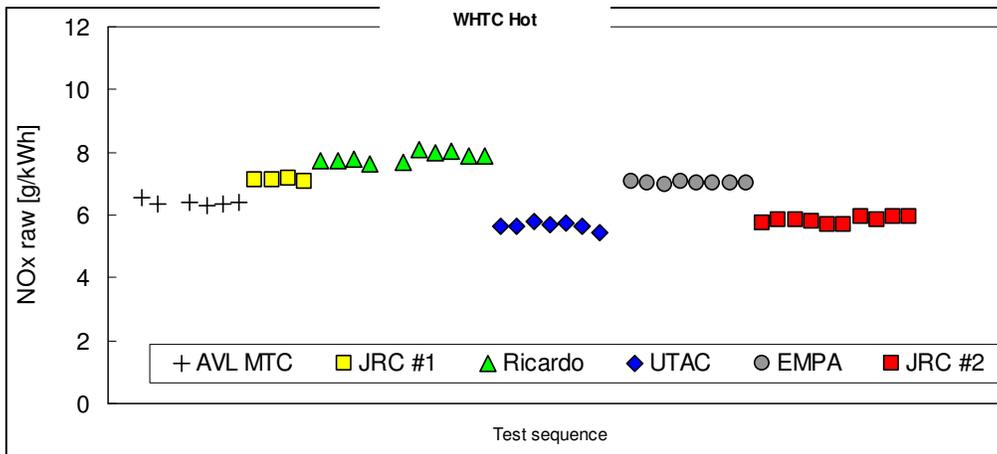
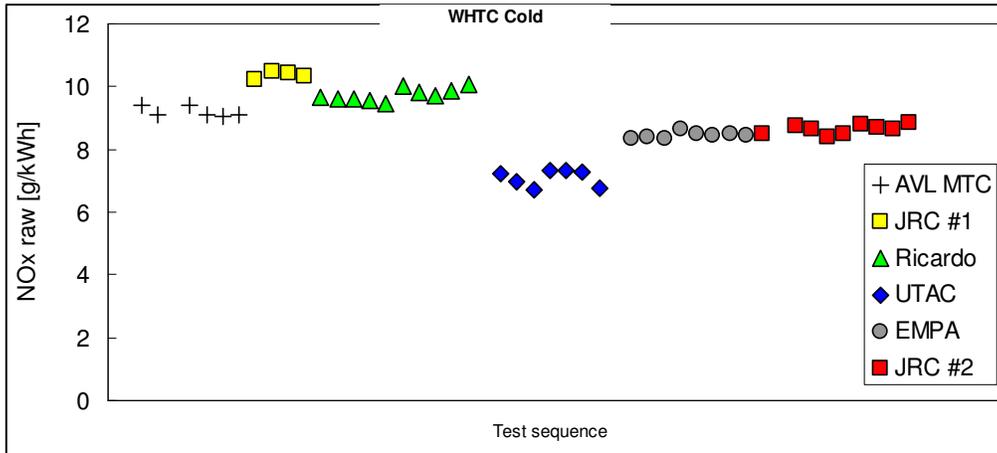


Figure 40: NOx – Consistency Across The Validation Exercise

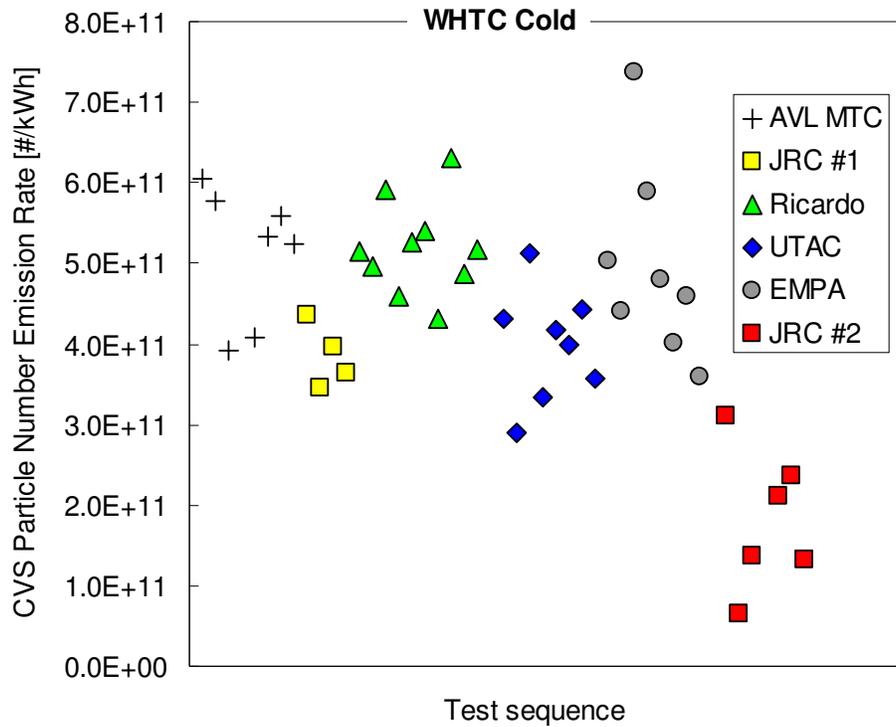


#### 6.4.2 Particle Number Emissions

The programme-wide emissions of particle number measured from the CVS over the cold start WHTC cycle are shown in Figure 41. Similar levels of solid particle number emission rates were determined from all labs, with the exception being the final tests

conducted at JRC. The levels measured during the second (and last) measurement campaign at JRC were systematically lower. This discrepancy holds for all test cycles and for both CVS and PDT-measured particle number emissions.

**Figure 41: PN from cold-WHTC: Consistency Through The Test Programme**



A comparison of the real-time particle number emission rates measured during the first (Figure 42) and second campaigns (Figure 43) at JRC suggests that an apparent increase of the filtration efficiency of the DPF filter was seen during the second measurement campaign. Results in the first phase were typically in the range  $3 \times 10^{11}$  to  $5 \times 10^{11}$  /kWh, while emissions in the second phase dropped to between  $1 \times 10^{11}$  and  $3 \times 10^{11}$  /kWh. An examination of the back pressure and temperature data revealed only marginal differences.

In order to further investigate this issue, the entire daily test protocol was repeated twice after an extended preconditioning consisting of 2 hours operation at ESC mode #10. The intention of this exercise was to passively regenerate the DPF to ensure a complete purge of soot and then, without adding any additional soot, run through the daily matrix.

Emissions levels over the cold WHTC from the two days' testing were unchanged after this extended conditioning of the DPF, showing emissions levels of  $\sim 2 \times 10^{11}$  /kWh – in the middle of the band of emissions levels seen in the second formal test phase.

If the engine-out PM had increased, this might have led to a more rapid generation of a filter cake, reducing particle numbers. However, since PN was still reduced relative to the first JRC measurement campaign following an extensive passive regeneration,

this can be discounted. Consequently there are three possible explanations for the reductions in PN seen.

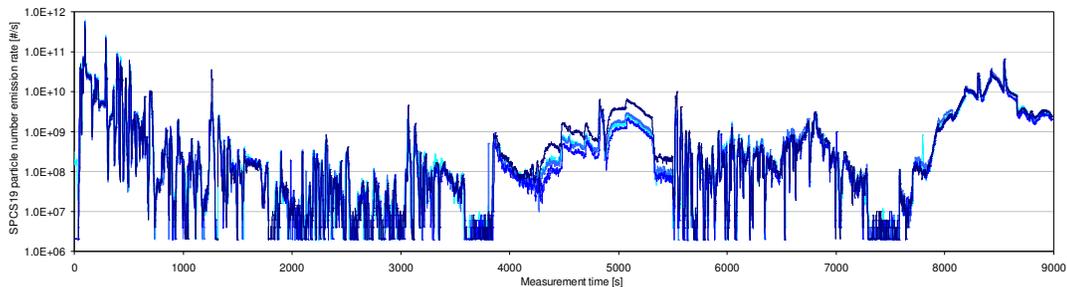
- Reduction in engine-out PN leading to lower post DPF emissions
- Change in the performance of the SPCS or CVS
- Increase in the filtration efficiency of the DPF leading to lower post-DPF emissions

From cold start cycles, PN emissions are generally associated with elemental carbon, which in turn relates to PM. Therefore, in order for engine-out PN to reduce between the two measurement campaigns at JRC, engine-out PM should also reduce. Since NOx and PN trade-off, any reduction in engine-out PN would be accompanied by an increase in engine-out NOx. In fact, NOx is generally lower from tests in the second measurement campaign at JRC. As a consequence, it is unlikely that a reduction in engine-out PN is due to a change in the engine-out emissions.

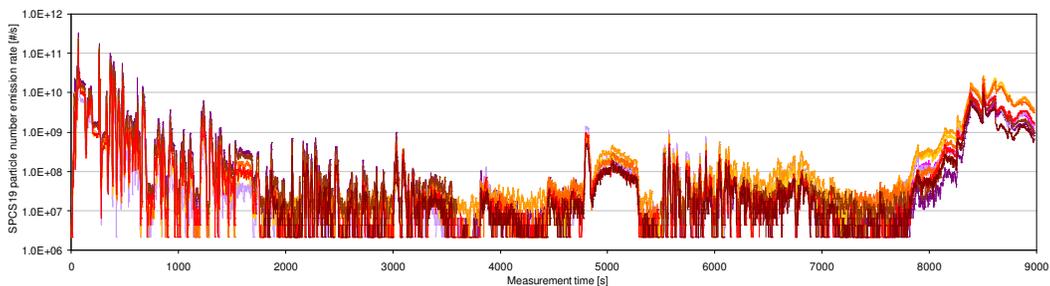
Emissions levels from the PDT and CVS correlated equally well from the two JRC measurement campaigns. This eliminates issues from the CVS and SPCS as responsible for the change in emissions levels observed.

Consequently, the most likely explanation is a change in the filtration performance of the DPF. Soot has been ruled out as the key factor, so it is possible that the ash level in the DPF reached a critical point during preconditioning at JRC prior to the test programme and this resulted in a step change in filtration efficiency.

**Figure 42: Real time PN Production from the CVS- Cold WHTC (JRC#1)**



**Figure 43: Real time PN Production from the CVS- Cold WHTC (JRC#2)**



## 7. ADDITIONAL TESTWORK OVERVIEW

### 7.1 Mass Contributed by EC and by Particles

During some of the tests conducted in the second measurement campaign in JRC, an AVL 483<sup>21</sup> soot sensor was employed to determine the mass of soot emitted and a Dekati Mass Monitor<sup>22</sup> was used to measure the mass of aerosol.

The Soot Sensor sampled directly from raw exhaust at a constant dilution ratio of about 2, while the DMM sampled from the CVS tunnel via a Dekati thermodenuder operating at 300 °C. In parallel for these tests, PM was collected on TX40 filters.

The mass measured as soot (AVL 483) and contributed by solid particles (DMM) was only a small portion of that determined gravimetrically. Table 12 summarizes the average and the standard deviation of these fractions for the different test cycles while Figure 44 and Figure 45 indicate the percentage contributions of solid particles and soot respectively to measured PM.

Over the cold start WHTC, both AVL483 and DMM measured mass concentrations ~10% of those determined gravimetrically. This fraction is similar to that determined for cold NEDCs during the light duty inter-laboratory correlation exercise.

During hot start test cycles, the DMM signal was at the zero levels of the instrument which is around 300 #/cm<sup>3</sup>. Consequently, mass estimates from these cycles constitute a maximum level. Concurrently measured SPCS data verifies that the PMP particle number concentrations were also below 300#/cm<sup>3</sup> in the CVS. Even though DMM data will have overestimated the contribution of solid particles to PM from hot cycles, the calculated mass emission rates were still only ~0.5% of that determined gravimetrically.

The mass concentrations determined with the AVL483 suggest a ~7% to ~19% soot content in the PM collected on filters from hot start cycles. These figures suggest higher soot fractions than seen from the cold start tests, an observation which is not substantiated by any other measurement method. These high results might indicate that measurements were made below the sensitivity levels of the AVL483 ~ 5µg/m<sup>3</sup>, but since the concentration range of emissions was 5µg to 125µg/m<sup>3</sup> this is unlikely. It is also possible that there was interference from gaseous components in the AVL483 signal.

**Table 12: Contribution of soot and solid airborne particles on the PM collected on filters as determined by the Soot Sensor and the DMM, respectively**

	WHTC Cold	WHTC Hot	WHSC	ETC	ESC
Soot content (CVS)	11.2% ± (3.81%)	7.31% ± (1.13%)	18.81% ± (4.79%)	15.52% ± (3.03%)	14.89% ± (3.39%)
Soot content (PDT)	12.33% ± (2.29%)	9.53% ± (1.5%)	15.2% ± (1.26%)	15.76% ± (1.28%)	10.22% ± (1.01%)
Airborne mass (DMM)	10.4% ± (3.52%)	1.38% ± (1.05%)	0.93% ± (0.65%)	0.54% ± (0.2%)	1.51% ± (1.22%)



## 7.2 Further Filter Media Evaluations

In the second measurement phase conducted at JRC, following completion of the validation exercise, the daily test protocol was repeated three times employing Teflo filters. Sampling was undertaken from both the CVS secondary tunnel and from the PDT.

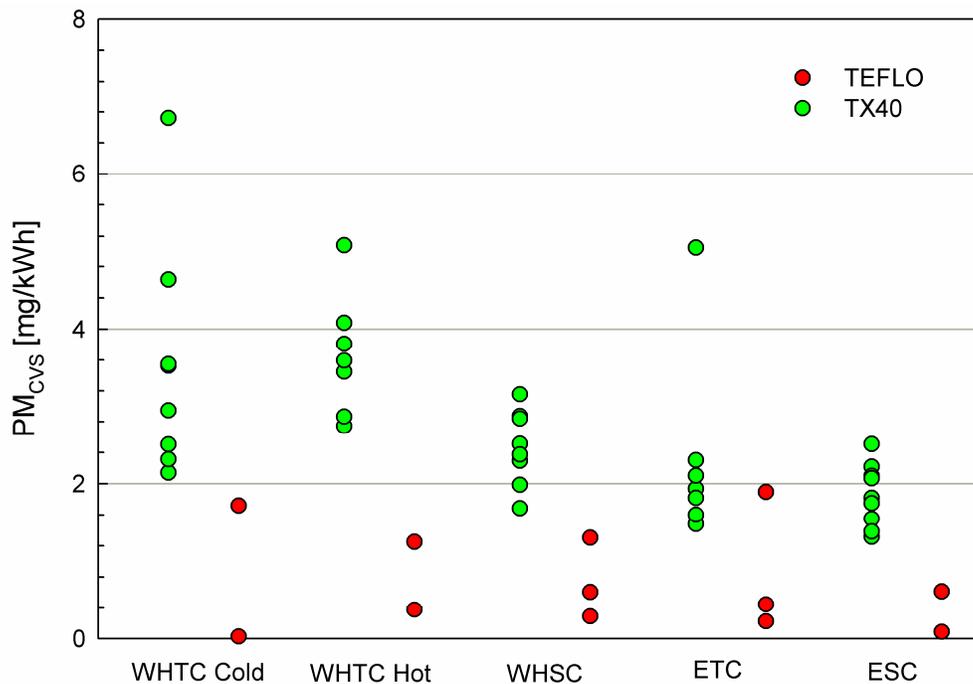
The PM results collected during these three sets of tests have been compared to the data from the main measuring campaign (JRC#2) where TX40 filters were used.

In both CVS (Figure 46) and PDT testing (Figure 47) the levels determined using TEFLO filters were systematically lower than results using TX40 filters.

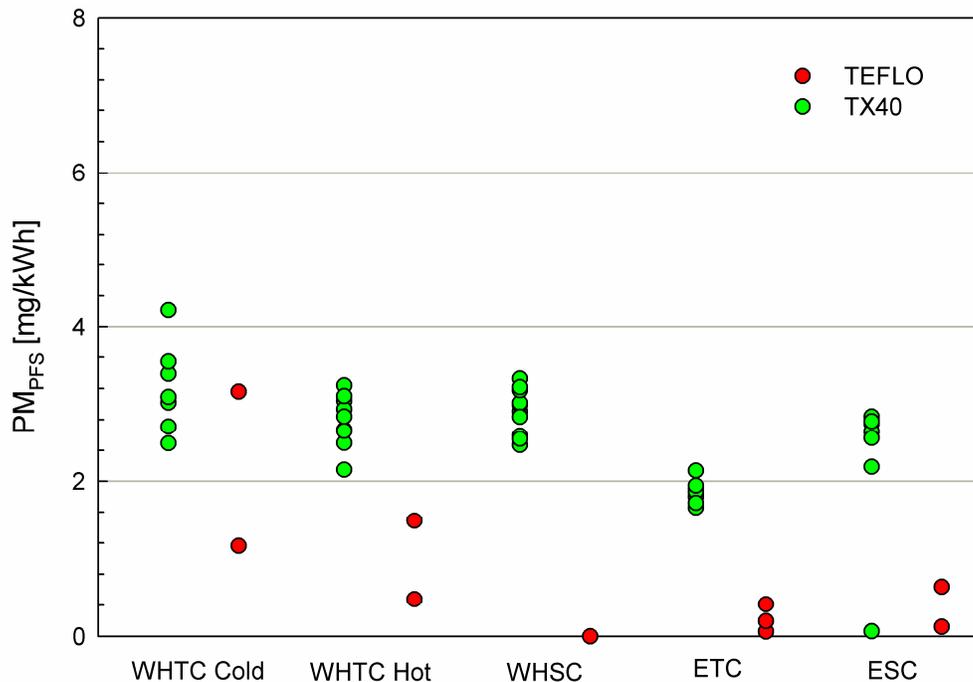
Mass emissions were on average 63% (ETC) to 81% (ESC) lower from TEFLO filters than from TX40 filters when samples were taken from the CVS - secondary tunnel. Similar results, showing a range of 31% (WHTC cold) to 88% (ETC) reductions were observed from PDT samples' results.

Particle number emissions recorded with the two Golden SPCS instruments (from primary CVS and PDT) during these tests were found to lie within the range of values recorded during previous TX40 filter sampling. Therefore, the observed difference between TEFLO and TX40 results indicates a true directional effect. As TEFLO filters are less prone to volatile adsorption artifacts<sup>23</sup>, these results suggest that a significant amount of the mass collected on the TX40 filters results from adsorption of gaseous compounds and that the TEFLO filters collect less of this artefact. However, the levels of PM observed even on the TEFLO filters are substantially higher than the mass attributed to solid particles (Section 7.1), so it is likely that this filter medium still collects some volatile or semi-volatile material.

**Figure 46: PM results obtained using TX40 and TEFLO filters – JRC CVS**



**Figure 47: PM results obtained using TX40 and TEFLO filters – JRC PDT**



### 7.3 Particle Number Measurements from PDT at Constant Dilution Factors

There is a possibility that particle number emissions from DPF equipped engines may, especially when the DPF is highly loaded, be delayed in reaching the exhaust due to transit through the filter substrate and filter cake. If this is the case, the dilution ratio in the PDT, which varies with engine exhaust flow could be incorrect at the time (following transit delay) the particles and PM actually reach the dilution tunnel. If this is the case, there is actually no merit, specifically for post-DPF PN tests, to undertake proportional sampling. Consequently, a fixed dilution ratio PDT measurement combined with a real-time exhaust flow measurement would be an inexpensive alternative.

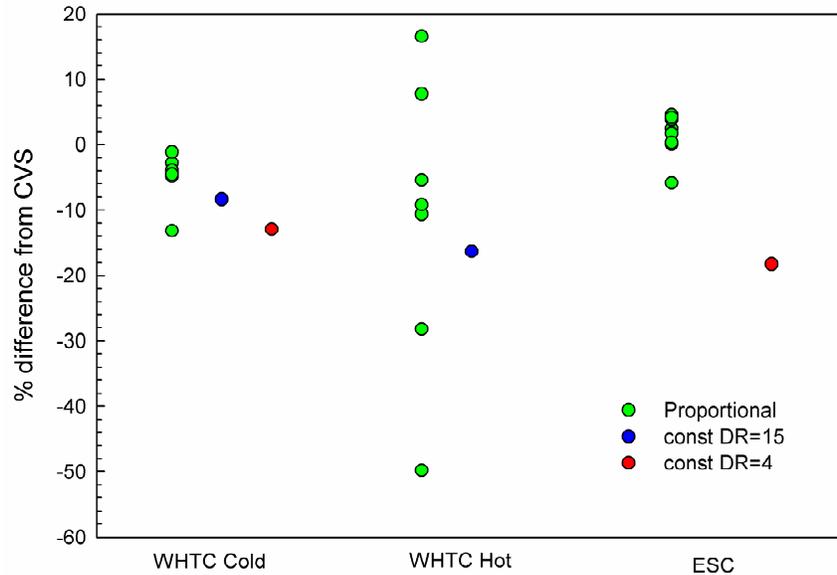
In order to investigate the possibility of employing a simpler partial flow system operating at constant dilution ratio, the test protocol was repeated twice at JRC employing constant dilution ratios of 15 and 4, respectively, in the partial flow system (AVL SPC-472 Smart Sampler). These two values correspond to the average and minimum, respectively, dilution ratio in the CVS tunnel over the WHTC cycle. Unfortunately, due to some problems with the control software, the SPC did not sample correctly in some of the tests, but sufficient data were still acquired to perform a comparison.

The use of a constant dilution ratio in the PDT system does complicate the calculations: the particle number emission rate (number of emitted particles per second) requires a second-by-second multiplication of the particle number signal with the measured exhaust flow rate after careful alignment of these two signals.

The percentage difference between the calculated PDT and CVS results for all valid tests are compared to those determined during the main measurement campaign in Figure 48. This shows percentage differences between the cycle average particle

number emissions measured from the CVS tunnel and the partial flow system, when the PDT sampled at a flow proportional to the exhaust flow rate and also at constant dilution ratios of 15 and 4.

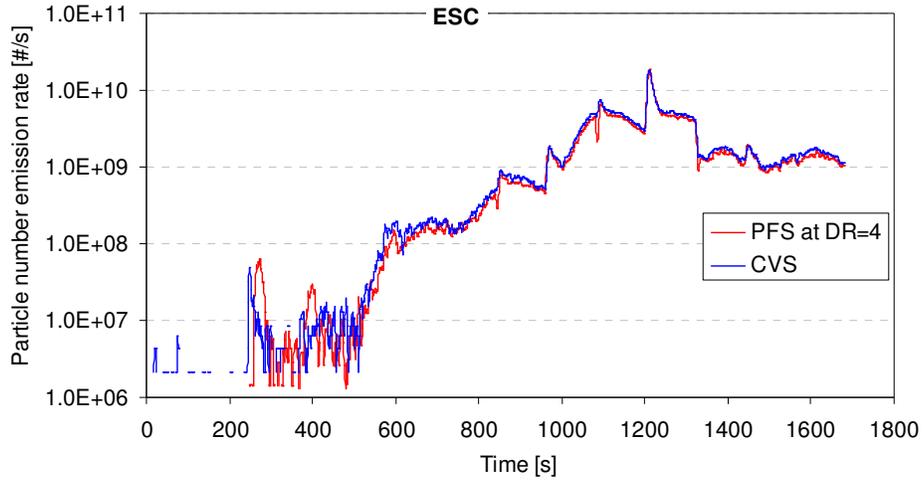
**Figure 48: Cycle Averaged PN Results: Proportional Vs. Constant Dilution**



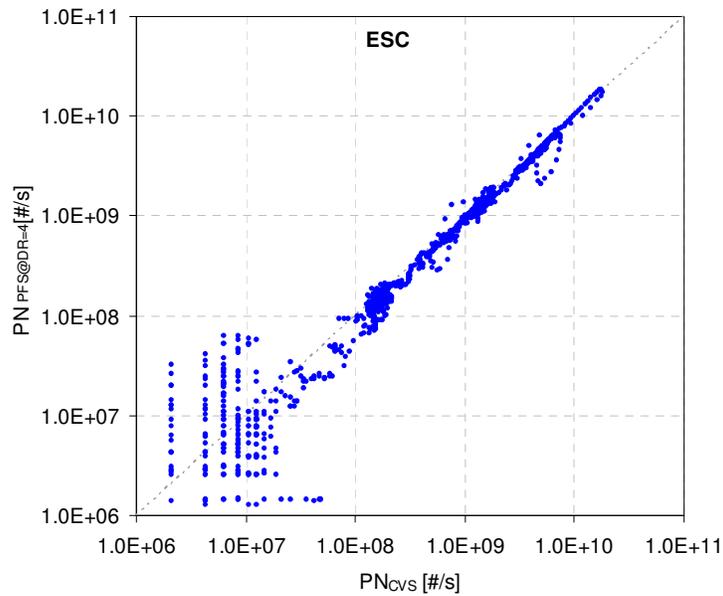
The limited data available suggests that PN emission levels can be determined with acceptable accuracy (better than ~15%) when sampling from the exhaust at constant dilution ratio. In general though, this approach seems to systematically underestimate the emission levels measured from the CVS tunnel.

The good agreement with the CVS tunnel data is also evident in the real time recordings. As an example, Figure 49 shows the real time particle emission rates over ESC measured from the PFS running at a constant DR of 4 compared with data from the CVS tunnel. This is the test which gave the largest difference, but still the number concentrations measured from the two SPCS units are very similar, as seen in Figure 50.

**Figure 49: PN from Proportional and Constant Dilution Sampling Compared**

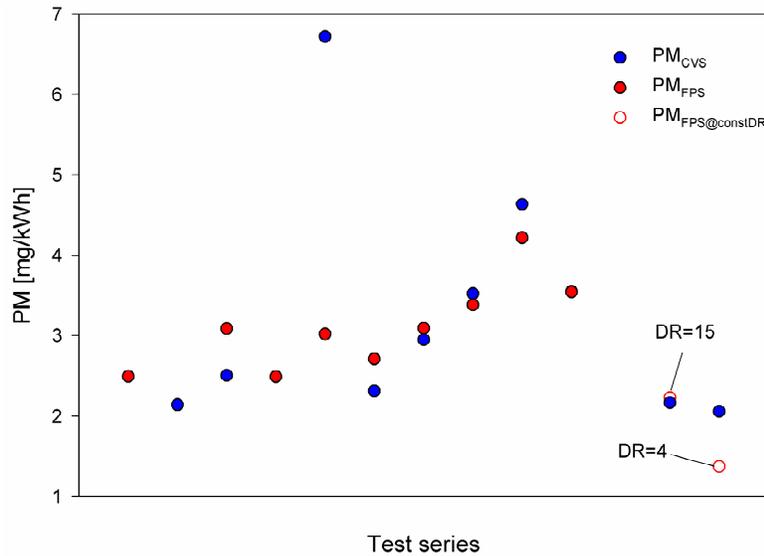


**Figure 50: Correlation of PN from Proportional and Constant Dilution Sampling**



Since PN levels from a PDT at constant dilution ratio seem to be similar to PN levels drawn during proportional sampling, it is interesting to assess the impact of these approaches on PM. Figure 51 shows a comparison for one-off cold WHTC tests at dilution ratios of 15 and 4 with cold WHTC data from the CVS and PDT.

**Figure 51: PM Sampled From Proportional Dilution and Constant Dilution**



The mass measured at fixed DR=4 is substantially lower than seen from either the partial flow or full flow systems (proportionally sampled), but the mass measured at fixed DR=15 is similar to the low-end results from the CVS.

The indications are that mass is underestimated by the constant dilution approach (and it can't be corrected because there are no real time data). However, the mass emissions from many labs appear to be indistinguishable from zero if the background is subtracted. On this basis, mass as a metric is of little value and if particle number was the only metric, the constant DR PDT approach would be a valid and cost-effective approach.

## 8. COMPARISONS OF MEASUREMENT SYSTEMS

This section discusses the relationships between particle and particulate measurements made from full and partial flow dilution systems. Comparisons are made between mass and number metrics from full and partial flow dilution systems.

### 8.1 Comparison of Particle Number Measurements from CVS and PDT

Figure 52 shows the correlation between PN emissions measured simultaneously from the full and partial flow systems at JRC only (lhs) and all labs (rhs). Data are shown from all emissions cycles. It's clear from the JRC data that during both measurement campaigns, despite the shift observed in the levels, the same correlation between full and partial flow measured PN was present. This correlation seems to hold over almost 3 orders of magnitude.

The background levels in the JRC CVS and partial flow systems are known to be low (Section 6.2.1) and similar. This was not true at all labs, and the differential between the backgrounds of CVS and PDT systems at the same labs leads to poorer correlations, as the right hand figure shows.

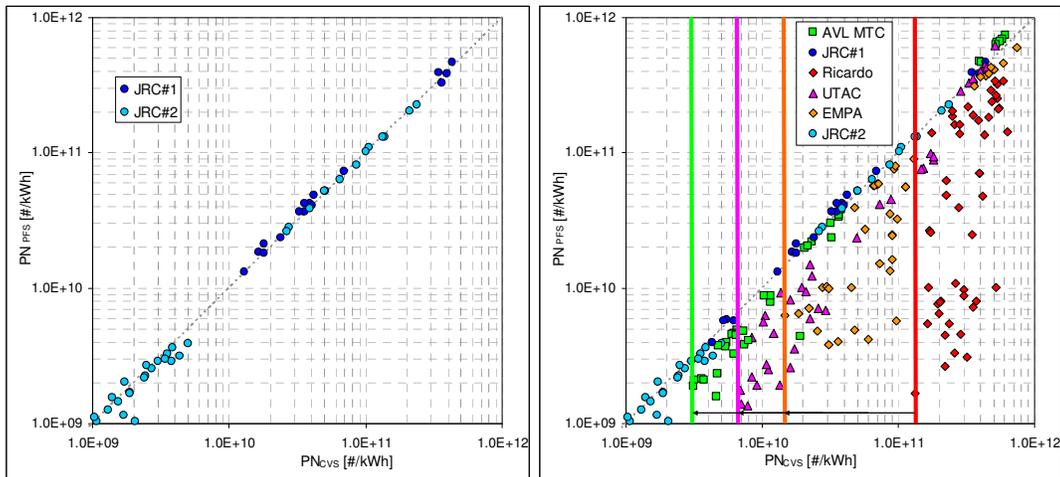
The differences in background levels can be compared by considering the lowest recorded cycle emissions from each lab, as these must be higher than or equal to the background. Levels are overlaid in Figure 52, with the red line indicating the lowest emission at Ricardo ( $\sim 10^{11}$ /kWh), the orange EMPA's lowest emission ( $\sim 10^{10}$ /kWh),

violet the lowest levels at UTAC ( $\sim 7 \times 10^9/\text{kWh}$ ) and green UTAC's results ( $\sim 3 \times 10^9/\text{kWh}$ ). The background at JRC was at or below  $10^9/\text{kWh}$ .

In general, above  $\sim 5 \times 10^{11}/\text{kWh}$  all labs data are broadly similar.

These data show that full and partial flow dilution systems can provide almost identical results, but that these will be dependent on the level of background present in the system. From the results of this work, partial flow systems seem to have inherently lower backgrounds than full flow systems.

**Figure 52: Correlations between PN Measured from CVS and PDT Systems**



Considering the JRC results in more detail, Figure 53 shows the results of cross-plotting the CVS and PDT sampled real-time data (>1000 points) from several emissions cycles. These charts demonstrate that the real time responses of the PDT and CVS, as well as the cycle averaged data, correlate well. This demonstrates that:

- Low background dilution facilities provide almost identical data, irrespective of whether they are CVS or PDT
- That the principal differences between CVS and PDT, such as a PDT's flow control and response time, do not significantly impact particle measurements sampled at 1Hz

Figure 53 also shows that as measured particle numbers reduce, the correlation between PDT and CVS weakens.

**Figure 53: Correlations between Real-time PN from CVS and PDT Systems**

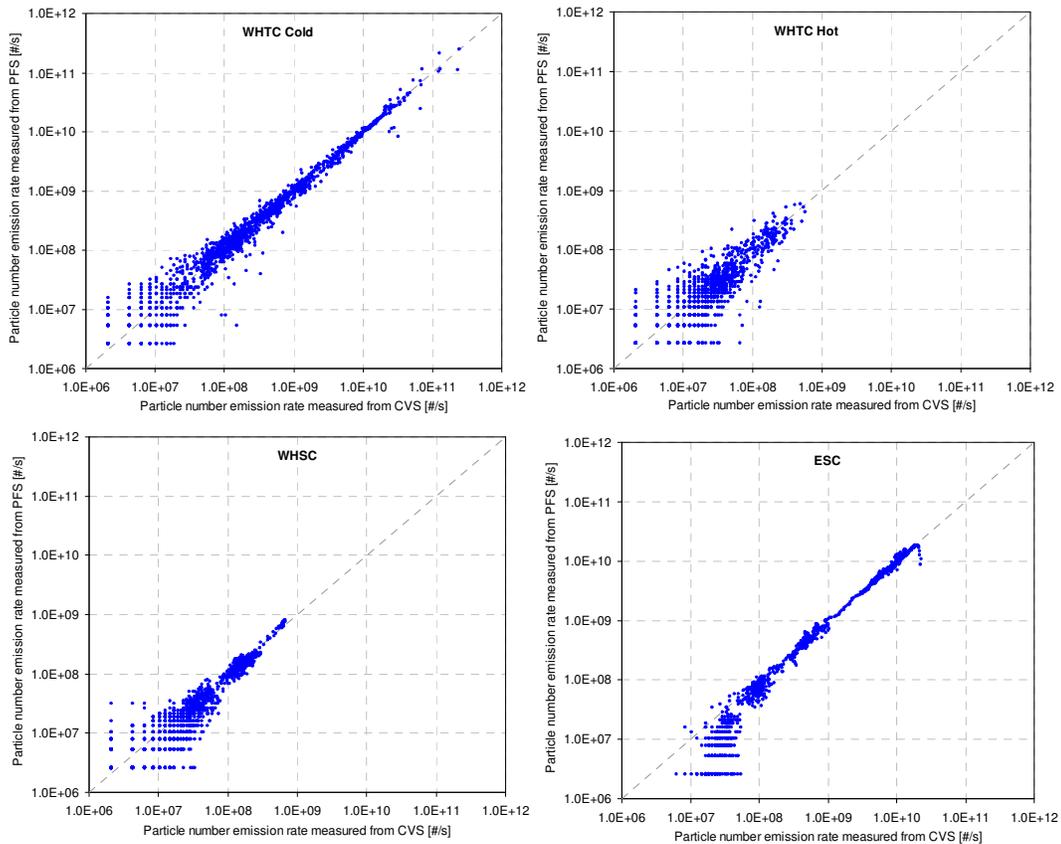


Figure 54 illustrates the percentage change in PN emissions from the partial flow system relative to the levels measured from the CVS. These are calculated as follows

$$((\#/km\ PDT - \#/km\ CVS) / (\#/km\ CVS)) \times 100$$

In this comparison, zero emissions from the PDT represents -100% difference between systems, the same emissions from the two systems represents 0% difference and higher emissions levels from the PDT appear as +ve % differences.

With the exception of JRC, which shows a range from -12% to ~0% from ~10<sup>9</sup>/kWh right up to 10<sup>12</sup>/kWh, and Ricardo, which has a best result of ~40% at >10<sup>11</sup>/kWh, all labs results were better than -20% at emissions levels above 10<sup>11</sup>/kWh.



**Figure 55: Correlations between PM Measured from CVS and PDT Systems**

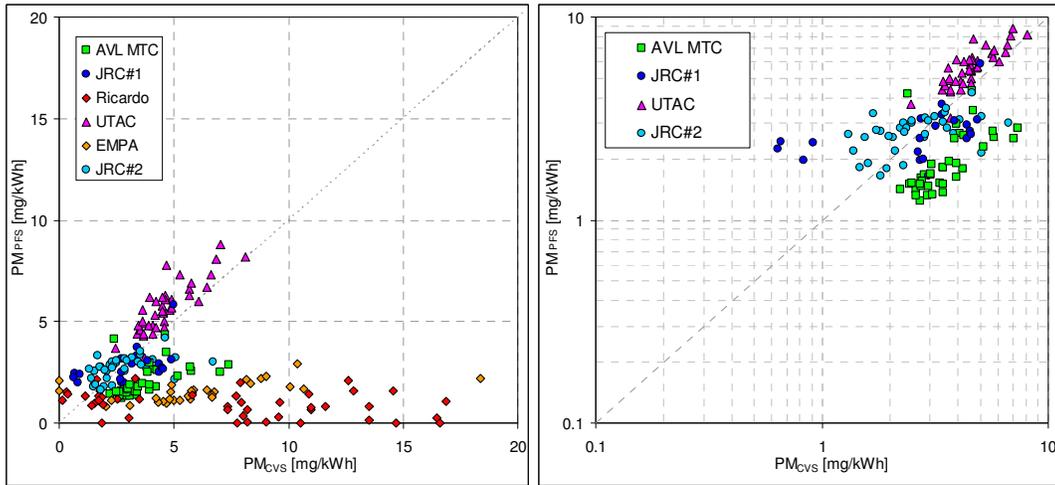
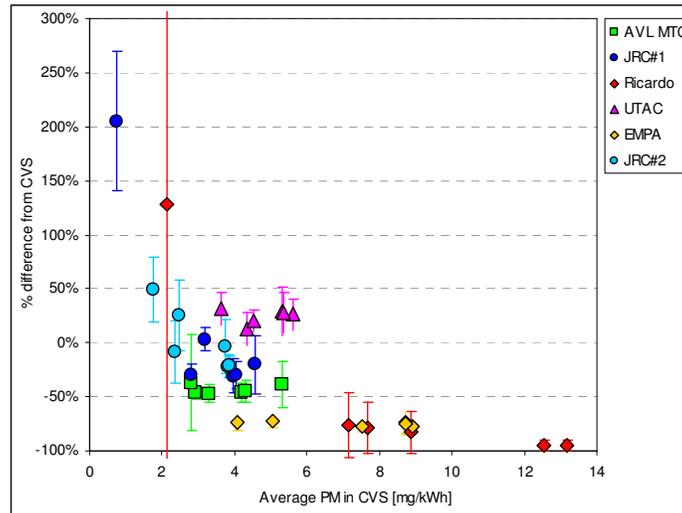


Figure 56 illustrates the percentage changes in PM emissions from the partial flow system relative to the levels measured from the CVS. These are calculated as follows

$$((\#/km PDT - \#/km CVS) / (\#/km CVS)) \times 100$$

In this comparison, zero emissions from the PDT represents -100% difference between systems, the same emissions from the two systems represents 0% difference and higher emissions levels from the PDT appear as percentages greater than zero.

**Figure 56: PDT PM results: % Difference to CVS PM Data**



In general, emissions ranged from 50% higher in the CVS than in the partial flow system to 50% higher in the PDT than in the CVS. Labs either showed one trend or the other and these results were seen in the mass range from ~2mg/kWh to ~6mg/kWh.

On average, CVS and PDT Pm levels broadly agree, but so do CVS and PDT backgrounds (Section 6.1.3). In addition (with the exception of ESC cycles), filter

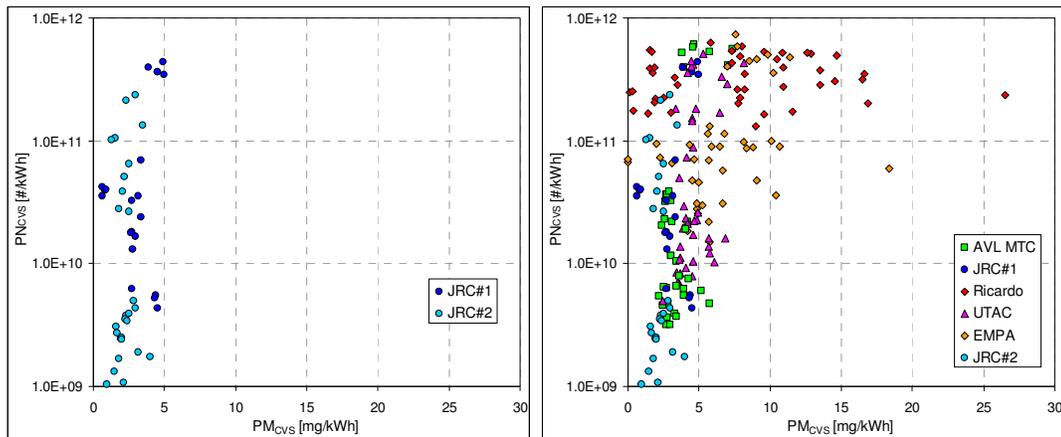
mass levels on both sample and background filters are the same from many dilution systems at several labs. On this basis, the fact that CVS and PDT agree and they can be repeatable, but results are the same as the background, means that both PM methods may just be reporting background that varies in response to the emissions cycle's pressure and temperature transients. The actual PM emission is effectively zero in many cases.

### 8.3 Mass vs. Number full flow

*This section is incomplete*

- At JRC partial flow PN and full flow PN correlated well, so agreement between solid particles emissions is very good
- Comparison between PN and Pm (Figure 57, lhs) shows that highest mass samples do have highest mass, but that this relationship is tenuous
- Poor relationship between CVS mass and CVS number must be related to the volatile contribution to PM or to the CVS background
- Number is much more sensitive than mass (a factor of >300 covering the PN emissions corresponds to a difference of ~5mg/kWh)
- The apparent tenuous mass Vs. number relationship seen at JRC would disappear if PM data was background subtracted (all PM data except ESC reduced to zero)
- Considering all labs' data (Figure 57, rhs) it appears that either labs show similar results to JRC – a wide range of PN levels in a narrow band of PM values - or the high background labs show a wider range of PM values confined to a narrower (but still factor of 10 or more) band of PN values. In both cases there is no obvious relationship between number and mass from CVS systems.

**Figure 57: Relationship between Mass and Number Measurements (CVS)**



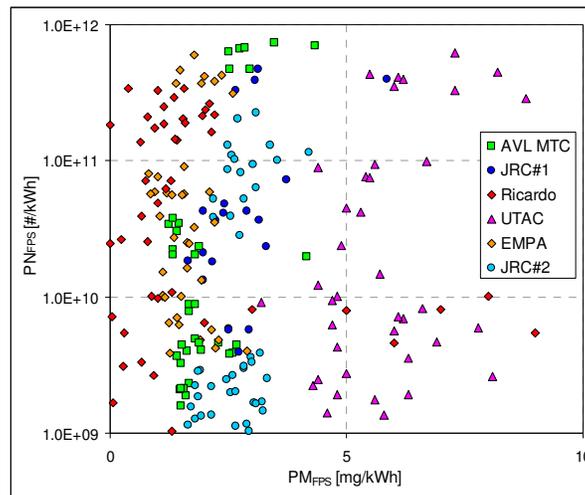
### 8.4 Mass vs. number partial flow

*This section is incomplete*

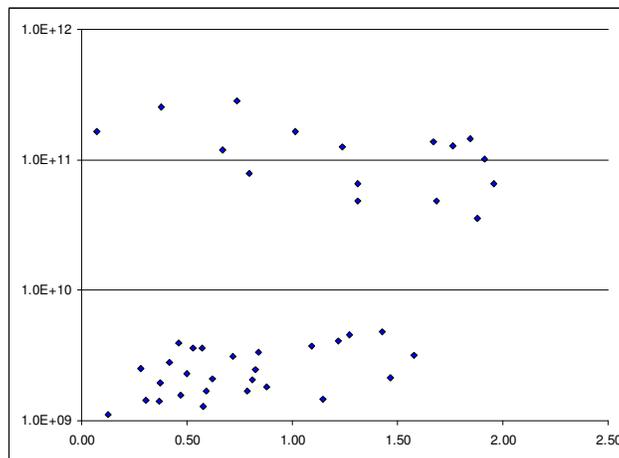
- At JRC partial flow PN and full flow PN correlated well, so agreement between solid particles emissions is very good
- The JRC PDT was the only system in this project in which PM could be definitively discriminated from the PM background, so if this system shows no relationship between mass and number it is highly unlikely that one exists

- Comparison between PN and Pm (Figure 58) shows that the highest mass samples do not necessarily have highest number and that individual labs appear to occupy discrete, narrow mass emissions bands while spanning a wide PN range
- Poor relationship between PDT mass and PDT number must be related to the volatile contribution to PM or to the PDT background
- There is no mass vs number relationship for PDT (Figure 50), generally PN is sensitive but PM only varies slightly and absolute levels are different from different labs.
- It is possible that a relationship could exist between PDT PM and PN if an accurate background could be subtracted from all PDT PM results, but this is not supported even by the low background JRC PDT data (Figure 54).

**Figure 58: Relationship between Mass and Number Measurements (PDT)**



**Figure 59: No Correlation Exists PM & PN Even in a Very Low Emissions PDT**



## 8.5 Comparisons Of Alternative And Additional Systems

### 8.5.1 Alternative and Additional Systems

In addition to the two GPMS systems used with the SPCS, a number of alternative systems (which fulfilled the requirements specified in R83), and additional systems

(which use different concepts for the dilution and thermal treatment of the aerosol) were evaluated in this work.

The alternative systems were:

- Nanomet by Matter Engineering
- Dual ejector plus evaporating tube system by Dekati
- Homemade dual ejector (Palas) plus evaporating tube from EMPA
- AVL Particle Counter (APC)

Additional systems were:

- Dekati thermodenuder (TD): employed sampling from the CVS tunnel either directly or downstream of a Dekati ejector diluter.
- Dual ejector (Dekati) plus evaporating tube system developed at EMPA: employed sampling aerosol directly from the tailpipe

#### *Particle Number Counters*

Alternative and additional systems were tested using particle number counters (PNCs) of different models and from different manufacturers. All were condensation nucleus counters (CNCs) from GRIMM or TSI. TSI models are known as condensation particle counters (CPCs). PNCs used were:

- TSI 3010D
- TSI 3790
- TSI 3010
- Grimm's 5.404

TSI 3010 CPC's were operated at a condenser-evaporator temperature difference of 9°C in order to effectively shift the 50% counting efficiency to 23 nm as required by the legislation. Grimm's CPC also operated in PMP mode by appropriate modification of the instrument firmware. TSI 3010D and TSI 3790 CPCs are supplied by the manufacturer to be compliant with PMP requirements.

#### *8.5.2 Particle Losses*

Particle losses within the measurement systems vary, so in order to make fair comparisons, these need to be taken into account. Of all the alternative and additional systems examined, only AVL's APC units were calibrated by their manufacturer for particle losses. AVL incorporate this correction in the reported particle concentration results.

To enable particle penetrations through the two Golden SPCS units, two of the three different Nanomet systems, Dekati's ejectors and the Dekati TD to be determined, evaluations using NaCl particles were undertaken at JRC before their first measurement campaign. These have been published elsewhere [<sup>24</sup>]. EMPA also calibrated their two homemade systems using NaCl particles. The penetration values determined in these studies, and which were also used for the comparisons shown in this section, are summarized in Table 13.

Particle losses inside the Nanomet system tested at Ricardo were not thoroughly investigated. However, preliminary work conducted by AEAT on this system

suggested similar losses to those of an identical specification system measured at JRC.

The Dekati dual ejector plus evaporating tube system was not calibrated as an entire system, and as a consequence only the particle losses inside the two ejectors can be accounted for in the calculations. Thermophoretic losses in the evaporating tube of this system should be low as the thermally treated sample exiting the evaporating tube is immediately diluted in the second ejector diluter.

**Table 13: Particle penetrations through the various alternative – additional systems used in the PMP HD validation exercise.**

	P (30 nm)	P (50 nm)	P (100 nm)	Correction
SPCS	71%	83%	86%	1.25
Nanomet JRC & RCE	68%	88%	95%	1.20
Nanomet LD GPMS	52%	65%	90%	1.45
TD	67%	73%	77%	1.38
EMPA's homemade (CVS)	70%	71%	72%	1.41
EMPA's homemade (direct)	61%	63%	65%	1.59
Ejector (heated)	96%	98%	100%	1.02
Ejector (not heated)	100%	99%	100%	1.00

As the different CPC units employed might exhibit different correlations relative to the primary calibration (indicated as the slope of a direct cross-plot between the two) it is also important to account for this difference in the comparisons. Most of the CPCs employed in the study were cross-compared with the Golden 3010D PNC employed with the SPCS usually connected to the CVS tunnel in the validation exercise (SPCS19). This was the ideal reference as the slope of this particular unit is 0.99. A direct comparison with this PNC provided the means to determine the slope of the individual CPCs employed with alternative and additional systems, and also with the PNC used with the second SPCS. The results of these comparisons are summarized in Table 14.

**Table 14: Percentage difference between the different CPCs employed and the Golden CPC of SPCS19.**

Grimm (JRC)	-5%
TSI's 3010 (JRC)	-10%
3010D (SPCS-20)	-1%
TSI's 3790	+11%
LD GPMS Golden CPC	+5%

No information is available for the two CPC units employed in EMPA's homemade systems and for the TSI 3010D CPC employed in the Nanomet system tested at Ricardo. Based on the observed differences, an additional  $\pm 10\%$  uncertainty is to be expected from the results obtained from these systems. The manufacturer's calibration of the APC systems takes the CPC slope into account so there was no need to correct the results of these systems.

## 8.6 Results from Golden Engine equipped with DPF

### 8.6.1 Alternative systems

Data from all individual tests with alternative systems are compared to the GPMS results (SPCS19 or SPCS20 depending on the sampling position of the alternative systems) in Figure 60.

All data sit very close to the  $x=y$  line suggesting a reasonable agreement between all PN measurement systems employed. The correlation tends to break down for some systems (such as the dual ejector and evaporation tube used at JRC) at the lower emission levels. This is due to the higher background levels seen with these systems.

As an example of this effect of elevated system backgrounds, Figure 61 shows a comparison of the real-time particle number concentrations from the SPCS and from a dual ejector plus ET with Grimm CPC. These data are from cold and hot WHTC tests measured from the CVS at JRC.

It can be seen that the dual ejector system has 20 times higher background levels than the SPCS. However, the levels measured from the two systems are in excellent agreement at levels above the dual ejector system background. Over the cold start WHTC, where the number concentrations are up to three orders of magnitude above the background levels, the cycle average results calculated with the two systems agree to within 1%. From hot start WHTC however, the particle emissions levels are below the dual ejector system background from most of the test cycle, but when the concentrations do rise above the background level of the ejector system, the good agreement is maintained.

The cycle average emissions from the dual ejector system over the hot start cycle were more than twice the levels (+111%) of those from the SPCS. The two GPMS units incorporate a much more efficient dilution air filtration system than any alternative systems employed in this study, and therefore the comparisons at the lower range of measured emission rates are affected by this artefact. As a consequence, only the results obtained over the higher emissions WHTC cold and ESC test cycles are considered in the following analyses, as the emission levels from these were sufficiently high to be relatively unaffected by background particle contributions.

**Figure 60: Correlation between the alternative and the GPMS systems**

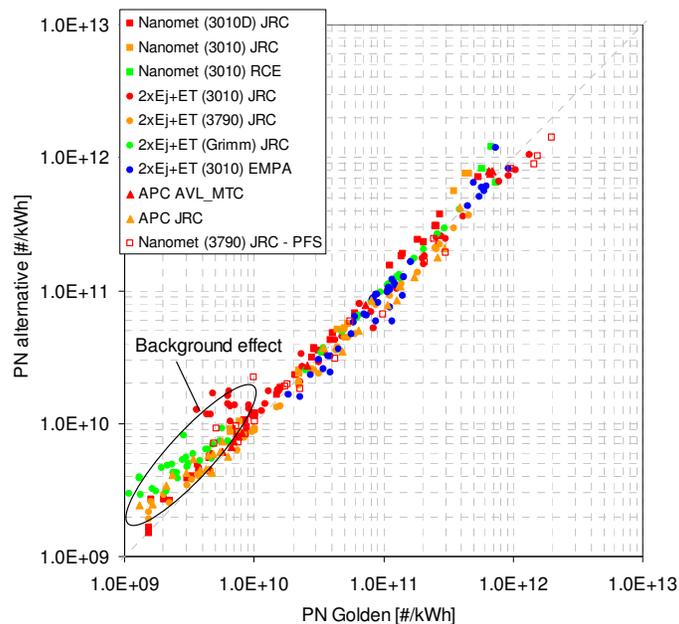


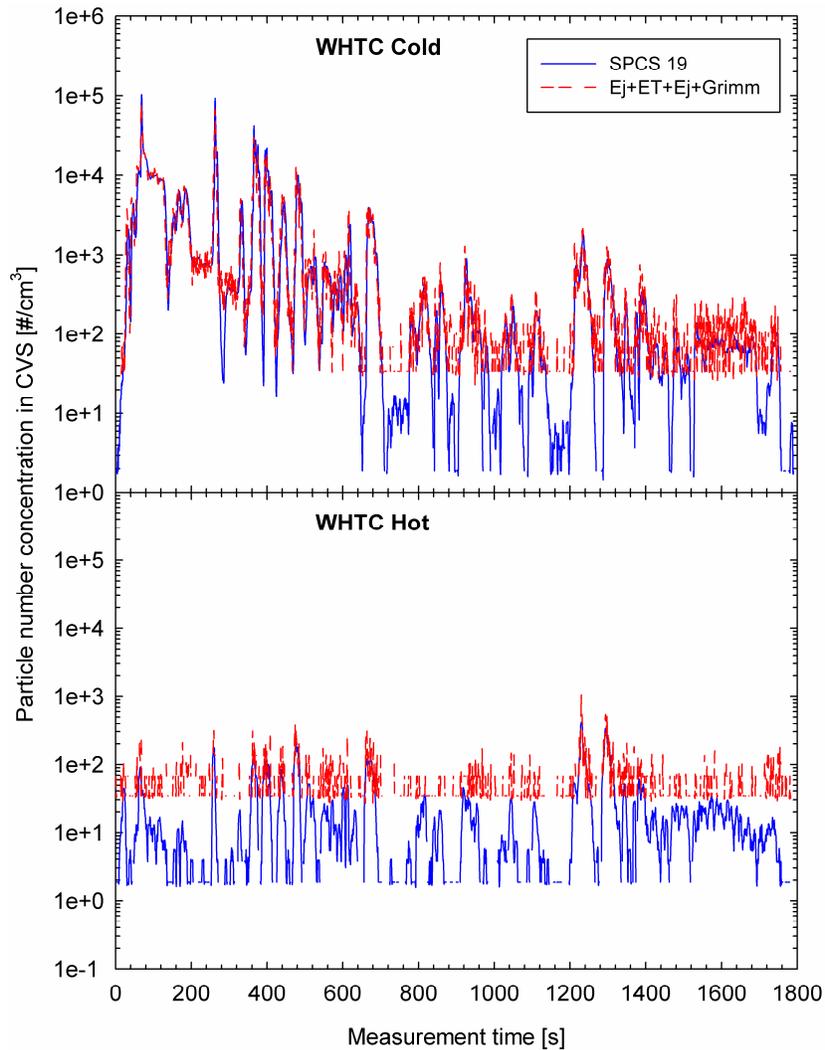
Table 15 summarizes the average and standard deviation of the individual percentage differences between the different systems employed and the GPMS. The results obtained with the different alternative systems over the WHTC cold and the ESC test cycles agreed within  $\pm 30\%$  and  $\pm 15\%$ , respectively.

All Nanomet systems connected to the CVS tunnel measured systematically higher number concentrations than the GPMS (by about 30% over WHTC Cold and 10% over ESC). Both JRC and Ricardo found that the background levels of the Nanomet systems increased during the measurement campaign. This has been attributed to production of wear particles from the diamond-like carbon (DLC) rotating disk of the primary diluter and the manufacturer has developed an alternative disc coating to avoid this. The disc coating deterioration could partly explain the observed overestimation in the particle number emissions determined with those systems. Additionally, the three Nanomet systems employed in the particular study are of an older design that does not take into account the pressure at the sampling point. When the sampling location is from a depression (which is the case in both CVS and PFS) the indicated dilution ratio may be incorrect and this may also have contributed to the observed overestimation of the particle number emissions. This may also explain the differences observed when the Nanomet was sampled from the CVS and from a PDT. This discrepancy might also be associated with errors in the setup of the PDT (e.g. errors associated with the control of the flowrate extracted by the PN measurement system and/or the make up air that compensates for this flow).

The dual ejector system results were found to be at the same or slightly lower level (up to 20%) than the GPMS. This consistent underestimation of the particle number concentrations determined with the Dekati system is probably associated with unaccounted particle losses inside the evaporating tube.

The results obtained from two APC systems agreed within  $\pm 15\%$  with the GPMS ones. This can be considered to represent the uncertainty levels from PN measurement systems produced and calibrated in accordance with the requirements of the R83 regulations.

**Figure 61: Comparison of real time particle number concentrations in the CVS tunnel determined with the GPMS and a dual ejector plus ET system over WHTC Cold and WHTC Hot.**



### 8.6.2 Additional systems

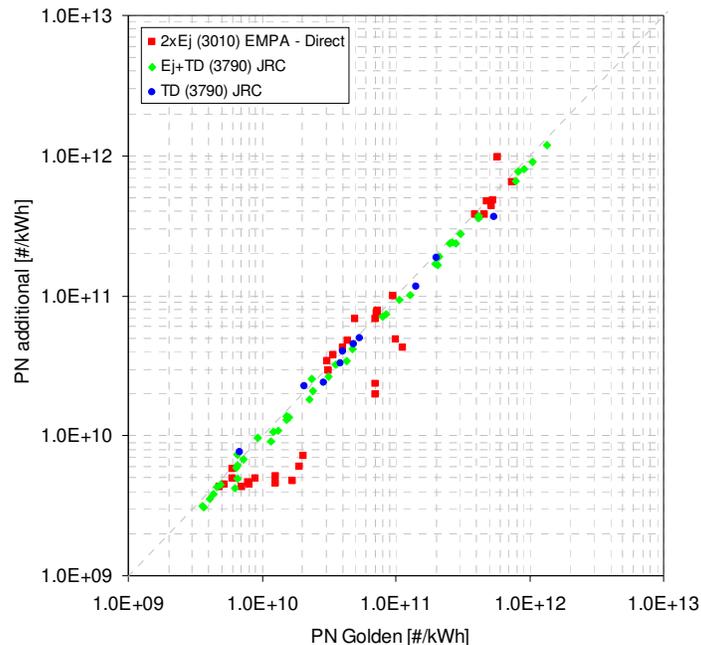
The additional systems investigated were also found to be in good agreement with the GPMS systems (Figure 62).

Those systems utilizing Dekati's TD gave about 10% lower emission levels than SPCS over all test cycles. These particular systems utilize lower or even no dilution and this has the advantage of minimizing the effect of particle background. This explains the consistency of the results obtained over all test cycles.

EMPA's system connected directly to the tailpipe also gave comparable results to the SPCS, with the differences being on average 1% and -7% over WHTC cold and ESC, respectively. This is a very interesting finding, as the setup employed simplifies the measurement procedure considerably. Care needs to be taken for the accurate calculation of the true particle emissions, as the measured particle number concentration signals need to be precisely time aligned with the exhaust flow rate traces. Additionally, the dilution ratio of the ejector diluter is known to be strongly

affected by pressure and temperature variations at the sampling point (Giechaskiel et al.<sup>25</sup>). The use of a trace gas for a real time determination of the dilution ratio (as performed by EMPA) can resolve this problem, but this approach usually results in a noisy DR signal which introduces some uncertainty in the exact determination of the cycle average results. These two issues might be responsible for the relatively high variability observed in the results (of the order of  $\pm 30\%$ ).

**Figure 62: Correlation between the additional and the GPMS systems**



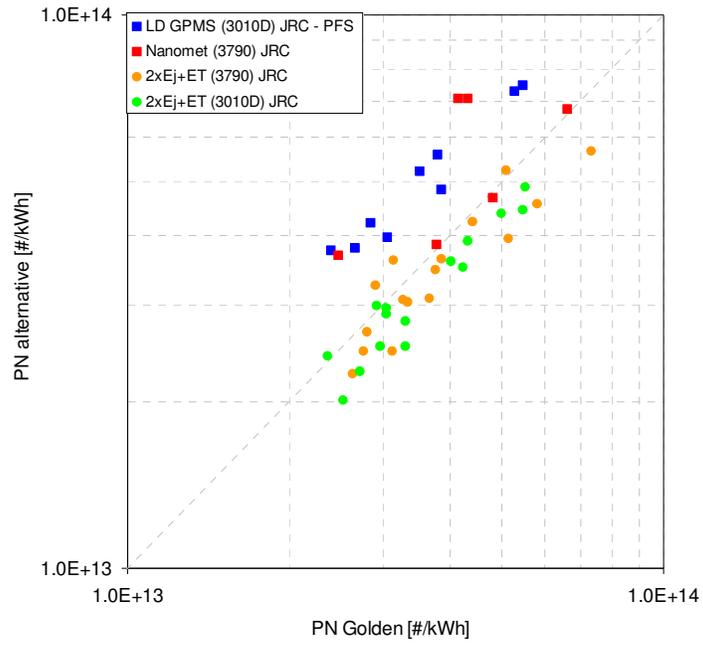
### 8.7 Engine out and open flow emission levels

A limited number of tests were conducted at JRC in which the DPF was replaced with an EMITEC Partial Flow Deep Bed Filter “Open filter” and from engine-out exhaust. This provided the means of comparing some of the alternative and additional PN measurement systems at higher particle number emission levels.

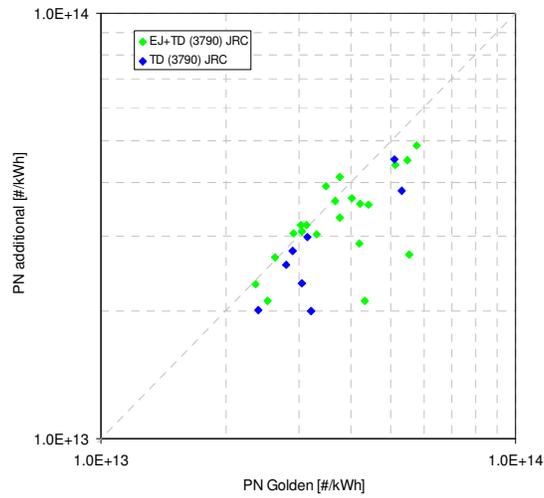
The results obtained with the alternative and the additional systems are compared with the GPMS units in Figure 63 and Figure 64, respectively. The average and standard deviations of the individual differences determined are summarized in Table 15.

Similar trends were observed at these higher emission levels. In particular, the Nanomet systems were found to systematically overestimate the particle number emissions. The dual ejector and the thermodenuder systems gave slightly lower particle number concentrations ( $\sim 10\%$ ). This consistency in the results over a 4 orders of magnitude variation of the vehicle emissions suggests that the observed differences are associated with errors in the calibration of the systems.

**Figure 63: Correlation between the alternative and the GPMS systems at engine out emission levels**



**Figure 64: Correlation between the alternative and the GPMS systems at engine out emission levels**



**Table 15: Percentage differences in the number concentrations measured with the alternative – additional systems and the GPMSs.**

		WHTC Cold	WHTC Hot	WHSC	ETC	ESC
AL T	<b>Golden Engine (with CRT)</b>					
	<b>Nanomet (3010D) JRC</b>	30.62% ± 7% (8)	29.4% ± 16% (9)	15.72% ± 9.09% (8)	16.38% ± 7.18% (8)	11.95% ± 2.52% (5)
	<b>Nanomet (3010) JRC</b>	66.84% ± 7.49% (3)	34.28% ± 3.06% (3)	14.89% (1)	8.01% ± 3.92% (2)	5.68% ± 1.81% (2)
	<b>Nanomet (3010D) Ricardo</b>	30.72% ± 38.33% (4)				
	<b>2xEj+ET (3010) JRC</b>	-19.09% ± 4.26% (5)	162.99% ± 55.73% (9)	13.43% ± 19.3% (7)	16.62% ± 23.58% (11)	-16.26% ± 9.96% (10)
	<b>2xEj+ET (3790) JRC</b>	-19.37% ± 2.97% (8)	20.81% ± 19.52% (10)	-6% ± 12.37% (8)	-5.46% ± 8.89% (8)	-16.69% ± 5.49% (8)
	<b>2xEj+ET (Grimm) JRC</b>	-0.03% ± 3.7% (9)	118.08% ± 60.64% (10)	70.17% ± 44.62% (9)	74.52% ± 44.06% (9)	1.54% ± 2.33% (11)
	<b>2xEj+ET (3010) EMPA</b>	7.42% ± 24.62% (8)	-14.28% ± 9.83% (8)	-11.29% ± 10.58% (8)	-19.68% ± 11.09% (8)	-6.46% ± 22.29% (8)
	<b>APC AVL MTC</b>	14.99% ± 4.06% (3)	4.87% ± 1.39% (2)	2.13% ± 5.8% (2)	0.67% ± 7.79% (2)	6.32% ± 1.19% (2)
	<b>APC JRC</b>	-16.22% ± 17.77% (6)	49.15% ± 30.68% (5)	21.7% ± 25.93% (5)	30.24% ± 33.74% (4)	-15.79% ± 17.03% (7)
	<b>Nanomet (3790) JRC - PFS</b>	-29.58% ± 10.32% (4)	7.58% ± 14.95% (5)	-0.4% ± 32.23% (4)	55.23% ± 56.26% (4)	-22.93% ± 16.36% (4)
	<b>Golden Engine (without CRT)</b>					
	<b>Nanomet LD GPMS (3010D) JRC - PFS</b>	48.07% ± 16.31% (3)	32.66% ± 11.01% (2)	45.09% ± 3.78% (2)	36.68% ± 1.08% (2)	47.72% ± 1.32% (2)
	<b>Nanomet (3790) JRC - PFS</b>	63.97% (1)	70.56% (1)	24.73% ± 32.43% (2)	1.84% (1)	-3.17% (1)
	<b>2xEj+ET (3790) JRC</b>	-11.45% ± 5.3% (4)	-1.51% ± 10.82% (4)	-6.23% ± 16.68% (3)	-14.62% ± 14.92% (3)	-13.24% ± 12.58% (2)
<b>2xEj+ET (3010) JRC</b>	-11.53% ± 12.24% (3)	-14.2% ± 10.49% (3)	-6.08% ± 8.83% (3)	-14.36% ± 4.21% (3)	-12.57% ± 3.95% (3)	
ADD	<b>Golden Engine (with CRT)</b>					
	<b>2xEj+ET (3010) EMPA - Direct</b>	0.56% ± 30.42% (7)	-39.31% ± 29.45% (7)	-13.14% ± 32.67% (8)	-45.34% ± 16.26% (6)	-7.67% ± 35.65% (8)
	<b>Ej+TD (3790) JRC</b>	-12.42% ± 3.01% (7)	-8.31% ± 11.88% (9)	-10.2% ± 8.25% (8)	-15.41% ± 8.29% (10)	-13.33% ± 4.2% (10)
	<b>TD (3790) JRC</b>	-25.58% ± 10.94% (2)	-3.38% ± 20.27% (2)	-4.42% ± 4.38% (2)	-3.73% ± 17.28% (2)	-8.29% ± 1.14% (2)
	<b>Golden Engine (without CRT)</b>					
	<b>Ej+TD (3790) JRC</b>	-4.65% ± 7.93% (4)	4.54% ± 9.26% (4)	-1.33% ± 7.44% (4)	-24.59% ± 17.75% (4)	-25.33% ± 16.58% (5)
<b>Ej+TD (3010D) JRC</b>	-12.36% ± 5.39% (2)	-21.37% ± 23.21% (2)	-14.44% ± 13.75% (2)	-19.68% ± 12.12% (2)		

The percentage values correspond to the average ± 1 standard deviation of the individual test differences while the numbers in parentheses indicate the number of tests from which these figures were calculated.

## 8.8 Raw and dilute gases

### *This section is incomplete*

- Raw emissions appear more repeatable than dilute emissions
- Some labs had high levels of CO and HC backgrounds
- Substantial differences in raw Vs. dilute emissions exist, even for 'high emissions' gases such as CO<sub>2</sub>.
- Few labs measure 'bagged emissions' from HD testing

## 9. DISCUSSION AND OVERVIEW

This section draws together the discussion points from the report and summarises the critical issues for use of the measurement equipment and procedures in legislative procedures.

### 9.1 Particulate Measurements

#### 9.1.1 *Recommended Filter Loading*

From the partial flow measurement systems used in this work, filter masses seldom reached 50µg with 47mm TX40 filters. Given that a high proportion of this is almost certainly volatile artefact, and it is likely that Teflon membrane filters which exclude some of these volatiles will also be permitted as part of future HD legislation, it would be sensible to set the recommended filter loading to 20µg.

#### 9.1.2 *Validation Exercises*

Reference filter variation was higher than seen in previous test programmes including the ILCE\_LD, despite stable environmental conditions. Occasionally one filter showed considerably higher variation than the other two, which indicates that baseline differences in filter background rather than environmental changes may be responsible for excessive reference filter variability.

If the batch of filters used in this work is representative of all TX40 batches, it would be wise to increase the permitted reference filter variance to  $\pm 10\mu\text{g}$ .

#### 9.1.3 *Background Mass Levels - CVS*

Background (tunnel) PM measurements were made in 3 of the 5 test laboratories. In some labs PM backgrounds from CVS systems were extremely high – due to the testing history of these systems. Active regeneration and testing fuels with high levels of FAMEs seem to leave residual carbon and semi-volatile materials in the dilution system that are not readily removable, even by the 2h full load operation undertaken by all labs before the start of the measurement campaign. These materials do, however, seem to release over time.

In other labs, CVS backgrounds were much lower. However, in all the labs, masses collected on the background filters from CVS systems were equivalent to sample filter masses, with the exception of samples from the ESC which were always higher than the background.

The ESC cycle has a substantial period of operation at high exhaust temperatures and this may lead to emissions of low volatility compounds that are efficiently collected and then retained by the filter. Filters from other cycles collect higher volatility materials from the exhaust and dilution air, but these can be released following acquisition through volatilisation or through a washing effect as further aerosol is drawn through the filter.

Data suggests that the CVS PM method is capable of resolving PM emissions from ESC tests from background levels. Results from other cycles, including the cold WHTC are subject to high uncertainty and would reduce to zero if background subtraction was undertaken.

#### *9.1.4 Background Mass Levels - PDT*

Background PM levels from PDTs were, at all laboratories, at the low end of levels from CVS systems. Despite the generally lower background levels, 2 of the 3 labs' partial flow systems backgrounds were also similar to sample levels, except for the ESC cycle.

The third lab, JRC, showed similar background levels to the other laboratories but slightly higher emissions levels, making it just possible to discriminate samples from background on all emissions cycles.

Since PDTs are a newer technology than CVS systems, these have seen less usage with older, sootier engines. CVS systems may have substantial levels of elemental carbon accumulated on the walls of the dilution tunnel over many years. These dilution tunnels tend not to be cleaned. This carbon may capture volatile materials and further soot more efficiently than the cleaner walls of a newer partial flow system. Subsequent release of these materials will contribute a high and variable CVS background, while the relatively clean PDT has a much lower, more consistent background.

Most PDT systems have removable dilution tunnels which can be easily cleaned and replaced, further reducing background contributions.

#### *9.1.5 Emissions Levels*

After exclusion of the results from the two test laboratories that had very high PM backgrounds as outliers, PM levels measured directly from CVS systems were <6mg/km from all test cycles, with no obvious difference in emissions between the cold and hot start WHTC cycles. These levels are substantially below the 10mg/kWh limits set for the weighted WHTC and WHSC at Euro V, and expected for Euro VI.

PM emissions from PDTs were generally lower than the CVS levels and less than 4mg/kWh from all cycles except at one lab where emissions from all cycles filled a narrow mass band between 4mg/kWh and 7mg/kWh.

Correction of the low background JRC PDT results would reduce the emissions levels from cold start WHTC to (generally) <1mg/kWh, hot start WHTC to 0.5g/kWh or less, WHSC to ~1.2g/kWh, ETC to 0.5g/kWh or less and ESC to <2mg/kWh. The weighted WHTC result would be substantially below 1mg/kWh.

#### *9.1.6 Background Subtraction*

Due to the high variation in background masses from both CVS and most partial flow systems, subtraction of tunnel backgrounds may result in increased variation in corrected PM mass emissions compared with uncorrected results.

Nevertheless, indications are that PM emissions, using current dilution systems that meet all the regulatory criteria, are in many cases zero, since the sample masses are indistinguishable from the background. With the ESC, the only cycle that consistently showed emissions above background levels from CVS systems in this work, a more accurate emissions value is obtained by subtracting a tunnel background.

Similarly, subtracting tunnel backgrounds from partial flow and full flow dilution systems will converge results from the two dilution systems, even if this agreement is at zero.

On this basis, tunnel background subtractions should be permitted.

#### *9.1.7 Partial Flow or Full Dilution*

The results of this work indicate that partial flow dilution systems should be favoured over CVS systems for PM measurements. This is purely a consequence of the lower backgrounds present in these systems and the fact that at one laboratory at least, it was possible to discriminate emissions levels from background levels for all cycles tested.

## **9.2 Particle Number Measurements**

#### *9.2.1 Golden Systems – PCRF Correction*

The SPCS systems used throughout this work were not subjected to a manufacturer's PCRF calibration prior to the commencement of the test programme. Subsequent work conducted by JRC indicates that applying a Particle Concentration Reduction Factor (PCRF) correction to the particle number data from these two systems would increase the measured emissions by ~25%. This incremental factor should be considered if results from this work are to be compared with emissions measured by fully PMP compliant systems in other studies.

#### *9.2.2 Particle Number Backgrounds*

The high levels of PM background seen in two laboratories was also reflected as high PN backgrounds, meaning that there must have been a substantial contribution of either EC or low volatility HCs, or both.

At the lab with the highest background levels, these were the equivalent of  $\sim 4 \times 10^{10}$ /kWh over the ETC. In comparison, two other labs had CVS backgrounds that were 60 and 120 times lower.

Backgrounds from PDT systems were both lower and much more consistent: three labs showed levels equivalent to ETC emissions of between  $2.7 \times 10^8$ /kWh and  $2.9 \times 10^8$ /kWh. This close agreement in solid particle backgrounds from PDTs indicates that the greater variation in PM backgrounds from PDTs must be due to volatiles.

#### *9.2.3 Real-time Particle Emissions Elevated at Cold Start*

Emissions from the cold start WHTC were dominated by the first 700s of the cycle, where particle numbers were several orders of magnitude higher than in the remaining 1100s. This cold start effect reflects the observations made in the light-duty PMP validation exercise. It has been hypothesised [REF] that these high emissions following cold start are due to reduced filtration efficiency that occurs when the filter cake cracks as it dries and cools following high temperature operation. Particles follow the cracks and escape through the filter substrate until the cracks fill with freshly emitted soot and the filter cake regains its integrity.

Emissions from the hot start WHTC show lower emissions from the start of the cycle: as the filter cake is now in place and filtration efficiency is maximised.

Transient particle emissions from the WHSC, alternatively, are low from the start but increase after ~1200s. This may be the point at which on-going passive regeneration within this cycle appreciably reduces the filter cake and it is also where the exhaust temperature is highest. High exhaust temperatures may promote thermal release of low volatility materials which the PN measurement system sees as solid particles.

#### 9.2.4 *PN Emissions Levels Compared with Backgrounds*

Particle number emissions from the cold WHTC were sufficiently high that they were substantially above the background levels from both CVS and PDT systems in all the test labs. However, CVS background levels at Ricardo and EMPA were sufficiently high that emissions levels from several cycles (hot WHTC, WHSC, ETC, ESC at Ricardo; hot WHTC, WHSC, ETC at EMPA) could not be discriminated from the background. These data were excluded as outliers in the statistical analyses.

In comparison, background levels in the partial flow systems were sufficiently low that no labs data were identified as outliers based upon high emissions levels attributable to the background.

As with the PM measurements, it is clear that CVS systems are prone to higher PN backgrounds than partial flow systems.

#### 9.2.5 *PN Emissions levels*

From both CVS and PDT cases, mean PN emissions, including all labs results, were highest from the cold start WHTC at  $\sim 4 \times 10^{11}$ /kWh. At this level of emissions, contributions from the background, even from labs with very high backgrounds, do not have a substantial impact on emissions.

Lowest emissions were observed from hot cycles which do not have substantial periods of passive regeneration: hot WHTC and ETC. These cycles showed emissions levels of  $5 - 6 \times 10^9$ /kWh from the PDT and  $8 - 9 \times 10^9$ /kWh from the CVS once outlier laboratories were excluded. Laboratories considered to be outliers reported emissions levels from these cycles to be substantially above  $10^{11}$ /kWh.

Weighted WHTC results were of the order  $4 - 5 \times 10^{10}$ /kWh from the PDT and CVS (outliers excluded) and  $\sim 10^{11}$ /kWh from the CVS when all labs data were considered.

ESC and WHSC cycles results were generally more variable than the hot start ETC and WHTC due to the presence of passive regeneration during these cycles. Passive regeneration may reduce filtration efficiency by reducing or removing the filter cake but high temperatures may also liberate low volatility HCs which contribute to solid particles: both of these result in higher PN emissions from the ESC and WHSC than from the ETC and hot WHTC. The ESC cycle, which has a 2 minutes period of operation at full load, and other modes with very high exhaust temperatures, sees a higher contribution of low volatility HC 'solid particles' than the lower temperature WHSC. Emissions from the WHSC were around  $2-3 \times 10^{10}$ /kWh from PDT and CVS (outliers excluded) and  $6 - 8 \times 10^{10}$ /kWh from the ESC with outliers excluded from the CVS data.

## 9.3 Repeatability and Reproducibility

### 9.3.1 *PM and PN – Repeatability*

The repeatability of CVS PM measurements, expressed as CoV, was lowest for the cold WHTC cycles at ~35%, with other cycles in the range 50% to 56%. There were no labs' data that were considered outliers.

PDT PM measurements showed CoV ranging from 20% to 30% across all cycles, with one lab's data excluded as an outlier by the statistical analysis.

By contrast, no labs' results were excluded from the PDT PN data set, but with CVS measurements outlier analyses excluded all hot cycle results from Ricardo and all but the cold WHTC and ESC from EMPA.

Following the exclusion of outliers, particle number repeatability levels were broadly similar: CVS CoVs ranged from ~20% to ~60% and PDT CoVs from ~20% to ~70%.

Focusing on the Euro VI legislative cycles in isolation, shows that the CVS approach has better repeatability over the weighted WHTC (21.1% Vs. 22.8%) and over the WHSC (59.2% Vs. 74.4%) than the PDT approach.

Taken at face value, and using the repeatability as the assessment approach, these data would recommend that:

- PDT is the favoured dilution system for PM measurements
- CVS is the favoured measurement system for PN
- PM is the better metric, since it is more repeatable than PN

In reality, only the first of these statements is true. PDT systems, with their lower backgrounds will produce an emissions result that is lower and therefore closer to the true value.

CVS is more repeatable for particle numbers, but only marginally and after 2 of 5 labs were rejected as outliers. It has a higher background than the PDT system, so again gives a result that is further from a true value.

PN is more repeatable than PM, but this is generally because PM measures mostly background and the background appears to be at least as repeatable as the emissions from the engine.

### 9.3.2 *PM and PN – Reproducibility*

CVS PM reproducibility levels were typically in the range 35% to 55%, averaging 42.7% for the 5 emissions cycles in the test matrix. PDT PM reproducibility levels ranged from ~30% to ~45%, averaging 36.1%.

The lower PM CoVs from the PDT systems probably reflect the greater consistency of background levels in the partial flow system compared to the CVS.

Considering just the Euro VI legislative cycles shows that the CVS approach has similar PN reproducibility over the weighted WHTC (41.4% Vs. 45.8%) and over the WHSC (81.7% Vs. 86.3%) to the PDT approach.

The higher variation in the PN results than the PM results from the WHSC cycle is an indication that the PM method is insensitive to the effects of passive regeneration in this cycle.

### 9.3.3 *Repeatability and Reproducibility Overview*

When considering a measurement system it is important to consider more than just the repeatability and reproducibility. The results of this study indicate that the most repeatable and reproducible methods do not necessarily discriminate the emissions from the background nor determine a true value. However, this work does indicate that PDT is the best method for PM determination and that both CVS and PDT show similar repeatability and reproducibility for the measurement of particle numbers.

## 9.4 **Elemental carbon and non-volatile particle contributions to PM**

Masses collected with TX40 filters were compared with simultaneous mass measurements from real-time instruments.

From cold start WHTC cycles, both the Dekati Mass Monitor (which calculates mass from the particle size distribution after evaporating volatile particles) and AVL483 (photoacoustic soot sensor) indicated mass levels ~10% of the filter mass. This suggests that 90% of the filter mass from this cycle is volatile and the other 10% is mostly elemental carbon. At this level of EC content, PM filters appeared slightly grey.

From all other (hot start) test cycles the DMM mass was  $\leq 0.5\%$  of the filter mass, indicating the volatile contribution to PM is ~99.5%. PM filters from hot start tests appeared unused.

Clearly, at a maximum of 10% EC in the PM measured on the filter, agreement between mass and number metrics would not be expected.

## 9.5 **Filter Media Effects**

In experiments at JRC, comparisons were made between PM sampled with 47mm TX40 and with 47mm Teflon membrane filters. Collected masses were always lower with TX40 filters, repeating the observations made in the light-duty PMP work.

Typical masses captured with the Teflon Membrane filters were 30% to 90% lower than recorded with TX40 filters. Considering also the observations in Section 9.4, this suggests that even the Teflon filters are still capturing some volatiles.

## 9.6 **Alternative Systems**

VPR systems which were calibrated as a whole unit either by the manufacturer (APC) or in the framework of this study (GPMS, EMPA's homemade system, systems utilizing a thermodenuder), differed by less than  $\pm 15\%$  when the results were corrected for the average PCRF value as described in the R83.

The observed differences were not affected by the emitted particle number concentrations (and therefore from the associated uncertainties in the dilution ratio determination) or by the CPC unit employed. Therefore, this is a PCRF related issue.

Inaccuracies in the determination of the PCRF values might have contributed to this difference. Most of the instruments used in this study were calibrated against NaCl

particles which were not thermally treated. Some preliminary tests suggested a change of structure of NaCl particles when heated which leads to particle shrinkage (SAE 2009-01-1115).

Uncertainties associated with the operation of the DMA used for the production of the monodisperse calibration aerosol might also have contributed in the observed discrepancies. In particular, uncertainties in the charge distribution acquired in the neutralizer and therefore in the contribution of multiply charged (larger) particles in the produced monodisperse aerosol might have affected the calculated PCRF values. The relatively high concentration required for the production of monodisperse aerosol at sufficiently high concentrations might give rise to space charge fields affecting the classified particle size.

Another reason for the observed discrepancies between the various alternative systems might be associated with the size depended losses inside the VPR systems. The calculations have been performed using the average PCRF value determined for particle mobility diameters of 30 nm, 50 nm and 100 nm, as suggested by the regulations. The correct approach, however, would be to use the PCRF value corresponding to the geometric mean diameter of the underlying distribution. This simplified approach, which is justified as the true size distributions is not generally known, also introduces some error depending on the underlying size distribution of the sampled aerosol but also on the steepness of the penetration characteristics of the VOR system employed (that is particle losses as a function of particle size). It is worth noting that most of the VPR systems tested exhibited steeper penetration curves from what is specified in the regulations.

It is therefore important to further investigate the calibration procedure for the VPR systems.

## **9.7 Should Solid Particles <23nm be Considered for European PN Legislation?**

Comparisons were made between non-volatile particles >3nm and non-volatile particles >23nm by using different particle counters as the counting elements of the SPCS systems. A number of different steady state and transient (including cold and hot WHTC) cycles were studied.

Irrespective of operating conditions the number of solid particles between 3nm and 23nm was never greater than the level of solid particles above 23nm. The highest level of particles between 3nm and 23nm was from the cold WHTC. Levels were ~85% of the number found above 23nm. Between 3nm and 23nm, primary carbon spheres are present at the upper end of the size range, however it is possible that additional solid particles are present. These may derive from the lubricant as metal oxides.

While there was some evidence that solid particles <23nm were present, the levels seen were not consistent with the orders of magnitude increases relative to >23nm particles reported from US engines. On this basis, it is considered reasonable to retain the size and volatility range of particles measured for light duty vehicles in heavy-duty engines' legislation.

## **9.8 Euro VI Certification**

Certification testing for Euro VI will include both WHTC and WHSC. From the emissions levels seen in this study a PN limit set mandating PDT and excluding CVS could be lower than a limit that permits either dilution system.

If either dilution system is permitted, the test laboratory or OEM would face substantially higher risk of non-compliance when using a full flow system, unless that CVS was well characterised and cleaned beforehand.

### **9.9 Achievable PN Limit for this Engine**

Across this test programme the highest single PN emissions result seen from any cycle across all labs was  $7.4 \times 10^{11}$ /kWh from a cold WHTC. If this engine and its DPF are considered to have representative PN emissions and both CVS and PDT dilution approaches are used, a PN limit of  $8 \times 10^{11}$ /kWh would be achievable for all emissions cycles tested.

Alternatively, considering the mean results across all labs, the starting point for calculating a PN limit for both WHTC and WHSC is a mean result at or below  $10^{11}$ /kWh.

### **9.10 Simulation of RR with alternative systems**

*This section is incomplete*

### **9.11 An Economical Approach to Legislative PN Measurements**

There is a possibility that particle number emissions from DPF equipped engines may, especially when the DPF is highly loaded, be delayed in reaching the dilution system due to transit through the filter substrate and filter cake. If this is the case, the dilution ratio in the PDT, which varies with engine exhaust flow could be incorrect at the time (following transit delay) the particles and PM actually reach the dilution tunnel. If this is the case, there is actually no merit, specifically for post-DPF PN tests, to undertake proportional sampling. Consequently, a fixed dilution ratio PDT measurement combined with a real-time exhaust flow measurement would be an inexpensive alternative.

Only limited tests were undertaken, but data available suggests that PN emission levels can be determined with acceptable accuracy (better than ~15%) when sampling from the exhaust at constant dilution ratio into a PDT. In general though, this approach seems to provide directionally lower emission levels than measured from the CVS tunnel.

Indications are, that mass is underestimated by the constant dilution approach (and it can't be corrected for real time flow because there are no real time data) so this is not appropriate for legislation. However, the mass emissions from many labs appear to be indistinguishable from zero if the background is subtracted. On this basis, mass as a metric is of little value and if particle number was the only metric, the constant DR PDT approach would be a valid and cost-effective approach.

Certification testing for Euro VI will include both WHTC and WHSC. From the emissions levels seen in this study a limit set mandating PDT and excluding CVS could be lower than a limit set that permits either dilution system. If either dilution system is permitted, the test laboratory or OEM would face substantially higher risk of non-compliance when using a full flow system, unless that CVS was well characterised beforehand.

## 10. CONCLUSIONS (*To be refined*)

### 10.1 Engine Operation

- Engine operation was sufficiently consistent across the test programme to enable comparisons between test laboratories

### 10.2 Measurement Systems

- The GPMS systems tested in this work, SPCS systems from Horiba, suffered no significant mechanical failures during the test programme and performed reliably passing all required validation checks in all test laboratories. The two SPCS systems supplied agreed to within ~5% when tested in parallel, enabling direct comparisons to be made when one was used to sample from CVS systems and the other from partial flow systems

### 10.3 PM Emissions

- The PMP mass method collects a large gaseous volatile fraction that may be 10 times the mass of the solid particles collected from the cold WHTC and 200 times the mass of solid particles from hot start cycles.

#### 10.3.1 Levels

- PM emissions levels from CVS systems, after exclusion of labs with high PM backgrounds were <6mg/kWh from all emissions cycles. However, background levels from CVS systems in all labs were equivalent to drive cycle emissions levels for all cycles except the ESC.
- The chemistry of PM from ESC tests comprises lower volatility HCs which are more effectively retained by the sample filter.
- PM emissions from PDT systems were generally lower than results from CVS systems – at <4mg/kWh from all emissions cycles. From PDT too, background levels were similar to or just below sample levels on all cycles except the ESC which could be discriminated from the background in all labs.
- One lab's PDT was able to discriminate sample levels from background PM and this revealed all mass emissions to be <2mg/kWh. Average emissions, following background subtraction, were ~0.6mg/kWh from the weighted WHTC, and approximately 1.2mg/kWh from the WHSC.

#### 10.3.2 Repeatability / Reproducibility

- PM repeatability levels from the PDT were between 20 and 30% for all emissions cycles, while CVS repeatability was best from the cold WHTC (~35%) and 50 to 56% for other cycles.
- Reproducibility levels from the CVS were similar to the repeatability levels, ranging from 35% to 55%. PDT PM reproducibility levels were slightly better, on average ranging from 35% to 45%.

## 10.4 PN Emissions

- The PMP number method determines real-time emissions that can be related to engine events with high sensitivity.

### 10.4.1 Levels

- PN emissions levels from the Cold WHTC were approximately  $4 \times 10^{11}$ /kWh from both full and partial flow dilution systems. At these levels of emissions the background contribution has no substantial impact on emissions
- Background PN levels in the CVS were generally higher than in PDT systems and in two labs sufficiently high for those labs to be identified as outliers since their background levels were as high or higher than emissions from many of the hot start cycles. In these cases, emissions from hot start cycles were  $\sim 10^{11}$ /kWh
- Low PN background levels were seen in PDTs, and since emissions levels were similar from background levels were also similar in all PDT
- Emissions levels from both PDT and CVS dilution systems with low PN backgrounds were  $5-9 \times 10^9$  from hot start WHTC and ETC cycles, but higher from WHSC ( $2-3 \times 10^{10}$ /kWh) and ESC ( $6-8 \times 10^{10}$ /kWh) where passive regeneration may oxidise the filter cake and reduce the filtration efficiency of the DPF.

### 10.4.2 Repeatability / Reproducibility

- Repeatability levels for the CVS and PDT were similar, ranging from  $\sim 20\%$  to  $\sim 70\%$ , with the cold WHTC most repeatable and the WHSC least repeatable.
- Reproducibility levels between CVS and PDT systems were also similar at 41-45% for the weighted WHTC and 81 – 86% for the WHSC.
- With the particle number measurement systems, it is clear that the passive regeneration present in the WHSC leads to increased variability. This effect is not seen in the PM results.

## 10.5 Relationships Between Measurement Approaches

### 10.5.1 Full Vs Partial Flow Mass

- Emissions levels from PDT systems were more repeatable and reproducible than measurements from CVS systems.
- One lab's PDT was able to discriminate mass emissions from background PM levels. Further research might identify procedures which will enable all labs to achieve this with their partial flow systems
- Mass emissions from PDT and CVS did not correlate: in most cases this was effectively attempting to correlate between systems' backgrounds

### 10.5.2 Full Vs Partial Flow Number

- PDT systems showed lower backgrounds than CVS systems, but when CVS system backgrounds were similar to PDT backgrounds the correlation between PN emissions was excellent.
- Higher background CVS systems still showed similar PN emissions levels to PDT systems from cold start WHTC tests.

### 10.5.3 Mass Vs Number

- Mass and number methods did not correlate. The majority of mass comes from volatile materials, which are unrelated to the materials comprising solid particles.

### 10.5.4 Number Vs Number

- At labs with low PN backgrounds in both CVS and partial flow systems excellent correlation between the dilution approaches is possible.
- At higher background labs the correlation weakens as the particle number approaches the background PN level

## 10.6 Alternative Systems

- The majority of the alternative systems correlated closely with the GPMS, the difference being on average  $\pm 15\%$  after accounting for the PCRF values and the slopes of the CPCs.
- Systematic differences were observed between the various alternative systems employed. These differences hold for emission levels spanning over 4 orders of magnitude as well as when different CPC units are employed. This points towards inaccurate calibrations of the PCRF values but could also partly be associated with differences in the penetration curves (penetration as a function of particle size).
- Simplified approaches such as the use of dual ejector systems sampling directly from the tailpipe or operation of the partial flow systems at constant dilution ratios resulted in similar levels of agreement.
- The alternative systems examined had almost an order of magnitude higher background levels from the GPMS. More efficient conditioning of the dilution air is necessary in order to accurately determine the emission levels over the hot start transient test cycles and the WHSC

## 10.7 General Conclusions

- ***This section is incomplete***
- In this work, PM emissions from an engine with an efficient wall-flow DPF, measured from PDTs, and without any correction for background, were consistently below 10mg/kWh across all the cycles tested.

- In this work, PM emissions from an engine with an efficient wall-flow DPF and measured by CVS systems, with correction for background, were consistently below 10mg/kWh across all the cycles tested.
- But, for every emissions cycle except ESC, PM emissions measured from all CVS and PDT dilution systems, excepting one PDT system, were indistinguishable from the background levels.
- The PM method is suitable to determine the absence of PM material at the emissions levels and from the drive cycles likely to be required for Euro VI (10mg/kWh for the WHTC and WHSC cycles), but is not suitable for quantifying the actual emissions levels
- In this work, PN emissions from an engine with an efficient wall-flow DPF, measured from PDTs, and without any correction for background, ranged from  $\sim 10^9$ /kWh to  $>10^{11}$ /kWh across all the cycles tested.
- In this work, PN emissions from an engine with an efficient wall-flow DPF, measured from low background CVS systems, and without any correction for background, ranged from  $\sim 10^9$ /kWh to  $>10^{11}$ /kWh across all the cycles tested.
- Emissions levels from every emissions cycle, with both PDT and low-background CVS systems, were substantially above background levels.
- From all PDT systems and low background CVS systems in this work, the PN method is suitable to determine the actual emissions levels from all drive cycles tested, and at levels  $\geq 10^{10}$ /kWh. This lower emissions threshold accounts for a PCRF correction of 1.25 to PDT and CVS particle number data from the SPCS systems in this study.
- Considering WHTC and WHSC results, the PM emissions method may appear more repeatable and reproducible than the PN method, but a direct comparison between the two is inappropriate: the PM figures represent the repeatability levels of the background and the PN figures the true variability of an unstable DPF system.

## 11. RECOMMENDATIONS

- PM by PDT to be recommended
- PN from PDT to be recommended

Including possible changes to DR49

***This section is incomplete***

## Appendices

Appendix 1: ILG\_HD

Interlab guide

## Appendix 2: Fuel Specification: RF06-03-PMP



### Direction Additifs et Carburants Spéciaux

Chemin du canal - BP 22 - 69360 Solaize France  
Tél: +33 4 78 02 60 64 - Fax: +33 4 78 02 60 91

APPELLATION : GAZOLE TYPE CEC RF 06-03			Référence analyse : 6160	
GAZOLE INDUSTRIE	N° de lot : B7274081	Date : 03/09/2004		
CERTIFICAT DE CONFORMITE <input checked="" type="checkbox"/>		BULLETIN D'ANALYSES <input type="checkbox"/>		
GAZOLE	SPECIFICATIONS	UNITE	RESULTATS	METHODES
<b>DONNEES PHYSIQUES</b>				
Masse Volumique 15 °C	833 à 837	kg/m3	835	ASTM D 4052
Viscosité à 40°C	2.3 à 3.3	mm2/s	2.7	ASTM D 445
<b>DISTILLATION</b>				
PI		°C	185	ASTM D 86
5 % Vol		°C	201	ASTM D 86
10 % Vol		°C	208	ASTM D 86
20 % Vol		°C	219	ASTM D 86
30 % Vol		°C	233	ASTM D 86
40 % Vol		°C	251	ASTM D 86
50 % Vol	245 mini	°C	274	ASTM D 86
60 % Vol		°C	293	ASTM D 86
70 % Vol		°C	309	ASTM D 86
80 % Vol		°C	320	ASTM D 86
90 % Vol		°C	333	ASTM D 86
95 % Vol	345 à 350	°C	346	ASTM D 86
PF	370 maxi	°C	356	ASTM D 86
E 250 °C		%Vol	39.6	ASTM D 86
E 350 °C		%Vol	96	ASTM D 86
E 370 °C		%Vol	96.5	ASTM D 86
<b>INDICE DE CETANE</b>				
Cétane calculé		index	53.5	ASTM D 4737
Cétane mesuré	52 à 54	index	53	ISO 5165-98
Point Eclair	55 mini	°C	75	EN 22719
<b>COMPOSITION</b>				
Aromatiques Totaux		%Mass	21.8	IP 391
Poly-Aromatiques	3.0 à 6.0	%Mass	4.4	IP 391
<b>TENUE AU FROID</b>				
Point de trouble		°C	-9	ASTM D2500
TLF	-5 maxi	°C	-18	EN 116, NF M 07042
<b>COMBUSTION</b>				
Pouvoir Calorique Inférieur (G)		MJ/kg	43.355	ASTM D 4868
%C, %H, %O		%Mass	87.4/11.4/<0.5	GC / Calculated
<b>DONNEES COMPLEMENTAIRES</b>				
Stabilité à l'Oxydation	25 maxi	g/m3	10	ISO 12205
Corrosion Cuivre 3H, 50°C	C1	merit	1a	ASTM D 130
Soufre	10 maxi	mg/kg	8	ISO 4260 / ISO 8754
Carbone conradson sur résidu 10% Vol	0.2 maxi	%m/m	0	ISO 10370
Teneur en cendres	0.01 maxi	%m/m	0,01	ISO 6245
Indice d'acide	0.02 maxi	mg KOH/g	0	ASTM D 974
Teneur en sédiments		mg/kg	2	ASTM D 2276
Teneur en esters méthyliques d'acides gras	néant	%Mass	0	
Teneur en eau	200 maxi	mg/kg	55	EN ISO 12937
Pouvoir Lubrifiant à 60°C	400 maxi	µm	360	ISO/DIS 12156
<b>Observation :</b>				
<b>VALIDATION LABO</b> le 24/09/2004 par Metin KELLE 		Document confidentiel. Diffusion extérieure soumise à l'accord de RM/SPE/ACS L'interprétation des résultats des mesures relève de la norme NF EN ISO 4259		
		Fiche de données de sécurité : 60030000 DE / EN / ES / FR / IT		

Date specs : 26/06/2003 Rév: 0

24/09/2004

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