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Particle Measurement Programme (PMP) Heavy-Duty (HD) Inter-laboratory Exercise

Validation exercise tests at JRC (Phase A: Feb'08 and Phase B: June'08)

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Contents

List of Figures

List of Tables

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1. INTRODUCTION

The mandate given to the Particle Measurement Programme (PMP) Working Group by the UN-ECE GRPE (Working Party on Pollution and Energy) was to develop new particle measurement techniques to complement or replace the existing filter-based particulate mass measurement method, with special consideration given 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 European Union (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 investigate and demonstrate the repeatability and reproducibility of the proposed techniques. PMP was also tasked with accumulating data on the particle emissions performance of a range of engine and vehicle technologies when tested according to the proposed procedures.

The Light-Duty and Heavy-Duty inter-laboratory correlation exercises of the PMP were designed to enable an evaluation of the repeatability and reproducibility of particle number and mass measurements made with the systems recommended following the PMP Phase 1 and Phase 2 studies. The two recommended systems were (PMP 2003):

- A filter mass method (PM) based broadly upon those currently used in Europe and the US and that proposed for the United States for 2007 type approvals (CFR 2001).
- A particle number method (PN) using a particle counter, a defined size range and a sample pre-conditioning to exclude semi-volatile particles.

The Light-Duty exercise preceded that for Heavy-Duty and circulated a Euro 4 Diesel vehicle with DPF plus a reference particle measurement system between laboratories. Each lab was invited to employ its own particle measurement system and to test other Euro 4 vehicles. The results of the Light-Duty inter-laboratory exercise were reported during 2007 (Andersson et al. 2007, Giechaskiel et al. 2007, Giechaskiel et al. 2008a, b).

The Heavy-Duty exercise consists of three parts:

- The *exploratory work* at JRC for the definition of the measurement protocol.
- The *validation exercise* for the evaluation of the particle number repeatability and reproducibility using the same systems at all labs (Golden Systems). In the validation, exercise an engine (Golden Engine) will be circulated along with two Golden Systems which will be used at the full and partial flow systems respectively. The Golden Engineer with the project manager will ensure that the participating labs will follow precisely the measurement protocol. Low sulfur fuel and lubricant from the same batch will be used from all labs. The participating labs are JRC, AVL_MTC (from Swedish government), RICARDO (from U.K government), UTAC (from French government), and EMPA (from Swiss government). JRC will measure again at the end of the exercise to ensure that nothing has changed at the engine during the exercise.
- The *round robin exercise* for the evaluation of the particle number repeatability and reproducibility using different systems. In the round robin, a reference engine will circulate, but each lab will use its own particle number systems at the full flow dilution tunnel and optionally at the partial flow systems. All labs will use fuel and lubricant of the

same type (but not of the same batch). The participating labs are from EU, Japan Korea, and Canada (to be confirmed).

The validation and the round robin exercises started after the exploratory work in JRC had been finalized (Giechaskiel et al. 2008c) and they run in parallel. The expected timetable is given in Table 1:

Table 1: Expected time schedule

Date	*Validation Exercise*	*Round Robin*
Oct – Feb 2008	JRC (exploratory work)	
Jan – Feb 2008	JRC (Phase A)	
Mar – Apr 2008	AVL_MTC	
May – Jun 2008	JRC (Phase B)	TUV
Aug – Oct 2008		RICARDO
Nov – Dec 2008	RICARDO	Japan, Korea
Jan – Feb 2008	UTAC	
Apr – Jun 2009	EMPA	
Jul – Aug 2009		JRC
Sep – Oct 2009	JRC	UTAC
Nov – Dec 2009		TNO
Jan – Feb 2010		VTT
Mar – Apr 2010		SCANIA
May – Aug 2010		Environment Canada (tbc)
Sep – Oct 2010		Volvo
Jul – Aug 2010		Daimler Chrysler

This document reports the results of the validation exercise during the PMP Heavy-Duty inter-laboratory exercise in Feb. ‘08 (Phase A) and June ’08 (Phase B) conducted at the Vehicles Emissions Laboratory (VELA-5) in the Transport and Air Quality Unit of the European Commission’s Joint Research Centre (JRC, Ispra). This report presents the results of the work undertaken on an IVECO Cursor 8 Heavy-Duty engine equipped with a Continuous Regenerating Trap (CRT), with a Partial Flow Deep Bed Filter from EMITEC (EMITEC) and without any after-treatment devices. The tests included European and World Harmonized cycles following a strict protocol. Mass and number measurements were conducted simultaneously at the full flow and the partial flow sampling systems.

2. EXPERIMENTAL FACILITIES

In the following sections, the experimental details for the measurements conducted in the JRC facilities will be described.

TEST ENGINE

The engine used in this study (Figure 1a) was the PMP "Golden Engine", i.e. an IVECO Cursor 8 Euro 3 engine with a Continuous Regenerating Trap (CRT) (Figure 1b) (Table 2). The Golden Engine was provided by the UK Department for Transport which signed a contract with Ricardo to this respect. Ricardo provided the technical assistance to install the engine on the test bench. The distance between the engine and the "golden" after-treatment device was 270 cm (internal diameter 15 cm) and insulated during the official tests. Exhaust gas temperatures and pressures were recorded upstream and downstream of the after treatment device. Engine coolant and intercooler temperatures were controlled respectively at 75 and 40-45°C.

The engine was also tested with an EMITEC Partial Flow Deep Bed Filter (Figure 1c) and without any after-treatment device (Figure 1d). For the last case the engine was not throttled to simulate the pressure drop of the after-treatment devices.

Table 2: Golden Engine Information

Make and model	IVECO Cursor 8 (Euro 3)
Engine configuration and capacity	7.8 l, 6 cylinder, 4 valves/cylinder
Compression ratio	17:1
Maximum power	260 kW @ 1900 to 2400 rpm
Maximum torque	1280 Nm @ 1000 to 1900 rpm
After-treatment	Continuous Regenerating Trap (CRT)

Table 3: Characteristics of the second after-treatment device used.

Manufacturer / Type	EMITEC / PM Metalit
Designation of particle filter family	Partial Flow Deep Bed Filtration
Regeneration procedure	Continuous (without fuel borne catalyst)
Matrix dimension	254x150 – 0.686 kg/l
Material	Matrix: 1.4767 + 1.4525 Mantle: 1.4509
No of cells per square inch	200 cpsi
Wall thickness / filter depth	0.3 mm
Sizing (flow rate / frontal area)	49 (l h)/mm2 +/-15%
Maximum operating temperature	900°C

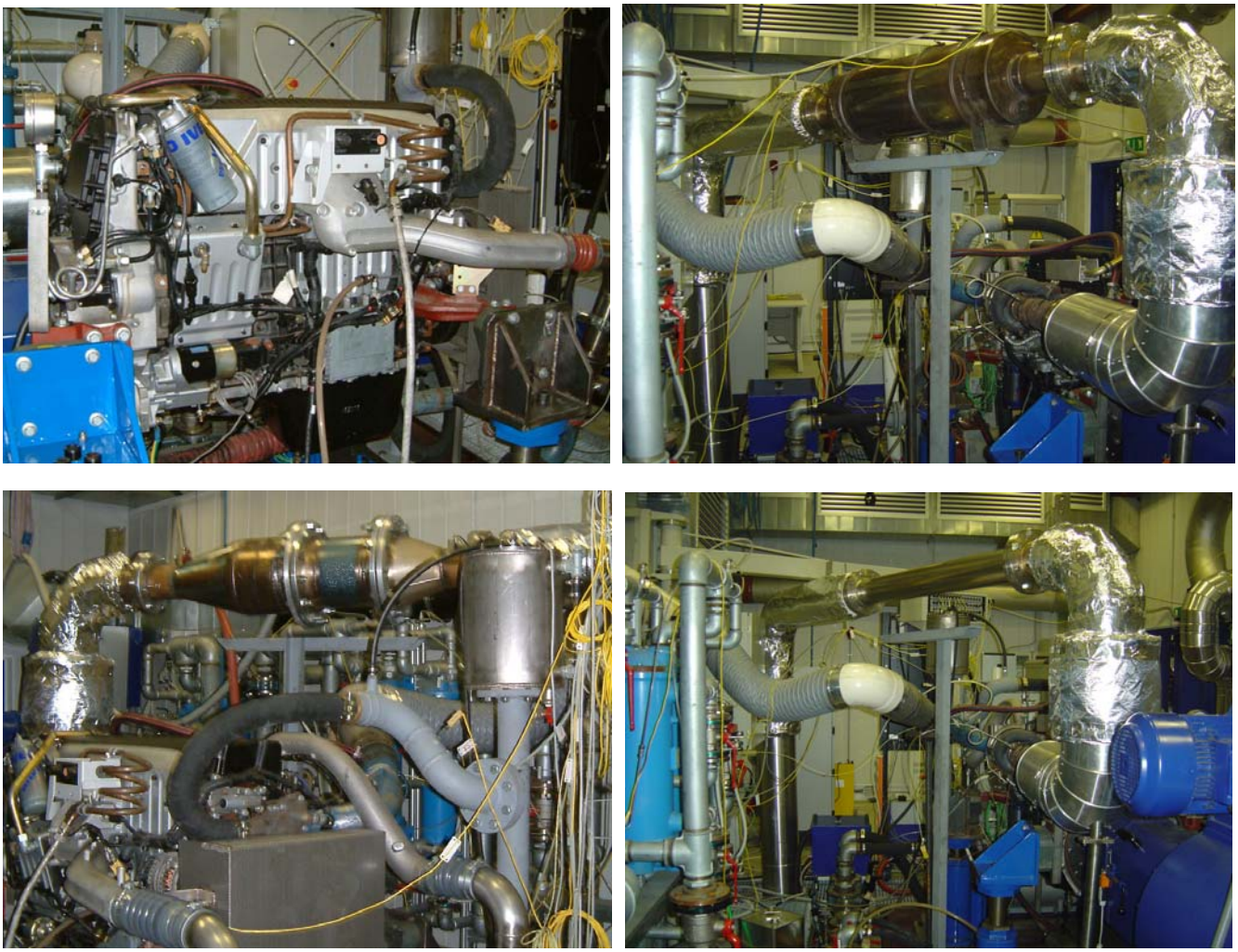

Figure 1: a) Golden Engine (IVECO CURSOR 8) b) golden after-treatment device, CRT c) EMITEC Partial Flow Deep Bed Filter d) no after-treatment

FUEL AND LUBE OIL

The lubricating oil used was purchased by BP lubricants. The test lubricant was a BP Vanellus E8 fully synthetic, 5W/30 PAO (polyalphaolefin) based oil with <0.2% sulfur content (Table 4). The lubricant was added to the engine following the procedure described in the inter-laboratory guide (Andersson and Clarke 2008). The lubricant conditioning consisted of 3 cycles of 10 min at mode 10 (ESC) and 10 min at low load (800 rpm / 200 Nm) the first day and 4 cycles of 15 min at mode 10 (ESC) and 5 min at idle the next day.

The fuel used in this engine (RF06-03 PMP) was purchased by Total, which prepared a dedicated batch for the PMP exercise (same batch for all labs participating in the validation exercise). The fuel was a certified CEC reference fuel complying also with Annexes 3 and 4 of Directive 2003/17/EC describing fuel specifications to be employed after 1st January 2009 (i.e. sulfur content of lower than 10 ppm). The most important properties can be seen in Table 5 and the detailed specifications in Annex A.

Table 4: Lubricant specifications.

Properties	*Method*	*Units*	*Value*
Density @15 ^{o}C	ASTM D4052	g/ml	0.860
Cinematic Viscosity @100 ^{o}C	ASTM D445	mm^2/s	12.03
Viscosity Index	ASTM D2270	^{o}	163
Viscosity CCS @ -30 ^{o}C	ASTM D2602	cP	5260
Total Base Number	ASTM D2896	Mg KOH/g	15.9
Sulphated Ash	ASTM D874	^{o}C	1.9
Specifications: SAE 5W-30 ACEA E4/E5/E7 MB approval 228.5 MAN M3277 Volvo VDS-2 Scania LDF			RVI RXD Cummins CES 20072/77 MTU Type 3 Mack EO-M Plus DAF HP1/HP2

Table 5: Fuel specifications

Properties	*Method*	*Units*	*Value*
Density @ 15 ^{o}C	EN ISO 3675-98	[kg/m^3]	834.9
Viscosity @ 40 ^{o}C	ASTM D445	cSt	2.654
IBP ^{o}C	ASTM D86	^{o}C	171
FBP	ASTM D86	^{o}C	357
10% vol	ASTM D86	^{o}C	204
50% vol	ASTM D86	^{o}C	277
95% vol	ASTM D86	^{o}C	346
Cetane Number	ISO 5165-98	[-]	53.1
%Carbon	GC / calculated	% mass	86.7
%Hydrogen	GC / calculated	% mass	13.2
%Oxygen	GC / calculated	% mass	< 0.2
Polycyclic aromatics	IP391	[%] by mass	5.1
Sulphur	ISO 4260 / ISO 8754	[ppm] or [mg/kg]	7
Water content	EN ISO 12937	mg/kg	30

SAMPLING SYSTEMS AND CONDITIONS

The measurements were done on a test bench at the VELA-5 JRC laboratories (Motor AFA-TL 510/1.9-4, 500 kW, 2500 Nm, 3500 rpm). A general description of the set up follows (Figure 2). A figure with the most important dimensions of the installation is given in Annex B.

Dilution air

Following the PMP recommendations, the exhaust was primarily diluted and conditioned following the Constant Volume Sampling (CVS) procedure. Highly efficient dilution air filters for particles and hydrocarbons that reduce particle contributions from the dilution air to near zero were used (H13 of EN 1822).

Primary Full Dilution tunnel

The exhaust was transported to the primary full dilution tunnel through a 9.5 m long (the first 3 m and the last 3 m were insulated) stainless steel tube (Reg. 49). The exhaust gas was introduced along the tunnel axis, near an orifice plate that ensured rapid mixing with the dilution air. The flow rate of diluted exhaust gas through the tunnel was controlled by a critical orifice venturi. A flow rate of 80 m^3/min at normal reference conditions (0°C and 1 bar) was used for most measurements (unless specified otherwise). The tunnel operated in the turbulent flow regime (Re = 25000 depending on the diluted gas temperature). The residence time of the exhaust in the dilution tunnel was in the order of 0.5 s (for 80 m^3/min). The schematic of the set up can be seen in Figure 2.

It was found that for the first tests of Phase A (till 13/2/08) the critical venturi couldn't be held at constant temperature, as the heat exchanger was not operating properly. For this reason the cycles at the end of the day were conducted with high venturi temperatures (thus leading to lower CVS flow rates). Although the correct flow rate was taken into account for the calculations at CVS, the lower flow rate had as a result different dilution ratios in the CVS and in the partial flow systems (which were set for a CVS flow rate of 80 m^3/min). In addition, because the heat exchanger was not operating, the CVS flow rate (due to different diluted exhaust temperatures) was different at different points of the cycle (with lower CVS flowrates at high engine modes). This affected the proportionality and the mass collected on the filter. This effect couldn't be taken into account for the PM emissions. However, some number calculations were conducted assuming a CVS sampling temperature of 20°C at the beginning of the cycle and 150°C at the end of the cycle (worst case hypothetical scenario). The calculations showed that the overestimation (assuming an average CVS flow) would be +10% for the cold WHTC (where the particle emissions are high at the beginning of the cycle) and -5% for the steady cycles (where the emissions are high at the end of the cycle. However, for the rest tests of Phase A and for the tests of Phase B the cooling system was operating normally.

Three probes (of inner diameter 12 mm) were used for sampling, placed at the same cross-section of the tunnel and facing upstream the flow. One probe was used for the secondary dilution tunnel and the particulate mass (PM) measurements and the other two for particle number (PN) measurements. At one of the probes, a URG-2000-EP cyclone was installed (see Appendix C for cut-points). These probes were installed 10 tunnel diameters downstream of the mixing point to ensure complete mixing of the dilution air and the exhaust gas.

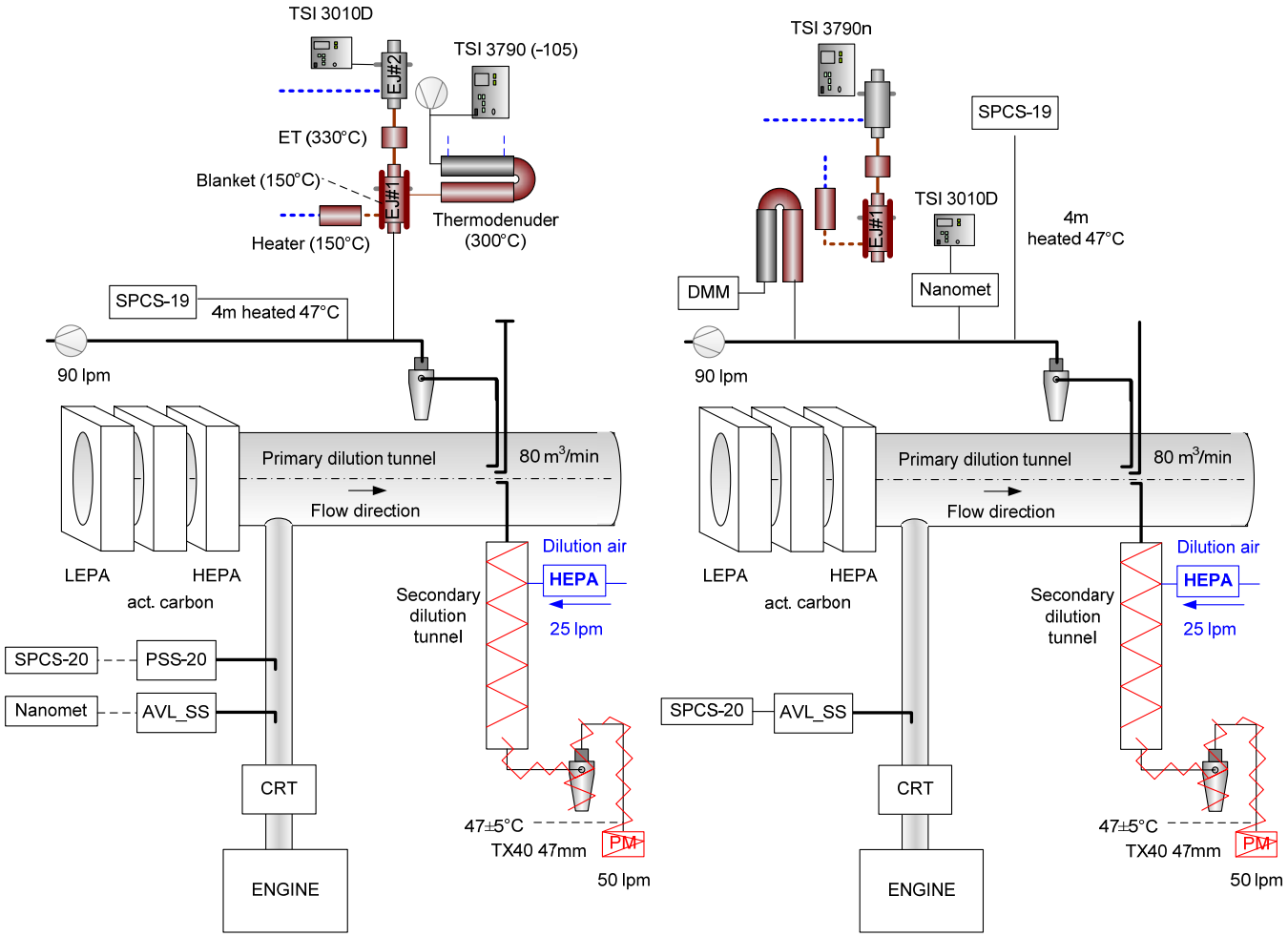

Figure 2: Schematic of the set up (Phase A and Phase B).

Secondary dilution tunnel (PTS) and Particulate Mass (PM) sampling

The secondary dilution tunnel used for PM measurements met the requirements of Heavy-Duty Engines regulation (Reg. 49). The ratio of dilution air to sample aerosol flow (from the primary tunnel) was usually 1:1 (25 lpm sample, 25 lpm dilution air, and 50 lpm total flow to the filters at normal reference conditions 0°C and 1 bar) so the dilution ratio was 2:1. A cyclone pre-classifier (URG-2000-30EP) was used to limit the contribution of re-entrained and wear materials to the filter mass (cut-point at 4 µm see Appendix C). The filter holder and transfer tubing were usually externally heated by direct surface heating to permit aerosol stabilization of >0.2 s prior to sampling and to ensure close control of the filter face temperature to 47°C (±5°C). The temperature was measured 20 cm upstream of the filter. PM samples were collected on 47 Teflon-coated glass-fiber Pallflex® TX40H120-WW filters (TX40). One single 47 mm filter was used rather than primary and back-up filters to minimize weighing errors and the volatile artifacts of the back-up filter.

To estimate the filter face velocity surface areas of 11.3 cm^2 was assumed for the 47 mm filters. The filter face velocity was calculated for 47°C and 101.3 kPa. The flow rates of the mass flow controllers were considered to be given at normal conditions (0°C and 101.3 kPa). The resulting filter face velocities were 86 cm/s for the 47 mm filters at 50 lpm. If the pressure at the filter holder was assumed to be 4-5 kPa lower, then the velocities would have been higher by ~3 cm/s.

Particle Number (PN) sampling

Aerosol samples for particle number measurement were drawn from the primary dilution tunnel. A cyclone pre-classifier (URG-2000-30EP) with a 50% cut-size at 2.5 μm (for a flow rate of 90 lpm) was used. The following sampling systems were connected to the primary dilution tunnel:

- SMPS
- Ejector dilutors (Dekati) with thermodenuder (Dekati) or evaporation chamber (Dekati)
- Old Nanomet (Matter Eng.)
- Nanomet (Matter Eng.)
- SPCS (Horiba)

A short description follows:

Scanning Mobility Particle Sizer (SMPS): A TSI 3936 SMPS (DMA 3080L and CPC 3010) was used to measure the particle number size distributions from the full dilution tunnel or downstream of other particle number systems (SPCS, ejectors) during Phase A. The sample/sheath flowrates used were 0.9/9 lpm. For Phase B a nano-SMPS was used (DMA 3085N and CPC 3025A) with flowrates 15/1.5.

EJ(150)+ET(330)+EJ: A Dekati ejector diluter (EJ) with dry, filtered dilution air at 150°C was used as primary diluter. The evaporation chamber (ET) was set to 330°C. The volume was 67 cm^3 (L [cm] x D [cm] = 7 x 3.5) and for a flow rate of 2.6 lpm (the flow rate of modified ejector dilutor downstream of the evaporation chamber) the residence time was 0.8 s. An ejector diluter at ambient temperature was used as secondary diluter. The dilution ratio of the ejector dilutors was determined by measuring sample and total flow rates at ambient temperature with a 4040 TSI flow meter (Giechaskiel et al. 2004) (EJ#1 10.2, EJ#2 11.4) and applying the correction factors These were 1.05 for the primary for the hot dilution air and the under-pressure at CVS, 1.3 for the secondary for the hot sample. When the system was used cold a 1.14 factor was used for the under-pressure at CVS (Giechaskiel et al. 2008c). The filtration system of the manufacturer was not adequate and a HEPA filter was added to the ejector dilution air line to decrease the background levels to <0.2 #/cm^3. A modified 3010 (with ΔT evaporator-condenser at 9°C, see Liu et al. 2005) was used to measure particles >23 nm (named 3010D') during Phase A and a 3790 was used during Phase B (named 3790n because at phase A was at Nanomet).

Thermodenuder (TD): A thermodenuder (TD) from Dekati Ltd. was used. The temperature of the heater was set to 300°C (residence time 0.3 s for 10 lpm flow rate). The carbon section had an annular design, i.e. the carbon was placed at both sides of the sample flow. The inner cylinder was cooled by forced convection (air in these experiments) and the outer by natural convection. The residence time in this section was 2.7 s (for a flow rate of 10 lpm). The particle losses *L* are given by the equations (Ntziachristos et al. 2004) (for 250°C):

$$L = -9.7 \ln D_p - 0.5Q + 68 \quad \text{for } 30 < D_p < 70 \text{ nm} \quad \text{Eq. 1a}$$

$$L = -0.5Q + 28.7 \quad \text{for } 70 < D_p < 500 \text{ nm} \quad \text{Eq. 1b}$$

Where D_p is the particle size [nm] and Q is the flow rate through the thermodenuder [lpm]. These equations were used to estimate the losses when the particle size distribution was known. A correction factor of 1.28 was used for the calculation of the results (losses 22%) when the size distribution was unknown (Ntziachristos et al. 2004). It was also shown that using a constant factor for size distributions without nucleation mode has <1% error in comparison with the size dependant correction (Ntaziachristos et al. 2005). However, when there is nucleation mode the losses should be taken into account. A Dekati Mass Monitor (DMM) was used during phase B. Its results have been presented in Giechaskiel et al. (2008c).

EJ(150)+TD(300)+3790: A Dekati ejector diluter (EJ) with dry, filtered dilution air at 150°C were used as primary diluter. A thermodenuder (300°C) was used as volatile removal. A 3790 model (borrowed form TSI) was used.

Nanomet: A recently bought rotating disk based system from Matter Eng. was used. This system consisted of a primary rotating disk diluter heated at 150°C, a 1 m line, an evaporation tube at 300°C and a secondary simple mixer diluter. Both diluters had adjustable dilution ratios. Total dilution ratio of 200 was used (40 x 5) was used in these experiments (Potentiometer setting of primary diluter at 50%). The primary dilution factor was based on the particle reduction factor of 80 nm CAST particles (manufacturer's calibration). As the peak of the accumulation mode was close to 80 nm, the primary dilution factor of the manufacturer included partly the losses in the system. The secondary diluter was a simple mixer. Thermophoretic losses in the system were not taken into account. The system was available only for a limited number of tests in Phase A due to some functional problems (Giechaskiel et al. 2008c). Between Phase A and B was sent to the manufacturer and repaired and then was available for the whole Phase B.

Old Nanomet: For a limited number of tests (for Phase A) the old golden system at the light-duty inter-laboratory exercise was also used (previous version of Nanomet). The setting at the potentiometer was 20% (primary dilution ratio 55 with the temperature correction), the dilution temperature was 150°C, 1 m line was used and the evaporation tube temperature was 300°C. The secondary dilution ratio was 5.2 (because no particle counter was used upstream of the evaporation tube). This system was calibrated last time in Feb 2007. Since then it was used in CARB. It arrived back to JRC in Nov 2007. The following problems were found and repaired:

- The axis that connects the rotating disk with the dilution head was broken.
- There was a leakage between the dilution head and the controller unit (the o-rings were missing).

Flow measurements after the repair showed that the unit should be operating properly. After the end of the measurement campaign the unit was calibrated in JRC and the results showed that the unit was operating similarly as in the light duty inter-laboratory exercise (Giechaskiel et al. 2008c). The manufacturer's dilution value of 272 was used.

SPCS: Two prototype Solid Particle Counting Systems (SPCSs) from Horiba were used. They consisted of a primary hot diluter (PND1) at 150 to 200 °C, an evaporation tube (300 to 400 °C) and a secondary diluter (PND2) at ambient temperature (Wei et al. 2006). The PND1 could be adjusted between 2 to 100 or between 8 and 1000 depending on the orifice being used. PND2 dilution ratio could be adjusted between 10 and 50. A TSI 3010D was included in the instruments.

For tests at JRC, the temperatures at the units were set at:

- Cabinet temperature (before primary dilution): 47°C
- Hot dilution air temperature for PND1: 170°C
- Mixer Temperature for PND1: 170°C (It is set as same as hot dilution air temperature)

- Evaporation tube: 350°C

The manufacturer's dilution ratios were derived from flow rate measurements. The user defined (in the prototype units used) the primary (PND1) dilution ratio, the secondary (PND2) dilution ratio, the primary (PND1) and secondary (PND2) dilution air flow rates and the bypass flow rate. All of those flows refer at 70 °F (21.1 °C) and 760 mmHg (1 atm) ambient air pressure.

Typical values that were used at JRC are (unless otherwise specified):

- PND1: Primary hot dilution ratio: 10, Primary dilution air: 11.5 (lpm)
- PND2: Secondary cold dilution ratio: 15, Secondary dilution air: 10.5 (lpm).
- Bypass: 2 (lpm)

The results of SPCS shown in this report were always corrected for the dilution ratios measured form the unit (not the particle reduction factor found in Giechaskiel et al. 2008c). No correction for particle losses was applied at this report. According to the manufacturer solid particle losses should be less than 15% for monodisperse aerosol (Wei et al. 2006a, b) and 5% for polydisperse aerosol (Wei et al. 2008). More information about the instrument can be found in Giechaskiel et al 2008c.

Coincidence correction: The results reported here are corrected for coincidence for the 3010 and 3010D counters according to the equation given in their manuals (TSI).

$$N_a = N_i \exp(N_a Q \tau) \qquad \text{Eq. 2}$$

Where

N_a the actual concentration (#/cm^3)

N_i the indicated concentration (#/cm^3)

Q units transformation16.67 cm^3/s

τ effective time each particle resides in the viewing volume

The N_a in the exponent can be approximated by N_i. Three iterations were used for the final result. For the 3010 a reading of 10^4 #/cm^3 needs a 7.4% correction (τ=0.4). For 3010D the correction is +10.6% (τ=0.55). The 3790 uses a continuous, live-time coincidence correction and doesn't need any external correction.

Correction for the slope coefficient was applied only when mentioned in the text. The slope differences were independently investigated (see Giechaskiel et al. 2008c and Giechaskiel et al. 2008d).

Note: The term *non-volatile* and *solid* particles are used interchangeably and indicate particles that survive downstream of a hot dilution (150°C) plus an evaporation tube (300°C) or a thermodenuder (300°C).

PARTIAL FLOW SYSTEMS

Two partial flow sampling systems were used: The AVL Smart Sample SPC-472 and the Control Sistem PSS-20 (Figure 3). Sampling and measurements with the partial flow sampling systems were undertaken according to ISO 16183 and the inter-lab guide (Andersson and Clarke 2008). Exhaust gas mass flow was determined by fuel consumption (gravimetrically) and

air consumption (hot-wire anemometer). The resulting data were used for controlling the sample flow from the raw exhaust in the partial flow systems.

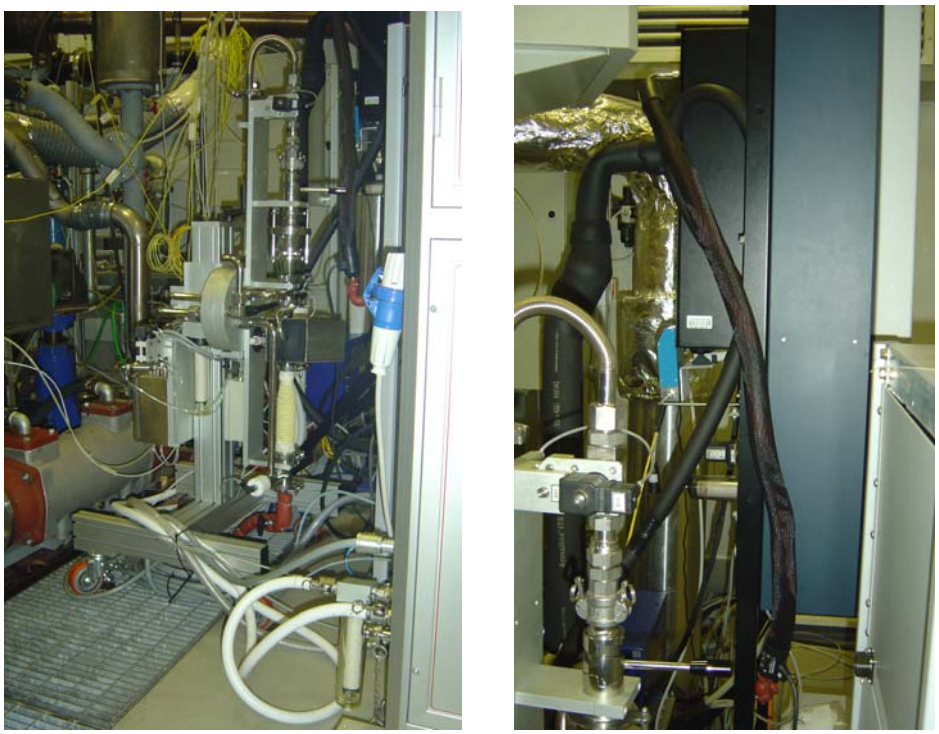

Figure 3: Partial flow systems (Control Sistem PSS-20 and AVL Smart Sampler SPC-472).

AVL Smart Sampler SPC-472

The AVL Smart Sampler (SPC-472), a partial flow system, simulated the operation of the full dilution tunnel by sampling a constant ratio of the exhaust flow (split ratio). This was achieved by changing the dilution air flow rate while the total flow rate remained constant. The SPC-472 was recently upgraded (cyclone installed, 47mm filter holders and controlled temperature of the filters at 47±5°C by external heating) to meet the requirements of the PMP protocol (Andersson and Clarke 2008). However extra work was necessary which included:

- Insulation of the cyclone and the tubes as the temperature couldn't reach 47°C.
- Modification of the system downstream of the cyclone to connect the particle number system.
- Addition of a tube downstream of the filter to feed back a flow equal to the one sampled from the particle number system. A mass flow controller connected at pressurized filtered air was used to feedback the flow rate that the number system was extracting.
- Addition of HEPA and Carbon filters at the dilution air line.

The sampling point of the SPC-472 system was positioned 5 m from the after-treatment device. The sampling probe was sharp-edged and open ended, facing directly into the direction of flow and was provided by the manufacturer. The dilution took part <20 cm from the exhaust tube with filtered air. The mixing tunnel was 63.5 cm long with 3 cm diameter (heated so the temperature never drops <35°C). The residence time of the diluted sample for the flow rate selected (1.08 g/s) assuming 47°C was ~0.45 s. There was also another insulated tube 100 cm (~3.5 cm inner diameter) (residence time 1 s). Downstream of the dilution tunnel a URG-2000-

30EP cyclone was installed with a 50% cut-size at 4 μm (for a flow rate of 50 lpm, see Appendix C). The extra tube, which was added when the cyclone was installed, was around 75 cm (12 mm inner diameter). The filter holder and transfer tubing from the cyclone till the filter were heated to ensure close control of the filter face temperature to 47°C (±5°C). The temperature was measured 5 cm upstream of the filter. However, the aerosol stabilization time in this tube was 0.1 s. PM samples were collected on 47 mm Teflon-coated glass-fiber Pallflex® TX40H120-WW filters. The estimated filter face velocity for the specific flow rate (G_{tot} 1.08 g/s) 50 lpm or and 47°C was 86 cm/s. The split ratio r was set to 0.0626%.

Control Sistem PSS-20

PSS-20, a partial flow sampling system which doesn't require compressed air or cooled water, sampled a small quantity of exhaust gas and diluted it with filtered ambient air. The diluted gas passed through a cyclone and a 47 mm (or 70 mm) filter for the identification of PM emissions (partial flow-total sampling dilution system). The system kept the temperature of the filter at 47±5°C by heating the dilution air.

The length of the tube from the exhaust gas tube to the mixing chamber was 75 cm insulated with internal diameter 4 mm. The mixing chamber, which was heated, was 25 cm long with inner diameter 4.5 cm (residence time 0.5 s). For this system the only extra work conducted was to insulate the cyclone. The extracted flow from the system was taken into account with the system's software by adjusting the total flow. Total flow G_{tot} was set to 3000 nl/h, parallel flow (extracted from SPCS) was set to 185 nl/h and G_{edf} (CVS simulated flowrate) was set to 6200 kg/h.

PN measurement from partial flow systems

The systems that were used for PN measurement from the partial flow systems were:

- SPCS-20
- Old Nanomet
- Nanomet

The description of these systems was given previously. The only difference is that the sampling line from the partial flow to the SPCS or Nanomets was 1.5 m for the SPC-472 and 20 cm for the PSS-20 (insulated lines) (internal diameter 4 mm).

GASEOUS POLLUTANTS

The Heavy-Duty test cell was equipped with two AVL CEB II (raw and diluted bench) measuring system, which operation could be achieved via a host computer for combustion analysis carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO and NO_x), hydrocarbons (THC). Exhaust gases were sampled by two separated lines, the diluted gas via CVS and the raw gas directly from exhaust line to the CEB II analyzers. The gas analyzers were calibrated between Phase A and B. However during Phase B probably there was a leakage on one of the pneumatic valves, so NO_x and THC values were lower.

TEST PROTOCOL

The details of the protocol are described in Andersson & Clarke (2008). In the following, the basic sequence of the tests and the differences from the protocol will be described.

Test matrix of official tests

Table 6 gives the general overview of the measurements conducted for the official JRC measurements.

Lubricant change

As mentioned earlier, the lubricant was added to the engine following the procedure described in the inter-laboratory guide (Andersson and Clarke 2008). The lubricant conditioning (LC) during Phase A consisted of 3 cycles of 10 min at mode 10 (ESC) and 10 min at low load (800 rpm / 200 Nm) the first day and 4 cycles of 15 min at mode 10 (ESC) and 5 min at idle the next day. During Phase B the LC consisted of 45 min at mode 10 (ESC), 5 min at idle and 15 min at mode 10 (ESC) twice (morning and afternoon).

Cycles

A cold World Harmonized Transient (WHTC) was followed by a hot WHTC with 5, 10 or 20 min soak. The World Harmonized Steady Cycle (WHSC) followed and then the European Transient Cycle (ETC) and the European Steady Cycle (ESC). Before WHSC 10 min at mode 9 (of WHSC) proceeded. Before ETC and ESC the Continuity protocol was applied (5 min at mode 7 (of the ESC cycle) and 3 min at idle. At the end of the day the after-treatment devices were conditioned. See Table 7 for details.

Table 6: Test matrix of official PMP validation tests

Day	Tests	SPC-472	PSS-20	CVS	Comments
PHASE A					
Golden engine					
1	Cold WHTC, ETC	SPCS-20		SPCS-19, Nanomet, EJ+ET+EJ, TD	
2	ETC			SPCS-19, Nanomet, EJ+ET+EJ, TD	
3	Lubricant conditioning (LC)		SPCS-20	SPCS-19, Nanomet, EJ+ET+EJ, TD	Lubricant change
4	Lubricant conditioning (LC)				No recordings
5	3xETC		SPCS-20	SPCS-19, Nanomet, EJ+ET+EJ, TD	
6	Protocol	SPCS-20	Nanomet	SPCS-19, EJ+ET+EJ, EJ+TD	SPC-472 with constant DR
7	Protocol		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 1, soak 5 min
8	Cold WHTC, prec		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Soak 5 min, Power failure
9	Protocol		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 2, soak 5 min

10	Protocol		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 3, soak 10 min
11	Protocol	Nanomet	SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 4, soak 10 min
12	Protocol	Nanomet	SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 5, soak 10 min
13	Cold WHTC, hot WHSC, prec		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Soak 20 min, problems with eng. communication
14	Protocol		SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 6, soak 10 min
15	Protocol	Nanomet	SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 7, soak 10 min, extra prec
16	Protocol	Nanomet	SPCS-20	SPCS-19, EJ+ET+EJ, EJ+TD	Day 7, soak 10 min, no prec
Golden engine with after-treatment device #2					
17	Cold WHTC, hot WHTC, WHSC, ETC, prec	Nanomet	SPCS-20 (40x25)	SPCS-19, EJ+ET+EJ, EJ+ET+EJ+TD	Tests with empty device
18	Protocol		SPCS-20 (25x25)	SPCS-19, EJ+ET+EJ, EJ+ET+EJ+TD	Day 1
19	Protocol		SPCS-20 (10x25)	SPCS-19, EJ+ET+EJ, EJ+ET+EJ+TD	Day 2
20	Protocol		SPCS-20 (40x25, bypass 3)	SPCS-19, EJ+ET+EJ, EJ+ET+EJ+TD	Day 3, slightly different prec
21	Protocol	Old Nanomet	SPCS-20 (10x50)	SPCS-19, EJ+ET+EJ,	Day 4
22	Protocol		SPCS-20 (10x25)	SPCS-19, EJ+ET+EJ+TD	Day 5, slightly different prec
23	Protocol		SPCS-20 (10x25)	SPCS-19, EJ+ET+EJ+TD	Day 6
24	Protocol		SPCS-20 (40x15)	SPCS-19, EJ+ET+EJ	Day 7
25	Protocol (no prec)	SPCS-20 (10x25)	Old Nanomet	SPCS-19, EJ+ET+EJ	Extra test
Golden engine w/o any after-treatment					
26	WHTC cold, WHTC hot	Old Nanomet	SPCS-20 (25x25)	SPCS-19 EJ+ET+EJ+TD	

PHASE B					
Golden engine					
1	Lubricant conditioning (LC)				
2	3xETC, prec	SPCS-20		SPCS-19, Nanomet+3010D', EJ+ET+EJ+3790n, TD+DMM	
3-9	Protocol	SPCS-20		SPCS-19, Nanomet+3010D', EJ+ET+EJ+3790n, TD+DMM	3025A at various positions. Comparison of systems
10	Protocol	SPCS-20		SPCS-19,TD+DMM Nanomet+3010D', EJ+ET+EJ+3790n,	
11	Protocol	SPCS-20		SPCS-19,TD+DMM Nanomet+3010D', EJ+ET+EJ+3790n,	Day 1
12	Protocol	SPCS-20		SPCS-19,TD+DMM Nanomet+3010, EJ+ET+EJ+3790n,	Day 2
13	Protocol	SPCS-20		SPCS-19,DMM Nanomet+3010, EJ+ET+EJ+3790n,	Cold EJ, Nanomet Day 3
14	Protocol	SPCS-20		SPCS-19,DMM Nanomet+3010, EJ+ET+EJ+3790n,	No EJ da heating Day 4
15	WHTC cold, hot (no prec)	SPCS-20		SPCS-19,DMM Nanomet+3010, EJ+ET+EJ+3790n,	3025A at CVS Day 5
Golden engine with after-treatment device #2					
16	Protocol (no prec)	SPCS-20 (10x15)		SPCS-19,(+3025A) Nanomet+3010, EJ+ET+EJ+3790n, TD+DMM	
Golden engine w/o any after-treatment					
17	Protocol, WHTC hot (no prec)	SPCS-20 (10x15)		SPCS-19,(+3025A), Nanomet+3010, EJ+ET+EJ+3790n, TD+DMM	

During the prec tests of SMPS was measuring size distributions.

Table 7: Daily protocol

Test lab		
Day 0	Day 1-7	Day 8
	IFV	IFV
oil change (only VE)	cold WHTC	cold WHTC
LC	10 min soak	10 min soak
	hot WHTC	hot WHTC
	10 min mode #9 (WHSC)	10 min mode #9 (WHSC)
	WHSC	WHSC
	CP	CP
	ETC	ETC
	CP	CP
3xETC	ESC	ESC
	PC	PC
Prec	Prec	no Prec

LC	Lubricant conditioning
IFV	Instrument Functional Verification
WHTC	World Harmonised Transient Cycle
WHSC	World Harmonised Steady Cycle
ETC	European Transient Cycle
ESC	European Steady Cycle
CP	Continuity Protocol (5 min mode #7 (ESC) and 3 min idle)
PC	Full load curve
Prec	15 min at mode #10 and 30 min at mode #7 (ESC)

Phase A and B cycles

Two series of measurements (Phase A and B) were conducted. The targets of Phase A was: i) to compare the after-treatment devices ii) investigate the differences between full flow and partial flow systems and iii) compare different particle number systems. Phase B was the execution of the official PMP tests.

During Phase A due to a wrong setting at the automated software of the facilities (due to the recent upgrade), the cycles were not performed in full agreement with the legislation. The main differences are (Figure 4-Figure 8):

- *WHTC hot and cold.* The speed range used during Phase A was narrower than the one used at Phase B. The idle speed at Phase A was set to 900 rpm instead of 700. Also the speed corresponding to 100% was set lower during Phase A. The torque traces were similar.
- *WHSC:* During Phase A slightly higher engine speeds were used.
- *ETC:* Torque was similar, but speed range during Phase A was different. Speed corresponding to 100% was much higher during Phase A.
- *ESC:* Speeds were similar except. Higher torque measured at Phase A in mode 2 (full load).
- For Phase B the idle speed was set to 700 rpm and not 600 rpm as is the engine idle by ECU software.

Although the Phase A tests cannot be considered valid for the PMP official tests, they provided valuable data for the comparison of the after-treatment devices and the particle number systems. The results of the two phases will be examined separately.

Pre-conditioning at the end of the day

In order to minimize any desorption/release phenomena and to have similar "load" conditions for the after-treatment device a standard preconditioning was performed on the days before a cold start WHTC test. It consisted of 30 min at mode 7 of the ESC, preceded by 15 min at mode 10 of the ESC (Giechaskiel et al. 2008c). Mode 10 regenerated the filter. In addition, it raised the temperature of the engine's exhaust system, transfer tube to the dilution tunnel and dilution tunnel to a level above that experienced during the daily test. This purged the exhaust and transfer system of materials that may have contaminated the test result, especially at such low levels of PM emissions, and ensured that any small contribution from mode 7 conditioning would be replicated exactly from test-to-test, thus reducing variability. After the pre-conditioning was complete, the dilution tunnel was left running for 5 min (with the engine still attached) to enable materials released from the exhaust and sampling system during cooling to be drawn away. After the preconditioning, the engine was left to cool for at least 16 hours (soaking) before the beginning of another measurement (maximum one cold test per day). No preconditioning was conducted during the last day of the measurements.

Weighing procedure

The filters were conditioned in an open dish (protected form dust) for 16-80 h before the test in an air-conditioned room. The temperature and humidity of the room were 23±2°C and 51±4% respectively (within the specification 22±3°C and 45±5%) (Andersson and Clarke 2008). Filters were weighed with a Mettler Toledo model UMX2 balance with 10^{-7} g precision. Electrostatic charge effects were minimized by the use of HAUG Type EN SL LC 017782100 neutralizer and grounded conductive surfaces. Each filter was weighed at least three times, and the average of the weighings was used in calculating mass changes.

In parallel two unused (blank) reference filters of the same size and material (47mm TX40) were weighed in order to check the stability of the conditions in the weighing room. The average weight of the reference filters between sample filter weighings was always within ±5 μg.

The filters for the WHTCs were weighed the evening before the test (i.e. ~16 h before the tests) and they remained in the weighing room. The filters for the rest cycles were weighed the same day that the tests were conducted. The weighed filters were used for test within 1 h of their removal of the weighing room. After the tests, the filters were left in the room for 4-80 h for conditioning before being weighed with the same balance, following the same procedure. Some preliminary tests showed that weighing the filters within 2 h after the end of the test resulted in unstable weight.

It should be mentioned that a simple batch of filters was used and that all labs that participate in the validation exercise will use filters from this batch. It has to be mentioned that the weight of the filters of the first box was ~90 mg and the weight of the filters of the second box was ~100 mg. However, there were many filters in the second box which weighed less (~60 mg) and they were more transparent when looking at them at a light. These filters were not used for the tests but they consisted a considerable amount of the filters (20%). If the boxes sent to other labs also contain such filters, it will be necessary to send more filters. In addition, the advantage of using filters of the same batch (if any) is questionable.

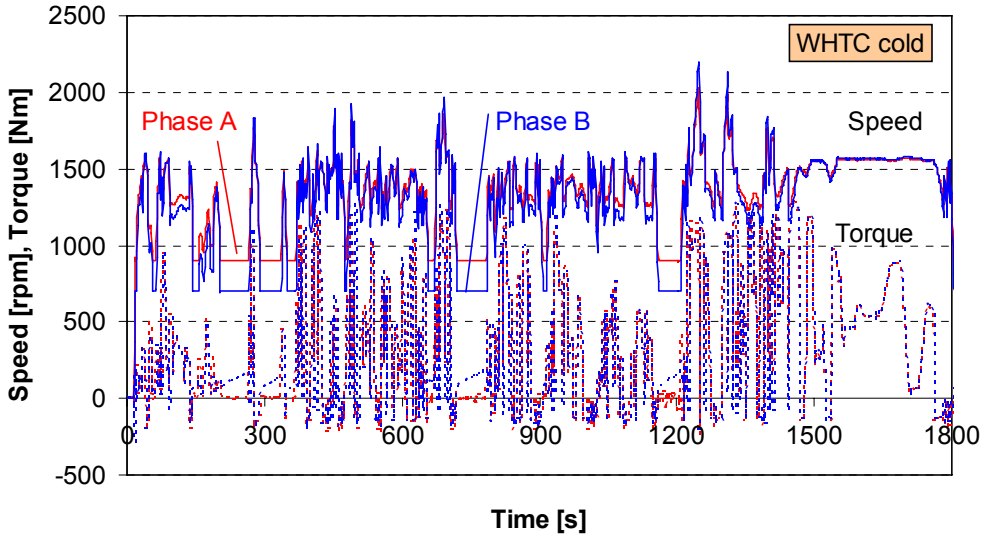

Figure 4: Cold WHTC speed and torque.

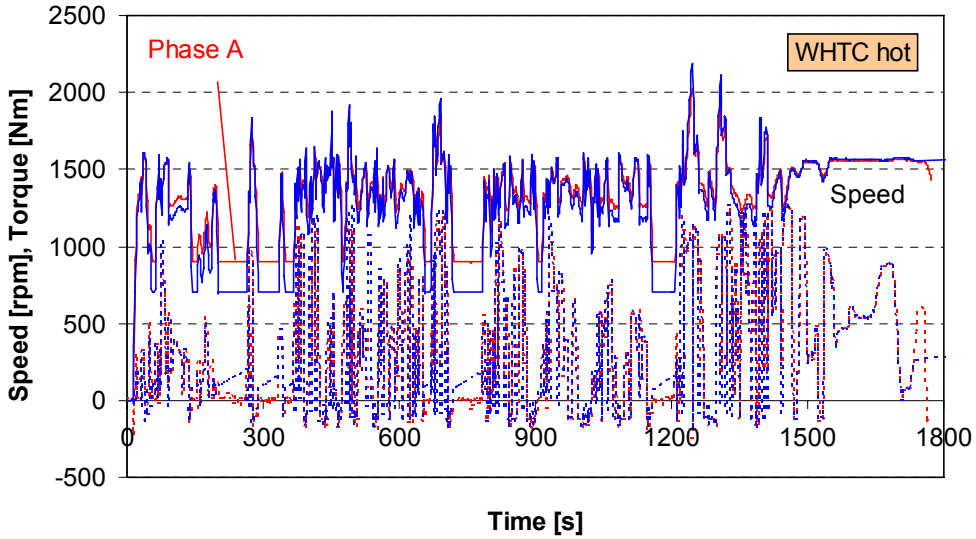

Figure 5: Hot WHTC (10 min) speed and torque.

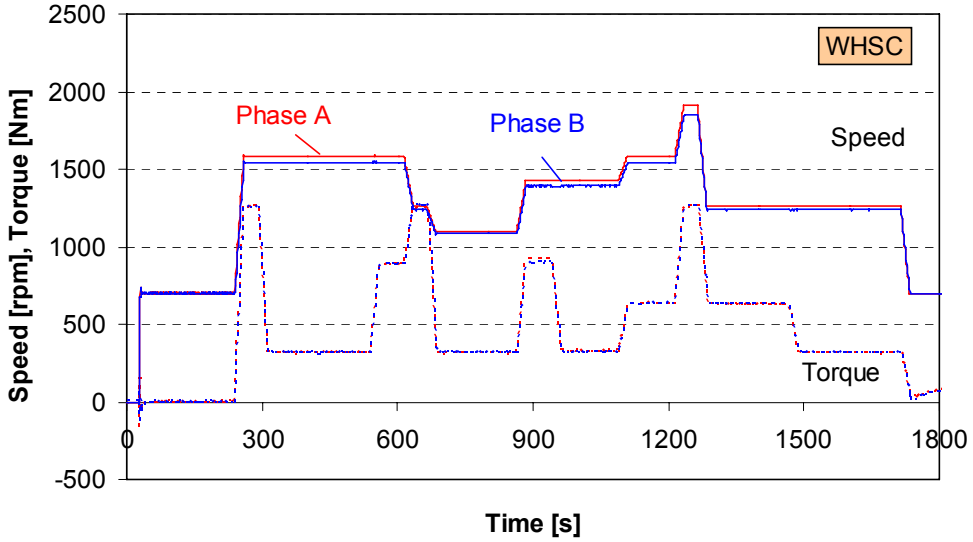

Figure 6: WHSC speed and torque.

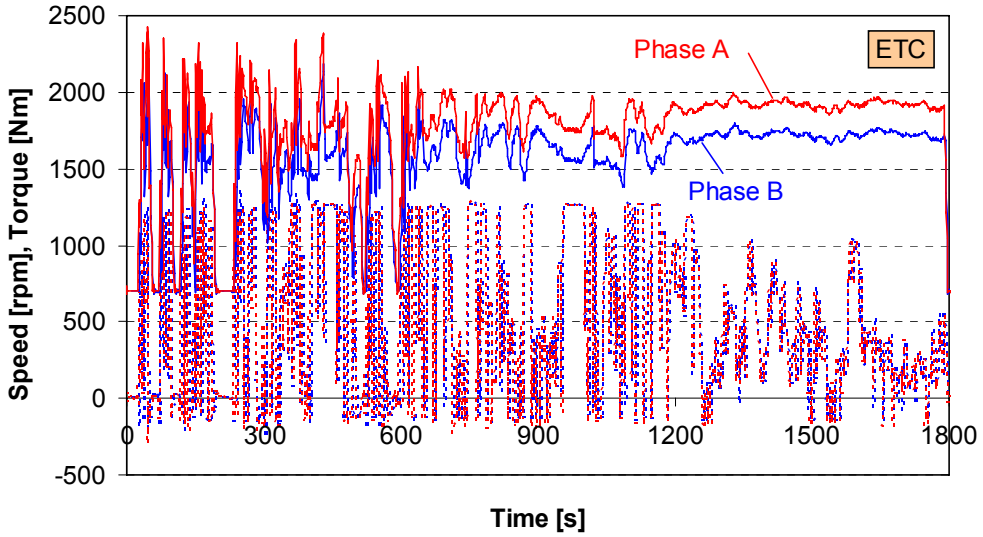

Figure 7: ETC speed and torque.

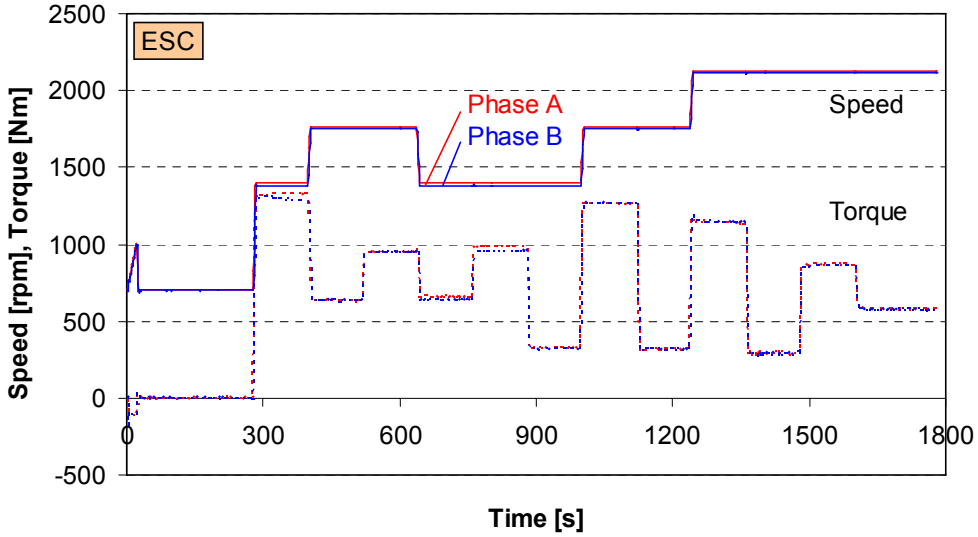

Figure 8: ESC speed and torque.

CALCULATIONS

Full dilution tunnel

The following equations were used for the calculation of the mass (PM) results for WHTC, WHSC and ETC tests from the double dilution tunnel (Reg. 49):

$$PM = \frac{M_f}{M_{TOT} - M_{SEC}} \frac{G_{EDFW}}{W_{act}} \frac{t}{1000} \qquad \text{Eq. 3}$$

Where:

M_f	[µg]	Particulate mass on the filter sampled over the cycle
G_{EDFW}	[kg/h]	Flow rate of diluted exhaust gas
t	[h]	Duration of the cycle
M_{TOT}	[kg]	mass of double diluted exhaust gas through particulate filter
M_{SEC}	[kg]	mass of secondary dilution air
W_{act}	[kWh]	actual cycle work

No background correction was applied. For the ESC case, where sampling is conducted only for a few s for each mode *i*, the following formulas were used:

$$G_{EDFW} = \sum_{i=1}^{n} G_{EDFW,i} WF_i \qquad \text{Eq. 4}$$

$$M_{TOT} = \sum_{i=1}^{n} M_{TOT,i} \qquad \text{Eq. 5}$$

$$M_{SEC} = \sum_{i=1}^{n} M_{SEC,i} \qquad \text{Eq. 6}$$

$$W_{act} = \frac{\sum_{i=1}^{n} P_i WF_i}{t} \qquad \text{Eq. 7}$$

Where:

P_i	[W]	Power at mode *i*
WF_i	[-]	weighting factor of mode *i*

Note that *t* is not necessary for the calculation of the ESC PM emissions. It was used only for the estimation of the W_{act} at the database (*t* for ESC was 1000 s). The filter was sampling the following times:

Table 8: Sampling times for ESC.

Mode i	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Start	120	310	420	540	700	820	940	1020	1140	1270	1420	1540	1630
End	269	389	519	639	749	869	989	1109	1239	1349	1469	1589	1679
Duration	150	80	100	100	50	50	50	90	100	80	50	50	50

For number emissions from the full dilution tunnel the following equations were used:

$$PN = N \frac{G_{EDFW}}{W_{act}} t \qquad \text{Eq. 8}$$

Where:

$$N = PRF \frac{PNC}{\rho} 10^6 \qquad \text{Eq. 9}$$

PNC	[#/cm^3]	Average concentration over the cycle given by the PNC
PRF	[-]	Particle Concentration Reduction Factor or Dilution Factor (DF)
ρ	[kg/m^3]	Density of gas at the nozzle pressure and temperature of the PNC

As there were no data available for the conditions at the nozzle of the counters, the conditions at the inlet of the counters were used. As most counters were from TSI, which calibrates them such as the inlet flow is 1 lpm at TSI standard conditions (21.3°C and 101.4 kPa) this density was used for the calculations (=1.2). Note that the mass flow rate (due to the critical orifice) depends only on the inlet pressure and not on the temperature (the temperature at the critical orifice is constant around 41°C). The effect of the inlet pressure should be negligible as it was close to atmospheric conditions for all counters. Note also that the effect of the different than 1 flow rate is taken into account in the slope of the counters.

Table 9: Summary of corrections for PN systems

PN system	*PRF* or *DF*	*Coincidence*
EJ(150)+ET(330)+EJ+3010D’	159 (DF see Giechaskiel et al. 2008c)	yes
EJ(150)+TD(300)+3790	13.7 (TD correction included)	no
Old Nanomet (3790)	272 (PRF form manufacturer)	no
Nanomet (3790n)	200 (DF based on units software values)	no
SPCS	150 (DF from manufacturer)	yes

Note that for ESC number emissions the mass procedure was followed (average of number emissions during specific times of the ESC cycle). The gas procedure could be also

followed (average of the last seconds of each mode and correction with the weight factor). Both approaches in theory should give identical results. Comparison of the ESC results with the two approaches gave a ±10% difference (higher only in a few cases were the ESC emissions were very low). The first approach was followed and reported here as then the comparison of the PN and PM results (e.g. variability) are more comparable.

Partial flow systems

For mass emissions with the PSS-20 the following equations were used for WHTC, WHSC and ETC:

$$PM = \frac{M_f}{M_{diff}} \frac{M_{exh}}{W_{act}} \frac{1}{1000} \quad \text{Eq. 10}$$

Where:

M_{exh} [kg] mass of exhaust flow of the engine

M_{diff} [kg] mass of the exhaust flow sampled at the partial flow system

Eq. 10 is equivalent to:

$$PM = \frac{M_f}{M_{TOT}} \frac{G_{EDFW}}{W_{act}} \frac{t}{1000} \quad \text{Eq. 11}$$

Where (see Eq. 7)

$$G_{EDFW} = \frac{M_{TOT}}{M_{DIFF}} M_{EXH} \quad \text{Eq. 12}$$

Equivalently:

$$PN = N \frac{G_{EDFW}}{W_{act}} \frac{t}{1000} \quad \text{Eq. 13}$$

For the ESC cycle (Reg. 49):

$$PM = \frac{M_f}{M_{TOT}} \frac{G_{EDFW}}{W_{act}} \frac{t}{1000} \quad \text{Eq. 14}$$

$$G_{EDFW} = \sum_{i=1}^{n} G_{EDFW,i} WF_i \quad \text{Eq. 15}$$

$$M_{TOT} = \sum_{i=1}^{n} M_{TOT,i} \qquad \text{Eq. 16}$$

$$W_{act} = \frac{\sum_{i=1}^{n} P_i WF_i}{t} \qquad \text{Eq. 17}$$

Again, *t* is not necessary for the calculations.

The same equations were also used for SPC-472. The only difference is that at SPC-472 the extracted flow was not taken into account in the unit's software and a (filtered) flow was fed back. The correction for this fed back was taken into account by the correction factor:

$$M_{TOT} = \sum_{i=1}^{n} \left(M_{TOT,i} - M_{FB,i} \right) \qquad \text{Eq. 18}$$

Where

$M_{FB,i}$ [kg] Mass of the filtered air that was fed back

In the following sections the results of the validation tests are presented. In most figures only one test is reported to improve the readability of the figures, as all other tests showed similar results. Emissions that are reported in [kWh^{-1}] refer to tailpipe conditions and concentrations given in [#/cm^3] refer to the primary dilution tunnel, unless specified differently. When more than one measurement is reported, then the average value is given. In this case, the ratio of the standard deviation of the measurements to the average value of the measurements, the Coefficient of Variance (CoV), is sometimes referred as repeatability of the measurements. Error bars show one standard deviation.

The statistical analysis for the equivalency of systems is given in the Appendix D.

Note: The symbol "#" will be used to indicate number of particles in this report (and probably in the future number legislation).

3. RESULTS (PHASE A)

3.1 GOLDEN ENGINE (WITH CRT)

Lubricant change 3 x ETC

After the lubricant change, the engine, the after-treatment and the lubricant were conditioned (see section 2). Then 3 ETC cycles were run. The results of these cycles are presented below in comparison with the ETC of the official tests (Figure 9). The results show that the emissions immediately after the lubricant change and preconditioning were similar with the emissions during the campaign. This indicates that the lubricant conditioning was enough.

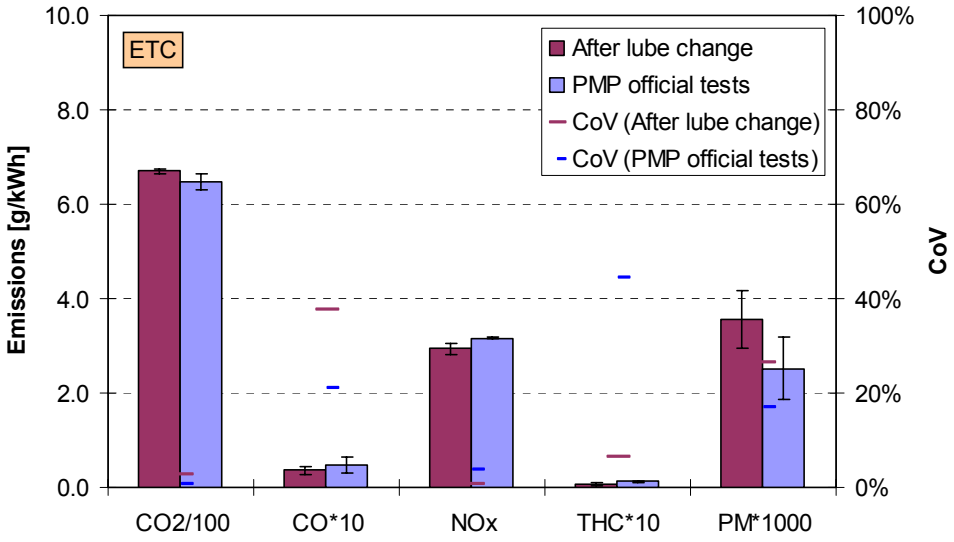

Figure 9: ETC pollutants results after the lubricant change.

Temperature profiles

The following figures (Figure 10-Figure 14) show typical temperature profiles at the exhaust line, the dilution tunnel and the filter. The main conclusions are:

- The exhaust gas temperatures are around 400°C for the transient cycles and 500°C for the steady cycles.
- The temperature at the inlet of the dilution tunnel can reach 400°C at the ESC cycle.
- The PM sampling point temperature at the full dilution tunnel is around 60°C but can reach 100°C at the ESC cycle.
- The PM filter temperature is around 50°C.

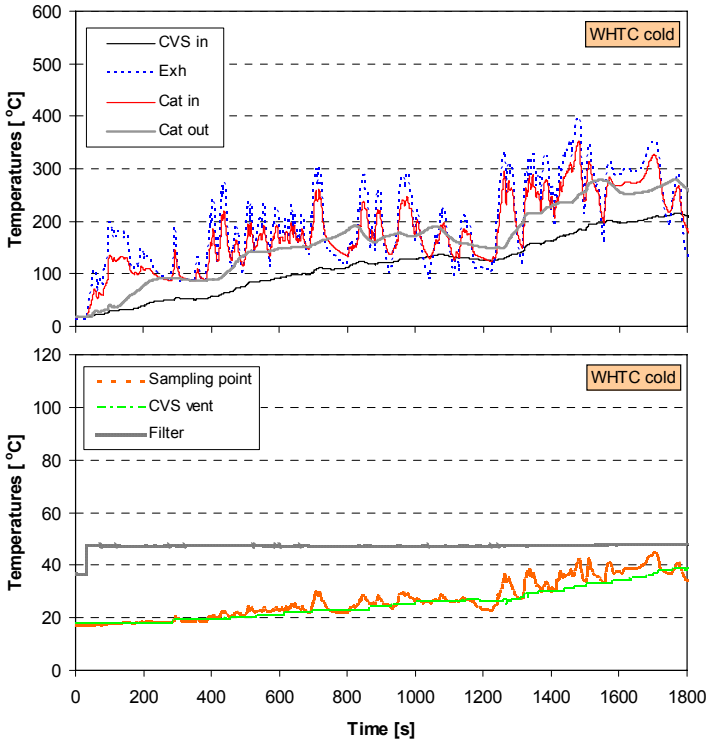

Figure 10: Temperature profiles over cold WHTC.

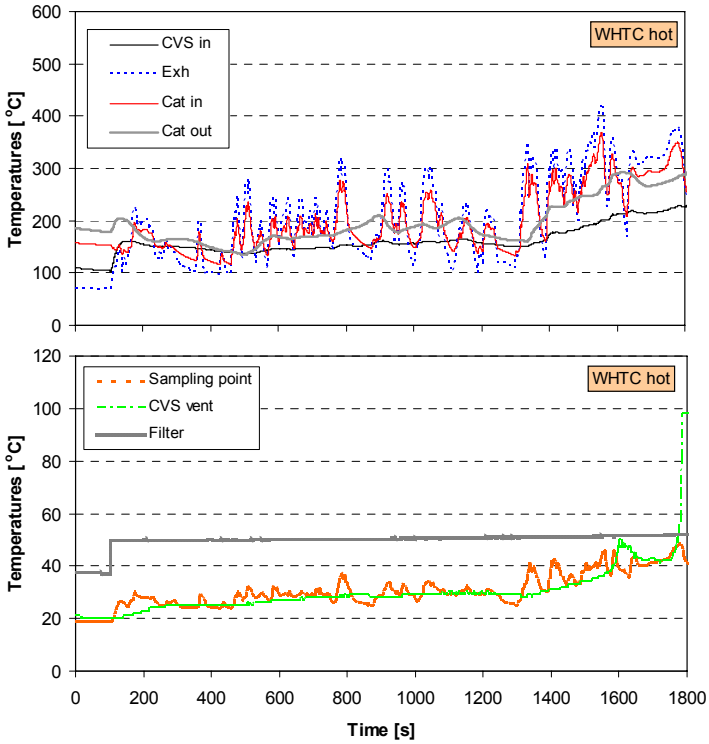

Figure 11: Temperature profiles over hot WHTC (10 min soak).

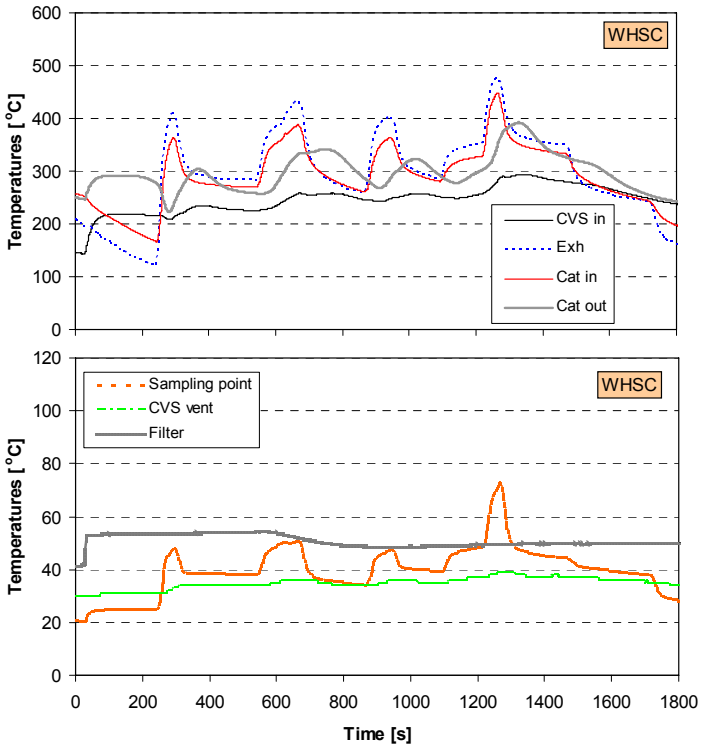

Figure 12: Temperature profiles over WHSC.

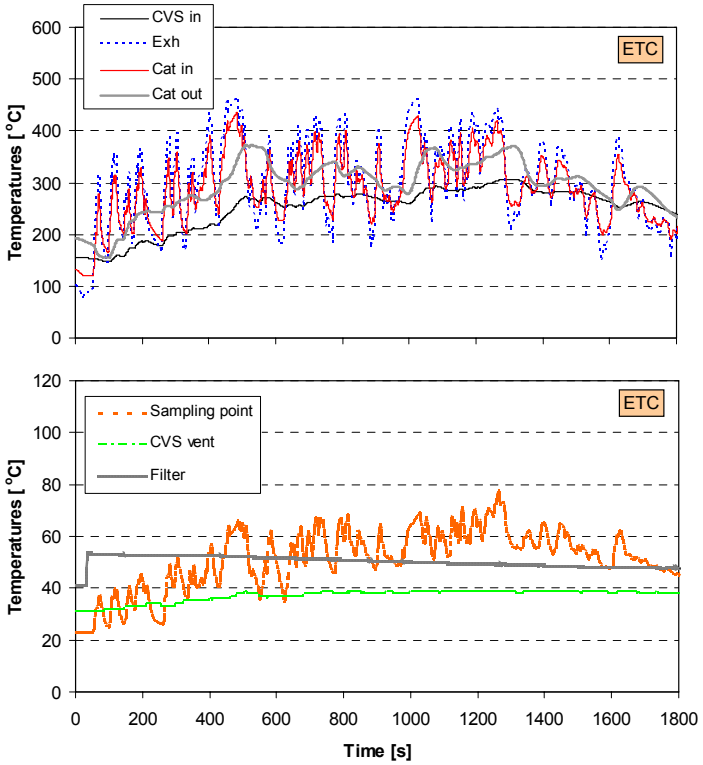

Figure 13: Temperature profiles over ETC.

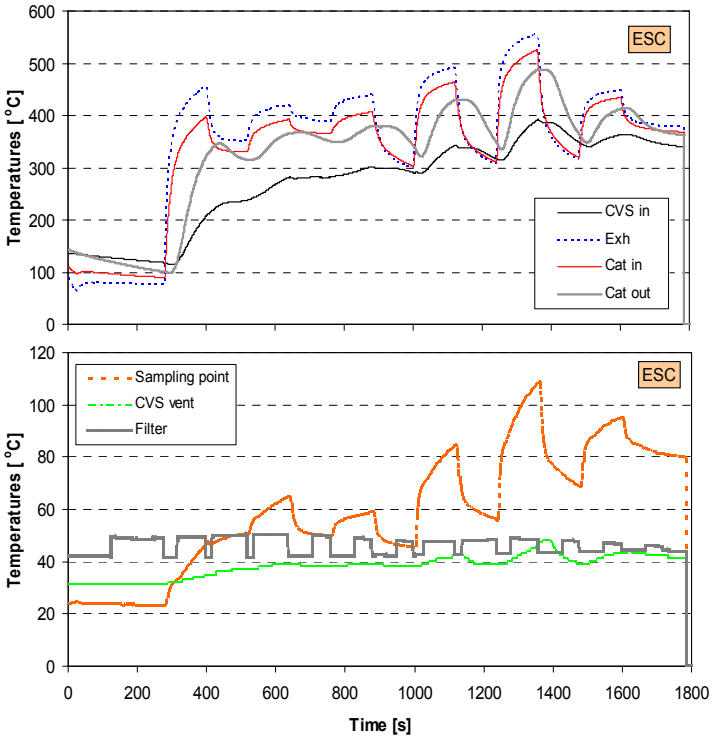

Figure 14: Temperature profiles over ESC.

Legislated pollutants

The results from the legislated pollutants are shown in the following figures (Figure 15-Figure 19). Both raw (from exhaust tailpipe) and diluted (from the full dilution tunnel) results are shown. The main conclusions are:

- The CO_2 emissions were around 700 g/kWh
- The CO emissions were <0.1 g/kWh with the exception of the cold start WHTC (0.5 g/kWh)
- The NO_x emissions decreased over time. They were high at the cold start cycle (8 g/kWh) and dropped to half at the final cycle (4 g/kWh).
- The THC were very low (<0.05 g/kWh) for all cycles except for the cold start (0.1 g/kWh).
- The PM emissions were <6 mg/kWh. The were high at the WHTC cycles and lower at the rest cycles.

WHTC cold – hot

The higher emissions at the WHTC cold cycle have to do with the higher emissions of the engine due to the cold start and the low temperatures at the after-treatment device. Figure 20 shows as an example the CO emissions of a cold and hot WHTC with and without CRT. The higher CO emissions at the cold WHTC have to do with the high engine out CO at the cold WHTC and the low temperatures of the CRT at the beginning of the cycle. After 400 s the emissions of the cold and hot WHTC tend to equalize as the CRT has been warmed up.

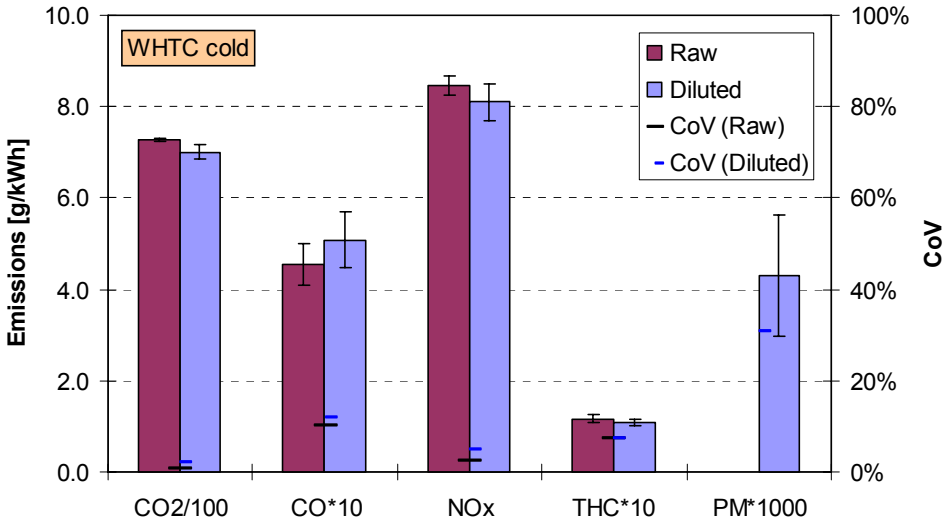

Figure 15: WHTC cold legislated pollutant results.

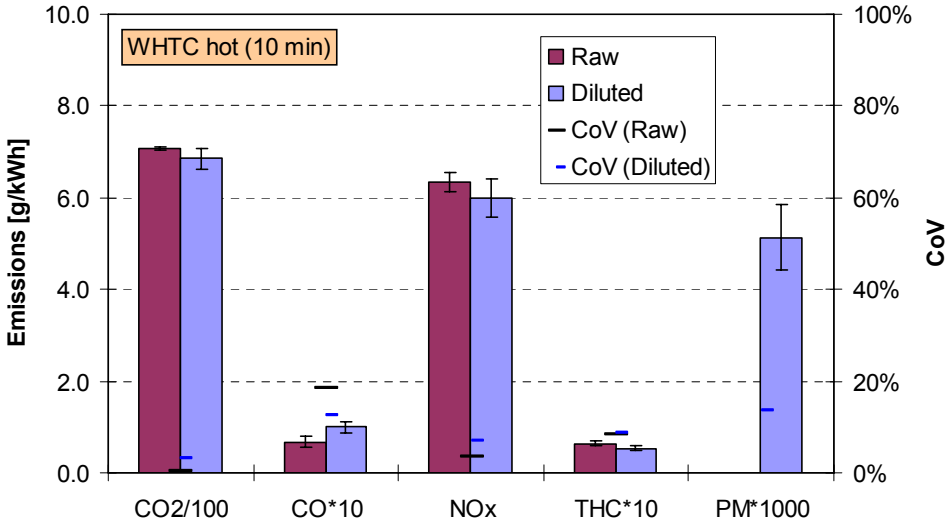

Figure 16: WHTC hot (10 min soak) legislated pollutant results.

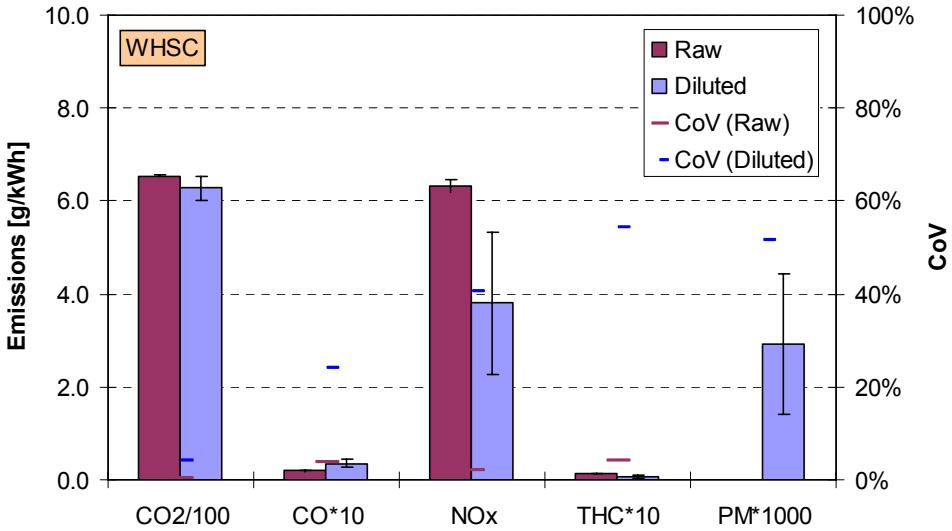

Figure 17: WHSC legislated pollutant results.

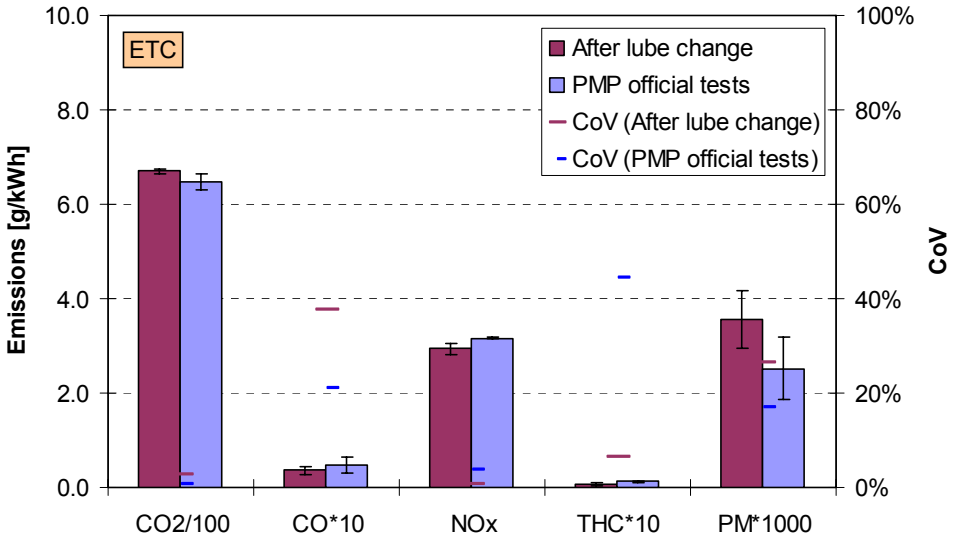

Figure 18: ETC legislated pollutant results.

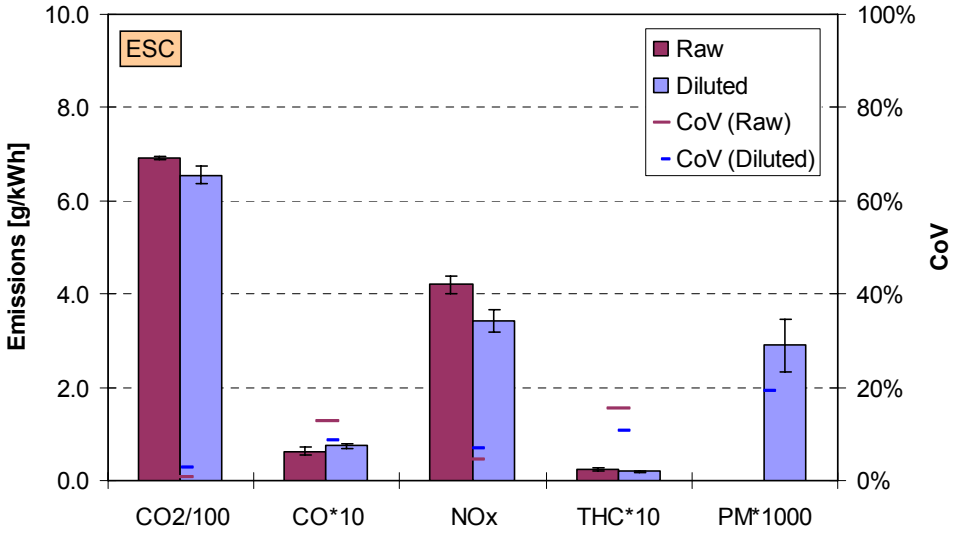

Figure 19: ESC legislated pollutant results.

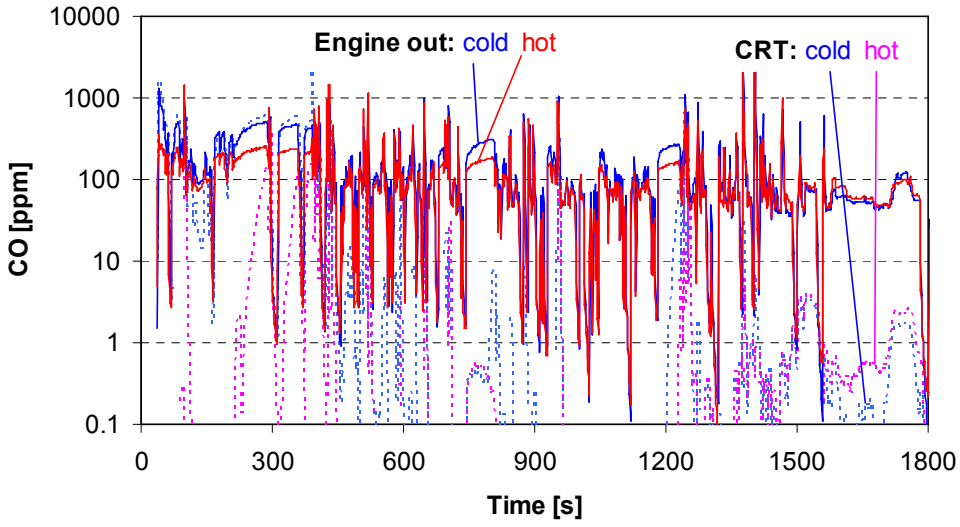

Figure 20: CO emissions over a cold and hot WHTC.

WHTC (Soak time)

The 5 or 10 min soak didn't have any effect on the legislated emissions (Figure 21). The number emissions didn't have any statistically significant difference (Figure 22). With the 10 min soak they were in average 20% lower. The PM were also 12% lower.

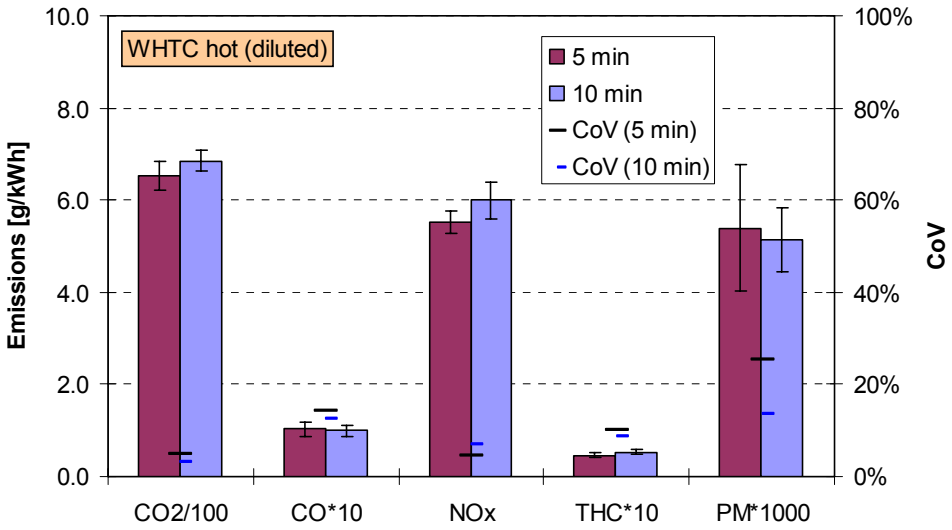

Figure 21: Hot WHTC legislated pollutants.

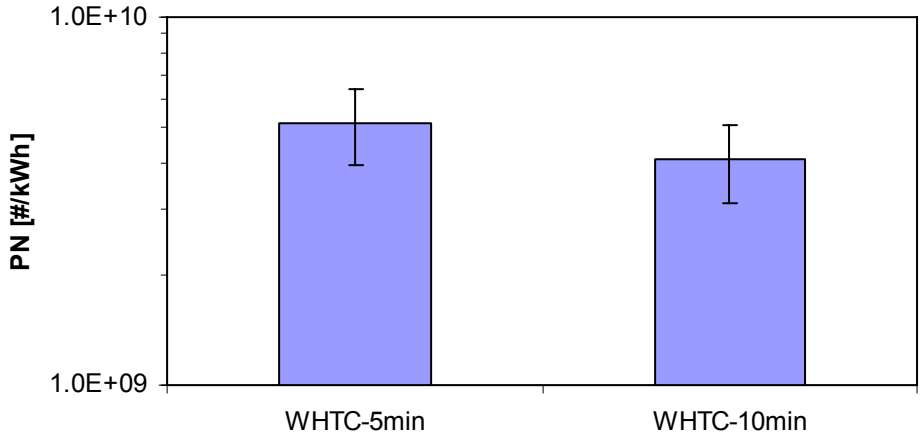

Figure 22: Hot WHTC PN emissions.

Particle number

Figure 23-Figure 27 show the real time pattern of the particle number system for the SPCS at CVS during a cold WHTC, a hot WHTC, a WHSC, an ETC and an ESC. The emissions of the cold WHTC are very high at the beginning of the cycle. The emissions decrease as the engine warms up and are low over the hot WHTC. The WHSC emissions are slightly higher and increase at the high temperature modes. The ETC emissions are low. The ESC emissions are high due to the high temperature modes. The discussion on the number emission patterns can be found in Giechaskiel et al. (2008c).

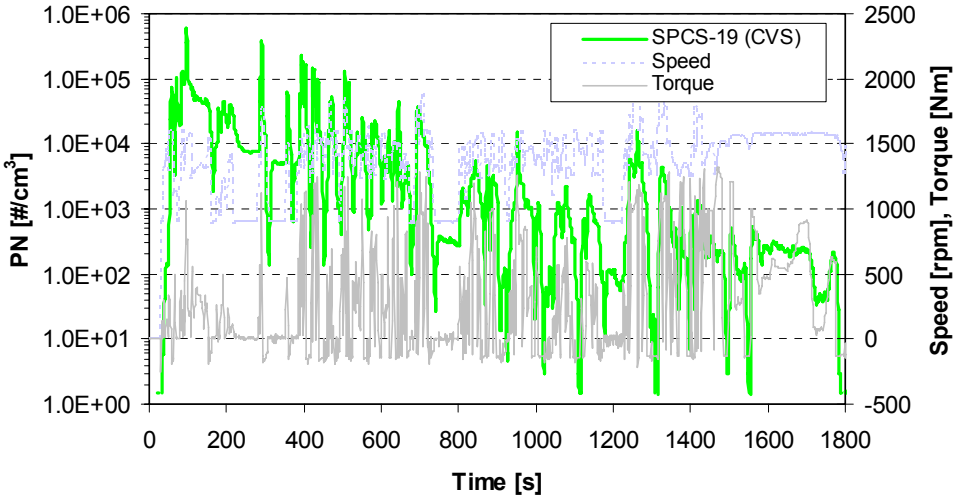

Figure 23: Particle number flux over the cold WHTC.

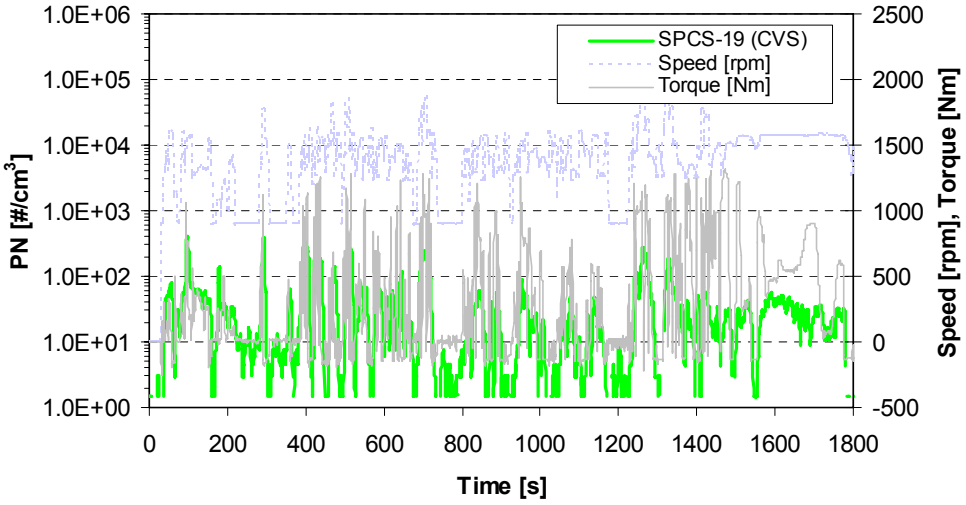

Figure 24: Particle number flux over the hot WHTC.

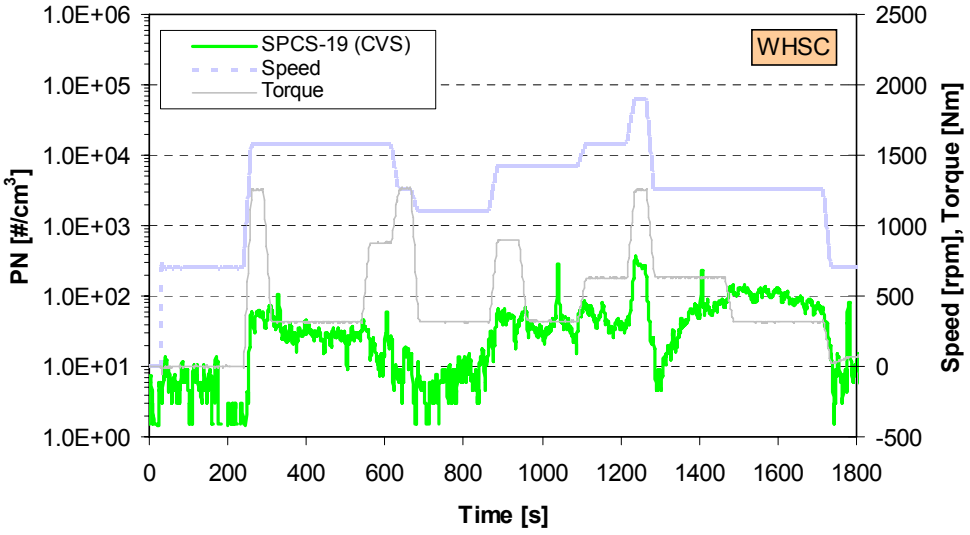

Figure 25: Particle number flux over the WHSC.

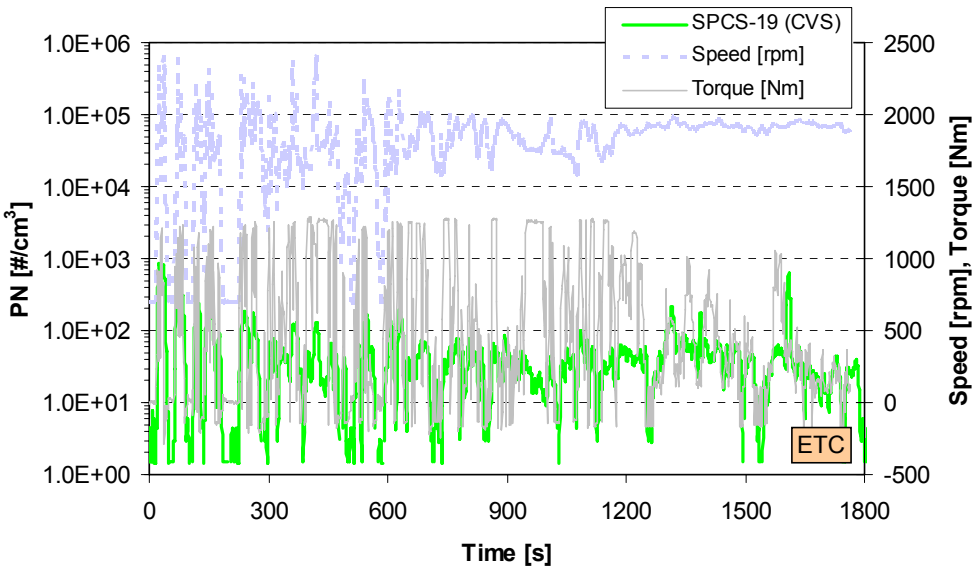

Figure 26: Particle number flux over the ETC.

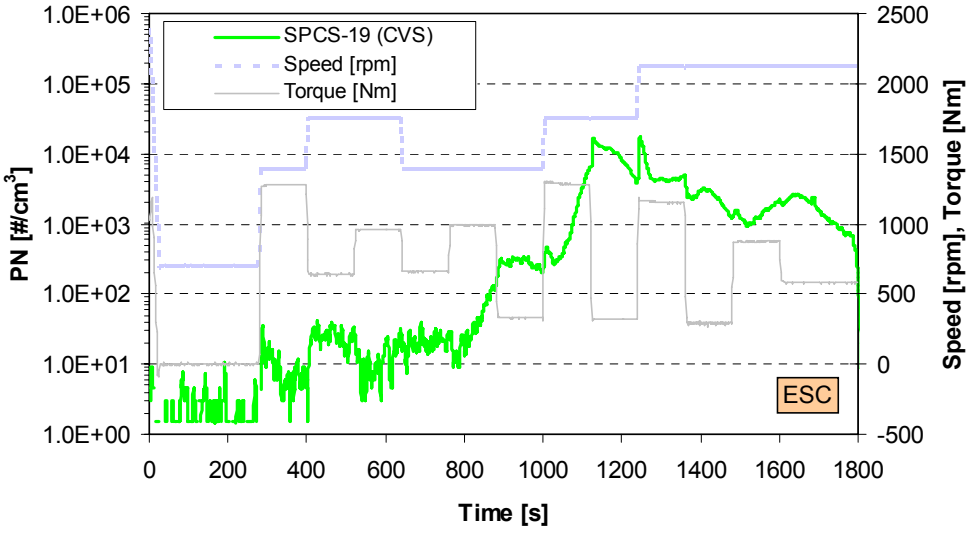

Figure 27: Particle number flux over the ESC.

Comparison of partial and full flow systems (mass)

The mass results from the partial and full flow systems can be seen in Figure 28 for SPC-472 and Figure 29 for PSS-20. The differences of full flow and partial flow the systems at these low levels are ±35% (Table 10).

Table 10: Average of relative difference of PM measurements at SPC-472 and PSS-20 compared to CVS. The number after ± indicates the standard deviation of the difference.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
PM(SPC)	24% (±31%)	-34% (±24%)	6% (±23%)	5% (±39%)	-5% (±25%)
PM(PSS)	-7% (±37%)	-36% (±27%)	19% (±69%)	-6% (±26%)	22% (±34%)

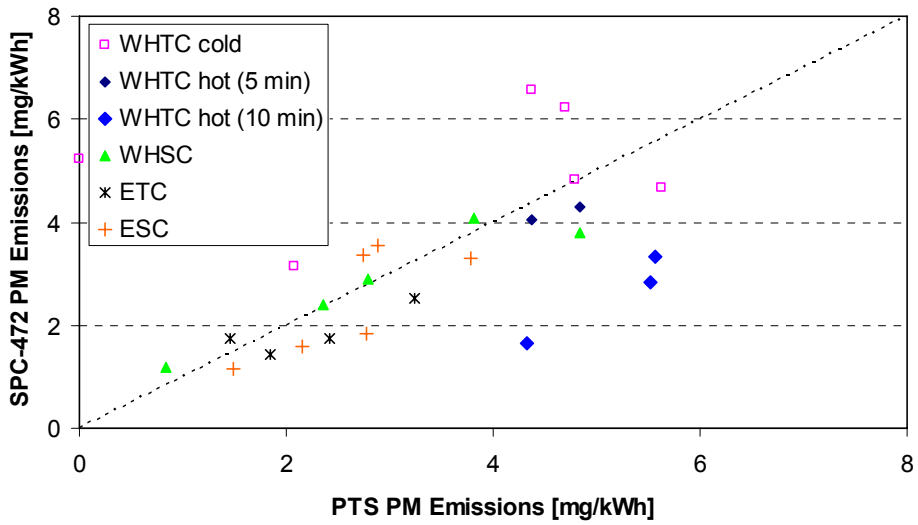

Figure 28: Comparison of PM emissions at PTS (CVS) and SPC-472.

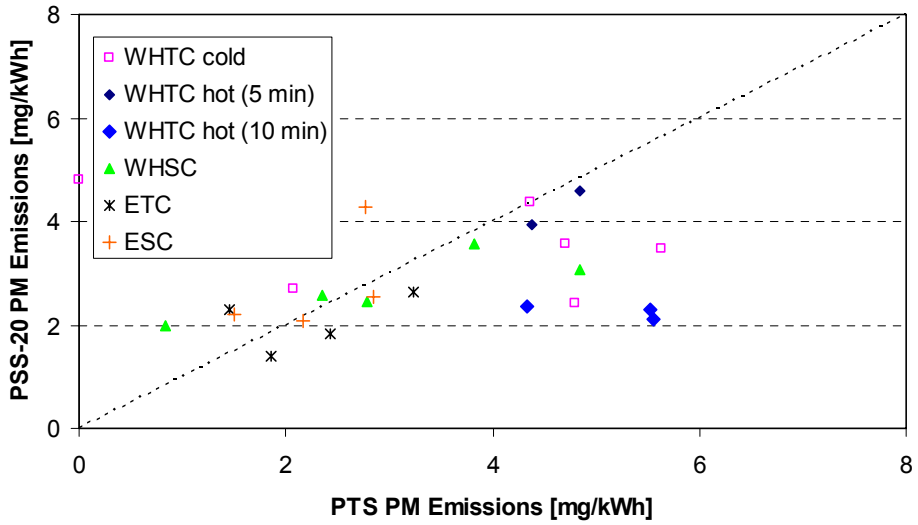

Figure 29: Comparison of PM emissions at PTS (CVS) and PSS-20.

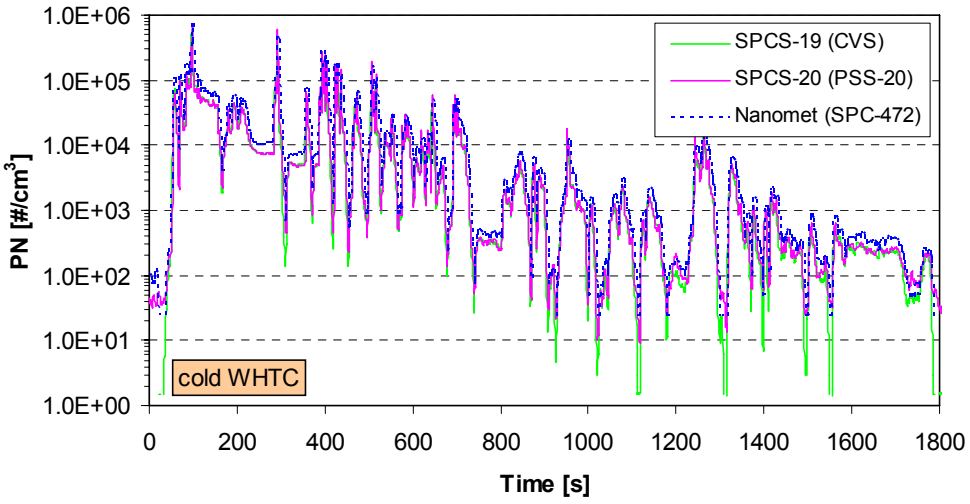

Figure 30: Particle flux over the cold WHTC for the full flow and the partial flow systems.

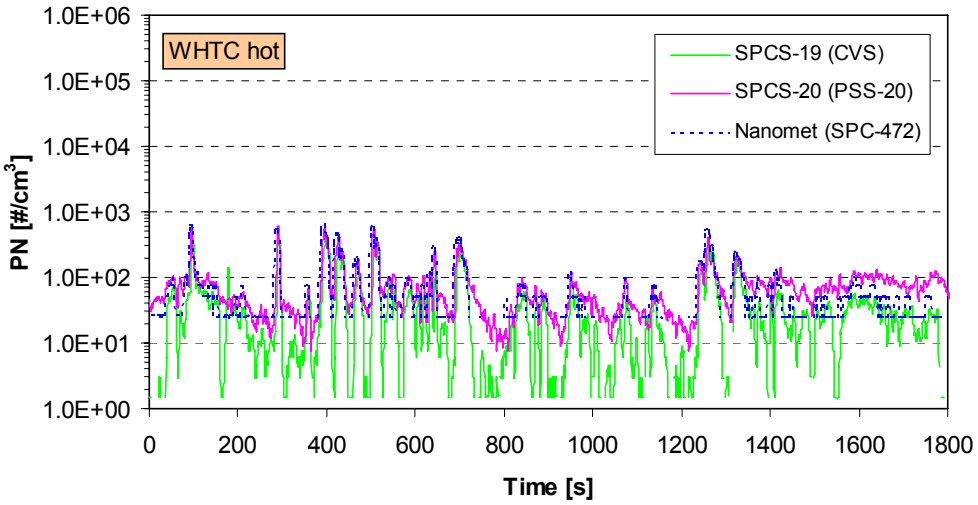

Figure 31: Particle flux over the hot WHTC for the full flow and the partial flow systems.

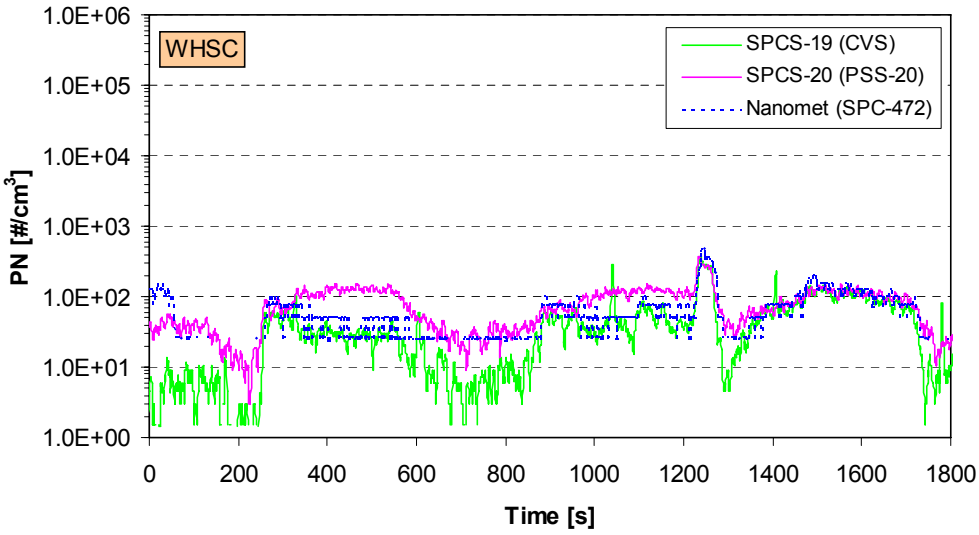

Figure 32: Particle flux over the WHSC for the full flow and the partial flow systems.

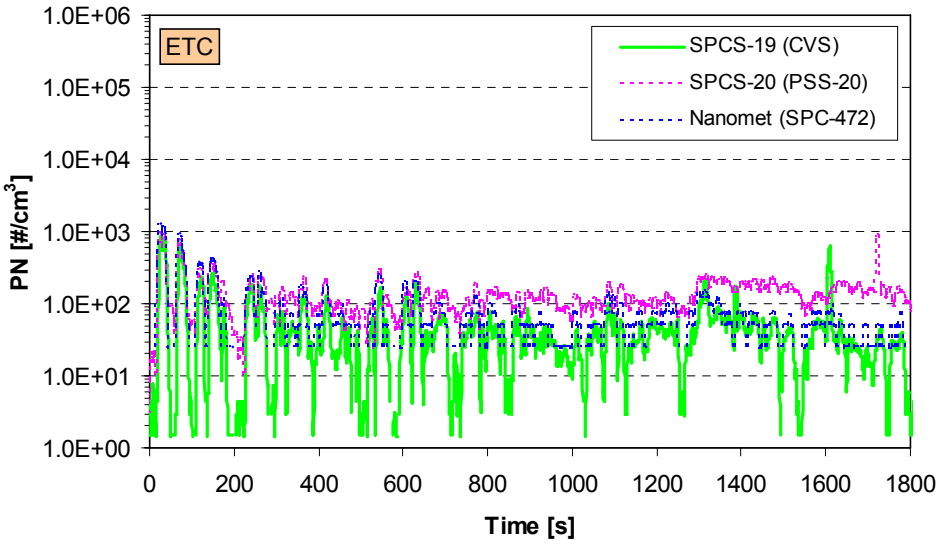

Figure 33: Particle flux over the ETC for the full flow and the partial flow systems.

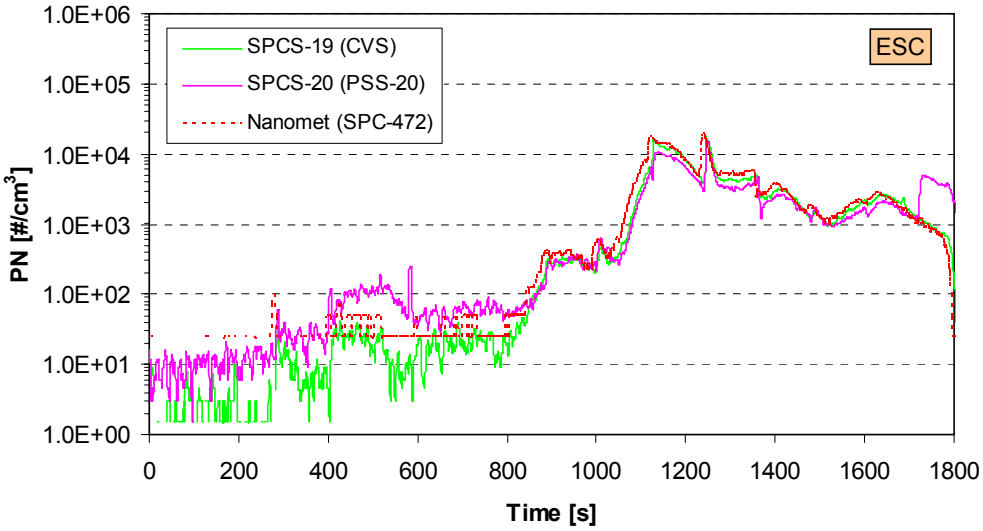

Figure 34: Particle flux over the ESC for the full flow and the partial flow systems.

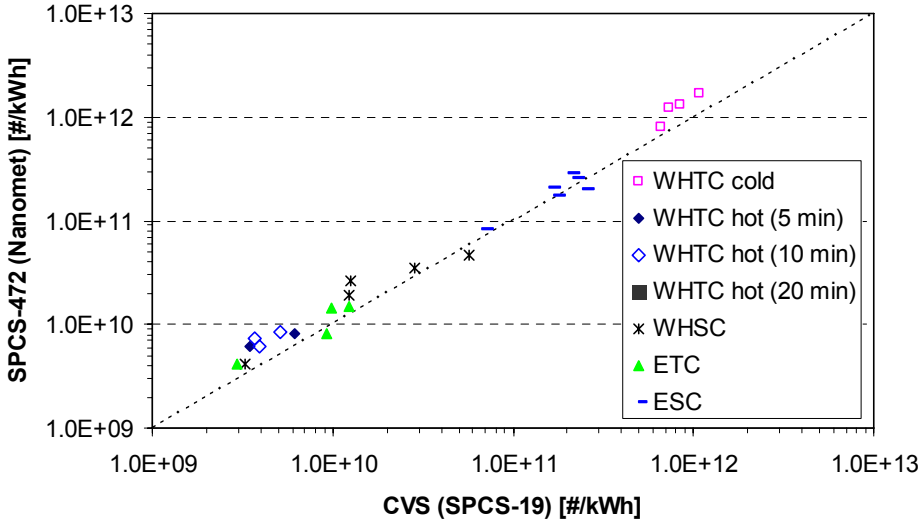

Figure 35: Comparison of the CVS (with SPCS-19) with the SPC-472 (with Nanomet).

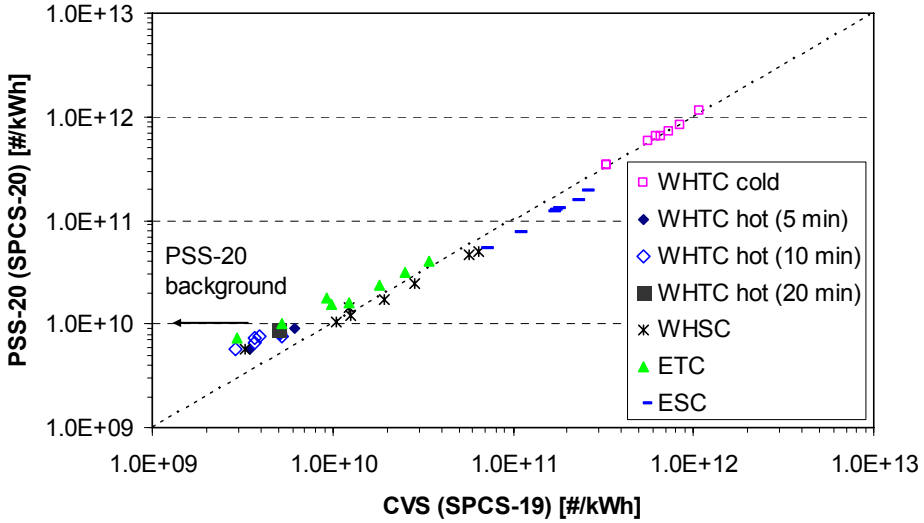

Figure 36: Comparison of the CVS (with SPCS-19) with the PSS-20 (with SPCS-20).

Comparison of partial and full flow systems (number)

The real time comparison between different number systems at full flow and partial flow systems can be seen in Figure 30-Figure 34. The SPCS-20 was connected to the PSS-20 and the Nanomet to the SPC-472. At CVS the SPCS-19 was used. The comparison with CVS for the cycle average emissions can be seen in Figure 35 for SPC-472 and Figure 36 for PSS-20. Table 11 shows the differences of the partial flow systems compared to the CVS. Generally differences in the order ±15% were observed. The hot WHTC had higher difference because the partial flow systems had high background, close to the emissions of the cycle. In the case of the SPC-472 the background was high due to the Nanomet's background. In the case of the PSS-20 the background was high due to its filters. Other reasons for these differences include:

- CVS high venturi temperature (wrong estimation CVS flowrate, DR different)
- Particle peaks at partial flow systems (change of split ratio, see Giechaskiel et al. 2008c)

Table 11: Average of relative differences compared to the CVS (SPCS-19). SPCS-20 was used at PSS-20 and Nanomet at SPC-472.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
PSS (SPCS-20)	1% (±3%)	67% (±18%)	-7% (±14%)	48% (±31%)	-23% (±3%)
SPC(Nanomet)	48% (±19%)	66% (±24%)	1% (±44%)	26% (±27%)	7% (±18%)

Comparison of particle number systems

Figure 37-Figure 41 show as an example the real time patterns of the various systems for various cycles. The dual ejector system was used with the 3010D' (modified 3010) while the ejector with thermodenuder system was used with the 3790. The emissions of this system were corrected for the 3790 overestimation of the emissions(see Giechaskiel et al. 2008c). The agreement between the various systems is good. The thermodenuder system measures 25% while the dual ejector system 10%. However, the dual EJ system has high background levels, even though a HEPA filter was installed (for this reason it measures 256% higher at the hot WHTC). For this reason at low emissions cycles (WHTC hot and ETC) high differences compared to SPCS-19 are observed.

Figure 42-Figure 44 summarize the average cycle emissions of the different systems in comparison with the SPCS-19 at CVS. Table 12 shows the differences of the various systems compared to the SPCS-19. The differences are in the same order as the differences of the particle number systems at CVS and the partial flow systems.

Table 12: Average of relative differences of particle number systems measuring from CVS compared to the SPCS-19 (also connected at CVS).

	WHTC cold	WHTC hot	WHSC	ETC	ESC
EJ+ET+EJ	2% (±5%)	63% (±41%)	43% (±24%)	47% (±30%)	6% (±13%)
EJ+TD	22% (±4%)	29% (±1%)	21% (±4%)	17% (±12%)	20% (±6%)
Nanomet	35%		16%	50% (±28%)	

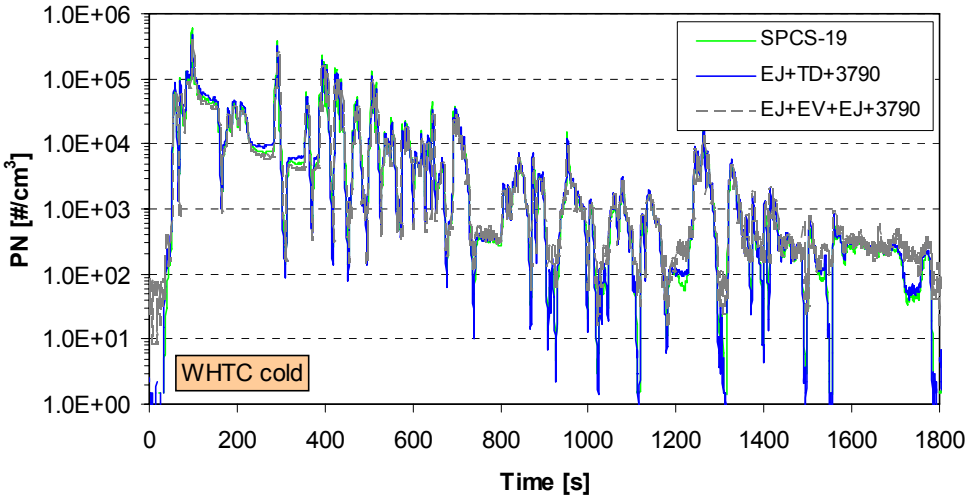

Figure 37: Comparison of particle number systems at CVS over the cold WHTC.

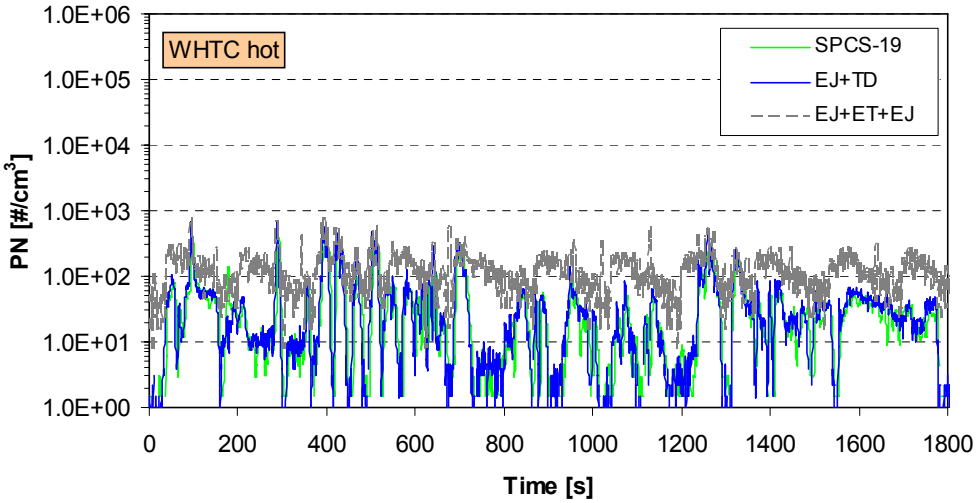

Figure 38: Comparison of particle number systems at CVS over the hot WHTC.

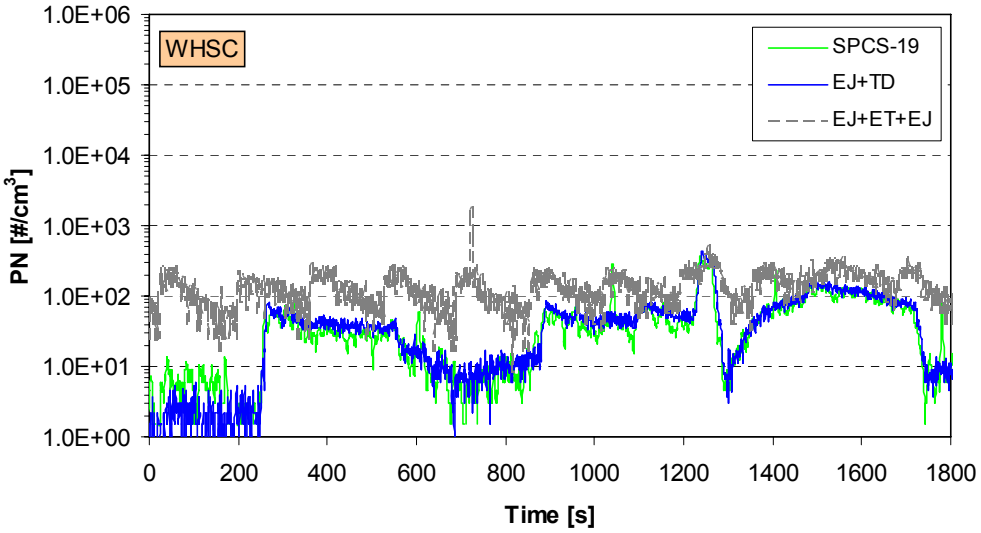

Figure 39: Comparison of particle number systems at CVS over the WHSC.

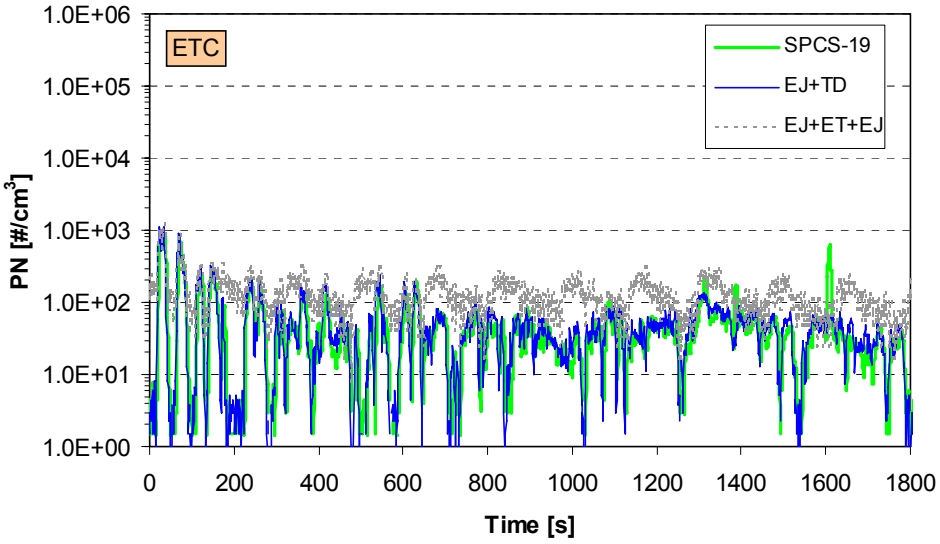

Figure 40: Comparison of particle number systems at CVS over the ESC.

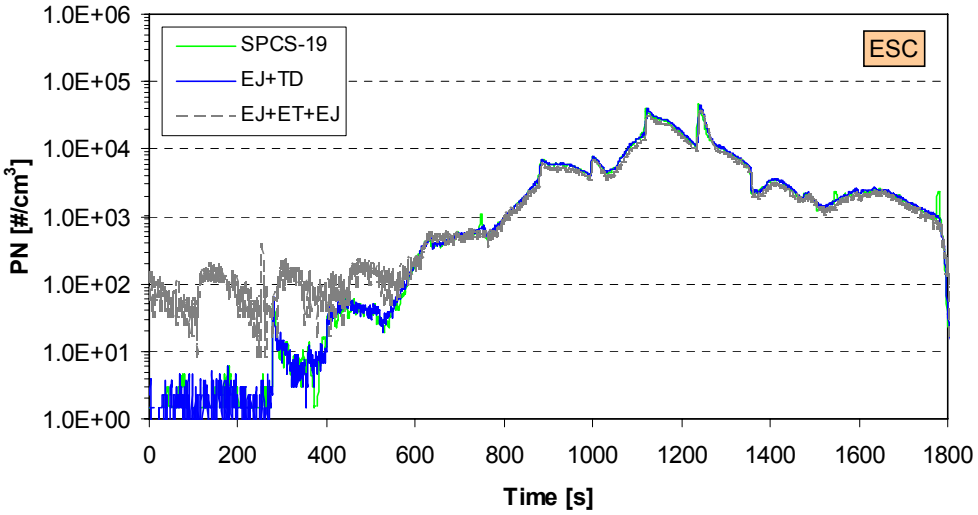

Figure 41: Comparison of particle number systems at CVS over the ESC.

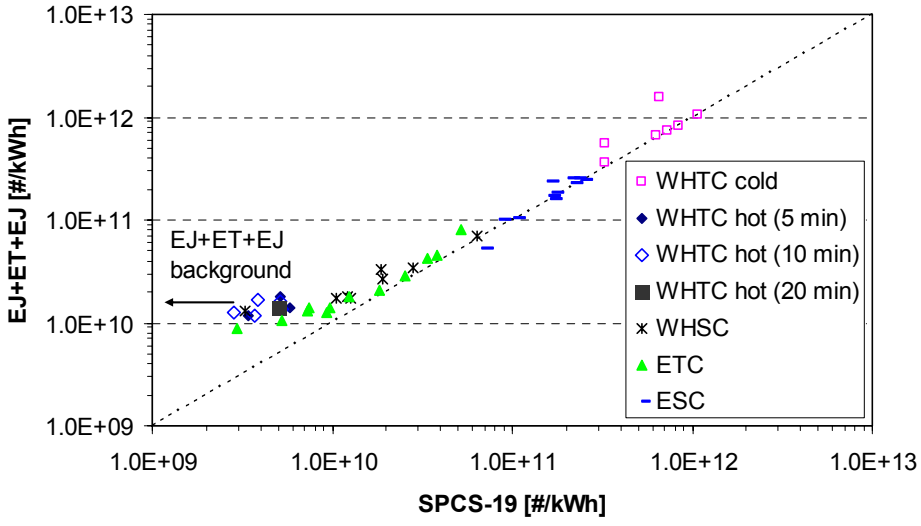

Figure 42: Comparison of SPCS-19 with the dual ejector system (both at CVS).

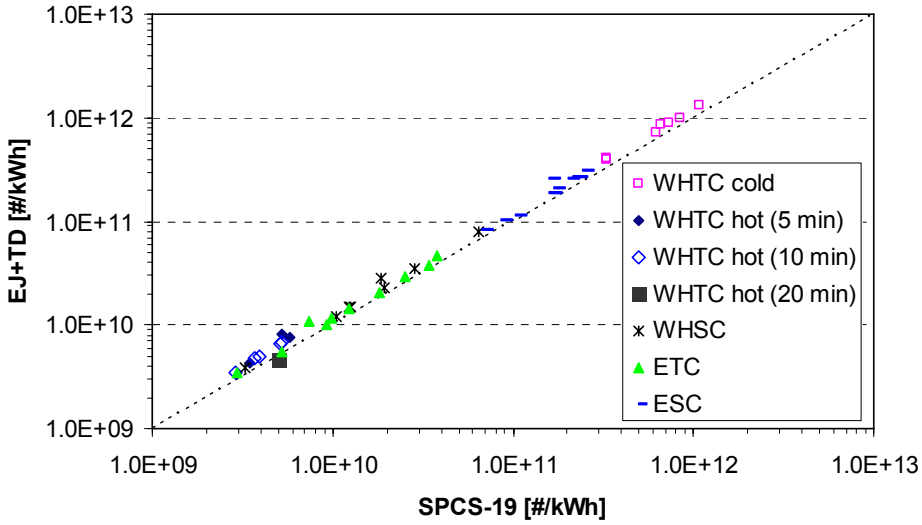

Figure 43: Comparison of SPCS-19 with the ejector with thermodenuder system (both at CVS).

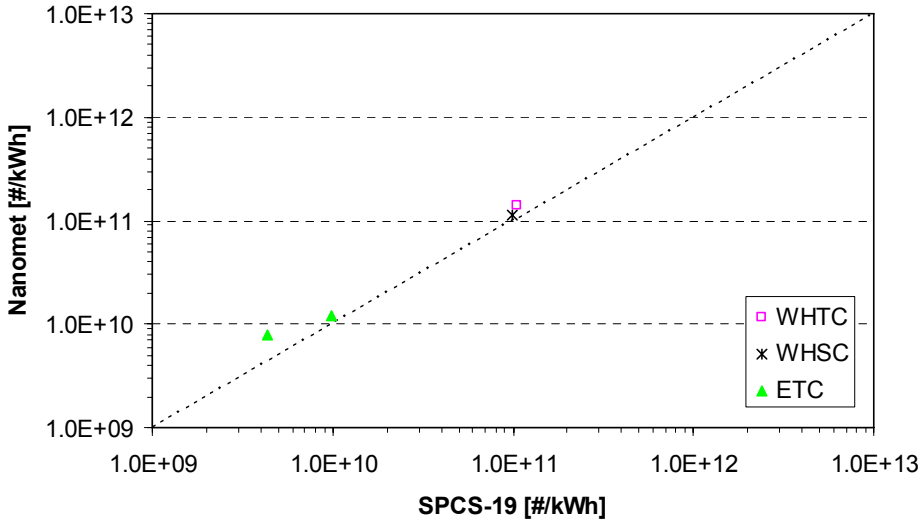

Figure 44: Comparison of SPCS-19 with Nanomet (both at CVS).

Steady states

Figure 45 shows the particle emissions during regeneration (mode 10) and loading (mode 7) of the CRT as measured from an EEPS and SPCS-19 connected directly at the CVS. Figure 46 shows the size distributions (total particles) measured from EEPS. The pattern is as follows (more details can be found in Giechaskiel et al. 2008c):

- Blow out of non-volatile particles due to the acceleration (point 2, and size distribution 2).
- Increase of volatiles due to the increase of the temperature (point 3, 4, 5, and size distributions 3, 4, 5)
- Decrease of solids at mode 7 but for a short period high amount of volatiles due to the increased temperature and decrease available surface.
- Decrease of volatiles and non-volatiles.

The number size distributions as measured downstream of various instruments can be seen in Figure 47 for mode 10 (ESC) and Figure 48 for mode 7 (ESC). Although there is a nucleation mode at CVS all systems can remove it efficiently.

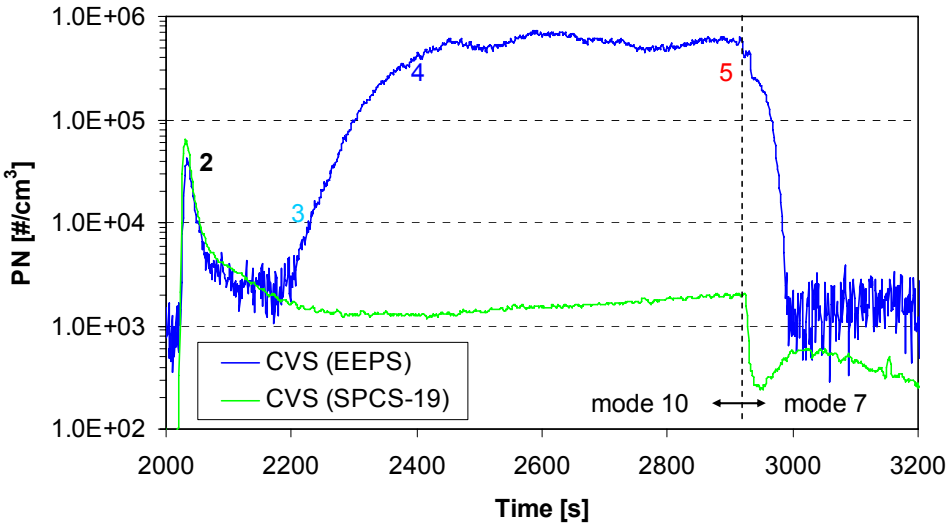

Figure 45: PN flux during mode 10 and mode 7 as measured from an EEPS and SPCS-19.

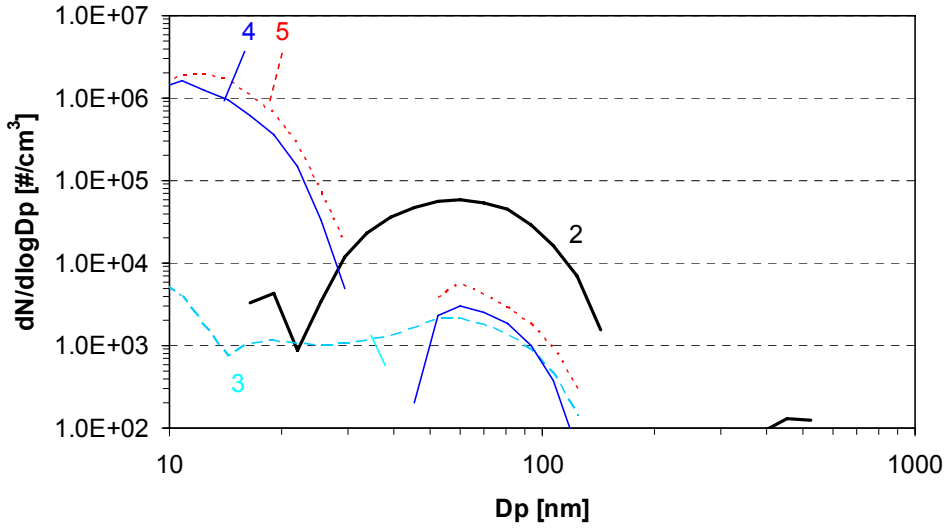

Figure 46: Number size distributions measured from EEPS. The numbers correspond to the times that the corresponding numbers in the previous figure are.

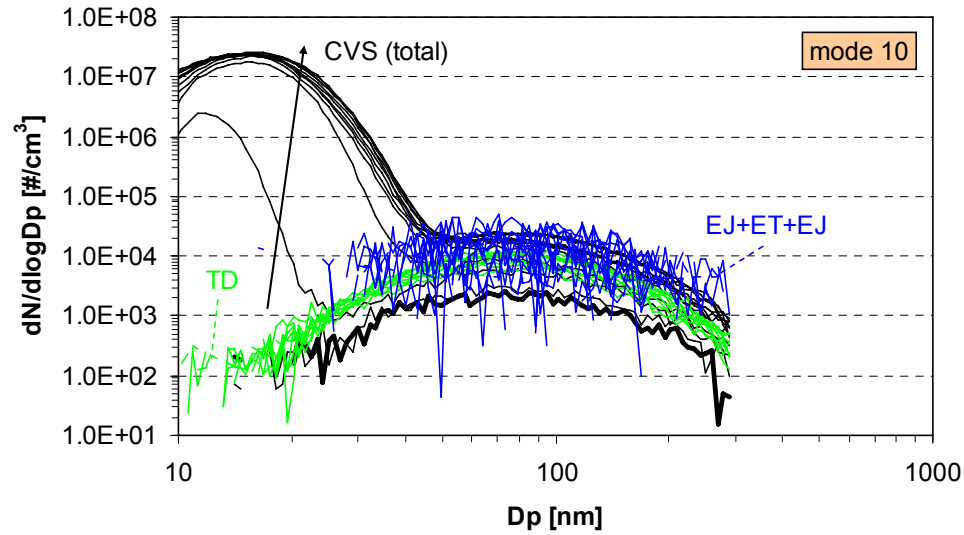

Figure 47: Number size distributions measured with a SMPS 3936 at CVS or downstream of various particle number systems (mode 10).

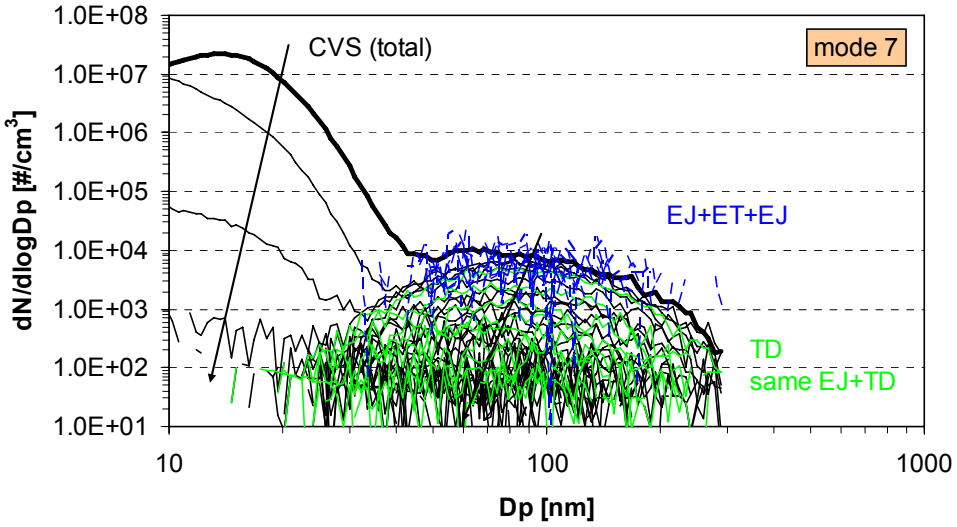

Figure 48: Number size distributions measured with a SMPS 3936 at CVS or downstream of various particle number systems (mode 7).

3.2 GOLDEN ENGINE WITH EMITEC FILTER

The following section describes the results of the Golden engine with the second after-treatment device, the Partial Flow Deep Bed Filter from EMITEC.

Temperatures

The following figures (Figure 49-Figure 53) show typical temperature profiles at the exhaust line, the dilution tunnel and the filter. The main conclusions are:

- The exhaust gas temperatures reach ~400°C for the transient cycles and ~500°C for the steady cycles.
- The temperature at the inlet of the dilution tunnel can reach 400°C at the ESC cycle.
- The PM sampling point temperature at the full dilution tunnel is around 60°C but can reach 100°C at the ESC cycle.
- The PM filter temperature complies with the 42-52°C requirement.

The temperatures are similar to those measured with the CRT.

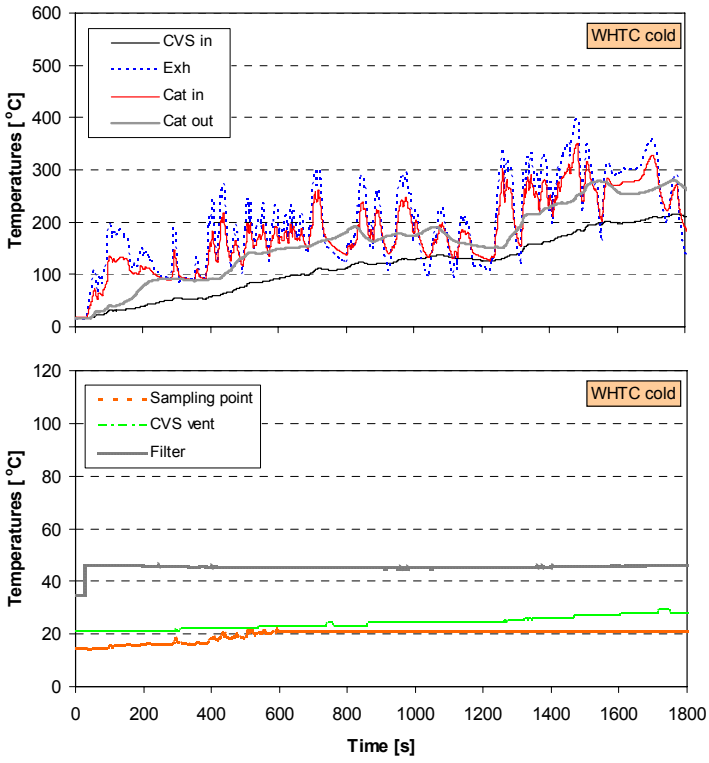

Figure 49: Temperature profiles over cold WHTC.

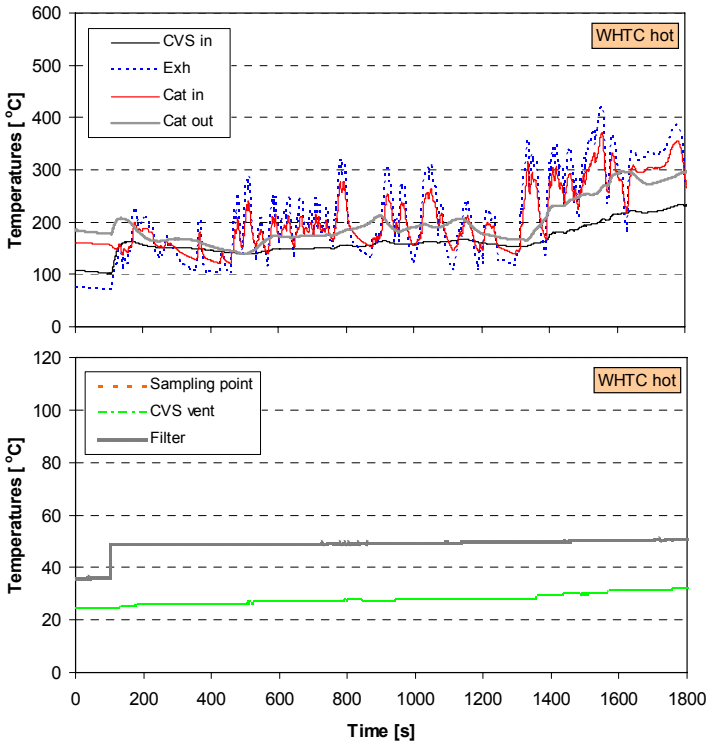

Figure 50: Temperature profiles over hot WHTC (10 min soak).

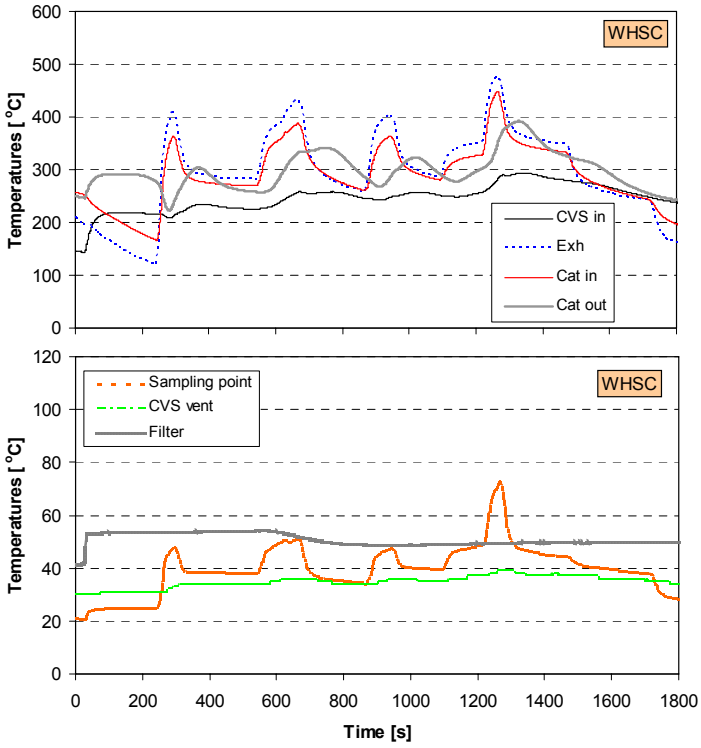

Figure 51: Temperature profiles over WHSC.

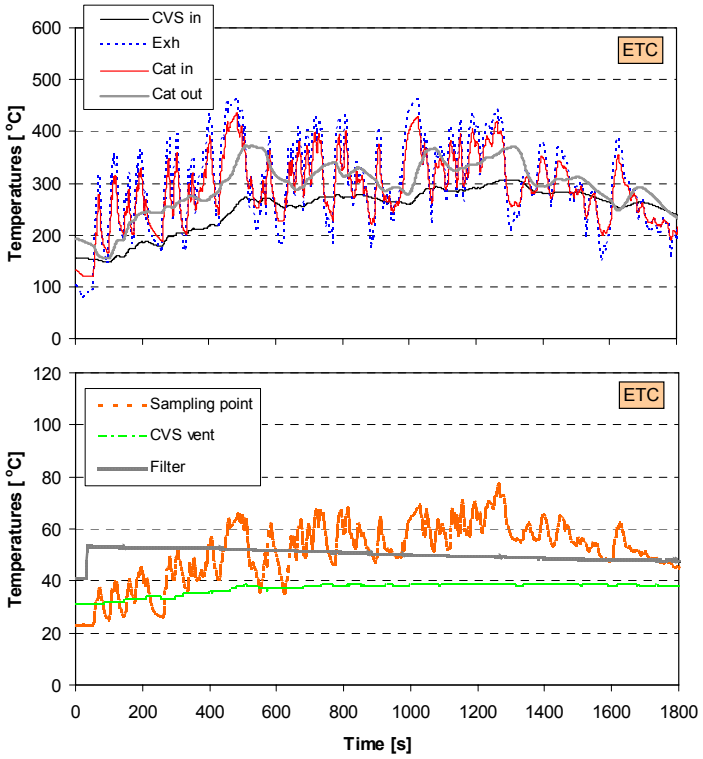

Figure 52: Temperature profiles over ETC.

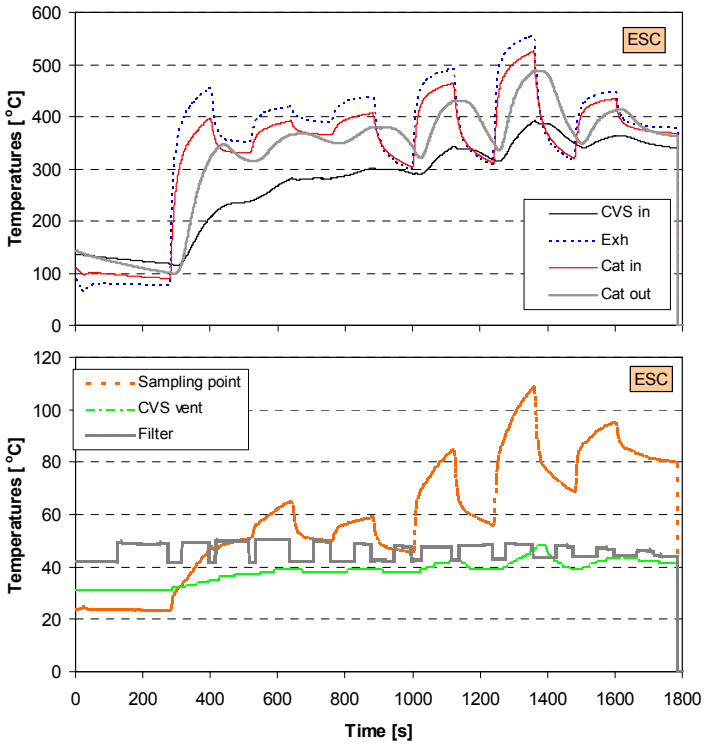

Figure 53: Temperature profiles over ESC.

Legislated pollutants

The results for the legislated pollutants are shown in the following figures (Figure 54-Figure 58). Both raw (from exhaust tailpipe) and diluted (from the full dilution tunnel) results are shown. The main conclusions are:

- The CO_2 emissions were around 700 g/kWh
- The CO emissions were <0.1 g/kWh with the exception of the cold start WHTC (0.5 g/kWh)
- The NO_x emissions decreased over time. They were high at the cold start cycle (8 g/kWh) and dropped to half at the final cycle (4 g/kWh).
- The THC were 0.2 g/kWh for the cold WHTC, 0.1 for the hot and <0.05 for the rest.
- PM emissions were 30 mg/kWh for the ETC cycle and 25 mg/kWh for the rest cycles.

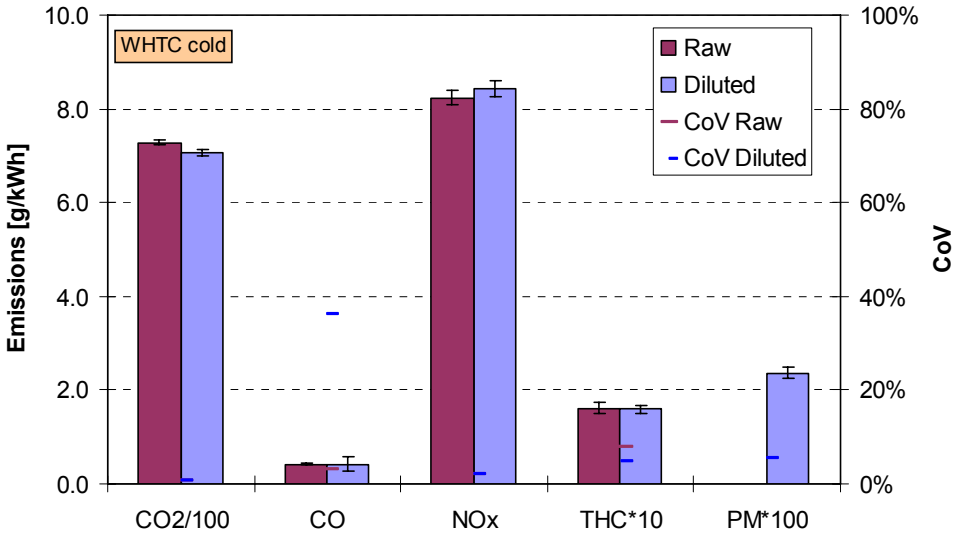

Figure 54: WHTC cold legislated pollutant results.

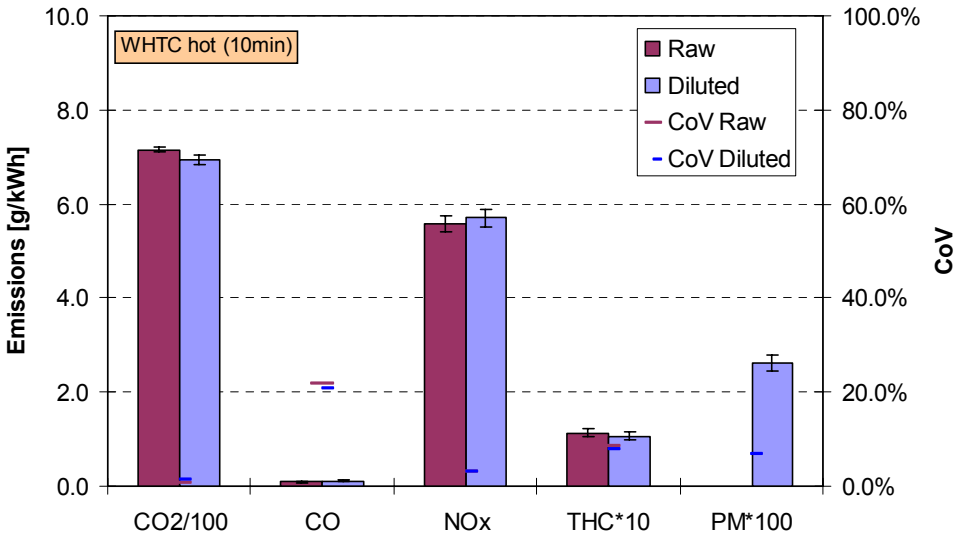

Figure 55: WHTC hot (10 min soak) legislated pollutant results.

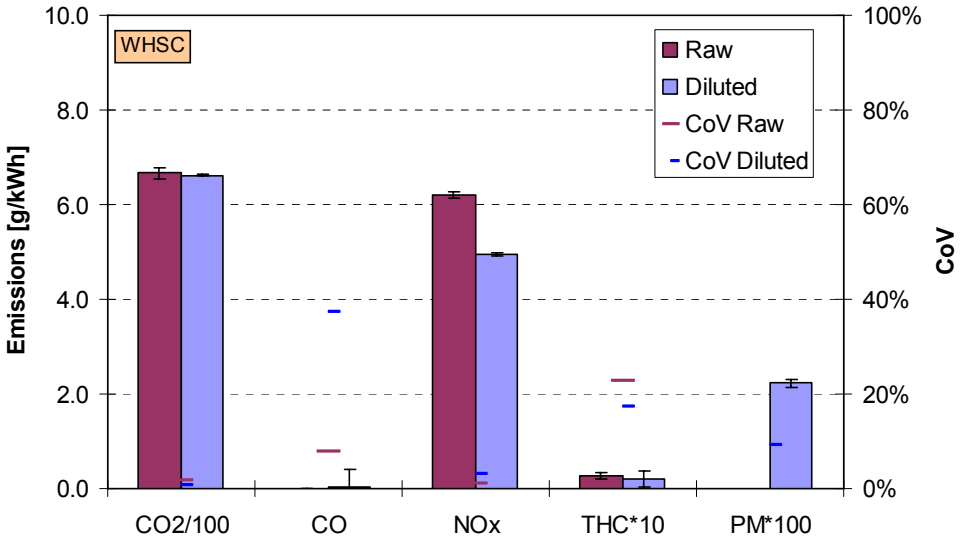

Figure 56: WHSC legislated pollutant results.

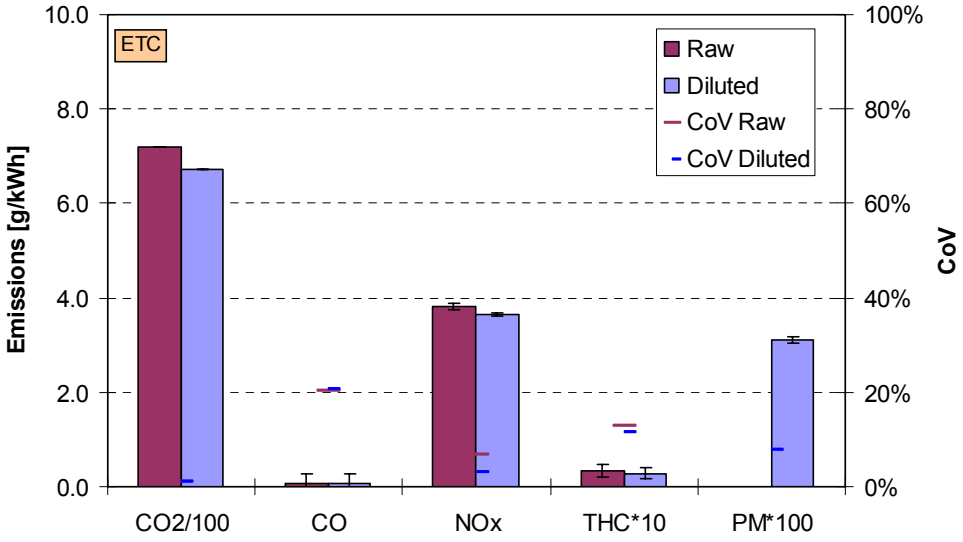

Figure 57: ETC legislated pollutant results.

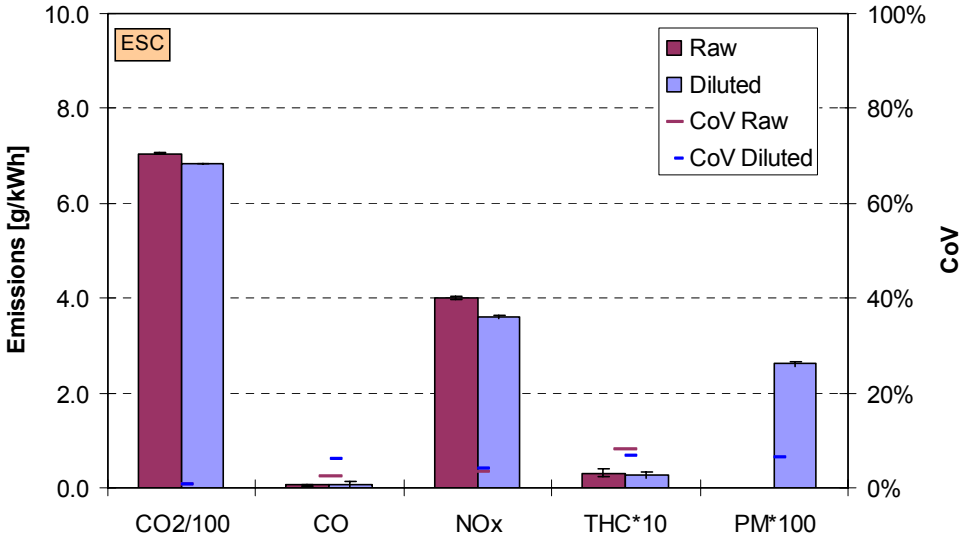

Figure 58: ESC legislated pollutant results.

Particle number

Figure 59-Figure 63 show the real time particle number emissions. They follow the cycle acceleration and decelerations. The emission levels are higher than with the CRT. The cold start effect is very small (the cold WHTC emissions at the beginning of the cycle are slightly higher than at the hot WHTC. However, the hot WHTC emissions at the end of the cycle are higher than the cold's. This has to do probably with the engine out higher emissions at the hot cycle (see next chapter).

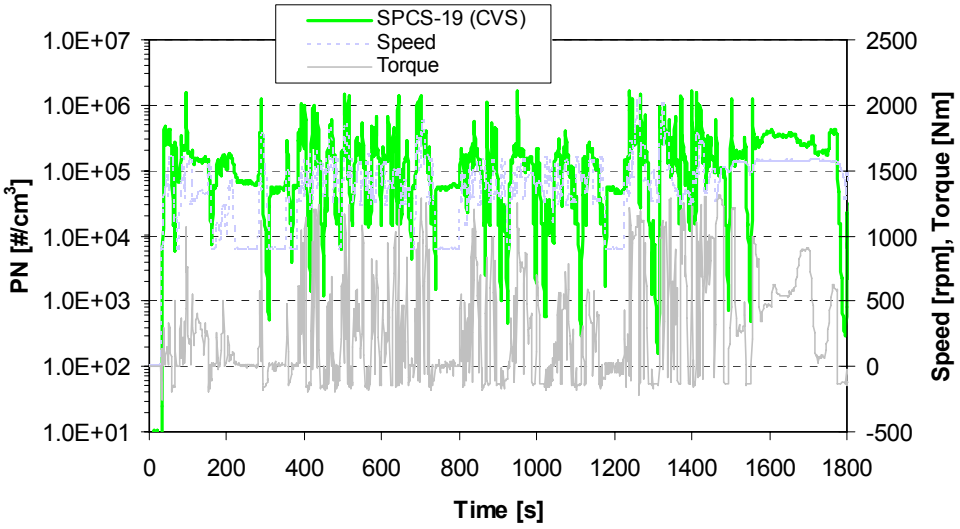

Figure 59: Particle number flux over the cold WHTC.

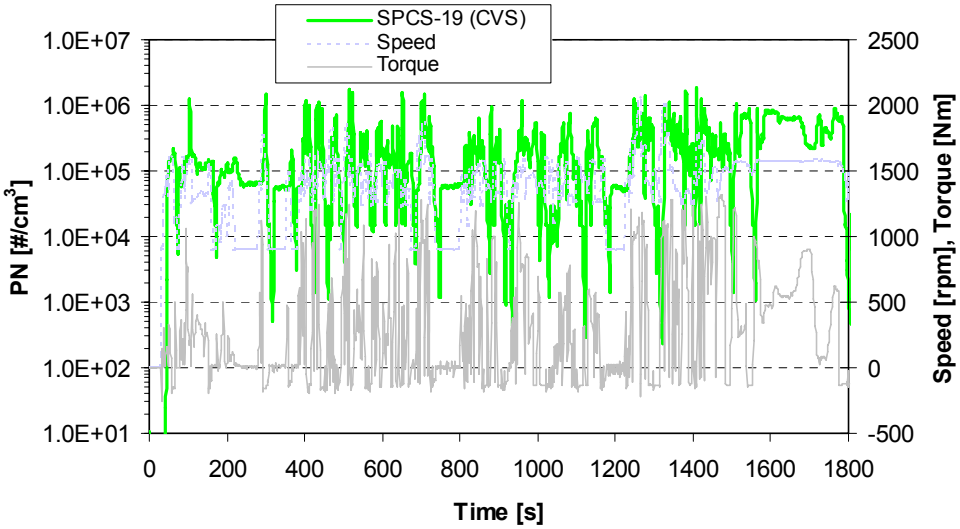

Figure 60: Particle number flux over the hot WHTC.

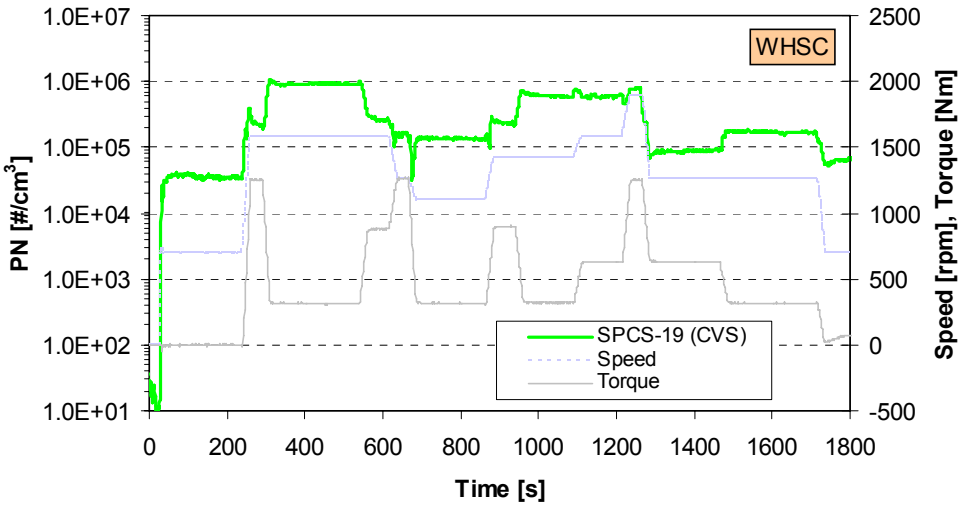

Figure 61: Particle number flux over the WHSC.

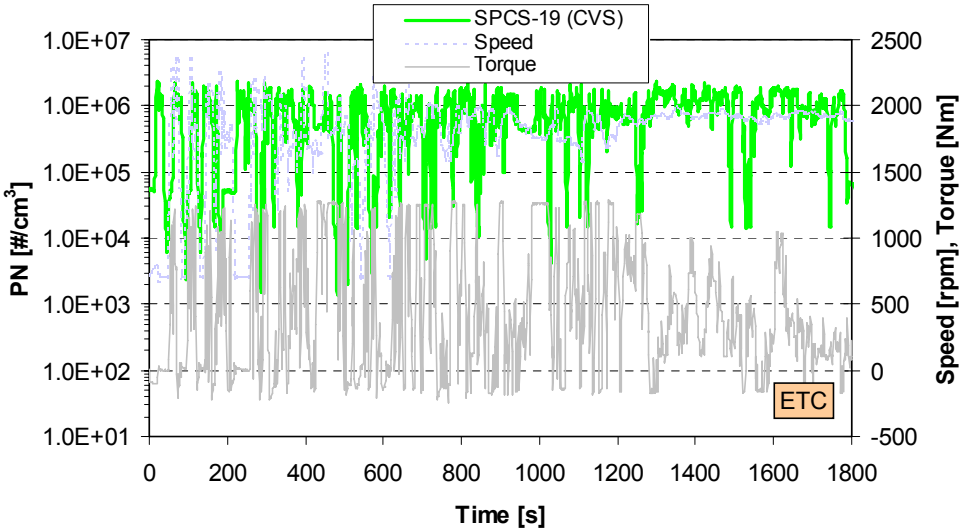

Figure 62: Particle number flux over the ETC.

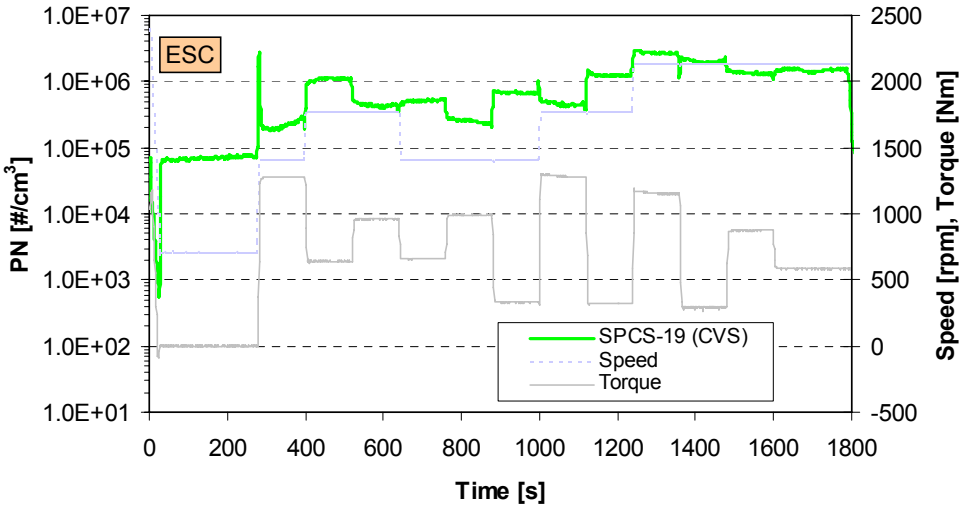

Figure 63: Particle number flux over the ESC.

Partial-Full flow systems (mass)

The comparison of the results of each cycle for the full flow and partial flow systems can be seen in Figure 64 for SPC-472 and Figure 65 for PSS-20. The emissions at the partial flow systems are lower 25% than those at the full flow system. This has to be further investigated.

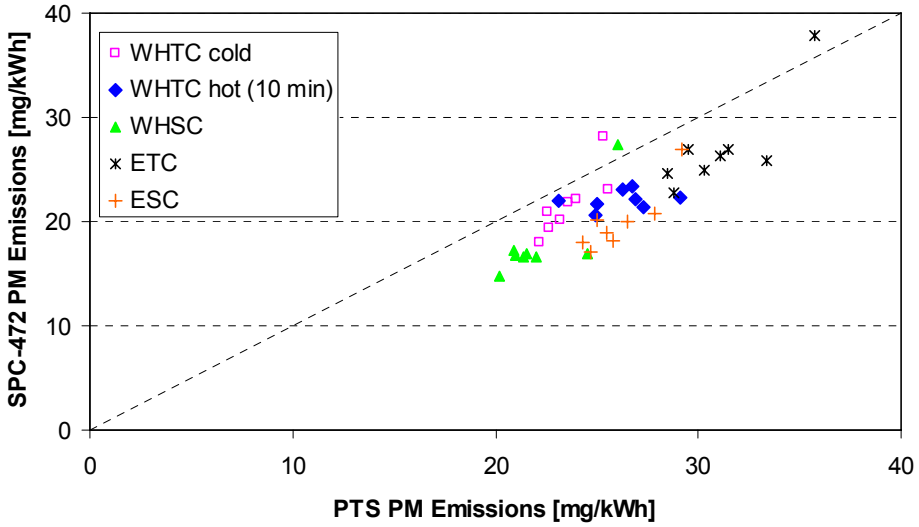

Figure 64: Comparison of PM emissions at PTS (CVS) and SPC-472.

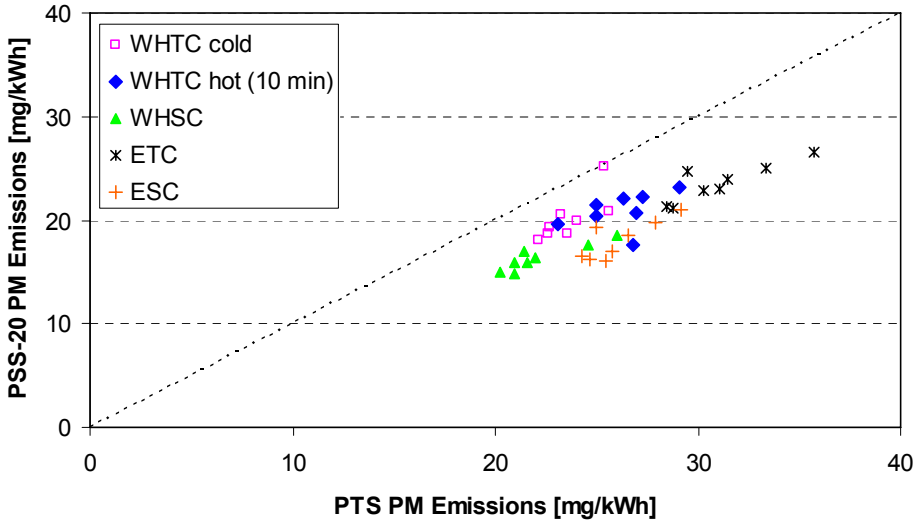

Figure 65: Comparison of PM emissions at PTS (CVS) and PSS-20.

Table 13: Average of relative PM differences between full and partial flow systems. Number after ± indicates the stdev of the difference.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
SPC (Nanomet)	-10% (±9%)	-16% (±6%)	-23% (±6%)	-17% (±5%)	-27% (±3%)
PSS (SPCS20)	-15% (±6%)	-20% (±6%)	-26% (±3%)	-24% (±3%)	-31% (±4%)

Partial-Full flow systems (number)

The comparison of the number emissions from the full flow and the partial flow systems can be seen in Figure 66. Similar patterns were observed at the other cycles. The old Nanomet at SPC-472 measures 10-30% higher (Figure 67); similar differences were found in Giechaskiel et al. (2008c). If the differences of the particle number systems is taken into account (i.e. the PRFs are used) the difference between full and partial flow systems drops to <5%. The differences of the CVS and PSS-20 are within 15% (Figure 68). As mention in Section 3, reasons of these differences are the venturi temperatures and the peaks of particles at the partial flow systems.

Table 14: Average of relative PN differences between full and partial flow systems. Number after ±indicates the stdev of the difference. Nanomet at SPC-472 and SPCS-20 at PSS-20.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
SPC (Nanomet)	30% (±7%)	24% (±3%)	8% (±14%)	19% (±10%)	8% (±12%)
PSS (SPCS-20)	15% (±16%)	4% (±13%)	-13% (±6%)	5% (±15%)	-13% (±8%)

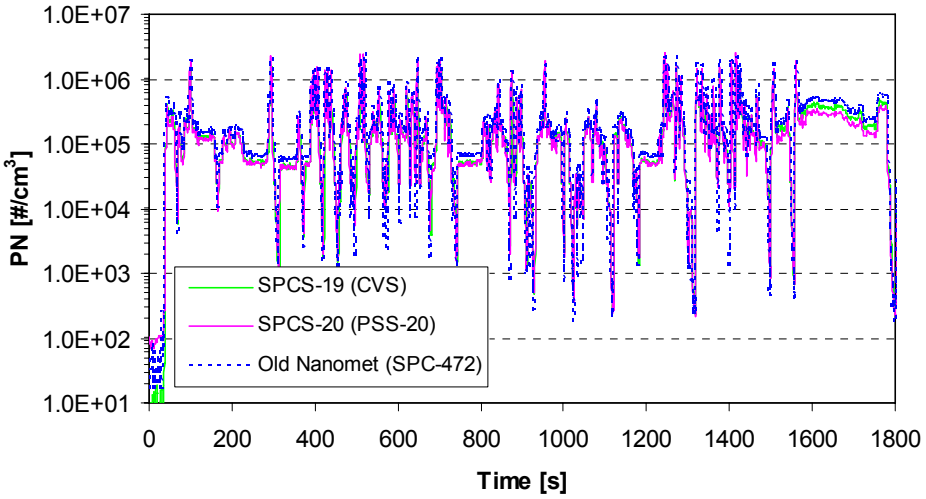

Figure 66: Particle flux over the cold WHTC for the full flow and the partial flow systems.

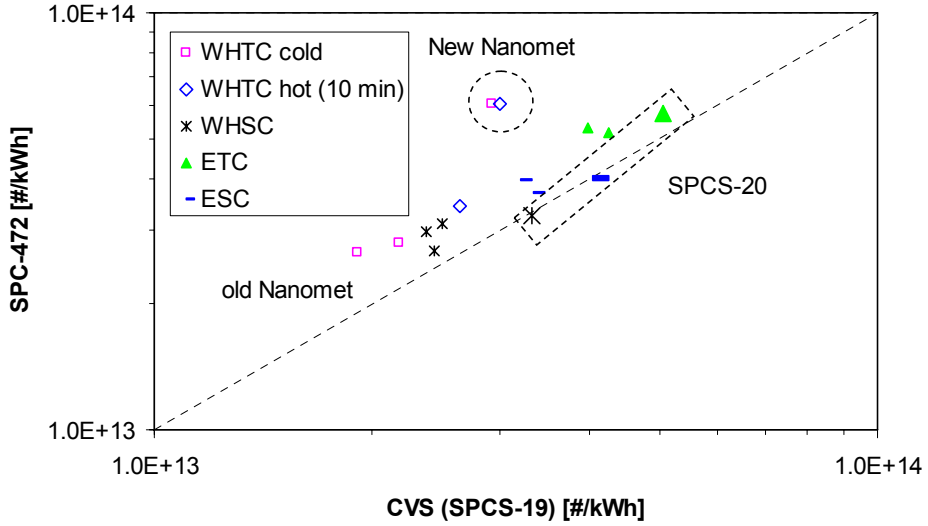

Figure 67: Comparison of the CVS (with SPCS-19) with the SPC-472.

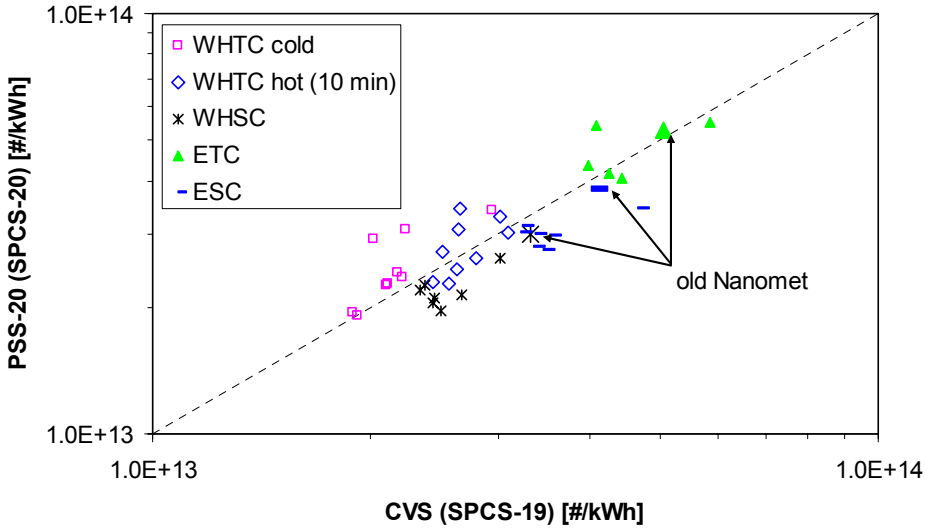

Figure 68: Comparison of the CVS (with SPCS-19) with PSS-20 (with SPCS-20).

Comparison of systems

The comparison of various particle number systems all connected at CVS can be seen in Figure 69 (as an example, cold WHTC). The results for the rest cycles are similar. The comparison of the cycle emissions for the systems can be seen in Figure 70 and Figure 71. The conclusions are similar with those with the CRT.

Table 15: Relative PN differences between different number systems.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
EJ+ET+EJ	27% (±13%)	31% (±27%)	29% (±17%)	5% (±20%)	4% (±23%)
EJ+ET+EJ+TD	15% (±11%)	21% (±18%)	22% (±16%)	11% (±13%)	10% (±10%)

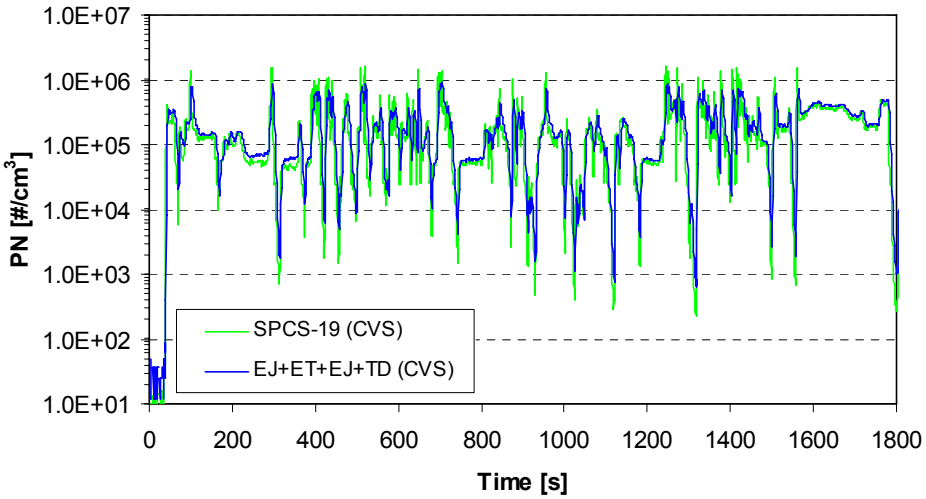

Figure 69: Comparison of particle number systems at CVS over the cold WHTC.

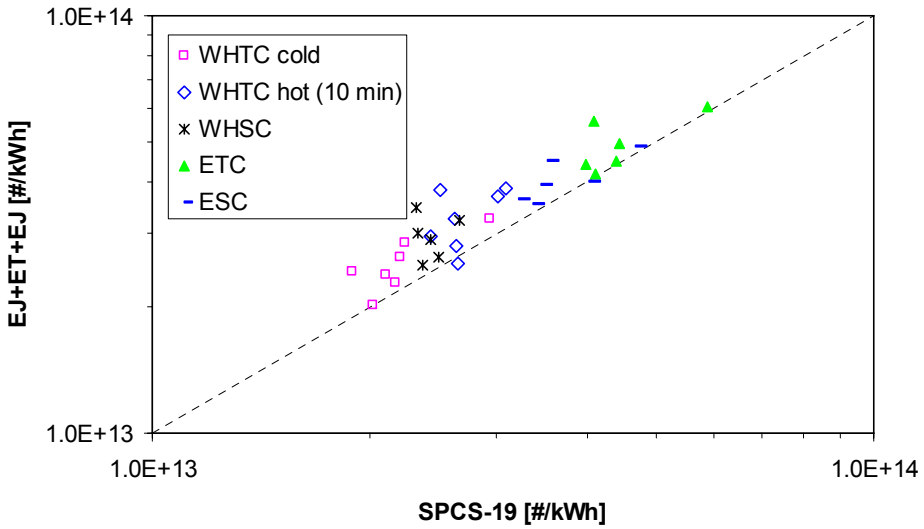

Figure 70: Comparison of SPCS-19 with the dual ejector system (both at CVS).

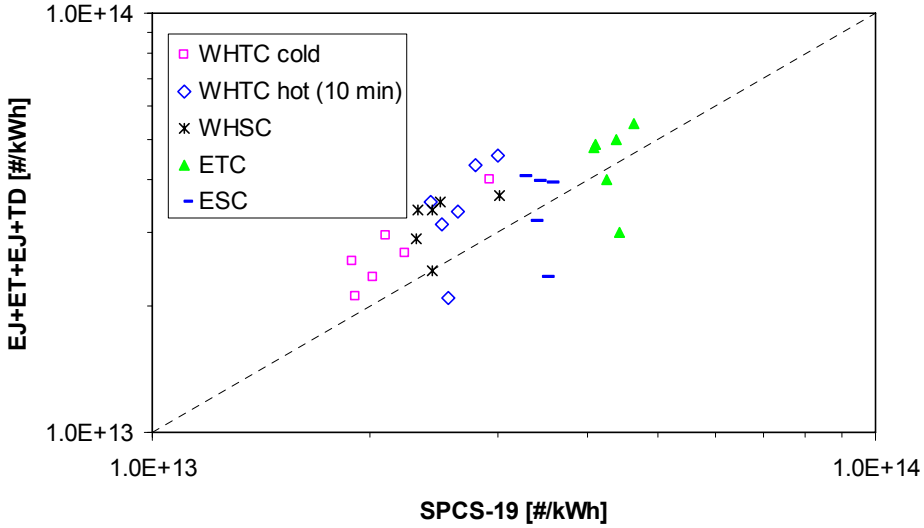

Figure 71: Comparison of SPCS-19 with the dual ejector system and the thermodenuder (both at CVS).

Steady states

The following figures (Figure 72, Figure 73, Figure 74) show the size distributions measured with SMPS directly connected at CVS (total particles) or downstream of the dual ejector system (non-volatiles). At low engine modes (idle, mode 7) the total and non-volatile size distributions are similar (Figure 72, Figure 73) indicating that only non-volatile particles are at CVS. At mode 10 (Figure 74) there is a nucleation mode at CVS probably due to the high SO_2 to SO_3 conversion due to the high exhaust gas temperature. This is removed from the number systems.

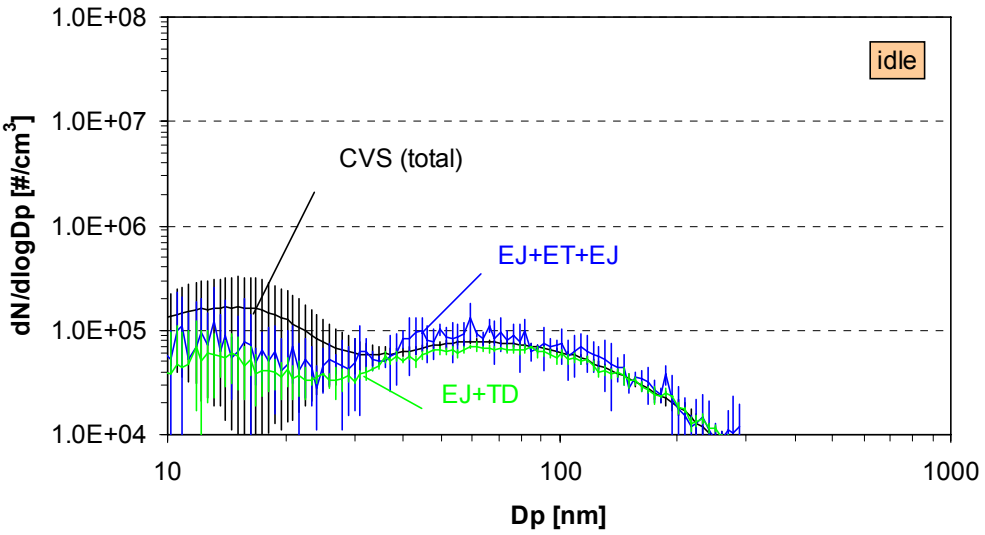

Figure 72: Size distributions at idle

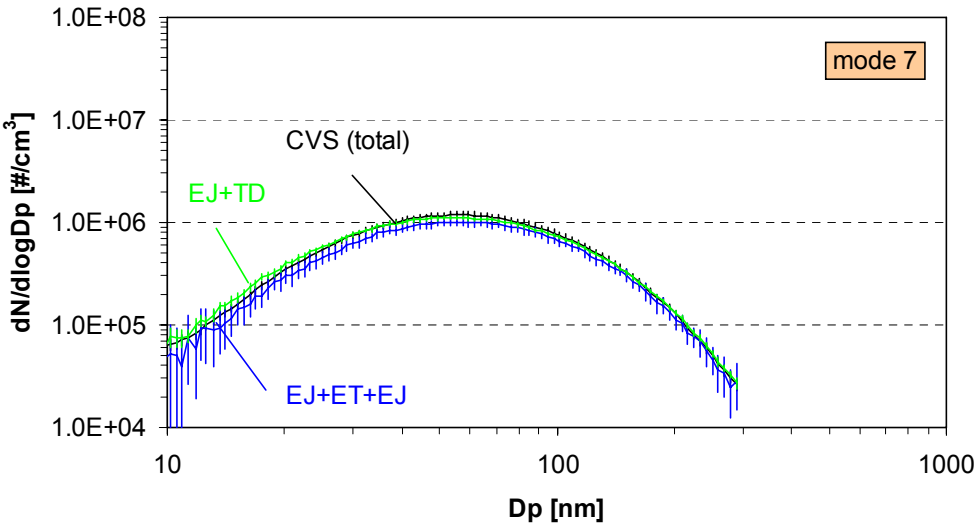

Figure 73: Size distributions at mode 7 (ESC).

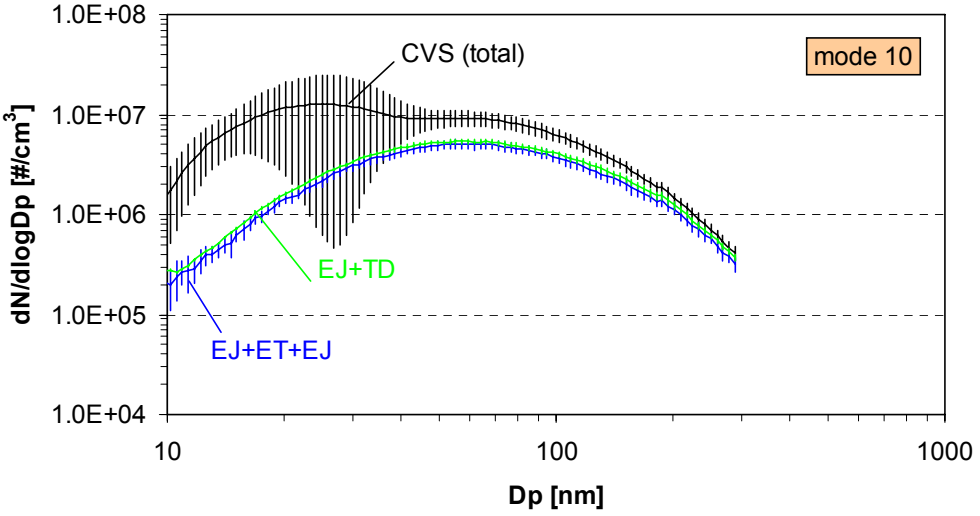

Figure 74: Size distributions at mode 10 (ESC).

3.3 ENGINE OUT

Temperatures

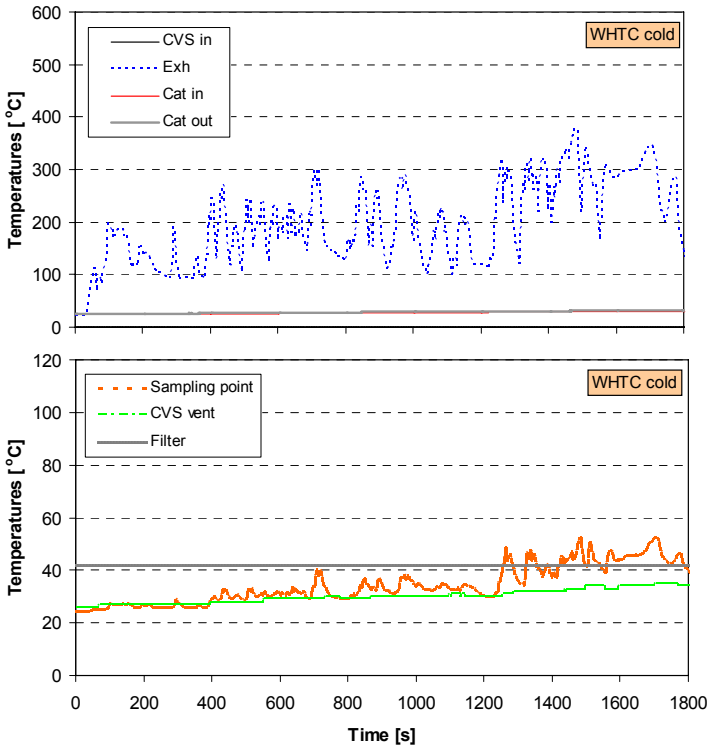

Figure 75: Temperature profiles over cold WHTC.

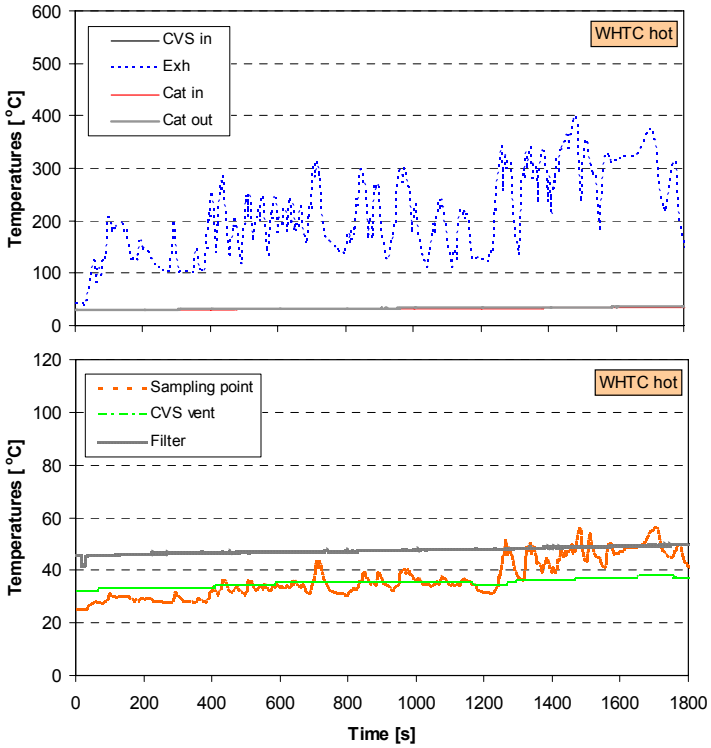

Figure 76: Temperature profiles over hot WHTC.

The temperature profiles (Figure 75, Figure 76) are similar with those with the after-treatment devices, although the exhaust gas temperature without any after-treatment device is slightly lower.

Legislated pollutants

The legislated emissions of the engine without any after-treatment device can be seen in Figure 77 for cold WHTC and Figure 78 for hot WHTC. The CO, THC and PM emissions are high. WHTC cold and hot have similar emissions for all pollutants except NO_x, which are lower at the hot cycle.

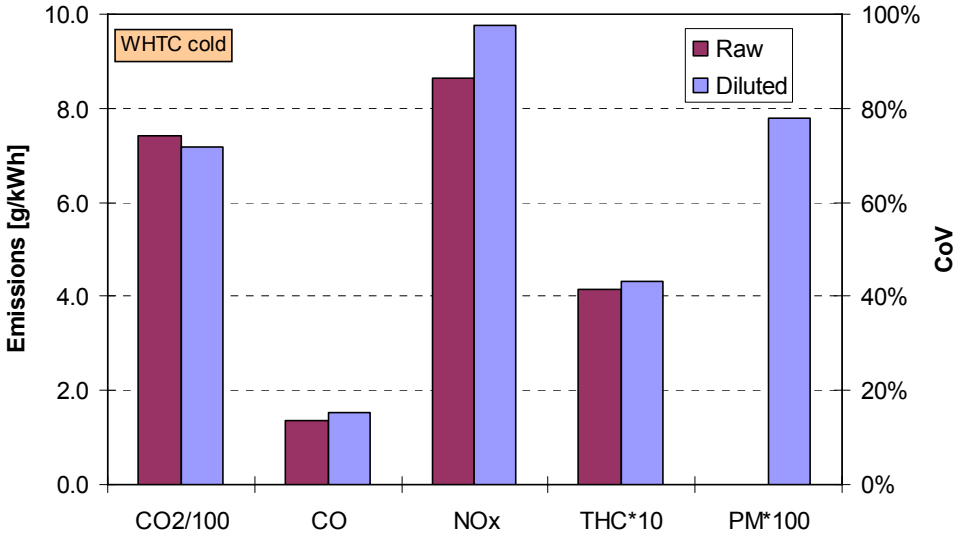

Figure 77: WHTC cold legislated pollutant results.

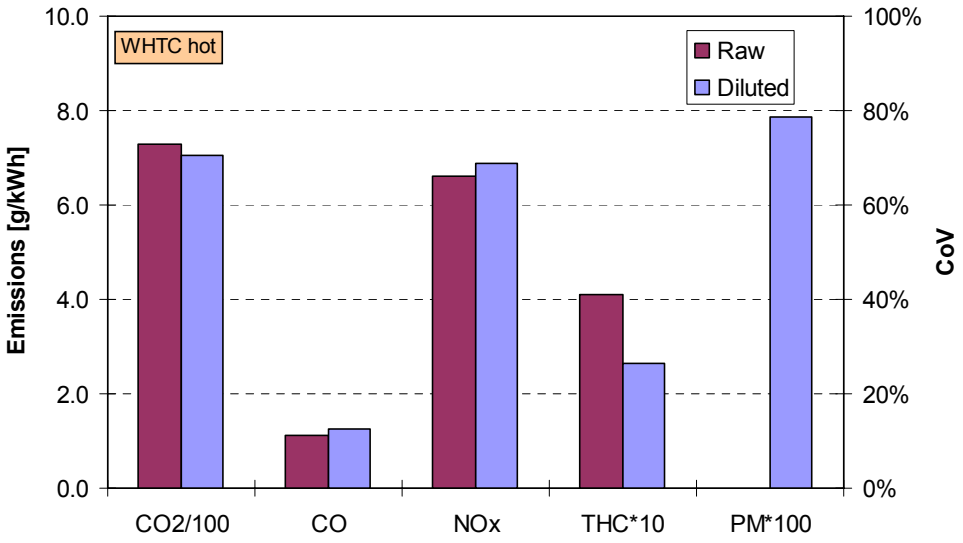

Figure 78: WHTC hot legislated pollutant results.

Comparison of full and partial flow systems

The comparison of full and partial flow systems for both cycles for PM can be seen in Figure 79 and for number in Figure 80. There is a difference of 20% between full and partial flow systems that need to be further investigated. The number emissions were similar for PSS-20 (with SPCS-20) and higher with SPC-472 (with Nanomet).

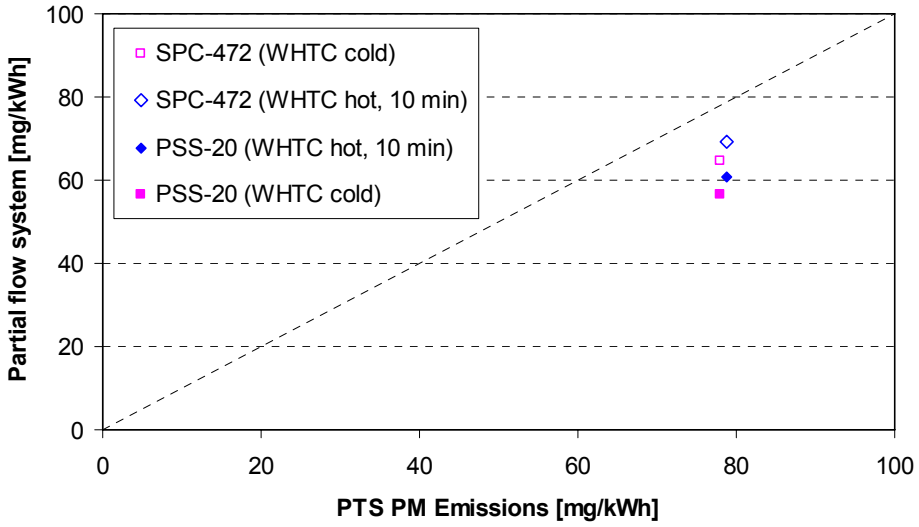

Figure 79: Comparison of PM emissions at full flow and partial flow systems.

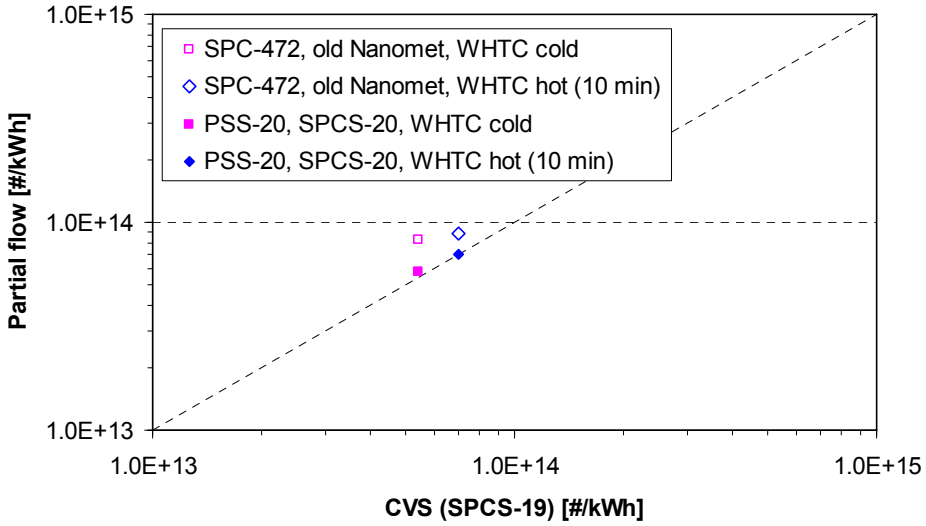

Figure 80: Comparison of PN emissions at full flow and partial flow systems.

Table 16: Relative differences to CVS values.

	WHTC cold	WHTC hot	WHSC	ETC	ESC
PM(SPC)	-22%	-17%			
PM(PSS)	-27%	-23%			
PN(SPC)	49	21			
PN(PSS)	7%	-1%			

Steady states

The steady state emission can be seen in Figure 81 for mode 10 and Figure 82 for mode 7. There is no NM at high mode, but there is at low mode. This is in agreement with other investigators.

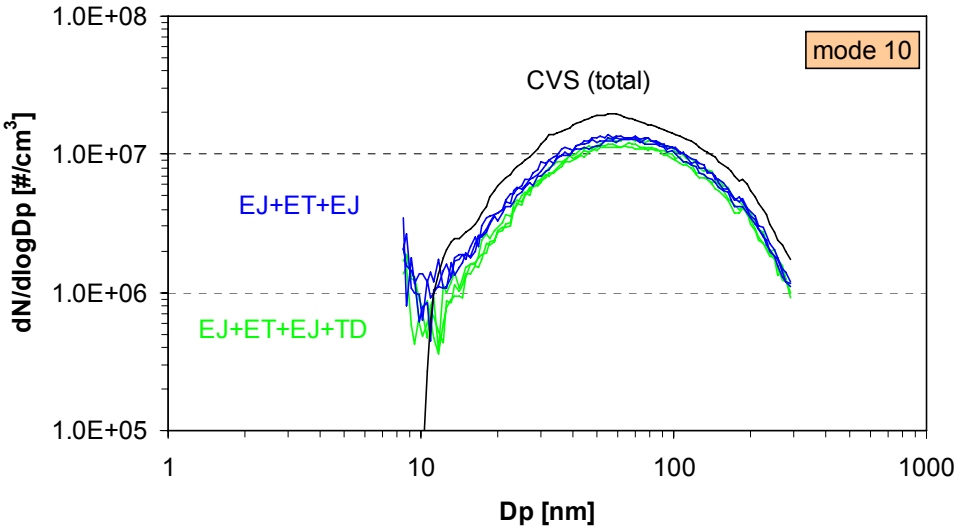

Figure 81: Size distributions at mode 10 (Engine out).

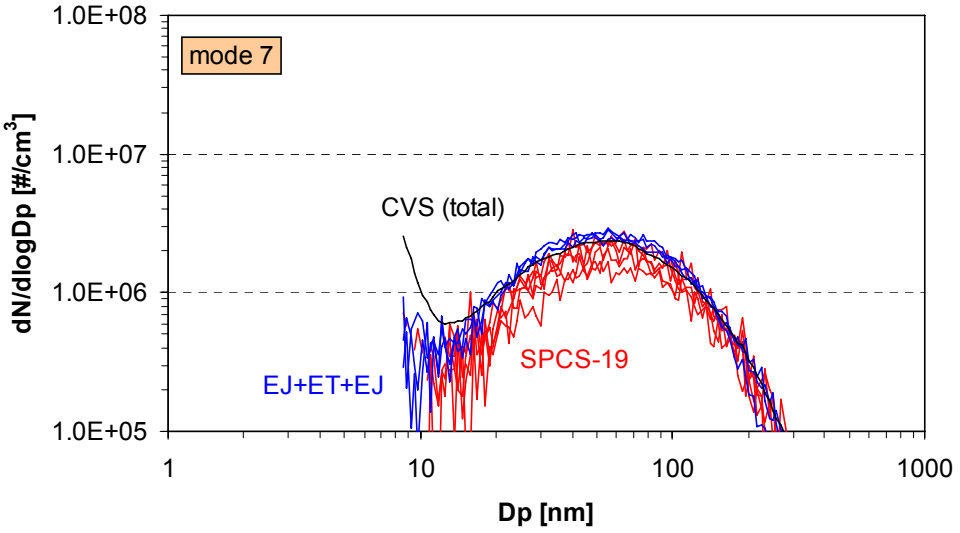

Figure 82: Size distributions at mode 7 (Engine out).

3.4 AFTER-TREATMENT COMPARISONS

Legislated emissions

The legislated emissions with the various after-treatment devices compared to the engine out emissions can be seen in Figure 83 and Figure 84. CO_2 and NO_x emissions are the same but an important decrease is observed for CO, THC and PM with the after-treatment devices. The efficiencies of the after-treatment devices for the WHTC cycles can be seen in Table 17.

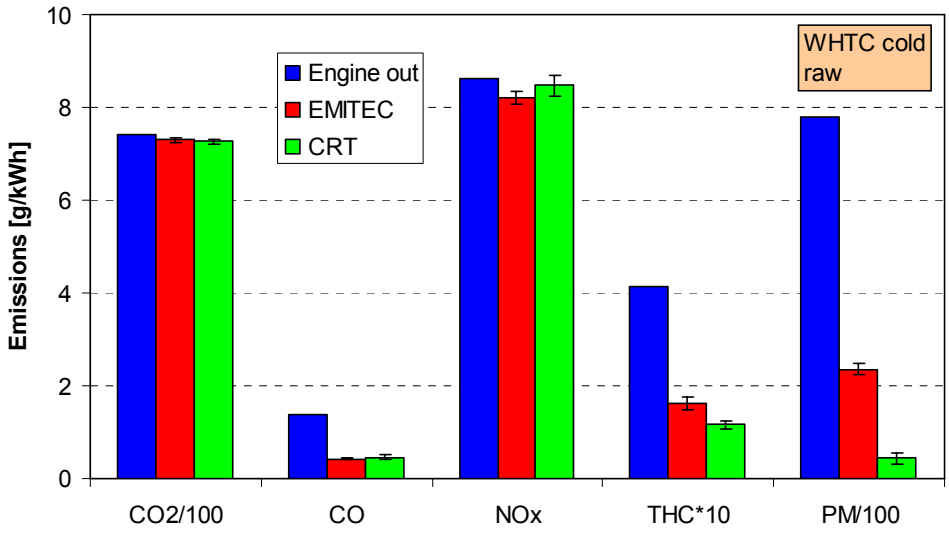

Figure 83: Effect of after-treatment devices on legislated emissions measured from the tailpipe for a cold WHTC.

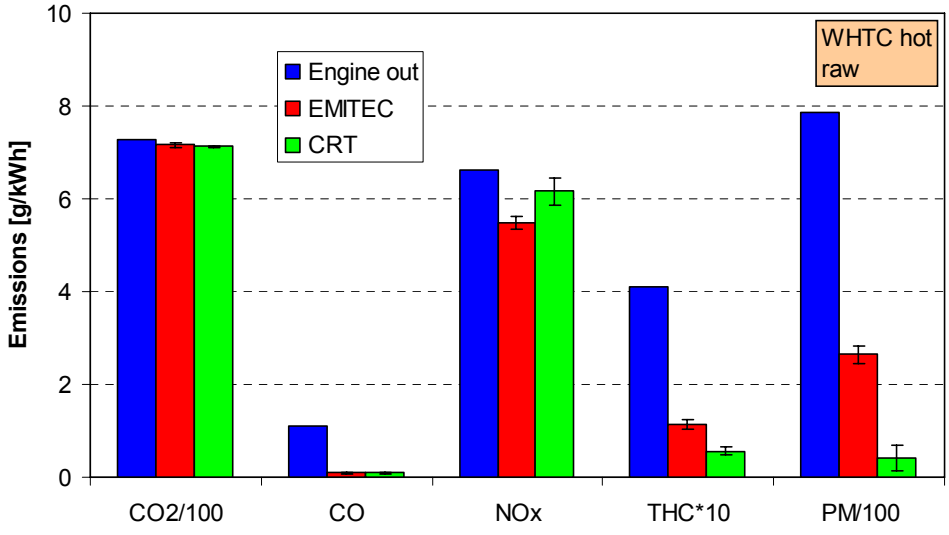

Figure 84: Effect of after-treatment devices on legislated emissions measured from the CVS for a hot WHTC.

Table 17: Efficiency of the after-treatment devices.

Cycle	*from*	*CO_2*	*CO*	*NO_x*	*THC*
EMITEC					
WHTC cold	Raw	1.7%	68.9%	5.0%	61.1%
	Diluted	1.0%	69.2%	14.7%	62.5%
WHTC hot	Raw	1.6%	92.2%	16.9%	72.2%
	Diluted	0.7%	91.5%	18.1%	59.6%
CRT					
WHTC cold	Raw	2.1	66.7	2.0	72.0
	Diluted	2.2	66.9	17.2	74.9
WHTC hot	Raw	2.0	92.1	6.7	86.2
	Diluted	7.3	91.8	19.8	82.6

PM emissions

Figure 85 and Figure 86 show the PM emissions for the different after-treatment devices for the full flow system CVS and the partial flow systems. The higher emissions of the engine out (without after-treatment) at CVS are probably due to higher volatile artifact on the filters, but this is something that needs to be further investigated.

PN emissions

The PN emissions for the different after-treatment devices for the full flow and the partial flow systems can be seen in Figure 87 and Figure 88. The PN reduction with EMITEC is 65% while with the CRT is 99% for the cold WHTC. For the hot WHTC the efficiency of the EMITEC is similar but for the CRT is 100%. The lower efficiency of the CRT at the cold WHTC has to do with the high particle emissions at the beginning of the cycle. This can be seen in Figure 89. It's also interesting to note that the PN emissions pattern is similar for all cases, even with CRT indicating that the particles that are measured are particles that are not efficiently trapped and escape and not re-entrained particles from the exhaust line or CVS. Steady state emission comparisons are shown in Figure 91-Figure 93.

Cycle	*PM (CVS)*	*PM (SPC)*	*PM (PSS)*	*PN (CVS)*	*PN (SPC)*	*PN (PSS)*
EMITEC						
WHTC cold	69.7%	65.8%	64.9%	62.4%	67.8%	60.5%
WHTC hot	66.1%	66.8%	64.5%	61.5%		60.8%
CRT						
WHTC cold	94.5%	91.2%	94.2%	99.0%	98.7%	99.0%
WHTC hot	94.0%	96.1%	96.3%	100.0%		100.0%

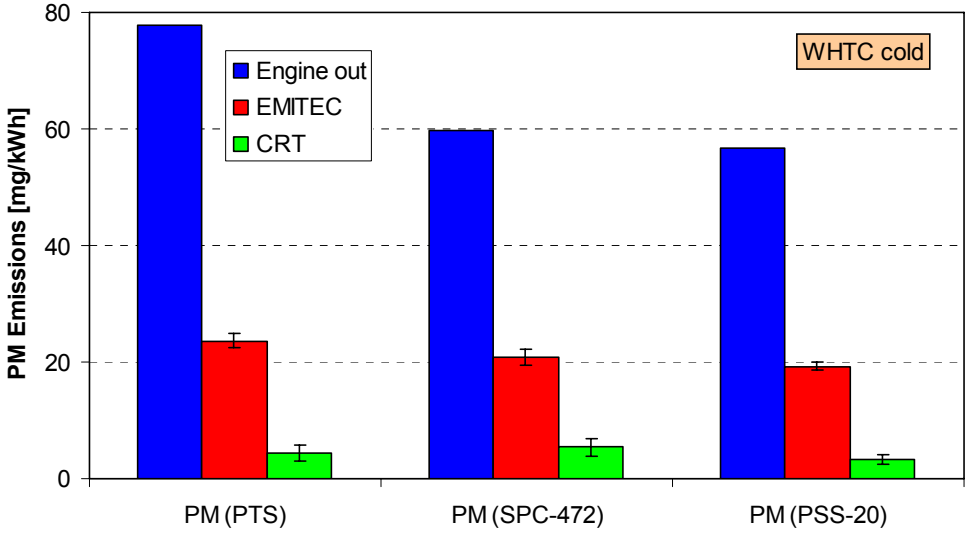

Figure 85: Effect of after-treatment devices on PM emissions (cold WHTC).

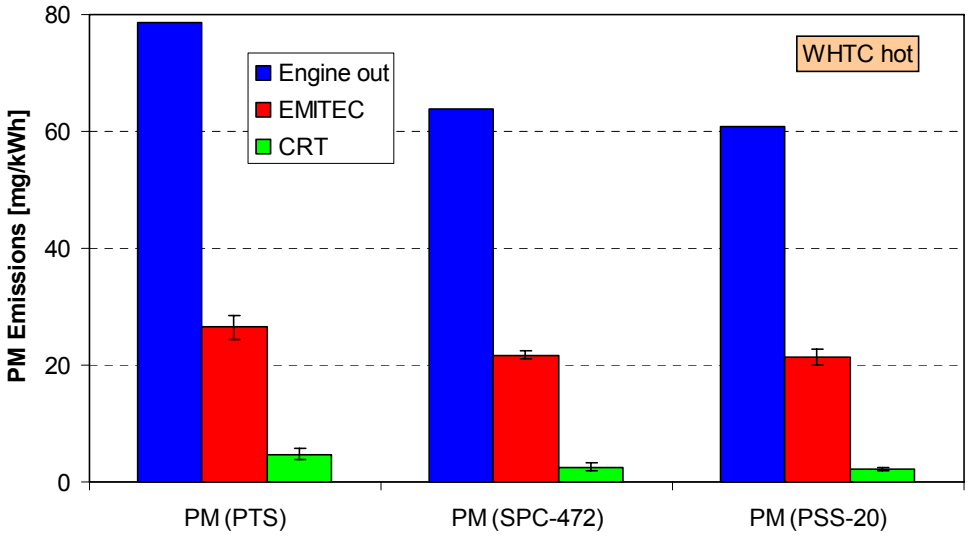

Figure 86: Effect of after-treatment devices on PM emissions (hot WHTC).

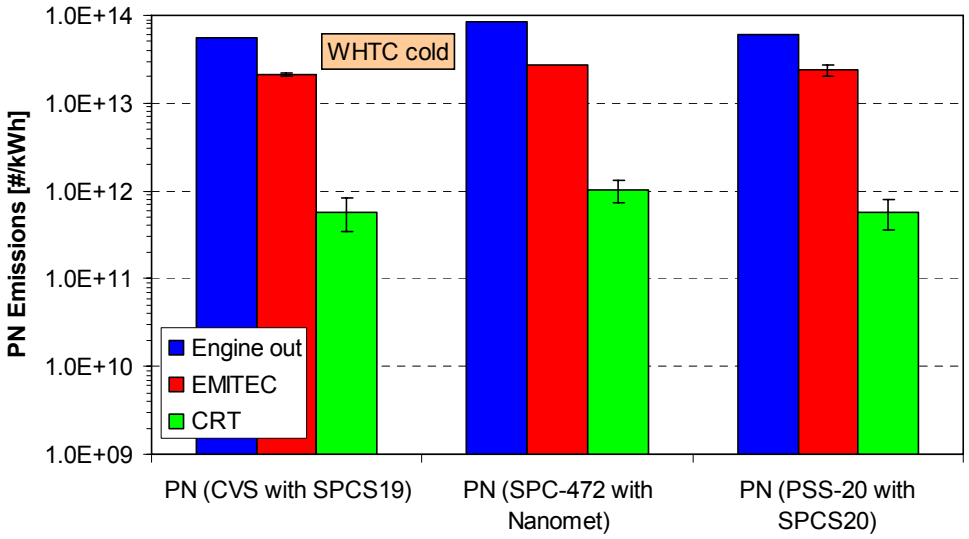

Figure 87: Effect of after-treatment devices on PN emissions (cold WHTC).

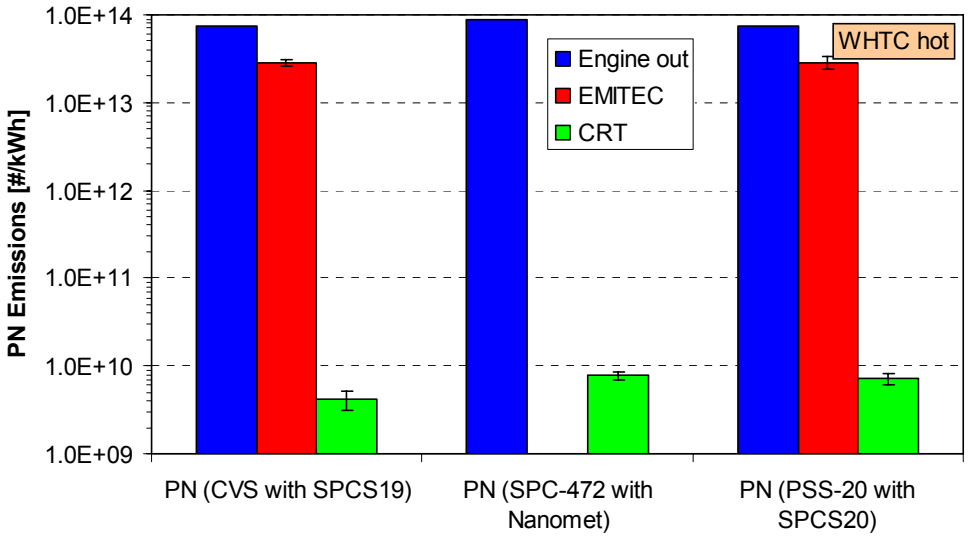

Figure 88: Effect of after-treatment devices on PN emissions (hot WHTC).

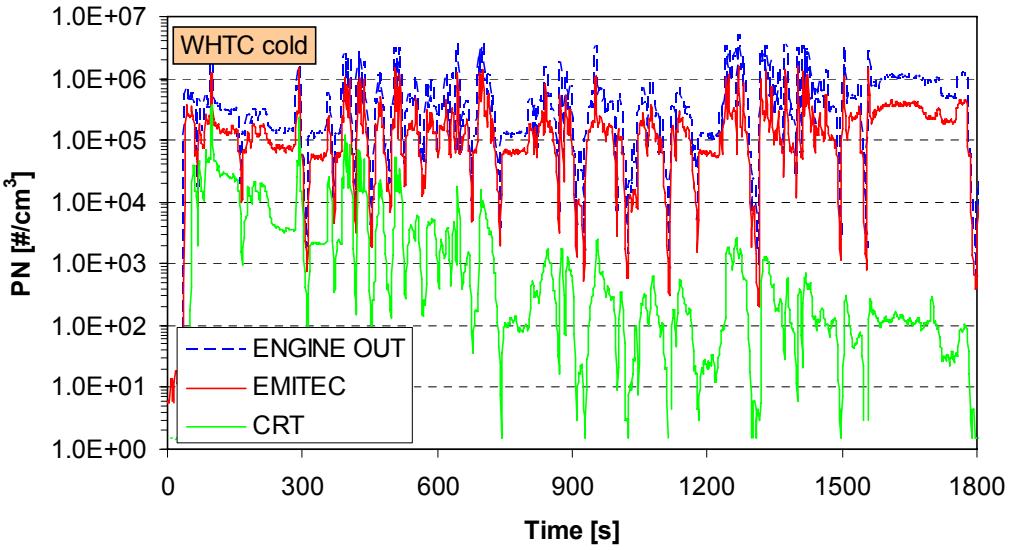

Figure 89: Real time PN pattern over the cold WHTC.

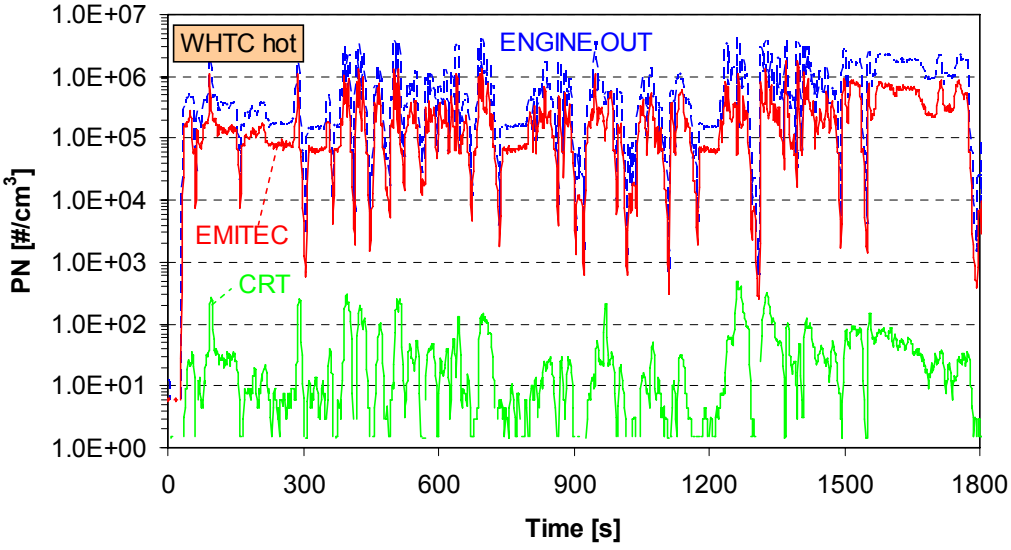

Figure 90: Real time PN pattern over the hot WHTC.

Steady states

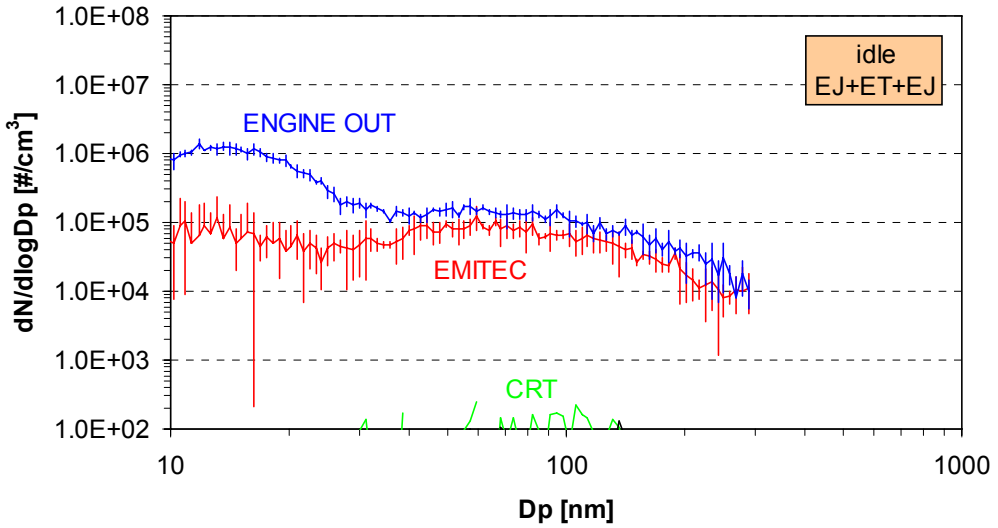

Figure 91: Comparison of various after-treatment devices at idle.

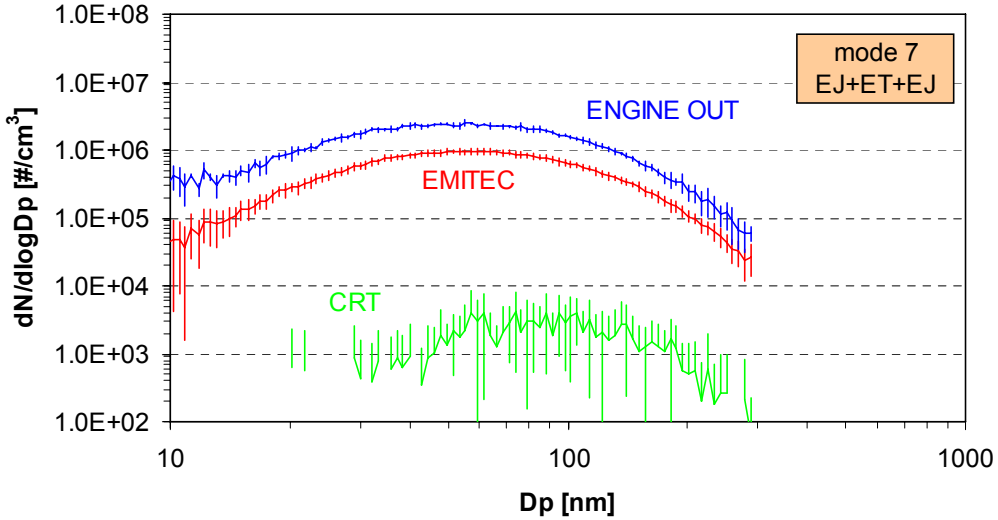

Figure 92: Comparison of various after-treatment devices at mode 7.

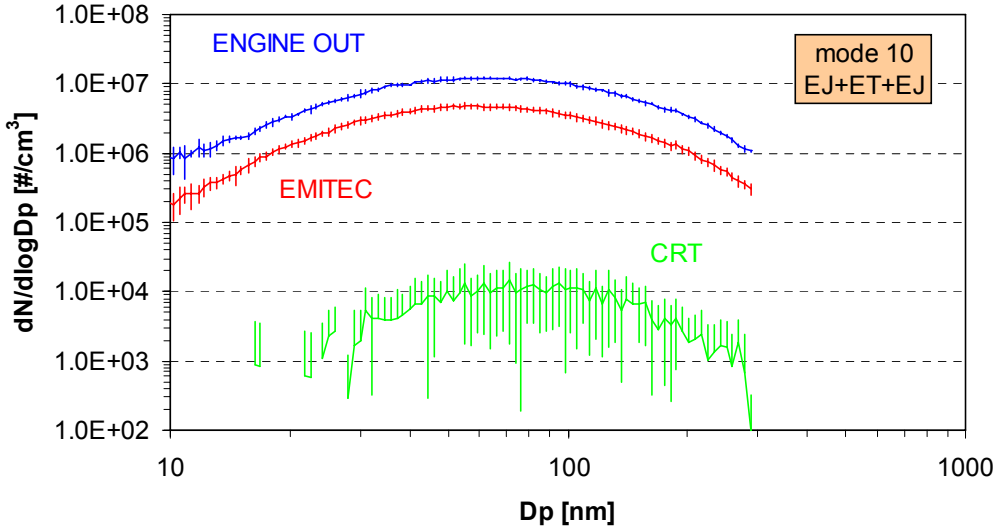

Figure 93: Comparison of various after-treatment devices at mode 10.

4. RESULTS (PHASE B)

These are the official PMP results of HRC for the validation exercise.

4.1 GOLDEN ENGINE WITH CRT

Temperatures

The following figures (Figure 94-Figure 98) show typical temperature profiles at the exhaust line, the dilution tunnel and the filter. The main conclusions are:

- The exhaust gas temperatures are around 400°C for the transient cycles and 500°C for the steady cycles.
- The temperature at the inlet of the dilution tunnel can reach 400°C at the ESC cycle.
- The PM sampling point temperature at the full dilution tunnel is around 60°C but can reach 100°C at the ESC cycle.
- The PM filter temperature is around 50°C.

The results are similar with Phase A temperatures, even for the ETC which had the big difference between the two phases.

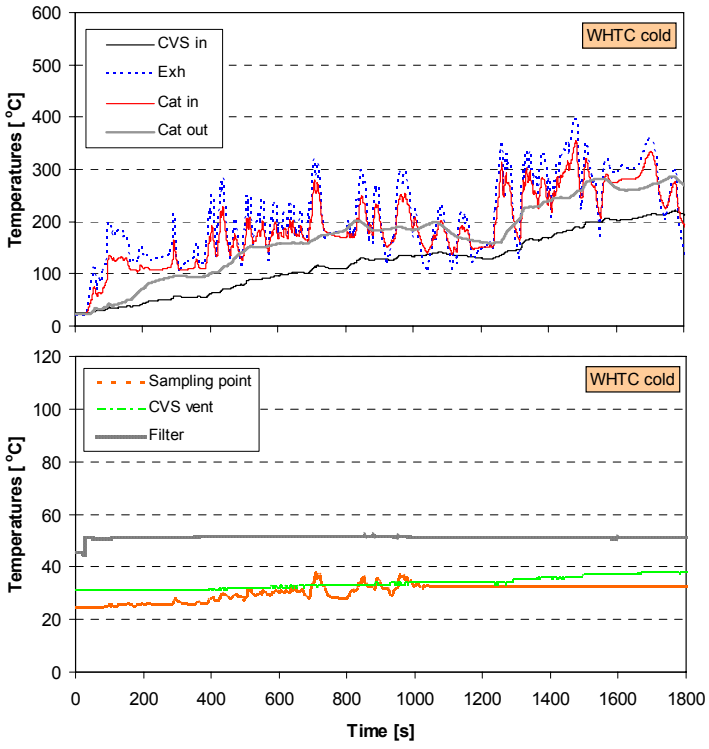

Figure 94: Temperature profiles over cold WHTC.

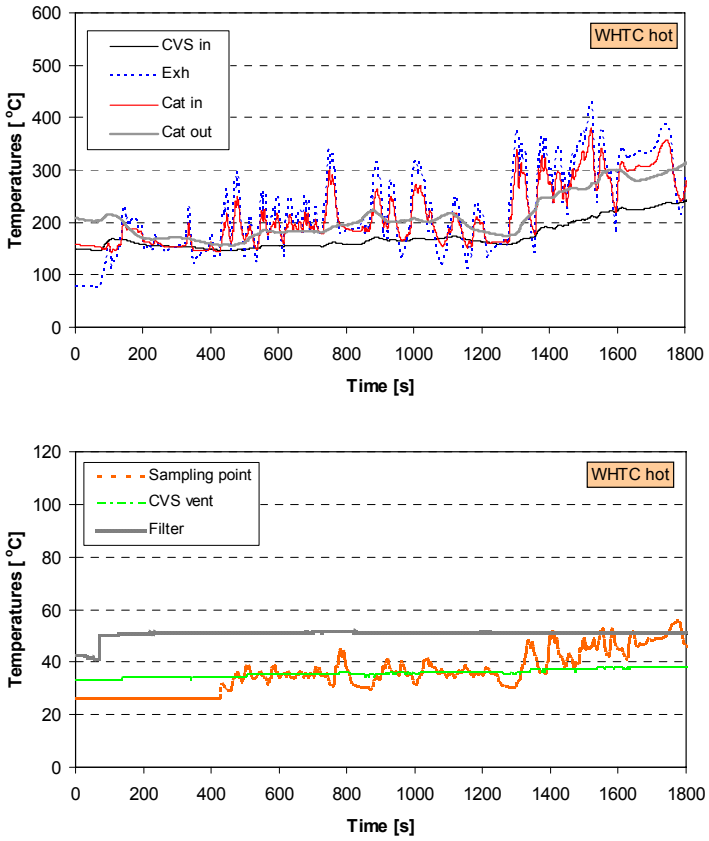

Figure 95: Temperature profiles over hot WHTC.

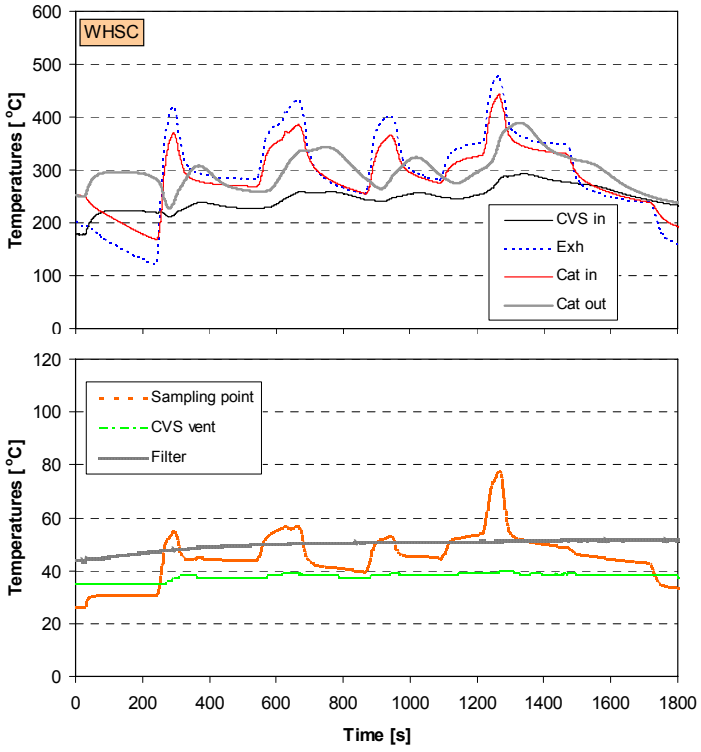

Figure 96: Temperature profiles over WHSC.

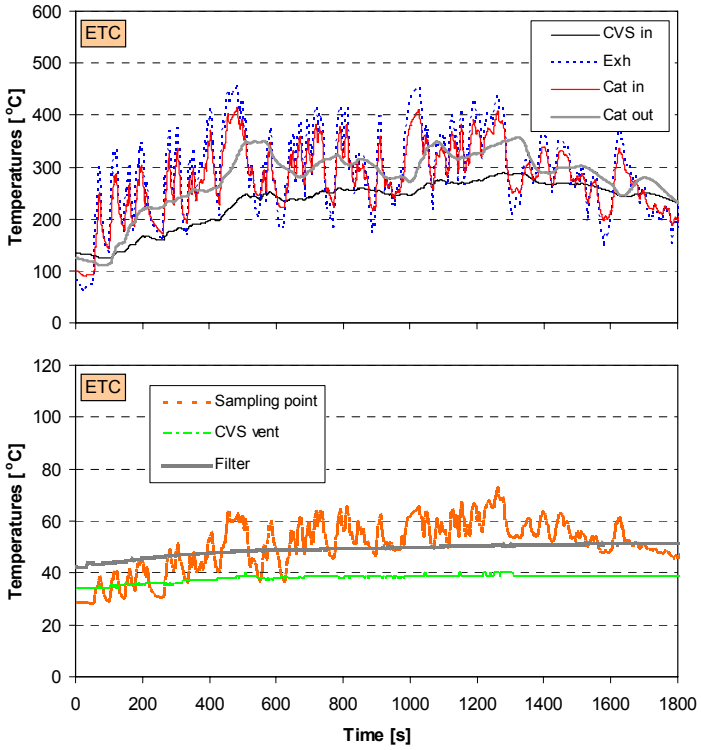

Figure 97: Temperature profiles over ETC.

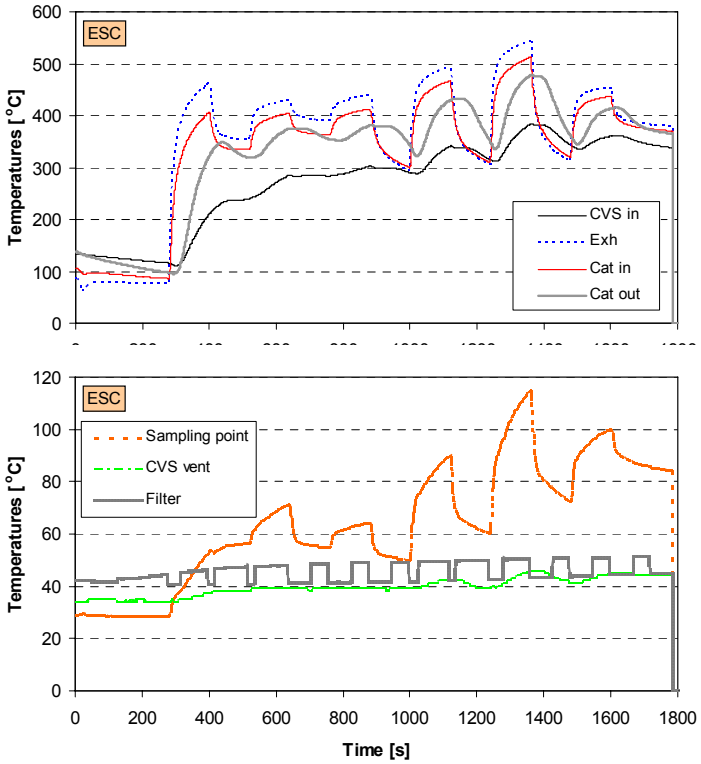

Figure 98: Temperature profiles over ESC.

Legislated pollutants

The results from the legislated pollutants are shown in the following figures (Figure 99-Figure 103). Both raw (from exhaust tailpipe) and diluted (from the full dilution tunnel) results are shown. The main conclusions are:

- The CO_2 emissions were around 700 g/kWh
- The CO emissions were <0.4 g/kWh
- The NO_x emissions decreased over time. They were high at the cold start cycle (9 g/kWh) and dropped to less than half at the final cycle (4 g/kWh).
- The THC were very low (<0.04 g/kWh) for all cycles except the cold start (0.1 g/kWh).

The difference between raw and diluted NO_x emission results probably due to leakage at one of the pneumatic valves at the diluted line (as the AVL system was calibrated between Phase A and B). The differences between Phase A and B were small.

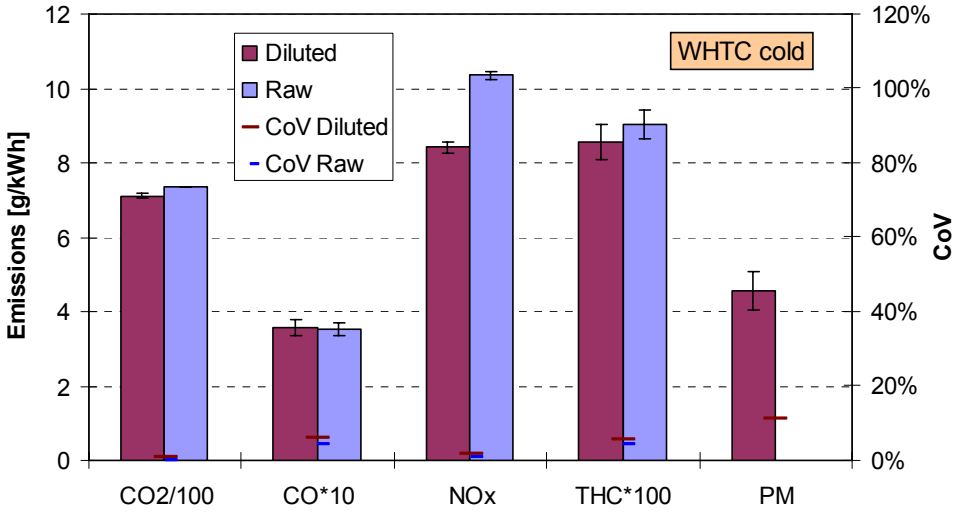

Figure 99: WHTC cold pollutants results.

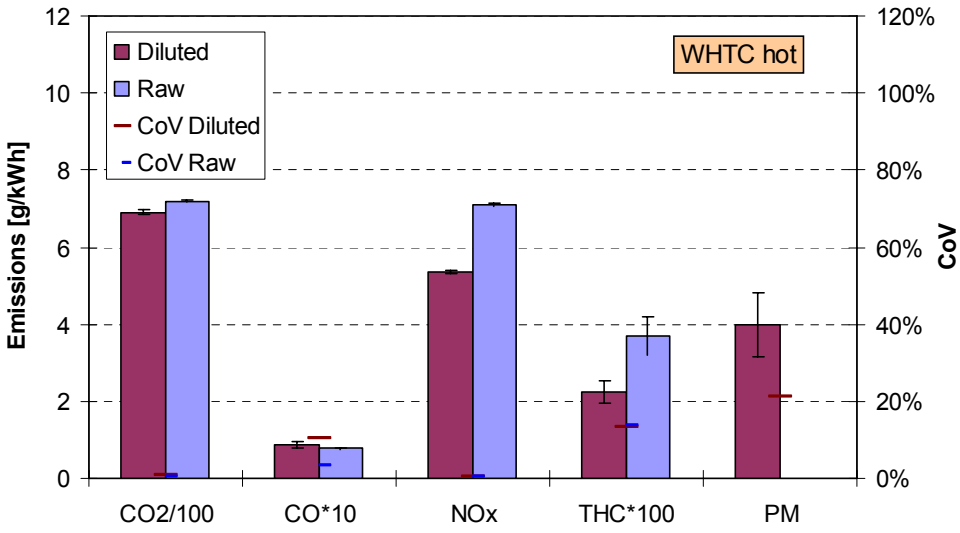

Figure 100: WHTC hot (10 min) pollutants results.

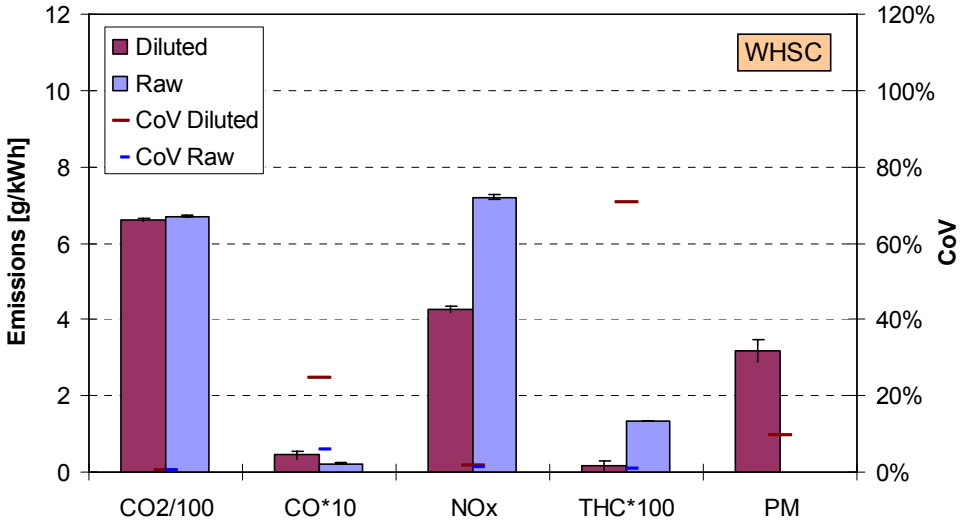

Figure 101: WHSC pollutants results.

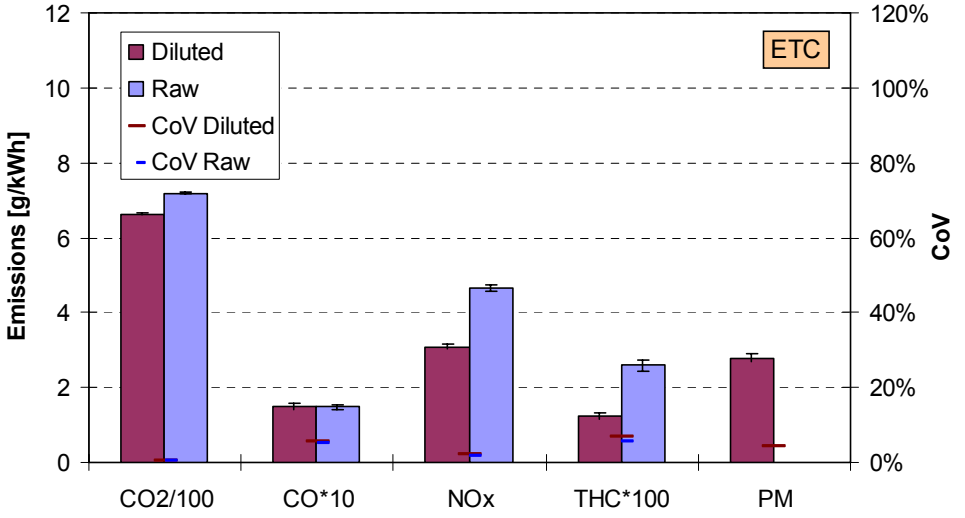

Figure 102: ETC pollutants results.

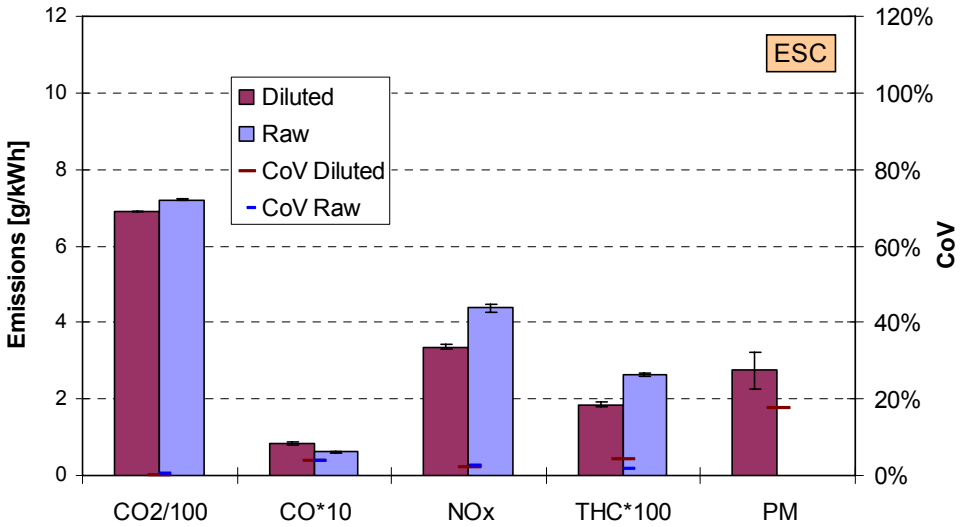

Figure 103: ESC pollutants results.

Real time PN emissions

Figure 104-Figure 108 show the real time pattern of the particle number system for the SPCS-19 at CVS and SPCS-20 at SPC-472 during a cold WHTC, a hot WHTC, a WHSC, an ETC and an ESC. The emissions of the cold WHTC are very high at the beginning of the cycle. The emissions later and at the hot WHTC are low. The WHSC are slightly higher than at the hot WHTC. The ETC emissions are low. The ESC emissions are high due to the high temperature modes. The discussion on the number emission patterns can be found in Giechaskiel et al. (2008c). A very good agreement is observed between the full flow and partial flow system. The backgrounf levels of all systems (CVS, SPC-472, SPCS-19 and SPCS-20) are in the order of a few particles and for this reason even the emission pattern of the ETC cycle can be seen. It has to be emphasized that the peaks during the ETC or hot WHTC (1000 #/cm^3) mean translate to 7 #/cm^3 at the CPC.

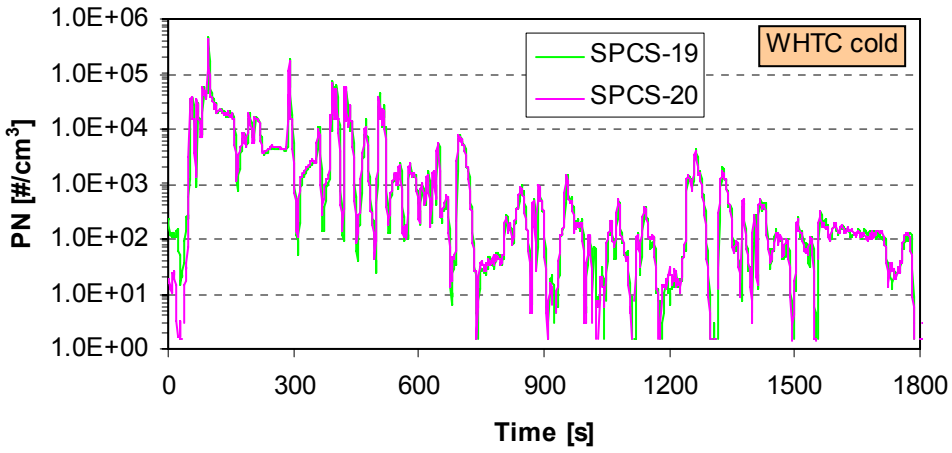

Figure 104: Real time PN emissions from CVS and the partial flow system over cold WHTC.

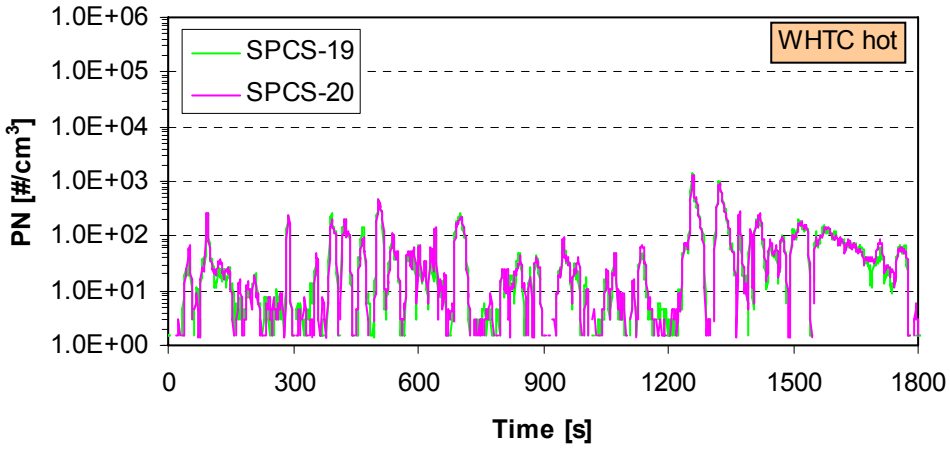

Figure 105: Real time PN emissions from CVS and the partial flow system over hot WHTC.

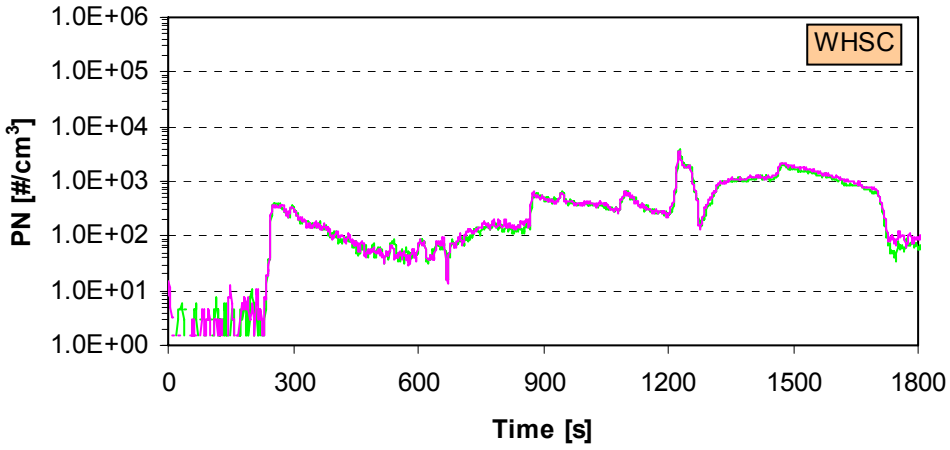

Figure 106: Real time PN emissions from CVS and the partial flow system over WHSC.

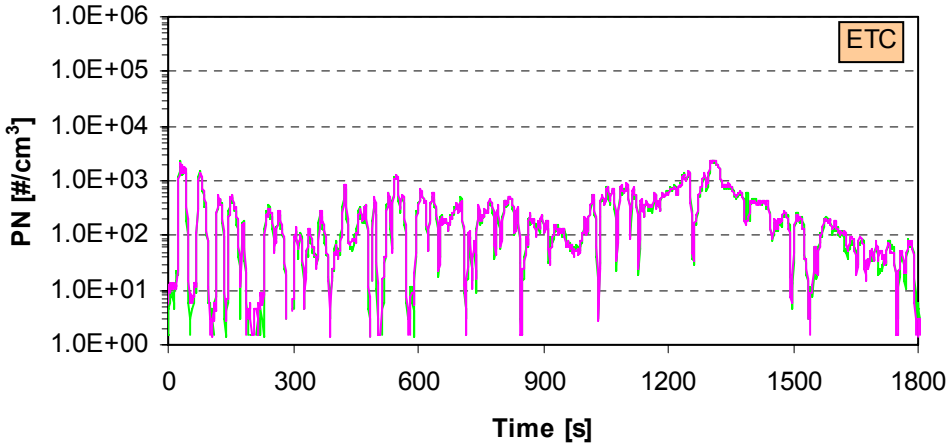

Figure 107: Real time PN emissions from CVS and the partial flow system over ETC.

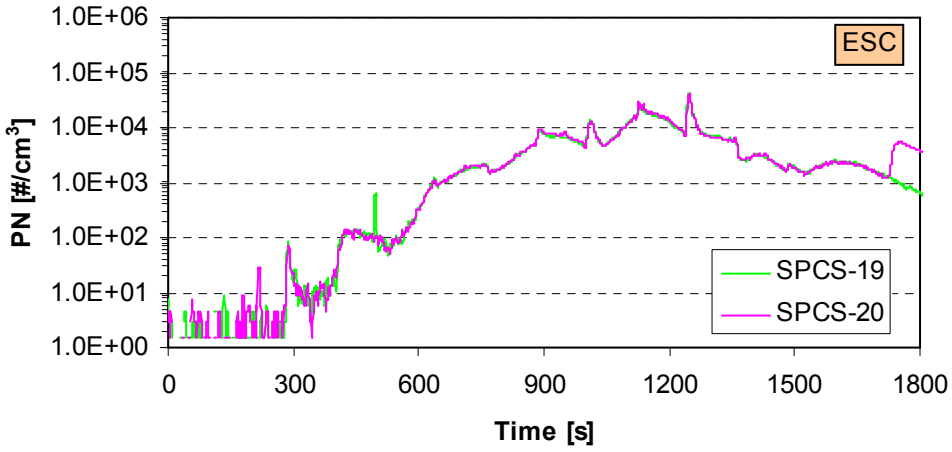

Figure 108: Real time PN emissions from CVS and the partial flow system over ESC.

Summary of legislated emissions

The summary of the legislated results can be seen in Figure 109. The cold cycle CO, NO_x and THC emissions are much higher than at the rest cycle. For PM, the difference between cold and hot WHSC is not statistically significant. The summary of the PM emissions at CVS and at the SPC-472 can be seen in Figure 110. The PM emissions from SPC-472 are generally 30% lower. The correlation is shown in Figure 111. (See also Table 18 and Table 19).

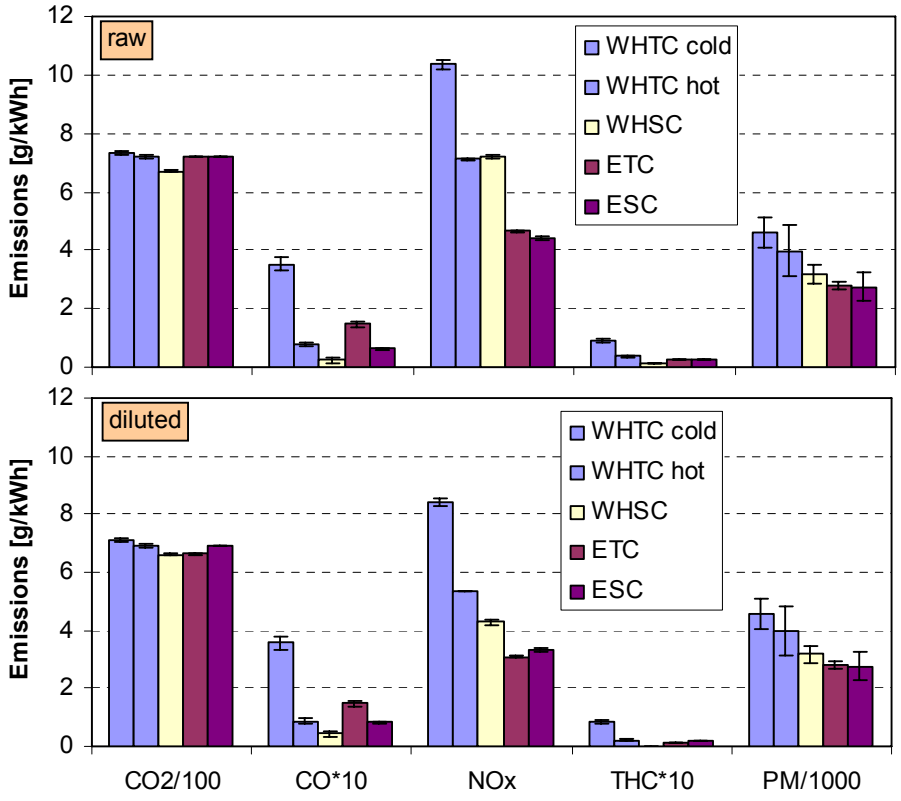

Figure 109: Summary of legislated pollutant results.

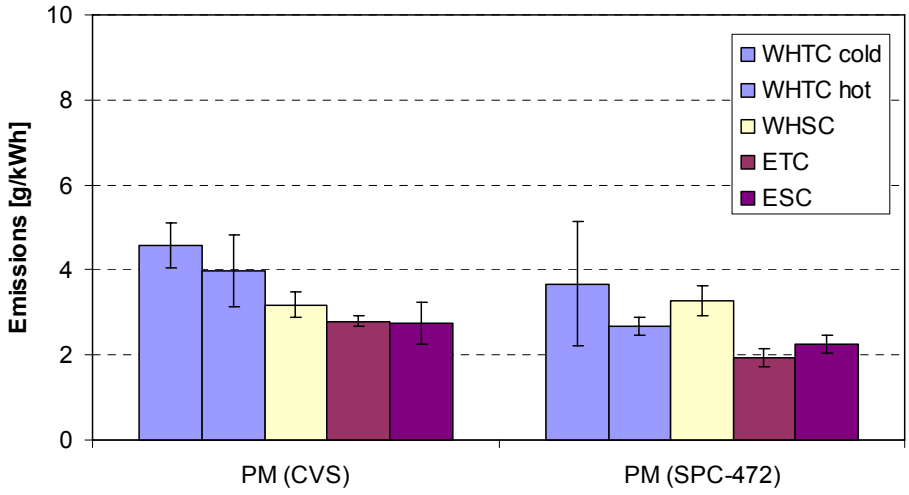

Figure 110: Summary of PM results.

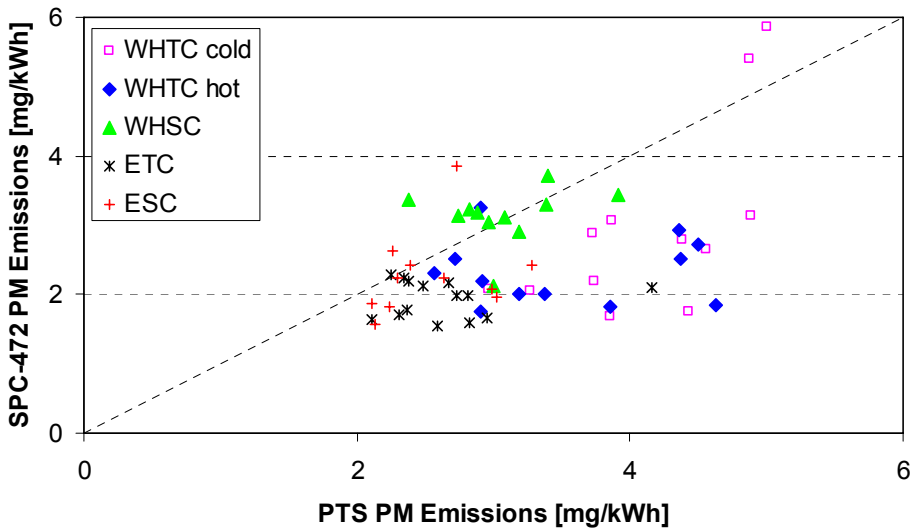

Figure 111: Correlation of PM emissions at CVS and at the SPC-472.

Summary of PN emissions

The results for PN can be seen in Figure 112. The different emissions of the different cycles can be observed. In addition the close correlation of the CVS and SPC-472 can be observed. The correlation of the two systems for all cycles can be seen in Figure 113. Table 18 shows the absolute levels and Table 19 summarizes the differences. The SPCS-20 at the partial flow system was measuring 5% higher than the SPCS-19 at CVS. However, the difference was not statistically significant as the variability of the differences was 10%.

Table 18: PM and PN emissions (mg/kWh for PM and#/kWh for PN). Number after ± indicates the CoV.

[…/kWh^{-1}]	*WHTC cold*	*WHTC hot*	*WHSC*	*ETC*	*ESC*
PM(CVS)	4.6 ±11%	4.0 ±21%	3.2 ±10%	2.8 ±4%	2.7 ±18%
PM(SPC)	3.7 ±40%	2.7 ±7%	3.3 ±11%	1.9 ±11%	2.3 ±9%
PN(CVS)	3.9x10^{11} ±10%	5.3x10^{9} ±15%	4.0x10^{10} ±50%	1.6x10^{10} ±15%	1.4x10^{11} ±7%
PN(SPC)	4.0x10^{11} ±14%	5.3x10^{9} ±17%	4.4x10^{10} ±49%	1.8x10^{10} ±19%	1.5x10^{11} ±12%

Table 19: Averages of relative difference compared to CVS. The number after ± indicates the standard deviation of the difference (more tests included).

	WHTC cold	*WHTC hot*	*WHSC*	*ETC*	*ESC*
PM difference	-30% (±24%)	-31% (±20%)	4% (±18%)	-25% (±15%)	-10% (±23%)
PN difference	5% (±12%)	-1% (±9%)	6% (±11%)	5% (±8%)	6% (±7%)

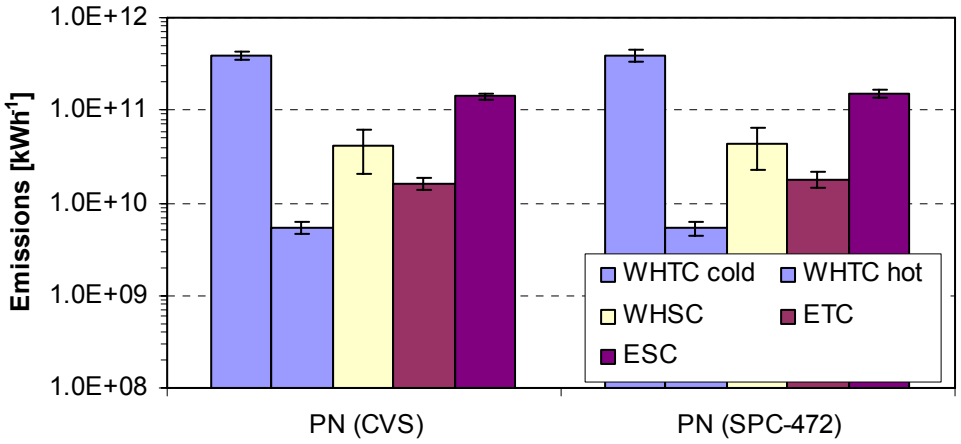

Figure 112: Summary of PN results.

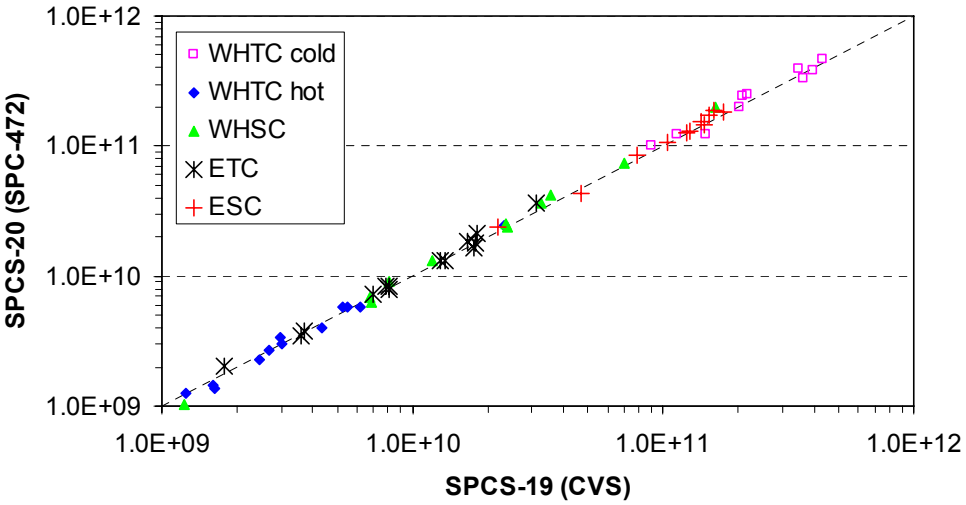

Figure 113: Correlation of PN emissions at CVS and SPCS-472 for all cycles.

Comparison with other systems

The real time emissions of various number systems at CVS for various cycles can be seen in Figure 114 - Figure 118. The summary is given in Table 20. The 3025A was corrected for the 12% overestimation of emissions (slope).

The particle number systems at CVS correlated well. The Nanomet (with a 3010D') measured 25% higher, while the dual ejector system (with a 3790) 10%. The thermodenuder system 20% higher. Taking into account the PRFs the differences would be lower.

Comparing the emissions from the Nanomet with particle counters of different cut points shows that the non-volatile particle emission >23 nm (with 3010D') and >10 nm (3010) are similar for most cycles (similarly higher than SPCS). Only in the case of the cold WHTC there is a 40% difference. The 3025A (>3 nm) measured 30% higher emissions (in the case of the cold WHTC +90%) indicating the existence of non-volatile particles between 3 and 23 nm. Similar results were measured with the 3025A downstream of the thermodenuder or the SPCS.

Comparing the emissions of a 3790n at the dual ejector system with hot or cold dilution shows small differences at most cycles with the exception of the cold WHTC where 50% more

volatiles (>23 nm) are measured. Comparison of the emissions of the 3025A at CVS or at SPCS shows that the volatiles are 30-60%. Only the hot WHTC shows high volatile emissions probably due to the low non-volatile emissions of the cycle (low available surface area). The cold WHTC on the other hand are very low probably due to the high non-volatile emissions.

Table 20: Average of relative difference compared to SPCS-19 at CVS. The number after ± indicates the standard deviation of the difference.

	WHTC cold	*WHTC hot*	*WHSC*	*ETC*	*ESC*
CPC 3790n					
EJ+ET+EJ (8)	-4% (±3%)	42% (±17%)	13% (±14%)	13% (±10%)	2% (±8%)
TD (2)	-7%* (±15%)	21% (±25%)	19% (±5%)	20% (±22%)	15% (±1%)
Cold EJ+EJ (1)	50%	20%	-4%	-5%	-8%
CPC 3025A					
CVS (3)	93%**	330% (±69%)	68% (±10%)	83% (±8%)	48% (±2%)
TD (3)	71% (±24%)	84% (±11%)	41% (±1%)	39% (±1%)	39% (±3%)
SPCS (4)	76% (±38%)	50% (±31%)	27% (±17%)	23% (±5%)	10% (±6%)
Nanomet with					
3010D' (10)	37% (±7%)	31% (±9%)	21% (±10%)	22% (±8%)	17% (±3%)
3010 (2)	79% (±4%)	41% (±4%)	20%	13% (±4%)	11% (±2%)
3010 (cold) (1)	218%	486%	130%		38%
3025A (1)	128%	85%	48%	40%	37%

* saturation of CPC

** downstream of the cold dual ejector system

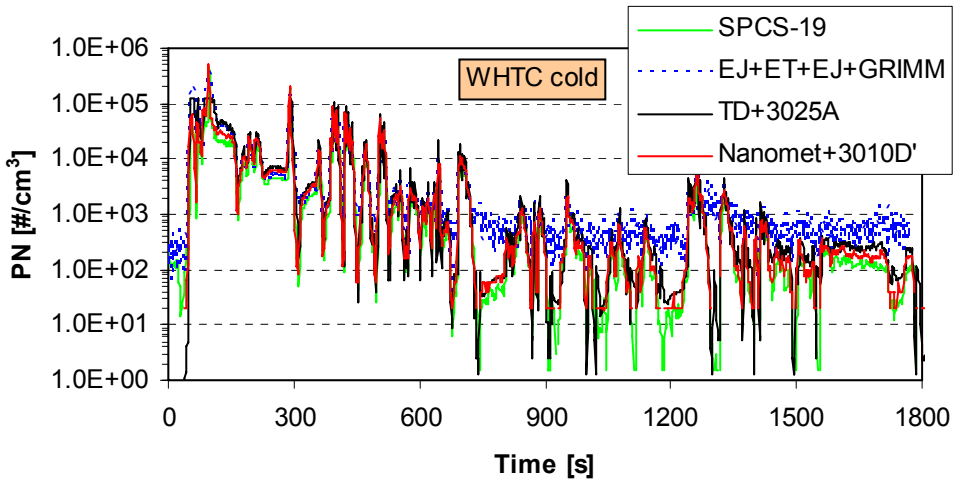

Figure 114: Real time emissions over a cold WHTC.

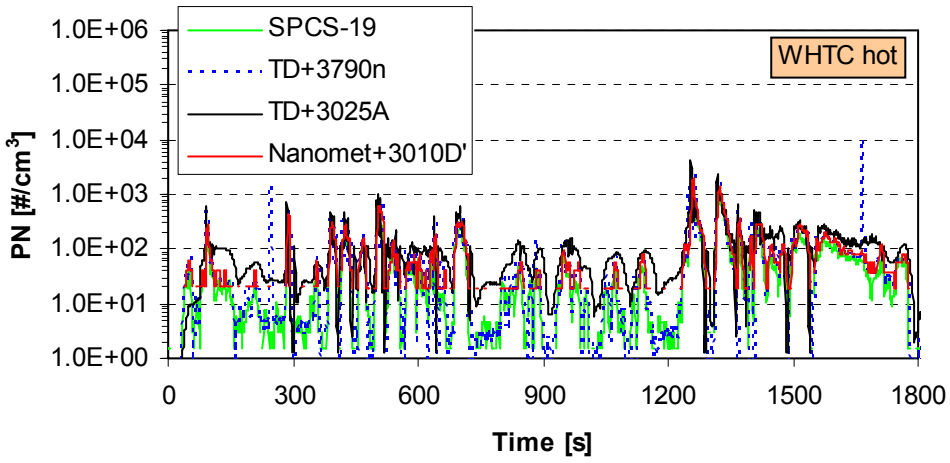

Figure 115: Real time emissions over a hot WHTC.

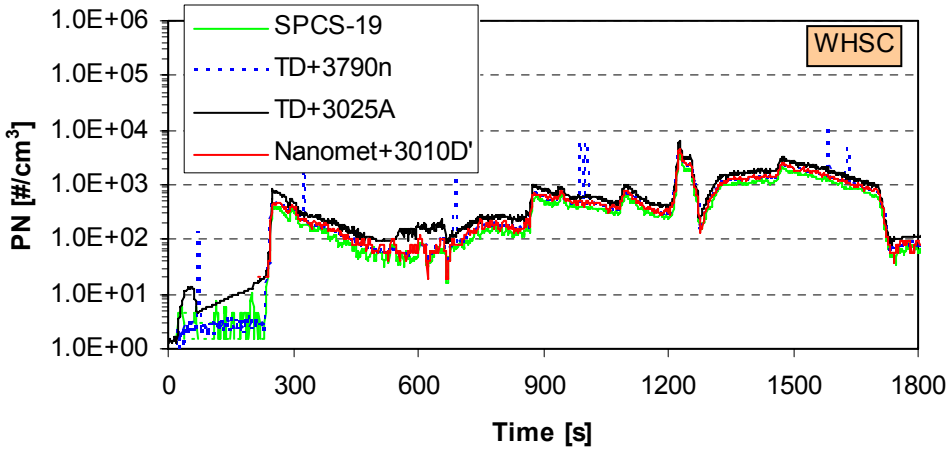

Figure 116: Real time emissions over a WHSC.

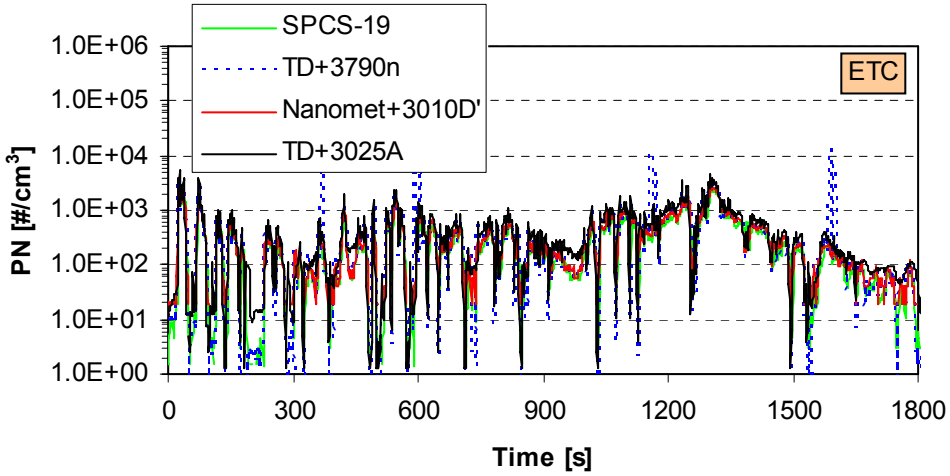

Figure 117: Real time emissions over an ETC.

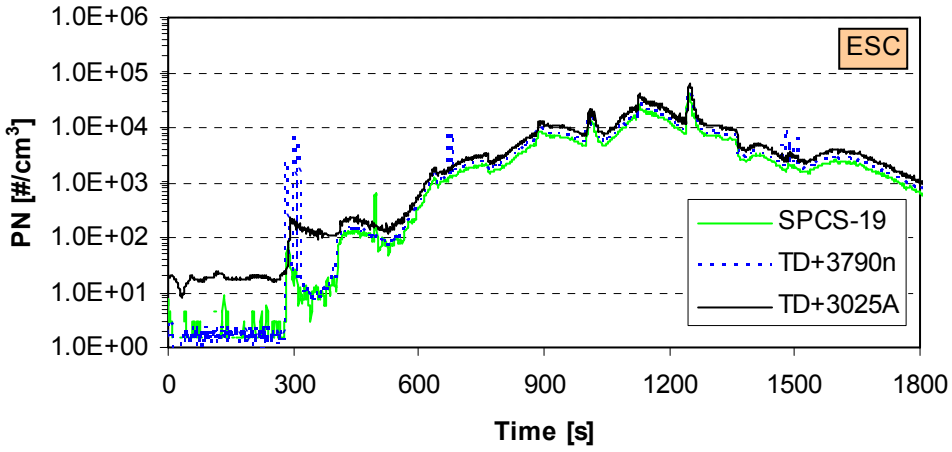

Figure 118: Real time emissions over an ESC.

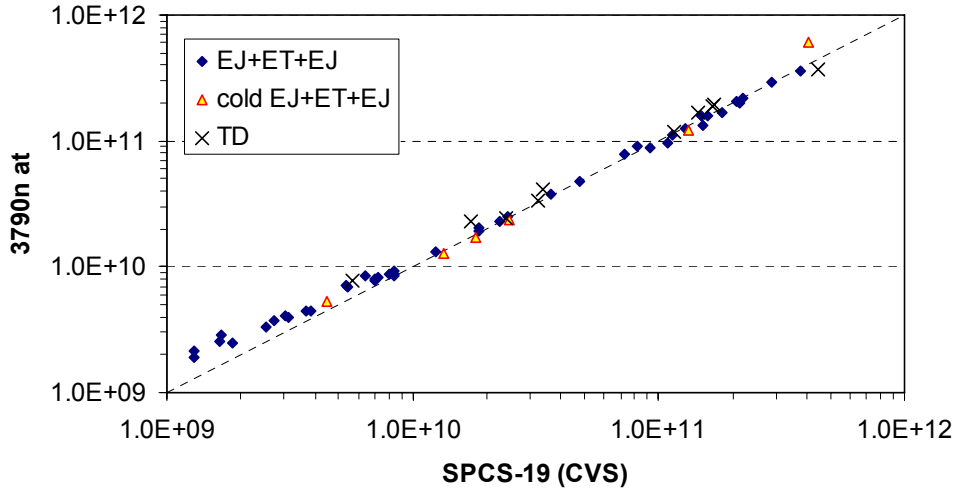

Figure 119: Correlation of SPCS-19 with the ejector systems and the thermodenuder (TD).

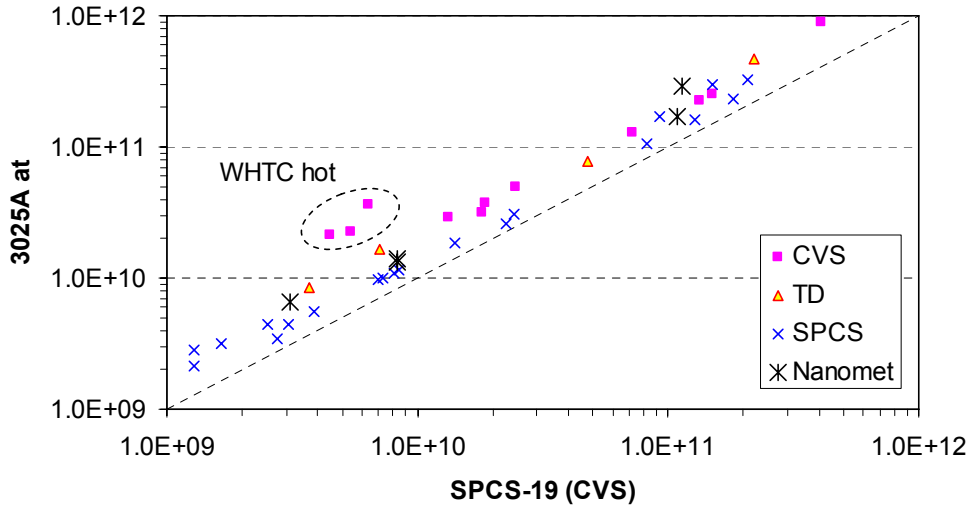

Figure 120: Comparison of SPCS-19 (>23 nm) with the 3025A (>3 nm) at the CVS, or downstream of the thermodenuder (TD), SPCS or Nanomet.

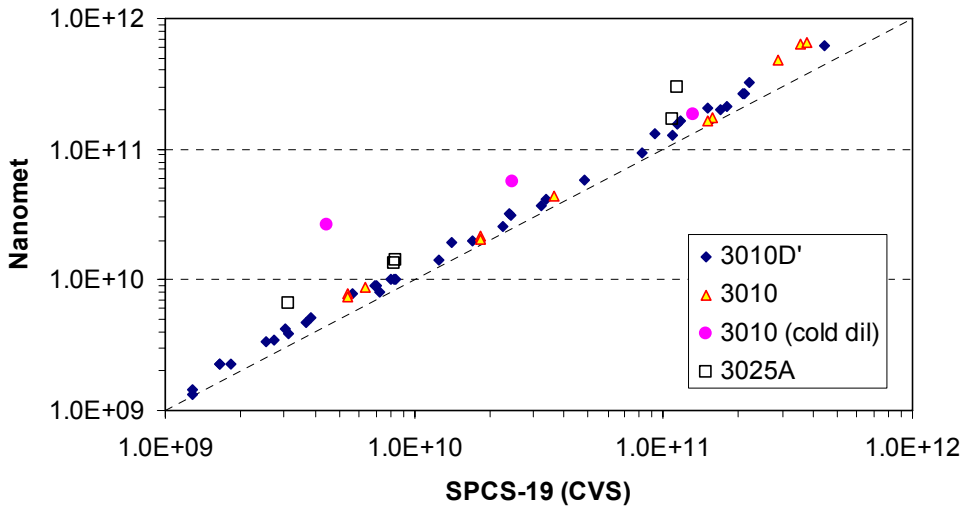

Figure 121: Comparison of SPCS-19 with Nanomet.

4.2 AFTER-TREATMENT EFFECT

Legislated pollutants

The legislated emissions with the various after-treatment devices can be seen in Figure 122-Figure 126. CO_2 and NO_x emissions are the same but an important decrease is observed for CO, THC and PM. The efficiencies of the after-treatment devices for the WHTC cycles can be seen in Table 21.

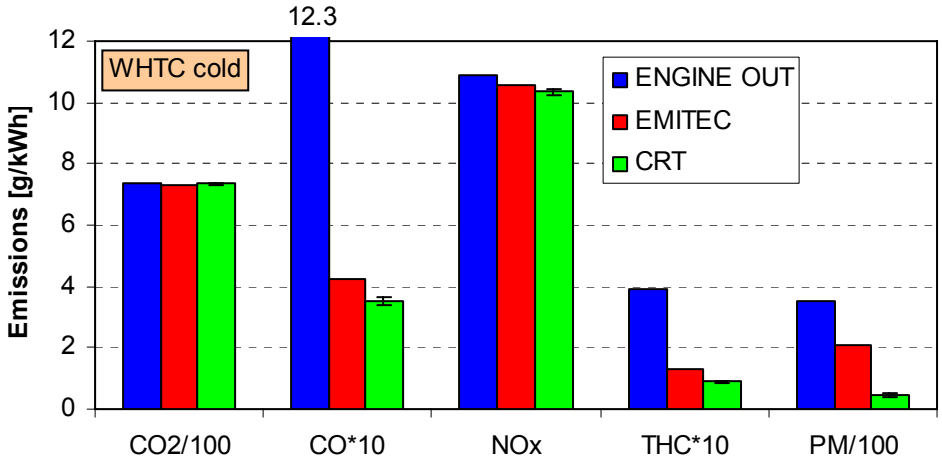

Figure 122: Comparison of after-treatment devices (WHTC cold).

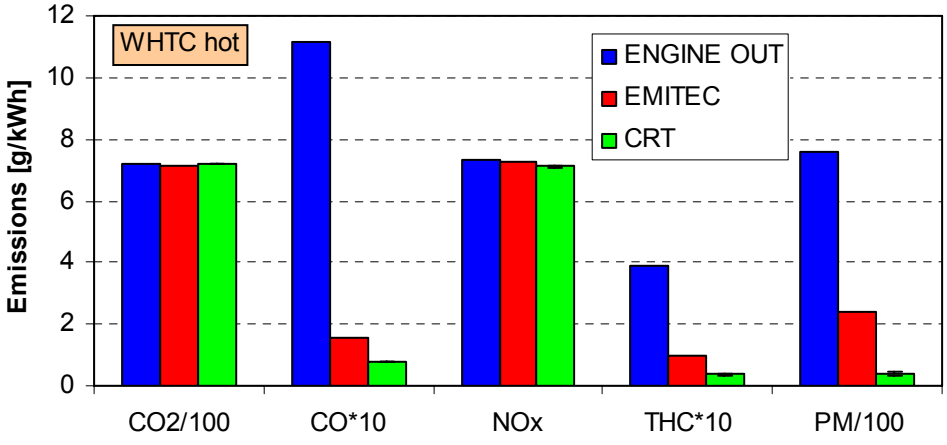

Figure 123: Comparison of after-treatment devices (WHTC hot).

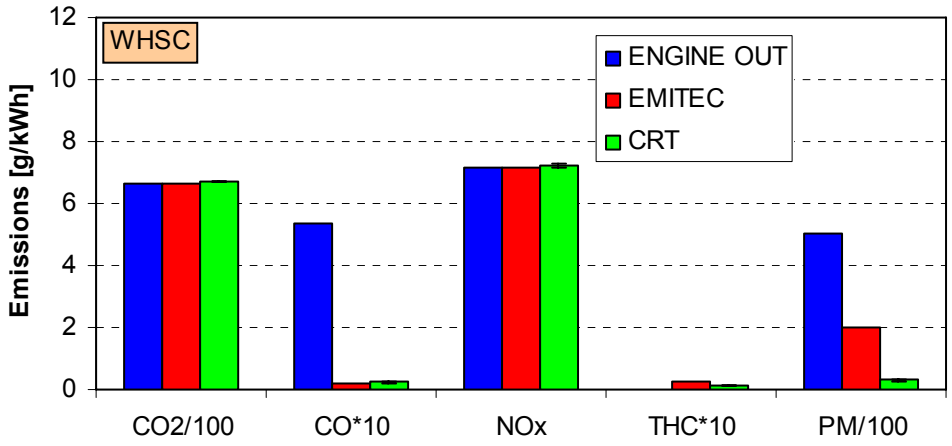

Figure 124: Comparison of after-treatment devices (WHSC).

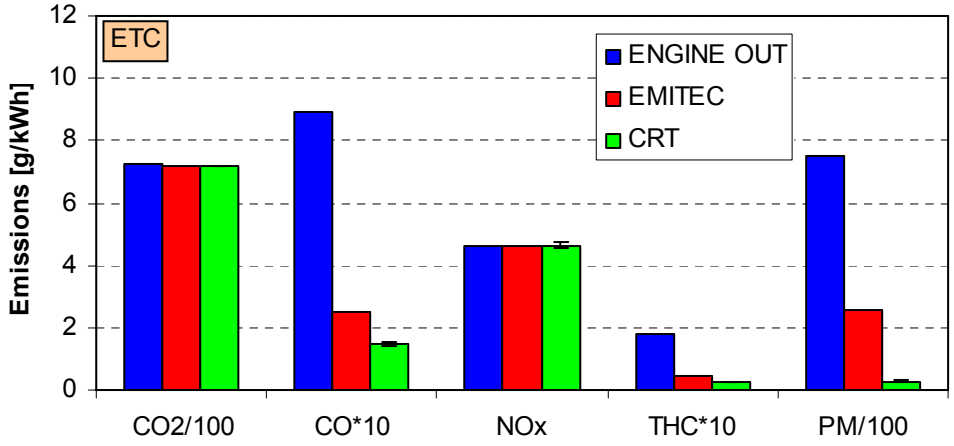

Figure 125: Comparison of after-treatment devices (ETC).

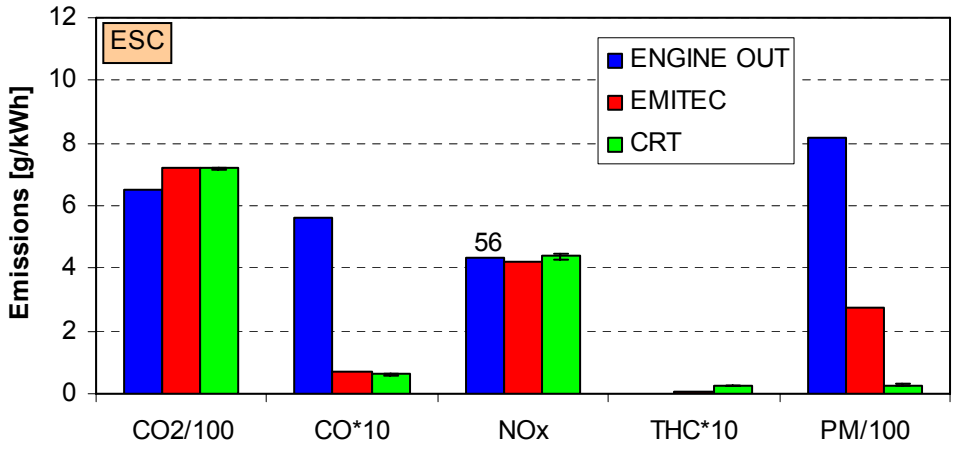

Figure 126: Comparison of after-treatment devices (ESC).

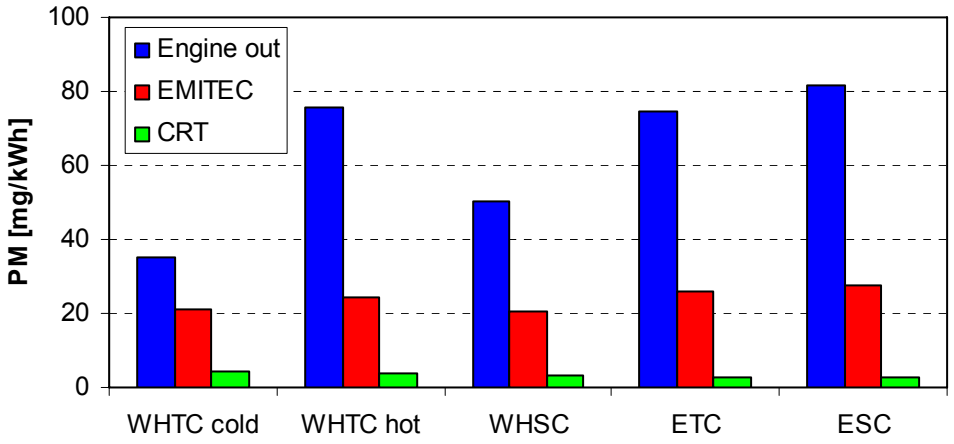

Figure 127: Mass emissions of after-treatment devices.

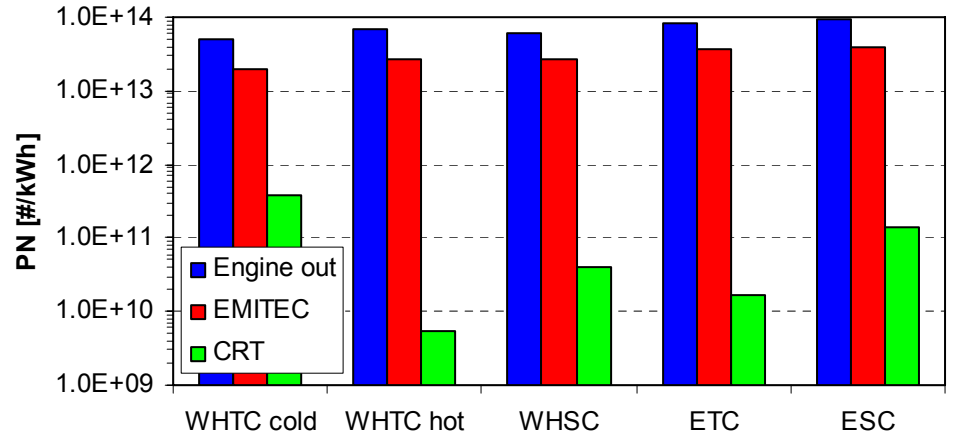

Figure 128: Number emissions of after-treatment devices.

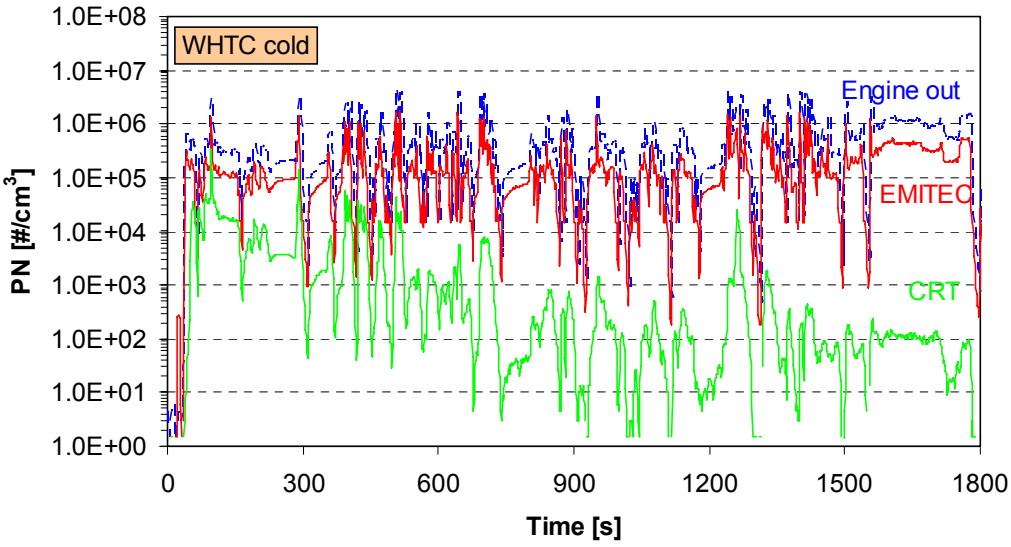

Figure 129: Real time emissions of the various after-treatment devices (WHTC cold).

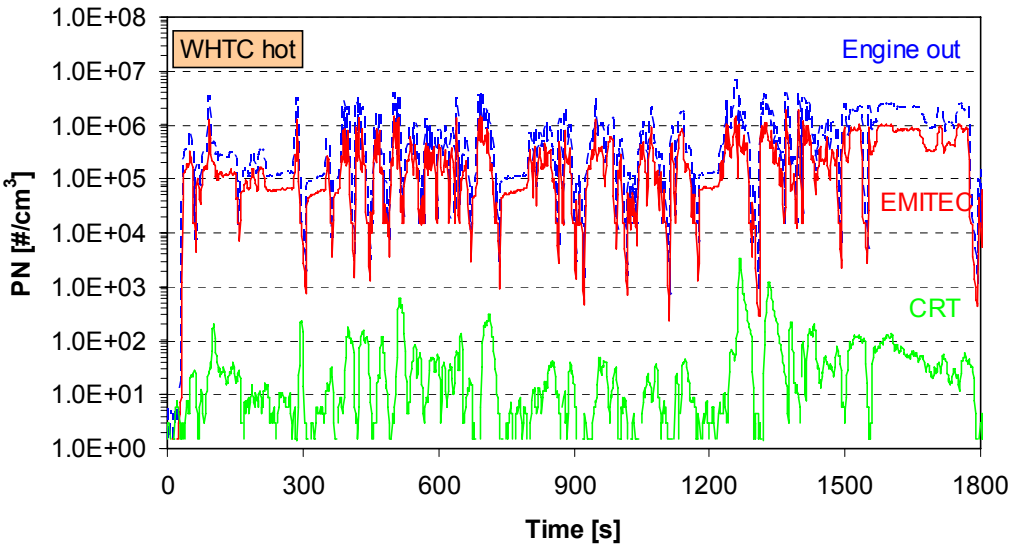

Figure 130: Real time emissions of the various after-treatment devices (WHTC cold).

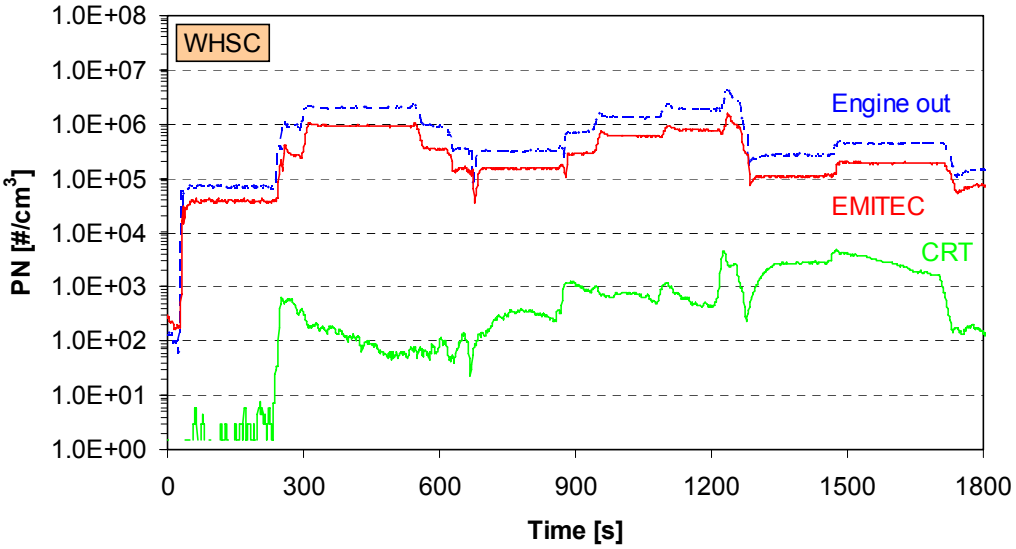

Figure 131: Real time emissions of the various after-treatment devices (WHTC cold).

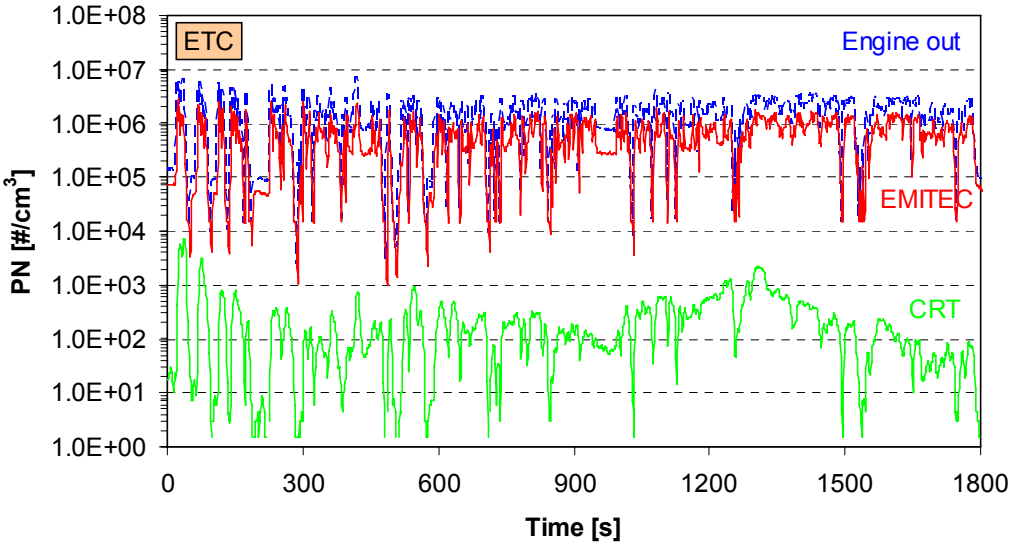

Figure 132: Real time emissions of the various after-treatment devices (WHTC cold).

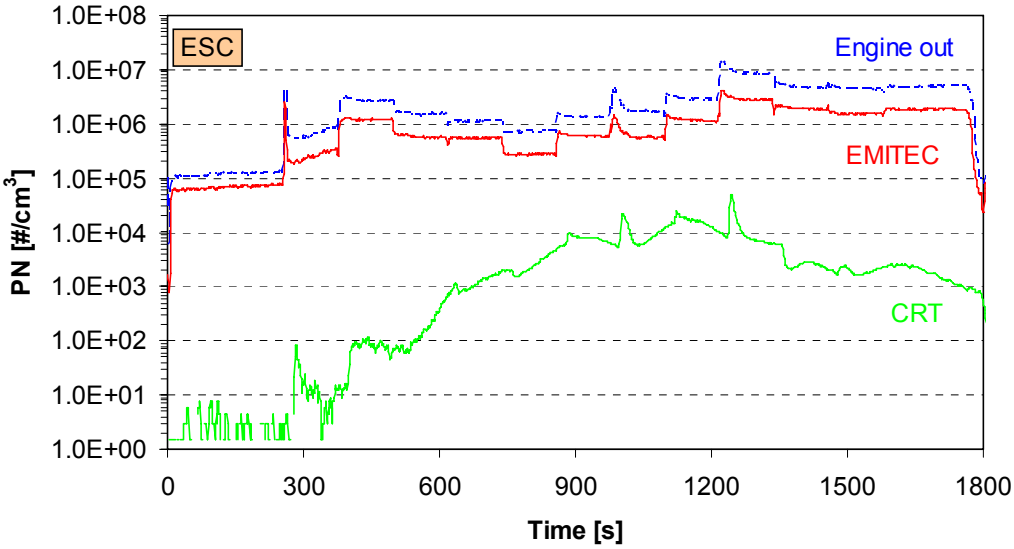

Figure 133: Real time emissions of the various after-treatment devices (WHTC cold).

Table 21: Efficiencies of the after-treatment devices.

Cycle	*CO_2*	*CO*	*NO_x*	*THC*	*PM (CVS)*	*PN (CVS)*
EMITEC						
WHTC cold	0.7	65.4	3.0	67.2	40.1	61.8
WHTC hot	1.0	85.8	0.9	74.9	68.0	58.4
WHSC	-0.2	96.3	0.5		59.4	55.3
ETC	1.2	72.1	0.0	74.5	65.7	56.2
ESC	-11.0	87.9	3.3		66.5	58.9
CRT						
WHTC cold	0.0	71.3	4.9	76.8	87.0	99.2
WHTC hot	0.0	93.0	3.4	90.4	94.7	100.0
WHSC	-1.1	95.7	-0.2		93.6	99.9
ETC	0.8	83.4	-0.5	85.6	96.3	100.0
ESC	-11.0	89.0	-0.9		96.6	99.9

5. CONCLUSIONS

For the official PMP validation exercise tests, the Golden Engine was tested in three different configurations: with a continuous regenerating filter (CRT), with a Partial Flow Deep Bed Filter form EMITEC (EMITEC) and without any after-treatment devices. Low sulfur fuel (7 ppm) and lubricant (<0.2%) were used. Two series of measurements (Phase A and B) were conducted. The targets of Phase A were i) to compare the after-treatment devices ii) investigate the differences between full flow and partial flow systems and iii) compare different particle number systems. Phase B was the execution of the official PMP tests. Emissions of Phase A and B are not completely comparable since the cycles at Phase A were run with slightly different dyno software settings. This affected mainly the idle point and the ETC cycle.

All tests were conducted according to the PMP sequence and protocol. This means that a cold WHTC was run in the morning, followed by a hot WHTC (10 min soak). Then the WHSC followed (with preconditioning at mode 9 of the WHSC for 10 min). Then the ETC and ESC cycles were executed, each preceded by a continuity protocol (5 min at mode 4 of ESC and 3 min at idle) to warm up the engine. At the end of the measurement day the pre-conditioning was conducted (15 min at mode 10 and 30 min at mode 7 of the ESC).

Particulate total mass (PM) was measured with 47 mm filters at 47±5°C from the full flow dilution tunnel (through a secondary dilution tunnel with dilution to sample ratio 1:1) and from two different partial flow systems (AVL Smart sampler SPC-472 and Control Sistem PSS-20).

Number measurements (PN) were conducted with the two golden instruments (Horiba SPCS): one measuring from the full flow dilution tunnel and the other from the partial flow system (PSS-20 at Phase A and SPC-472 at Phase B). Other particle number systems (Nanomet from Matter Eng., Ejector dilutors from Dekati) were also used at CVS or at the partial flow systems.

Phase A

The conclusions of Phase A were:

After-treatment devices

- The efficiency of EMITEC was in the order of 65% for PM and 61% for PN for both WHTC cold and hot.
- The efficiency of CRT was 94% for PM and 98% for PN for the cold WHTC. For the hot WHTC the efficiencies were 96% and almost 100%.

Full flow – partial flow systems

- The differences of emissions between full flow and partial flow system for PM for the different cycles were ±25%. At higher emission levels (engine out or engine with EMITEC) the partial flow systems measured 25% lower than the full flow system. This had to do with probably with the volatiles on the filter, but needs to be further investigated.
- The differences of emissions between full flow and partial flow system for PN were ±15% for low (CRT) or high (EMITEC and engine out) emissions. Higher differences (up to 75%) were observed at the hot cycles with CRT, where the emissions were very low (close to the background levels of the PSS-20 and/or Nanomet).

Particle number systems

- The particle number systems at CVS correlated very well. The dual ejector system measured 10-20% higher and the thermodenuder system 5-30% higher. The Nanomet also measured 30% higher than the SPCS-19. The differences were similar for low emissions (CRT) or high (engine out). Higher differences were observed at the hot cycles with CRT due to the high background levels of the ejector systems. Smaller differences would be observed if the PRFs (Particle Reduction Factors) were used.

Equivalency of systems (statistical analysis)

Statistical analysis for equivalency of systems showed:

- For PN measurements, the partial flow system (PSS-20) with the SPCS-20 was equivalent with the CVS with SPCS-19. The other systems (SPC-472 with Nanomet and ejector systems at CVS) were not equivalent due to the difference in the absolute levels they measured (higher).
- For PM emissions, both partial flow systems (PSS-20 and SPC-472) were equivalent with the CVS in the case of the golden engine with CRT. However, they were not equivalent when the golden engine with the EMITEC was tested.

PHASE B

The conclusions of Phase B were:

Mean emissions

- The PM emissions were between 2 and 5 mg/kWh for all cycles. Higher emissions were measured at the cold WHTC cycle. The variability (expressed as CoV) of the PM emissions were between 4% and 21%.
- The PN emissions were between $5x10^{9}$ kWh^{-1} (hot WHTC) and $4x10^{11}$ kWh^{-1} (cold WHTC). ETC and ESC had emissions lower than 10^{11} kWh^{-1}, while the ESC had emissions slightly higher than 10^{11} kWh^{-1}. The variability (expressed as CoV) of the PN measurements was between 7% and 15%. The only exception was the WHSC which showed a variability of 50%. This high variability had to do probably with the high temperature preconditioning which regenerated the filter (to different degrees) thus affecting the CRT fill state before the beginning of the cycle.
- High non-volatile emissions were observed during the cold WHTC. Blow-out of loose solid particle depositions, as the filter is exposed to highly transient operation with respect to the thermal and flow conditions, results to the increased particle number. In addition, particles formed by the nucleation-condensation of semi-volatile material earlier stored within the substrate and/or the particulate layer and released during the cold-start cycle as the CRT heats up might also contribute. High non-volatile emissions are also observed during the high engine temperature modes of the steady cycles ESC and WHSC. Probably this has to do with the lower efficiency of the CRT as it regenerates at high temperatures.

After-treatment devices

- Both after treatment devices increased the CO_2 emissions 11%, they didn't affect the NO_x emissions and decreased the CO and THC more than 80%.

- The efficiency of EMITEC was approximately 65% for PM and 58% for PN (non-volatiles >23 nm).
- The efficiency of CRT was approximately 95% for PM and 100% for PN (non-volatiles >23 nm).
- Both systems had lower efficiency for PM at the cold WHTC.

Full flow – partial flow systems

- The correlation between full flow and partial flow system showed that the partial flow systems measured 20% lower PM that the full flow system (CRT case, no data for the EMITEC and engine out). The difference had also a high scatter of ±20%
- The PN emissions of the partial flow system (SPCS-20 at SPC-472) was 5% higher than at the full flow dilution tunnel (SPCS-19 at CVS). The difference had a scatter of ±10%.

Particle number issues

- *Systems:* The particle number systems at CVS correlated well. The Nanomet (with a 3010D') measured 25% higher, while the dual ejector system (with a 3790) 10%. The thermodenuder system measured 20% higher. The differences would be lower if the PRFs were used.
- *Non-volatiles:* Tests with the Nanomet and particle counters with different cut points showed that the non-volatile particle emissions >23 nm and >10 nm are similar for most cycles. Only in the case of the cold WHTC there was a 40% difference. The 3025A (>3 nm) measured 30% higher emissions (in the case of the cold WHTC +90%) indicating the existence of non-volatile particles between 3 and 23 nm. Similar results were found with the 3025A downstream of the thermodenuder or the SPCS. During regeneration (e.g. at the pre-conditioning phase) high concentration of non-volatile particles <23 nm were observed in some cases.
- *Volatiles:* Comparing the emissions of a 3790n at the dual ejector system with hot or cold dilution showed small differences at most cycles (thus not many volatiles >23 nm exist) with the exception of the cold WHTC where 50% more volatiles (>23 nm) were measured. Comparison of the emissions of the 3025A at CVS or at SPCS showed that the volatiles are 30-60%. Only the hot WHTC showed high volatile emissions probably due to the low non-volatile emissions (and thus available surface for condensation) of the cycle. The cold WHTC volatile emissions on the other hand were very low probably due to the high non-volatile emissions.

Equivalency of systems (statistical analysis)

Statistical analysis for equivalency of systems showed:

- For PN measurements, the partial flow system (SPC-472) with the SPCS-20 was equivalent with the CVS with SPCS-19.
- For PM emissions, the partial flow systems (SPC-472) was not equivalent with the CVS (only case of the golden engine with CRT was examined).

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CoV:	Coefficient of Variance
CPC:	Condensation particle Counter
CRT	Continuous Regenerating Trap
CVS:	Constant Volume Sampler
DPF:	Diesel Particulate Filter
EEPS:	Engine Exhaust Particle Sizer
EGR:	Engine Gas Recirculation
EJ	Ejector dilutor
ESC	European Steady Cycle
ET:	Evaporation Tube
ETC	European Transient Cycle
EU	European Union
HEPA	High Efficiency Particle Filter
JRC:	Joint Research Centre
LC	Lubricant Conditioning
LEPA	Low Efficiency Particle Filter
MFC	Mass Flow Controller
PFS	Partial Flow System
PM:	Particulate Matter
PMP:	Particle Measurement Programme
PN:	Particle Number
PSS	Control Sistem Partial Flow System
PTS	Secondary Dilution Tunnel
RT	Residence Time
SMPS	Scanning Mobility Particle Sizer
SPC-472	AVL Smart Sampler
SPCS	Solid Particle Counting System
TD	Thermodenuder
THC	Total Hydrocarbons
TX40	TX40H120-WW
VELA:	Vehicles Emissions Laboratory
WHSC	World Harmonized Steady Cycle
WHTC	World Harmonized Transient Cycle

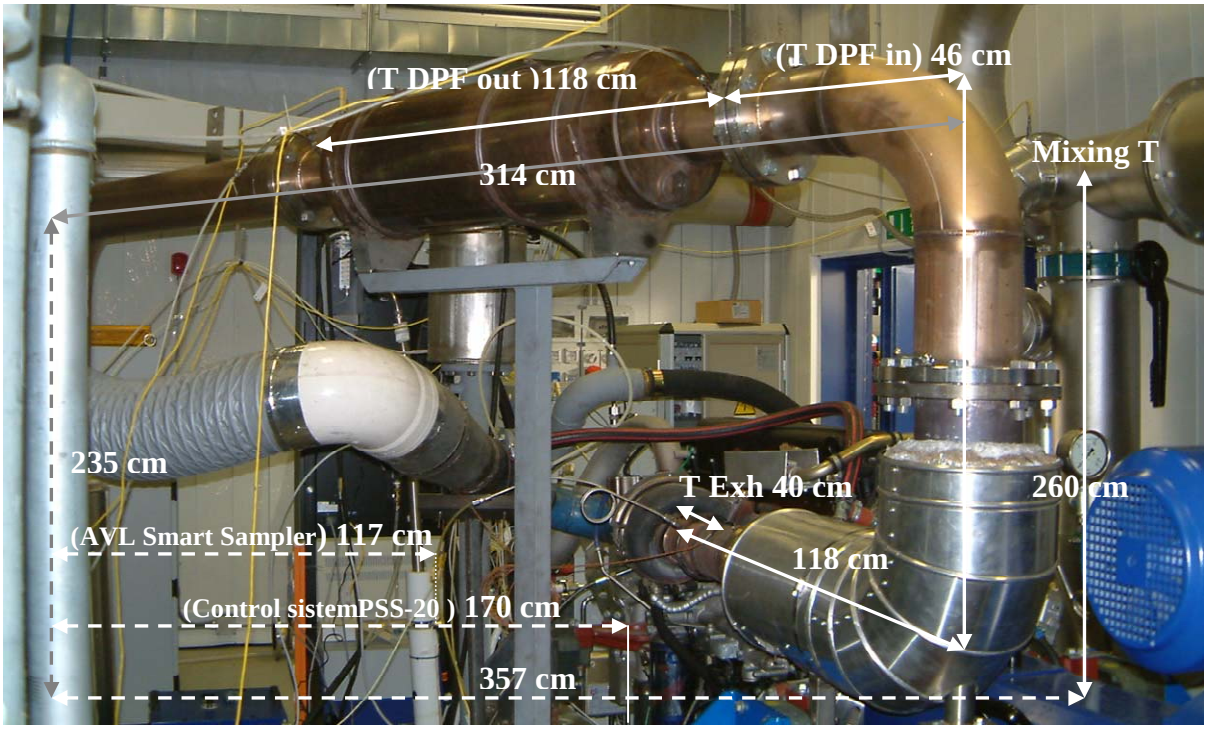
ANNEXES

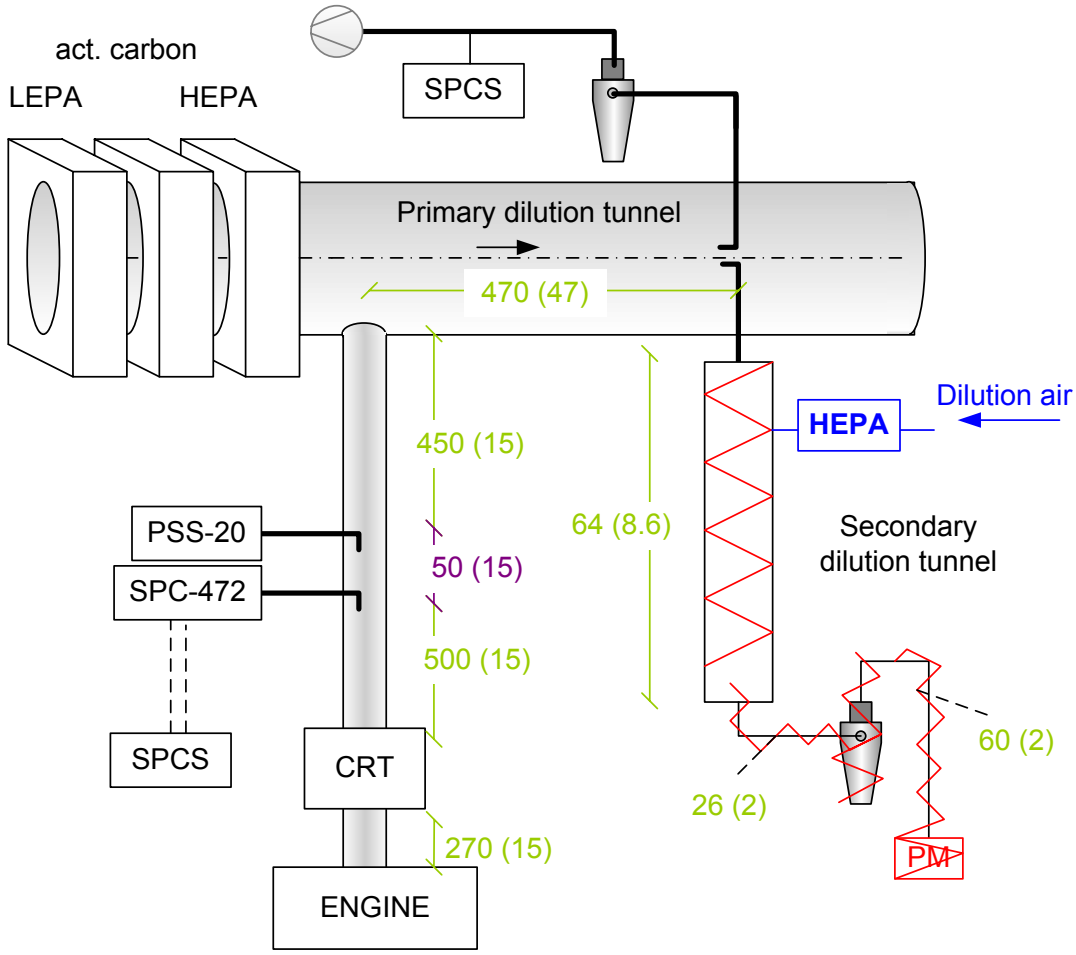
Annex A. Test fuel specifications for the exploratory work and the validation exercise.

APPELATION : gazole type CEC RF 06-03 PMP			Reference of analysis : 9460
N° of samples : 0	N° of batch : B7277051		Date: 05/06/2007
COMPLIANCE CERTIFICATE	☐	BULLETIN OF ANALYSIS	X

DIESEL FUEL	RESULTS	UNITS	METHODS
PHYSICAL DATA			
Density 15 °C	**834.9**	kg/m3	EN ISO 3675-98
Viscosity 40°C	**2.654**	cSt	ASTM D 445
DISTILLATION			
IBP	**171**	°C	ASTM D 86
5 % Vol	**196**	°C	ASTM D 86
10 % Vol	**204**	°C	ASTM D 86
20 % Vol	**224**	°C	ASTM D 86
30 % Vol	**242**	°C	ASTM D 86
40 % Vol	**262**	°C	ASTM D 86
50 % Vol	**277**	°C	ASTM D 86
60 % Vol	**291**	°C	ASTM D 86
70 % Vol	**304**	°C	ASTM D 86
80 % Vol	**318**	°C	ASTM D 86
90 % Vol	**334**	°C	ASTM D 86
95 % Vol	**346**	°C	ASTM D 86
FBP	**357**	°C	ASTM D 86
FBP	**357**	°C	ASTM D 86
E 250 °C	**33.8**	%Vol	ASTM D 86
E 350 °C	**96.1**	%Vol	ASTM D 86
CETANE NUMBER			
Cetane number	**53.1**	index	ISO 5165-98
Flashpoint	**67**	°C	EN 22719
COMPOSITION			
Poly-aromatics	**5.1**	%Mass	IP 391
COLD BEHAVIOUR			
Cold Filter Plugging Point (CFPP)	**-17**	°C	EN 116, NF M 07042
COMBUSTION			
Lower Calorific Value	**46.4**	MJ/kg	ASTM D 4868
%C, %H, %O	**86.7/13.2:<0.2**	%Mass	GC / Calculated
COMPLEMENTARY DATA			
Oxidation stability	**2**	g/m3	ISO 12205
Copper Strip Corrosion at 50 °C	**1**	merit	ISO 2160
Sulfur content	**7**	mg/kg	ISO 4260 / ISO 8754
Conradson Carbon Residue on 10% Dist.Residue	**<0.2**	%Pds/%mass	ISO 10370
Ash content	**<0.001**	%Pds/%mass	ISO 6245
Neutralisation Number	**<0.02**	mg KOH/g	ASTM D 974
Sediment content	**6**	mg/kg	ASTM D 2276
Fatty Acid Methyl Ester	**<0.2**	%Mass	
Water content	**30**	mg/kg	EN ISO 12937
HFRR 60°C	**310**	µm	ISO/DIS 12156

Annex B: Experimental set up details





Numbers indicate distances in cm and numbers in parenthesis indicate the inner diameter of the tubes in cm

Annex C: Cyclone cut-points (URG-2000-30EP, 91 lpm 2.5 µm)

Flow Rate [lpm]	*Cut-Point [µm]*
1.0	99.76
3.5	35.84
6.0	23.07
8.5	17.36
11.0	14.06
13.5	11.89
16.0	10.35
18.5	9.19
21.0	8.29
23.5	7.56
26.0	6.96
28.5	6.46
31.0	6.03
33.5	5.66
36.0	5.34
38.5	5.05
41.0	4.80
43.5	4.57
46.0	4.37
48.5	4.18
51.0	4.01

Flow Rate [lpm]	*Cut-Point [µm]*
51.0	4.01
53.5	3.86
56.0	3.72
58.5	3.59
61.0	3.47
63.5	3.36
66.0	3.25
68.5	3.15
71.0	3.06
73.5	2.98
76.0	2.90
78.5	2.82
81.0	2.75
83.5	2.68
86.0	2.62
88.5	2.56
91.0	2.50
93.5	2.45
96.0	2.39
98.5	2.34
101.0	2.30

*No information was given by the manufacturer regarding the steepness of the curve at specific flowrates.

Annex D: Equivalency of systems: Statistical analysis

According to GRT 4 (ECE/TRANS/180/Add.4, Annex 4) the determination of system equivalency shall be based on a 7 (or larger) sample pair correlation study between the candidate system and the reference system.

The statistical method proposed examine the hypothesis that the sample standard deviation and sample mean value between the two systems do not differ. The *F*-test is used for the standard deviation check and the two sided Student *t*-test for the mean check.

The equations used are (assuming the number of measurements of both systems are *n*):

Standard deviation check (*F*-test)

$$F = \frac{s_{\text{major}}^2}{s_{\text{minor}}^2}$$

$$df_{F-test} = n - 1$$

The candidate system is equivalent to the reference if:

$$F < F_{crit}$$

Where F_{crit} is defined by the $df_{F\text{-}test}$

Mean check (*t*-test)

$$t = \frac{\left|x_C - x_R\right|}{\sqrt{s_C^2 + s_R^2}}\sqrt{n}$$

$$df_{t-test} = 2n - 2$$

The candidate system is equivalent to the reference if:

$$t < t_{crit}$$

Where t_{crit} is defined by the $df_{t\text{-}test}$

The candidate system must pass both criteria to be considered equivalent to the reference.

The above tests are commonly used in independent tests. For example if a candidate system measures a property A of a sample and then the reference system measures the same property of another sample. This would be the case e.g. if the tests were conducted on different days, i.e. 8 tests of the WHTC first with CVS (reference system) and then 8 WHTC with a partial flow system (candidate system). In this case, the standard deviation of the measurement systems includes the variance of the engine. Usually this variance is very high, thus no statistically significant conclusions can be drawn. When the tests are conducted in parallel, as required in ECE/TRANS/180/Add.4, Annex 4, the correct statistical test is the dependent *t*-test (or paired *t*-test).

Comparison of systems (Paired *t*-test)

In this case, we do not compare the means x_C and x_R, but their differences:

$$D = \frac{\sum_{i=1}^{n} \Sigma x_{Ci} - x_{Ri}}{n}$$

Then the *t*-statistic is:

$$t = \frac{D}{s_D} \sqrt{n}$$

Where s_D is the standard deviation of the differences D_i.

However, when two particle number systems are compared where the emissions have difference of orders of magnitude, D will be always very small compared to s_D. For this reason, it is suggested to compare the relative differences of the systems:

$$D_{\%} = \frac{\sum_{i=1}^{n} (\Sigma x_{Ci} / x_{Ri} - 1)}{n}$$

Then the *t*-statistic is:

$$t = \frac{D_{\%}}{s_{D_{\%}}} \sqrt{n}$$

The *F* test for the comparison of the stdev of the systems remains the same.

Example

Let's assume a candidate PM system that measures 30% more than the reference PM system. The 8 measurement results and the results from the statistical analysis are:

Measurement	**Reference**	**Candidate**	Difference	Difference
#1	1.0	1.3	-0.3	25%
#2	2.0	2.7	-0.7	35%
#3	3.0	3.9	-0.9	30%
#4	4.0	5.2	-1.2	30%
#5	5.0	6.5	-1.5	30%
#6	3.0	3.9	-0.9	30%
#7	4.0	5.2	-1.2	30%
#8	6.0	7.8	-1.8	30%

According to GRT 4

	Reference	Candidate	
count	8	8	
mean	3.5	4.6	
stdev	1.6	2.1	
a	0.1		
Mean			
df-t	14		
t	**1.14**		
t crit	1.76		
	equivalent		
stdev			
df-F	7		
F	**1.30**	stdev	
F crit	2.78		
	equivalent		
Final result	**equivalent**		

According to paired t-test:

System (paired t-test)	
count	8
mean	-1.05625
stdev	0.48
a	0.1
df	7
t	6.22
t crit	1.89
	different

Or

System (paired t-test)	
count	8
mean differ	30%
stdev	0.027
a	0.1
df	7
t	31.75
t crit	1.89
	different

Although the two systems on average have 30% difference, the mean difference of the systems is lower than their pooled standard deviation (because the standard deviation includes the variability of the cycles also). Thus, we get a *t*-statistic 1.14 (in the independent case), which is lower than the critical 1.76. Thus, the systems seem equivalent. Obviously, the correct method is the second one. The two systems have a 30±3% difference in the emissions, thus they are different (statistically significant difference). Thus, the GRT 4 suggested method can't distinguish easily differences between the systems.

PHASE A results

CRT: Paired *t*-test. Comparison with Reference system: **CVS + SPCS-19**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	*t*	*F*	Result
PSS-20 + SPCS-20						
WHTC cold	8	1	3	EQ	EQ	EQ
WHTC hot (all soak)	7	67	18	NO	NO	NO
WHSC	7	-7	14	EQ	EQ	EQ
ETC	7	48	31	NO	EQ	NO
ESC	7	-23	3	NO	EQ	NO
all	37	18	39	NO	EQ	NO
All (-5 extreme)	32	8	30	EQ	EQ	EQ
SPC-472 + Nanomet						
WHTC cold	4	48	19	NO	EQ	NO
WHTC hot	5	66	24	NO	EQ	NO
WHSC	6	1	44	EQ	EQ	EQ
ETC	4	26	27	EQ	EQ	EQ
ESC	4	7	18	EQ	EQ	EQ
all	23	28	38	NO	EQ	NO
CVS + EJ+ET+EJ						
WHTC cold	5	2	5	EQ	EQ	EQ
WHTC hot (all soak)	10	63	41	NO	EQ	NO
WHSC	7	43	24	NO	EQ	NO
ETC	11	47	30	NO	EQ	NO
ESC	11	6	13	EQ	EQ	EQ
all	43	35	35	NO	EQ	NO
CVS +EJ+TD						
WHTC cold	7	22	4	NO	EQ	NO
WHTC hot	3	29	1	NO	EQ	NO
WHSC	7	21	4	NO	EQ	NO
ETC	10	17	12	NO	EQ	NO
ESC	10	20	6	NO	EQ	NO
all	37	21	7	NO	EQ	NO

CRT: Paired *t*-test. Comparison with Reference system: **CVS + PTS + PM**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	*t*	*F*	Result
PSS-20 + PM						
WHTC cold	6	-7	37	EQ	EQ	EQ
WHTC hot (all soak)	5	-36	27	NO	EQ	NO
WHSC	5	19	69	EQ	EQ	EQ
ETC	10	-6	26	EQ	EQ	EQ
ESC	4	22	34	EQ	EQ	EQ
all	30	-3	41	EQ	EQ	EQ
SPC-472 + PM						
WHTC cold	5	24	31	EQ	EQ	EQ
WHTC hot (all soak)	5	-34	24	NO	EQ	NO
WHSC	5	6	23	EQ	EQ	EQ
ETC	10	5	39	EQ	EQ	EQ
ESC	7	-5	25	EQ	EQ	EQ
all	32	0	33	EQ	EQ	EQ

EMITEC: Paired *t*-test. Comparison with Reference system: **CVS + PM**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	*t*	*F*	Result
PSS-20 + PM						
WHTC cold	8	-15	6	NO	EQ	NO
WHTC hot	8	-20	6	NO	EQ	NO
WHSC	8	-26	3	NO	EQ	NO
ETC	8	-24	3	NO	EQ	NO
ESC	8	-31	4	NO	EQ	NO
all	40	-23	7	NO	EQ	NO
SPC-472 + PM						
WHTC cold	8	-10	9	NO	EQ	NO
WHTC hot	8	-16	6	NO	EQ	NO
WHSC	8	-23	6	NO	EQ	NO
ETC	8	-17	5	NO	EQ	NO
ESC	8	-26	-3	NO	EQ	NO
all	40	-18	8	NO	EQ	NO

EMITEC: Paired *t*-test. Comparison with Reference system: **CVS + SPCS-19**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	*t*	*F*	Result
CVS + EJ+ET+EJ						
WHTC cold	6	27	13	NO	EQ	NO
WHTC hot	6	31	27	NO	EQ	NO
WHSC	6	29	17	NO	EQ	NO
ETC	6	5	20	EQ	EQ	EQ
ESC	5	4	23	EQ	EQ	EQ
all	29	20	23	NO	EQ	NO
CVS + EJ+ET+EJ+TD						
WHTC cold	7	15	11	NO	EQ	NO
WHTC hot	7	21	18	NO	NO	NO
WHSC	6	22	16	NO	EQ	NO
ETC	6	11	13	EQ	NO	EQ
ESC	6	10	10	NO	NO	NO
all	32	16	14	NO	EQ	NO
SPC-472 + Nanomet						
all	12	16	13	NO	EQ	NO
PSS-20 + SPCS-20						
WHTC cold	9	15	16	NO	EQ	NO
WHTC hot	9	4	13	EQ	EQ	EQ
WHSC	8	-13	6	NO	EQ	NO
ETC	6	5	15	EQ	EQ	EQ
ESC	8	-13	8	NO	EQ	NO
all	40	0	16	EQ	EQ	EQ

PHASE B results

CRT: Paired *t*-test. Comparison with Reference system: **CVS + SPCS-19**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	*t*	*F*	Result
SPC-472 + SPCS-20						
WHTC cold	9	5	12	EQ	EQ	EQ
WHTC hot	12	0	9	EQ	EQ	EQ
WHSC	11	6	11	EQ	EQ	EQ
ETC	14	5	8	NO	EQ	NO
ESC	11	6	7	NO	EQ	NO
all	57	4	9	NO	EQ	NO
all (-7 extremes)	49	2	8	EQ	EQ	EQ
CVS + Nanomet (3010D')						
WHTC cold	8	37	7	NO	EQ	NO
WHTC hot	9	31	9	NO	EQ	NO
WHSC	8	21	10	NO	EQ	NO
ETC	8	22	8	NO	EQ	NO
ESC	5	17	3	NO	EQ	NO
all	38	26	10	NO	EQ	NO
CVS + EJ+ET+EJ (3790n)						
WHTC cold	7	-4	3	NO	EQ	NO
WHTC hot	9	42	17	NO	EQ	NO
WHSC	8	13	15	NO	EQ	NO
ETC	8	13	11	NO	EQ	NO
ESC	8	0	7	EQ	EQ	EQ
all	40	14	20	NO	EQ	NO

CRT: Paired *t*-test. Comparison with Reference system: **CVS + PM**

Cycle	Count	Mean difference $D_{\%}$	stdev of differences $s_{D\%}$	t	t_{crit}	Result
SPC-472 + PM						
WHTC cold	12	-30	23	NO	EQ	NO
WHTC hot	12	-31	20	NO	EQ	NO
WHSC	11	4	18	EQ	EQ	EQ
ETC	14	-25	15	NO	EQ	NO
ESC	11	-10	23	EQ	EQ	EQ
all	60	-19	23	NO	EQ	NO

Note: There are some differences of the averages and stdev compared to the results reported in the text because more tests are compared here.

EQ = Equivalent

NO = Not equivalent

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Abstract
This document reports the results of the validation exercise during the PMP Heavy-Duty inter-laboratory exercise in Feb. '08 (Phase A) and June '08 (Phase B) conducted at the Vehicles Emissions Laboratory (VELA-5) in the Transport and Air Quality Unit of the European Commission's Joint Research Centre (JRC, Ispra). This report presents the results of the work undertaken on an IVECO Cursor 8 Heavy-Duty engine equipped with a Continuous Regenerating Trap (CRT), with a Partial Flow Deep Bed Filter from EMITEC and without any after-treatment devices. The tests included European and World Harmonized cycles following a strict protocol. Mass and number measurements were conducted simultaneously at the full flow and the partial flow sampling systems.

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