

Heavy Duty Particle Measurement Programme (PMP): Exploratory Work for the Definition of the Test Protocol

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ABSTRACT

The heavy duty Particle Measurement Programme (PMP) inter-laboratory exercise consists of three parts: 1) the exploratory work to refine the measurement protocol, 2) the validation exercise where each lab will measure the emissions of a “golden” engine with two “golden” particle number systems simultaneously sampling from full and partial flow dilution systems, and 3) the round-robin where the emissions of a “reference” engine will be determined with a lab’s own particle number instrumentation. This paper presents the results of the exploratory work and describes the final protocol for testing in the validation exercise (and round robin) along with the necessary facility modifications required for compliance with the protocol. Key aspects of the protocol (e.g. filter material, flow rates at the full and partial flow systems, the pre-conditioning etc.) are explained and justified. Finally, the results of particle emissions measurements during the World harmonized and the European cycles are given focusing on volatility and the presence of non-volatile materials above and below 23 nm.

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. The PMP has therefore sought to investigate and demonstrate the repeatability and reproducibility of the proposed techniques. The 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 [1]:

- A filter based particulate mass (PM) method based broadly upon this currently used in the United States for 2007 type approvals [2].
- A particle number method (PN) using a particle counter, a defined size range and sample pre-conditioning to exclude volatile and semi-volatile particles.

The light duty exercise preceded that for heavy duty and circulated a Euro 4 Diesel vehicle with a Diesel Particulate Filter (DPF) plus a reference “Golden” particle measurement system between laboratories. In addition, 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 [3, 4, 5].

The heavy duty exercise consists of three parts:

- The exploratory work: for the definition of the measurement protocol (at the European Commission’s Joint Research Centre, JRC, Ispra).
- The validation exercise: for the evaluation of particle number repeatability and reproducibility using the same systems at all labs (Golden Systems). In addition, full flow (CVS) and partial flow systems will be compared. In the validation exercise an engine (Golden Engine) is circulated along with two Golden Systems which are used to sample from the full (CVS) and partial flow dilution systems in tandem. The Golden Engineer and project manager ensure that participating labs closely follow the measurement protocol. Low sulphur fuel and lubricant from the same batches will be used at all labs. The participating labs, following JRC are, AVL_MTC, RICARDO, UTAC, and EMPA (each funded by their respective national governments). JRC will repeat their measurements at the end of the exercise to indicate consistency of emissions through the programme.
- The round robin exercise: for the evaluation of particle number repeatability and reproducibility using different measurement systems. In the round robin, a reference engine is circulated, but each lab uses its own particle number systems from full flow dilution tunnels. Optionally, number measurements may also be made from partial flow systems. All labs will use fuel and lubricant of the same type (but not necessarily from the same batch). Laboratories from EU, Japan, Korea and Canada have expressed interest in participating in such round robin exercise.

The validation and the round robin exercises started after the exploratory work in JRC had been finalized and now run in parallel. The expected timetable and the expected participating labs are given in Table 1.

This paper reports the results of the PMP heavy duty inter-laboratory exercise exploratory work undertaken from Oct. '07 to Feb. '08. This work was conducted at the Vehicle Emissions Laboratory (VELA-5) in the Transport and Air Quality Unit of the European Commission’s Joint Research Centre (JRC, Ispra site). The main objective of these tests was to finalize the measurement protocol that will be used in the validation exercise and round robin. The protocol was based upon the light duty vehicles’ protocol [6]. However, there were some issues that needed further attention due to

differences between light and heavy duty in emissions and testing. The exploratory work included evaluating the mass and number backgrounds, filter media effects, cyclone and heated line effects, pre-conditioning, and the investigation of particle number emissions during different cycles. The details of the final heavy duty protocol, composed after completion of the exploratory tests, are now published [7].

Table 1: Expected time schedule.

<i>Date</i>	<i>Validation Exercise</i>	<i>Round Robin</i>
10-02/2008	JRC (exploratory)	
01-02/2008	JRC (Phase 1A)	
03-04/2008	AVL_MTC (SE)	
05-06/2008	JRC (Phase 1B)	
09-10/2008		RWTUEV (DE)
11-12/2008		RICARDO (UK)
01-02/2009	RICARDO (UK)	NTSEL (JP)
03-05/2009	UTAC (FR)	JARI (JP)
06-07/2009	EMPA (CH)	NIER (KR)
08-09/2009	JRC (Phase 2)	
10-11/2009	Final report	VOLVO (SE)
12-01/2010		JRC (EU)
02-03/2010		UTAC (FR)
04-05/2010		TNO (FR)
06-07/2010		VTT (FI)
08-10/2010		SCANIA (SE)
11-12/2010		Environ. Canada
01-02/2011		Daimler Chrysler

EXPERIMENTAL

GOLDEN ENGINE

The engine used in this study was the one selected as the “Golden Engine” for the PMP Validation exercise, i.e. an IVECO Cursor 8 Euro 3 engine with an oxidation catalyst plus uncoated DPF (DOC-DPF) (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 (turbo outlet) and the front face of the aftertreatment device was 270 cm (internal diameter 15 cm). Exhaust gas temperatures and pressures were recorded upstream and downstream of the aftertreatment device. Engine coolant and intercooler temperatures were controlled respectively at 75 and 40-45°C.

FUEL AND LUBE OIL

The test lubricant was a BP Vanellus E8 fully synthetic, 5W/30 PAO (polyalphaolefin) based oil with <0.2% sulphur content (Table 3). The lubricant was changed following the prescribed procedure in the inter-laboratory guide [7].

The fuel used in this engine (RF06-03 PMP) complies with Annexes 3 and 4 of Directive 2003/17/EC describing fuel specifications to be employed after 1st January 2009 (i.e. sulphur content of lower than 10 ppm). It is a CEC (Coordinating European Council) certified reference fuel (Table 4). More information can be found in [8, 9].

Table 2: Validation exercise "Golden Engine" characteristics.

Make and model	IVECO Cursor 8 (Euro 3)
Engine configur. 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
Aftertreatment	4.25 l Pt-based DOC upstream of a 24 l wall-flow DPF

Table 3: Lubricant characteristics.

Properties	Units	Value
Density @15 °C	g/ml	0.860
Cinematic Viscosity @100 °C	mm ² /s	12.03
Viscosity Index	°	163
Viscosity CCS @ -30 °C	cP	5260
Total Base Number	Mg KOH/g	15.9
Sulphated Ash	% mass	1.9

Table 4: Fuel characteristics.

Properties	Units	Value
Density @15 °C	kg/m ³	834.9
Viscosity @ 40 °C	cSt	2.654
IBP °C	°C	171
FBP	°C	357
10% vol	°C	204
50% vol	°C	277
95% vol	°C	346
Cetane Number	-	53.1
Carbon	% mass	86.7
Hydrogen	% mass	13.2
Oxygen	% mass	< 0.2
Polycyclic aromatics	% mass	5.1
Sulphur	mg/kg (ppm)	7
Water content	mg/kg	30

SAMPLING SYSTEMS AND CONDITIONS

The measurements were conducted on a test bench at the VELA-5 JRC laboratories (max power 500 kW and max speed 3500 rpm). A general description of the set up follows.

Dilution air

Highly efficient filters for particles and hydrocarbons that reduce particle contributions from the dilution air to near zero were used (H13 of EN 1822) for the CVS dilution air.

Primary Full Dilution tunnel (CVS)

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 [10] (Figure 1). 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 the diluted exhaust gas through the tunnel was controlled by a critical orifice venturi. A flow rate of 80 m³/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 = 240000 depending on the diluted gas temperature). The residence time of the exhaust in the dilution tunnel was in the order of 0.6 s (for 80 m³/min). The schematic of the set up can be seen in Figure 1.

Three probes (of inner diameter 12 mm) were used for sampling. These were radially spaced in the plane of the tunnel, parallel to the flow and 10 tunnel diameters downstream of the mixing point to ensure complete mixing of the dilution air and the exhaust gas. One probe led to the secondary dilution tunnel for particulate mass (PM) measurements and the other two to particle number (PN) measurement equipment. At one of the two PN probes a URG-2000-EP cyclone was installed (50% cut point d₅₀ at 2.5 µm). The other was used for some tests to check the effect of the cyclone on the number emissions.

Secondary dilution tunnel

The secondary dilution tunnel used for PM measurements met the regulatory requirements of heavy duty engines concerning dimensions, temperatures, flow rates etc. [10].

The ratio of dilution air to sample aerosol flow (from the primary tunnel) was 1:1 (25 L/m sample, 25 L/m dilution air, and 50 L/m total flow to the filters at normal reference conditions 0°C and 1 bar) so the Dilution Factor (DF) was 2:1. Some tests were conducted with different flow rates to check the effect of the filter face velocity on the PM emissions (but always with ratio 1:1). The 1:1 ratio of sample to dilution air was chosen as a compromise between the low (1:3) and high (3:1) ratios that the labs usually use. With DF 2:1 it is possible for all labs to maintain 47°C at the filter face either by heating the dilution air or by externally heating the secondary tunnel. During JRC experiments, it proved more difficult to reach the desired temperature by heating the dilution air than by using external heating: the high surface area of the secondary tunnel led to high heat losses.

decrease in the diluted gas temperature. For this reason, external heating of the secondary tunnel was selected. A cyclone pre-classifier (URG-2000-30EP) was used downstream of the secondary tunnel and upstream of the filter holder to limit the contribution of re-entrained and wear materials to the filter mass (d_{50} at $4\text{ }\mu\text{m}$).

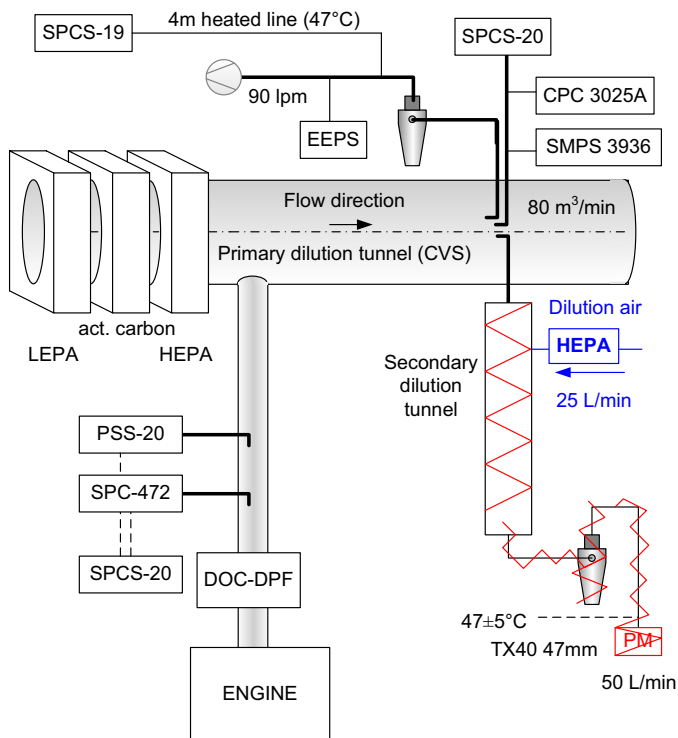


Figure 1: Schematic of the set up. Explanations in the text. See also definitions at the end of the paper.

Particulate Mass (PM) sampling

Direct surface heating was applied to the secondary tunnel, the cyclone, and the filter holder to permit aerosol stabilization of $>0.2\text{ s}$ prior to sampling, and to ensure close control of the filter face temperature to 47°C ($\pm 5^\circ\text{C}$). The temperature was measured $<20\text{ cm}$ upstream of the filter. PM samples were collected on 47 mm Teflon-coated glass-fiber Pallflex® TX40H120-WW filters (TX40). Some tests were also conducted with 70 mm filters. Usually, 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 quantify this artifact effect some tests were conducted with two filters (main and back-up filter). Some extra tests were conducted with 47 mm PALL Teflo, PTFE with polymethylpentene support ring, pore size $2\text{ }\mu\text{m}$ (Teflo) in order to compare the effect of volatile artifact depending on the material of the filter.

To estimate the filter face velocity, surface areas of 11.3 and 27.3 cm^2 were assumed for the 47 and 70 mm filters respectively. 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 69 cm/s for the 47 mm filters at 40 L/m , 103 cm/s for the 47 mm filters at 60 L/m and 43 cm/s for the 70 mm filters at 60 L/m . If the pressure at the filter holder was assumed to be $4\text{--}5\text{ kPa}$ lower, then the velocities would have been higher by $\sim 3\text{ cm/s}$.

Particle Number (PN) sampling

Aerosol samples for particle number measurement were drawn from the primary dilution tunnel, via a cyclone and pump sampling 90 L/m (d_{50} of the cyclone at $2.5\text{ }\mu\text{m}$). Two prototype Solid Particle Counting Counters (SPCS) from Horiba were used ("Golden Instruments") [11]. The primary hot diluter was set to 170°C , the evaporation tube at 350°C with the secondary diluter cooling the sample to ambient temperature. The primary DF was set to $10:1$ and the secondary at $15:1$. A TSI CPC 3010D was included in the systems (d_{50} at 23 nm). The two systems were compared with each other (measuring in parallel from the CVS) and $<5\%$ difference was found. The real time patterns of the two systems were also identical. Details for the instruments can be found in [8].

The reason that non-volatile particles $>23\text{ nm}$ will be measured for the heavy duty exercise is that a similar PN principle for both light and heavy duty testing was desirable (thus minimizing the cost impact for OEMs and labs). The d_{50} at 23 nm ensures that the primary soot particles are also measured but limits detection of any nucleation mode particles that escape the evaporation tube. There are concerns that non-volatile particles $<23\text{ nm}$ can appear in the exhaust gas of heavy duty engines [9, 12, 13]. However, these particles do not always appear downstream of DPFs [14]. For some tests a TSI CPC 3025A (d_{50} at 3 nm) was connected downstream of the SPCS (in parallel with the 3010D) to measure non-volatile particles $>3\text{ nm}$. This was done in order to confirm that the contribution of $<23\text{ nm}$ non-volatile particles is small. In addition, a TSI CPC 3025A, a TSI SMPS 3936 and a TSI Engine Exhaust Particle Sizer (EEPS) (d_{50} at 5.6 nm) were also connected to the CVS to measure total (volatile and non-volatile) particles.

PARTIAL FLOW SYSTEMS

Two partial flow sampling systems were used: the AVL Smart Sampler SPC-472 and the Control Sistem PSS-20. Sampling and measurements with the partial flow sampling systems were undertaken according to ISO 16183 and the inter-lab guide [7, 15]. Exhaust gas mass flow was determined in real-time by fuel consumption (gravimetrically) and air consumption (hot-wire anemometer). The resulting data were used for controlling the transfer flow from the raw exhaust to the partial flow systems.

Partial flow systems are designed to replicate the dilution regime in a full flow dilution tunnel. At the dilution tunnel (CVS) at any given time the dilution factor DF_{CVS} is:

$$DF_{CVS} = \frac{G_{CVS}}{G_{exh}} \quad \text{Eq. 1}$$

Where:

G_{CVS} is the total flow rate of the full flow dilution tunnel

G_{exh} is the engine exhaust flow rate

The DF_{PFS} at the partial flow system (PFS) is:

$$DF_{PFS} = \frac{G_{tot}}{G_p} \quad \text{Eq. 2}$$

Where:

G_{tot} is the (total) flow rate through the tunnel at the partial flow system and

G_p is the exhaust sample flow rate.

As G_p must be a constant portion of the exhaust flow and G_{tot} is usually constant, G_p is changing by controlling the dilution air:

$$G_p = G_{tot} - G_{da} \quad \text{Eq. 3}$$

Where

G_{da} is the flow rate of the dilution air at the partial flow system.

In most partial flow systems, the total tunnel flow passes through the PM filter. This was true of both SPC-472 and PSS-20 systems. If an additional flow is extracted from the partial flow system (e.g. with a particle number system) then, the extracted flow must be taken into account in the partial flow system's software (e.g. PSS-20) or an identical flow must be fed back (e.g. SPC-472). Note that for the second case (where particulate free air is fed back), a correction must be applied for the associated reduction in collected PM [9].

As the dilution factor at the full dilution tunnel (Eq. 1) and at the partial flow systems (Eq. 2) should be equal (secondary tunnel not considered):

$$\frac{G_{CVS}}{G_{exh}} = \frac{G_{tot}}{G_p} \quad \text{Eq. 4}$$

The split ratio r is defined as the ratio of the sampled exhaust gas G_p to the exhaust gas flow rate G_{exh} :

$$r = \frac{G_p}{G_{exh}} \quad \text{Eq. 5a}$$

Rearranging Eq. 4, in order to have equal dilution factors at the full dilution tunnel and at the partial flow system and using Eq. 5a, the split ratio should take the value:

$$r = \frac{G_p}{G_{exh}} = \frac{G_{tot}}{G_{CVS}} \quad \text{Eq. 5b}$$

The dilution factor of a partial flow system DF_{PFS} is:

$$DF_{PFS} = \frac{G_{tot}}{G_p} = \frac{G_{tot}}{rG_{exh}} \quad \text{Eq. 6}$$

And dividing Eq. 1 and Eq. 6:

$$\frac{DF_{CVS}}{DF_{PFS}} = \frac{G_{CVS}}{G_{tot}} r \quad \text{Eq. 7}$$

The ratio of DFs of two partial flow systems would be:

$$\frac{DF_{PFS1}}{DF_{PFS2}} = \frac{G_{tot1}}{G_{tot2}} \frac{r_2}{r_1} \quad \text{Eq. 8}$$

Note that G_{tot} is set by the user (=1.08 g/s to have a filter face flow rate of 50 L/m at normal conditions) and the dilution tunnel flow rate G_{CVS} is also defined by the user (80 m³/min at normal conditions). Then the split ratio r is also defined (=0.000626) from Eq. 5b. If the split ratio has a different value than the one from Eq. 5b, then the dilution factors at the full dilution tunnel and the partial flow system are different and this might affect the volatiles collected on the filter.

Note that G_{CVS} is referred as G_{edf} in the PSS-20 manual and the exhaust gas flow G_{exh} as F_{exh} . In PSS-20 G_{tot} and G_{edf} are set by the user. Typical values used where $G_{edf} = 80 \text{ nm}^3/\text{min} = 4800 \text{ nm}^3/\text{h} = 6200 \text{ kg/h}$ and $G_{tot} = 50 \text{ L/m} = 3000 \text{ nl/h}$. The split ratio for PSS-20 can also be calculated from Eq. 5b using G_{edf} (and not the real dilution tunnel flow G_{CVS}).

It has to be emphasized that the parameters chosen at the CVS and the partial flow system were such that the DFs were very similar in the two systems. However, for PM the total dilution factor for full-flow measurements is higher than from the partial flow system as there is also secondary dilution. This difference can affect the PM results due to a difference in volatiles collected on the filter [16].

Labs that use different CVS flow rates can determine the split ratio r from equation 5b if they want to have the same dilution factors at the CVS and at the partial flow systems. However, for the validation exercise all labs will use the values that were given previously irrespective of the CVS flow rates. This was decided in order to be able

to compare the partial flow system independently from the full-flow results at the end of the exercise.

AVL Smart Sampler SPC-472

The AVL Smart Sampler (SPC-472) is a partial flow system that simulates the operation of the full dilution tunnel by sampling a constant ratio of the exhaust flow (split ratio). This is achieved by changing the dilution air flow rate as the total flow rate remains constant. The SPC-472 was recently upgraded (cyclone installed, 47 mm filter holders and controlled temperature of the filters at $47\pm5^{\circ}\text{C}$ by external heating) to meet the requirements of the PMP full-flow protocol [7]. However extra work from JRC was necessary which included:

- Insulation of the cyclone and the tubes as the temperature couldn't reach the 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 extracted from the particle number system. Filtered pressurized air was fed to the system through a mass flow controller that controlled the flow rate equal to the flow rate that the number system was extracting. For the final JRC PMP tests the SPC-472 software will be upgraded so the feed back flow will not be necessary.
- Addition of HEPA and Carbon filters at the dilution air line. The existing ones were not adequate for particle number measurements (high number background). Note that the addition of filters at the dilution air line after the unit's mass flow controller reduces the response time (out of the legislation limits) and this might lead to underestimation of the emissions. However, comparison of the real time particle number emissions didn't show any effect. In the future these filters will be removed and a high pressure particle filter will be added upstream of the mass flow controller at the dilution air line.

The sampling point of the SPC-472 system was positioned 5 m from the aftertreatment 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 place <20 cm from the exhaust tube using filtered air. Downstream of the mixing tunnel, a URG-2000-30EP cyclone was installed with d_{50} at $4\text{ }\mu\text{m}$ (for a flow rate of 50 L/m). The transfer tubing between the cyclone and filter was heated to permit aerosol stabilization prior to sampling and to ensure close control of the filter face temperature to 47°C ($\pm 5^{\circ}\text{C}$). The temperature was measured 5 cm upstream of the filter. 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 and 47°C was 69 cm/s.

Control Sistem PSS-20

PSS-20 is a partial flow sampling system which doesn't require compressed air or cooled water. It samples a small quantity of exhaust gas and dilutes it with filtered ambient air. The diluted gas passes 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 keeps the temperature of the filter at $47\pm5^{\circ}\text{C}$ 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 0.4 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.

TEST PROTOCOL

The details of the protocol are described in [7]. In the following, the basic sequence of the tests and the differences of the protocol between validation exercise and round robin are described.

Test matrix of official tests

Table 5 gives the general overview of the sequence of the official measurements.

Lubricant Preconditioning

The lubricant aging/conditioning consisted of 120 min at mode #10 (ESC). The lubricant change [7] and ageing is obligatory only in the validation exercise since the engine is shipped with an oil charge for round-robin tests. The 3 ETCs after the lubricant ageing are conducted to confirm the proper operation of the engine.

Cycles

Each measurement day started with a cold-start World Harmonized Transient Cycle (WHTC), a 10 min soak followed and then a hot WHTC. Next, the World Harmonized Steady Cycle (WHSC) the European Transient Cycle (ETC) and finally the European Steady Cycle (ESC) were tested. Between the hot WHTC and WHSC, 10 min at WHSC mode #9 was run (as required by the legislation). Before the ETC and ESC the Continuity protocol was applied (5 min at ESC mode #7 and 3 min at idle). The reasoning behind this pre-conditioning will be given in the results section. At the end of the each test day the aftertreatment devices were conditioned (see next paragraph).