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EU-PEMS PM EVALUATION PROGRAM - First Report

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1 List of acronyms

A/F	Air-Fuel ratio
CH4:	Methane gas
CO:	Carbon monoxide gas
CO2:	Carbon dioxide gas
ECU:	Engine Control Unit
EFM:	Exhaust Flow Meter
ESC:	European Steady state Cycle
ETC:	European Transient Cycle
FID:	Flame Ionisation Detector analyser
FS:	Full Scale
GPS:	Global Positioning System
I/O:	Input / Output
ISC:	In Service Conformity
IUC:	In Use Compliance
NDIR:	Non-Dispersive Infrared analyser
NDUV:	Non-Dispersive Ultraviolet analyser
NO:	Nitric oxide gas
NO2:	Nitric dioxide gas
NOx:	Nitric oxides gases
NTE:	Not To Exceed
O2:	Oxygen gas
PEMS:	Portable Emission Measurement System
PM:	Particulate Matter
PPFS	Proportional Partial Flow Sampling
PID:	Vehicle data Parameter IDentifier
QCM	Quartz Cristal Microbalance
SAE:	Society of Automotive Engineers
STP	Custom Step Cycle
TEOM	Tapered Element Oscillating Microbalance
THC:	Total Hydrocarbons

2 Background and objectives

2.1 Initial steps: the EU-PEMS project

The European emissions legislation requires to verify the conformity of heavy-duty engines with the applicable emissions certification standards: these provisions are identified as "In Service Conformity" (ISC).

It was considered impractical and expensive to adopt an in-service conformity (ISC) checking scheme for heavy-duty vehicles, which require removal of engines from vehicles to test pollutant emissions against legislative limits. Therefore, it has been proposed to develop a protocol for in-service conformity checking of heavy-duty vehicles based on the use of Portable Emission Measurement Systems (PEMS).

The European Commission through DG ENTR in co-operation with DG JRC launched in January 2004 a co-operative research programme to study the feasibility of PEMS in view of their application in Europe for In-Service Conformity of heavy-duty engines. The technical and experimental activities were started in August 2004 to study the feasibility of PEMS systems and to study their potential application for on-road measurements on heavy-duty vehicles. The project focused on gaseous emissions only, as the technological progress on the portable equipment to measured PM was judged insufficient.

The main objectives of the above project had been defined as follows:

- To assess and validate the application and performance of portable instrumentation relative to each other, and in comparison with alternative options for ISC testing;
- To define a test protocol for the use of portable instrumentation within the ISC of heavy-duty vehicles;
- To evaluate the US 'Not To Exceed' (NTE) approach and possibly develop a simplified method in order to propose ISC pass/fail criteria;
- To address the need of the European industry, authorities and test houses to go through a learning process.

2.2 EU heavy-duty pilot program

Following the successful outcome of the EU-PEMS project, the Commission announced the intention to launch a manufacturer-run Pilot Programme at the 97th MVEG Meeting on 1 December 2005. The main purpose of the programme was to evaluate the technical (PEMS

based) and administrative procedures for a larger range of technologies and in statistically more relevant numbers.

The PEMS Pilot Programme was started in autumn 2006 with the main aim to confirm and validate the robustness of the PEMS test protocol that has been developed in the EU-PEMS Project. It was also designed to contribute to the sharing of 'best practice' approach amongst all interested parties, including Member State authorities and technical services. The outcome of the programme will provide further information on the introduction of ISC provisions based on the PEMS approach in the European type-approval legislation.

2.3 Objectives of the work

2.3.1 Introduction

Both the EU-PEMS project and the follow-up pilot program did not require the measurement of PM emissions: this was due to the absence of commercially available portable systems able to measure the PM mass emissions following the requirements of the laboratory standards (in terms of dilution, temperature control and filter media conditioning for instance).

When the pilot program started, such instruments were available as prototypes which had already been studied or correlated to other systems in various projects. It was therefore decided to launch a laboratory evaluation program to assess their potential. This decision has been formalized by the European Commission in a Call for Expression of Interest[1]. The text of the call underlined the objectives of the program and defined the list of the basic technical requirements to be met by the instruments to be valid candidates.

2.3.2 Technical requirements for the portable systems

The candidate instruments had to fulfil a few basic requirements:

- To measure the total PM mass over a long sampling period, either following the standard method or using a method proven to be equivalent to the standard method;
- To provide a second-by second ("real-time") information on the emitted PM mass at any time during the test. This is a necessary pre-requisite for evaluating the data according to the moving average window (MAW) method (work or CO2 based);
- To be ready for on-vehicle tests and in particular to include a solution to transport the raw or the diluted exhaust, to allow for

[1] http://ec.europa.eu/enterprise/automotive/pagesbackground/pems_project.htm

an installation of the system within a few meters from the vehicle tailpipe.

Measurement principles that were not fully in line with the laboratory standard methods to measure PM mass were also accepted for evaluation, either with variations of the dilution method (e.g. constant dilution) or with alternative physical principles (e.g. measurement of the soot instead of total PM).

Upon the conclusions of the study, the main conclusions of the project were to recommend the candidate principle(s) and to discuss whether the corresponding technological progress of the instruments was sufficient to foresee a short term introduction in the legislation.

2.4 Design of the program

The program is designed to provide a direct empirical comparison of portable systems relative to reference laboratory systems, under controlled laboratory conditions. The following evaluation criteria and sub-criteria were used to evaluate their measurement performance:

- Under controlled conditions
  - Proportional dilution of the portable dilutors, when applicable;
  - Correlation to the reference PM mass measurement;
  - Ability to calculate MAW results, possibly determining levels of accuracy or uncertainty.

- On-board
  - Transport and direct sampling (as defined ins section 4.3)
  - Stability and performance for long durations (>=90 minutes)

For the measurement performance on the total PM mass, the portable instruments were required to correlate with the reference instrument, regardless of the conditions (engine, fuel, cycle). Regarding the physics and the linearity of the real-time instruments, no reference system was available. Some attention was paid on their reliability (based to the test-to-test repeatability) and their sensitivity at low PM levels.

It goes without saying that the measurement performance on-board could not be fully checked under the conditions of a test cell. However, the ability of the instruments to sample for durations that are typical for on-road tests was also verified. The results are presented in section 5.2.2.3.

Other characteristics of the candidate systems were also evaluated. Their conformity with the current EU laboratory standard was also judged on the following points:

- The partial and proportional dilution;
- The temperature control of the dilution and sampling system;
- The filter based gravimetric principle.

The calibration procedures and their 'portability' (i.e. their size, weight, installation, power consumption, dilution air control, easiness of use and installation on vehicles) were also considered.

3 Candidate Instruments

Several commercially available PM PEMS, meeting the aforementioned basic requirements were submitted by various instrument manufacturers:

- Control Sistem micro-PSS (m-PSS)
- AVL Micro Soot Sensors (MSS)
- Dekati Mass Monitor (DMM)
- Dekati Electrical Tailpipe PM Sensor (ETaPS)
- Horiba On board System Transient PM Mass Measurement (OBS-TRPM)
- Sensors Portable Particulate Measurement Device (PPMD)

3.1 Control Sistem micro-PSS

The Control Sistem micro-PSS is shown in Figure 1: it is a portable instrument working according the PPFS principle. It uses a 47 mm filter and collects PM with a filter face velocity of 43-65 cm/s at a filter temperature of 47 ± 5ºC. In its standard laboratory configuration (PSS-20), it can also uses filters with 70 mm diameter of as for the PTS method.

Figure 1 Control Sistem m-PSS

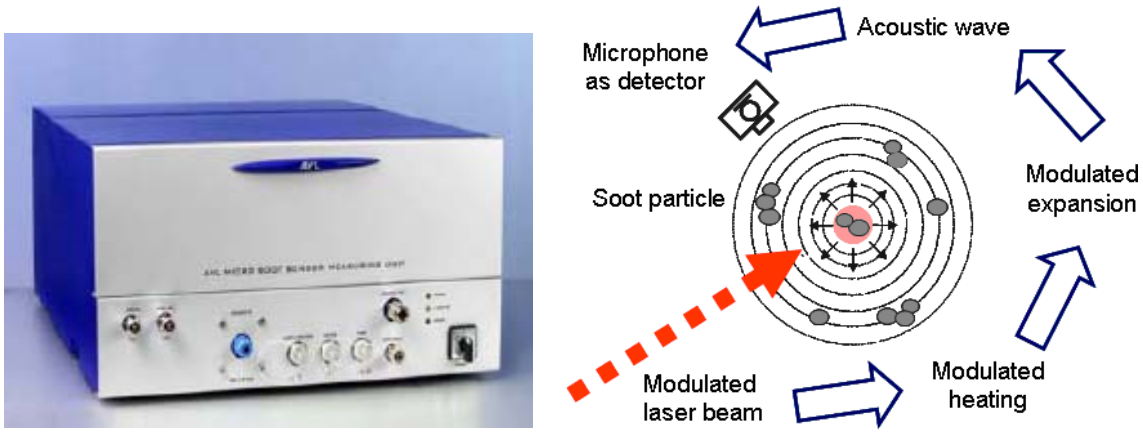
The MPSS was associated with the Dekati ETaPS (See section 3.4) as real time detector.

3.2 AVL Micro Soot Sensor (MSS) (R16, R17)

The Micro Soot Sensor (MSS), based on photo-acoustic measurement principles was used as it is possible to do real-time measurement of soot concentration with high sensitivity (detection limit ≤ 10 µg/m³, typically ~5 µg/m³). The instrument picture and its working principle is shown in Figure 2; the exhaust gas is directed through a measuring chamber and thermally animated by a modulated laser beam; modulated heating produces periodic pressure pulsation, which will be detected by a microphone as acoustic wave. The signal is then amplified in a pre-amplifier and filtered in a "Lock-In" amplifier.

Under laboratory conditions, the MSS was used to measure soot on diluted exhausts: its own exhaust conditioning unit allows:

- A dilution with constant ratio up to 10 (partial dilution);
- A temperature and pressure conditioning of the diluted exhaust (temperature below 60ºC and pressure at ambient ±50 mbar).



(a) (b)

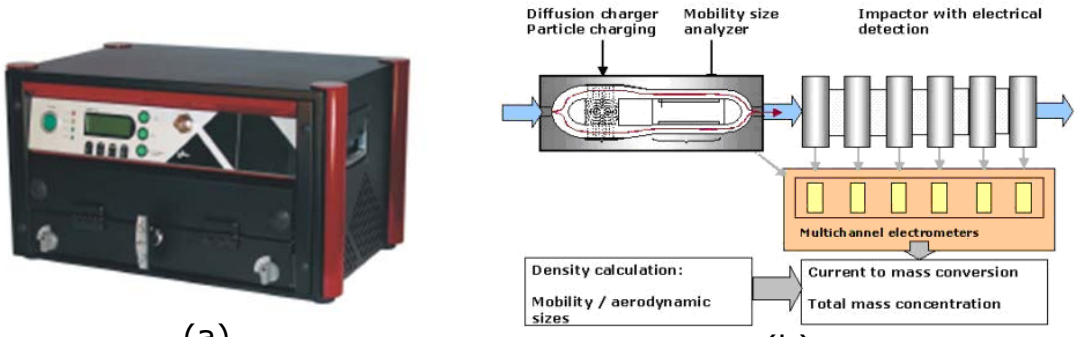
Figure 2 AVL 483 micro soot sensor (MSS) (a) and a schematic of its principle of operation (b)

As the MSS measures only soot (and not total PM as required by the laboratory standard), AVL has complemented it with a model [R17] to predict the missing fractions of the PM, i.e. the Volatile Organic Fraction (VOF) and the sulfates. The model also predicts thermophoretic losses. More recently, the MSS has been equipped with a Gravimetric Filter Box (GFB), which allows the sampling of the total PM.

3.3 Dekati Mass Monitor (DMM) (R25, R26, R27, R28, R29)

Based on the ELPI™ technology, the DMM 230 consists of a corona charger complete with on-line particle density measurement, and an inertial 6-stage impactor with electrical detection. A diffusion charger is used to charge precisely the particles. The charge level is close to the saturation charge for each particle size. After the charging region, a static electrical field is used to deflect smallest particles to the charger mobility electrode and an electrometer is used to measure this current. This construction is used as a particle mobility size analyzer.

After the charger, the particle size classification is accomplished in a 6-stage inertial impactor. Sensitive electrometers are connected to impactor collection sensors and the particles impacting to a corresponding collection plate generate an electrical current for that electrometer. This current is proportional to the amount of particles in each size range. Combining the particle mobility size information from the charger and aerodynamic size from the impactor enables calculation of the effective density of the particles required for conversion from measured current values to particle mass concentration.



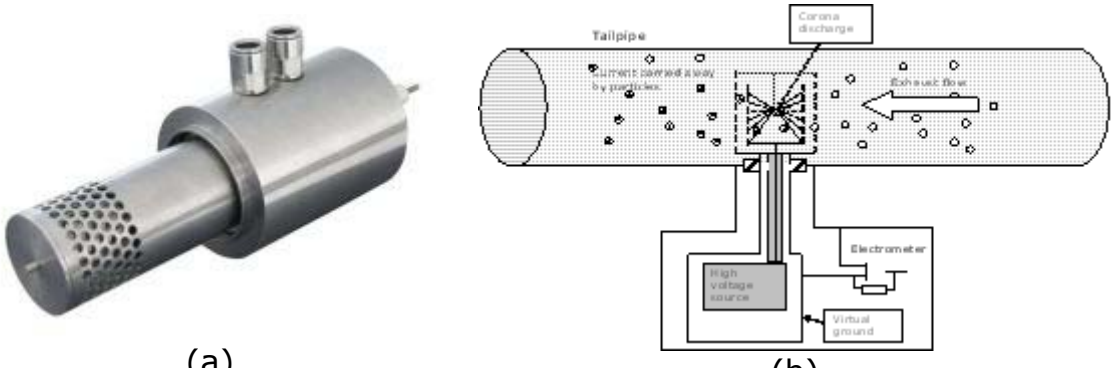
(a) (b)

Figure 3 DMM (a) and a schematic of its principle of operation (b)

3.4 Dekati Electrical Tailpipe PM Sensor (ETaPS)

Dekati's ETaPS, Electrical Tailpipe PM Sensor is a real-time detector for vehicle PM emission measurements. Sensor is located inside or right after the tailpipe and it is measuring the amount of either solid or volatile aerosol particles flying through the sensor head.
Instrument is based on particle charging and electrical detection of charged exhaust particles. A high voltage power supply is used to create a corona discharge into a charging chamber with perforated walls. This chamber is placed into the exhaust flow, and a portion of the exhaust flows through the chamber. Particles that flow through the device become charged and a sensitive electrometer is used to measure the amount of electrical charge escaping the chamber with the particles.

Since the ETaPs is located in the exhaust flow it does not need any dilution or sampling equipment, and it makes the installation and usage easier than with any other PM measuring sensor.



(a) (b)

Figure 4 Dekati ETaPS (a) and a schematic of its principle of operation (b)

3.5 Horiba On board System Transient PM Mass Measurement (OBS TRPM) (R22, R32)

The OBS-TRPM is a filter based partial flow diluter, provided with a cyclone (cut point at 6 um) and PM a dilution and sampling system temperature controlled at 47°C. In addition, it is provided with a diffusion charge sensor (DCS) which is used as real-time detector and measures the particles length.

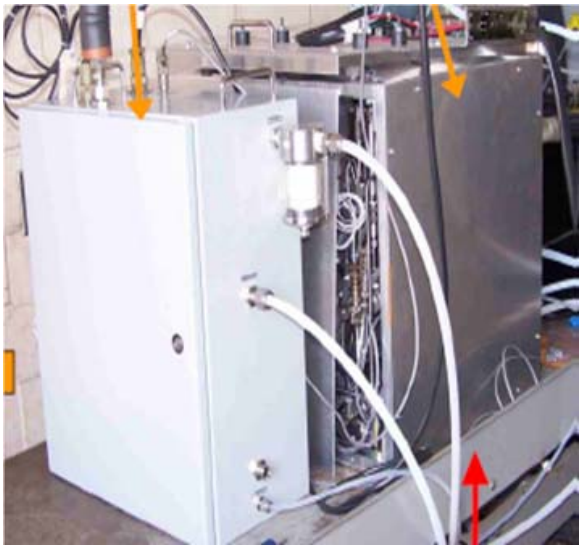


Figure 5 Horiba OBS-TRPM

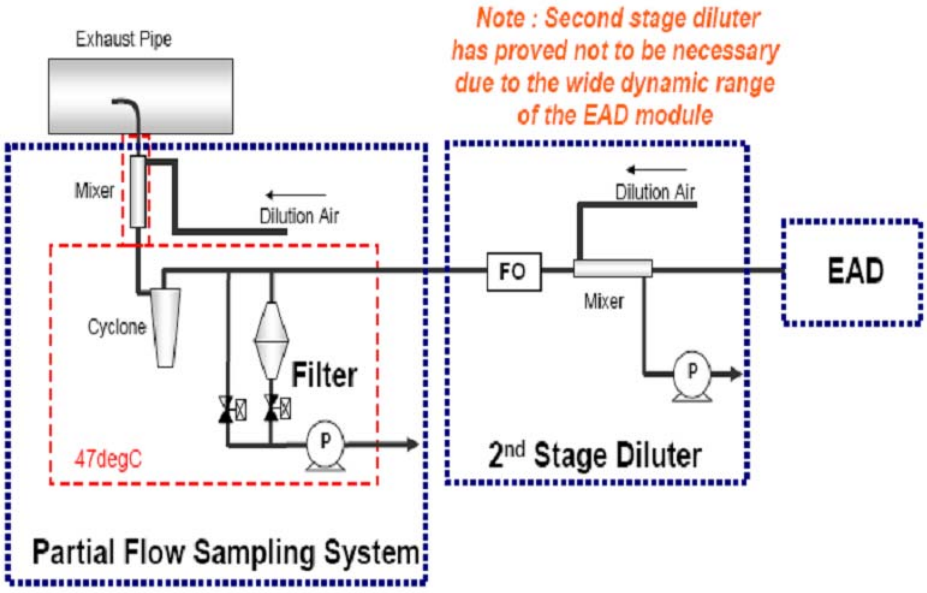


Figure 6 Horiba OBS-TRPM: schematic of its principle of operation

As shown in Figure 6, the partial flow sampling system extracts a proportional amount of raw exhaust and dilutes it with HEPA filtered dilution air. The total flow through the heated transfer line is 30 lpm. A small amount of this diluted exhaust is bypassed to the DCS module for the real time measurement. The rest of the diluted

exhaust is either passed through the analytical filter or goes through a bypass filter.

3.6 Sensors Portable Particulate Measurement Device (PPMD) (R22, R23, R24, R25)

The portable particulate mass measuring device (PPMD) by Sensors Inc. is composed of two micro-proportional sampling systems (MPS) for exhaust dilution and a carousel quartz crystal microbalance (QCM).

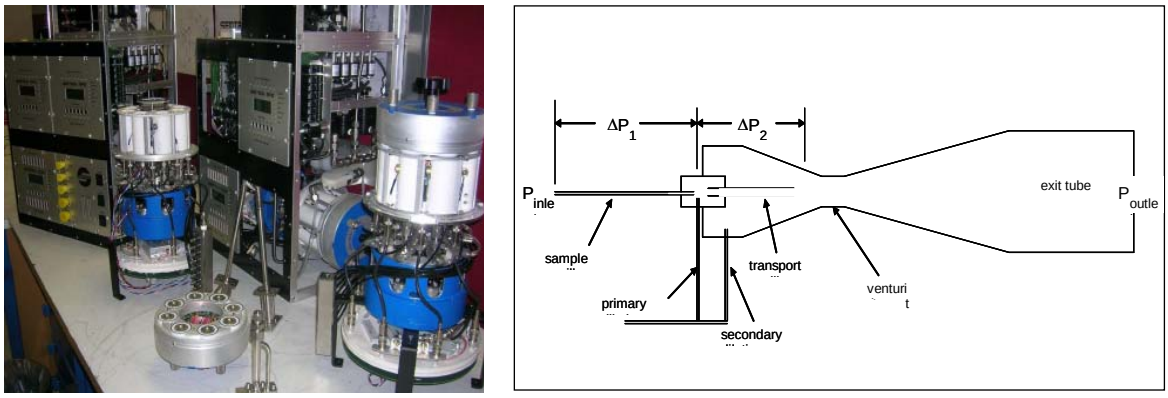


Figure 7 PPMD (left) and Schematic of dual dilution sample (right)

The MPSs are partial and proportional exhaust flow sampling systems. The second MPS, which allows an additional dilution for 'dirty' engines, was not used in the present program. Its design is illustrated in Figure 7 which illustrates the sample and transport capillaries, the primary and secondary dilution, and the venturi. This design is adapted from Brockmann et al [R23].

The QCM (Figure 8) employs piezoelectric crystals as sensitive microbalances. Electrostatic precipitation collects aerosol particles on the surface of the crystals. The crystals are excited in their natural frequency, which decreases with the increasing mass load on its surface. Thus, the particulate mass collected on the crystal can be determined by measuring the change in the crystal natural frequency. The frequency to mass relationship is defined as according to Sauerbrey [R25].

Figure 8 SEMTECH PPMD: Details of the carousel QCM

3.7 Principles of the candidate instruments: overview

The measurement principles of the candidate instruments is summarised in Table 1. This summary shows that some proposed systems (MPSS, OBS) were fully in line with the European reference laboratory standards and were delivered with the additional features required for the on-board/in-service testing application: the transport line and the real-time detector.

The dilutor of the PPMD also meets the requirements of the existing standards (e.g. ISO 16183-81) for partial and proportional exhaust flow sampling. The QCM of the PPMD, that carries out the PM mass measurements, is able to provide a mass increase after the sampling period on a crystal. In this program, the sampling duration was set to 2 minutes thus not completely providing a second-by-second (real-time) PM mass data. For all these instruments, the exhaust flow signal is used to control the proportional dilution.

The DMM was provided without dilutor: it was used either with a constant dilutor or directly on the CVS. The MSS has its own dilution and conditioning unit. For both the DMM and the MSS, the exhaust flow is required to calculate the total mass (PM or soot) at the end of a test.

	SUB SYSTEMS					
	SAMPLING		DILUTION - PARTIAL FLOW		TOTAL MASS	REAL TIME DETECTOR
	DIRECT	TRANSPORT	PROPORTIONAL	CONSTANT		
LABORATORY REFERENCE (SPC)	Yes		Yes		Pallflex TX40	
IDEAL' ON-BOARD PEMS PM i.e. IN LINE WITH THE LABORATORY STANDARD	Yes	Yes	Yes		Pallflex TX40	Equal to Filter Mass
PORTABLE CANDIDATE INSTRUMENTS						
MICRO-PSS + ETAPS	**Yes**	**Yes**	**Yes**	No	Pallflex TX40	ETAPS [mV]
OBS-TRPM	No	**Yes**	**Yes**	No	Pallflex TX40	EAD [mm/cm3]
PPMD	**Yes**	**Yes**	**Yes**	No	QCM	
DMM	**Yes**	No	No	**Yes**	No	DMM [mg/cm3]
MSS	No	**Yes**	No	**Yes**	No	MSS [mg Soot/cm3]
(*) For averaging work or CO2 based window, integration is done for durations in the range of 20 to 40 minutes						

Table 1 Measurement principle of the candidate instruments versus the European laboratory standard (for which Pallflex TX40 is the reference media)

4 Test Program

4.1 General test set-up

Unless a breakdown or technical problem occurred on an instrument, the candidate instruments were tested simultaneously. Figure 9 shows the complete test set-up with the laboratory systems (CVS, SPC), the engine and its trap (when present) and the position of the candidate systems.

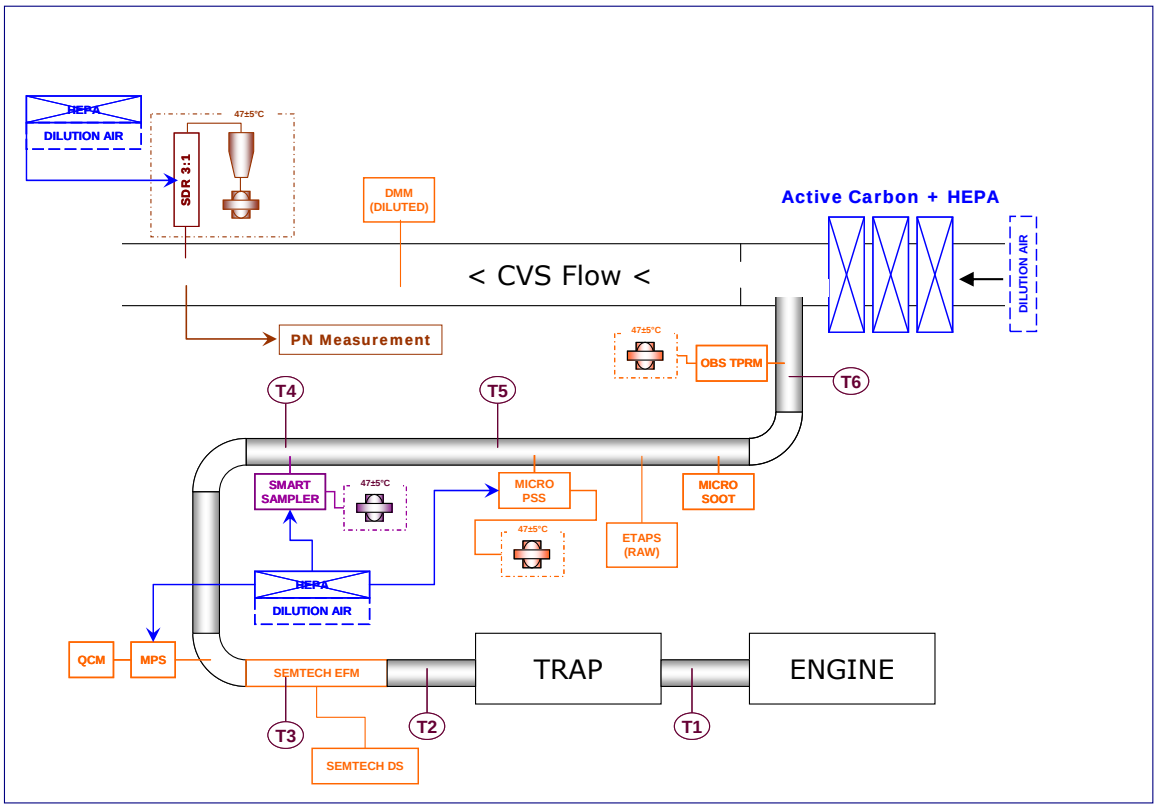


Figure 9 Test set-up showing the CVS, SPC (Smart Sampler) and layout of the candidate instruments

The candidate systems using the PPFS principle used the exhaust flow signal of the test cell as input, except the PPMD which uses the Sensors exhaust mass flow meter (EFM) equipped. This device (shown in Figure 10) is equipped with differential pressure devices and thermocouples to obtain the exhaust mass flow and temperature and it is directly connected through the EFM to the engine exhaust.

The OBS TRPM sampling point was located just before the valve of the CVS. The dilution of its exhaust sample was done at the sampling point. The sampling points for the other instruments such as MSS, MPSS-ETaPs are downstream the PPMD are located between the PPMD and the OBS TRPM as shown in Figure 9.

Figure 10 Photos of the test set-up showing the candidate instruments

Particle number measurements according to the PMP procedure have been also conducted during some of the tests. These results are reported in a companion publication (Giechaskiel et al. [R18]).

4.2 SPC settings

The AVL Smart Sampler (SPC 472) was used as reference instrument for the PPFS principle; it is a partial-flow tunnel for gravimetric measurement of diluted particulates. From the total engine exhaust flow only a small partial flow is sampled into the mini dilution tunnel and diluted with air, which the system conditions internally. The dilution ratio is adjusted and the partial flow rate set by the mass flow controllers for the dilution air and the total tunnel flow; this principle allows not only the simulation of a CVS full-flow dilution tunnel but also the adjustment of constant dilution ratios at constant total tunnel flow.

The sampling point of the SPC system at the tailpipe was positioned 5 m downstream of the after treatment device. The sampling probe was sharp-edged and open ended, facing directly into the direction of flow. The dilution took place <20 cm from the exhaust tube using filtered air. In order to achieve extremely low particle number background (<10 p/cm^3) HEPA and Carbon filters were added at the dilution air line. Downstream of the mixing tunnel, a URG-2000-30EP cyclone was installed with $d_{50\%}$ at 6 μm (for a flow rate of 30 L/min). 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 (±5°C) (for the PM tests).

All PPFS system, except the PPMD, used settings identical to ones of the reference partial flow system (SPC).

4.3 Sampling strategies

As introduced in section 2.3.2, the candidate instruments had to be 'ready' for on-vehicle tests and in particular to include a solution to transport the raw or the diluted exhaust. This would allow for an installation of the system within a few meters from the vehicle tailpipe.

Definitions have been proposed for the two main sampling strategies: *direct sampling* and *transport*. *Direct sampling* means that the instrument can be installed within a distance of approximately 1 m from the tailpipe. In this case, it is assumed that the physical characteristics of the exhaust gas are not modified significantly and that the deposition of PM is limited to a minimum. The transport means that either the raw or the diluted exhaust gas is transported to the instrument and that the system is engineered to minimise the modifications of the gas and to limit the PM deposition.

An extension line of 5 meters was provided with most instruments, as shown in Table 1. When possible, some of the experiments were conducted with and without the transport line.

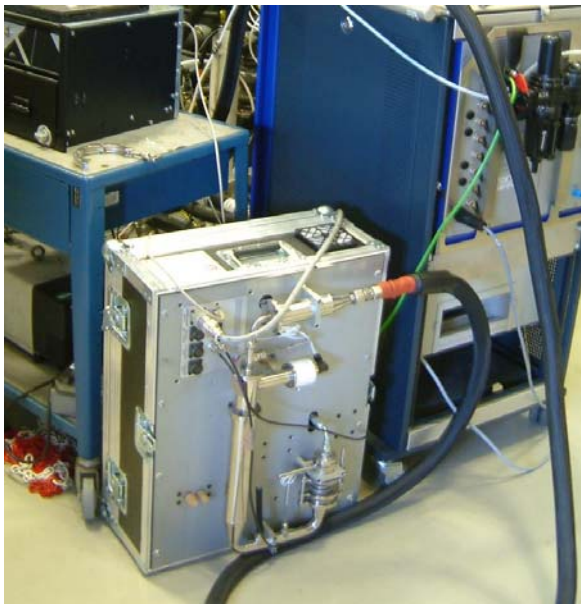


Figure 11 Photos of the sampling lines on some of the candidate instruments

4.4 Engines and after-treatment systems

To challenge the measurement capabilities of the instrument for different engine and after-treatment technologies, 3 engines which covering various emissions standards were used:

- Engine#1 was an Iveco Cursor 10 meeting certified (without DPF) according to the EURO III standards and retrofitted with an Emitec Diesel Particle Filter (DPF) whose efficiency was between 40 and 60 %.;

- Engine#2 was an MAN D2066 LF certified according to the EURO V standards and equipped with a Selective Catalyst Reduction (SCR) after-treatment system. The reagent (AdBlue ®) is a urea-water solution of 32/68% by weight, post-injected at the exhaust;

- Engine#3 was a Cummins ISX 500 certified according to the US 2007 standards US07 engine and equipped with a DPF.

The main engine characteristics and their emissions performance on the European Transient Cycle (ETC) are reported in 0. Note that Engine#3 was certified according to the US cycles and certification procedures. It may therefore not meet the EURO V standards for some pollutants.

For Engine#3, the Engine Control Unit (ECU) monitored continuously the inlet and outlet pressures and temperatures of the DPF. The DPF regeneration was performed every 20 test cycles, using a specific interface communication with the ECU. The regeneration consisted of a stationary phase of 45-60 minutes where a post injection of fuel was injected on the exhaust to promote the oxidation within the DPF. The process was controlled by the ECU monitoring that the DPF temperatures did not to exceed 600°C. An example of parameters

recorded during a regeneration cycle is given in Figure 12: The post injection of fuel in the exhaust increased the DPF outlet temperature at 560°C to promote the PM oxidation, thus increasing the soot concentration (measured by the MSS).

Engine	**1**	**2**	**3**
Applicable emissions standard	EURO III[2]	EURO V	US07
Cylinders	6	6	6
Engine capacity (liters)	10.3	10.0	15.0
Max power (kW @ rpm)	316 @ 2100	324 @ 1900	373 @ 2000
Max torque (Nm @ rpm)	1900 @ 1050-1750	2100 @ 1000-1400	2500 @ 1200-1500
After-treatment	Partial flow DPF	SCR	DPF
ETC PM Emissions (g/kWh) on SPC	*0.041*	*0.022*	*0.002*
ETC NOx Emissions (g/kWh)	4.0	1.596	1.339
ETC CO Emissions (g/kWh)	0.07	0.259	0.025
ETC THC Emissions (g/kWh)	0.0269	0.018	0.0
WHTC PM Emissions (g/kWh) on SPC	*0.0638*	*0.0304*	*0.003*
WHTC NOx Emissions (g/kWh)	7.315	5.544	2.246
WHTC CO Emissions (g/kWh)	0.766	0.623	0.345
WHTC THC Emissions (g/kWh)	0.063	0.020	0.017

Table 2 Test Engine Characteristics

[2] Without DPF

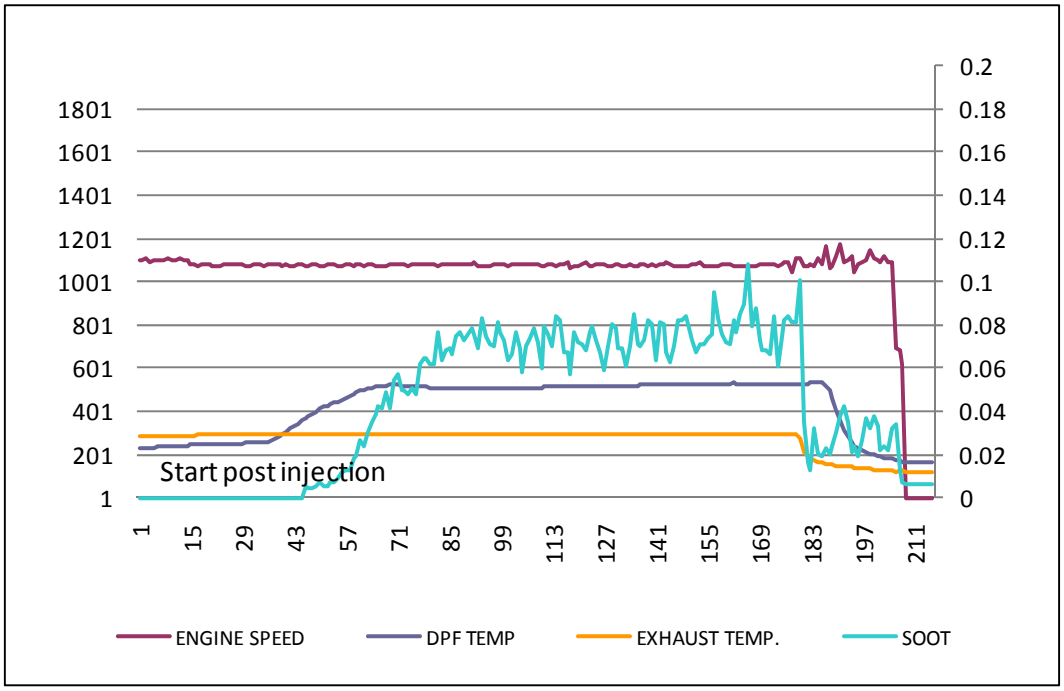


Figure 12 Regeneration of DPF on Engine#3 (Left Y-axis: engine speed and temperatures - Right Y-axis:MSS soot concentration)

Figure 13 Photos of 3 engines, from left to right: Iveco Cursor 10, MAN DF2066 LF and Cummins ISX 500

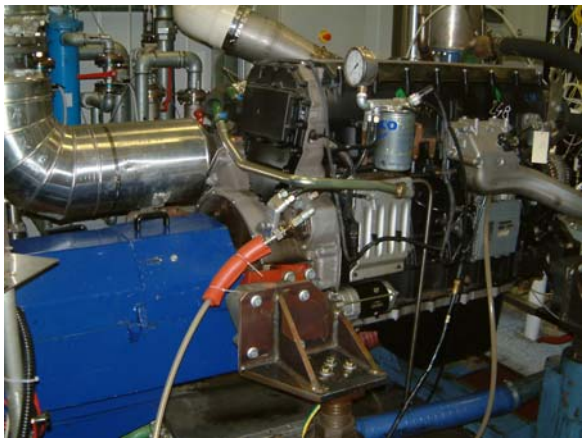


Figure 14 Photos of Engine#1 (Iveco) in the test cell

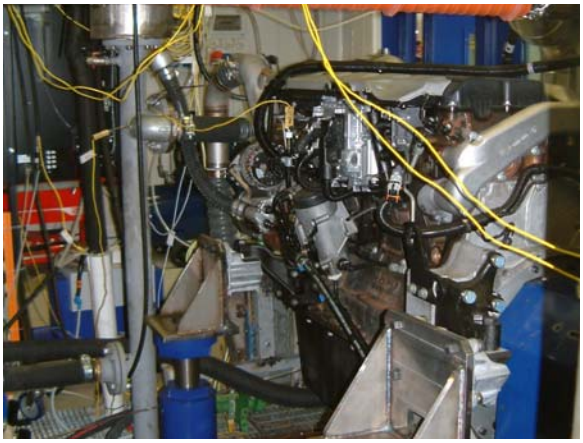


Figure 15 Photos of Engine#2 (MAN) in the test cell

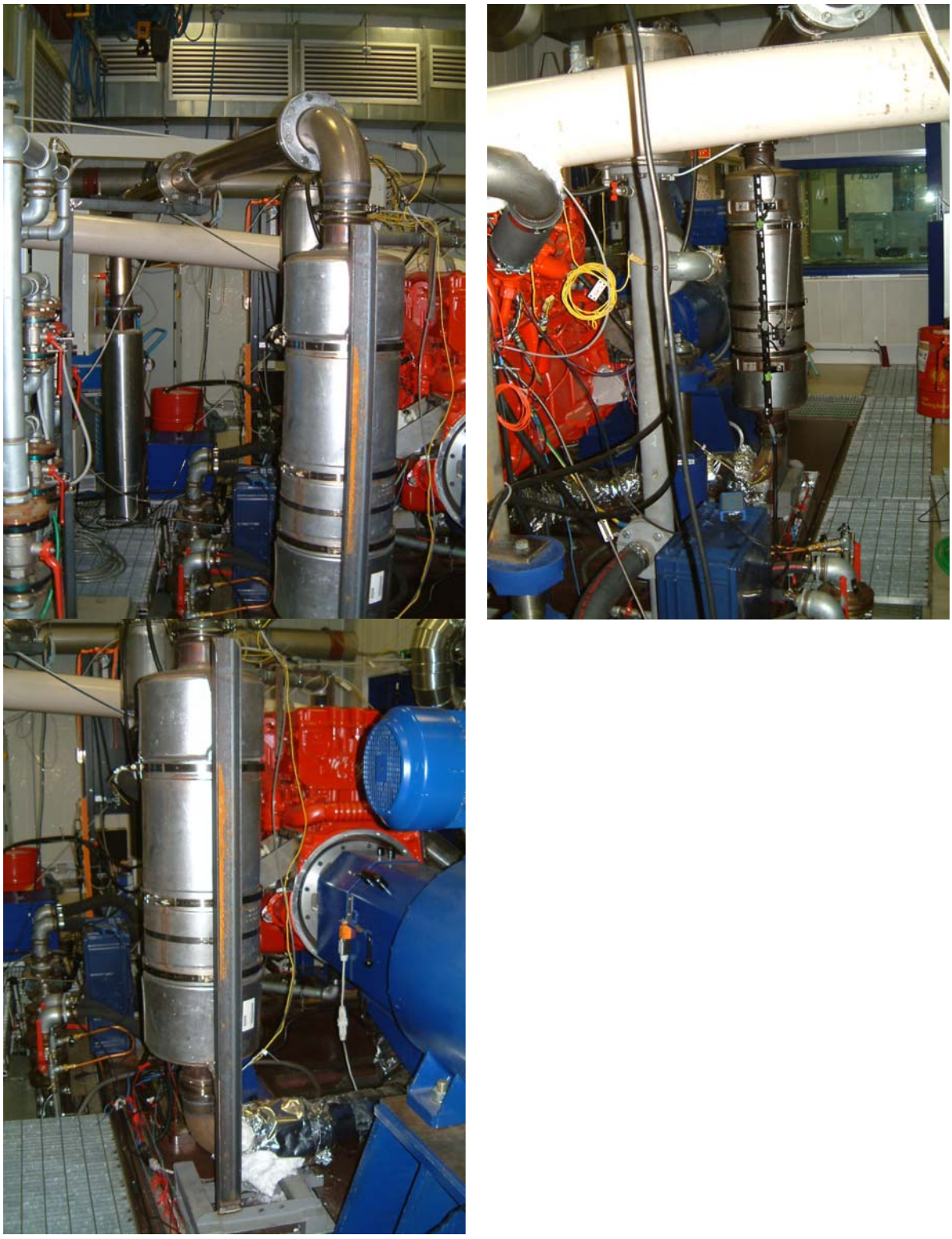


Figure 16 Photos of Engine#3 (Cummins) in the test cell

4.5 Test fuels

The main properties of the test fuels are reported in Table 3. Fuel A was used with engines 1,2 and 3 whereas fuels B and C were only used in phase 2. Fuel A is a European fuel, meeting the EN590 diesel

fuel specifications. Fuel B is similar to Fuel A with 5% of Fatty Acid Methyl Ester (FAME). Fuels A and B have very similar properties. Fuel C is a US reference fuel. Compared to European standard fuels it has:

- A higher density (+1.4%);
- A lower average boiling point (much lower T95%);
- A higher total aromatic content (36% vs 23%);
- A lower heating value but higher density -> higher volumetric heating value (+0.68%).

		Fuel A	**Fuel B**	**Fuel C**
		RF-06-03	RF-06-03+5% FAME	US 86.113-07
Density @ 15 C	kg/m3	833.6	833.6	845.4
Cetane Number		52.9	53.1	46.9
Distillation				
IBP	ºC	204	207	197.5
10% v/v	ºC	233.7		217.7
50% v/v	ºC	275.3	278.1	272.3
90% v/v	ºC	322.3		311.6
95% v/v	ºC	348.4	349	
FBP	ºC	357.7	356.7	333.6
Viscosity @ 40 C	mm2/s	2.93	2.93	2.55
Aromatics				
Total	%wt	23.4	22.8	36.3
Mono	%wt	19	18.8	
Poly	%wt	4.4	4	
Sulphur	mg/kg	1.6	1.7	7
Net heating value	MJ/kg	43.199	42.942	42.886
FAME	%vol		5.1	
Oxygen	%wt		0.7	

Table 3 - Test fuel properties

4.6 Test cycles

The main cycle used in this program is the Worldwide Harmonised Transient Cycle (WHTC), which should become the new European transient certification cycle from the EURO VI standards of heavy-duty engines.

A few other cycles (ETC, ESC, WHSC) were run during the program. However, to get a statistically significant number of similar cycles and conditions to evaluate the instruments, the analysis of the results has been conducted using the results from the WHTC cycle only. In total, more than 150 'official' WHTC test cycles (20 tests for phase 1, 90

tests – with 3 fuels - for phase 2 and more than 40 tests for phase 3) were run during the program.

On the engine#3, several (3) consecutive transient cycles were run in order to evaluate the filter loadings for test durations that are close to the ones likely to be encountered during on-road testing.

4.7 Other test conditions

4.7.1 Engine and after-treatment conditioning

The strategy for the conditioning of the engine systems was chosen as follows:

- Engine#1: No pre-conditioning cycle, leading to various engine thermal conditions at test start-up;
- Engine#2: Cold WHTC in the morning and several consecutive hot WHTC tests;
- Engine#3: Cold WHTC in the morning and several consecutive hot WHTC tests, with some specific cycles for DPF regeneration, as explained in section 4.4.

The effect of the engine condition is illustrated respectively in Figure 17 for engine #1 and in Figure 18 for engine#2. These figures which shows the variations of the PM emissions mainly caused by:

- For engine#1, the different engine conditions and DPF loadings;
- For engine#2, the effect of cold and hot WHTC tests.

The average PM emissions results for engine#1 are by far below the applicable limit (EURO III), as this engine was retrofitted with a partial flow trap (Table 2).

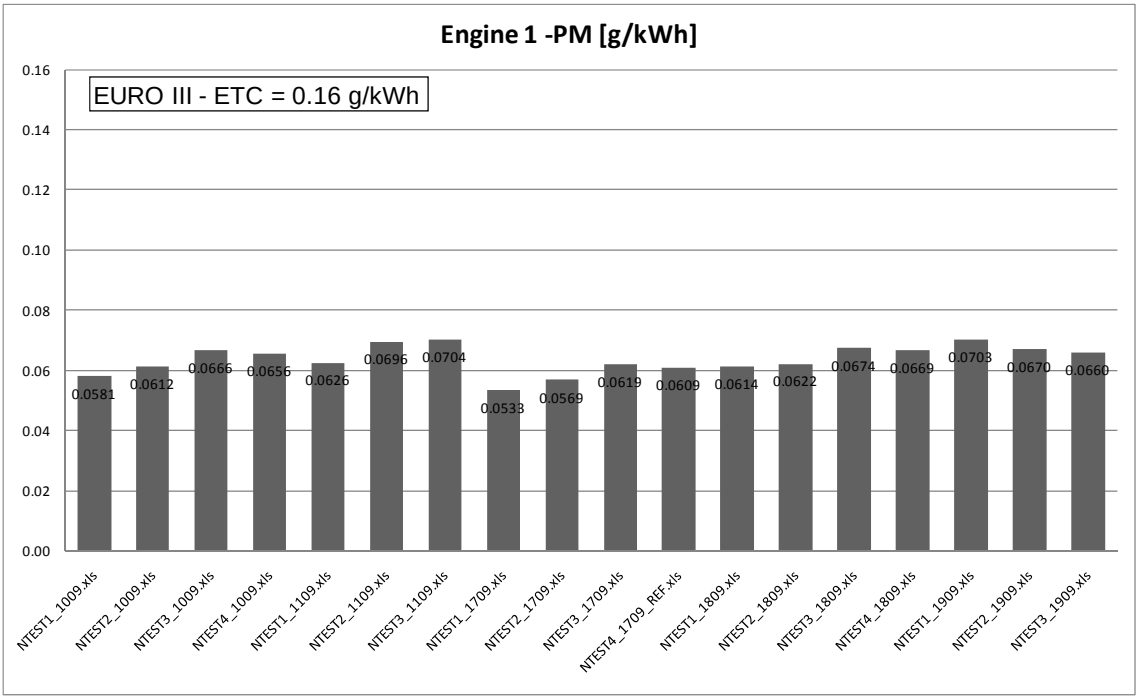


Figure 17 Engine#1 – Effect of engine condition upon PM emissions

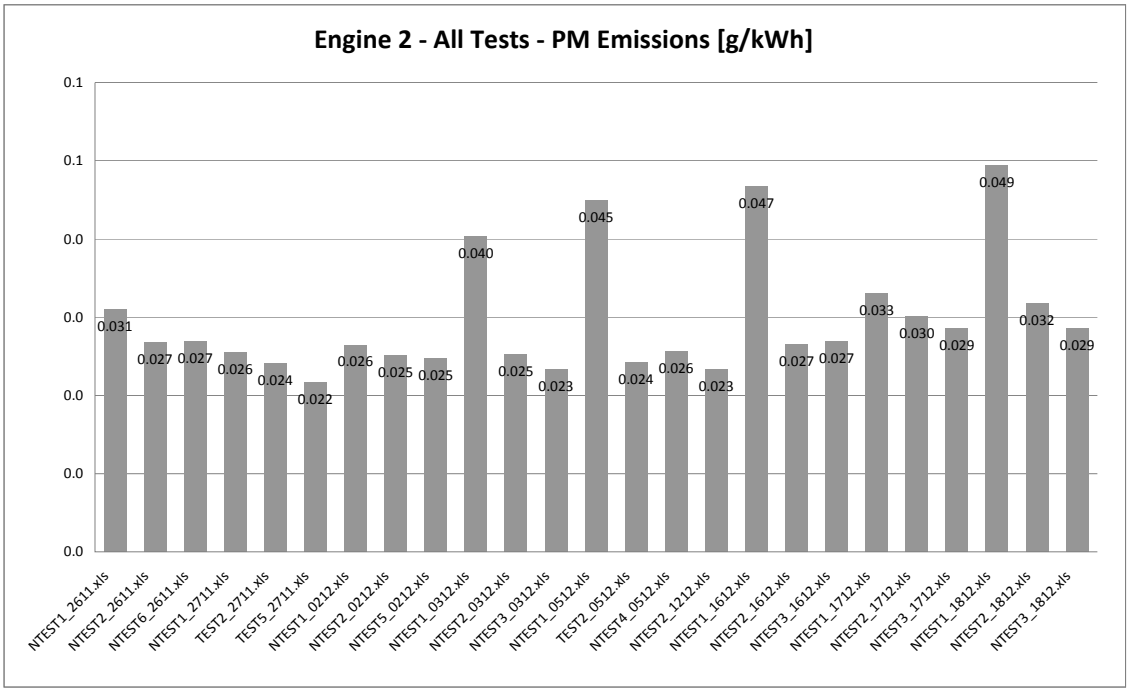


Figure 18 Engine#2 – Effect of engine condition upon PM emissions

4.7.2 Filters and filter weighting procedure

The European standard Pallflex TX40 Fluorocarbon coated glass fibre filters have been used.

The filter weighting procedure covers filter conditioning, handling and weighting. It followed the PMP requirements and in particular:

- The use of a high precision balance;
- The control of temperature and humidity of the weighting room;
- The use of a reference filter (+/- 5 micrograms).

Further details on the procedure are available in Annex (Section 8.3).

4.8 Data handling procedures and tools

The data was analysed using the raw data files from the candidate instruments. The files were processed according to the standard calculations for time-alignment and the total mass, except for Sensors PPMD for which the software provided by Sensors Inc. was used.

5 Experimental Results

5.1 Introduction

The SPC was used as reference laboratory system. No reference instrument nor calibration apparatus were available to check the real-time instruments. However, the instantaneous information is critical in view of the PEMS post-test evaluation following either the US Not To Exceed (NTE) principle or the European Moving Averaging Window (MAW) method. The proposed methodology is detailed below.

Total PM cumulated mass

The first step was to verify whether the candidate PEMS measure the same level of PM emissions over the complete cycle, compared to the reference laboratory instrument (SPC).

Real-time detectors

The second step was to evaluate the measurement performance of the real-time detectors. In the absence of a reference system/sensor, this was done by:

- An inter-comparison of their second-by-second results;
- The calculation of the mass accumulation rates, i.e. the cumulated total PM mass versus time during the cycle, using the moving averaging window.

It is well understood that the real-time detectors, because of their different measurement principles, capture different physical properties of the Particulate Matter. Ideally, they should measure the PM mass (but they don't) or measure some properties which may allow to recalculate the PM mass under certain assumptions.

For the real-time detectors (ETaPS, EAD), the mass accumulation was calculated in the following way: the real-time data (regardless of its unit) is multiplied by the applicable dilution ratio (constant for the micro-soot sensor, variable for the others) to obtain the equivalent quantities on the raw exhaust. The previous data is then multiplied by the exhaust flow and summed over the test to obtain a quantity which is assumed either to be equal (DMM, MSS) or proportional (ETaPS, EAD) to the total PM mass for the test.

5.2 Total Mass Results

5.2.1 Results per Engine

The results are presented for each engine, first for the absolute PM emissions in g/kWh then relative as a percentage of the result

obtained for the reference laboratory system, i.e. the SPC. Each bar represents the average of the valid tests carried out with each instrument. When present, the error bars show the minimum and maximum measured within the series of tests. The error bars are shown only when the engine conditioning was controlled, i.e. for the hot WHTC tests on engine#2.

The results obtained with the various instruments for engine#1 are shown in Figure 19. Both the DMM and the MPSS correlate with the reference system (SPC). The MPSS was used with both the transport and the direct sampling strategies and no difference could be noted between the two. Finally, from the MSS results, one can observe that the soot mass emissions for this engine/fuel/after-treatment/cycle combination was around 70% of the total PM mass.

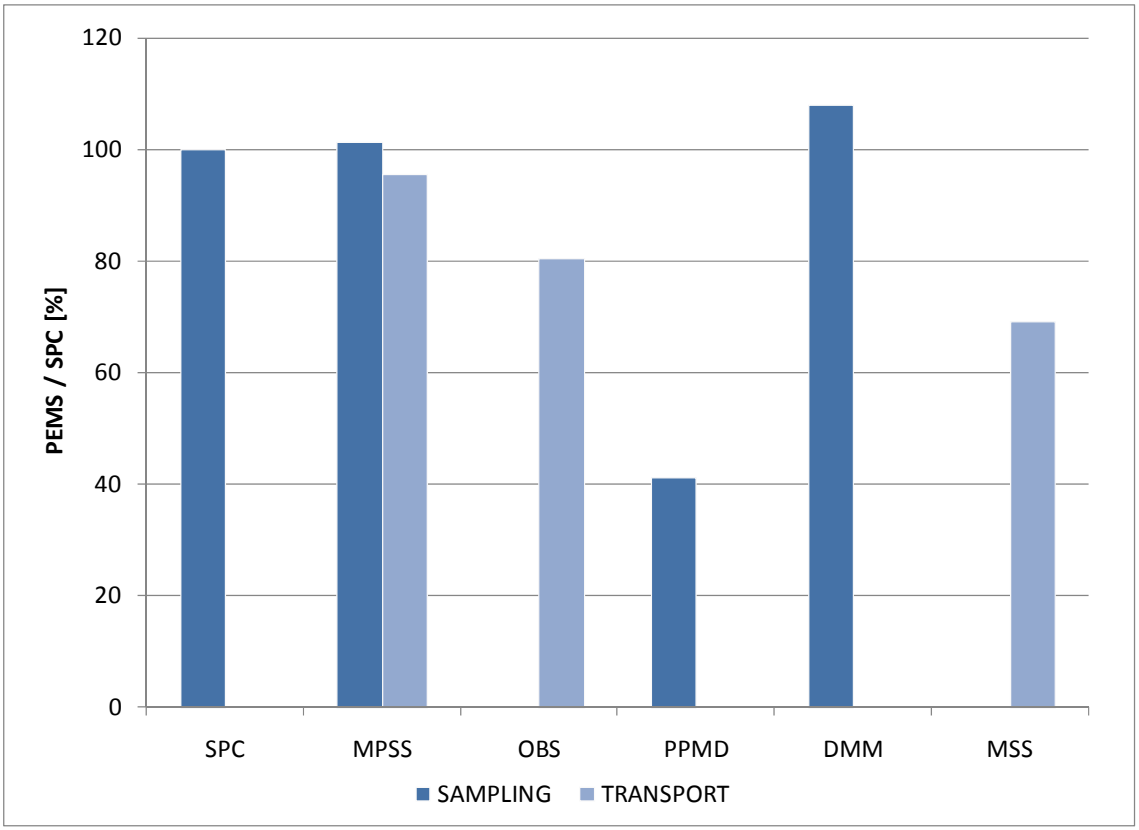


Figure 19 Engine#1: Average PM emissions as % of the average SPC value for the different instruments

The results obtained with the various instruments for engine#2 are shown in Figure 20 (for fuels 1 and 2) and Figure 21 (for fuel 3, with the transport sampling strategy). Even if the candidate instruments had to correlate with the reference system (SPC), the results have also been presented to evidence possible effects of the fuel (3 fuel compositions, reported in section 4.5) or of the engine conditioning

(hot and cold engine). The corresponding values are reported and discussed further in section 5.2.4.

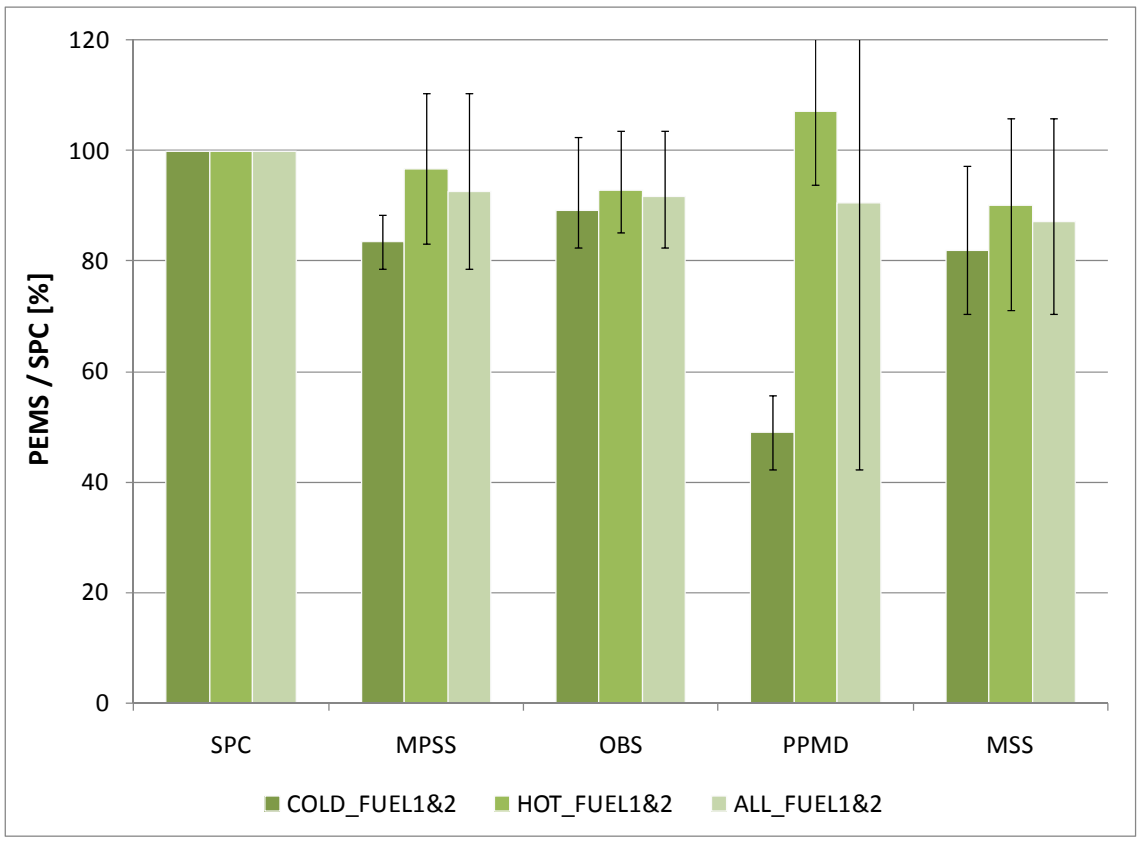


Figure 20 Engine#2: Average PM emissions as % of the average SPC value for the different instruments - Fuels 1 and 2

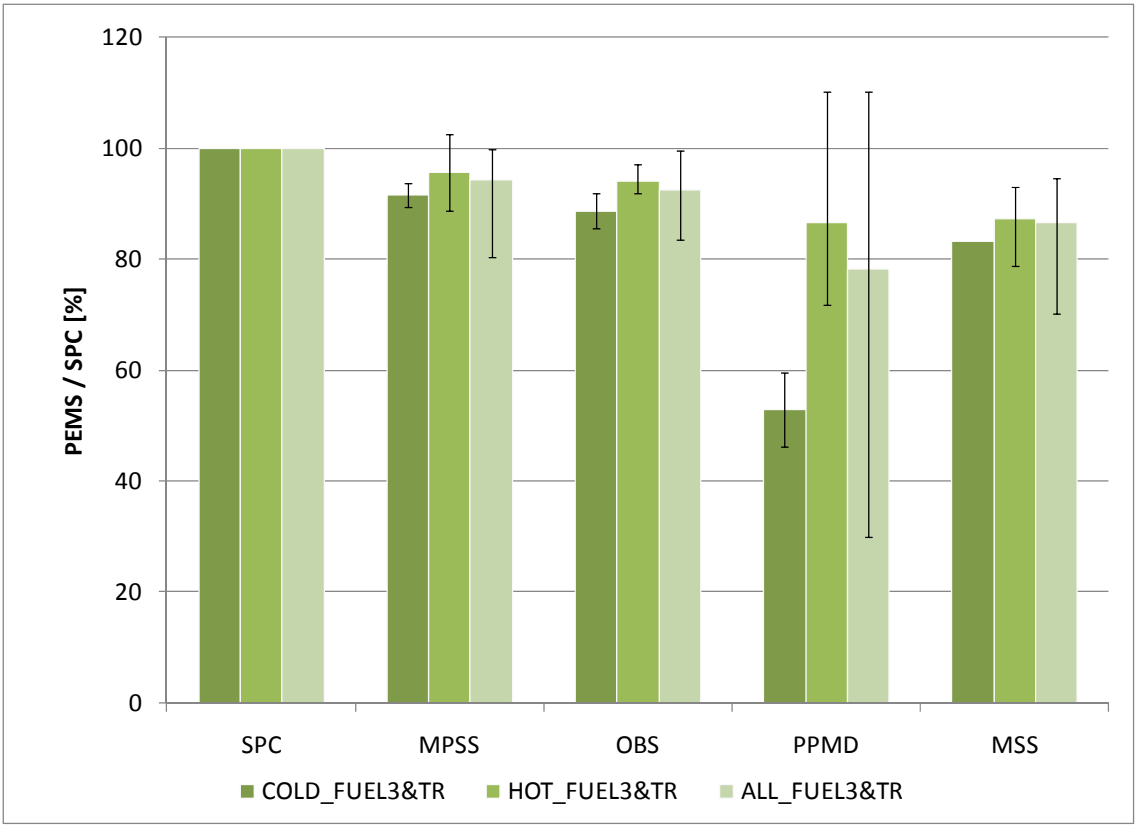


Figure 21 Engine#2: PM emissions as % of the SPC value for the portable instruments - Fuel 3, transport sampling for all portable instruments

The results obtained with the various instruments for engine#3 are shown in Figure 22. The portable systems (MPSS, OBS) have on average sampled much lower PM masses compared to the SPC whereas the MSS figure represents only the average soot content of the PM for that particular engine (i.e. around 10%). The average results per instrument should be taken with care: a very high scatter was observed for most instruments, as discussed in sections 5.2.3 and 5.2.4.

None of the results are corrected for thermophoretic losses. In the case of the MSS, such corrections associated with the SOF calculations (using the method described in R17) were carried out to give the total PM, giving an increase of the values by 20 to 30% for engine 1 and 2, and probably a factor of 2 to 3 for engine 3.

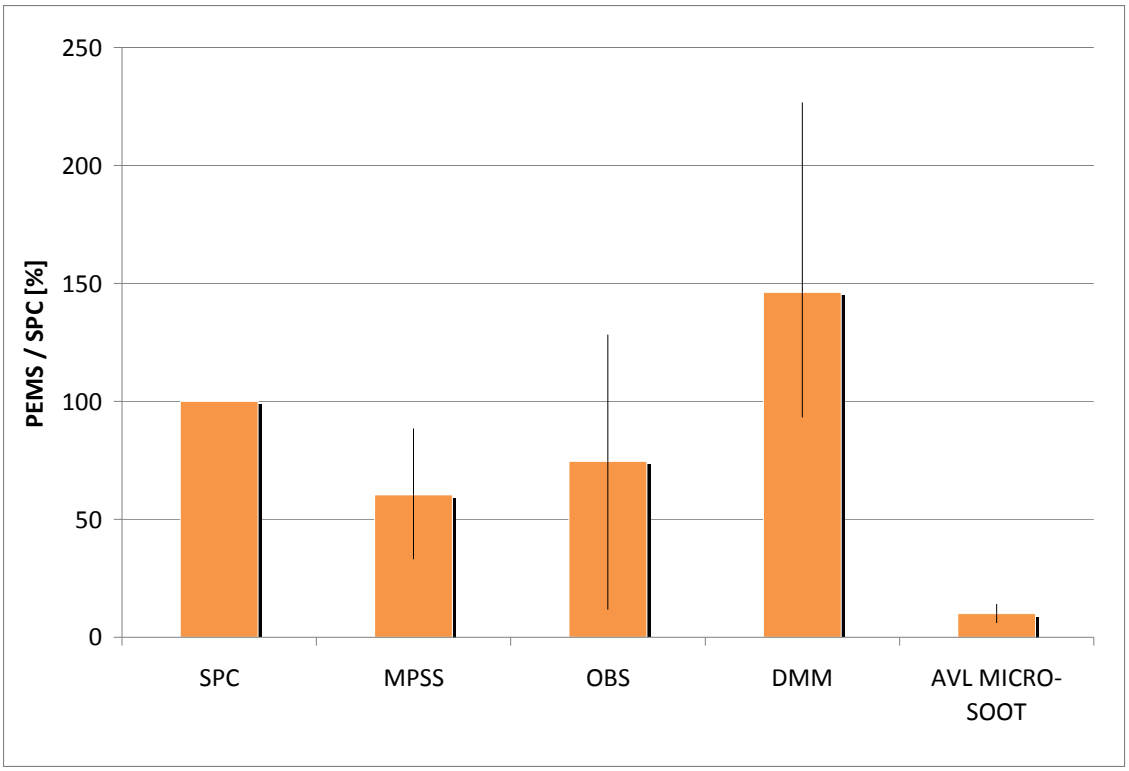


Figure 22 Engine#3: PM emissions as % of the SPC value for the portable instruments

5.2.2 Supplemental tests on Engine#3 (DPF, Low emissions)

5.2.2.1 Introduction

The very low PM emissions of engine#3 have confirmed the lack of sensitivity of the gravimetric method. This is evidenced for instance by the scatter of the results (for both laboratory and portable systems) and the background values reported in the following section.

5.2.2.2 Background measurements

To evaluate the background obtained with the various systems, sampling was performed by simulating a WHTC cycle, (Principle illustrated in Figure 23) where the pre recorded signal of the tested engine exhaust flow was given to the PPFS, the sampling probe was disconnected from the raw exhaust tube and a HEPA filter was connected at the inlet. The filtered sample mass was measured with a mass flow. The background levels of Partial flow systems were also measured with a TSI 3025A particle number counter connected downstream the cyclone. For the mass background 47 mm TX40 filters were used.

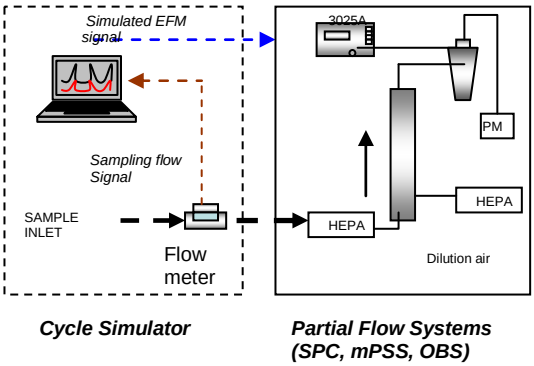


Figure 23 Schematic diagram of background measurement with sampling simulator

The main advantage is that the sampling conditions similar to those of the cycle. The results showed that the mass collected on the filters after a simulated WHTC cycle, was on average ~6 µg for all instruments. Further details on the background measured on the different systems are given in Table 4. The average background value corresponds to a value of approximately 0.5 mg/kWh, which can be compared to the average engine emissions reported in section 5.2.3.

	SPC	MPSS	OBS	ALL
AVERAGE	10.9	5.9	0.7	6.1
ST. DEV	5.3	1.3	N/A	5.0

Table 4 - Average background (µg) on filter for different systems

5.2.2.3 Sampling of consecutive transient cycles

The sampling durations for on-road tests are expected to be much longer than a standard cycle (30 minutes), as a typical test lasts between 2 and 3 hours. To evaluate whether the mass collected on the filters increases proportionally to the sampling duration, sampling was conducted on 3 consecutive WHTC cycles.

Figure 24 compares the brake-specific PM emissions results for one and three WHTC cycles. The lower specific emissions obtained for the longer sampling durations show that the PM mass sampled on the filters does not increase proportionally to the sampling duration. Furthermore, these values (averaged and obtained from several test runs) are only slightly higher than the background emissions reported in the previous section. This confirms the findings from [R19], where these effects have been attributed to the presence or absence of volatiles in the PM. The results of the MSS which are not affected by

the presence of volatiles confirm this hypothesis. In the literature, this effect is often referred to as "volatile artifacts". The term artifact is not used in the present work, as these volatile components are clearly a part of the total particulate mass collected on the filters with the standard method and fall therefore under our definition of PM.

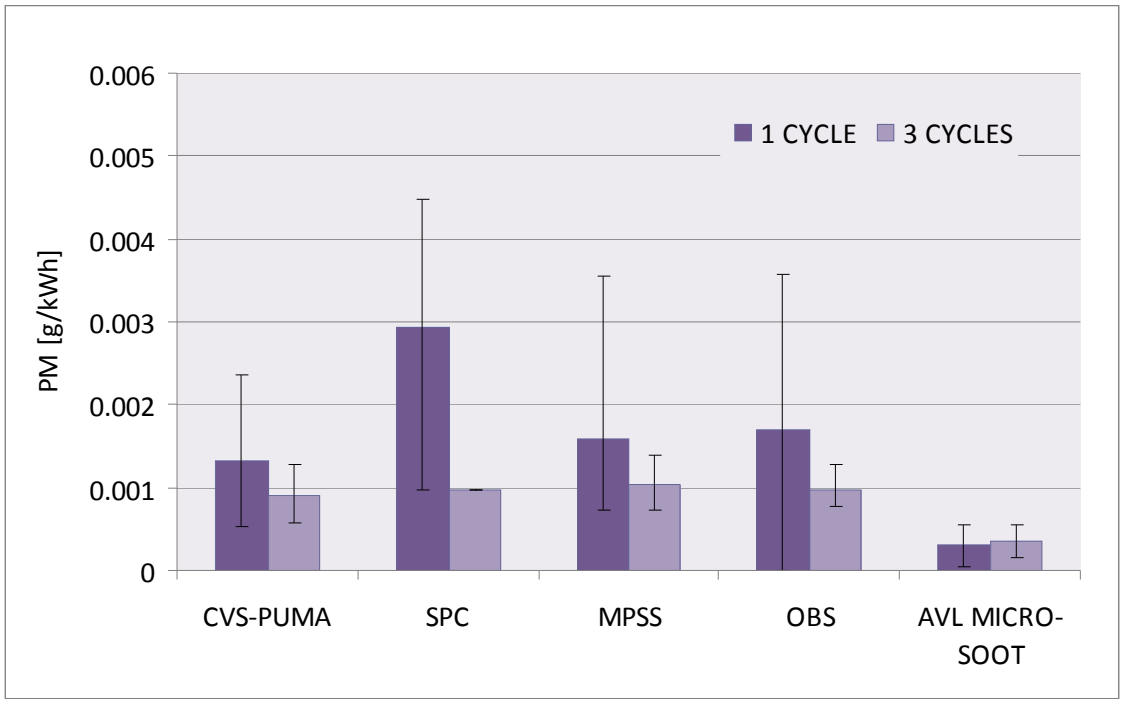


Figure 24 Effect of sampling duration upon total PM emissions

5.2.3 Results per instrument

In the present section, the results presented in 5.2.1 are shown per candidate instrument and expressed in g/ kWh. The expression of PM emissions in g/kWh also shows the effect of the engine technology and the engine conditioning upon the total PM mass results

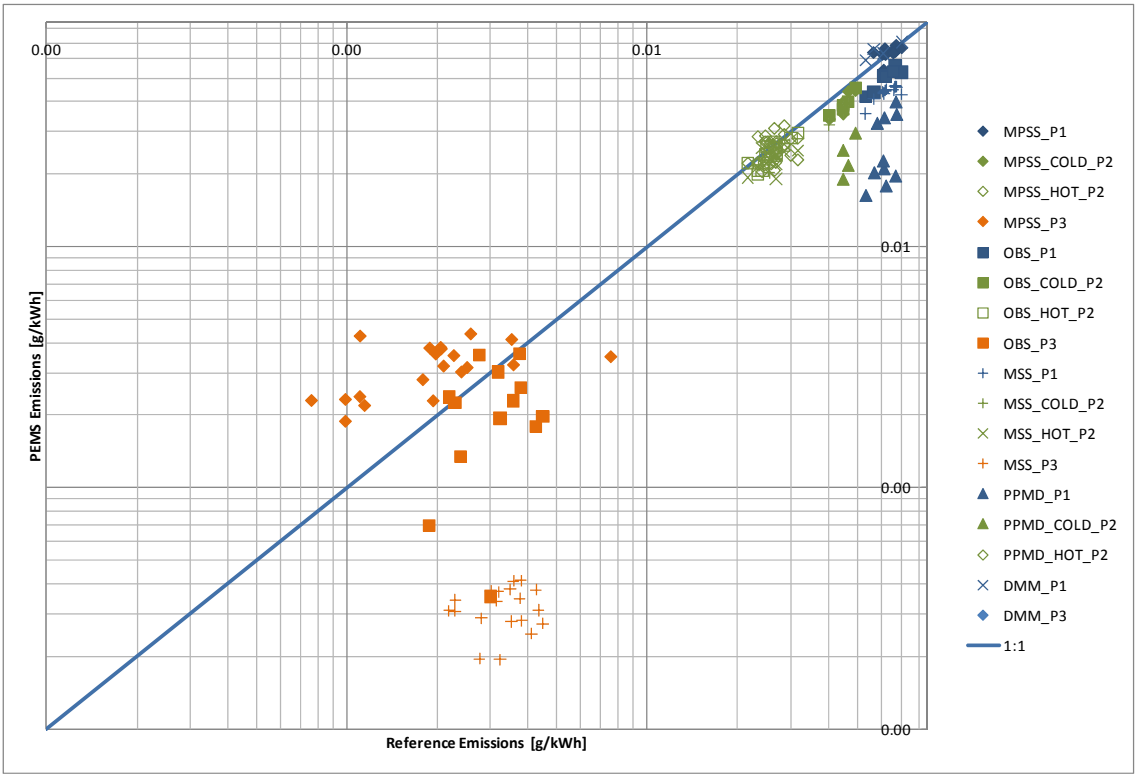


Figure 25 All candidate instruments: Total PM emissions versus SPC value for the 3 engines (P1, blue = Phase 1 - P2, green = Phase 2 - P3, orange = Phase3)

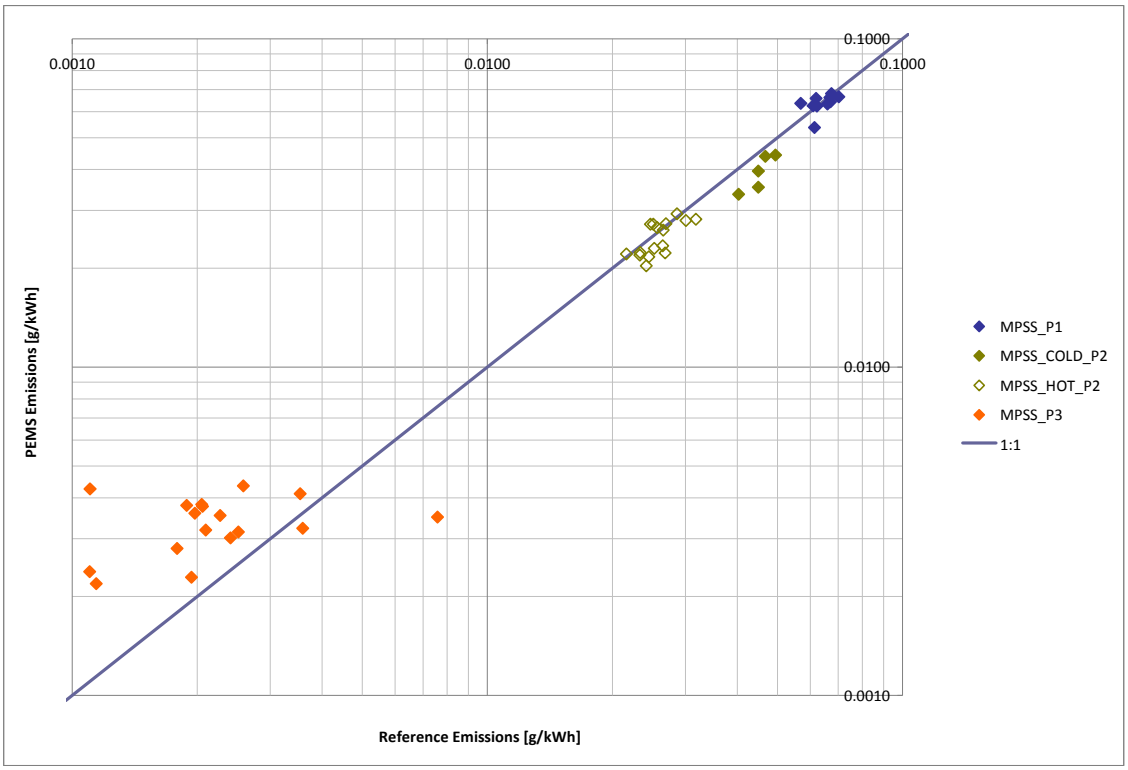


Figure 26 Control Sistem MPSS: Total PM emissions versus SPC value for the 3 engines (P1, blue = Phase 1 - P2, green = Phase 2 - P3, orange = Phase3)

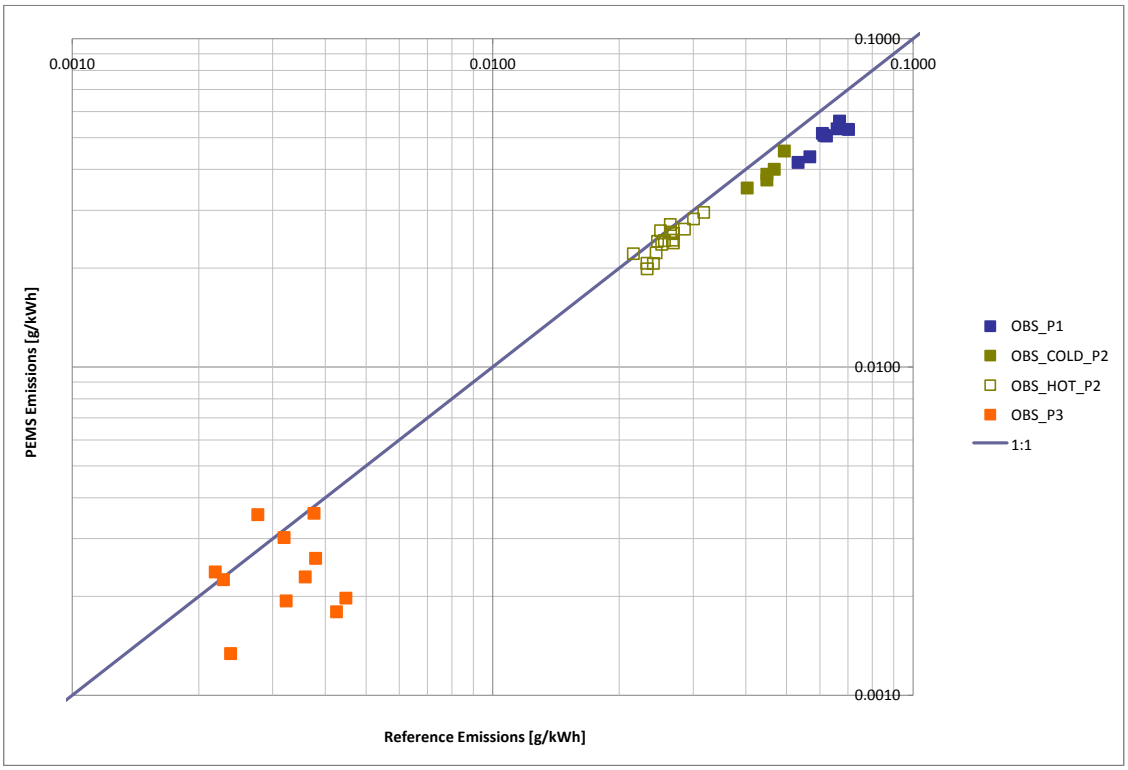


Figure 27 Horiba OBS-TRPM: Total PM emissions versus SPC value for the 3 engines (P1, blue = Phase 1 - P2, green = Phase 2 - P3, orange = Phase3)

5.2.4 Summary of total mass results

To compare different instruments it is very common to use a linear regression analysis. The slope is considered the bias of the systems, the R^2 the precision and the intercept the offset. However, linear regression can lead to wrong conclusions when some of its assumptions are violated or when many orders of magnitude are compared. For example it is possible that the slope is defined mainly from the points with the highest concentrations. For more details, see Giechaskiel and Stilianakis [R14].

In the existing standards [R5], the equivalence of 2 systems is determined from a t-test, using data from the average of 7 test repeats. This approach can also lead to wrong conclusions especially when the tests results have a high variability (e.g. engines with DPFs) [R20]. In the present work, most of the tests were conducted simultaneously. Because of the abovementioned reasons, only the relative differences of each instruments to the SPC results for each test are reported.

The number of valid tests per candidate instrument is reported in Table 5. For all instruments except the ETaPS, the comparison with

the number of tests from the SPC gives an indication of the 'invalid' measurements (e.g. recording lost, measurement not conducted etc).

Engine	SPC	MPSS	OBS	MSS	PPMD	DMM	ETaPS
#1	11	10	8	11	8	4	10
#2	26	22	23	22	15	N/A	N/A
#3	22	12	9	12	N/A	8	N/A

Table 5 - Number of valid tests with the different instruments.

Engine	SPC (g/kWh)	MPSS	OBS	MSS	PPMD	DMM
#1	0.063	100 (7)	80 (3)	69 (3)	41 (13)	108 (7)
#2	0.029	93 (9)	92 (6)	87 (9)	84 (25)	N/A
#3	0.003	63 (15)	75 (34)	10 (3)	N/A	146(46)

Table 6 - Average and standard deviation (in parenthesis) total PM emissions from the candidate instruments in % of the SPC results.

The following comments can be made for each portable instrument:

- MPSS: the equivalency with the SPC is good for all engines, except the third one. The companion instrument (ETaPS) was used only for engine #1.
- OBS: the equivalency with the SPC is good for all engines, except the third one. Note that the instrument was technologically improved between the first 2 phases, thus leading to results more comparable with the SPC on the second engine.
- MSS: it measures only soot, not total PM but offers a high level of repeatability, as evidenced by the standard deviations.

5.3 Real-time detectors

The evaluation of the total PM mass measured by the different candidate instruments was a straightforward comparison with the results obtained with a reference instrument. Such an approach cannot be taken for the real-time detectors, as no reference instrument and no accepted calibration procedure were available. An additional difficulty lies in the different metrics provided by the various instruments, summarised in Table 7.

Detector	OBS-EAD	MSS	ETaPS	DMM
Measured on	Diluted	Diluted	Raw	Diluted
Metric	mm/cm^3	mg/cm^3	[A]	mg/cm^3 or $\#/cm^3$

Table 7 - Metric of the PM detectors

The results are presented in 2 different ways. The first analysis is a direct and visual comparison of the data measured by the different detectors. This provides only qualitative information and indications on both the response time and the sensitivity of the detectors at low levels. The second set of results is - in the absence of calibration procedure - a tentative to estimate the uncertainty on the mass accumulation rate (i.e. the mass as a function of time), which would be needed to run the moving averaging window calculations (See section 5.1).

5.3.1 PM detectors real-time results

Figure 28 to Figure 30 show the raw data provided by different detectors respectively on Engine #1, 2 and 3 for a complete WHTC cycle. On all engines, the MSS, the OBS-EAD and the DMM exhibit a high correlation. The DMM is not shown for engine#2, as the instrument was not available for that engine (due to a breakdown).

The comparative analysis of Figure 28 to Figure 30 also shows the decrease in the PM concentration caused by the 3 different engine technologies. For instance, the range of the MSS data (representing the soot concentration of the raw exhaust) varies between:

- 0.01 and 10 mg/cm^3 for engine #1;
- 0.01 and 1 mg/cm^3 for engine #2;
- 0.001 and 0.01 mg/cm^3 for engine #3.

The results of the ETaPS have been plotted separately and only for engine#1. The ETaPS, which was used on raw exhaust, exhibits sensitivity problems at low PM levels: this is evidenced its inability to capture the low concentrations measured by the other instruments. This effect may be observed on engine #1, where all the instruments went down to low PM/soot concentrations (down to 0.01 for the MSS) whereas the ETaPS signal remained quasi-constant at low levels. The ETaPS was not further considered for the tests conducted on engines #2 and #3.

Figure 28 Real-time detectors results - Engine#1, WHTC cycle (Top: MSS, EAD, DMM - Bottom: ETaPS)

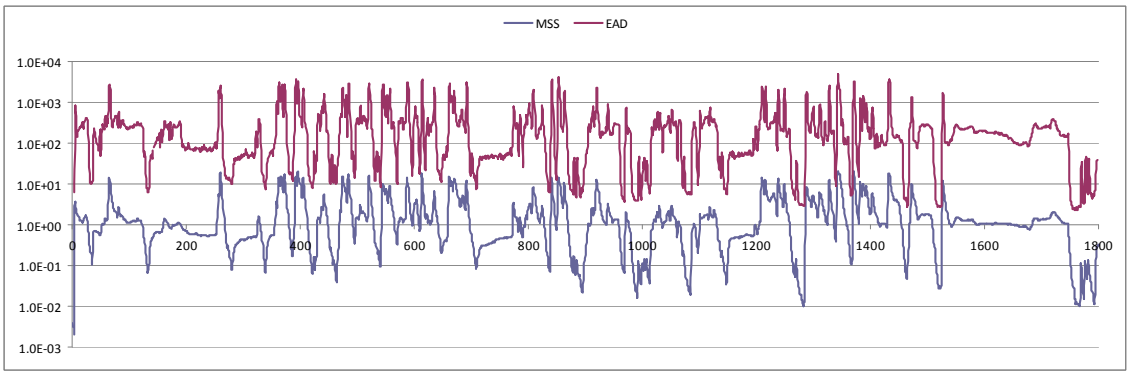


Figure 29 Real-time detectors results on Engine#2, WHTC cycle

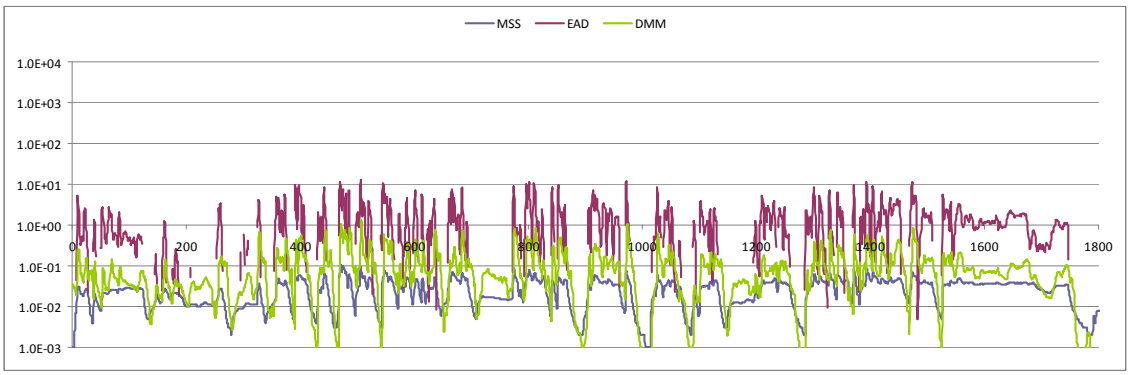


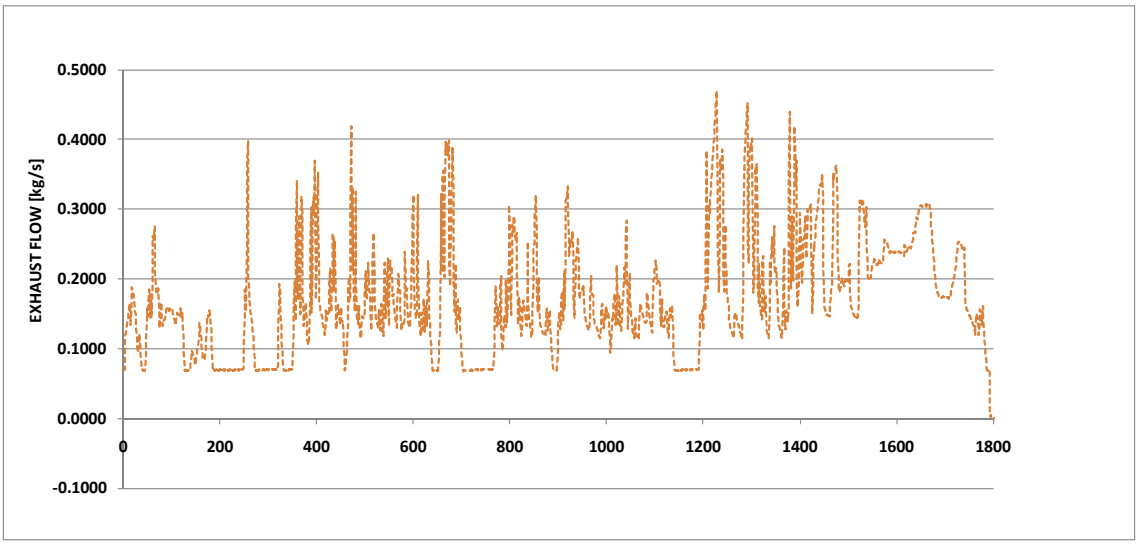
Figure 30 Real-time detectors results on Engine#3, WHTC cycle

5.3.2 Real-time detectors: cumulative mass calculations

In the absence of reference and calibration procedure for all the real-time detectors, their ability to estimate the cumulative PM mass was verified. The data was evaluated using the moving averaging window method (based on the CO2 mass), which is the European 'official' methodology to process on-road emissions results.

For the present work, the calculations were conducted using one third (1/3) of the CO2 mass emitted by the engine on the WHTC cycle. The results presented in show respectively for Engine #1, 2 and 3 how the real-time detectors estimate the percentage of the total PM mass. The first data point indicates the value (i.e. the percentage of the total mass) for the first averaging window. For example, on engine #1 and using the EAD, one would determine that the PM mass is 46% of the total PM for the first window and 32% of the total PM for the last window.

The purple line - referred to the right vertical axis - shows the maximum difference between the PM detectors, interpreted as an uncertainty. For example, the first uncertainty value on engine #1 (2%) is the result of the difference between the cumulative mass estimated from the DMM (48%) and the OBS-EAD (46%). As shown in the three figures, this uncertainty is relatively low and reaches a maxima of 5% for the first 2 engines and 10% for engine #3.



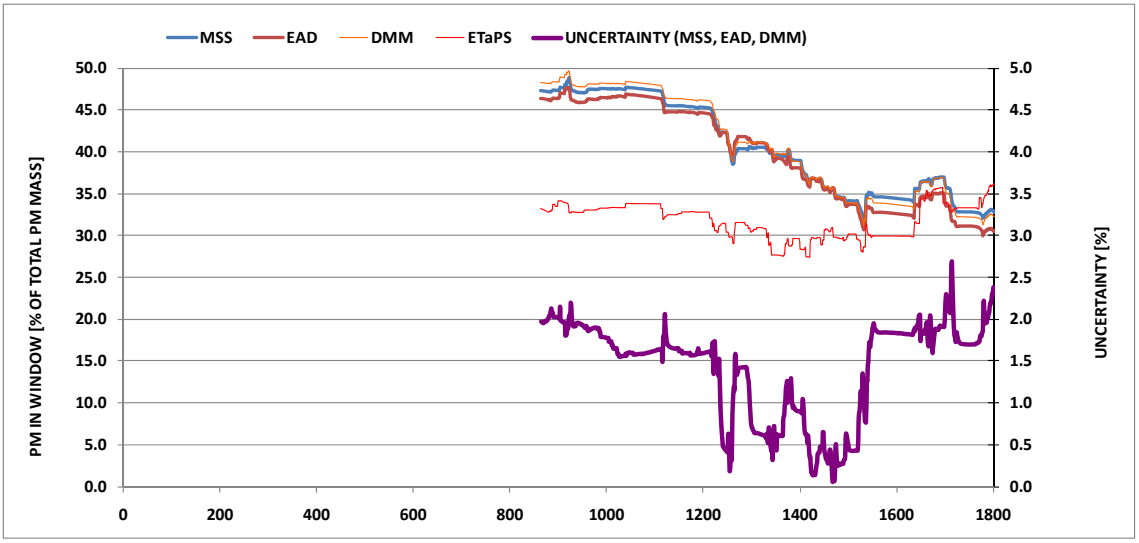


Figure 31 Differences between real-time detectors on mass accumulation - Engine#1, WHTC cycle Top - Engine Exhaust Flow

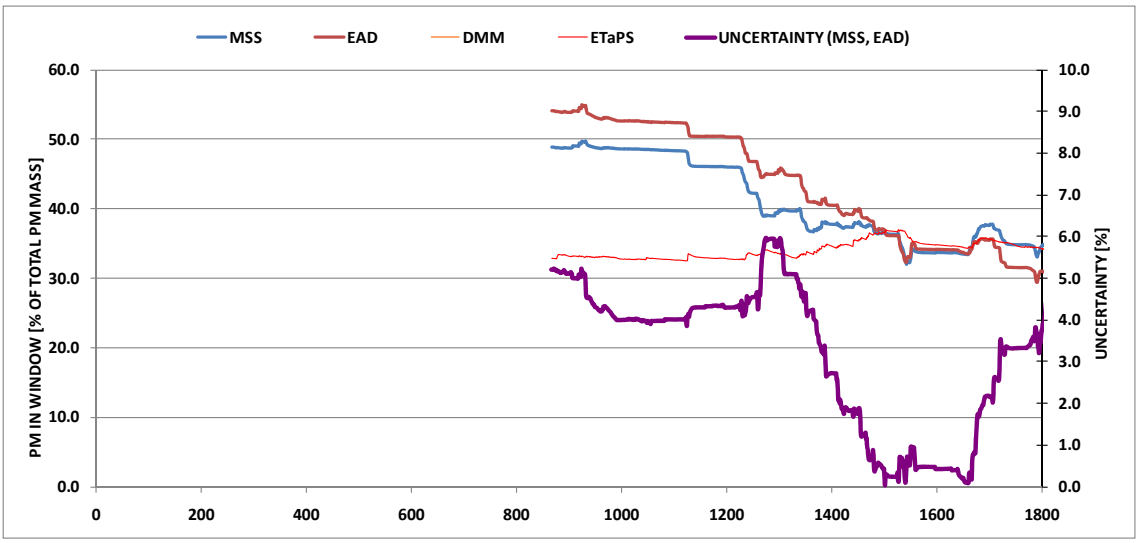


Figure 32 Differences between real-time detectors on mass accumulation - Engine#2, WHTC cycle

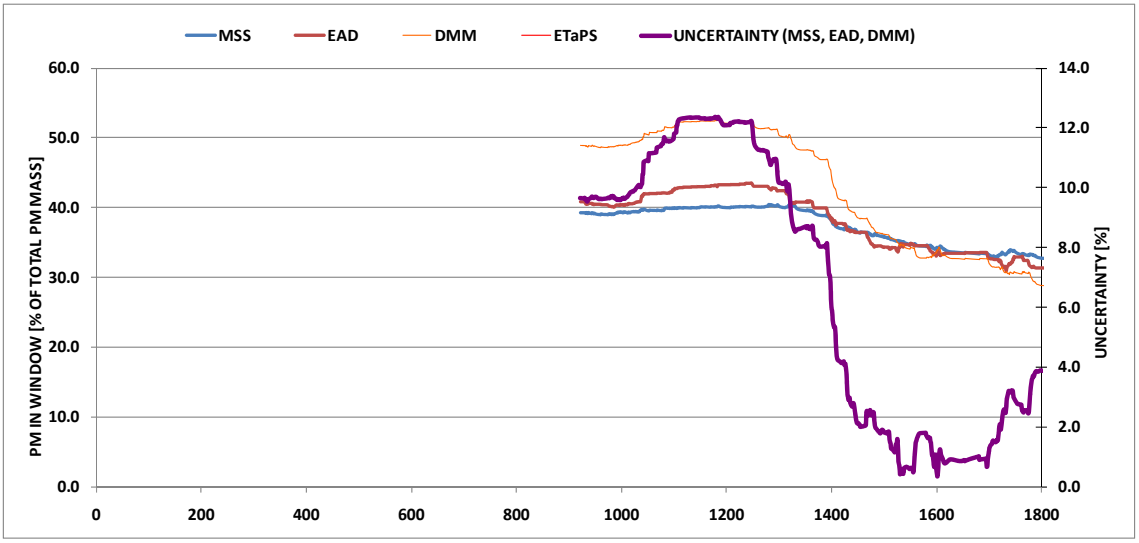


Figure 33 Differences between real-time detectors on mass accumulation - Engine#3, WHTC cycle

6 Conclusions - Next steps

6.1 Technological status of PEMS-PM instruments

The measurement performance of PEMS-PM instruments under controlled laboratory conditions has been evaluated according to the following criteria:

- *Proportional dilution:* portable partial and proportional flow systems are able to comply with the laboratory requirements in terms of proportionality and temperature control of the dilution and sampling system.

- *Total PM mass measurements:* the correlation between the laboratory references the portable 'systems' using the same principle is relatively good, as the difference between them does not exceed 10% on average for engines#1 and #2. The differences observed on the total mass for engine#3 are larger. However, as the scatter of results (evidenced by the standard deviation, Table 6) is equal for both, the difference can be attributed to the lack of sensitivity of the mass based method at these low emissions levels. The results for longer sampling durations obtained on the DPF engine (#3) show a *better correlation between the systems and lower specific emissions*.

- The measurement performance of PEMS-PM instruments on-board has not been fully evaluated yet. However, their stability and performance for long durations (90 minutes) is satisfactory.

- The real-time detectors have different measurement principles. However, a few of them (MSS, EAD, DMM) offer both the sensitivity required at low emissions levels and a sufficient level of 'information' to determine the PM mass accumulation rates.

6.2 Conclusions, proposal and next steps

The results show that the *standard laboratory principle* - i.e. the proportional and partial flow sampling (PPFS) using a filter to collect the PM sampled in the diluted exhaust - *is reproducible* at a lower scale, whereas some real-time detectors (MSS, EAD, DMM) exhibit a satisfactory sensitivity, even at post-DPF emissions levels. It is therefore proposed as reference measurement principle:

- An exhaust PPFS and a filter mass based method, following the design and performance requirements used for laboratory equipment;

- A complementary real-time detector on diluted and temperature controlled exhaust, to estimate the PM mass accumulation rate.

The above proposal for the reference measurement principle reflects the evaluation conducted until October 2009 and some portable candidate instruments were - at that date - already partially or totally in line with the proposed base principle. To complete the work and possibly to keep the door open for other systems to become equivalent to the reference, the EU-PEMS PM experts group has also agreed on the following working items:

- The constant dilution and/or a real-time detector (DMM, MSS with a Gravimetric Filter Box)
- Alternative weighting methods (PPMD QCM or even a different filter media)

For the particular case of the reference measurement principle, the following points will be further investigated:

- The calibration and verification procedures for the real-time detectors;
- The in-use filter handling and conditioning procedures.

The above listed issues were addressed in a follow-up phase of the program conducted between November 2009 and March 2010. The work will be reported in a follow-up document.

In view of the changes in the laboratory method for the EURO VI standards (i.e. the introduction of a particle number limit and of the PMP protocol), the possibility to "PN" in addition to "PM" and/or the use of a particle counter as real-time detector has been studied. This investigation has been reported in a separate document [R21].

7 References

R1. Proposal for a Regulation of the European Parliament and of the Council on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information (As adopted by the European Parliament) (16.12.2008)

R2. Commission Directive 2006/51/EC "implementing Directive 2005/55/EC of the European Parliament and of the Council relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles and amending Annexes I, II, III, IV and VI thereto"

R3. Commission Directive 2005/78/EC "implementing Directive 2005/55/EC of the European Parliament and of the Council relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles and amending Annexes I, II, III, IV and VI thereto"

R4. Directive 2005/55/EC of the European Parliament and of the Council on the "approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive-ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles"

R5. UNECE Regulation No. 49 - "Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive-ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles"

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8 Annexes

8.1 Evaluation checklist for the portable instruments

EU-PEMS PM evaluation program

PARTICIPANT: X
INSTRUMENT ID: Y

MAIN TECHNICAL CHARACTERISTICS

Description of the principle:	**- Partial flow sampling** **- Proportional dilution** **- Sampling on filter** **- Real-time detector on diluted exhaust (EAD)**
Transport strategy	Yes (5 meters sampling probe)
Temperature control of sampling probe	Yes, @ ?°C
Temperature control of dilution air	None
Filtering of dilution air	HEPA
Temperature control of sampling media (when applicable)	Yes, heated enclosure @47°C ± 5°C
Calibration:	- Flow - Procedure needed for the Real-time Detector
Portability	- Size and Weight: ?kg - Power Consumption: ?kW

INSTRUMENT SETTINGS

Instrument settings	- Dilution : min. 4 - max. 28 - Flow: 30 l/min
Data recording settings	- Sampling rate: 10 Hz - Test parameters: As in standard

EVALUATION RESULTS

Measurement performance:

- Partial flow sampling > OK
- Proportional dilution > OK
- Sampling on filter > OK
- Real-time detector on diluted exhaust (EAD) > OK
- Transport strategy >OK

Other:

- Conformity / current laboratory standard for PM mass > OK
- Temperature control of sampling probe > OK
- Temperature control of dilution air > TBD
- Filtering of dilution air > OK
- Temperature control of filter holder > OK

- Flow Calibration > OK
- Calibration of the Real-time Detector > TBD

- Easiness of use (installation) > TO BE IMPROVED
- Easiness of use (testing) > OK
- Software and integration > TO BE IMPROVED

- Size and Weight > TO BE IMPROVED
- Power Consumption > OK
- Other > Requires Exhaust Flow input for proportional dilution

8.2 Principle of the averaging window calculations

The emissions are integrated using a moving averaging window method, based on the reference CO_2 mass or the reference work. The principle of the calculation is as follows: The mass emissions are not calculated for the complete data set, but for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the engine CO_2 mass or work measured over the reference laboratory transient cycle. The moving average calculations are conducted with a time increment Δt equal to the data sampling period.

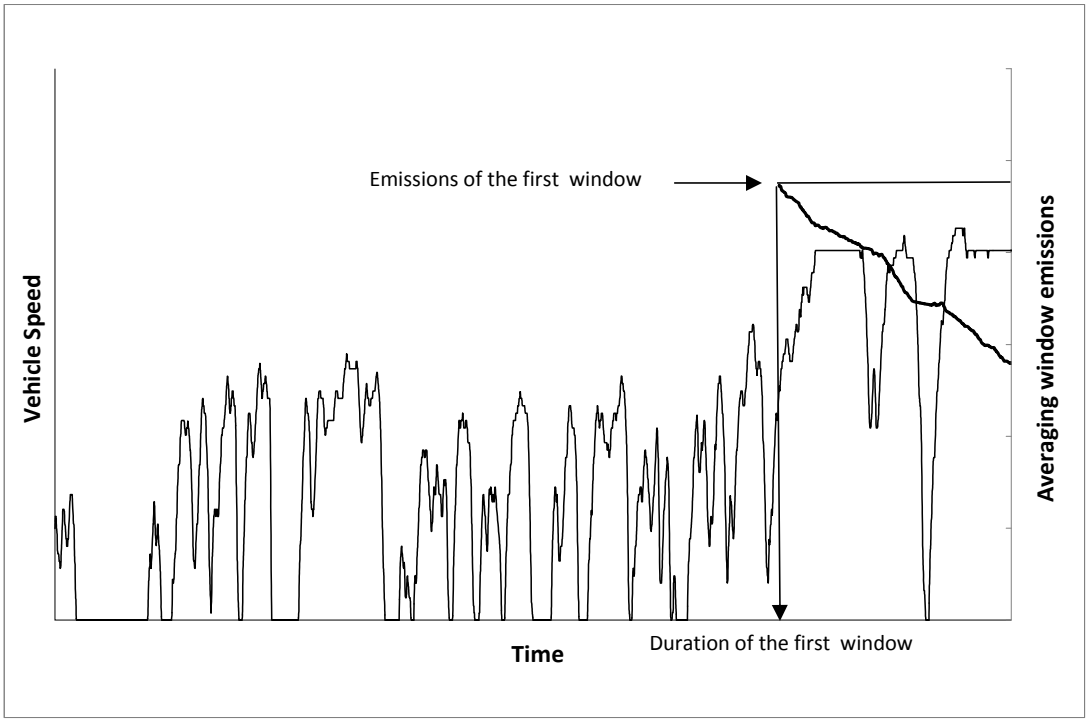


Figure a. Vehicle speed versus time- Vehicle averaged emissions versus time, starting from the first averaging window.

For the CO_2 mass based method, the duration $(t_{2,i} - t_{1,i})$ of the i[th] averaging window is determined by:

$$m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i}) \geq m_{CO2,ref}$$

Where:

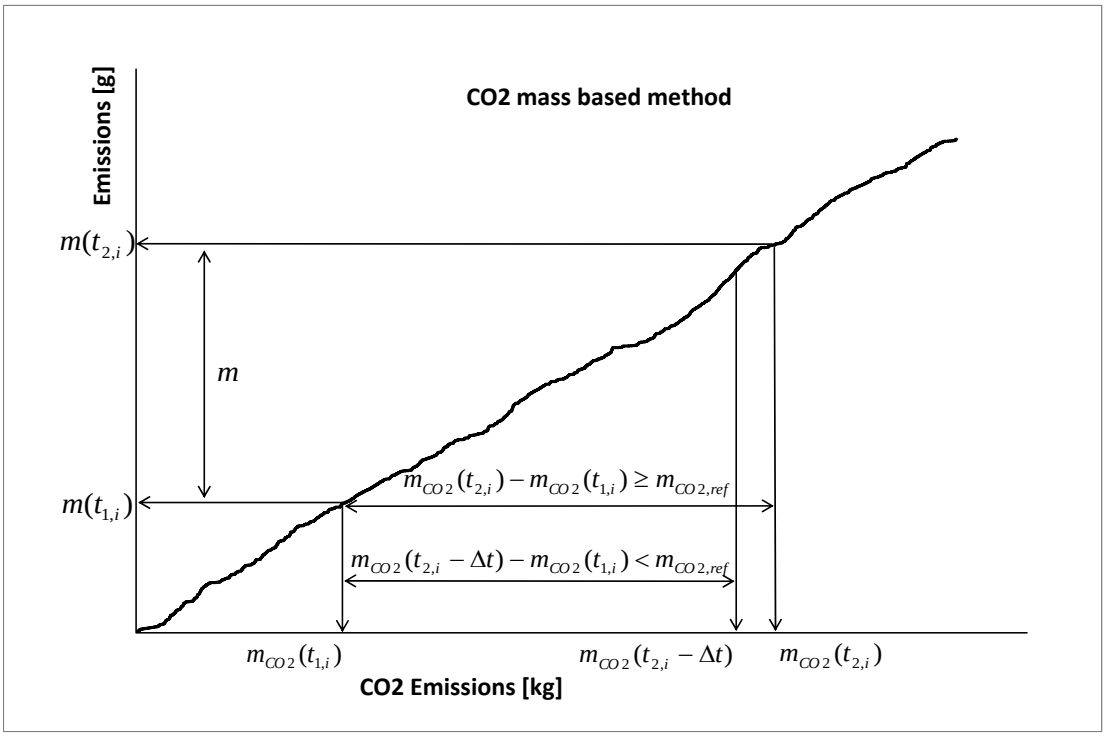
$m_{CO2}(t_{j,i})$ is the CO_2 mass measured between the test start and time $t_{j,i}$, kg;

$m_{CO2,ref}$ is the CO_2 mass determined for the WHTC, kg;

$t_{2,i}$ shall be selected such as:

$$m_{CO2}(t_{2,i} - \Delta t) - m_{CO2}(t_{1,i}) < m_{CO2,ref} \leq m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$$

Where Δt is the data sampling period, equal to 1 second or less.


CO2 mass based method
Emissions [g]
$m(t_{2,i})$
m
$m(t_{1,i})$
$m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i}) \geq m_{CO2,ref}$
$m_{CO2}(t_{2,i} - \Delta t) - m_{CO2}(t_{1,i}) < m_{CO2,ref}$
$m_{CO2}(t_{1,i})$
$m_{CO2}(t_{2,i} - \Delta t)$
$m_{CO2}(t_{2,i})$
CO2 Emissions [kg]

8.3 Filter preparation and weighting procedure

Preparation of filters

- The filters will be conditioned in a room as regards temperature and humidity for at least 8 and no more than 80 hours.
- The conditions of the room shall be temperature 22±3°C and relative humidity 45±8%.
- The filters will be in an open dish that protects them from dust.

Weighting procedure

- The filters will be weighted with a microbalance with a precision (standard deviation) of better than 2 µg for a clean filter; better than 1µg for a reference weight and a readability of 1µg or better.
- To eliminate the effects of static electricity the balance should be grounded through placement upon an antistatic mat and particulate filters should be neutralised prior to weighing; this can be achieved by a Polonium neutraliser or a device of similar effect.
- The temperature of the room in which the particulate filters are conditioned and weighed must be maintained to within 22±3°C during all filter conditioning and weighing. The humidity must be maintained to relative humidity of 45±8%.
- At least two unused reference filters must be weighed at the same time as the sample filter weightings. They must be the same size and material as the sample filters.
- If the specific weight of any reference filters changes by more than ±5µg between sample filter weighing, then the sample filter and reference filters shall be reconditioned in the weighing room and then reweighed.
- The comparison of reference filter weightings shall be made between the specific weights and the rolling average of that reference filter's specific weights. The rolling average shall be calculated from the specific weights collected in the period since the reference filters were placed in the weighing room. The averaging period shall be at least 1 day but not exceed 30 days.
- Multiple reconditioning and reweighting of the sample and reference filters are permitted until a period of 80 h has elapsed following the measurement of gases from the emissions test.
- If, prior to or at the 80h point, more than half the number of reference filters meet the ±5µg criterion, then the sample filter weighing can be considered valid.
- If, at the 80h point, two reference filters are employed and one filter fails the ±5µg criterion, the sample filter weighing can be considered valid under the following condition: the sum of the

absolute differences between specific and rolling averages from the two reference filters must be less than or equal to 10µg.

- In the case that less than half of the reference filters meet the ±5µg criterion the sample filter shall be discarded, and the emissions test repeated. All reference filters must be discarded and replaced within 48h.
- In all other cases, reference filters must be replaced at least every 30 days and in such a manner that no sample filter is weighed without comparisons with a reference filter that has been present in the weighing room for at least 1 day.
- If the weighing room stability criteria outlined in paragraph 1.3.4. is not met, but the reference filter weightings meet the above criteria, the vehicle manufacturer has the option of accepting the sample filter weights or voiding the tests, fixing the weighing room control system and re-running the test.

During tests

- The filters will be used within 1 hour of their removal from the weighting room unless:
- a stabilised filter (filters) is placed and kept in a sealed filter holder assembly with the ends plugged, or;
- a stabilised filter (filters) i placed in a sealed filter holder assembly which is then immediately placed in a sample line through which there is no flow.

After tests

- The filters will be placed in an open dish that protects them from dust.
- The filters will be conditioned in a room as regards temperature and humidity for at least 8 and no more than 80 hours.
- The conditions of the room shall be temperature 22±3°C and relative humidity 45±8%.
- The filters will be weighted according to the procedures mentioned above.

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Abstract

The European legislation has adopted the Portable Emissions Measurement Systems (PEMS) as a tool to check the conformity of heavy-duty engines during their real operation. The current developments foresee the verification of gaseous emissions. The measurement and the control of in-service Particulate Mass (PM) emissions using on-board equipment has been delayed, as the technological status of the portable PM instrumentation had been judged insufficient. The European PEMS PM project was launched in 2007. Its main objective was to assess the technological status of the PEMS PM equipment. Initially, the main requirements set for the candidate instruments were:
- to measure the PM mass, possibly according to existing standards;
- to be designed for on-board testing regarding handling, test durations and power consumption;
- to be advanced prototypes or commercially available equipment.
An additional but important requirement was introduced: to be able to evaluate the in-service emissions (which is done in the United States through the Not To Exceed (NTE) approach), the European legislation has adopted a moving averaging window method. For such calculations, the accumulated PM mass had to be measured or estimated at any time during a test.

The strategy used to evaluate the candidate instruments was simple and empirical. Using different engines, test cycles and fuels, the candidates were required to provide the best possible correlation with the reference laboratory systems. This ¿laboratory to portable¿ comparison was carried out for to the total PM mass measurements. The real-time PM results have been cross-correlated. In parallel to the program, some Particle Number (PN) measurements have been performed using equipment and test procedures in line with the European standards developed to test light-duty vehicles. This abstract provides the main findings of this project regarding PM, as presented and discussed in the final report of the European PEMS PM program. Furthermore, it gives the engine PN emissions and provides a first clue regarding the feasibility of PN for in-service testing.

Different PM PEMS were evaluated in the lab with 3 heavy-duty engines which cover a wide range of emissions. The PM differences were in general 15% lower (SPC, OBS, micro-PSS) than the PM measured with a full dilution tunnel. Higher differences (35%) were found for MSS which measures soot. For the DPF engine the differences were >50% due to the volatile artifact on the filter. The PN differences between CVS and SPC were for all engines (and emission levels) within 15%. In addition to the PN method (non-volatiles measured with a CPC), MSS and DC were found to be sensitive enough at the low emission levels (post DPF). ETaPS and DMM (with dilution) were not sensitive enough for DPF engine. The conclusion of this work is that mass (on a filter) is not sensitive enough for low emission engines and the number method should be preferred. If PEMSs continue to use the filter method, then the real time instrument they use can affect the calculation factor as each instrument measures different particle property (number, surface, mass). Nevertheless, all these parameters do not affect the result enough to exceed the 10 mg/kWh limit of the future European HD regulation. They should be however seriously taken into account for lower emission levels.

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