

Portable Emission Measurement System (PEMS) For Heavy Duty Diesel Vehicle PM Measurement: The European PM PEMS Program

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ABSTRACT

Portable Emissions Measurement Systems (PEMS) represent a robust and accurate solution to study the in-use emissions of combustion engines and are becoming part of the emissions control regulations, as evidenced by the latest requirements introduced in the United States. Their application is ranging from large heavy duty engines to small light-duty vehicles and off-road mobile machinery. Currently, PEMS for gaseous exhaust measurements exhibit performances that are close to the ones of laboratory grade systems, but the development of portable PM instruments remain a complex challenge, as simultaneous progress take place in engine and after-treatment technologies.

This paper presents the PM phase of the European PEMS program, aiming at checking the feasibility of PEMS to measure accurately particle mass at low PM levels. Several PEMS, (Dekati DMM, ETaPs, Horiba OBS TRPM, Sensors SEMTECH-PPMD, AVL MSS, Control Sistem micro-PSS) are evaluated in parallel under controlled laboratory conditions (i.e. on reference test cycles) against laboratory instruments using a Euro III and a Euro V heavy-duty engine, running on low sulphur fuel. Preliminary results are presented.

INTRODUCTION

Portable Emission Measurement Systems (PEMS) have become an important tool to monitor the in-service conformity of large on and off-road engines from heavy-duty vehicles, construction and agricultural equipment. This trend, initiated in the late 90s in the United States, is also taking place in Europe: PEMS are envisaged as a tool to check the

emissions from heavy-duty engines during their real operation [1, 2]. More recently, programs have also been launched to evaluate the feasibility of PEMS for non-road equipment and light-duty vehicles as reported in [3, 4].

PEMS have been proven to be a cost effective solution to perform in-service testing of heavy-duty engines: rather than extracting the engines from the vehicles and then installing them on an engine dynamometer to run their official regulatory cycles (European Steady State Cycle (ESC) or Transient Cycle (ETC)), the vehicles are equipped with onboard emissions measurement systems and tested during their real in-use operation. The test trucks or test buses are run on their normal operating routes and payloads. Thus, PEMS represent a major step towards a transparent way to demonstrate what engines do actually emit during their real use.

Currently, only two PEMS are commercially available to measure the gaseous regulated emissions (THC, CO, NO_x + CO₂). Both systems are compliant with the only official standard the US CFR Part 1065 [5].

To measure PM emissions on-board several technologies and instruments are currently available and more effort is ongoing to make these technologies more compact and suitable for on vehicle testing. To judge whether the improvements are sufficient to foresee a short term introduction in the European legislation, The European Commission has launched a Call for expression of interest to participate in the EU-PEMS PM evaluation program [6].

The instruments, to be eligible for the program, had to meet the following criteria:

- - be traceable (or at least present some correlation) to the heavy-duty laboratory standard instruments in terms of dilution and total PM mass measurements;
- - provide “real-time” (second-by-second) information on the total PM concentration in the diluted or raw exhaust of the vehicle;
- - be commercially available or at least advanced prototypes that are close to a commercial application.

The current European EU-PEMS PM evaluation program runs in parallel with the another research legislative program such as the US PEMS PM Measurement Allowance (MA) program, conducted at the Southwest Research Institute and funded by US-EPA and still on-going. Both the European and the US programs shall conclude on the short-term feasibility of the proposed measurement technologies. Results are not yet available from the US program.

The EU PEMS program is developed in 3 phases, in which different engines and after-treatment technologies, fuels and duty cycles are used to check the response of the candidate instruments. The present paper shows some results from the first phase. It is also a follow-up of the first research efforts in PEMS evaluation already reported in [7]. The discussion in the last section focuses on the methodological approach used to evaluate the candidate PEMS PM instruments and shows preliminary results obtained for one engine technology.

OVERVIEW OF LABORATORY STANDARDS

As one of the main criterions for the portable PM instrumentation is its traceability to laboratory standards, several aspects of the standards have been considered such as the sensitivity for future low PM levels, the sampling and dilution techniques and the mass measurements method.

In the US heavy-duty engine certification scheme, transient cycles have been used already for a number of years: These cycles are supposed to better reflect the real-life engine operation than steady-state testing. Starting with the Euro III regulations for the year 2000, transient-type testing was also introduced in Europe. The Directive 1999/96/EC requires gas engines and diesel engines with advanced exhaust after-treatment to be tested over the dynamic European Transient Cycle (ETC). From 2005 onwards, ETC is required for all types of engines. In the US, new emission regulations will be phased in between 2007 and 2010 with limits down to 0.27 g/kWh for NO_x and 0.014 g/kWh for PM; together with emission reductions, EPA has also promulgated a regulation that reduces the fuel sulfur content from 500 ppm to 15 ppm sulfur to be implemented on July 1st 2006 [5]. As the current laboratory methods do not seem to be any longer sensitive to

characterize PM emissions from the future engine technologies and aftertreatment, because of the low PM levels, improvements or modifications of the official test procedures have been implemented [5] or are being discussed. In Europe for instance, the introduction of PM number counting is proposed together with an improvement of the mass measurement method, under the auspices of the United Nations GRPE PMP working group [8]. However, the current legislation in Europe and US requires the measurement to be done, according to the definition of PM, at a gas temperature below 52°C, precisely at 47 ± 5 °C according to the PMP protocol [8].

Stationary tests can be performed with partial or full-flow dilution tunnels. For transient tests only full flow systems are allowed so far. Great effort has been undertaken to improve the detection limit, above all for modern low-emission engines. This resulted in Environmental Protection Agency (EPA) 2007 regulation [5] where new filter media, higher resolution of the balance, tighter tolerances for the temperature and so on allow lowering the detection limit. A pre-classifier (cyclone) is also used to prevent the coarse material to be deposited on the filter. A similar approach has been proposed for future European regulations, which has been extensively tested and compared to the existing method with new guidelines proposed for PM and particle number within the PMP program [8]. However, a great doubt that remains is whether artifact free measurements are possible; of great concern is the collection of organic vapors by the filters [9].

Furthermore, the new ISO 16183 standard [10] specifies the measurement and evaluation methods for gaseous and particulate exhaust emissions from HDVs under transient conditions on a test bed. It focuses on the introduction of Partial Flow Sampling Systems (PFSS) and the procedure defined can be applied to any transient test cycle that does not require extreme system response times. In PFSS, a small, but proportional to the total flow, fraction of the total exhaust is sampled and used for the determination of the PM emission rate. The proportionality ratio between sampling flow and total exhaust flow is often called “split ratio” and needs to be kept constant throughout the measurement. Depending on the method of controlling and determining the split ratio, PFSS are distinguished into three configurations: (1) isokinetic systems, (2) flow controlled systems with concentration measurements and (3) flow controlled systems with flow rate measurements, where all of the diluted exhaust is led through the PM filter; more details can be found in [28]. The flow controlled systems with flow rate measurements are the most common type of PFSS, where the extraction of a sample proportional to the exhaust flow is usually achieved by keeping the diluted exhaust constant and varying accordingly the dilution air flow rate. Several designs are commercially available: AVL's Smart Sampler SPC472, Horiba's MDLT, Control Sistem PSS-20, and Sierra Instruments BG-2. A

number of correlation studies proved good agreement between CVS and PFSS techniques as discussed in [11].

Measuring problems and sampling artifacts associated with the use of many of the instruments presented above, based on different principles and techniques for PM measurements, have been identified and reported in [12]. Relatively few studies were found in the literature, which actually compare different measuring methods on the same diesel aerosol.

From laboratory standards to on-board PM measurements

The objective of the present experimental work is to evaluate the measurement performance of the candidate portable systems compared to a standard method and also to check their sensitivity for the future low PM emissions standards. However, other criteria must be fulfilled to use the systems on road and for off-road vehicle application. The on board application of the standard PM measurement principles is challenging as PEMS are required:

- - to be small, lightweight and easy to install;
- - to be simple to operate;
- - to work with low power consumption,
- - to have good sensitivity for low PM concentrations to have a low to medium cost.

Additionally, the portable candidate systems have at least to:

- - sample and dilute the vehicle exhaust according to existing standards (ISO 16183, US standards);
- - provide the total PM mass over a test cycle, by collecting the PM on a media and/or integrating data ;
- - provide test data compatible with the work/CO₂ averaging window method and/or the US-NTE standards.

The candidate PEMS have also to face two challenges:

- - installation on the vehicles: how shall the equipment be installed and the exhaust sampled and conditioned?;
- - post-test evaluation method: Not To Exceed (NTE) in the US and moving averaging window (MAW) in Europe.

The first point above is delicate in the sense that the portable instrument shall be as compact as possible. When measuring gaseous emissions, the exhaust gas is sampled from the tailpipe and taken to the gas analyzers using a heated sampling line. The length of the line (3 or 5 meters) offers the flexibility to install the PEMS in the cabin or on the load area of a truck. When measuring PM emissions, the use of a (long) sampling line is critical as losses may occur by deposition on the line and therefore affect the total PM collected by the instrument. The best way to minimize losses is to install the PEMS PM as close as possible to the sampling point, i.e.

close to the tailpipe of the vehicle. Unfortunately, the layout of the exhaust system on European trucks does not allow to place near the tailpipe any device whose size would be close to the one of a gaseous PEMS.

To overcome the problem, it was proposed in this program:

- - to accept the losses caused by the transport of the diluted or raw exhaust;
- - to freeze the geometry of the sampling/transport line to 5 meters;
- - to allow for the transport of the raw or the diluted exhaust, depending on the engineering strategy followed by each instrument manufacturer.

Losses evaluation was conducted using:

- - direct sampling, where the instrument is close to the tailpipe;
- - transport sampling, where the instrument is far from the tailpipe and the diluted or raw exhaust is taken to the instrument using a heated and temperature controlled line;

A schematic of direct (a) and transport sampling (b) according to the program is shown in [Figure 1](#); it was mandatory for each candidate instrument to provide the two strategies.

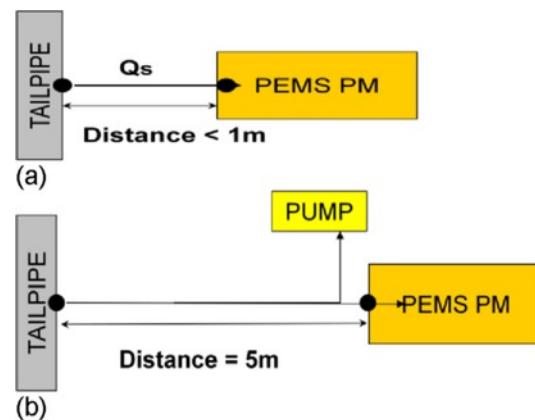


Figure 1: Schematic of direct (a) and transport (b) sampling for PEMS testing.

The second challenge faced by the candidate PEMS is the data evaluation method. For both the US NTE and the European Moving Averaging window (MAW) methods, some information is needed on the PM accumulation rate over a test. For the NTE, one has to detect mass changes for durations as short as 30 seconds and corresponding to the 'NTE events', i.e. when the engine operates for at least 30 seconds in a defined control area. For the MAW, the principle is as follows: starting from the first data point, the moving average process is conducted using a reference

quantity (the engine work or CO₂ emissions on its reference certification cycle) and a time increment of 1 second for gaseous emissions. More details on the NTE and MAW may be found in [1, 2, 3]. The candidate PEMS instruments fulfill the requirement to provide the mass accumulation rate in the following ways:

- - The Horiba OBS-TRPM, the AVL MSS, the Dekati DMM and ETaPS (in combination with the Control Sistem MPSS) deliver a second-by-second signal that may be used to infer the PM accumulation over the test;
- - The Sensors PPMD provides mass measurements continuously by giving the mass increments measured by each crystal before and after the sample interval and after a stabilization time; the crystal sampling time was set to 2 minutes. The implication for the MAW method is either to use a time increment corresponding to the crystal sampling duration (2 minutes in the present case) or to interpolate the data between 2 measurements.

Another objective of the program is to understand how the measurement techniques proposed to estimate the PM mass accumulation rate compare to each other. It is also envisaged to determine which technologies are the most suitable and if they will be sensitive enough, especially at low emission levels. Some guidelines were already proposed and reported in [7] but this work provides a deeper evaluation of the available PM PEMS instrumentation.

OVERVIEW OF PM MEASUREMENT PRINCIPLES AND TECHNIQUES

A wide variety of instruments and measurement techniques have historically been used to characterize compressed ignition combustion generated PM. These techniques range from the simple filter sampling to highly sophisticated instrumentation. In this context, only a brief overview is provided, as it is not the scope of the paper to present all possible techniques for neither PM measurements, nor the objective of the program to evaluate all the principles as the requirements to be eligible for the program were already introduced in the previous sections.

Optical methods, including light extinction (opacity) and laser scattering can be used to measure the carbonaceous mass of PM (i.e. soot). Until now, opacity was widely used as the indirect mass measurements and opacity meters were the only online instruments; nowadays, with the introduction of after-treatment systems, they are facing problems with the detection limit in presence of low mass concentration and NO₂ [15].

Absorption measurements can be used to determine the carbon mass. A number of techniques have been developed for absorption measurements [16]. However, besides difficulties with data interpretation, the method is not

sensitive enough to measure low concentration, typical of modern and trap equipped engines. Hence, optical techniques are very suitable when soot concentrations are prominent but can be insensitive when PM is dominated by volatile species, such as downstream of Diesel Particulate Filters (DPFs).

Photo-acoustic spectroscopy is a technique where particles are heated by absorption of light from a chopped light beam. The resulting acoustic wave is then measured by a microphone. This principle has been largely used to measure diesel particles in the past for laboratory applications [17] and more recently, thanks to technical progress in high power laser diodes and sensitive miniature electret microphones, a commercial device, the Micro Soot Sensor (MSS), has been introduced on the market [18].

Laser-induced Incandescence (LII) [19] and Photoelectric Aerosol Sensor (PAS) [20] could also be considered but data interpretation is complex, limited to a certain particle size and shape and with a response that may vary in presence of high Soluble Organic Fraction (SOF).

Techniques for particulate mass determination in real time are the Tapered Element Oscillating Microscope (TEOM) [21] and the Quartz Cristal Microbalance (QCM), both based on a change in resonance frequency of a collecting device due to acquired mass. They both offer a good resolution and sufficient sensitivity. The main drawbacks of the TEOM are uptake of water and other volatile material, which may lead to artifacts [22] and, for on-vehicle application, interferences caused by vibrations and vehicle movements; its sensitivity to fluctuations in pressure and temperature causes problems with diesel particle measurements application.

The recent introduction of the SEMTECH Portable Particulate Mass Device (SEMTECH-PPMD), which includes a micro-proportional sampling system (MPS), an Exhaust Flow Meter (EFM) and a QCM by Sensors Inc. seems very promising for exhaust PM measurements above all at low emission levels [23].

The Electrical Tailpipe PM Sensor (ETAPS), based on electrostatic principles for particle detection in real time has been introduced by Dekati [24]; this is a new-sensor type device for in-situ tailpipe PM measurements; it seems promising as it can be used with no dilution and directly at the tailpipe but further data and calibration are needed.

Other recent instruments include the Horiba OBS TRPM, which combines the gravimetric principle of depositing and measuring PM on filter with real time measurements of particle length through a diffusion charge sensor (DCS) that is used as PM detector, with the assumption that the mass accumulated on the filter is proportional to the PM length parameter [25].

More details on the SEMTECH-PPMD, OBS TRPM and ETaPs are provided in the following section as these are candidate instruments for the on-going PM PEMS program.

An alternative to gravimetric methods for PM mass measurements is thermal mass analysis of organic carbon and sulfates. Carbon and sulfur are oxidized in a furnace and measured as CO₂ and SO₂. This principle has been realized with high sensitivity by Horiba in their super low mass particulate matter analyzer (MEXA-1370PM). [26].

In addition to mass, particle number and size measurements are of increasing importance because of adverse health effects associated with ultrafine particle emissions [27, 28]. A variety of aerosol instrumentation is available for particle number and size measurements: TSI Scanning Mobility Particle Sizer (SMPS), Condensation Particle Counter (CPC), Dekati Electrical Low Pressure Impactor (ELPI) [29] and more recently TSI Engine Exhaust Particle Sizer (EEPS) and Cambustion Differential Mobility Spectrometer (DMS) to better follow engine transients. An instrument comparison can be found in [30, 31]. The Diffusion Charger (DC) can be used to measure particle surface area, which is converted to mass concentration [31]. Most of these aerosol instruments can be used on board and can be found on the Mobile Emissions Laboratory (MEL) [32].

However, so far, all the official PM emission limits are still defined in terms of total mass, as determined by gravimetric analysis, specific to either distance for light-duty vehicles or work for heavy-duty vehicles. As the current rules for type approval are still based on filter mass based measurement from diluted exhaust, partial flow sampling (PFS) and gravimetric methods for PM, the methodology to follow is to combine these methods with real time PM or partial PM (i.e. soot) measurements as accuracy is decreasing with decreasing mass on filters.

The PM PEMS program is designed to provide an inter-comparison of portable systems relative to reference laboratory systems, under controlled laboratory conditions. The candidate portable instruments are evaluated under controlled laboratory conditions (i.e. on reference test cycles such as the world harmonized transient (WHTC) and steady state (WHSC) cycles against reference laboratory instruments using a Euro III engine with partial DPF and a Euro V heavy-duty engine, running on low sulphur fuel. The evaluation methodology is presented, discussed and illustrated with some results.

EXPERIMENTAL

LABORATORY TEST CONDITIONS AND INSTRUMENTATION

Engines and cycles

As underlined in the introduction, the program includes 3 phases to check the response of the candidate instruments on three different PM levels. In the first phases reported, the laboratory tests were conducted on a Euro III heavy-duty engine (IVECO Cursor, 10.6 litre) with a partial DPF and a EU V engine (No DPF) running on low sulfur fuel (S < 10 ppm).

Tests were carried out on both the WHTC and WHSC cycles. For the standard gravimetric method (PTS) PM was collected on a Teflon coated glass fiber filter (PallflexEMFABTX40HI20 and weighted on a microbalance according to procedures currently in use in the Particulate Measurement Program (PMP) for filter weighting, conditioning and handling.

Reference laboratory instruments

The standard gravimetric method using the conventional Constant Volume Sampling (CVS) for dilution was compared to portable instruments such as the AVL Smart Sampler (SPC) and the portable micro-PSS from Control Sistem [33] using the partial flow sampling (PFS) principle.

The AVL Smart Sampler (SPC 472) was used as reference instrument for the PFS 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.

Candidate PM PEMS Instruments

Several commercially available PM PEMS, meeting the requirements listed in the introduction and in the previous section, were submitted by instrument manufacturers. These are:

- Control Sistem m-PSS
- AVL Micro Soot Sensors (MSS)
- DEKATI DMM
- DEKATI ETaPS
- Horiba OBS TRPM
- Sensors SEMTECH-PPMD

A brief description of each instrument and its measurement principle is provided below.

Control System micro-PSS

A description of the control system m-PSS and its performance in the laboratory and on road has been already reported in [7]. A picture of the portable micro-PSS is shown in [Figure 2](#). This is a prototype portable instrument working according the PFS principle; it uses a 47 mm filter and collects PM with a filter face velocity of 43 cm/s at a filter temperature of $44 \pm 1^\circ\text{C}$. In its standard laboratory configuration (PSS-20), it uses filters of same type but with 70 mm diameter of as for the PTS method [33].

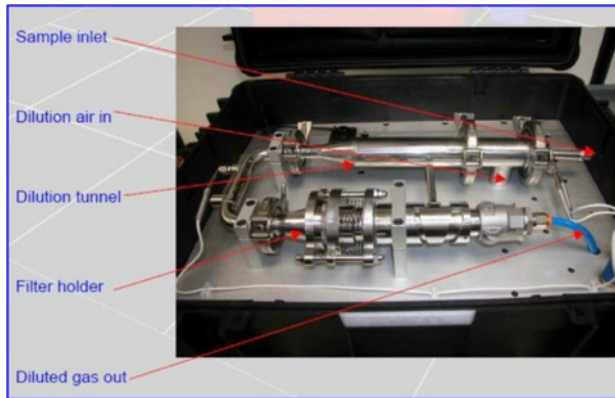


Figure 2: Control Sistem m-PSS [33].

Micro Soot Sensors (MSS)

The Micro Soot Sensor (MSS), based on photo-acoustic measurement principles [18, 33] was used as it is possible to do transient measurement of soot concentration with high sensitivity (detection limit $\leq 10 \mu\text{g}/\text{m}^3$, $\sim 5 \mu\text{g}/\text{m}^3$). The instrument picture and its working principle are shown in [Figure 3](#); 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 preamplifier and filtered in a „Lock-In“- amplifier.

Under laboratory conditions, the MSS was used to measure diluted exhausts from the CVS (full dilution) or directly at the tailpipe by using its own exhaust conditioning unit [33] with a dilution ratio of 10; the latter allows a dilution with constant ratio up to 10 (partial dilution) and a conditioning of the diluted exhaust (temperature below 60°C and pressure at ambient $\pm 50 \text{ mbar}$). No correction for losses or additional MSS calibration was needed when using its exhaust conditioning unit.

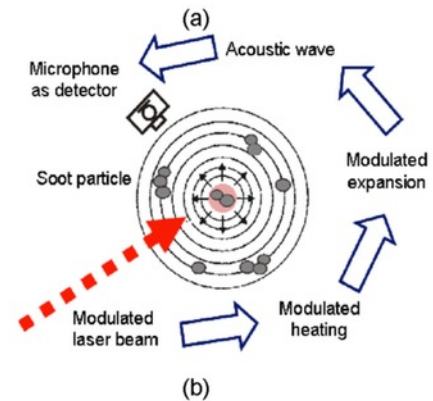


Figure 3: AVL 483 micro soot sensor (MSS) (a) and a schematic of its principle of operation (b) [12, 32].

DEKATI Mass Monitor (DMM)

Based on the ELPI™ technology [29], 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 give precisely determined charge to all measured particles. Charge level is close to saturation charge level for each particle size. After the charging region a static electrical field is used to deflect smallest particles to the charger mobility electrode; an electrometer is used to measure this current. After the charger particle size classification is accomplished in a 6-stage inertial impactor. Sensitive electrometers are connected to the impactor collection sensors and 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 the conversion from measured current values to particle mass concentration [35]. A schematic is provided in [Figure 4](#).