Facing the Challenge
Particle Measurement for Euro 5/6 and Alternative Particle Measurement Technology

While nanoparticle emissions continue to be the subject of ongoing discussions on the reduction and limitation of exhaust gas emissions, measuring these particulate emissions from combustion engines is posing an ever-increasing challenge. On the one hand, the relevant measurement quantities and the way they change inside the exhaust gas system and upon emission into the atmosphere are still undergoing research and development. On the other hand, the assessment of soot emissions and suitable methods of acquisition in terms of measurement technology have been the subject of political, public and technical discussions for many years. The measurement device manufacturer AVL List GmbH works since many years with the particle measurement technology. Some of these experiences, in special regarding alternative particle measurement, are described in this article.

1 Introduction

The drastic tightening of future emission limits requires of vehicle and component manufacturers an increased development effort when it comes to exhaust gas aftertreatment. Measuring downstream of diesel particulate filters is not only necessary during development and for certification, but is also required for tests in accordance with in-vehicle (in-use conformity or in-use compliance) legislation which requires that motor vehicles be tested in real driving operations on the road to determine whether or not exhaust gas limits are being met.

At present, it is mainly the overall particulate mass – depending on the legislation, it is sampled and acquired gravimetrically from full flow or partial flow tunnels – which is restricted. Apart from the question of certification rules, there is also the question of suitable measuring methods for the development of vehicles with very low particulate emission. In modern diesel engines with particulate filters, particulate emission has dropped to such low levels that conventional measuring devices are touching on the limits of measurability. Accordingly, e.g. the emissions downstream of a diesel particulate filter can no longer be reliably quantified using the conventional gravimetric filter-based method, because the mass on the filter is that small that there is practically no difference between measurements with ambient air ("background") and exhaust gas from the engine [1].

For this reason, alternative measurement technologies are highly sought after. The AVL Micro Soot Sensor (MSS) is an alternative device that measures the soot concentration in exhaust gas dynamically. The measuring device is based on the photoacoustic principle and is only sensitive to the solid carbon fraction (soot). Another alternative method is the determination of the particle-number concentration. Besides the limitation of the particulate mass emission from diesel and/or gasoline direct injection (GDI) engines, toxicological results caused health experts to demand a limitation of the particle number concentration in the range of a few nanometers up to the micrometer range. An expert group of the UNECE-GRPE (PMP Working Group) is currently dealing with this issue. This PMP Working Group has proposed introducing a further limit value for the particle number in addition to the gravimetric filter method. The PMP Working Group defined that only nonvolatile particles should be counted. The reason for this is that the solid components are suspected of being more harmful to human beings than volatile particles. A further reason is the fact that due to condensation effects that heavily depend on the conditions in the exhaust gas system resp. dilution system it is very difficult to obtain reproducible results [2]. The AVL Particle Counter (APC) was developed to handle these new requirements for certification of ligh-duty vehicles concerning the particle number limits. Apart from that, the AVL Particle Counter can also be used in R&D applications and is prepared already for the planned heavy-duty certification procedure.

2 Euro 5/6 (V/VI) Requirements

Especially in the area of diesel technology considerable effort is currently being spent on seeking answers to the exciting

Table 1: Overview limits for Euro 4 to 6

		Euro 4	Euro 5	Euro 5+	Euro 6
Particulate mass [mg/km]	GDI	no	5	4.5	4.5
	Diesel	25	5	4.5	4.5
Particle number [#/km]	GDI	no	no	?	?
	Diesel	no	no	6×10^{11}	6×10^{11}
NO_x [mg/km]	Gasoline	80	60	60	60
	Diesel	250	180	180	80

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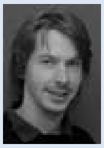

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Table 2: Proposed limits for Euro VI summarized and shown in comparison to Euro IV and V

	Euro IV	Euro V	Euro VI
Particulate Mass [g/kWh]	0,02/0,03	0,02/0,03	0,01
Particle number [#/kWh]			?
NO_x [g/kWh]	3,5	2	0,4

question of how to lower the number of emitted particles and the NO_X emissions in passenger vehicles and commercial vehicles to such an extent that they also satisfy legislative requirements in the long run. Globally established companies that are required to adapt their products to varying limit values in different parts of the world, in particular, face great challenges in this respect.

Up until now, the main development goal was always increased efficiency in commercial vehicle drives while driving pleasure and comfort optimization was the key objective for passenger car drives. Now increased consideration must be given to the exhaust gas aftertreatment. Yet this expenditure is hardly a sales argument since customers will regard an exhaust gas system conforming to law merely as a matter of course. This means that the development of an exhaust gas aftertreatment system must be a cost-efficient solution with the greatest possible efficiency.

The trend towards standard engines designed for various vehicle types by calibration, entails an increased adaptation effort for the entire system including exhaust gas aftertreatment.

2.1 Euro 5/6 for Passenger Cars

Due to the Euro 5 emission limits that will take effect in October 2009, the diesel drive will have to become noticeably “cleaner” than it is today. The limit value for particulate mass emission will be reduced by a factor of five compared to the present valid limit value. This is practically only possible if particulate filters are used. For the sake of a clean environment many passenger car manufacturers today already use particulate filter systems as a standard.

The latest draft of the technical part of the light-duty Euro 5 and Euro 6 Regulation was discussed and agreed at a meeting of the Committee for Adaptation to Technical Progress (CATP) on 1st October 2007. The particle number restrictions are expected to be required starting with the Euro 5 amendment in September 2011. The proposed limit of the emission for diesel engines will be 6^*10^{11} particles per km [3]. For light-duty gasoline direct injection (GDI) engine the limits for particulate emission have not been fixed. The procedure for particle counting is going to be released in the next ECE R83 (June 2008).

The planned particulate mass limits for Euro 5+ and Euro 6 will be 4.5 mg/km (compared to 5mg/km in Euro 5) [4], **Table 1**.

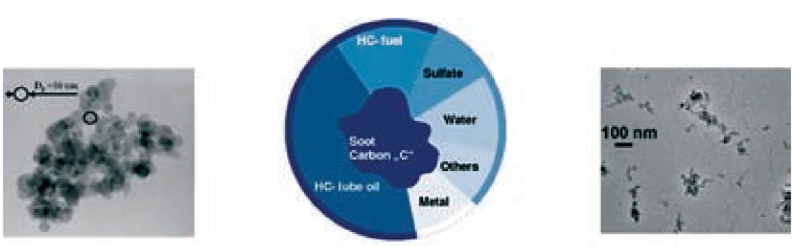
2.2 Euro V/VI for Commercial Vehicles

The introduction of Euro V will lead to no changes in the particulate limit values for heavy-duty engines, however a minor reduction in nitrogen oxides (NO_X) will be required.

Euro VI will however bring about a massive reduction both in particulates as in NO_X limit values. The Commission of the European Union has proposed to reduce emissions from trucks and buses of nitrogen oxides by 80 % and soot particulate matter by 66 % compared to the Euro V emission standards. The proposed limits for Euro VI are summarized in **Table 2** and shown in comparison to Euro IV and V.

According to the latest technology, not only engine-related measures (e.g. exhaust gas recirculation – EGR) are needed to be able to comply with these limits, but also the use of exhaust gas aftertreatment systems. In this respect, no particular technology has been specified, however the new limit value can hardly be complied with without a diesel particulate filter (DPF). Additionally, the Euro VI proposal will be a step towards global harmonization as it foresees limit values similar to those of the U.S. The Euro VI emission standards are expected to take effect in 2013 [5].

It is expected that with the implementation of Euro VI the measurement of particle number emissions will also be required for heavy-duty engines. The PMP evaluation program for the validation and recommendation of techniques for HD comprises the HD interlaboratory exercise and the HD round robin test. It started in the first quarter of 2008 and is planned till end of 2010. Once the results of the UN-ECE’s heavy-duty particle measurement program (PMP) are available, a particle number limit proposal and probably also a modified measuring method (compared to light duty) will be implemented [4].



(a) (b) (c)

Figure 1: Particulates in exhaust gas (a) and (c) exhaust gas particulates from a diesel engine (b) material composition of a particle

3 Definition of Particles

An understanding of the future measurement regulations as well as an optimal development strategy also require an understanding of the characteristics of particles emitted from combustion engines and how they change in the exhaust system and when they are diluted.

Essentially, particulates in the exhaust gas of diesel engines consist of

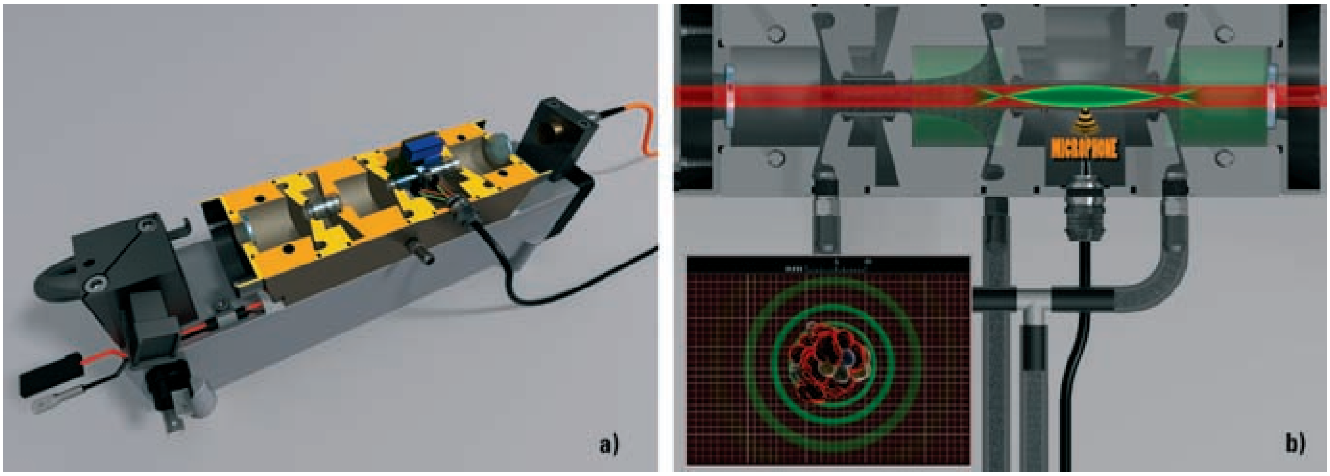


Figure 2: a) Section through the measuring cell of the Micro Soot Sensor; b) standing wave in the measuring tube of the measuring cell

soot, organic components adsorbed on the soot, condensed and adsorbed sulfuric acid and minor quantities of solid components such as abrasion, ash and metallic oxides, **Figure 1**. The soot particles represent the main problem. Soot particles are nonvolatile products of a partially incomplete combustion. They consist mainly of elementary carbon with a molar hydrogen fraction between 10 and 20 %. As a rule, carbon exhibits an amorphous structure, yet with modern engines quasi-crystalline carbon structures can be found as well. In air amorphous soot particles exhibit an oxidation temperature above 550 °C [6].

Downstream of a diesel particulate filter (DPF) – except during regeneration – the soot quantity is minimal. The particles consist almost exclusively of homogeneously nucleated, volatile hydrocarbons and sulfuric acid. During active regeneration, minor quantities of soot are also emitted as well as semi- and non-volatile compounds, the exact composition of which is currently the subject of research.

4 Dynamic Measurement of Soot Concentration

Up until now, the type approval was limited to particulate mass emission and exhaust gas opacity at the Smoke puff. However, in engine development the soot emission was always measured in the first instance, as this is an important indicator for combustion quality, and is generally a main contributor to particulate emission.

In principle, soot concentration can be determined indirectly by tried and tested methods, e.g. by means of the optical density of the blackening of a filter paper or by the opacity of the exhaust gas. Besides other disadvantages (time resolution, low sensitivity) the main drawback of these procedures is most importantly measurement inaccuracy (precisely because the soot concentration cannot be determined directly).

4.1 The Functional Principle of Photoacoustic Measurement

Photoacoustic analysis is a very sensitive method that was originally developed for immission measurement [7]. It was adapted for diesel exhaust soot measurement back in 1979 [8], but only just recently – due to advancements in laser and microphone technology – did it become possible to produce a simple, cost-effective instrument [9].

The measurement principle is based on the periodic irradiation of an absorb-

Figure 3: AVL micro soot sensor

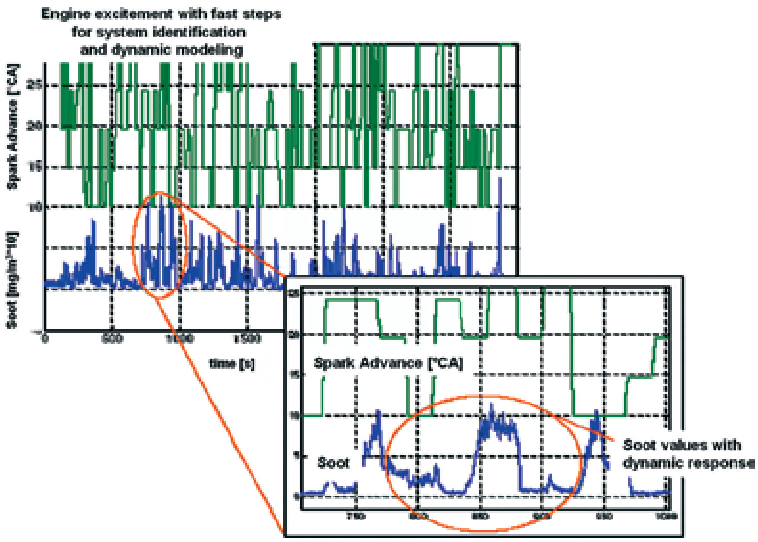


Figure 4: Dynamic soot measurement can ideally be used to optimize combustion processes

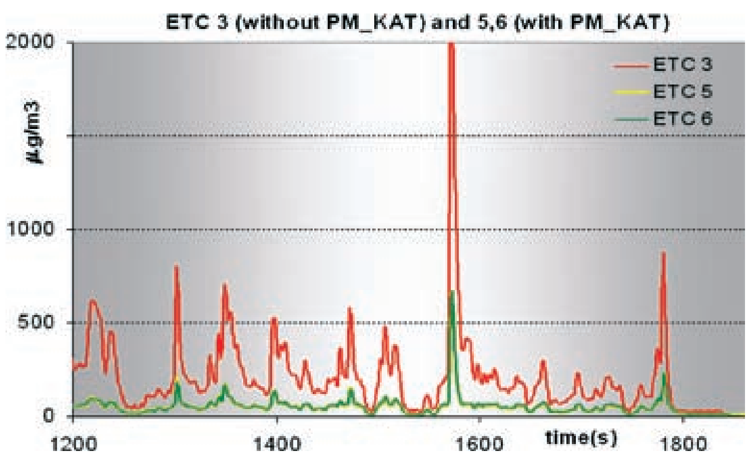


Figure 5: Application of photoacoustic soot measurement upstream and downstream of the “PM-CAT“ particulate filter (ETC 5 and 6 downstream of particulate filter, ETC 3 upstream of particulate filter)

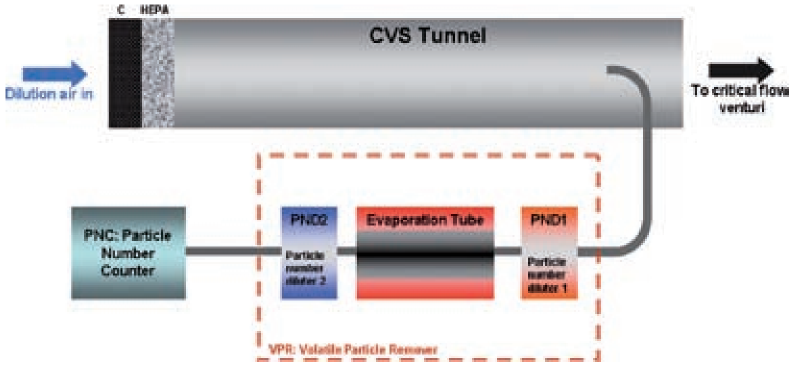


Figure 6: Schema of the proposed particle counter system [2]

ing sample (soot particle), typically in the (near) infrared region of the spectral range. The resulting periodic heating and cooling of the absorber induces a periodic expansion and contraction of the carrier gas. Pressure waves develop around the particle and are detected as sound waves. In a resonant measuring cell with a length adapted to the irradiation period, the reflection at the ends of the cell causes a standing wave to form. (A sudden expansion of a tube-shaped channel represents an acoustic reflector.) The more particles that are inside the measurement tube, the greater the amplitude will be of the standing wave. This is registered by a supersensitive microphone and is directly proportional to the soot concentration. If appropriately laid out, a very good selectivity, i.e. low cross-sensitivity can be achieved enabling the measurement of soot concentrations below 5 µg/m³ with a time resolution of below one second, Figure 2.

4.2 Applications

The Micro Soot Sensor, Figure 3, measures the carbon content (“soot”) of the particulate emissions and is entirely insensitive to the impact of soluble fractions such as hydrocarbons, etc.

The Micro Soot Sensor enables dynamic measurements of soot concentration with a time resolution of 1 s which helps users gain a much more detailed insight into combustion processes. Due to the high sensitivity (measurements down to 5 µg/m³) and the greater measurement range (up to 50 mg/m³), the Micro Soot Sensor enables exhaust gas measurements for the development of new engines with extremely low emission levels, Figure 4.

For sampling from raw exhaust gas, the Micro Soot Sensor is equipped with a conditioning unit that enables accurate measurements at high temperatures of up to 1000 °C and exhaust gas back pressures of up to 2000 mbar. Among other things, this enables the photoacoustic Micro Soot Sensor to measure carbon-particulate emissions up- and downstream of the exhaust gas aftertreatment system time resolved in order to model regeneration and determine the filter system’s efficiency. Since the device even records soot emissions as minimal as 5 µg/m³, it is used for developing innovative drive systems with low emission values and for detecting leaks and small defects in high-efficiency DPFs, Figure 5.

5 Particle Counting

The PMP Working Group, responsible for defining this new measurement

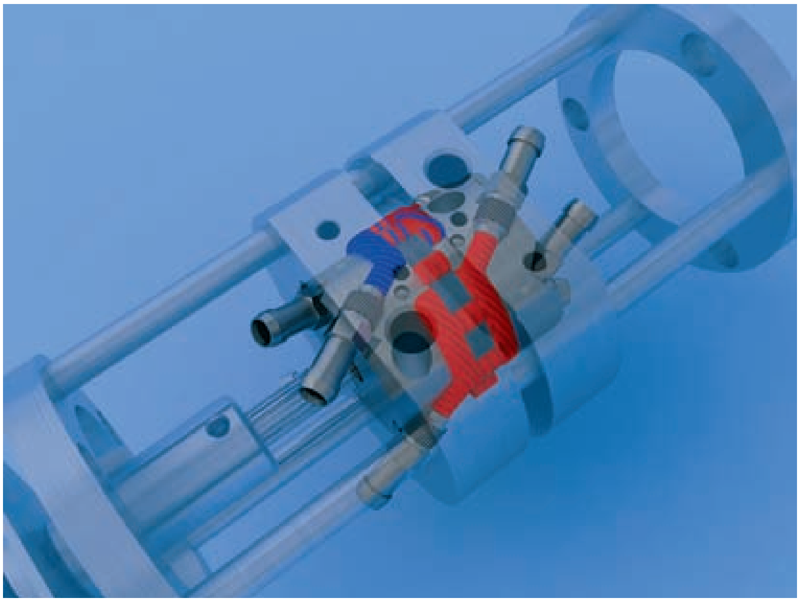


Figure 7: AVL chopper diluter

method and incorporating it into legislation, defined that only nonvolatile particles are to be counted. So besides the sensor (Condensation Particle Counter/CPC, as known from clean room measurement), the system for measuring the particle number concentration also consists of an elaborate conditioning system. To ensure that only nonvolatile particles are counted, the volatile particles have to be removed by employing a defined removal procedure.

5.1 PMP Particle Counting Proposal

In order to remove the volatile particles so that the non-volatile particles can be counted, the PMP Working Group defined a special removal methodology, **Figure 6**, [2]. First of all, very large particles (>2.5 μm) are eliminated by using either a special sampling probe or a cyclone. Next, the sampled exhaust gas or a portion of it is diluted with clean hot air (150 °C) (factor 10 to 200).

This prevents volatile particulate components from condensing and transfers most of the homogenously nucleated volatile particulates to the vapor phase.

Then the diluted exhaust gas is heated to a temperature between 300 °C and 400 °C, because dilution alone is not always sufficient to transfer all volatile particles to the vapor phase.

A secondary dilution with a dilution rate of 10 to 15 cools the exhaust gas and prevents recondensation or adsorption of volatile material by the once again reduced partial pressure of the volatile material. In addition, the thermophoretic particle deposition is prevented (an effect that is unavoidable if cooling is done by heat transfer over the sampling line). Now the solid particles in the CPC with the appropriately set "cut-off" diameter are counted. CPCs are very efficient and highly sensitive instruments for the acquisition of number concentrations of nanoparticles.

5.2 The Functional Principle of the Chopper Diluter

The AVL chopper diluter, **Figure 7**, is an improved rotating disc diluter. It utilizes the benefits of the rotating disc diluter over the conventional mass flow dilution technique. The main improvement is the avoidance of the particle size dependency of the dilution and it also opens up new ways for applications in aerosol measurement, in particular, applications where a wide range of dilution ratios is required. The chopper diluter is designed for hot dilution up to 200 °C. The hot dilution prevents homogeneous and heterogeneous nucleation and condensation of volatiles. The particle number and size distribution is frozen.

Another characteristic of the chopper dilution is that the exhaust is sampled into the diluter with a constant flow, and a feedback into e.g. a partial flow dilution tunnel is possible, so there is no influence of the partial flow system dilution rate. As a result, the parti-

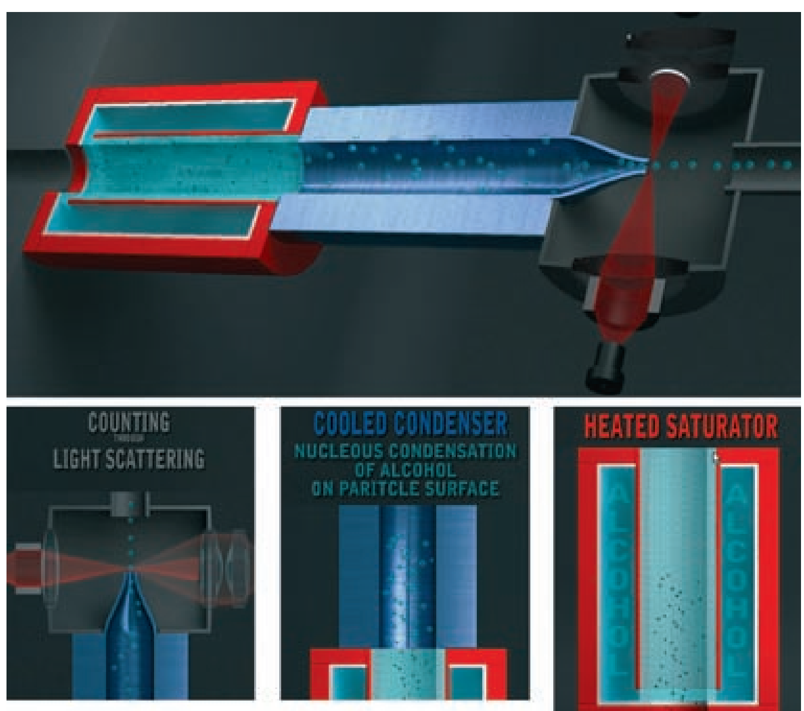


Figure 8: Functional principle of a condensation particle counter (CPC)

cle losses in the undiluted exhaust sampling system are constant and can be corrected.

The main characteristics of the AVL chopper dilution design is the use of flow-through channels instead of cavities and that at least three different channels are always open. These design features guarantee a continuous flow through the chopper diluter, which reduces the tendency of particulate deposition. Consequently, the availability of the system is increased and the cleaning and maintenance effort is reduced. Furthermore, the continuous flow particularly reduces losses because there are no changes in the flow direction. Another design characteristic of the chopper diluter is the option to change between big and small channels. This guarantees a wide measurement range.

The rotating channel disc used by the AVL chopper diluter consists of a special material that prevents the particle's deposition tendency and reduces the cleaning and maintenance effort. In addition, a change of the disc for high and low dilution ranges is not necessary, which results in a reduced operation effort. Due to the chosen technology sampling is possible from CVS, from partial flow dilution systems as well as from the tailpipe.

Figure 9: AVL Particle Counter

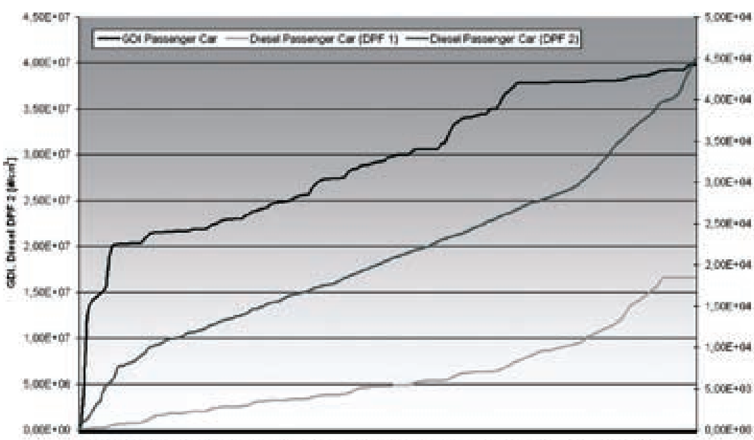


Figure 10: Cumulative particle number concentration curve of three different applications

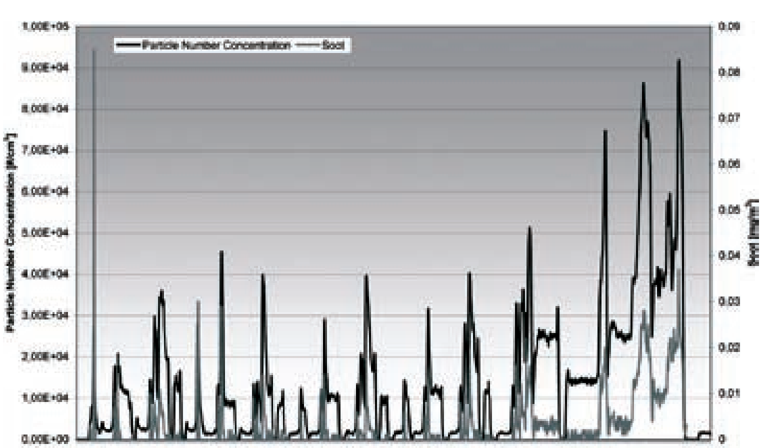


Figure 11: AVL Micro Soot Sensor and AVL Particle Counter measurement during an NEDC cycle

5.3 The Functional Principle of the Condensation Particle Counter

Condensation particle counter (CPC) systems are the most sensitive systems for counting particles in the range of few nanometers up to several micrometers. The functional principle of a CPC is shown in **Figure 8**.

According to the PMP's specifications, particles with sizes between 23 nanometers and 2.5 micrometers has to be recorded. To be able to count even the smallest particles, these are first sent through a chamber with saturated butanol vapor (saturator) that condensates on the particles due to the fast subsequent cooling in the condenser. This turns the nanoparticles into microparticles and the enlarged particles can be counted using light scattering. By changing the temperature difference between saturator and condenser the smallest particle size to be detected ("cut-off") can be defined.

6 Measuring Results

The AVL Particle Counter (APC), **Figure 9**, is a complete system consisting of a dilution system (including primary dilution, evaporation tube and secondary dilution) and a condensation particle counter. The entire system conforms to the latest PMP proposal that lays down the requirements for measuring the particle number concentration in the Draft UNECE Reg. 83 procedure [2].

Figure 10 and **Figure 11** show the results of various measurement programs on different chassis dynos. Different applications were tested with a number of different vehicle types and exhaust gas aftertreatment systems.

A comparison of the cumulative concentration of the particle number during an NEDC cycle between a GDI vehicle and a diesel vehicle with two different diesel particulate filters (DPFs) is shown below in Figure 10.

Figure 11 shows an NEDC cycle where the AVL Micro Soot Sensor was operated together with the AVL Particle Counter. While you can see a relatively good correspondence in the dynamic behavior, this does not permit any conclusive statements on the correlation of absolute values of mass and number. Generally speaking, it can be stated that there is no generally valid correlation between particulate mass and particle number since the number measurement delivers no information about the particle size. A relative comparison would only be possible with a constant particle size distribution, which would only be achieved by an unchanged measurement set-up and the same engine at the same conditions. For this reason, also in R&D applications, particle number measurement can complement but not replace mass-based measuring methods.

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