CHALLENGES OF INTRODUCING PN-PTI IN GERMANY AND OTHER COUNTRIES

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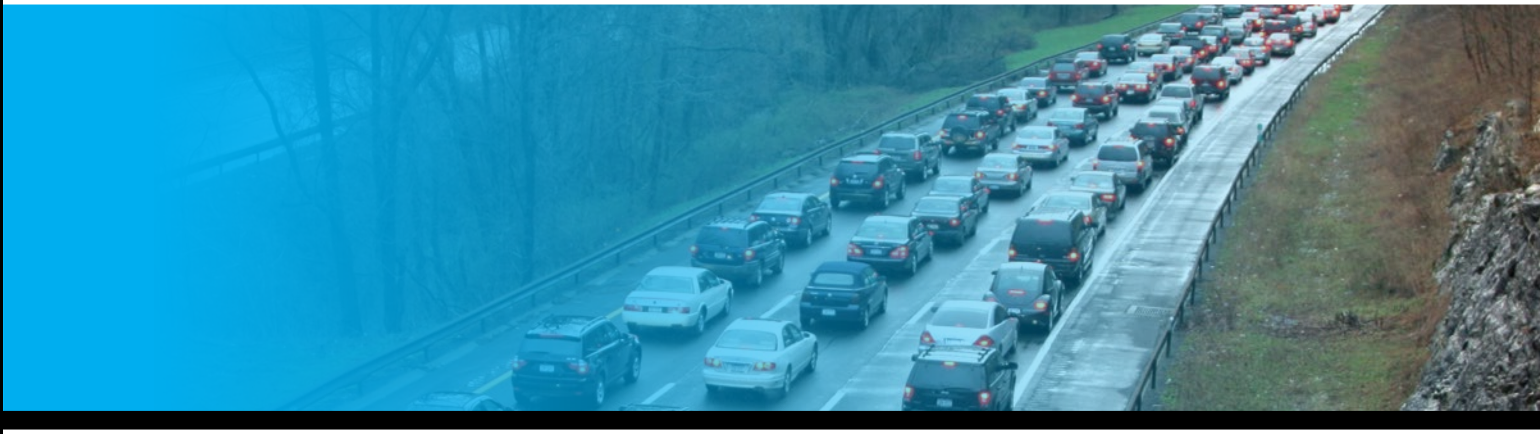

1. Abstract/State of Play

The Federal Republic of Germany decided to replace opacity measurements currently used during the Periodic Technical Inspections (PTI) of vehicles with a new emission test procedure. Effective from January 1, 2021, all Euro 6/VI compression ignition vehicles must be tested for their particle number (PN) emission. This announcement was published in Germany by the Ministry for Traffic and digital Infrastructure in 2017 [1]:

*"**Überprüfung der Partikelanzahl:***
Ab dem 01.01.2021 wird im Rahmen der Abgasuntersuchung bei Kraftfahrzeugen mit Kompressionszündungsmotor die Überprüfung der Partikelanzahl durch Messung am Auspuffendrohr eingeführt. Das BMVI wird dazu das anzuwendende Messverfahren und die zulässigen Grenzwerte durch Änderung dieser Richtlinie bekannt geben."

*"**Checking the Particle Number:***
From 01.01.2021, the checking of the particle number by measurement at the exhaust tailpipe will be introduced as part of the exhaust emission test for motor vehicles with compression ignition engines. For this purpose, the BMVI will announce the measuring method to be used and the permissible limit values by amending this Directive."

The goal is to increase the quality of the periodic emission check by improving fault detection and to make sure that the emission behavior does not deteriorate because of decay, manipulation, lack of service or improper repairs [2]. The new test method recognizes that particle filters with a high collection efficiency are indispensable to reduce the adverse impact of nanoparticles on human health and air quality.

In preparation for this regulation, various studies have been conducted in the Netherlands [3], the United Kingdom, Spain, Belgium, Mexico, and Switzerland or are presently ongoing, e.g. in Germany (by BASt, VdTÜV and DEKRA). Based on the experiences gained in these studies – which, in some cases, have not yet published final reports – it can be assumed that common ground was found in the design of a test procedure and a limit value. A simple test conducted during idling of the vehicle generates meaningful results over a 120 to 180 seconds total test duration. This avoids an increase of labor cost compared to today's opacity measurement procedures. A distinction into three test phases and averaging of individual and collective test phases allows to evaluate the emission behavior of a vehicle, especially when emission results near the anticipated limit value of 250,000 particles/cm³ are reached. Preliminary results of various studies indicate that vehicles equipped with well-functioning particle filters will not exceed 50,000 particles/cm³.

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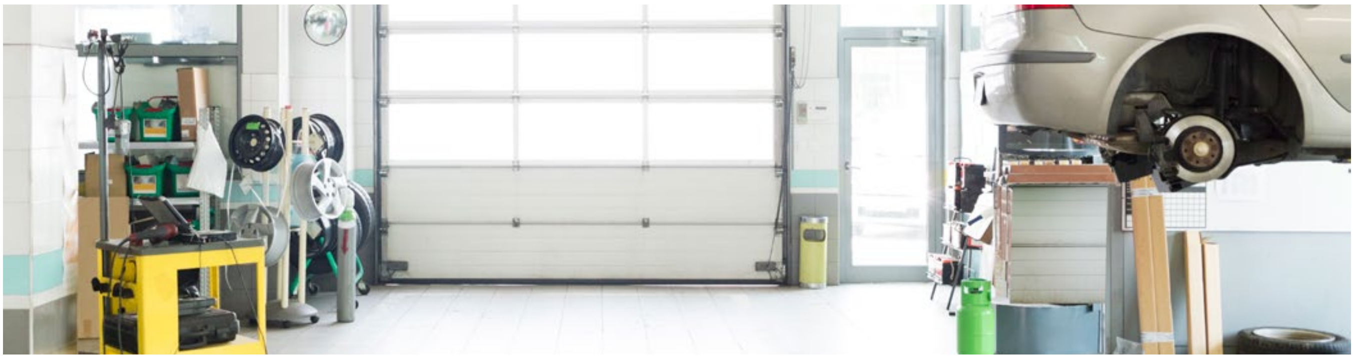


Further details of the test procedures (snap-acceleration, fast pass options, phase durations) have yet to be decided and may vary in different countries. Overall, a robust, simple, quick and cost-effective test procedure has been identified and is currently being finalized in the legal framework.

In parallel to the development of a suitable test procedure, various measurement technologies that can be used to report particle number concentrations have been evaluated. Candidate technologies included laser light scattering, high resolution opacity, condensation particle counting and diffusion charging techniques. The lack of sensitivity eliminated opacity and laser light scattering techniques as suitable candidate technologies already early on.

Condensation particle counters (CPC) have been used for more than four decades [4]. Modern day thermal-cooling CPCs first became commercially available in 1979 (CNC model 3020, TSI Inc.). While their use was initially limited to fundamental and atmospheric research, they were installed as continuous monitors in semiconductor cleanrooms already in the mid-1980s. Today CPCs have found a widespread use in various industries and applications, which include but are not limited to indoor air quality validation, cleanroom monitoring, ambient air quality measurements, filter efficiency testing and respirator fit testing. CPCs are also the established particle number (PN) measurement technique for vehicle homologation [4-6]. Already since September 2011 a PN limit of 6×10^{11} particles/km is required for type approval of initially light-duty diesel vehicles, which was later extended also to heavy duty diesel vehicles as well as vehicles using gasoline direct injection engines [7]. Furthermore, CPCs are also the leading measurement technique used for real driving emissions (RDE), on-road vehicle testing with portable emission measurement systems (PN-PEMS).

Calibration standards are also well defined by the International Organization for Standardization in ISO standard 27891 [8]. The initial studies mentioned above confirmed the suitability of this technology for PTI applications. Currently, there are at least six manufacturers of condensation particle counters active on the German and European markets: Grimm Aerosol Technik GmbH & Co.KG (Ainring, Germany), TSI GmbH (Aachen, Germany), Sensors Europe GmbH (Erkrath, Germany), Palas GmbH (Karlsruhe, Germany), Airmodus Oy (Helsinki, Finland) as well as AVL List GmbH (Graz, Austria). Some of these manufacturers already supply OEM components and analyzers to garage equipment manufacturers. One of these manufacturers already produces 1000's of CPCs on an industrial scale annually. A recent survey confirmed that production facilities can be scaled to meet an increase in demand necessary to satisfy the German market for PN-PTI. Moreover, to the author's best knowledge there is no controlled intellectual property restrictions for other vendors to introduce CPC technology into this marketspace.

The other candidate technique under consideration is diffusion charging. Diffusion Charging (DC) devices have been uses predominately in handheld instruments since the early 2000's. These devices do not actually count particles but rely on a metrics that is between the length and the surface area of the particles, which is then converted into a PN value using some assumptions regarding the particle size distribution. This need for signal manipulation and the fact that there is no established calibration method were key factors why the DC technique was not further pursued as candidate for the particle number measurement for type approval. That said, there is also a variety of Diffusion Charger devices in various stages of development who may enter the German market. Key manufacturers include: Naneos Particle Solutions GmbH (Windisch, Switzerland), AVL Ditest GmbH (Graz, Austria), Testo SE & Co. KGaA (Lenzkirch, Germany), Capelec (Montpellier, France), Test Equipment Nederland B.V. (Abcoude, The Netherlands) The devices are now classified into Advanced Diffusion Charges and Simple Diffusion Chargers, which have different performance characteristics. Some of the DC manufacturers and technology providers have been participating in various studies, some are in various stages of the development process and some have experience in automotive exhaust emission measurement.

It can also be assumed that the market could be satisfied with sufficient quantities around the implementation date, provided a corresponding new calibration standard will be developed in time to provide the possibility to include diffusion charger based instrumentation.

Overall, both technologies have oligopolistic to polypolistic market structures and are open and available to all manufacturers of garage equipment and other stakeholders. Monopolistic structures can easily be avoided regardless if one or two or more technologies will be introduced into PN-PTI.

2. Description and Comparison of Suitable Technologies

2.1 Condensation Particle Counter (CPC) Based Emission Analyzers

One strength of a CPC based emissions analyzer is that it uses direct particle counting for measuring particle concentration. This measurement provides a primary particle counting method in which every single particle is counted. The particle number concentration is simply computed from the number of pulses counted and the sample flow rate.

ISO 27891 "Aerosol particle number concentration – Calibration of condensation particle counters" describes how to determine the detection efficiency of a CPC together with the associated measurement uncertainty.

CPC based emission analyzers can measure emissions down to below 1 particle/cm^3. This allows a functional check of the instrument in the ambient shop air and also simplifies a leak test to connecting a zero count filter to the sampling inlet. Furthermore, this measurement is not at all influenced by the particle size distribution emitted from the different engine types. In consequence, a measurement accuracy of ±10% is specified by most manufacturers. As importantly, CPCs have a measurement efficiency of 100% at the mode of typical emission size distributions, so between 50 and 200 nm.

Often the fact that CPCs use a working fluid is seen as a disadvantage. However, the fluid (i.e. IPA) is commonly used in hospitals as a cleaning agent or disinfectant and keeps the sensor clean so that CPCs themselves are low maintenance. The fact that the resulting droplets from the condensation process have nearly all the same size is used as real-time quality control (i.e. pulse height monitor of the scattered light signal) for proper operation of the instrument. Further, solutions have been presented that eliminate the need for users to handle the fluid.

2.2 Diffusion Charger (DC) based emission analyzers

The main advantages of basic diffusion chargers lie in their compact size and comparatively lower cost, which lead to them being used as handheld particle detectors. There are three limitations for their successful use as PN emission analyzers:

1. Their measurement response is greatly influenced by any change in the particle size distribution, e.g. during different engine load or drive conditions. The particle size distributions emitted from gasoline, diesel and CNG engines are also different, so a DC-based analyzer will report different particle numbers for different engine types compared to a reference particle number counter (CPC). This effect is further increased by the use of different fuel blends, e.g. varied bio-fuel contents.
2. A DC-based emission analyzer cannot meet very stringent counting efficiency requirements (i.e. an efficiency of 80-100% from 41nm to 200nm).
3. Any regulatory legislation will require an internationally recognized calibration standard to ensure measurement quality. There is no ISO or related standard for calibrating a DC, and none is foreseen for the next 5 years, to the best of current knowledge.

3. Challenges

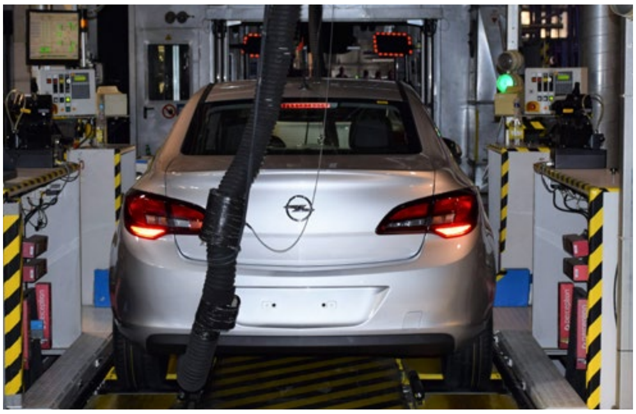
When being faced with the implementation of a new PTI program all stakeholder involved in the drafting process encounter challenges from present requirements. Additional complexity is added when considering future requirements of geographical, political or technological nature.

3.1 Present Requirements

Many of the challenges have already been mastered so that this paper focusses on major milestones that have yet to be reached. There are additional requirements which are outside the scope of this paper.

3.1.1 Performance-Based Standards Versus Technology-Based Standards

One of the fundamental guidelines in drafting new legislations and standards is that performance-based standards are preferred over technology-based standards to promote competition and free access to markets. For PN-PTI applications performance-based standards help focusing on key metrological requirements and avoid unfair favoring of single technologies which may block innovative ideas from future market entry. Sometimes performance-based standards are interpreted as technology neutral in a sense of defining the lowest common denominator of two or more technologies however, this is not the goal of a performance-based standard.



The goal is to determine the standard which is best suited to achieve the required performance, reliability, traceability and measurement uncertainty needed for a sound and expandable PN-PTI regulation provided target price-performance ratios are being met, monopolies are avoided and wide equipment availability is guaranteed regardless of the applied technology.

3.1.2 Traceability / Measurement Uncertainty

From a judicial perspective but also from user and consumer perspectives a traceable reference chain back to national standards is a must. Measurement equipment used in mandatory emission tests has to be verified in a stringent homologation process and needs to be calibrated regularly against traceable reference equipment to guarantee proper functioning before market entry and during its useful life. Test conditions should reflect the application for which the equipment is being used and the expected ambient conditions [9]. Both, comprehensive homologation tests in a controlled laboratory environment but also testing a variety of vehicles against a reference device at the Technical Service Providers (in Germany currently TÜV and Dekra) will ensure that emitted particles will be counted accurately and reliably regardless of size composition. The foundation are sound standards for repeatability and reproducibility in the defined concentration range and in the defined counting efficiencies. The test design needs to take varying particle size distributions into account as can be reasonably expected due to different fuel compositions, aging effects and various exhaust aftertreatment strategies.

Equally important is the measurement uncertainty which is directly related to the number of steps in the traceability chain. Current assessments assume an uncertainty budget between 20 to 30% for each step. This uncertainty budget could even increase when varying aerosol sources and varying technologies in reference equipment are being used. Equally, tight measurement tolerances in concentration and in counting efficiencies at varies particle sizes also help to reduce the measurement uncertainty. The goal is to avoid false passes and false failures when it comes to expensive repairs for the vehicle owner. Varying test results, especially near the limit value or near plausibility check concentration levels need to be reduced as far as possible as they bare the risk of discrediting the entire usefulness of PN-PTI jeopardizing the implementation of the program.

3.1.3 Cost Effectiveness of the Program

The cost effectiveness of an emission program is determined by three influencing factors:

1. The duration of the test procedure as it has a direct impact on labor cost as most expensive contributor. With a probable test duration of 120 to 150 seconds the future PN-PTI meets the expectation. As the majority of currently tested vehicles equipped with well-functioning particle filters will not exceed 50,000 particles/cm³ a fast pass could further reduce the duration and effort of the PN-PTI test. When the test equipment provides a reliable measurement at the low end of the measurement range unnecessarily long test procedures can be avoided.
2. The price target for PTI measurement equipment was limited to an upper boundary of 10.000,- Euro in the early stages of program development. Preliminary cost assessments from various suppliers of CPC and DC based devices indicate that no manufacturer is likely to exceed this upper limit. On the contrary, competition in both technologies promote superior technical solutions and will result in competitive market pricing below this upper target price [10].
3. Life time cost is an equally important influencing factor for cost effectiveness. Besides regular maintenance intervals, regular calibration and Eichung are the most expensive contributors. Duality of calibration and Eichung in Germany on an annual basis can easily exceed the initial price of the equipment over a 10-year period and thus be disproportional. Dividing tasks between calibration and Eichung and/or a bi-annual interval will safeguard the implementation and avoid that test sites will no longer participate in the program.

3.2 Future Requirements

Next to important considerations about immediate requirements stakeholders also need to consider near and midterm requirements which can already be foreseen.

3.2.1 Drafting of an OIML Standard

Germany and The Netherlands took the lead to draft an OIML standard for PN-PTI. This document needs to take international requirements and prerequisites into account as it will set global standards for the next decades. Different vehicle population, different fuels, different PTI scenarios in a global environment require a stringent standard to reduce measurement uncertainty and to facilitate traceability as much as possible.

3.2.2 Gasoline direct injection (GDI) vehicles

Research has demonstrated that gasoline fueled vehicles with direct injection emit high particle concentrations. In consequence, a particle number limit value has already been implemented 2014 at type approval, so that Gasoline Particle Filters became the standard exhaust aftertreatment solution. Once a particle number test is introduced successfully in the field there is a consensus among most stakeholders that gasoline fueled vehicles should also be tested for particle number emissions in a next stage. The fuel type and combustion strategy have a direct impact on particle size distribution so counting efficiencies need to be specified across the size range from 23 to 200 nm applying tight tolerances. Initial research demonstrates the need for a low measurement uncertainty.

3.2.3 Sub 23 nm measurements

In 2013, the European Union requested further investigation of particle number emission from spark ignition engines relating to particle size from the PMP group. After evidence of significantly higher fractions of sub-23 nm particles for certain technologies like PFI and CNG engines, the European Commission has expressed the intention to lower the cut-off size in order to improve the control of particle emissions whatever is the average size of the particles emitted. Starting from mid-2018 a round robin exercise has been carried out to investigate the possibility to use the existing PMP methodology properly modified in order to count particles down to about 10 nm. It is therefore likely that a particle number concentration measurement down to 10 nm will be introduced with Euro 7.

Similar efforts are well underway for PEMS equipment. Three European funded Horizon 2020 research projects, PEMs4Nano [11], DownToTen [12] and Sureal23 [13] aim on developing new test procedures for sub 23 nm particles. Instrument manufacturers are already preparing for the introduction of a 10 nm counting efficiency requirement. It is preferable if type approval, RDE testing and PTI testing is harmonized as much as possible to be able to compare and to evaluate the emission behavior of vehicles over time. It can therefore be assumed that also in PTI a 10 nm counting efficiency will be introduced in the future.

3.2.4 Reduction of Limit Value

Studies in Belgium and The Netherlands have demonstrated that about 7% (+/-3%) of the tested vehicle fleet exceed the limit value of 250,000 particles/cm³ [14]. The other outcome of those studies is that the vast majority of tested vehicles dispose of well-functioning particle filters which would allow a limit value of 50,000 particles/cm³. Higher values are an indicator of deterioration and defects which should be eliminated as early as possible to improve air quality. In the continued quest to improve air quality for people living in urban areas it can be expected that politics will lower the limit value in the future. It is then important to define standards and tolerances which typically do not exceed 10% of the limit value.

3.3 Summary and Outlook

PN-PTI test procedures, limit values and equipment performance standards are at an advanced stage and lots of progress has been made [15]. Cost-effective solutions are being demonstrated and will be available to all garage equipment manufacturers and other interested parties. PN-PTI needs a sound performance based standard that fits the current needs but also considers future developments. To protect consumers and regulators while improving air quality the influence of engine technology, fuels and aftertreatment on particle size must be minimized in order to provide reproducibility, traceability and repeatability of the measures undertaken. Following the European Integrated Pollution Prevention and Control IPPC Directive (IPPC - 96/61/EC) the Best Available Technology Not Entailing Excessive Cost (BATNEEC) should be applied. Only then the measurements will be meaningful and accepted by the general population and service providers.

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