



SURFACE VEHICLE RECOMMENDED PRACTICE

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Recommended Practice for Improving Measurement Quality of Particle Number Counting Devices

RATIONALE

Since the introduction of the first particulate mass emissions standard for heavy-duty diesel engines in 1988, engine and vehicle manufacturers have substantially reduced particulate matter (PM) mass emissions from modern internal combustion engines. PM emissions standard levels have decreased from 0.6 g/bhp-h to the current 0.01 g/bhp-h over the U.S. Heavy Duty Federal Test Procedure (FTP). This reduction in PM emissions resulted mainly from improvements in fuel-air combustion, the introduction of high-pressure fuel injection systems, fuel property improvements, and exhaust aftertreatment.

The introduction of catalyzed wall-flow particulate filters for compression ignition (CI) engines lowered the tailpipe particulate mass to very low levels. Testing, verifying, and certifying the improvements has largely been accomplished with PM sampling systems that collect PM mass on a pre-weighed 47 mm teflon filter during the prescribed test cycle, which is then weighed after sample collection and compared to the regulatory standard. This method requires the use of sensitive analytical balance instrumentation and may have reached a practical lower limit. The collected mass includes a number of contributors including ash, solid carbon particles, sulfates, nitrate compounds, and a mix of heavy hydrocarbons known as the soluble organic fraction (SOF). The smallest solid carbon components have been identified as primary soot particles, which can range in geometric mean diameter size from several nanometers to tens of micrometers. The interrelationship between these soot particles, human health effects, and poor urban air quality largely drove the development of instrumentation designed to measure the concentration of particles in the air. The European Union Particulate Measurement Program (PMP) was commissioned to investigate and recommend the best and most cost-effective way to measure the number of particles emitted by an engine during a given test cycle. Many of the recommendations by this group were codified into European Union Law/Regulation under UNECE R-83 with Standard Limits first included in EURO 5+ in 2011 for light-duty diesel passenger cars. Heavy-duty diesel engines were regulated by EU under Stage V and Euro 6.

As a result, multiple instrument manufacturers have introduced devices that measure solid particle number (SPN) under the EURO 5+ rules. As the use of SPN counters have become more wide-spread in both R&D and certification, a growing need has developed for a commonly understood recommended practice for the setup and use of these measurement devices. This recommended practice provides a guide for SPN measurement using the currently available measurement devices.

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1. SCOPE

The scope of this document focuses on the setup and use of solid particle number (SPN) counting devices in both engine development and certification environments. The document reviews best practices for collecting and measuring samples from both raw and diluted exhaust gas streams across several sample probe insertion locations relative to installed aftertreatment devices. Appropriate dilution techniques, sample transfer processes, and temperature management techniques are included. Finally, performance and validation checks are covered to ensure that long-term degradation and instrument failures can be identified quickly.

The particle size range targeted in this document is >23 nm, which aligns with the present EU SPN regulations and targets only solid particles. Current commonly available measurement devices are designed for counting efficiencies of 50% at 23 nm and 90% counting efficiencies at 40 nm so the contents of this document primarily address these particle sizes. It is expected that future regulations will target a lower 10 nm size cut-point. Consequently, a short section has been added discussing best practices that a user may need to consider when measuring particles in this size range.

1.1 Purpose

The purpose of this document is to provide guidance on the best practices to ensure high quality, repeatable results when using SPN counting systems in both engine-out and post aftertreatment applications. Prior to the application of this document, the user should review documentation provided by the measurement device manufacturer regarding regularly scheduled maintenance and calibration. Those procedures are not described herein because they are specific to the instrument manufacturer. The document also does not give guidance on the procedures required under certification protocols.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 EPA Publications

EPA Title 40: Protection of Environment, Chapter 1, Subchapter U, Part 1065: Engine Testing Procedures.

Federal Register Volume 76, No. 179/Thursday, September 15, 2011/Rules and Regulations Updates for PART 1065 - Engine Testing Procedures: Pages 57437-57470.

2.1.2 EU Publications

Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R1154&from=EN>, accessed December 2019.

2.1.3 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ISO 8178-1:2017 Reciprocating Internal Combustion Engines — Exhaust Emission Measurement — Part 1: Test-Bed Measurement Systems of Gaseous and Particulate Emissions

ISO 27891:2015 Aerosol Particle Number Concentration — Calibration of Condensation Particle Counters

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Czerwinski, J., Comte, P., Mayer, A., and Reutimann, F., "Investigations of Changes of the 2-Stroke Scooters Nanoparticles in the Exhaust- and CVS-System," SAE Technical Paper 2013-24-0178, 2013, <https://doi.org/10.4271/2013-24-0178>.

Giechaskiel, B., Carriero, M., Martini, G., Bergmann, A. et al., "Comparison of Particle Number Measurements from the Full Dilution Tunnel, the Tailpipe and Two Partial Flow Systems," SAE Technical Paper 2010-01-1299, 2010, <https://doi.org/10.4271/2010-01-1299>.

Giechaskiel, B., Zardini, A., and Martini, G., "Particle Emission Measurements from L-Category Vehicles," SAE Int. J. Engines 8(5):2322-2337, 2015, <https://doi.org/10.4271/2015-24-2512>.

2.2.2 Technical Papers

Giechaskiel, B., Mamakos, A., Andersson, J., Dilara, P., Martini, G., Schindler, W., and Bergmann, A. (2012). Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review. *Aerosol Science and Technology*, 46:719-749. doi: <https://doi.org/10.1080/02786826.2012.661103>.

Giechaskiel, B., Maricq, M.M., Ntziachristos, L., Dardiotis, C., Wang, X., Axmann, H., Bergmann, A., and Schindler, W. (2014). Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. *Journal of Aerosol Science*, 67(0), 48-86. doi: <http://dx.doi.org/10.1016/j.jaerosci.2013.09.003>.

Giechaskiel, B., Wang, X., Horn, H.G., Spielvogel, J., Gerhart, C., Southgate, J., Jing, L., Kasper, M., Drossinos, Y., and Krasenbrink, A. (2009). Calibration of Condensation Particle Counters for Legislated Vehicle Number Emission Measurements. *Aerosol Science and Technology*, 43:12, 1164-1173. doi: <https://doi.org/10.1080/02786820903242029>.

Hinds, W.C. (1982). *Aerosol Technology*. New York, John Wiley and Sons.

Kittelson, D.B., Watts, W.F. Jr., and Arnold, M. (1998). Review of Diesel Particulate Matter Sampling Methods Supplemental Report #2.

TSI Incorporated, 500 Cardigan Road Shoreview, Minnesota 55126 USA, www.tsi.com.

3. DEFINITIONS

3.1 DIESEL PARTICULATE FILTER OR DPF

Diesel particulate filter is an exhaust aftertreatment device in which all the exhaust gas is forced to flow through a porous wall which filters out solid matter of varying size over time.

3.2 DILUTION FACTOR

Dilution factor is the ratio of the undiluted analyte to that of the analyte after addition of a diluent by a diluter operating at specified conditions.

3.3 FILTRATION EFFICIENCY

Filtration efficiency of a filter is calculated as the difference of one minus penetration or 100% minus penetration in percent. Filtration efficiency is usually indicated as a percentage and a negative filtration efficiency indicates higher emissions after the filter system and points to secondary formation of pollutants.

3.4 FULL FLOW DILUTION

Full flow dilution is a process of mixing dilution air with the total exhaust flow prior to extraction of a fraction of the diluted exhaust stream for analysis.

3.5 MOBILITY DIAMETER

Mobility diameter is equivalent to the diameter of a sphere that indicates the same mobility as the observed particle which is normally not spherical. The mobility diameter is not dependent on the density of the particle.

3.6 MONODISPERSE

Monodisperse means that the particles in the exhaust or sample flow are of uniform size.

3.7 PARTIAL FLOW DILUTION

Partial flow dilution is a process of extracting a portion of the raw exhaust from the total exhaust flow, then mixing it with an appropriate amount of dilution air prior to particulate sampling.

3.8 PARTICLES

Particles mean the components of the exhaust that are dispersed at 573 K (300 °C) in the form of solid particles or droplets in suspension.

3.9 PARTICLE CONCENTRATION

Particle concentration means the number of solid particles per gas volume unit in a given size class.

3.10 POLYDISPERSE

Polydisperse means that the particles in the exhaust or sample flow are of varied size.

3.11 PARTICLE CONCENTRATION REDUCTION FACTOR

Particle concentration reduction factor, or PCRf, is a factor used to correct the particle number measured at the sensor to the particle number present at the inlet of the particle counting system. It corrects for actual dilution and all particle losses within the volatile particle remover.

3.12 REGENERATION

Regeneration is the combustion of soot collected and stored in the diesel particulate filter. This process is initiated when the combustion temperature of the soot is reached, and this may take place continuously or intermittently. If the regeneration process is initiated via a control unit or impulse—for example, in combination with the input of energy—this is referred to as “active regeneration.” Passive regeneration occurs when conditions allow for soot combustion without such an input of energy.

3.13 VOLATILE PARTICLE REMOVER

Volatile particle remover, or VPR, is an instrument that suppresses volatile gaseous nucleation within the sample by heating and then diluting the sample in one or more stages while at the same time achieving a particle number concentration below the upper threshold of the single particle count mode of the particle number counter and a gas temperature below 35 °C at the inlet to the particle number counter.

4. ABBREVIATIONS AND SYMBOLS

The abbreviations used in the document have the following meanings in both capital and lower case.

%	Percent
°C	Degree Celsius
CAST	Combustion Aerosol Standard
CFR	Code of Federal Regulations
CFO	Critical Flow Orifice
CI	Compression Ignition
cm ³	Cubic Meter
CMD	Count Mean Diameter
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CPC	Condensation Particle Counter
CVS	Constant Volume Sampling
D50	50% Counting Efficiency
D90	90% Counting Efficiency
DC	Diffusion Charger
DF	Dilution Factor
DMA	Differential Mobility Analyzer
DPF	Diesel Particulate Filter
E	Efficiency
EPA	Environmental Protection Agency
EU	European Union
FTP	Federal Test Procedure
GPF	Gasoline Particulate Filter
H ₂ O	Water
HC	Hydrocarbon
HEPA	High Efficiency Particulate Air
HHC	Heavy Hydrocarbon
ISO	International Organization for Standardization

K	Kelvin
kPa	Kilo-Pascal
m	Meter
MFC	Mass Flow Controller
mg/m ³	Milligram per Cubic Meter
NaCl	Sodium Chloride
NIST	National Institute of Standards and Technology
nm	Nano-Meter
OBD	On-Board Diagnostic
PCRF	Particle Concentration Reduction Factor
PEMS	Portable Emission Measurement System
PFD	Partial Flow Dilution
PM	Particulate Matter
PMP	Particle Measurement Program
PN	Particle Number
PNC	Particle Number Counter
PND1	Particle Dilution 1
PND2	Particle Dilution 2
R	Ratio of the Response
RDE	Real Driving Emission
s	Second
SOF	Soluble Organic Fraction
SPN	Solid Particle Number
TÜV	Technischer Überwachungsverein
UNECE	United Nations Economic Commission for Europe
U.S.	United States
VPR	Volatile Particle Remover
WRCD	Wide Range Continuous Diluter

5. BACKGROUND AND USE CASE GUIDANCE

Understanding how particles are defined and behave in exhaust samples is an important element in successfully and reliably measuring them. This section provides background information useful to any user of particle number counters.

5.1 Basics of Particle Counting

5.1.1 Background - Original Intended Use of SPN

An important benefit of the European Union (EU) Particulate Measurement Program (PMP) definition of SPN is that it provides a particle measurement methodology that is traceable to primary standards, can be reasonably well calibrated, and can be standardized from laboratory to laboratory. However, SPN counting, as it applies to motor vehicle exhaust, is a PN emissions protocol based on a specific sampling and sample preparation procedure. This regulatory definition of SPN poses certain limitations that need to be considered when extending the method beyond the regulatory application to more general engine exhaust measurements beyond type approval and emissions certification.

The PMP defines solid particle counting in terms of the regulatory approach to vehicle exhaust sampling, namely constant volume sampling (CVS) into a dilution tunnel. In this procedure, vehicle exhaust is transported through a high temperature resilient hose to the dilution tunnel where the exhaust mixes with clean, humidity- and temperature-conditioned dilution air. Sufficiently far downstream to ensure good mixing, diluted exhaust is sampled into the volatile particle remover (VPR) that precedes the particle counter. This consists of three parts: a high temperature diluter ($\geq 150^\circ\text{C}$), here termed PND1, an evaporation tube (300 to 400°C wall temperature), and a room temperature diluter, PND2. Alternatively, a catalytic stripper or thermodenuder can be used to remove semi-volatile species in place of the evaporation tube. This additionally diluted exhaust then enters a particle counter with counting efficiencies of 50% at 23 nm (D50 lower size cut-point of 23 nm) and minimum 90% at 41 nm. This lower size limit was instituted to avoid counting volatile particles that can potentially re-nucleate downstream of the VPR. In the future, this limit may be lowered to 10 nm.

The determination of SPN emission rates rests on the particle concentration reduction factor (PCRF) associated with the VPR and applied to the condensation particle counter (CPC) value. The PCRF is a function of both the dilution and the losses that occur in the SPN system. PCRF (or f_r) is calculated from:

$$f_r(d_i) = \frac{N_{in}(d_i)}{N_{out}(d_i)} \quad (\text{Eq. 1})$$

where:

$N_{in}(d_i)$ = upstream particle number concentration for particles of diameter d_i

$N_{out}(d_i)$ = downstream particle number concentration for particles of diameter d_i

PCRFs are measured at monodisperse aerosol particle sizes of 30 nm, 50 nm, and 100 nm to derive a composite PCRF:

$$\text{PCRF}_{\text{composite}} = 1/3 (\text{PCRF}_{30} + \text{PCRF}_{50} + \text{PCRF}_{100})$$

which is then combined with the CVS dilution factor and distance traveled or brake horsepower-hour to convert the raw CPC SPN counts to emission rates.

5.1.2 Applications for Particle Number Measurements

Four important non-standard use cases or applications for PN measurements include: (1) engine out SPN emissions rates, (2) diesel particulate filter (DPF) efficiency, (3) on-board diagnostics (OBD) testing, and (4) real-world driving emissions.

1. Engine-out SPN measurement differs from the regulatory application in two important ways: the exhaust is sampled directly from the exhaust pipe instead of the CVS dilution tunnel or partial flow dilution (PFD) system (hence the often-used terminology “raw measurement”) and the particle concentration is typically orders of magnitude higher than at the tailpipe. Immediate dilution is required to cool the sample and to reduce the rate of particle coagulation (see [5.2](#)). For practical reasons, “immediate” often includes some distance of transport from sample point to initial dilution. This may require use of insulated and/or heated lines to avoid thermophoretic losses. The longer this transport requires, the less accurate the PN measurement becomes.

2. The best way to measure DPF particle filtering efficiency is by simultaneous measurement of PN pre- and post-DPF. This avoids variability associated with vehicle/engine operation in two separate tests, but care must be taken with this approach. Sampling and dilution systems at each location should be exactly matched. Even when they are, coagulation in the pre-DPF sampling path can lead to underprediction of the actual efficiency. It should also be noted that a minimum 10% uncertainty between the two SPN devices exists and should also be considered.
3. OBD testing includes the introduction of fault conditions. Some of these can lead to high PN concentrations. Therefore, the sampling system needs to be set up in a way that minimizes the effects of particle coagulation, namely short transport times to the first dilution point.
4. Real driving emissions (RDE) testing involves PN measurement while the engine/vehicle is being operated on the road. This type of testing differs from chassis dynamometer testing primarily in that there is no CVS dilution tunnel and the particle counting instrumentation can differ from the standard butanol-based CPCs used in the laboratory. This application primarily addresses tailpipe emissions, which occur downstream of exhaust particulate filters. Thus, particle concentrations are expected to be very low and the effects of particle coagulation to be minimal. However, if particle counts are recorded upstream of the exhaust particulate filter (if present), particle concentrations may be sufficiently high that coagulation may affect count rates. Care must also be taken that particles are not lost by thermophoresis or diffusion prior to entering the first stage diluter. In addition, there may be some systematic differences between the particle counters used in on-board SPN counters versus laboratory CPC based counters that need to be considered.

The important point is that the SPN method was developed specifically for regulatory measurements of low particle concentrations near room temperature and pressure. It cannot be directly applied to “raw” exhaust measurements, which are typically at high temperature, high pressure, and may include high particle concentrations. Instead, additional sampling precautions are necessary, chief amongst them rapid dilution close to the sampling point that simultaneously reduces sample temperature and particle concentration.

5.2 Solid Particle Counting: Coagulation and Dynamic Range

The purpose of this section is to explain some of the difficulties inherent in extending SPN from the original regulatory application, which is aimed at very low-level particle emissions measured from a CVS system at near room temperature, to other situations where particle concentrations and temperatures may be much higher. The main problems associated with this stem from two related factors: particle number is not a conserved quantity and the rate of particle coagulation is heavily concentration and temperature dependent.

5.2.1 Particle Coagulation

Particles collide through their random thermal motion. Except for very small particles (<23 nm), particles stick with near 100% probability. Therefore, the coagulation rate equals the collision rate. According to kinetic theory, this is given by:

$$\frac{dN}{dt} = -k N^2 \quad (\text{Eq. 2})$$

where:

N = the particle concentration

t = time

k = a rate constant