Comparison of Solid Particle Number Emission of Gasoline Direct Injection Vehicles between CVS and Tailpipe Samplings

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ABSTRACT: In order to investigate the difference of SPN emission from G-DI vehicles, which is caused by sampling locations, ninety-six tests were conducted at three vehicle benches with each two particle counters; the one was deployed at a CVS tunnel in compliance with UNECE Regulation 83 whereas the other was equipped at tailpipe with a pitot-type exhaust flow meter considered as a practice for RDE frontloading developments. As a result, the differences of all tests were within ± 30%. This was attributed to internal particle processes as well as misalignment of signals between particle number concentration and exhaust flow rate.

KEY WORDS: environment, emissions, solid particle number, gasoline direct injection engines (D2)

1. Introduction
Air pollution is the fifth leading risk factor for mortality worldwide [1]. Particles with diameters below 0.1 μm (ultrafine particles) originating from vehicular traffic contribute significantly to ambient particulate concentrations [2] and have been associated with various adverse inflammatory and cardiovascular changes [3]. The European Union has therefore imposed regulatory limits on the Solid Particle Number (SPN) emissions of light-duty (LD) Diesel and Gasoline Direct Injection (G-DI) vehicles since 2011 (Euro 5b) [4] and 2014 (Euro 6) [5], respectively. An SPN emission limit of $6 \times 10^{11}$ particles/km has been applied to these vehicles, and compliance with this limit is tested under laboratory conditions by diluting the vehicle’s exhaust using a Constant Volume Sampler (CVS) system [6] while driving the vehicle on a bench under the speed-load conditions of the Worldwide harmonized Light vehicles Test Cycle (WLTC), which replaced the New European Driving Cycle (NEDC) [7].

The methodology for sampling and measuring the SPN emissions of LD vehicles is being developed based on the recommendations of the Particle Measurement Programme group [8] under the umbrella of the United Nations Economic Commission for Europe (UNECE). Sampling is performed from the CVS tunnel using a (recommended) hat probe, an isokinetic probe, or a cyclonic separator. The SPN measurement instrument (particle counter) consists of a two-stage dilution system featuring a so-called Volatile Particle Remover (VPR) followed by a Condensation Particle Counter (CPC) with 50% detection efficiency at a particle diameter of 23 nm. The VPR consists of a primary dilution system (heated to $> 150 \, ^\circ C$), an Evaporation Tube (ET) (heated to 300–400 °C), and a recommended secondary dilution system. The ET vaporizes volatile particles and the remaining solid particles are further diluted by the secondary dilution system. Finally, the particle concentration is measured by the CPC, whose accuracy is highest when operated in single-particle counting mode.

In 2017, the LD vehicle type approval procedure was updated and Real Driving Emission (RDE) testing procedures [9] were introduced to complement laboratory tests. In RDE tests, the
vehicle’s SPN emissions are measured using an on-board Portable Emissions Measurement System (PEMS) that samples the undiluted exhaust from a tailpipe line. Emission measurements obtained in this way may differ from those obtained during laboratory tests involving sampling diluted exhaust from the CVS tunnel because of particle losses in the exhaust transfer line upstream of the CVS tunnel and internal particle processes (e.g., agglomeration) that may reduce the apparent particle concentration [10, 11]. Other potential sources of differences between CVS and PEMS measurements include uncertainties in the measured SPN concentration by PN-PEMS instead of a particle counter, the Exhaust Flow Rate (EFR) determination [12], or misalignment of the corresponding signals during tailpipe measurements. Because of these effects, current regulations specify a Conformity Factor (CF) of 1.5 for SPN emission measurements obtained by PEMS-based RDE testing.

In order to investigate the influence of sampling locations on the SPN emission measurements, which is a part of the uncertainties in RDE testing, this paper compares the SPN emissions of LD vehicles determined by tailpipe sampling to those obtained using a CVS tunnel with two particle counters. The uncertainties caused by the different instruments between particle counter and PN-PEMS is not a scope of this study. G-DI vehicles are tested with and without a Gasoline Particulate Filter (GPF), mainly over the WLTC. The differences between the abovementioned sampling strategies are discussed and analyzed in detail.

2. Challenges of exhaust sampling for SPN emission measurement

Exhaust sampling for measurement of particle emissions is challenging because the choice of sampling method influences the final results. This is due to internal particle formation and destruction processes as well as particle losses when exhaust gas is sampled at the CVS tunnel or the tailpipe. This section highlights some factors that may contribute to differences between particle emission measurements obtained using different methods and useful hints for minimizing their impact.

2.1. Sampling SPN emissions from a CVS tunnel

When exhaust is transferred from the tailpipe to the CVS tunnel, some coagulation and agglomeration of particles will occur in the transfer line, reducing the SPN concentration at the CVS tunnel relative to that at the tailpipe. Theoretical and experimental studies on these coagulation and agglomeration processes revealed that they become important when the SPN concentration exceeds $10^8$ particles/cm$^3$ [10, 11]. Such high concentrations can be encountered in diesel vehicle exhaust without a Diesel Particulate Filter (DPF). For vehicles with a DPF, agglomeration is not expected to cause the SPN concentration in the CVS tunnel to differ markedly from that in the exhaust line. However, appreciable differences may be observed under cold-start conditions when incomplete combustion may give rise to high particle concentrations.

Another important difference between CVS tunnel and tailpipe sampling relates to a Particle Transfer System (PTS). A PTS consists of a sampling probe and a particle transfer tube, and its impact on particle losses is not currently accounted for in a Particle Concentration Reduction Factor (PCRF) of particle counters. To minimize particle losses, UNECE Regulation 83 [6] defines acceptable flow conditions in the PTS based on a Reynolds number and residence time. However, instrument manufacturers are permitted to design PTS that fall outside these specifications if their design can be shown to achieve a particle penetration equivalent to that of a compliant system for a particle diameter of 30 nm. The specifications of all PTS considered in this work are compliant with UNECE Regulation 83. However, there are currently no regulatory requirements applicable to PTS for other sampling methods such as sampling undiluted exhaust from the tailpipe. Therefore, particle losses via the PTS in such systems may lead to underestimation of SPN emissions. For this reason, it is recommended that the PTS should be designed to minimize particle losses irrespective of the exhaust sampling location. This can be achieved by applying suitable design criteria; for example, the PTS should be made from an appropriate material (e.g., stainless steel) and its length should be as short as possible.

Another important aspect of the sampling at the CVS tunnel is the location of the probe itself. UNECE Regulation 83 specifies that the probe shall be installed near the tunnel’s centerline and 10 to 20 tunnel diameters downstream of the exhaust inlet. The probe is oriented towards the upstream direction of the sample gas flow in the tunnel, with its axis at the tip parallel to that of the tunnel. If these conditions are not met, SPN emissions will probably be underestimated because the concentration is lower near the tunnel wall. For this reason, it is strongly recommended that compliance with the requirements mentioned above be demonstrated during PTS installation.

Other particle loss mechanisms such as electrostatic deposition and thermophoretic losses are not usually encountered during sampling at the CVS tunnel because the relevant regulations stipulate the use of conductive materials and insulated tubes for the exhaust transfer line. These factors should however be taken into consideration for sampling at the tailpipe, as discussed in more detail below.
2.2. Sampling SPN emissions from a tailpipe

When sampling undiluted exhaust from the tailpipe, good engineering practices should be implemented to minimize particle losses and other undesirable effects. Guidance on such practices has been published [10].

A hat probe is recommended when sampling undiluted exhaust from the tailpipe because it protects the device from coarse particles that may adversely affect the particle counter’s dilution system and the accuracy of the SPN measurement [13]. The hat probe also prevents contamination of condensed water in the exhaust and stagnated one in the pipe.

Alternatively, a multi-hole probe can be used when sampling the engine-out exhaust or upstream of an exhaust aftertreatment system where the exhaust flows asymmetrically along the cross-section of the pipe due to its bends or complex geometry (e.g. downstream of an exhaust manifold or a turbocharger). Such complexity may give rise to spatially inhomogeneous particle concentration distributions across the cross-section of the exhaust pipe at the sampling site, giving rise to non-representative results [14]. However, a multi-hole probe cannot protect the device from coarse particles. The use of such probes is also not recommended for tailpipe sampling because they may lead to the sampling of stagnant water, especially if the probe is installed in a horizontal or vertical direction. A multi-hole probe should thus not be used in the tailpipe where the exhaust flow is usually uniform across the pipe’s cross-section.

The PTS contains a probe and serves to transfer the exhaust to the particle counter. It is recommended that it be made from stainless steel to avoid electrostatic particle deposition, and that it be as short as possible (no longer than 1 meter). It should also be actively heated to avoid water condensation and minimize thermophoretic particle losses caused by the temperature gradient between the exhaust and the PTS wall. A wall temperature of 150 °C is enough to minimize thermophoretic losses in the PTS and ensure an acceptable sample gas temperature in the primary dilution system (e.g. < 200 °C) [10].

When many different devices are used to sample the exhaust from the tailpipe, separate probes should be used for each device. An appropriate spacing of the probes should be maintained; each probe should be separated from its nearest neighbors by at least 3 internal pipe diameters. It is recommended that devices requiring higher sampling flow rates be installed downstream of the others. If using two particle counters with the same optimal sampling flow rate, a common probe with a Y splitter upstream of each (identical) PTS should be used.

3. Experimental

3.1. Setup and instrumentation

UNECE Regulation 83 specifies procedures for the sampling, dilution, and measurement of SPN emissions from light-duty vehicles using a CVS system [6]. In this study, tests were conducted on three different vehicle benches equipped with CVS tunnels. In order to investigate the influence of sampling locations on the SPN emission measurements and the validity of the direct SPN measurements at tailpipe as a practice of RDE frontloading developments, two particle counters based on a CPC technology, which had been calibrated in accordance with UNECE Regulation 83 and provided by different manufacturers, were used at each bench: a Horiba Solid Particle Counting System (SPCS) (model: MEXA-2000SPCS [15]) was deployed in the CVS tunnel, and an AVL Particle Counter (APC) (model: APC 489 [16]) was installed at the tailpipe. Because they were calibrated in accordance with UNECE Regulation 83, the differences of up to 10% caused by the particle counters themselves can be assumed [16]. When it comes to RDE testing, a PN-PEMS shall be used to measure the SPN emissions at tailpipe instead of a particle counter. In this case, the difference caused by the devices can be larger because of the different calibration methodology. The diluted exhaust was transferred from the CVS tunnel to the SPCS using a PTS consisting of a probe and a 4-meter transfer tube (heated to 47 °C) as well as a cyclonic separator. Simultaneously, SPN emissions were measured at the tailpipe with the APC using a hat probe and a PTS consisting of a 1-meter stainless steel transfer tube heated to 150 °C (no additional diluter, so-called pre-diluter, was used). The difference between the SPN emissions measured at the CVS and the tailpipe was calculated, using the CVS measurement as a reference value because it is the method specified for SPN emission measurements under UNECE Regulation 83.

Both particle counters were built and calibrated in accordance with the requirements of UNECE Regulation 83 [6], which stipulates the inclusion of a VPR and a CPC. The VPR consists of a heated primary dilution system (SPCS: 190 °C; APC: 150 °C), an ET (heated to 350 °C for both SPCS and APC to vaporize volatile materials in the exhaust sample), and a secondary dilution system (in which the sample is diluted with ambient temperature air). The PCRFs (a dilution ratio including particle losses expressed as an average of the particle number concentration reduction for monodisperse particles with diameters of 30, 50, and 100 nm) were 180 and 500–1000 for the SPCS mounted in the CVS tunnel and the APC deployed at the tailpipe, respectively. The CPCs of the SPCS and the APC both have counting efficiencies of 50 ± 12 % and > 90 % at particle diameters of 23 nm and 41 nm, respectively.
To determine the EFR, an AVL M.O.V.E Exhaust Flow Meter (model: EFM 495) was mounted at the tailpipe end in conformity with Commission Regulation 2018/1832 [17], which specifies technical requirements for RDE testing. The flow meter measures pressure differentials caused by the exhaust flow in a tube deployed in the exhaust pipe. These pressure differentials are then converted into mass flow rates based on Bernoulli’s principle. Such so-called pitot probes are widely used in industrial applications. The flow sensor was installed at the tailpipe end, positioned such that there was more than 150 mm of straight pipe on either side of it. The sample for SPN measurement was extracted 150 mm downstream of the element, more than 200 mm away from the pipe’s exhaust orifice. The resulting measurement signal and data on the vehicle’s speed were transmitted to the appropriate APC via analog channels. Both EFR and speed signals were logged in real-time with a 10 Hz data rate and aligned with the APC’s particle concentration (also logged at 10 Hz) using the APC’s Device Control Software. A schematic depiction of the experimental setup is shown in Fig. 1.

The corresponding SPN emissions based on the tailpipe measurements were calculated by first determining the instantaneous particle number emission rate \( SPN_i \) as the product of the EFR \( Q_{exh} \) and the “instantaneous particle number concentration corrected by a PCRF and a CPC k-factor” \( C_{SPNi} \) normalized at 273.2 K and 101.33 kPa. This product was then divided by the exhaust gas density \( \rho_{exh} = 1.293 \text{ kg/m}^3 \). To correlate the EFR with the particle number concentration, the Pearson coefficients of the two data series were computed within ± 10 s using the AVL CONCERTO post-processing tool. The correlation coefficient for two signals \( x \) and \( y \) is computed as follows:

\[
\text{Corr}(X,Y) = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}
\]

The signals were aligned so as to maximize this coefficient. The total SPN emissions at the tailpipe \( SPN_{TP} \) were calculated by integrating the \( SPN_i \) over the appropriate time interval and then dividing by the corresponding driving distance \( D \) [km]. The equations used to compute \( SPN_{TP} \) were:

\[
SPN_{i} = \frac{C_{SPNi} \cdot Q_{exh,i} \cdot 10^6}{\rho_{exh}}
\]

\[
SPN_{TP} = \frac{\sum_{i=1}^{n} SPN_{i}}{D}
\]

3.3. Vehicles and driving protocols

Over 25 G-DI vehicles were tested. All of them had a three-way catalyst (TWC); some had a GPF and others did not. Their engine displacements ranged from 1.5 to 3.0 l.

The vehicles were tested under various driving protocols including the NEDC, the WLTC, and an RDE cycle. Tab. 1 lists the key characteristics of the test cycles and the ambient temperature conditions for each test.

| Duration [s] | NEDC | WLTC | RDE |
|--------------|------|------|-----|
| 1180         | 1800 | 6500 |

| Distance [km] | NEDC | WLTC | RDE |
|---------------|------|------|-----|
| 10.9          | 23.3 | 87   |

| Average speed [km/h] | NEDC | WLTC | RDE |
|----------------------|------|------|-----|
| 33.3                 | 46.6 | 48.2 |

| Ambient temperature [°C] | NEDC | WLTC | RDE |
|--------------------------|------|------|-----|
| 25                       | 25   | 0    |

The vehicles were soaked for at least 12 hours before each test to enable observation of their cold-start behavior.
4. Results and discussion

In total, 96 tests were conducted. An overview of the test configurations including the driving protocols and exhaust aftertreatment systems used in each case is given in Tab. 2.

Tab. 2 Numbers of tests conducted using different test configurations and the corresponding ranges of the deviations of $\text{SPN}_{\text{TP}}$ from $\text{SPN}_{\text{CVS}}$.

| Test configuration | Number of tests | Deviation range of the $\text{SPN}_{\text{TP}}$ from the $\text{SPN}_{\text{CVS}}$ [%] |
|--------------------|----------------|----------------------------------------------------------------------------------|
|                    |                | min | Max | average |
| WLTC GPF           | 74             | -23.4 | 27.7 | -0.6   |
| WLTC without GPF   | 12             | -24.5 | 29.2 | -3.1   |
| NEDC               | 4              | -12.1 | 12.7 | -2.2   |
| RDE                | 6              | -19.3 | 16.4 | -7.3   |
| Total              | 96             | -24.5 | 29.2 | -1.4   |

Fig. 2 shows a plot of $\text{SPN}_{\text{CVS}}$ [particles/km] against $\text{SPN}_{\text{TP}}$ [particles/km] for several different tested configurations. The dashed lines in this figure show the Euro 6 SPN emission limit for G-DI LD vehicles based on $\text{SPN}_{\text{CVS}}$ and the corresponding limit for $\text{SPN}_{\text{TP}}$ for comparative purposes (although no such limit is specified in the Euro 6 regulations). The measured SPN emissions varied over three orders of magnitude, ranging from $4.7 \times 10^9$ particles/km to $2.2 \times 10^{12}$ particles/km. Not all the test results were below the SPN Euro 6 limit of $6 \times 10^{11}$ particles/km even though the vehicles were equipped with GPFs. This could be because the GPF was in a state associated with low filtration efficiency, which is often the case for new filters without accumulated soot. The vehicle’s state including the engine’s calibration and mileage may also affect emissions. Further investigation of these results is outside the scope of this paper.

The measured $\text{SPN}_{\text{CVS}}$ results deviated by less than $\pm 30\%$ from the corresponding $\text{SPN}_{\text{CVS}}$. The deviation appears to be independent of the absolute magnitude of the SPN emissions because there is no apparent trend in the data despite the fact that the $\text{SPN}_{\text{CVS}}$ values vary over three orders of magnitude (from around $10^9$ to $10^{12}$ particles/km).

Fig. 3 shows a plot of the $\text{SPN}_{\text{CVS}}$ [particles/km] (on a logarithmic scale) against the deviation of the $\text{SPN}_{\text{TP}}$ from the $\text{SPN}_{\text{CVS}}$ (expressed as a percentage of the $\text{SPN}_{\text{CVS}}$) for the tested configurations. The dashed line indicates the Euro 6 SPN emission limit for G-DI LD vehicles over the NEDC and WLTC. All of the $\text{SPN}_{\text{TP}}$ results deviated by less than $\pm 30\%$ from the corresponding $\text{SPN}_{\text{CVS}}$. The deviation appears to be independent of the absolute magnitude of the SPN emissions because there is no apparent trend in the data despite the fact that the $\text{SPN}_{\text{CVS}}$ values vary over three orders of magnitude (from around $10^9$ to $10^{12}$ particles/km).

The gray, green, and purple solid lines denote deviations of $0\%$, $\pm 30\%$, and $\pm 50\%$ of $\text{SPN}_{\text{TP}}$ from $\text{SPN}_{\text{CVS}}$, respectively.
Fig. 4 shows data from a WLTC test using a vehicle with a new GPF in which soot was not accumulated, which is considered as one of the examples shown as a green triangle in Fig. 3. The cumulative SPN emissions were calculated over the cycle and were found to increase substantially during the cycle’s first 300 s due to the cold-start conditions. It could be caused by inadequate air-fuel mixing and subsequent incomplete combustion [18] as well as the low filtration efficiency of the GPF. After this period, SPN emissions increased linearly until the end of the cycle. Overall, the SPN$_{TP}$ was 27% higher than the SPN$_{CVS}$. The final difference over the cycle was dominated by the cold-start period, where the high particle concentration may have caused the coagulation and agglomeration of particles in the transfer tube between the vehicle tailpipe and the CVS tunnel.

![Fig. 4 Cumulative SPN$_{TP}$ and SPN$_{CVS}$ emissions over the WLTC for a vehicle equipped with a new GPF in which soot was not accumulated.](image)

These results are in good agreement with previous studies: a recent publication [19] reported that the differences between SPN$_{TP}$ and SPN$_{CVS}$ were as high as +20% for gasoline vehicles with different injection technologies and different fuels (e.g., compressed natural gas). When a diesel vehicle equipped with a DPF was tested, the deviation was -10%. The negative deviation was attributed to low absolute emissions (which were close to the detection limit of $\sim 2 \times 10^9$ particles/km). An investigation focusing on the cold start period of the driving cycle (i.e., the first 300 s) revealed greater differences (up to +35%), which could be due to particle coagulation and agglomeration in the exhaust transfer tube between the vehicle and the CVS tunnel. Larger differences were observed for sub-23 nm SPN emissions ($\pm 45\%$). This indicates that the tailpipe SPN emission measurement method should be investigated further to evaluate its accuracy when used to measure sub-23 nm SPN emissions [20].

Tailpipe measurements of SPN emissions using a PEMS have been reported to differ from results obtained using reference laboratory particle counters installed in a CVS tunnel by around 50% [21]. On this basis, a CF of 1.5 has been suggested to account for the effects of the different sampling locations and instrument specifications used in the two methods. The results presented herein imply that the impact of changing the sampling location may be even greater than previously thought, by as much as $\pm 30\%$ when compared to previous reports.

Additional experiments were conducted to determine how misalignment of signals between the EFR and the particle number concentration affected the deviation between the SPN$_{TP}$ and the SPN$_{CVS}$. A misalignment of 5 s was found to increase the deviation of the final SPN$_{TP}$ value by around 5%. No such increase is observed for the corresponding SPN$_{CVS}$ values because when computing SPN$_{CVS}$ the measured particle number concentration is multiplied by the constant volume flow rate of the CVS system.

### 5. Conclusion

Ninety-six tests were conducted to determine how the measured SPN emissions of G-DI vehicles are affected by sampling the exhaust from the tailpipe compared to via a CVS tunnel. All the tested G-DI vehicles were fitted with a TWC, with or without a GPF. Tests were conducted using three different test benches equipped with a CVS system and two particle counters. SPN emissions were simultaneously measured by sampling the exhaust from the CVS tunnel in accordance with UNECE Regulation 83 (SPN$_{CVS}$) and from the tailpipe (SPN$_{TP}$). The differences between the SPN$_{TP}$ values and the corresponding SPN$_{CVS}$ values were as high as $\pm 30\%$. These differences were attributed to the following factors:

- **Particle losses due to coagulation and agglomeration of particles in the transfer tube between the tailpipe and the CVS tunnel.** This effect was seen when particle number concentrations exceeded $10^8$ particles/cm$^3$ and may cause underestimation of the SPN emissions when using the CVS method, especially during cold starts when the particle concentration is high.
- **Misalignment of particle number concentration signals with the EFR, which may cause deviations of up to 5%.** Based on these results, it is recommended that the PTS for tailpipe sampling be made from stainless steel to avoid electrostatic particle deposition. The PTS should also be as short as possible and actively heated to minimize diffusional and thermophoretic particle losses, respectively. Further studies on the measurement uncertainty of particle counters and EFMs are needed to fully explain the entire differences observed in this work.
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ABBREVIATIONS
APC AVL Particle Counter  
CF Conformity Factor  
CPC Condensation Particle Counter  
CVS Constant Volume Sampling  
DPF Diesel Particulate Filter  
EFM Exhaust Flow Meter  
EFR Exhaust Flow Rate  
ET Evaporation Tube  
G-DI Gasoline Direct Injection  
GPF Gasoline Particulate Filter  
LD Light Duty  
NEDC New European Driving Cycle  
PCRF Particle Concentration Reduction Factor  
PEMS Portable Emission Measurement Systems  
PTS Particle Transfer System  
RDE Real Driving Emissions  
SPCS Solid Particle Counting System  
SPN Solid Particle Number  
TWC Three Way Catalyst  
UNECE United Nations Economic Commissions for Europe  
VPR Volatile Particle Remover  
WLTC Worldwide Harmonized Light Duty Test Cycle
REFERENCES

(1) State of Global Air 2019, Special Report, Boston, MA, Health Effect Institute, 2019, https://www.stateofglobalair.org/sites/default/files/soga_2019_report.pdf

(2) Pant P., Harrison R.: Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review, Atmospheric Environment 77, p.78-97, (2013).

(3) Ohlwein S. et al.: Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence, International Journal of Public Health 64, p.547-559, (2019).

(4) Commissions Regulation (EC) No 699/2008 of 18 July 2008, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R0692&from=EN

(5) Commissions Regulation (EU) No 459/2012 of 7 May 2012, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0459&from=EN

(6) Regulation No. 83, Revision 5, “Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements” United Nations, 02/2015, http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29reg/R083r5e.pdf

(7) Commissions Regulation (EU) 2017/1151 of 1 June 2017, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1151&from=EN

(8) Giechaskiel B. et al.: Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review, Aerosol Science and Technology, 46, p.719-749, (2012).

(9) Commissions Regulation (EU) No 1154/2017 of 7 June 2017, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1154&from=EN

(10) Giechaskiel B. et al.: Sampling of Non-Volatile Vehicle Exhaust Particles: A Simplified Guide, SAE Int. J. Engines 5(2), p.:379-399, (2012).

(11) Isella L. et al.: Diesel-exhaust aerosol dynamics from the tailpipe to the dilution tunnel, Journal of Aerosol Science 39(9), p.737-758, (2008).

(12) Giechaskiel B. et al.: Framework for the assessment of PEMS (Portable Emissions Measurement Systems) uncertainty, Environmental Research, 166, p.251-260 (2018).

(13) Ntziachristos L. et al.: Comparative Assessment of Two Different Sampling Systems for Particle Emissions Type-Approval Measurements, SAE paper 2005-01-0198, (2005).

(14) Vincent J. H.: Aerosol Sampling. Science, Standards, Instrumentation and Applications. Willey, (2007).

(15) Wei Q. et al.: Real-Time Measuring System for Engine Exhaust Solid Particle Number Emission - Design and Performance, SAE Technical Paper 2006-01-0864, (2006).

(16) Giechaskiel B., et al.: Calibration and accuracy of a particle number measurement system, Meas. Sci. Technol. 21(4), 045102 (13pp), (2010).

(17) Commission Regulation (EU) 2018/1832 of 5 November 2018, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1832&from=GA

(18) Whitaker P., et al.: Measures to Reduce Particulate Emissions from Gasoline DI engines, SAE Int. J. Engines 4(1), p.1498-1512, (2011).

(19) Giechaskiel B. et al.: Regulating particle number measurements from the tailpipe of light-duty vehicles: The next step?, Environmental Research, 172, p.1-9 (2019).

(20) Nakamura K., et al.: Instrumentation Challenges for Measuring Sub-23 nm Particle Number Emissions from Transportation Sources, International Journal of Automotive Engineering 10(2), p.205-212, (2019).

(21) Giechaskiel B. et al.: Solid Particle Number (SPN) Portable Emissions Measurement Systems (PEMS) in the European Legislation: A Review, Int. J. Environ. Res. Public Health, 16(23), 4819, (2019).