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Particle number measurements in the European legislation and future JRC activities

The solid particle number method was introduced in the European Union (EU) light-duty legislation for diesel vehicles to ensure the installation of the best-available technology for particles (i.e., wall-flow diesel particulate filters) without the uncertainties of the volatile nucleation mode and without the need of large investment for purchasing the equipment. Later it was extended to gasoline vehicles with direct injection engines, heavy-duty engines (both compression ignition and positive ignitions) and non-road mobile machinery engines. Real Driving Emissions (RDE) testing on the road with Portable Emissions Measurement Systems (PEMS) for particle number (and NO_x) during type approval and in-service conformity testing was recently (in 2017) introduced for light-duty vehicles, and is under discussion for heavy-duty vehicles in-service conformity testing.

This paper will summarize the existing legislation regarding solid particle number and discuss the on-going activities at EU level. The main focus at the moment is on improving the calibration procedures, and extending the lower detection size below 23 nm with inter-laboratory exercises. In parallel, discussions are on-going to introduce testing at low ambient temperature, regeneration emissions in the light-duty regulation, a particle limit for other technologies such as gasoline port-fuel injection vehicles, and the feasibility of particle measurements to L-category vehicles (mopeds, motorcycles, tricycles and minicars). A short overview of periodical technical inspection investigations and the situation regarding non-exhaust traffic related sources with special focus on brakes and tyres will be described.

Key words: vehicle emissions regulation, particle measurement programme (PMP), portable emission measurement systems (PEMS), real driving emissions (RDE), periodical technical inspection, particle number, sub-23 nm

1. Introduction

Ultrafine particles (smaller than 0.1 μm) have been associated with adverse health effects and act through mechanisms not shared with larger particles [1]. Road traffic contributes significantly to Particle Number (PN) concentrations and can reach 90% in busy roads [2].

At the beginning of the 90's the Particulate Matter (PM) emissions were regulated for light-duty vehicles in the European Union (EU) by weighing the mass collected on filters before and after a prescribed test cycle (speed profile). However, since early 2000, the gravimetric method was not sensitive enough to accurately determine the PM emissions of vehicles equipped with Diesel Particulate Filter (DPF). The possibility to develop a more sensitive and accurate methodology that would replace or complement the regulated gravimetric procedure, requiring low investment costs, was the objective of the Particle Measurement Program (PMP). The final decided method was based upon counting solid (non-volatile) particles larger than 23 nm [3]. A minimum diameter of 23 nm size was selected in order to include the smallest soot particles and exclude volatile nucleation mode particles. Volatile particles were excluded in order to improve the repeatability and reproducibility of the method to levels acceptable for legislative purposes [4]. The PMP working group had no medical expertise and did not seek to pre-judge the advice from medical experts with respect to the most crucial particle characteristics affecting human health. The new method was introduced to ensure the installation of the best-available technology for particles (i.e., wall-flow DPFs) without the uncertainties of the volatile nucleation mode

and without the need of large investment for purchasing the equipment. Furthermore, the particle counting method did not replace but rather complemented the gravimetric procedure that is still in force.

The PMP group activities stopped at the end of 2011 with the introduction of the Solid Particle Number > 23 nm (SPN23) method in the light-duty and heavy-duty European regulations. In 2013 EU and Switzerland requested further investigation of particle number emissions from spark ignition engines. There were also concerns regarding the existence of sub-23 nm particles. The new Terms of Reference included the following topics [5]:

- Engine dyno raw exhaust SPN measurements for heavy-duty at type approval
- Emissions during regeneration events
- Emissions from Gasoline Direct Injection (GDI) vehicles
- Development of SPN equipment to measure below 23 nm
- Calibration procedures update (and if necessary for lower size)
- Non-exhaust particle emissions

The EU vehicle emissions legislation is the only one that controls SPN23 emissions, with the exception of the recently introduced China 5&6 limits. Since the introduction of the first SPN limit in 2011 (Euro 5b) for diesel vehicles the progress has been very fast. The first review on the SPN23 regulation in 2012 summarized the PMP activities until the introduction of the SPN23 limits in the light-duty and heavy-duty emissions regulations [4]. A later review summarised the European SPN23 legislations [6]. Other reviews summarised the instrumentation typically used for particle measurements [7, 8].

Table 1. Overview of European regulations regarding PM and SPN23 for light-duty, heavy-duty, NRMM and L-category vehicles. Status 2018

	Regulation	Cycle	PM [mg/km or mg/kWh]	SPN23 [p/km or p/kWh]
Light-duty (Euro 6)				
Type approval	2017/1151 2017/1154	WLTC On-road (RDE)	4.5	6×10^{11} CF = 1.5
ISC	To be adopted end 2018	WLTC On-road (RDE)	–	6×10^{11} CF = 1.5
Heavy-duty (Euro VI)				
Type approval	582/2011	WHTC WHSC	10 10	6×10^{11} 8×10^{11}
ISC		On-road	–	CF = 1.63 (tbc)
NRMM (Stage V)				
Type approval	2017/654 2016/1628	NRTC NRSC	15	1×10^{12}
ISC (monitoring)			–	–
L-category (Euro 5 from 2020)				
Type approval	2013/168	WMTC	4.5 (diesel/GDI)	–

However, since these reviews, and especially in 2017, many changes took place. The objective of this paper is to briefly update on the current status and near future activities regarding the SPN regulation. The focus is the EU legislation and in particular activities of the Joint Research Centre (JRC) of the European Commission.

2. SPN23 legislation in EU

An overview of current regulations regarding SPN23 emissions is given below and presented in Table 1.

2.1. EU and UNECE

In the framework of the United Nations' Economic Commission for Europe (UNECE) in Geneva, WP.29 (World Forum for Harmonization of Vehicle Regulations) and its subsidiary bodies are developing the Regulations under the 1958 Agreement in cooperation with all Contracting Parties to the Agreement and non-governmental organizations (NGOs). United Nations (UN) Regulations are not applicable on a mandatory basis, but if a Contracting Party decides to apply a UN Regulation, the adoption becomes a binding act.

The WP.29 and the European Commission are currently working on the harmonization between UN Regulations and EU Directives or Regulations. Currently, some of the EU Directives or Regulations are technically equivalent to UN Regulations or only refer to the requirements of the corresponding UN Regulation.

The UN Global Technical Regulations (GTRs) are the technical regulations being established under the 1998 Agreement and do not refer to a type approval or certification procedure as mentioned in the EU Directives or UN Regulations. The main reason is that the process of self-certification used in the United States is incompatible with the type approval. The UN Regulations are considered candidates for the elaboration of UN GTRs.

2.2. Light-duty vehicles

The EU emissions regulation requires, in addition to PM mass, the measurement of Solid Particle Number > 23 nm (SPN23) for type approval of diesel light-duty vehicles since 2011 (Euro 5b) (Regulation 692/2008) (limit 6×10^{11} p/km), and for Gasoline Direct Injection (GDI) light-duty vehicles since 2014 (Euro 6) (Regulation 459/2012) (limit 6×10^{12} p/km and 6×10^{11} p/km after 2017). Regulation 2017/1151 repealed Regulation 692/2008 and introduced

a new test cycle (WLTC). In addition, Real Driving Emissions (RDE) testing on the road with Portable Emissions Measurement Systems (PEMS) for SPN23 and NO_x during type approval (Regulation 2016/427) and in-service conformity testing (RDE 4th package) were introduced in 2017, where: from 2017 (Euro 6d Temp) a CF of 1.5 for SPN23 (Regulation 2017/1154) and 2.1 (Regulation 2016/646) for NO_x applies and from 2020 the CF of NO_x will be reduced to 1.5 (Euro 6d). The CFs are under annual revision. The first 2017 revision decreased the NO_x CF to 1.43 [9]. The test procedure and the test cycle are described in 2017/1151, of which Annex XXI is basically UNECE GTR No. 15.

2.3. Heavy-duty engines/vehicles

The type approval of an engine is conducted on an engine dynamometer with a cold start and a hot start transient cycle and a steady cycle. The SPN23 limit for heavy-duty engines was introduced in 2013 (Euro VI) for compression ignition (diesel) engines (Regulation 582/2011) and in 2014 for positive ignition engines (Regulation 133/2014). The limit is 6×10^{11} p/kWh for the transient cycle (weighing 14% the cold start cycle and 86% the hot start cycle) and 8×10^{11} p/kWh for the steady cycle. The SPN23 measurement procedure (Regulation 64/2012, UNECE Regulation 49) is almost identical to the light-duty vehicles procedure. The relevant GTR is UNECE GTR No. 4.

Since Euro VI the in-service conformity (ISC) testing of a heavy-duty engine is conducted on the road over normal driving patterns, conditions and payloads using PEMS (Regulation 582/2011). The testing is conducted over a mix of urban (50 km/h), rural, and motorway (highway) (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category (Regulation 2016/1718). The first in-use test should be conducted at the time of type approval testing and the result should be lower than the Euro VI limit corrected with a conformity factor (1.5 for gaseous pollutants) that takes into account the PEMS measurement uncertainty and the test-to-test variability. The PEMS testing is currently applicable only to gaseous pollutants. After a long evaluation of the PM mass method with PEMS [10], in 2015 it was decided to evaluate the SPN23 method. The evaluations at JRC [11] and OEMs [12] were promising and the ISC SPN23 PEMS method will be introduced in the next years.

2.4. Non-Road Mobile Machinery (NRMM)

Regulation 2016/1628 repealed Directive 97/68/EC in 2016 and introduced SPN23 limits to non-road engines (19–560 kW), inland waterway vessels (> 300 kW), and rail traction engines in 2017. The procedures and test cycles (NRSC and NRTC) are described in Regulation 2017/654. The 05 series of amendments updates UNECE Regulation No. 96, based on the European regulation. The relevant GTR is GTR No. 11.

In service monitoring (no conformity factor) is applicable to 56–560 kW engines (Regulation 2017/655) with PEMS, but only for gaseous pollutants. A near future amendment will include 19–56 kW engines and above 560 kW, while < 19 kW engines are currently under a feasibility study by JRC.

In addition to the type approval SPN23 limits, Swiss Regulation SR 941.242 (published in 2015) mandates the in-use compliance testing of all construction machinery DPFs, bi-annually starting from 2017 (SPN23 limit 250 000 p/cm³ at high idle).

2.5. L-category vehicles

Regulation (EU) 168/2013 provides the details of a revised vehicle classification together with the provisions for approval and market surveillance of L-category vehicles at Euro 4 (from 2016) and Euro 5 levels (from 2020). PM measurements were introduced at Euro 4 level with a lenient limit of 80 mg/km required for compression ignition (diesel) and gasoline direct injection (GDI) engines mounted on motorcycles, tricycles and minicars. A more stringent limit value of 4.5 mg/km is set at Euro 5 level for all sub-categories with GDI and compression ignition engines. No provisions on SPN23 were introduced. UNECE Regulation No. 40 (motorcycles) and UNECE Regulation No. 47 (mopeds) are outdated. The current GTR No. 2 does not contain SPN23 provisions either, but only PM and it is under revision by the relevant group within the UNECE (GRPE).

Article 23 of the Regulation 168/2013, mandated an environmental effect study to provide additional underpinning of the Euro 5 step through modelling, technical feasibility, and cost effectiveness analysis. JRC performed a Preparatory work phase [13] and Phase 1 [14] of this environmental effect study with the objectives to take stock of fleet and structure of the L-category vehicle sector, perform relevant data-mining, and to prepare the technical approach. The preparatory work showed that L-category vehicles can have high SPN emissions with a high percentage of them not counted by the current SPN23 protocol. However, it was argued that decreasing the lower detectable size could result in artefacts and more research was therefore considered necessary [15].

The final environmental study [16] concluded that introducing specific SPN23 limits for any L-category vehicles would first require better understanding of the emissions performance of such vehicles, as new emission control technologies at Euro 5 step become available. SPN emissions from L-category vehicles are mostly linked to lube oil consumption and upcoming stringent hydrocarbons limits at Euro 5 may be proven effective to control SPN emissions from such vehicles as well, without the need of mandating a separate SPN standard [16].

2.6. Other

Periodic Technical Inspection (PTI): Directive 2014/45/EU repealed Directive 2009/40/EC and includes only smoke (opacity) test for diesel vehicles. In general, there is no correlation between PM/PN emissions and smoke.

On-Board Diagnostics (OBD): There is only a PM limit for OBD (12 mg/km for light-duty vehicles and 25 mg/km for heavy-duty). NRMM do not have OBD requirements.

Low (ambient) temperature test (Type 6): Regulation 2017/1151 refers to UNECE Regulation 83. There is no PM or SPN limit.

3. PMP current activities

The following sections will summarise the progress on the topics that PMP deals with. Most topics relate to light-duty and heavy-duty vehicles. Nevertheless they are applicable to other vehicle categories as well.

3.1. Volatile Particle Remover (VPR) calibration

SPN23 systems consist of a Volatile Particle Remover (VPR), that dilutes the sample and removes volatiles, and a Condensation Particle Counter (CPC) that counts particles > 23 nm [4]. There are some concerns with respect to the accuracy of the instrument calibrations, and accordingly the comparability of results obtained using different commercial systems. A VPR inter-laboratory correlation study was launched in 2011 aiming at the assessment of the different VPR calibration procedures established by the different manufacturers. The “golden” VPR was a prototype two stage ejector system with an intermediate evaporation tube. The “golden” Aerosol Generator was a graphite spark generator. The “golden” instrumentation also included a CPC [17].

The average Particle Number Concentration Reduction Factor (PCRF) at 30, 50 and 100 nm values determined at eight of the total eleven laboratories using the golden instrumentation agreed within $\pm 5\%$, but three laboratories measured systematically higher values (10%, 20% and 40%, respectively) (Fig. 1). This overestimation was most probably related to a backpressure build-up at the exit of the second ejector, as verified in the lab with the highest overestimation.

The graphite particles produced from the Golden aerosol generator were found to be thermally stable. However, they were highly charged and when not neutralized, the size classified particles contained a large fraction of larger particles. On the other hand, thermally treated 30 nm particles of diffusion flame soot generators CAST (Combustion Aerosol Standard) still shrunk in the VPRs. It was recommended that a low cut-off size CPC is employed when CAST or NaCl particles are employed in PCRF calibrations.

The inter-laboratory exercise also showed that an accurate calibration of the VPR with polydisperse aerosol (using SMPS) was difficult and required that the concentration was at levels that would freeze coagulation.

At PMP meetings the VPR calibration topics were discussed and the following conclusions were taken in order to reduce the permitted flexibilities [18]:

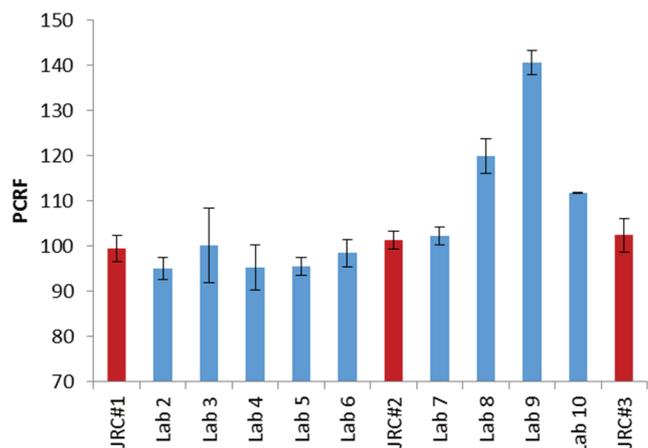


Fig. 1. Average Particle number Concentration Reduction Factors (PCRf) at 30, 50 and 100 nm graphite particles with the Golden aerosol generator and the Golden CPC at different laboratories [17]

- The reference CPC should have counting efficiency at 23 nm > 90%. It should be also calibrated for linearity.
- When the two CPCs method is used for calibration of VPRs, the two CPCs should be inter-calibrated.
- The stability of the aerosol during the VPR calibration should be improved from 10% to 5%.
- For the polydisperse validation a Count Median Diameter (CMD) and a Geometric Standard Deviation (GSD) should be defined. At the moment the suggestion is 45–55 nm and 1.6–1.8.
- The tetracontane requirements are easy to pass and a polydisperse test should be added: 1 mg/m³ of alkane or emery oil is the suggestion.

3.2. CPC calibration

The legislation does not define a calibration aerosol for CPCs and studies have shown that it has an influence on the counting efficiencies [19]. An inter-laboratory calibration exercise for engine exhaust CPCs was launched in 2016 to assess the repeatability and reproducibility of soot-like aerosols. During this exercise, three CPCs and one soot generator were circulated among 7 laboratories in Europe. The circulated instruments were compared with in-house reference counters and in-house spark-discharge soot, diffusion flame soot, silver nucleation and emery oil generators [21].

Figure 2 summarises the results. At the plateau region there was no significant difference between aerosols. At 70 nm the CPC efficiency was 2–3% below its maximum counting efficiency with soot-like aerosol, while with emery oil even at 55 nm the efficiency was maximum. At 23 nm the soot-like aerosol average counting efficiency was between 27.0% and 32.0%, while emery oil averaged 49.3%. At 41 nm the soot efficiencies were between 77.2% and 79.7%, while with emery oil 91.5%. The variance among in-house soot generators was on the same level as emery oil (3.1 percentage points at 55/70 nm) at all particle sizes; however, the variability with emery oil was due to a drift of the CPC. The main conclusion was that soot-like aerosol from diffusion flame and spark-discharge generators is a suitable candidate for the harmonization of particle number calibrations in automotive exhaust applications;

however, there are still concerns whether it can reach the same levels of accuracy as the emery oil.

Interestingly, only half of the laboratories calibrated the circulating 10 nm CPC, indicating that the calibration at that size with soot-like particles is more challenging.

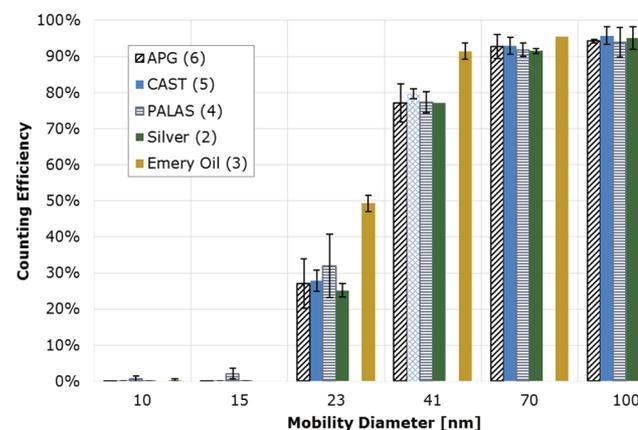


Fig. 2. Calibration results of the golden CPC with various particle generators across Europe. Number in brackets indicates number of laboratories [21]. APG = AVL Particle Generator (thermally stable CAST)

At PMP meetings the CPC calibration topics were discussed and the following conclusions were taken to reduce the permitted flexibilities [18]:

- The reference CPC should be calibrated according to ISO 27891.
- The slope should remain 0.9 to 1.1, but the residuals check should be reduced to $\pm 4\%$ (from the slope).
- The CPC slope calibration k factor should be included (and reported).
- The ISO 27891 should be adopted with application notes when some parts are not applicable.

At the moment the prevalent view is that the calibration material should be soot-like and other materials should be adjusted to soot.

3.3. Regeneration

The emissions during regeneration events are taken into account by weighing the final emissions with the emissions during regeneration events and the regeneration frequency. At the moment this applies to heavy-duty and NRMM, but not to light-duty vehicles. The main reason is that during the PMP investigations and the light-duty inter-laboratory correlation exercise, it was found that the contribution of the regeneration emissions was negligible [21]. However, later studies showed that is not necessarily true for other more aggressive cycles including prolonged operation at motorway driving conditions [22]. The SPN23 emissions during phases with regeneration can exceed many times the Euro 5b PN limit. Subsequently, DPF sizes, filtration characteristics and material options have evolved, and more complex NO_x and PN aftertreatment combinations are being employed. PMP investigated whether these changes require modifications to the regulatory procedure to adequately measure particles from regenerations [23], and whether there are any particular issues not to include regeneration in light-duty legislation.

Figure 3 (upper panel) shows the emissions of a vehicle during a regeneration event, measured with various instruments connected to the dilution tunnel (CVS). The total PN concentration (including volatiles), as measured by an Engine Exhaust Particle Sizer (EEPS) > 6 nm exceed 10^7 p/cm³. The SPN23 concentration is around 10^4 p/cm³, while SPN10 reaches 10^6 p/cm³ at the beginning of the regeneration and stabilises at 10^4 p/cm³ after 10 min. The SPN3 concentration is much higher for the whole regeneration event. It is important to note the robustness of the PMP protocol: The SPN23, SPN10, SPN3 emissions are not affected by a 10 times change of the PCRf (200 to 2000) during the test. Additionally, another system with catalytic stripper and a 10 nm CPC measured similarly with the PMP system and a 10 nm CPC (within experimental uncertainties and particle losses corrections). What is interesting though is that when the test was repeated with some instruments connected to the tailpipe (no instruments available at the CVS), the high sub-23 nm particles were not seen (Fig. 3 lower panel). For this test the accumulated soot/material was less.

The main conclusion is that the PMP methodology is robust enough to measure emissions during regeneration events (note that a PCRf of 1000 is recommended) [24]. The conclusion applies also to 10 nm measurements, although some concerns were raised for formation of “non-volatile” particles due to desorption of material from the vehicle or the tube between the vehicle and the CVS due to the high exhaust gas temperatures. Thus, it is important to properly precondition the vehicle and facilities before regeneration tests, in order to ensure minimum contribution from previous vehicles.

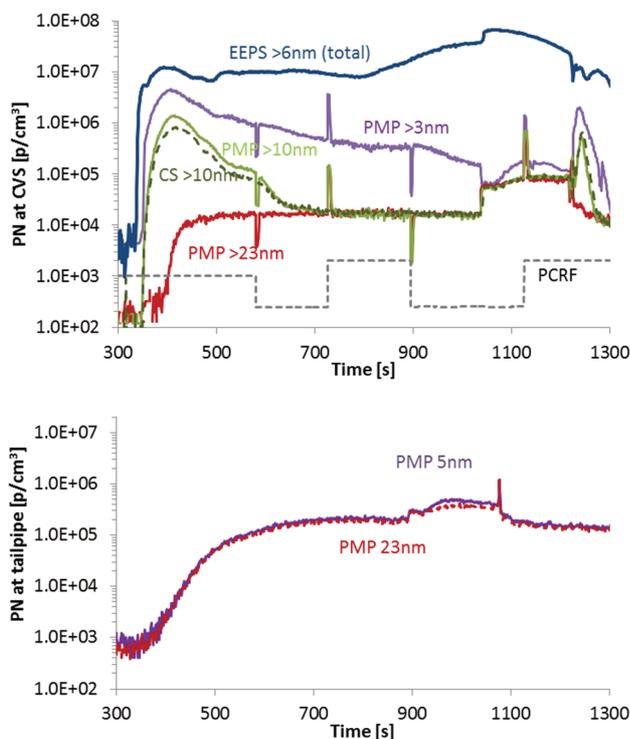


Fig. 3. PN emissions during triggered/forced regeneration with the vehicle parked. Upper panel: Measurements from the CVS. Lower panel: Measurements from the tailpipe (subsequent test) [25]

The emissions during regeneration events are taken into account by the K_i factor ($i = \text{SPN23}$ in this case):

$$M_{pi} = (M_{si} D + M_{ri} d) / (D + d) \quad (1)$$

where: M_{si} are the mean emissions of compound i without regeneration (p/km), M_{ri} are the mean emissions of compound i during regeneration (p/km), M_{pi} are the mean emissions of compound i (p/km), d is the number of complete applicable test cycles required for regeneration, D is the number of complete applicable test cycles between two cycles where regeneration events occur.

$$K_i \text{ (factor)} = M_{pi}/M_{si} \quad (2)$$

$$K_i \text{ (offset)} = M_{pi} - M_{si} \quad (3)$$

The K_i factor is not included in the light-duty regulation and there is no information in the literature about SPN. Table 2 summarises the results of the PMP Golden vehicle [21], presented data [26] and a few more internal JRC data. The followed procedure was not exactly the one prescribed in the regulation (continuous cycles until regeneration). Between regeneration events different cycles were conducted (even on road tests), thus the K_i factors are approximations, but nevertheless realistic. No vehicle exceeds the SPN23 limit even when considering the regeneration events. However, there are vehicles that remain more than one order of magnitude below the SPN23 limit, and others that are close to the limit. The range of the K_i factors (0–91) or offset (0– 4.9×10^{11} p/km) is very wide.

Table 2. Estimation of K_i factors for regeneration [21, 26]. All vehicles equipped with DPF

Vehicle	M_{si} [p/km]	D [km]	M_{ri} [p/km]	D [km]	M_{pi} [p/km]	K_i	K_i offset [p/km]
Euro 4*	1.3×10^{11}	1000	1.3×10^{11}	11.0	1.3×10^{11}	1.0	0
Euro 5	2.0×10^{10}	250	2.0×10^{12}	23.2	1.9×10^{11}	9.4	1.7×10^{11}
Euro 5	2.0×10^{11}	250	1.4×10^{12}	11.0	2.5×10^{11}	1.3	5.1×10^{10}
Euro 6	5.5×10^9	300	6.9×10^{12}	23.2	5.0×10^{11}	91	4.9×10^{11}
Euro 6	2.0×10^{10}	800	2.0×10^{10}	23.2	2.0×10^{10}	1.0	0
Euro 6	1.0×10^{11}	500	4.0×10^{12}	23.2	2.7×10^{11}	2.7	1.7×10^{11}
Euro 6	2.0×10^{10}	450	2.1×10^{11}	11.0	2.5×10^{10}	1.2	4.5×10^9
Euro 6	6.7×10^{10}	450	1.9×10^{12}	23.2	1.6×10^{11}	2.3	9.0×10^{10}
Euro 6	2.7×10^{10}	250	7.9×10^{10}	11.0	2.9×10^{10}	1.1	2.2×10^9

* Golden PMP vehicle provided by AECC

3.4. Sub-23 nm instrumentation

A feasibility study [27] concluded that regulating below 10 nm is not recommended due to extreme particle losses in the commercial systems at the sub-10 nm range and the possibility of artefacts (re-nucleation or pyrolysis). For > 10 nm measurements, a catalytic stripper and/or high dilutions are recommended in order to reduce the possibility for re-nucleation and growth of re-nucleated material. Updating existing systems to measure below 23 nm (e.g. from 10 nm) is possible without big investment costs.

After the JRC feasibility study, preliminary draft technical specifications were based on existing PMP systems with the only additions (still draft) [28]:

- PCRf at 15 nm
- CPC with 50% (or higher) at 10 nm

The main open questions are:

- Should the catalytic stripper be obligatory or not? If yes, what are the minimum technical specifications of the catalytic stripper?
- How to take into account the particle losses below 30 nm? Is an additional PCRF at e.g. 15 nm enough? Should the mean PCRF include the 15 nm point (weighted or not)?

Obviously, in case of lowering the lower detectable size, the material for both PNC and VPR calibration has to be re-investigated and the calibration procedures need to be updated. Additionally, the SPN-PEMS specifications have to be adjusted accordingly.

Figure 4 presents the penetration curves of two commercial systems (one with evaporation tube [29] and the other with catalytic stripper [30]) and the difference between them when measuring particles of different count median diameters (CMD). The difference becomes important (> 10%) when the CMD becomes smaller than 30 nm.

In order to avoid uncertainties for size distributions with low CMD or more complicated approaches like in aviation, the easiest way is to include the 10 nm CPC in addition to the 23 nm CPC. This would increase the investment costs of the OEMs, but has the advantage that the > 23 nm approach could remain and the sub-23 nm information could be used separately (e.g. regulating in addition a maximum sub-23 nm fraction or level). With two CPCs the sub-23 nm concentration can be estimated as follows:

$$(\text{SPN}_{10}-\text{SPN}_{23}) \times \text{PCRF}_{15} / \text{PCRF} \quad (4)$$

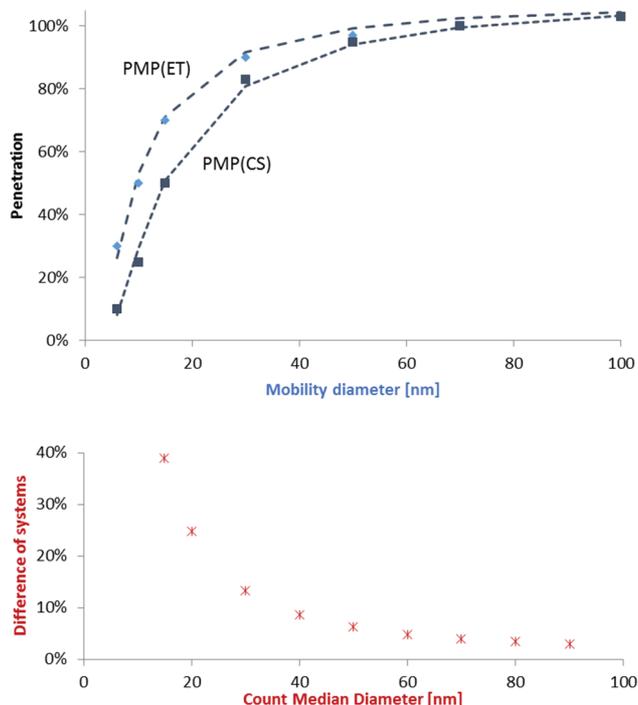


Fig. 4. Upper panel: Counting efficiency in function of monodisperse mobility diameter of two VPRs of PMP systems with Evaporation Tube (ET) [29] or Catalytic stripper (CS) [30] (examples). Lower panel: Difference of the two systems for various polydisperse size distributions with various Count Median Diameters (CMD)

3.5. Sub-23 nm round robin

In order to assess the repeatability and reproducibility of the SPN10 (and SPN23) method an inter-laboratory exercise was organised at the end of 2017. Two golden PMP systems (from different manufacturers) measured both from 10 nm and 23 nm and were compared with the lab systems measuring from 23 nm and additionally from 10 with two golden CPCs (from different manufacturers). The golden car was a GDI without particle filter. The testing started at JRC, Italy in October 2017 and the European part finished in June 2018.

The first results are promising and showed similar variability between 10 nm and 23 nm CPCs connected to systems with catalytic strippers [31].

3.6. Sub-23 nm monitoring

One major task of JRC is to monitor new technologies regarding existence of sub-23 nm particles. There are various JRC updates on the topic for light-duty [30, 32], L-category [15], heavy-duty [33]. Figure 5 summarises emission levels of various vehicle categories based on a few studies that focused on the most recent technologies: Euro VI heavy-duty vehicles, Euro 5 and Euro 6 light-duty vehicles (cold start included in the test cycle), Euro 2 and Euro 3 mopeds and motorcycles (cold start weighted 30%). Based on these results the sub-23 nm fractions are:

- 60–100% for spark ignition engines (natural gas, port fuel injection, mopeds and motorcycles)
- < 50% for diesel engines with or without DPF.

The conclusion of this study is that the solid sub-23 nm fractions can be significant; however, the sub-23 nm absolute emission levels might be low. For example, PFI vehicles are typically below the SPN limit even when including the sub-23 nm fraction. Thus, for regulatory purposes the current methodology still captures high emitters for most of the cases (i.e., a vehicle that passes with the 23 nm CPC would also pass with the 10 nm CPC and vice versa).

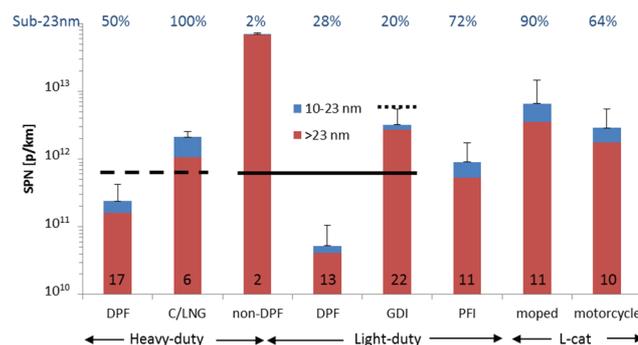


Fig. 5. Overview of emission levels of different current vehicle categories, based on JRC measurements [15, 30, 32, 33]. Error bars show one standard deviation (only positive side) for the number of vehicles shown in each bar. Horizontal lines give the European regulated SPN limits for SPN > 23 nm. Note that for the GDIs of this figure the limit was 6×10^{12} p/km (dotted line). The dashed line shows a limit of 6×10^{11} p/km. However, the SPN limit applies only to heavy-duty engines (not vehicles) and is expressed in p/kWh. All tests were conducted at temperatures around 23 °C

3.7. Low temperatures measurements

The emissions during low ambient temperatures (Type 6 test) of Regulation 2017/1151 refer to the UNECE Regulation 83. No SPN23 emissions are covered. The topic is

under discussion for the next revision of WLTP focusing on an engine/vehicle technology independent test procedure covering all pollutants (including SPN23). The PMP contribution was only to ensure that SPN23 are feasible without any particular requirements. The WLTP revised version will require that no condensation takes place until the measurement of the SPN23 (or PM) at -7°C .

Figure 6 summarises JRC results of the last years on the topic. The emissions are always higher at lower ambient temperature when there is no particle filter. When there is a particle filter (DPF or GPF) the emissions are usually higher but not always. Nevertheless, in this case, they remain below the 6×10^{11} p/km limit.

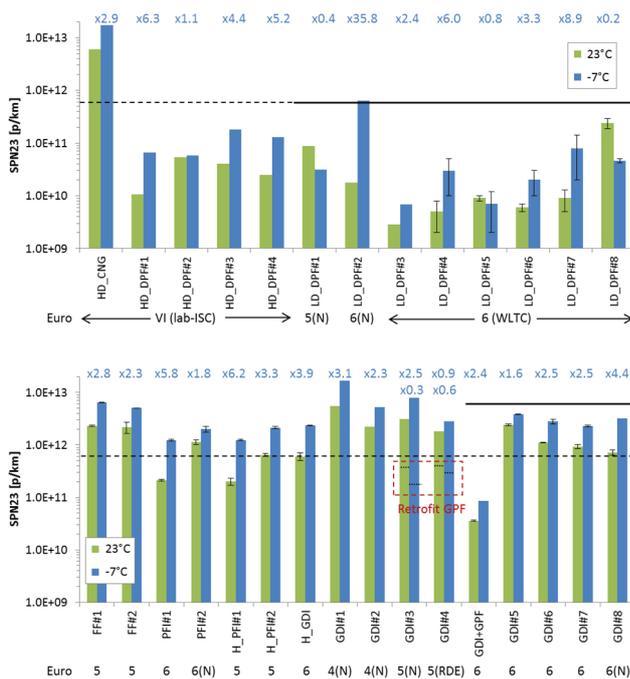


Fig. 6. Emissions from various vehicles at 23°C and -7°C . Upper panel: Heavy-duty (HD) vehicles and light-duty (LD) diesel vehicles. Lower panel: Gasoline light-duty vehicles. Data from [22, 32–37]. The solid line show the applicable limits of 6×10^{11} p/km for diesel light-duty vehicles and 6×10^{12} p/km for GDIs. Dashed lines are aid to the eye. The SPN limit applies only to heavy-duty engines (not vehicles) and is expressed in p/kWh. “N” for NEDC. Euro level is shown at the lower part of the figures. Ratio of -7°C to 23°C SPN23 emissions is given at the upper part of the figures

3.8. Raw exhaust sampling via fixed dilution

For type approval of light-duty vehicles raw exhaust sampling is not allowed. For heavy-duty vehicles proportional partial flow sampling systems are necessary for transient cycles. The reason is that proportional sampling is needed for the filter mass method to be equivalent to the full dilution method. However, the SPN method measures in real time, thus SPN emissions can be calculated if the exhaust flow rate is known. The investigations on the topic will follow these steps:

- Collection of experimental data (comparisons of CVS, partial flow systems and raw exhaust measurements with fixed dilution).
- Theoretical uncertainty analysis.
- Decision on technical specifications, in case raw exhaust sampling is proven to be robust and accurate.

The plan is to start with the heavy-duty evaluation because the conditions there are more extreme compared to light-duty vehicles (exhaust gas temperatures, high bio-fuel content, passive regenerations, pressure pulsations etc.) [38, 39].

Figure 7 summarises the experimental data available in the literature until today. The studies that were found are:

- JRC study with a Euro III engine equipped with different DPFs and a US2007 engine [40].
- PMP Heavy-duty inter-laboratory exercise [41]
- OEMs SPN PEMS validation [12]
- MAN study with a Euro VI diesel and a Euro VI CNG engine [42]
- CUMMINS study with Euro VI engines [43]
- HORIBA study with a DPF equipped engine [44]
- JRC light-duty SPN PEMS study [45]

In general the mean differences between raw exhaust (tailpipe) sampling and CVS or PFDS are within 30%.

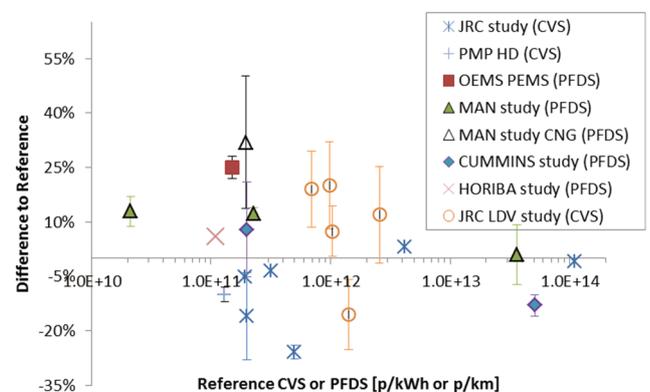


Fig. 7. Differences of SPN23 systems at the tailpipe from SPN23 systems at the CVS or PFDS. Each point is an engine with at least 3 tests. Error bars show one standard deviation of the differences

4. SPN PEMS

The interest for developing a procedure for on road testing of light-duty vehicles using Portable Emission Measurement Systems (PEMS) for SPN23 was announced in November 2012. In April 2013 the kick-off meeting took place. The group worked intensively and continuously until the end of 2015 on this issue. This work was independent from PMP activities.

4.1. Theoretical evaluation

In a preliminary study [46] a theoretical evaluation was conducted and showed that Diffusion Chargers (DCs) could be an acceptable alternative to CPC-based systems, if an extra uncertainty of around 50% when compared to CPCs would be acceptable. Based on the findings of that study, the minimum required specifications of the DCs were drafted.

4.2. JRC experimental evaluation: Phases I and II (light-duty)

At a next step (end of 2013) various prototype SPN23 PEMS (based on DCs) were evaluated in a chassis dynamometer lab to assess and validate the application and performance of portable SPN23 instrumentation [47]. The systems were measuring from the tailpipe and were compared to reference SPN23 systems (i.e. PMP compatible) at

the tailpipe and the full dilution tunnel with Constant Volume Sampling (CVS).

The results from three GDIs and one DPF equipped vehicle showed that the best performing SPN-PEMS (DC-based) was up to 100% higher when compared to the reference system at the dilution tunnel (CVS). Based on the findings of the previous studies, the technical requirements of the SPN-PEMS were drafted.

In the second evaluation Phase (which started in September 2014 and lasted till the end of that year) 8 SPN-PEMS (5 of them DC-based) were compared with legislation compliant SPN systems connected to the tailpipe and the dilution tunnel (CVS) [45]. The results of 7 GDIs, 3 PFIs, 2 DPFs, 3 motorcycles and 1 moped, confirmed the findings of Phase I: Diffusion Charging (DC) based systems are a feasible option to measure SPN. The best performing SPN-PEMS (DC-based, the same as in Phase I) had differences from the reference instrument at the dilution tunnel within 50% (with only a few exceptions).

However, one CPC-based SPN-PEMS, which arrived later in the program, had behaviour equivalent to the reference systems and better real time comparability with the reference systems compared to the DC-based systems. Further evaluation of the system after the campaign with another 10 vehicles confirmed these findings [45]. Based on the experimental data new and stricter efficiencies for SPN-PEMS were recommended for the technical requirements in order to reduce the measurement uncertainty of DCs at the CPC levels.

4.3. Inter-laboratory correlation exercise (light-duty)

The inter-laboratory exercise, which took place between September 2015 and December 2015 (one more lab measured in May 2016), aimed to assess the accuracy and precision of the method using two different SPN-PEMS (one DC-, and one CPC-based) on one Golden Vehicle in different laboratories across Europe directly involving other stakeholders, such as industry and technical services.

The SPN-PEMS DC-based deviation from PMP-CVS ranged from -34% to 53%, while SPN-PEMS CPC-based deviation from PMP-CVS ranged from -40% to 46% [48]. However, it should be noted that the main reason for these deviations was that some of the PMP-CVS systems were over- or underestimating (i.e., probably they had calibration issues).

4.4. JRC experimental evaluation (heavy-duty)

At the end of September 2015, in a heavy-duty vehicles PEMS meeting, it was decided to evaluate the particle number method, because the filter based PEMS method was not sensitive enough. The kick-off meeting was held in Ispra (Italy) in October of 2015. JRC evaluated some SPN PEMS instruments in the lab and on the road at different ambient temperatures from February until June 2016 [11] and then the commercial instruments in September 2016 [49]. The differences of the SPN-PEMS to the reference system at the dilution tunnel (PMP-CVS) were found within 35–50% for temperatures > 0°C for both DC- and CPC-based systems.

4.5. OEMs validation exercise

After the JRC evaluation, the European Automobile Manufacturers Association (ACEA) started the validation

phase testing an even wider range of engines and vehicles. One SPN PEMS (CPC-based) instrument was also circulated to all participants to evaluate the measurement uncertainty of the methodology with SPN PEMS. The two CPC-based PEMS had mean differences compared to the reference PMP systems of better than 20% with a standard deviation of 22%. The two DC-based systems had mean differences of 80% and decrease to less than 40% when a PMP correction was applied or if only emission levels > 3×10^{11} p/kWh were considered [12].

A theoretical study on the maximum expected uncertainty found a margin of around 63% [50]. Half of this uncertainty comes from the particle detector (33%) and up to 25% due to particle losses and dynamics, especially for CNG engines.

Figure 8 summarises, as an example, the results of the CPC-based SPN PEMS for all campaigns.

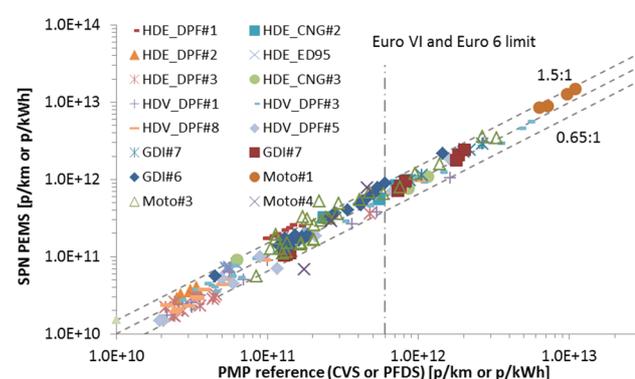


Fig. 8. Summary of L-category, light-duty and heavy-duty results for a CPC-based SPN PEMS compared to reference PMP systems at the full dilution tunnel (CVS) or proportional partial flow dilution systems (PFDS). Each point is a test cycle. Data from [11, 12, 45]

5. Horizon 2020 projects

One of the challenges identified in the GV-02-2016 Call ‘Technologies for low emission light duty powertrains’ was to create opportunities for real breakthrough research by addressing the need of the legislation and automotive industry for a sound metrological base for exhaust particles < 23 nm and by supporting the translation of findings into practice. Special attention should be paid on particle emissions of positive ignition engines under real driving conditions, since the emissions measured during the certification process do not always represent these in real world conditions. Three projects focus on the development of measurement systems (DownToTen [51], SUREAL-23 [52], PEMS4Nano [53]) with similar objectives:

- Investigate and quantitatively describe the nature and the characteristics of nanoparticles < 23 nm (formation, origin, physical and chemical character);
- Develop and set up a synthetic aerosol bench – similar to synthetic exhaust gas bench – and use it for fundamental studies at instrument level. Facilitation of metrology and evaluation purposes;
- Evaluate existing, proposed and under development particle measurement instruments against rigorous criteria for the measurement of the sub 23 nm particles, with emphasis on the performance within the demanding and hostile environment of PEMS;

- Analyse exhaustively and compare a large number of possible sampling and sample conditioning configurations (including dilutors, catalytic stripper, evaporation tube, thermodenuder, Constant Volume Sampling (CVS)). Benchmark them against a well-defined set of criteria (incl. losses, efficiencies, uncertainty, repeatability, reproducibility, robustness etc.) and under varying conditions of challenging aerosol from a variety of sources. Select the most promising combinations for further usage;
- Set-up an appropriate Particle Number – PEMS demonstrator that will materialise the findings and suggestions with respect to PN detection and sampling and conditioning;
- Use the above to measure a number of current and future engine and vehicle technologies as well as state-of-the-art exhaust aftertreatment systems in the laboratory and in real world conditions.
- Develop and propose an appropriate sampling and measurement methodology for the sub 23 nm particles both in the laboratory and real driving conditions to be employed during engine and vehicle type approval.

The progress of the projects is presented at the PMP meetings since October 2016.

6. New Periodical Technical Inspection (NPTI)

An initiative of VERT, launched in November 2016, addresses the needs of tamper-proof methods for exhaust assessment [54]. The initiative focuses on "New periodic technical inspection" (NPTI). The initiative is supported by the European Union as well as the governments of Germany, the Netherlands, Belgium, and Switzerland. The VERT/TNO NPTI proposal with the particle number test in idle run for diesel vehicles is summarised in a White Paper [55]. It is assumed that the process will be suitable with minor if any modifications also for petrol engines. The instrumentation is still under development. The first results are promising. Instruments in their prototype stage are already capable of recognizing vehicles that have been manipulated using partial bypass that resulted in SPN23 emissions close to maximum allow type approval levels (i.e. 6×10^{11} p/km) (see Fig. 9) and present a satisfactory correlation with SPN PEMS compliant instrumentation. Work on the testing procedure and pass/fail limit is still on going. This work is also under the evaluation of the Roadworthiness Technical Working Group which focuses on the roadworthiness aspects of tampering with exhaust emission control systems.

In September 2017 the Federal Council in Germany passed a law which demands periodical technical inspection of tailpipe emission applicable since January 2018 for gaseous pollutants (but currently no NO_x) and from January 2019 for particles.

Figure 9 summarizes the results from different studies:

- TNO study at low idle with three vehicles [56]
- JRC NPTI instruments pre-evaluation with one DPF equipped vehicle with bypass at low idle [57]
- SPN-PEMS evaluation study using idle data of the NEDC and WLTC [45].

The results show a medium correlation between emission levels during type approval cycle (NEDC or WLTC) and low idle emissions even with SPN-PEMS instruments. The scatter further increases when first generation NPTI instruments are included. Any low idle limit has to take into account this scatter, but the technical specifications of NPTI instruments should have acceptable uncertainty, with low cost.

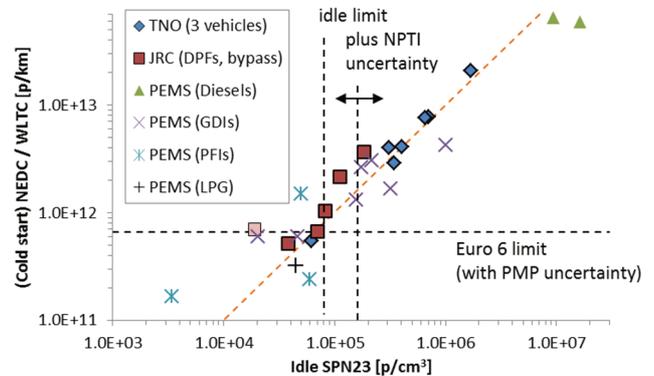


Fig. 9. Emission factor (#/km) during NEDC or WLTC vs raw exhaust concentration (#/cm³) measured during low idle with different PMP or SPN-PEMS instruments based on the PEMS project (Chapter 4). TNO data from [56]. JRC data and NPTI uncertainty estimation from [57]

7. Market surveillance

After the VW scandal a European Type Approval Authorities Experts Group (TAAEG) was set [58, 59] to ensure uniform application of the requirements for motor vehicles within the Community type-approval system, and to facilitate the exchange of information and experience regarding the implementation of type-approval legislation for vehicles. From the discussions of this group and with the contribution of the JRC, the Commission has published a guidance note to evaluate emissions strategies and to detect the presence of defeat device [60]. From this guidance, several requirements were included in the RDE regulation, with for instance the requirement of the manufacturer to provide to the Granting Type approval Authorities (GTAA) the extended documentation describing the auxiliary emission strategy of its vehicle (included in RDE 3rd package). Additionally, this guidance defined the requirements for an efficient in-service conformity checking, many of which have been included in the RDE 4, voted in May 2018.

In parallel, a revision of the EU type-approval framework was voted in 19 April 2019 that will replace Directive 2007/46/EC. Member states will be able to take measures (including ordering vehicle recalls and revoking type-approval certificates) against non-compliant vehicles sold in their national markets, instead of having to wait for the type-approval authority of the country that issued the vehicles' type-approval certificate to take action. The new type-approval framework introduces also an effective market surveillance system to control the conformity of vehicles already in circulation. The new Regulation for type-approval and market surveillance of motor vehicles will enter into force on September 2020, and the first in-service conformity testing in September 2019. While the focus is mostly NO_x and CO_2 , SPN is also being checked through

this new in service conformity process, as all the regulated pollutants.

8. Non-exhaust particle emissions

There is currently no regulation related to brakes particle emissions neither in Europe nor in any other part of the world [61]. This is due to several reasons with the most important being the lack of accurate scientific data on the relative contribution of brake wear particles to overall PM₁₀ pollution, the inaccurate – and sometimes outdated – brake wear PM₁₀ and PM_{2.5} emission factors reported in the literature as well as the lack of health studies directly linking brake wear particles to adverse health effects [62]. The PMP group is currently working on the development of a standardized test procedure for sampling, measurement and characterization of brake wear particles. The main goal of the methodology is to provide researchers and interested parties with a commonly accepted procedure for assessing real-world brake particle emissions. The first step of the procedure includes the development of a real-world braking test cycle. Real world PM and PN emission factors can be reported only if real world driving and braking conditions are examined. The analysis of the WLTP database showed that in many cases the driving conditions applied by researchers to study brake wear emissions were substantially different from real world driving and braking situations [63]. Further comparison of real-world driving and braking data with existing industrial braking cycles showed that the latest are very aggressive and in any case not representative of real world conditions [64]. For all these reasons it was decided to go towards the development of a completely new real-world braking test schedule. At the same time, the PMP is working on the development of a suitable methodology for sampling brake wear particles as well as on selecting the most suitable existing methods for brake wear particles' measurement and characterization. For that reason, a dedicated Task Force has been created within the PMP with the aim of accelerating the work [65]. The focus of the Task Force is on developing a methodology suitable for PM and PN concentration measurement. This is necessary as there is a great diversity among the published results. The Task Force includes representatives from the brake industry, OEMs, instrument manufacturers, regulatory bodies and universities/research institutes thus ensuring a holistic as well as a thorough technical support. The cycle was circulated through the PMP website in July 2018 and the goal is to deliver the proposed methodology by the end of the current mandate in June 2019. Figure 10 presents some PM mass and SPN results. Although the PM mass emissions over WLTCs can exceed the vehicle exhaust PM limit, the SPN emissions are very low.

Regarding tyre wear particles there is no regulation related to its particle emissions neither in Europe nor in any other part of the world [61]. Except for the reasons listed above and which also apply to tyre wear particle emissions, there is the issue of the direct dependence of tyre wear emissions to the type of road/pavement which makes it more difficult to regulate [68]. The PMP communicated the difficulties to the GRPE and made clear that a full scale investigation of the tyre related open issues would require a time and resource consuming large scale experimental

project. Neither the PMP, nor the JRC, had the necessary resources to perform such an experimental project. The GRPE decided to continue monitoring on-going projects and published data regarding the physical nature and size distribution of particle emissions from tyre wear and committed to eventually provide a report to GRPE on the investigation status and recommended next steps. In the meantime, JRC decided to perform a joint study with the Swedish National Road and Transport Research Institute (VTI) with the aim of exploring whether there is a relation between the Treadwear Rating (TWR) declared by the manufacturers at the sidewall of the summer tyres and the tread mass loss of the tyre. The relation between the TWR and the generation of tyre wear dust in the form of PM₁₀, PM_{2.5} and (S)PN concentration were also explored. The results of this study have been presented at the 47th PMP Meeting and will serve as a starting point for the discussion which will follow in order to come up with a recommendation for the next steps. The initial idea is to bring to the GRPE the need for the development of a standardized methodology for measuring the abrasion of the tyres. Such a methodology would give the opportunity to study not only tyre wear particle emissions but also emissions of other pollutants (i.e. microplastics).

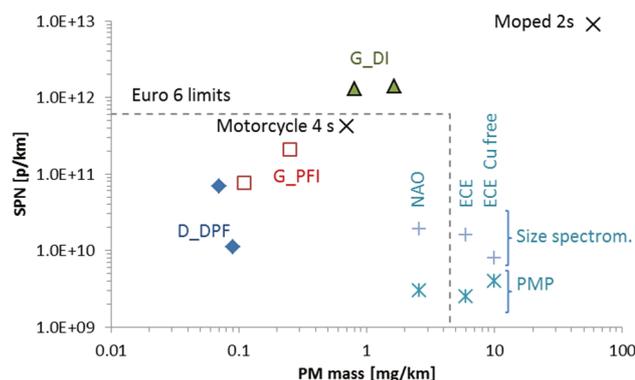


Fig. 10. PM mass and SPN measurements from a dilution tunnel using series-production pads from European market (ECE) and of non-asbestos organic (NAO) type (US market) with or without copper (Cu free). Results from [66, 67]. Results from exhaust emissions of various vehicles is also given for comparison [30]

9. Next steps: Post Euro VI and Euro 6

The major issues the last years were the development of more representative test cycles and procedures (WLTP) and on-road testing of vehicles. Even though RDE and WLTP were introduced, many other challenges lay ahead: Increased use of alternative fuels, electrification, the use of new technologies, increasing connectivity and automation and the advancement of measurement techniques, raise the need to evaluate what pollutants should be regulated in the future and how. Some of the main issues to be addressed, and closely related to SPN emissions, are:

- Review of the existing emission limits: Is there a need for a further reduction?
- Unregulated pollutants, including lower detected particle size.
- Full exploitation of on-board diagnostics and on-board monitors.

- Review of all existing tests (necessity, international harmonisation).
- Review of test cycles (mostly relevant for NRMM).
- Durability requirements review.
- Anti-tampering protection (especially at software level).
- Non-exhaust emissions.
- Interior vehicle air quality.
- Harmonization of regulations.

However, it is too early to foresee any directions, because it is still brainstorming and collection of input period.

10. Conclusions

The European vehicle emissions regulation includes a solid particle number > 23 nm (SPN23) limit for light-duty, heavy-duty on-road, and non-road mobile machinery (NRMM). For L-category vehicles at the moment the SPN emissions are being monitored by JRC.

In-Service Conformity testing includes SPN measurements with Portable Emissions measurement Systems (PEMS) for light-duty and heavy-duty vehicles. The additional uncertainty of SPN23 PEMS is covered with a so-called Conformity Factor (CF) that includes a margin for the instrument uncertainty. The uncertainty was based on theoretical and experimental evaluation at JRC and other laboratories.

The main topics that are under discussion at the moment are:

Calibration procedures: Some requirements that can be narrowed have been identified for both VPR and CPC calibrations. A very important finding is that soot-like aerosol is a suitable candidate for CPC calibration harmonizing the material for the various applications (VPR, CPC, PEMS).

Regeneration: The investigations confirmed that PMP systems can be used without any artefact issues during regeneration events of light-duty vehicles. Today there are no particular concerns that including the K_i factor will result in high emissions for DPF equipped vehicles. However this will be important if the emission limit is decreased.

Sub-23 nm feasibility: The feasibility study summarised that lowering the current lowest detectable size of 23 nm down to 10 nm is possible without large investment costs. An inter-laboratory exercise with prototype systems is currently on-going to confirm the theoretical assumptions. The two main open questions are 1) whether a catalytic stripper should be obligatory or not, and its specifications, and 2) how to take into account the losses at the sub-23 nm range. A simple solution could be to leave the PCRf as it is

today. A more accurate solution is adding a 10 nm CPC to the existing 23 nm CPC. However the feasibility of such solution for regulatory purposes has to be discussed.

Sub-23 nm monitoring: The sub-23 nm fraction is relatively high for spark-ignition engines exceeding 60%. However, at the moment the 23 nm lower detectable size captures the majority of vehicles exceeding the legislation limit.

Low temperatures testing: The testing is possible. At -7°C the emissions increase by a factor of > 2 in most cases without a particle filter.

Raw exhaust sampling: Preliminary literature overview showed that raw exhaust systems are within 30% of regulated systems. A more detailed experimental investigation is foreseen in the near future.

SPN-PEMS: The experimental uncertainty of the systems (plus the raw exhaust sampling) is around 50–60% today. Next steps include extension of PEMS testing to regulations that have a SPN laboratory limit (e.g. heavy-duty engines and NRMM).

NPTI: The on-going activities regarding new periodical technical inspection for particle number are promising. It seems feasible to measure at idle with sensors and identify a mal-functioning DPF. The technical specifications are being drafted and extension to gasoline engines is under-going.

Non-exhaust emissions: A test cycle has been prepared for brake wear emissions and the sampling methodology is under discussion. Tyre wear emissions will be investigated in more details the future.

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Conflicts of Interest

The authors declare no conflict of interest.

Disclaimer

The opinions expressed in this manuscript are those of the authors and should in no way be considered to represent an official opinion of the European Commission. Mention of trade names or commercial products does not constitute endorsement or recommendation by the authors.

Nomenclature

ACEA	Association for Emissions Control by Catalyst	ED95	95% Ethanol fuel
CAST	Combustion Aerosol Standard	EEPS	Engine Exhaust Particle Sizer
CF	Conformity Factor	ET	Evaporation Tube
CMD	Count Median Diameter	EU	European Union
CNG	Compressed Natural Gas	GDI	Gasoline direct Injection
CPC	Condensation Particle Counter	GRPE	Working Party on Pollution and Energy
CS	Catalytic Stripper	GSD	Geometric Standard Deviation
CVS	Constant Volume Sampler	GTR	Global Technical Regulation
DC	Diffusion Charger	HD	Heavy-Duty
DPF	Diesel Particulate Filter	HDE	Heavy-Duty Engine

HDV	Heavy-Duty Vehicle	PN	Particle Number
ISC	In-Service Conformity	PTI	Periodic Technical Inspection
JRC	Joint Research Centre	RDE	Real-Driving Emissions
LD	Light-Duty	SPN	Solid Particle Number
NEDC	New European Driving Cycle	TAAEG	Type Approval Authorities Experts Group
NPTI	New periodic Technical Inspection	TWR	Treadwear Rating
NRMM	Non-Road Mobile Machinery	UN	United Nations
NRSC	Non-Road Steady Cycle	UNECE	United Nations' Economic Commission for Europe
NRTC	Non-Road Transient Cycle	VERT	Verification of Emission Reduction Technologies
OBD	On-Board Diagnostics	VPR	Volatile Particle Remover
OEM	Original Equipment Manufacturer	WHSC	Worldwide Harmonized Stationary Cycle
PCRF	Particle number Concentration Reduction Factor	WHTC	Worldwide Harmonized Transient Cycle
PEMS	Portable Emissions Measurement System	WLTC	Worldwide harmonized Light-Duty Transient Cycle
PFDS	Proportional partial Flow Dilution System	WLTP	Worldwide harmonized Light-Duty Test Procedure
PFI	Port Fuel Injection	WMTC	Worldwide harmonized Motorcycle Transient Cycle
PM	Particulate Matter		
PMP	Particle Measurement Programme		

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