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Particle Number Emission for Periodic Technical Inspection in a Bus Rapid Transit System

Maria L. Botero[1] · **Javier Londoño**[1,2] · **Andrés F. Agudelo**[1] · **John R. Agudelo**[1]

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Abstract

This study was carried out under the Climate and Clean Air in Latin American Cities program (CALAC+) and aimed to evaluate the particle-number-based periodic technical inspection (PN-PTI) test in a public bus rapid transport (BRT) system and establish a baseline of PN emission. The PN-PTI test was performed in 1474 buses with emission standards from Euro II to Euro V without diesel particle filter (DPF), Euro V with retrofitted DPF, Euro VI diesel with original engine manufacturer DPF, and compressed natural gas (CNG) fueled. The median PN emission of buses with DPF is below 3000 #/cm^3. PN emission limits such as 1,000,000 #/cm^3 or 250,000 #/cm^3 would allow the approval of vehicles with DPF that are not fully operational. An additional high-idle test is proposed for buses with emissions above 50,000 #/cm^3, but below the test approval limit, to detect DPF that may require maintenance.For buses without DPF, which are the majority of the bus fleets in Latin America, the PN emission test can detect and target very-high emitters for developing special policies. CNG buses presented the lowest emissions, likely because of the detection limit of the equipment (23 nm) which cannot detect the large number of particles emitted by these vehicles in the sub-23 nm particle range.

Keywords PN-PTI · CPC · Particle number concentration · PN emission

1 Introduction

The introduction of particle number (PN) emission limits for the homologation of diesel vehicles has forced the use of diesel particle filter (DPF), achieving a reduction of up to 99.99% in exhaust particle matter emission. This advance led to the re-evaluation of the periodic technical inspection (PTI) tests to detect anomalies among these low emissions. DPF can break, get clogged, and in some cases are illegally removed to increase vehicle power. In such cases, the vehicle can have greater particulate emissions, even orders of magnitude larger than with a good working DPF [1]. Several European countries have approved a new PN based PTI test (PN-PTI) to replace the opacity test, in order to detect the removal/manipulation or failure of the DPF in vehicles. The regulation came into force on July 2022 in Belgium, and will be introduced in January 2023 in Germany, Netherlands and Switzerland. A thorough technical description and discussion of the PN-PTI test and its development was recently published [1, 2].

The PN emission of diesel vehicles with DPF at low idle are generally below 5000 #/cm^3, and lower than PN ambient concentrations, which facilitates the detection of defects in the DPF [1, 3]. Since the late 1990s the Verification of Emission Reduction Technologies Association (VERT) started quality checks of DPF that included particle counting and tests at low idle [4, 5]. The Swiss Federal Institute of Metrology (METAS) introduced since 2010 a PN-PTI protocol and specifications for the equipment requirements [6, 7], and by 2017 Switzerland had already introduced the PN-PTI test for construction machinery and boats. The Netherlands Organisation for Applied Scientific Research (TNO), by request of the Dutch government, investigated since 2016 the suitability of a new PTI test based on PN emission [8], resulting in the proposal of a test procedure for all vehicles with DPF, suggesting approval limits and equipment specification in 2019 [3]. In their studies, TNO found that when testing the vehicle in free acceleration tests, the high removal efficiency of the DPF was observed, with PN emission lower than 3000 #/cm^3, and vehicles

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✉ Maria L. Botero
mluisa.botero@udea.edu.co

[1] Department of Mechanical Engineering, Universidad de Antioquia UdeA, Medellín, Colombia

[2] Department of Mechanical Engineering, Institución Universitaria Pascual Bravo, Medellín, Colombia

with DPF leaks were found to have PN emission as high as 10,000,000 #/cm^3, which was not detected by opacity tests [1]. Additionally, the research revealed a linear correlation between the low-idle PN emission and total PN emission factor following the NEDC test cycle. This was used to estimate a low-idle PN emission limit for Euro 5b and Euro 6 diesel vehicles of 250,000 #/cm^3. This limit would allow to identify defective DPF. For Euro 3, 4 and 5a diesel vehicles without DPF, that do not have an emission regulation in number but in mass, a similar analysis resulted in low-idle PN emission limits between 1,000,000 and 1,500,000 #/cm^3. The European Commission Joint Research Center (JRC), in studies developed under the particle measurement program (PMP), also found the linear correlation between PN emissions at low-idle and homologation-cycle tests for diesel and natural gas fueled vehicles [9].

In 2016, a working group to progress towards a new particle emission test for vehicles was established by VERT, several governmental organizations, metrology institutes, research centers, and manufacturers from Switzerland, Netherlands, Germany, Belgium and the UK. The NPTI-VERT working group informed and guided European authorities, equipment manufacturers and PTI service providers in the implementation of the PN-PTI test [10]. In 2021, VERT published a technical document summarizing the suggestions regarding the test procedure, the typical PN emission values of DPF in good working conditions, with failure or requirement of maintenance [11], which can be used as a reference to establish approval limits. It must be noted that the PN-PTI test only concerns the particulate emissions, and it is not able to analyze gaseous emissions such as NOx.

In 2019, a study of light-duty diesel vehicles with DPF (263 Euro 4 and 41 Euro 6) was performed in Belgium [12], proving the viability of the PN-PTI test to detect high emitters. Results showed that 70% of the vehicles had very low PN emission (<25,000 #/cm^3), and that using an emission limit of 250,000 #/cm^3 would return approval rates of 84.8%. The mileage of the vehicles was identified as a factor for higher PN emissions. In a posterior measuring campaign [13], the same authors tested 757 light-duty diesel vehicles (368 Euro 5a, 261 Euro 5b and 128 Euro 6) to estimate the emission factors of these vehicles from the low-idle PN emission and the linear correlation found by TNO and JRC.

VERT has supported Latin American governments in the evaluation of the PN-PTI test. In Mexico City, the Environment Office (SEDEMA) installed PN emission measurement equipment in several PTI centers, integrating the PN-PTI test to the existing gas emission tests for gasoline vehicles with particle filter (GPF) [14]. They collected data from 32,560 vehicles, where only 2% were responsible for 62% of the total PN emission. Those vehicles were cataloged as very-high emitters, presenting PN emission higher than 3,000,000 #/cm^3. In the high emitter category (between 1,000,000 and 3,000,000 #/cm^3) only 2% of the vehicles contributed to 10% of the total PN emission. In 2018, JRC supported the evaluation of the data from 500,000 petrol vehicles that revealed that, in some vehicle classes, 3% were responsible for 90% of the PN emitted [15]. It has been demonstrated that the PN-PTI test can be used to detect particle filter malfunctioning in any type of vehicle.

Between 2004 and 2011, the Chilean authorities in cooperation with the Swiss government implemented a DPF retrofitting program in the public bus system of Santiago de Chile [16]. This program served as a pilot for local DPF certification and for the entrance of original equipment manufacturer (OEM) DPF buses in the country since 2010 [16]. As part of this program, in 2015, the first low-idle PN measurements of a large bus fleet were made in Latin America in 124 buses with DPF and 104 without DPF using a condensation particle counter (CPC) [17, 18]. In 2015, the DPF retrofitting pilot was extended to Bogotá (Colombia), under the Swiss government funded program CALAC. Since 2018, with the continuation of the program CALAC+, several studies on the adoption of DPF technologies, draft regulations for Euro 6/VI emission standards and PN-PTI standards have been performed in Mexico City, Bogotá, Lima and Santiago de Chile [19]. In 2020 the CALAC+ working group, after the evaluation of the studies performed by TNO and VERT, and consultation with equipment manufacturers, published a technical guide for the PN-PTI test that accounted for the special conditions of Latin American cities, with high altitudes and high relative humidity [20].

This investigation is part of the studies performed under the CALAC+ program in cooperation with TRANSMILENIO S.A, the operator of Bogotá's Bus Rapid Transport (BRT) system. The aim is to draw a baseline of solid PN emission (particle size range 23–1000 nm) in buses from Bogotá's BRT system. The campaign consisted on testing 1474 buses under the PN-PTI protocol developed by CALAC+ working group [20], comprising compressed natural gas (CNG) and diesel buses complying with emission standards from Euro II to Euro VI. The study is also aimed at gathering experience on the logistics, measurement equipment, and PN-PTI protocol, that allows to evaluate and suggest its implementation and the impact of emission limits in the approval rates for the different vehicle categories.

2 Methods

2.1 Vehicle Fleet

Tests were performed in a bus fleet of the mass public transport system of Bogotá, Colombia. Access to the buses, bus drivers, parking and maintenance yards was coordinated and provided by TRANSMILENIO S.A. The measuring campaign took place during May–June 2021 at 11 parking and maintenance yards from the bus operator companies. The fleet comprised a variety of model years, emission technology (based on Euro emission standards), mileage, vehicle class and engine size. Table 1 presents the main characteristics of the studied fleet.

2.2 PN-PTI Procedure and Equipment

Solid PN emissions were measured with an NPET 3795 (TSI Inc.). Solid particles are defined in this context as particles that remain in the aerosol phase after thermal treatment at around 300°C with diameters larger than 23 nm. The NPET is a nanoparticle emission tester based on condensation particle counting (CPC) technology and volatile particle removal with a catalytic stripper. This equipment is homologated for PTI measurement of non-road mobile machinery in Switzerland and the new PN-PTI for diesel vehicles with DPF in the Netherlands. The equipment counts solid particles with diameters between 23 and 1000 nm, the maximum particle concentration it can measure is 5,000,000 #/cm^3. The NPET used in this investigation was brand new with calibration from the manufacturer.

The test followed the procedure developed by the NPTI-VERT working group, and adopted by the Netherlands in 2019 [21] (revised in 2021 [22]) for the inspection of vehicles with DPF, and included particularities for Latin American countries proposed by CALAC+ [20]. The test is based on the quantification of the number of solid particle concentration (PNC #/cm^3) in the exhaust of the vehicle at low idle operation, as depicted in Fig. 1. The test is performed under warm engine conditions, which are verified by measuring the temperature at three positions on the exterior of the crankcase oil tank using a pyrometer. The vehicles were tested when the average temperature was higher than 60°C, otherwise they were sent to be warmed up with successive accelerations. The warm-up stage is essential for CNG buses, otherwise copious amounts of water vapor condensation was observed in the exhaust, which can be deleterious to the measurement equipment.

Diesel vehicles without DPF required the use of an external dilutor in order to protect the NPET from saturation. An eDiluter^{TM} Pro (Dekati) was used to dilute the exhaust gas before entering the NPET. The extra dilution was estimated from measurements of the raw exhaust with and without the external dilutor. This was performed at least 3 times at the beginning of each testing day and the average value was used to correct the measured PNC. Not all the non-DPF diesel vehicles required the external dilution step.

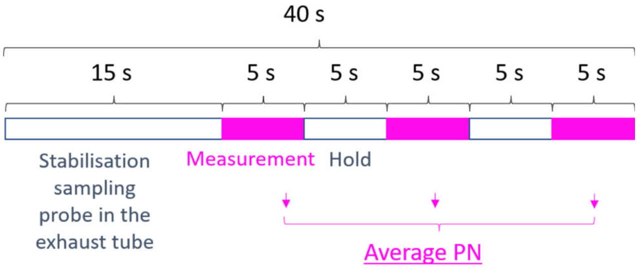


Fig. 1 PNC measurement scheme

PN emission measurements were made on-site, visiting the parking and maintenance yards of the buses. In general, the frequency of measurements depended on the yard logistics, and on the availability of drivers and buses to move into the measurement spot. It was possible to test a vehicle in 2 min. The fastest rate of testing was 27 vehicles per hour, with a total of 108 vehicles in 4 consecutive hours.

A visual inspection of the exhaust tube is necessary to verify that there were no adaptations or fissures that might dilute the exhaust before being sampled. An additional step in the test was implemented for randomly selected diesel vehicles with DPF: the low idle test was followed by a high idle measurement, where the driver accelerated the vehicle to approximately 2000 rpm. The purpose was to further evaluate the condition of the DPF.

2.3 Data Analysis

A database was created with preloaded information of the vehicles. The date, time, crankcase oil tank temperature, mileage, and measured PNC were registered on the spot. The database was analyzed to obtain statistical descriptors. The results are presented in box-and-whisker plots where the bottom and top of the box represent the Q1 and Q3 respectively, the center bar corresponds to the median value, and the whiskers the maximum and minimum without outliers.

A statistical analysis comparing the mean values was performed by means of an analysis of variance (ANOVA). Data groups with less than 3 observations were not included. The normality of the residuals' distribution was tested with Shapiro-Wilk test. When normality was attained, the Tukey test was performed to determine the differences between the data groups compared. In cases where a normal distribution of the residuals was not observed, the Kruskal-Wallis test was performed, with previous homoscedasticity verification. Due to the great difference in the magnitude of the PNC values, the original data were transformed in log10 base for the statistical analysis. Detailed ANOVA results are presented in the Supplementary Material

3 Results and Discussion

3.1 Total PN Emission Baseline

The results of exhaust PNC of the tested fleet according to the emission standard and the fuel are presented in Figs. 2 and 3 respectively. Table 2 shows the percentage of buses with different PNC emission ranges as well as median values.

Euro II to Euro V diesel buses that do not possess a DPF exhibit the highest PN emissions. Of these buses 75% presented PN emission in the range of 1,000,000 to 1,800,000 #/cm^3. The highest PNC value registered was 5,576,111 #/cm^3 in a Euro II bus from 2006. No statistical difference was found between the emission of Euro II, VI and V buses (p value >0.99). Diesel buses with DPF presented a reduction in the exhaust PNC up to 99.3% with respect to those without DPF. A statistically significant difference between the PN emission of buses without DPF (Euro II, IV and V) was found compared to buses with low-emission technology (Euro V+DPF and Euro VI diesel and CNG) with p value < 0.001. Of these buses 78% exhibited a PNC emission lower than 5000 #/cm^3. Diesel buses with retrofitted DPFs (Euro V + DPF) presented a higher PNC emission range versus those with OEM DPF (Euro VI) (p value $= 3.13\times10^{-43}$). The lowest PN emissions were observed in Euro VI buses: diesel (with OEM DPF) and CNG, where 98% of this fleet exhibited PNC below 5000 #/cm^3. As a reference value, we monitored the daily ambient PNC at the sites of the measuring campaign using the NPET. The average ambient PNC at each site was in the range of 718–6989 #/cm^3. Results of ANOVA tests for data sets in Figs. 2 and 3 are presented in the Supplementary Material.

3.2 Diesel Buses with DPF

The PN emission of buses with DPF is very low, with a median PNC lower than 5000 #/cm^3 (see Table 2) for both Euro VI and Euro V (DPF retrofitted). Comparing among Euro V buses with and without DPF (see Fig. 6),

Table 1 Characterization of the bus fleet studied

	Emission technology (Euro)							Average mileage (km)
Model year	II	III	IV	V	V (with DPF)	VI (diesel)	VI (CNG)	
2004	12							366,447
2005	6							353,102
2006	27							338,286
2007		2						1,256,524
2011			1					1,151,331
2012			12	10				752,468
2013				20				700,438
2014				10				620,544
2015				10				591,615
2019				3	210		26	170,695
2020				4	363	43	604	125,389
2021					87	23	1	430,966
Total	45	2	13	57	660	66	631	
After-treatment		DOC[a]	DOC[a]	DOC[a] SCR[b]	DOC[a], SCR[b] DPF retrofitted	DOC[a], DPF SCR[b]	TWC[c] EGR[d]	
Engine capacity (cm^3)	9603			12,130		4580 and 7700	9300	

[a] DOC: diesel oxidation catalyst

[b] SCR: selective catalytic regeneration

[c] TWC: three-way catalyst

[d] EGR: exhaust gas recirculation

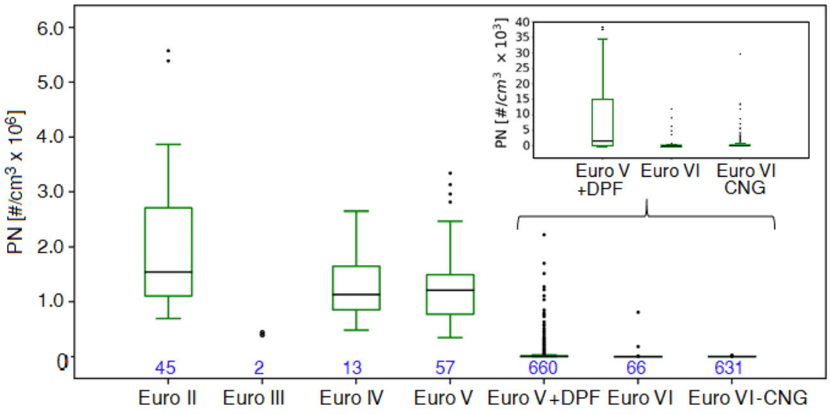


Fig. 2 Solid PNC for all tested buses according to the emission standard. The number below each box corresponds to the number of buses tested. The insert graph is a zoom of the low-emission technologies

the efficiency of filtration is estimated to be higher than 95%. Figure 4 presents the exhaust PNC of buses with DPF according to model year and mileage. Buses with retrofitted DPF (Euro V+DPF) showed higher Q3 values, which decreased from approximately 40,000 #/cm^3 for model year 2019 to 15,000 #/cm^3 for model year 2020 (p value = 0.000973) to less than 5,000 #/cm^3 for model year 2021 (p value = 1.03×10^{-9}). An increase in the number of buses with atypically high emission was also observed. This tendency seems to be related to the mileage of the buses. As mileage increases, more buses with emissions above the median values were found, as well as buses with higher PNC. From the mileage range of 50,000–100,000 km a statistically significant difference in the PN emission was observed (p value <0.004), entailing that the PN emission increased for the 100,000–150,000 km and the 150,000–200,000 km mileage range. This was not observed for Euro VI buses (OEM DPF) (p value = 0.25), all model years 2020 and 2021 with mileages less than 50,000 km. Results of ANOVA tests for data sets in Fig. 4a and b are presented in the Supplementary Material.

3.2.1 DPF Malfunction

The PN-PTI tests aim to determine failure or removal of the DPF. Several studies conducted by TNO and VERT have led to the suggestion of PN emission limits in the PN-PTI test to determine the failure or malfunction of a DPF. In this study 726 buses with DPF were tested, 68% emitted less than 5000 #/cm^3, indicating the ability of a DPF in good working conditions to reduce the PN emissions. It was found that 40 buses, 5.5% of this fleet, emitted more than 250,000 #/cm^3 (emission limit suggested by TNO [3]), of which 7 emitted more than 1,000,000 #/cm^3 (emission limit established officially by the Netherlands government), denoting DPF failure or malfunction. Of these buses only one had OEM DPF (1% of the Euro VI fleet) and the remaining had retrofitted DPF (6% of the Euro V+DPF fleet). The OEM DPF bus presented a PN emission of 811,088 #/cm^3 and had not started commercial operation (mileage of 1115 km), suggesting that it was damaged previously. The PN-PTI test can help identify such cases for the acquisition of large bus fleets with DPF. Of the 39

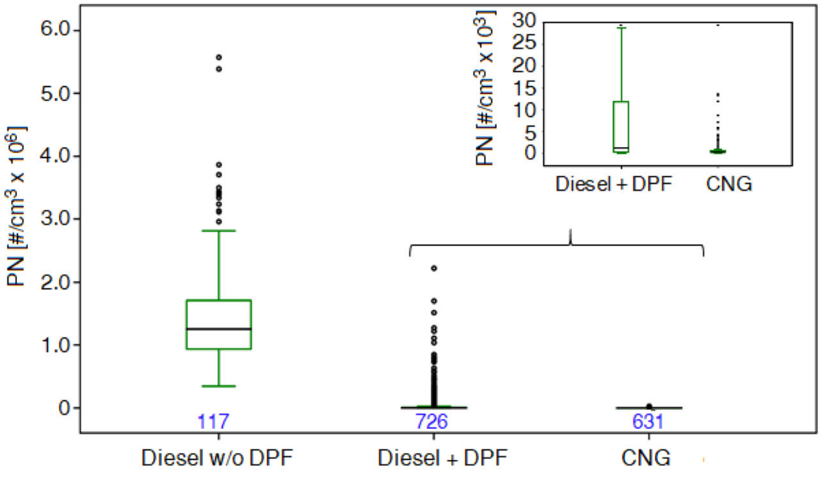


Fig. 3 Solid PNC for all tested buses according to the fuel. The number below each box corresponds to the number of buses tested. The insert graph is a zoom of the low-emission technologies

Table 2 PN emission range of vehicles with different emission technologies

Emission technology	# of buses	Median PNC [#/cm^3]	% of buses in PNC range [#/cm^3 × 10^3]			
			PN<5	5<PN<250	PN>250	PN>1000
Technologies without particle aftertreatment						
Euro II	45	1,541,481	–	–	18%	82%
Euro III	2	416,579	–	–	100%	–
Euro IV	13	1,131,873	–	–	31%	69%
Euro V	57	1,212,417	–	–	27%	63%
Total	117	1,255,729	–	–	30%	70%
Low particle-emission technologies						
Euro V+DPF	660	1537	65%	29%	5%	1%
Euro VI	66	16	92%	7%	1%	–
Euro VI (CNG)	631	171	98%	2%	–	–
Total	1357	324	82%	15%	2.5%	0.5%

retrofitted DPF buses with failure 27 (69%) were model year 2019 with average mileage of 170,255 km, and 12 (31%) were model year 2020 with average mileage of 158,266 km. It was also noted that these buses corresponded to two specific yards, implying that the maintenance program and operation of the vehicles are key to the preservation of the DPF.

A question arises: *what is happening to the DPF in vehicles with PN emissions higher than the typical values of good working conditions, but lower than the*

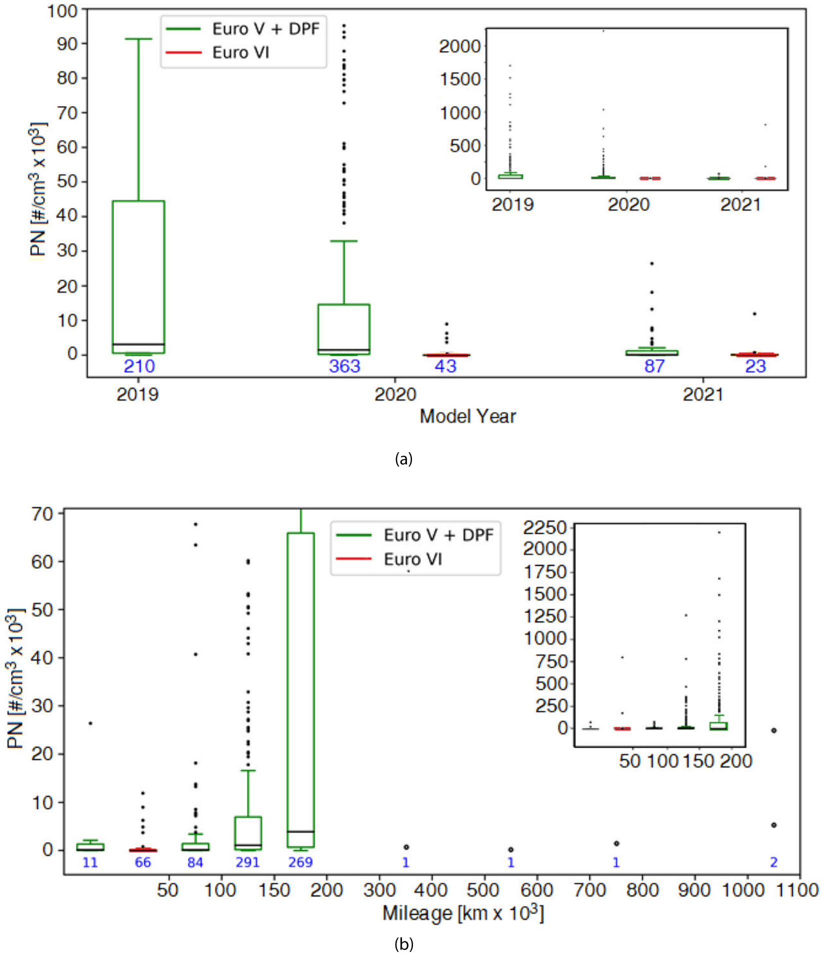


Fig. 4 PNC emitted from diesel buses equipped with DPF: Euro V (retrofitted) and Euro VI (OEM DPF), differentiated by (a) model year and (b) mileage. The number below each box corresponds to the number of buses tested. The insert graph in each figure shows the entire range of measured values, the axis have the same units

failure threshold?. VERT suggested that a DPF equipped vehicle with an emission higher than 50,000 #/cm^3 requires maintenance and should be flagged at the PN-PTI [11]. We found that 84.6% of the DPF fleet emitted less than 50,000 #/cm^3, and that 73 buses (10%) had PN emissions between 50,000 and 250,000 #/cm^3, indicating that they might require maintenance.

To investigate further the proposed question, high idle tests (200 rpm) were performed to randomly selected vehicles with exhaust PNC between 5000 and 250,000 #/cm^3. Results of this test in 20 buses are presented in Fig. 5. Two buses with low idle emission below 10,000 #/cm^3 (DPF 41 and 42) were tested during the DPF regeneration. At high idle these buses exhibited PN emission around 100,000 #/cm^3. Buses with low-idle PN emission below 25,000 #/cm^3 (DPF 43-45) did not surpass 250,000 #/cm^3 at high idle, and some of the buses with low-idle emission between 25,000 and 70,000 #/cm^3 (DPF 46-56) surpassed the limit at high idle. All buses with low-idle PN emission above 70,000 #/cm^3 (DPF 57-60) surpassed 250,000 #/cm^3 at high-idle. Bus DPF 60 with low-idle PNC of 100,000 #/cm^3 presented a high-idle PN emission of 1,000,000 #/cm^3. In order to protect the NPET, additional high-idle tests were not performed in buses with low-idle emission above 100,000 #/cm^3.

The high-idle tests suggested that vehicles with low-idle PN emission between 25,000 and 100,000 #/cm^3 might require DPF maintenance, and that buses emitting above 100,000 #/cm^3 at low-idle might present failure. Under the collected evidence, we support VERT's claim that the emission limits can be reduced to 50,000 #/cm^3 in order to detect DPF malfunction. Otherwise, we recommend the high-idle test for buses with low-idle PN emission above 50,000 #/cm^3, and those that emit more than 250,000 #/cm^3 at high-idle should be flagged for maintenance.

3.3 Diesel Buses Without DPF

The PN-PTI test from 117 diesel buses without exhaust aftertreatment, complying with emission standards Euro II to Euro V, revealed that 78% of this fleet had exhaust PN emission below 4,500,000 #/cm^3. Emissions as low as 345,529 #/cm^3 (Euro V bus) and as high as 5,576,111 #/cm^3 (Euro II bus) were observed. Figure 6 shows the PN emission results for buses with different model year or mileage. No statistical significant differences were found between the data groups, (p value $>$ 0.044) indicating that for diesel buses without DPF the emission standard and mileage do not determine the PN emissions. Results of ANOVA tests for data sets in Fig. 6a and b are presented in the Supplementary Material. A 2015 study in Israel had similar observations evaluating 6 buses [23].

For vehicles without DPF, the low-idle exhaust PNC measurement could be used to detect very-high emitters and label them, for example to create emission oriented policies that restrict their circulation under special circumstances such as in clean-air urban zones, or during periods of high air pollution, among other. We recommend the use of a high-concentration particle counter, because the use of an external dilution system increases the costs of the test and the complexity of the logistics.

3.4 CNG Buses

Table 2 shows that the exhaust PNC from Euro VI CNG buses is very low, with 98% of these vehicles having PN emissions below 5000 #/cm^3, and a median value of 324 #/cm^3, which is below the equipment lower limit of detection and the average ambient values at the testing sites.

Figure 7 presents the exhaust PNC of CNG buses according to model year and mileage. There is not an

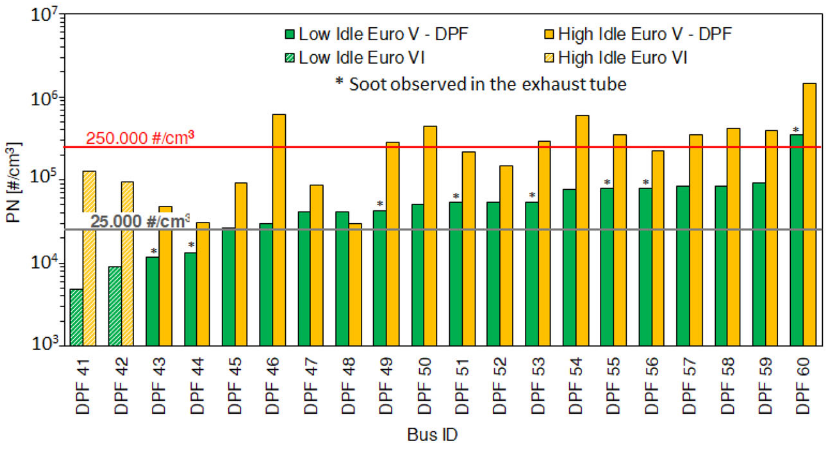
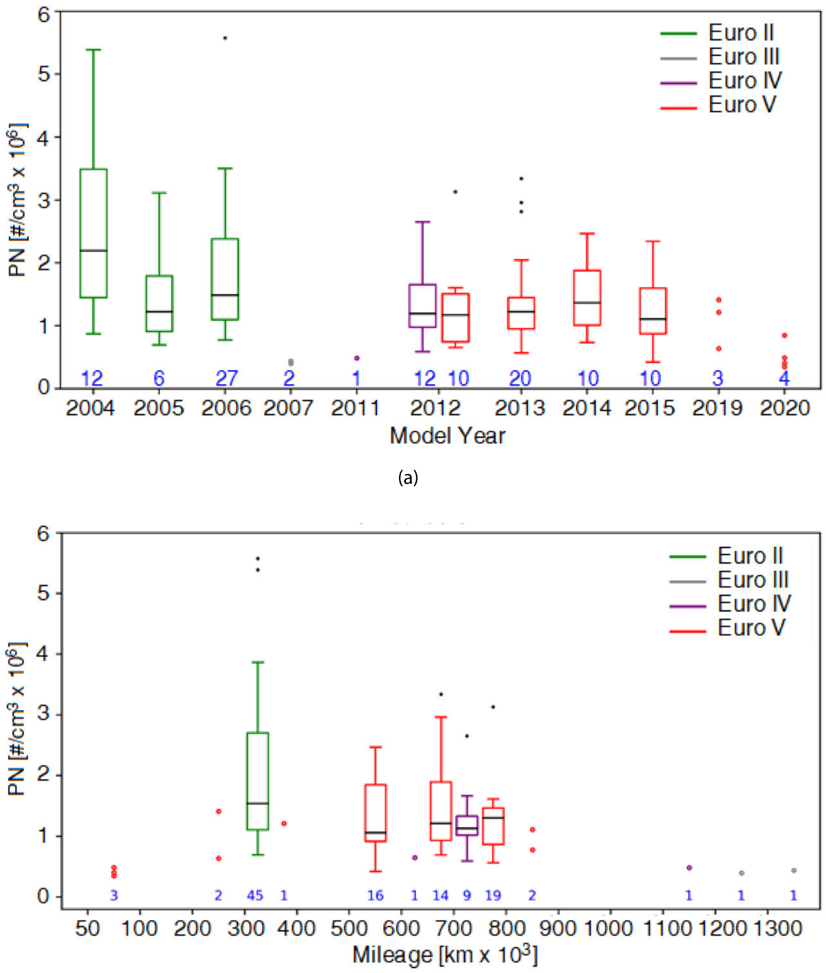


Fig. 5 Solid PNC for buses at low and high idle



(a)

(b)

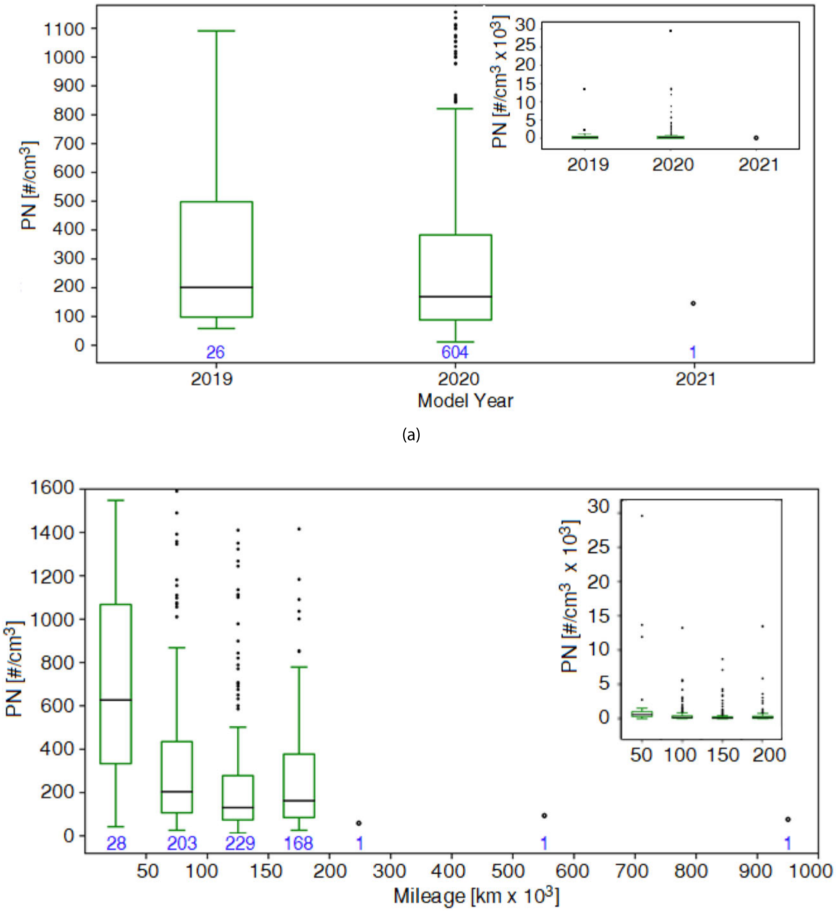
Fig. 6 Solid PNC emitted from diesel buses without DPF, emission standards Euro II to V differentiated by (a) model year and (b) mileage. The number below each box corresponds to the number of buses tested

statistically significant difference in the PN emission between 2019 and 2020 models (p value = 0.4092). When comparing with mileage, there is a slightly higher emission from vehicles with the lowest mileage (km < 50,000), the difference between this mileage range and all higher was found to be statistically significant (p value < 0.0025). Reviewing the individual data of these vehicles, it was found that two of them had exhaust PNC between 10,000 and 14,000 #/cm^3 and one close to 30,000 #/cm^3. Results of ANOVA tests for data sets in Fig. 7a and b are presented in the Supplementary Material.

It has been shown that PN emission from gas fueled vehicles is largely due to the lubricant oil [24], and for vehicles with low mileage the contribution from the lubricant could be higher than for vehicles with longer use [25]. Other 4 buses with higher mileage (>160,000 km) also presented emissions slightly above 10,000 #/cm^3. Although these PNC values are well below PN-PTI emission standards for DPF buses, they are atypical for the values measured in this CNG fleet, and might suggest the need for mechanical inspection.

The present results are in agreement with other studies that reported CNG vehicles as high suppressors of PN emission [26, 27]. However, these results only included particles emitted in the range of 23–1000 nm. Several recent studies have shown that CNG and liquified natural gas (LNG) vehicles have particularly high PN emissions in the sub-23 nm range [24, 27–29]. On-road tests of PN emission factors, with PNC measurements starting at a particle size of 2.5 to 5 nm, revealed that a CNG truck had higher emission than three diesel-fueled vehicles with DPF certified to the same emission standards [30]. Samaras et al. [29] evaluated the impact of the particle size detection range in the solid PN emission of gasoline, diesel and CNG vehicles. The PN emission of CNG vehicles for particles larger than 10 nm was found to be low, but the sub-10 nm emission was shown to be significantly elevated, increasing up to 90 times when extending the lower detection limit to 2.5 nm.

Fig. 7 Solid PNC emitted from CNG, Euro VI buses differentiated by (a) model year and (b) mileage. The number below each box corresponds to the number of buses tested. The insert graph in each figure shows the entire range of measured values



(a)

(b)

Lähde and Giechaskiel [27] measured the solid PN emission in two Euro 6d CNG and one liquified petroleum gas (LPG) light-duty vehicles, following the World harmonized Light vehicles Test Cycles (WLTC) on a chassis dynamometer, finding that the CNG operation had sub-23 nm PN emission between two and 10 times higher than >23 nm PN emission. Most of the excess emission was found in the particle range between 10 and 23 nm. Alanen [24] studied the process of particle formation and emission from natural gas engines. She concluded that the non-volatile particles between 1 and 6 nm emitted from the engine originated from fuel combustion, given their carbonaceous composition, whereas the particles between 5 and 10 nm originated mainly from the lubricating oil as they exhibited markers such as elemental calcium.

Results from the three Horizon 2020 projects, aimed at supporting the development of sub-23 nm particle counting methods and regulation [31], suggested that gaseous-fuel vehicles should be included in the PN emission regulation starting at least at 10 nm particle detection range. They also suggest the retrofit of GPF, which could reduce significantly (up to two orders of magnitude) the sub-23 PN emission [29, 31].

3.5 Impact of PN Emission Limits

Figure 8 presents the cumulative probability of low-emission technology buses from this study, according to PN emission. Three approval limits are included in the graph to demonstrate the approval rates of each fleet: the limit of 1,000,000 #/cm^3 proposed by the Netherlands, 250,000 #/cm^3 proposed by TNO and 50,000 #/cm^3 proposed by VERT.

The CNG fleet would approve all suggested limits indicating that, under the studied equipment detection ranges, this is not a good metric to evaluate PN emissions from this vehicle category. As explained in Section 3.4, sub-23 nm particles are emitted in high proportions in these type of vehicles. Euro VI diesel buses showed the highest probabilities to present PN emissions below 1000 #/cm^3, whereas for retrofitted DPF buses (Euro V) only about 40% of the fleet did. Under the Netherlands limit almost all DPF vehicles would approve the test (99% retroffited DPF, 100% OEM DPF), which would not allow to detect all DPF failure and high-emitter vehicles. The TNO limit would allow the approval of 95% of all DPF-equipped buses, whereas 92% would approve the more stringent limit of 50,000 #/cm^3

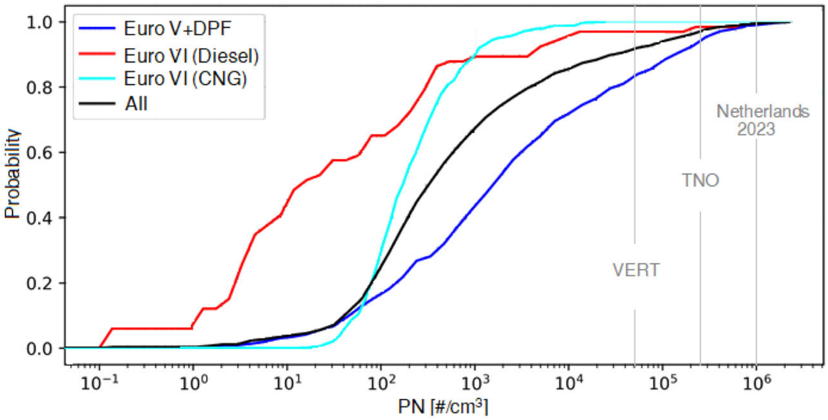


Fig. 8 Cumulative probability of PN emission of buses according to their emission standard. Vertical lines indicate proposed PN emission limits in the PN-PTI test

suggested by VERT (97% OEM DPF and 83% retrofitted). Together with the evidence of median PN emission below 5000 #/cm^3, these results indicate that the 50,000 #/cm^3 limit could be adequate to detect malfunctions in the DPF, or at least to flag them at the PN-PTI test for maintenance.

4 Conclusions

The solid PNC emission (for particles >23 nm) of 1474 buses was measured following the PN-PTI procedure developed by CALAC+. A wide spectrum of emission standards were tested from Euro II to Euro VI, vehicles equipped with retrofitted and OEM DPF, and CNG vehicles.

4.1 Diesel Buses with DPF

A reduction of approximately 99.5% of the PN emission is estimated in the studied fleet with the adoption of DPF technology. In particular OEM DPF buses presented very low exhaust PNC, 92% below 5000 #/cm^3, even lower than PNC in ambient air. For retrofitted DPF buses 65% exhibited exhaust PNC below 5000 #/cm^3. As mileage increased, the amount of buses retrofitted withe DPF with emission higher than 5000 #/cm^3 and 250,000 #/cm^3 increased. No correlation was found with model year or engine size.

The revision of PN-PTI approval limits revealed that limits of 1,000,000 #/cm^3 or 250,000 #/cm^3 would not detect all DPF malfunction. For a 250,000 #/cm^3 limit the approval rate would be 95%, and lowering the limit to 50,000 #/cm^3 would still return high approval rates of 92% (83% retrofitted and 97% OEM) and allow the detection of all malfunctioning DPF, either with failure or those that require maintenance.

The PN-PTI test is successful in detecting malfunction or failure in the DPF. Of the 726 buses with DPF, 5.5% (40 buses) had PN emission higher than 250,000 #/cm^3, indicating DPF damage or malfunction, 39 buses of these had retrofitted DPF. The bus with OEM DPF failure was new and had not entered operation yet, suggesting that the PN test may be required also for new vehicles. The retrofitted DPF with failure were found to belong mainly (98%) to two yards, indicating that operation and maintenance programs are key to the durability of the DPF.

High-idle tests were performed to investigate the performance of the DPF in vehicles with PN emission below 250,000 #/cm^3 but higher than the average. It was found that vehicles with low-idle PN emission between 50,000 and 250,000 #/cm^3 presented high PN emissions at high-idle, suggesting the need for maintenance. Adding a high-idle test to the PN-PTI procedure for vehicles with PN emission between 50,000 and 250,000 #/cm^3 may help to detect and flag DPF that are not working properly and require maintenance.

4.2 Diesel Buses Without DPF

The exhaust PNC measurement can be used to target very-high emitters for the implementation of special policies. The use of a high-concentration particle counter is suggested to avoid the need of external dilution systems.

4.3 CNG Buses

PN emissions were extremely low, probably because the lower detection limit of the equipment (23nm). For this vehicle category lower detection limits need to be considered for the implementation of PN-PTI tests.

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Author Contribution M.B coordinated the logistics of the experimental campaign, did analysis of results and wrote the main manuscript text, J.L performed the experimental measurements, A.A did the data analysis and prepared all figures, J.A sourced funding and coordinated the logistics of the experimental campaign. All authors reviewed the manuscript.

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Declarations

Ethics Approval Not applicable

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