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Comparative study of aftermarket and OEM DPFs for Periodic Technical Inspections (PTI) compliance with new PN emission limits

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This study evaluates the performance of aftermarket and OEM diesel particulate filters (DPFs) using a particle number counter (PNC) during stationary Periodic Technical Inspection (PN-PTI) tests. Several European countries have already implemented regulations requiring this test to ensure that vehicles equipped with DPFs meet the stringent particle number (PN) emission limits. In this work, measurements were conducted on various vehicles with new and conditioned DPFs. The results revealed significant variability in PN emissions, with some filters failing to meet the required limits. Key contributors to elevated PN levels were identified, including filter aging and inadequate conditioning procedures. Based on the findings, the paper proposes practical recommendations and diagnostic approaches to support compliance with PN-PTI test requirements.

Key words: *Periodic Technical Inspections, particle number counter, PN-PTI test, DPF*

1. Introduction

1.1. Aftertreatment technologies for particulate matter emission control

Stringent global emission regulations have necessitated the integration of advanced aftertreatment technologies in diesel vehicles. Among these technologies, Diesel Particulate Filters (DPF) have become essential for effectively reducing particulate matter emissions. DPFs are now standard in all new passenger and diesel vehicles due to European regulations [9]. The introduction of limits on particle number (PN), along with existing particulate matter (PM) standards, demonstrates the growing concern about the health effects of very fine particles [4]. These regulations have encouraged the development of DPF technology, creating a market with both original equipment and aftermarket alternatives. Periodic Technical Inspections (PTI) are essential to ensure that vehicles continue to comply with environmental and safety standards throughout their service life [14]. Emission tests during Periodic Technical Inspections help identify vehicles that release too many particles, confirming the proper operation of Diesel Particulate Filters. PTI procedures are created to find cars that don't have DPFs or DPFs that aren't working properly [9].

The effectiveness of a DPF is determined by a variety of parameters, including the design of the filter substrate, the materials used, and the regeneration process. Original Equipment Manufacturer (OEM) and aftermarket DPFs have different designs, materials, and production processes, which affect their performance and durability. A typical DPF consists of a metallic shell and a substrate made of cordierite or silicon carbide (SiC). The filter has a honeycomb structure with alternating plugged channels, forcing exhaust gas to flow through the porous walls [4, 16].

Diesel particulate filters (Fig. 1) are critical to reducing emissions of particulate matter from diesel engines, improving air quality, and public health. These filters trap particulate matter, or soot, and later burn it off in a process called regeneration, which significantly reduces the number of harmful particles released into the atmosphere. As exhaust gas flows through the DPF channels, particulate matter (mainly soot and ash) is trapped on the walls of the filter. The accumulated soot needs to be removed periodically to prevent excessive pressure drop and maintain filter efficiency. This is done through a process called regeneration, where the soot is oxidized at high temperatures [1, 4]. There are two main types of regeneration [1, 16]:

- passive regeneration: this occurs continuously during normal engine operation when exhaust gas temperatures are high enough (300–400°C) to oxidize the soot
- active regeneration: this is triggered when exhaust temperatures are not high enough for passive regeneration. It involves injecting extra fuel to raise the exhaust temperature and burn off the collected soot.

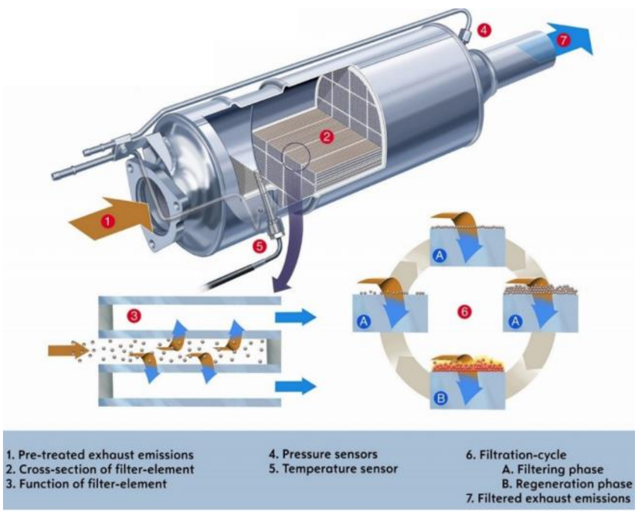

Fig. 1. Construction and operation of the DPF filter [1]

Even slight damage, such as small cracks on the DPF's substrate, whether from physical impact, thermal stress, erosion, or manipulation, can greatly impair its particle filtration performance. The presence of cracks enables exhaust gases to bypass the intended filtration channels, resulting in a rapid reduction in the DPF's ability to capture particles [4].

The porosity of the DPF substrate is a critical parameter influencing filtration efficiency and backpressure. Higher porosity can reduce backpressure, which may compromise filtration efficiency, while lower porosity can increase filtration efficiency, which raises backpressure. The optimal porosity is a balance between these competing effects. The introduction of particle number emission limits in addition to particulate matter mass limits has further necessitated the use of highly efficient DPFs capable of capturing even the smallest particles [14]. Typically, silicon carbide filter walls have a porosity of 40% to 50%. Cordierite DPFs, however, generally exhibit a porosity between 50% and 60%.

Diesel engine particle sizes (Fig. 2) typically range from 5 nm to 1000 nm (1 μm). Ultrafine particles (< 100 nm) can penetrate deep into the lungs and subsequently enter the bloodstream, primarily depending on their size. Insoluble particles, such as soot and metal oxides, are transported via the circulatory system throughout the body, crossing both the blood–brain barrier and the placenta [17]. Particle size distributions from diesel engines are often lognormal, with mean diameters ranging from 60 to 120 nm [7]. However, it's important to note that particle formation and size are affected by combustion conditions, engine operating conditions, and fuel composition [1, 2]. Particulate matter in diesel exhaust is a complex mixture of carbon soot, unburned fuel and lubricating oil, and products of fuel pyrolysis reactions. Typically, PM consists of four components: solid soot, soluble organic fraction, sulfur compounds, and ash. In modern engines, the sulfur content of the fuel significantly impacts particulate formation [2].

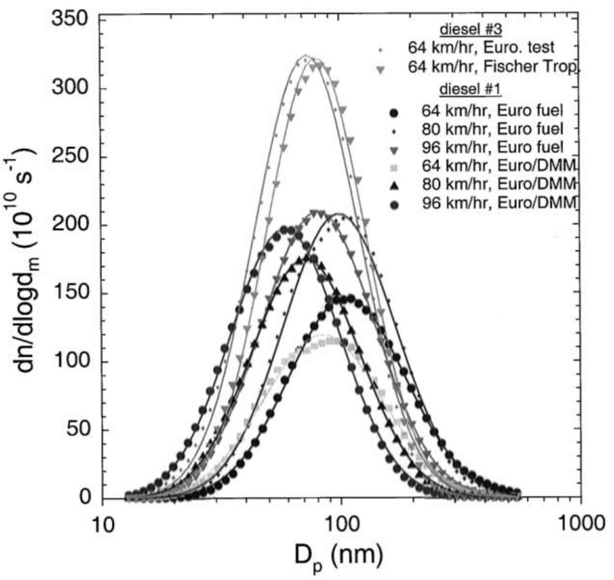

Fig. 2. Particle size distributions measured for a diesel vehicle under various engine speeds [7]

1.2. Current and planned particulate matter emission limits

The old opacimeter method measures smoke emissions from diesel vehicles during a free acceleration test. An opacimeter measures the absorption of light through the exhaust gas, providing a reading in m^{-1}. However, this method has limitations in assessing the performance of modern DPF equipped vehicles. Traditional opacimeters are not very effective in detecting DPF malfunctions. Even vehicles with damaged or removed DPFs can pass the opacity limits (< 0.5 1/m). The opacity limits in place are often too high to identify vehicles with malfunctioning DPFs. The accuracy of opacimeters can be limited, especially at low smoke emission levels [5, 9]. Several European member states are considering the introduction of SPN (solid particle number) concentration measurement in PTI [14].

Dynamometer testing, conducted within a controlled laboratory environment, serves to assess particulate matter and particle number emissions. Exhaust gases are then collected and analyzed using various instruments. Particulate matter can be measured using a filter method, while the solid particle number is measured using a particle counter. The emission is measured during a specific driving cycle, such as the New European Driving Cycle or the Worldwide Harmonized Light Vehicle Test Cycle [9, 18]. Comprehensive vehicle emissions assessments under controlled conditions offer several advantages, like the ability to measure multiple pollutants at once. However, they can be expensive and time-consuming and may not be suitable for large-scale fleet monitoring. The limitations of traditional opacity measurements in accurately evaluating DPF performance are prompting a shift towards particle number measurements. Measuring particle number at idle appears to be a promising way to detect DPF malfunctions [15].

The PN-PTI test is a method used during Periodic Technical Inspections to check the presence and proper functioning of diesel particulate filters in vehicles. It measures the concentration of solid particles in the exhaust gas [13]. Particle number concentration quantifies the number of particles within a specified volume of exhaust gas. The goal of PN-PTI is to identify vehicles that emit excessive particulate number due to DPF damage or removal. It is essential to guarantee compliance with emission standards and safeguard air quality [14]. PN-PTI utilizes specialized equipment to sample and measure the particle number concentration in the exhaust. The test is performed with the engine at idle speed. The procedure involves inserting a probe into the exhaust pipe to extract a sample of the exhaust gas. The gas sample is then processed to remove any volatile components, ensuring that only solid particles are measured. The concentration of solid particles is quantified using a particle counter. The result is compared with a set limit value [13, 14].

Table 1 presents an overview of PN-PTI measurement procedures and limits. The engine conditions, test duration, repetitions, and limit values exhibit variability across different countries.

Several issues and damages can affect DPF filters, leading to increased PN emissions and potential environmental concerns. Damage or malfunction of the DPF directly leads to a significant increase in PN emissions (Fig. 3). Even minor damage can cause emissions to exceed regulatory limits, and the PN-PTI test is designed to identify vehicles with such issues.

Table 1. PN measurement procedure during PTI in different countries [14]

Country	NL / BE	DE	CH
Effective date	07.2022	01.2023	01.2023
Engine conditions	Cold (only in case of "pass" result) or Hot	Hot (engine coolant > 60°C)	Hot
Sampling	15 s	30 s	5 s
Repetitions	1	3	3
Limit (#/cm^3)	1 000 000	250 000	100 000 * 250 000 **
Application	Euro 5 Euro 6	Euro 6	DPF equipped
* at low idling, ** at high idling (2000 rpm)			

The On-Board Diagnostics system may not always detect DPF failures, even when PM emissions are significantly higher than the regulation limit [18]. Because current EOBD systems lack PM or PN sensors, they cannot detect DPF failures and are easily manipulated when DPFs are removed. Also, engine behavior can strongly influence the PN emission. For example, the application of EGR can have a substantial effect on the PN emission of an engine at low idle speed. Therefore, the engine's condition should be taken into account during a PN-PTI test. Cracks or leaks in the DPF can result in significantly increased PN emissions. For instance, a DPF with a crack can lead to a PN emission of 2,000,000 #/cm^3 at low idle speed and over 6,000,000 #/cm^3 at high idle speed [9]. As mileage increases, DPF performance may degrade, leading to higher PN emissions, especially in retrofitted DPFs [3]. Furthermore, high sulfur content in fuel can negatively impact DPF regeneration [12]. Therefore, regular and appropriate maintenance practices are crucial to ensure continued optimal DPF functionality. The implementation of PN-PTI is expected to enhance the detection of malfunctioning or removed DPFs, contributing to improved air quality and environmental protection.

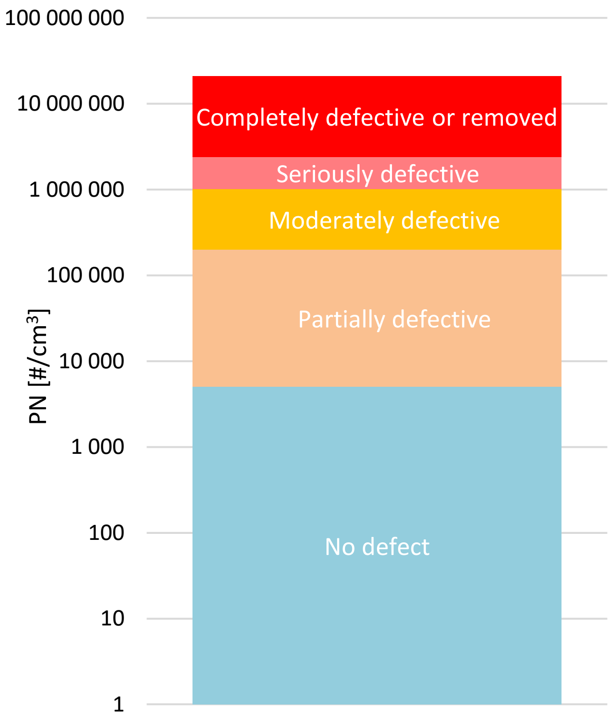

Fig. 3. DPF filter assessment depending on PN emissions [10]

2. Research methodology

2.1. Research objectives

The research aimed to evaluate the effectiveness of diesel particulate filters in meeting new periodic technical inspection (PTI) requirements based on particle number emissions. To achieve this, a series of emission tests were conducted using certified particle number counters (PNC).

The study was carried out in several stages. In the initial phase, PN emissions were measured from a variety of passenger vehicles equipped with diesel engines compliant with Euro 3, Euro 4, Euro 5, and Euro 6 standards. All vehicles were fitted with original (OEM) exhaust aftertreatment systems (Table 2). To provide a comparative baseline with legacy testing methods, an additional tester was used to assess particulate matter emissions based on smoke opacity, in accordance with the older methodology. The measurements were conducted at the beginning of the year on an outdoor parking area, with an ambient temperature of approximately 5°C. All tested vehicles had cold engines, and the measurements were taken 30 seconds after engine start, under idling conditions at low engine speed.

Table 2. Cars tested for different emission standards

Vehicle	Emission standard	Mileage ×10^3 [km]	Aftertreatment system
BMW X3 E83 3.0d 204 HP	Euro 3 (2004 year)	255	DOC without DPF
Toyota Auris 1.4 D4D 90 HP	Euro 4 (2007 year)	205	DOC without DPF
BMW 325d E91 3.0d 197 HP	Euro 4 (2007 year)	340	DOC with DPF but without filter inside
Peugeot 308 1.6 HDi 92 HP	Euro 5 (2012 year)	136	DOC with DPF
Skoda Octavia III 1.6 TDI 105 HP	Euro 5 (2014 year)	189	DOC with DPF
VW Passat B8 2.0 TDI 150 HP	Euro 6 (2019 year)	78	DOC with DPF and SCR

In the next stage of the research, a controlled test was performed on a Peugeot 308 passenger vehicle to investigate the impact of mechanical interference with the DPF on PN emissions (Fig. 4). The particle number measurements for the Peugeot 308 were conducted at an authorized service facility. The ambient temperature during testing was approximately 20°C. The vehicle arrived with a fully warmed-up engine, and the measurements were carried out 30 seconds after restarting the engine, under idling conditions at low engine speed. Three holes, each with a diameter of 10 mm, were drilled into the original diesel particulate filter to simulate unauthorized physical modifications made by the vehicle owner. Emission measurements were then taken to assess the effect of partial filter damage. Subsequently, the entire DPF core was removed from the housing, effectively disabling the particulate filtration system. Additional emission tests were conducted to evaluate particle number levels in the absence of any particulate control device. Finally, a new DPF unit was installed in the vehicle, and further tests were carried out to verify the performance of the fresh system in reducing particulate emissions.

In the following stage, new aftermarket diesel particulate filters were purchased from eight different suppliers operating in the secondary market.

Fig. 4. Tested DPF filters with 3 holes and empty

The selection included both silicon carbide (SiC) and cordierite DPFs. For comparison, original filters were also acquired, one OE filter (Eurorepar) and one OEM filter, to evaluate differences in performance between aftermarket and original equipment products. PN measurements were also performed at an authorized service center. The engine was already warmed up upon arrival, and the measurements were conducted 30 seconds after engine start, under idling conditions at low engine speed. All filters were tested for particle number emissions immediately after installation in the Peugeot 308 test vehicle, using a particle number counter. This allowed for a direct comparison of filtration efficiency among new and unused DPFs from different sources.

Additionally, two selected aftermarket DPFs were installed in the vehicle for real-world driving over defined distances (200 km and 1000 km, respectively), to evaluate how conditioning and initial soot loading affect filtration efficiency and PN emissions. These results provided insight into how aftermarket filters perform not only when new, but also after a short period of use under typical operating conditions.

In the final stage of the study, an additional test was conducted on a new aftermarket DPF. A forced regeneration procedure was carried out at an authorized service center (in the outdoor parking) for the Peugeot 308 vehicle. The regeneration was performed in stationary conditions according to the official guidelines provided by the vehicle manufacturer (Peugeot). Immediately after the forced regeneration (i.e., after conditioning the filter DPF), particle number emissions were measured using a particle number counter. This test aimed to evaluate the effect of the conditioning procedure on the initial filtration efficiency of a new aftermarket DPF.

An additional investigation was conducted on a used DPF that had been previously operated in a vehicle and exhibited particle number emissions exceeding the regulatory limits. To determine the possible cause of the poor filtration performance, the filter was sent to a specialized laboratory for a computed tomography (CT) scan. The CT analysis was performed to examine the internal structure of the DPF and verify whether the filter core had been damaged or degraded during use. This non-destructive diagnostic method allowed for a detailed internal inspection to identify potential structural defects or signs of mechanical interference that could explain the excessive PN emissions.

2.2. PTI-PN measurement devices

An opacimeter measures the opacity of smoke, indicating the concentration of particulate matter in the exhaust gas. It assesses how much light is blocked by the exhaust. During operation, a light beam is directed through a section of the exhaust gas stream. A sensor positioned on the opposite side of the exhaust gas stream measures the amount of light that passes through. The instrument then calculates the opacity based on the amount of light blocked, where higher opacity signifies more smoke [9, 18]. However, it's crucial to recognize that opacity tests possess a limited capacity to detect malfunctioning DPFs, in contrast to the heightened sensitivity of the PN-PTI method [14].

Particle Number measurement employs two primary technological approaches: condensation particle counters (CPC) and diffusion charging (DC) counters. Both types of particle number counters are utilized in PN-PTI tests to assess the performance of diesel particulate filters. Condensation particle counters (Fig. 5) are utilized to measure particle number during vehicle type approval, both in controlled laboratory settings and during on-road testing. Within a CPC, the process involves mixing the aerosol flow with a working fluid, often isopropanol, within a saturator, facilitating the fluid's evaporation. Subsequently, the saturated flow enters a condenser, where the isopropanol vapor condenses onto the particles, causing them to enlarge into detectable droplets. The instrument then counts these droplets by using light scattering to determine the number of particles [13].

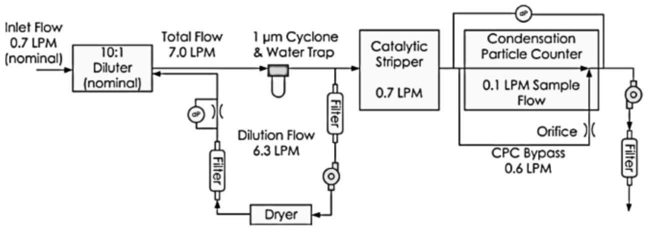

Fig. 5. Schematic of a CPC type counter [8]

DC-based PN counters (Fig. 6) are another type of instrument used in PN-PTI tests [6]. These counters work by first passing particles through a corona discharge, which transfers an electrical charge to them. The charged particles then enter an electric field. This electric field is used to collect the charged particles, and the instrument measures the electrical current produced. The measured current is proportional to the number of particles present in the sample [13].

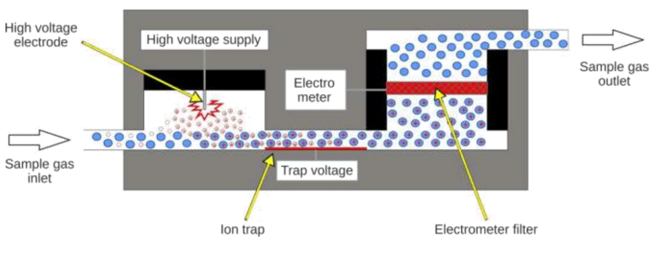

Fig. 6. Schematic of a DC type counter [20]

In summary, while opacity meters offer a simple check for excessive smoke, PN counters provide a more precise assessment of DPF performance by directly measuring the number of particles emitted, and different types of PN counters are available based on different measurement technologies. PN-PTI instruments should be robust, reliable, and easy to use. They also need to operate in a wide range of ambient conditions. The instruments determine the solid particle number concentration down to 23 nm [13].

3. Results

3.1. Overview of emission results for DPF filters

Using the Continental DX280 DC particle number counter, measurements of PN were conducted on vehicles compliant with Euro 3 to Euro 6 emission standards. The PNC used for testing was equipped with software calibrated for the Dutch market, where the limit is set at 1 000 000 #/cm^3. The device was borrowed courtesy of the director of Wijs-Air. Prior to testing, the PNC underwent a standardized warm-up procedure. Once ready, idle PN emissions were measured for all tested vehicles (Fig. 7). The result of each measurement was displayed on a wireless monitor approximately 15 seconds after the sampling began (Fig. 8).

Fig. 7. Measurement of PN and PM from the exhaust pipe

Fig. 8. PN measurement result on the Continental PNC display for the Peugeot 308 and for old OEM DPF

In addition, the same vehicles were also assessed for particulate matter emissions by measuring the exhaust smoke opacity using a DPF100 PM tester, which was also borrowed. For this device, results were categorized as follows: good (0–500 μg/m^3), marginal (500–1000 μg/m^3), and poor (above 1000 μg/m^3). Measurement results were visually indicated both by a corresponding LED on the tester's housing and on a wireless display (Fig. 9), which presented a real-time graph with horizontal limit lines for easy interpretation.

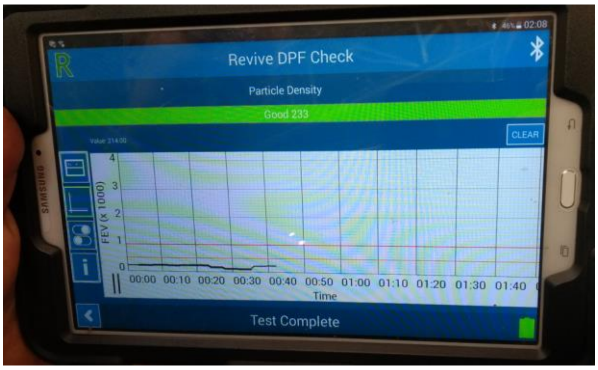

Fig. 9. PM measurement result (density) on the DPF100 tester display for the Peugeot 308 and for the old OEM DPF

As shown in Fig. 10, vehicles that were not originally equipped with a diesel particulate filter (BMW X3, BMW 325d, and Toyota Auris) exhibited PN emissions that exceeded the measurement range of the particle number counter, with values exceeding 20 million #/cm^3. In terms of PM emissions, the BMW vehicles recorded "poor" results, according to the DPF100 tester. Interestingly, the Toyota Auris, despite also lacking a DPF, showed a "good" PM result, with a value below 500 μg/m^3. This unexpected outcome for the Toyota may be attributed to the engine being fully warmed up at the time of testing. This suggests that the DPF100 PM tester may not be reliable as a standalone tool for verifying the presence or functionality of a DPF part, as thermal conditions can significantly influence the readings. For the Peugeot 308, the PN measurement exceeded 2 million #/cm^3, which clearly indicates a malfunction of the DPF. However, the PM tester reported a "good" result of 233 μg/m^3, again highlighting the limited diagnostic reliability of the DPF100 PM tester. Only the Skoda and Volkswagen vehicles produced PN results within the acceptable range, indicating that their DPF parts were functioning properly.

Figure 11 presents the results obtained from a series of controlled modifications performed on the DPF of a Peugeot 308. Initially, three 10 mm diameter holes were drilled into the existing DPF. In this configuration, the PNC immediately detected abnormally high PN emissions exceeding 10 million #/cm^3, indicating severe filter damage. However, the DPF100 PM tester reported a "marginal" result of 653 μg/m^3, suggesting that the filter was not in optimal condition.

In the next stage, the DPF core was completely removed. This resulted in an even higher PN reading from the PNC (over 20 million #/cm^3) and notably higher PM emissions measured by the DPF100 to 1154 μg/m^3, classified as a "poor" result. At this point, both devices correctly indicated the lack of DPF functionality.

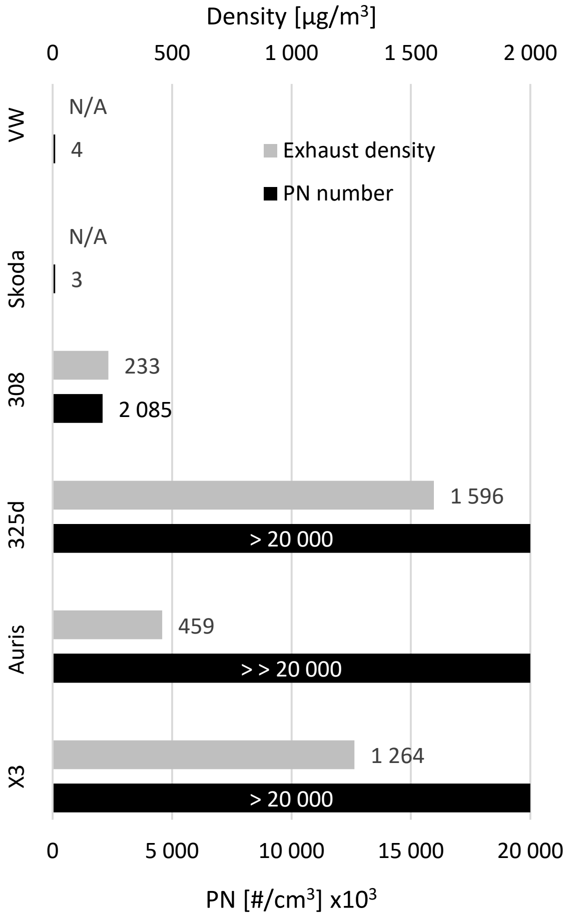

Fig. 10. DPFs assessment depending on PN emissions for different cars

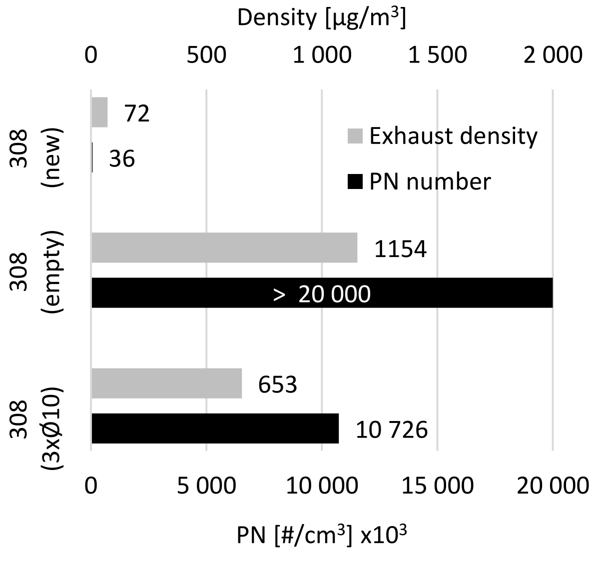

Fig. 11. PN emission results for damaged and new DPF in a Peugeot 308

Finally, after installing a new aftermarket DPF, both instruments recorded values consistent with proper filter operation. The PN count dropped dramatically to 36,000 #/cm^3, and the PM tester showed a "good" result of 72 μg/m^3. These results confirm that while both devices can detect a fully removed or replaced filter, only the PNC counter reliably identifies partial damage (e.g., drilled holes), highlighting its superior sensitivity to even minimal damage to the DPF.

The next stage of the study involved evaluating the performance of newly purchased diesel particulate filters, both original equipment manufacturer parts and aftermarket alternatives supplied by major secondary market producers. The tested DPFs included filters based on both silicon carbide (SiC) and cordierite substrates. Particle number measurements were carried out using a newly acquired Bartec nEC particle number counter (Fig. 12). Each measurement was conducted immediately after the installation of the respective DPF, under idle conditions. The vehicle used for all tests was the previously examined Peugeot 308 1.6 HDi.

The software of the Bartec nEC particle number counter was configured for the Swiss market and validated with the homologation certificate number CH-K4-23008-00. In accordance with current Swiss regulatory requirements, the measurement consists of three exhaust samples, from which the software calculates a final averaged PN emission result (an example is shown in Fig. 13 – test failed). The first stage of the measurement is performed at idle, with a strict limit of 100,000 #/cm^3 for the final result. If this maximum allowable value is exceeded, the procedure moves on to the second stage, where the software prompts the user to increase engine speed to 2000 rpm while remaining at idle. In this second stage, the emission limit is raised to 250,000 #/cm^3. All tested DPFs were evaluated during the first measurement stage only, at idle and under the 100,000 #/cm^3 limit. The emission levels observed were high, and proceeding to the second stage would likely have led to even higher emission values.

Fig. 12. Purchased Bartec nEC PNC for measurements

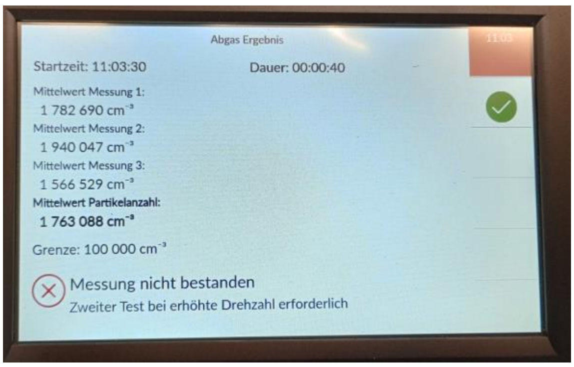

Fig. 13. PN measurement result on the Bartec nEC PNC display for the Peugeot 308 and for the cordierite DPF of competitor 8

Referring to the results shown in Fig. 14, none of the aftermarket DPFs tested (representing eight different competitors) passed the particle number emission tests, regardless of substrate type (SiC or cordierite). The average particle number for these aftermarket parts was significantly high, reaching approximately 1.6 million #/cm^3. Only the OEM DPF remained within the acceptable upper limit, achieving a value of 137,280 #/cm^3.

Interestingly, the OE Eurorepar filter ("OE_ER._SiC") also failed the test, clearly exceeding the regulatory limits. Although labeled as OE, this filter had been sourced through an aftermarket supplier, which was evident from its physical construction and manufacturer markings.

Additionally, after the initial testing, the OE Eurorepar part remained installed in the vehicle and was driven for approximately 1,000 km. A follow-up measurement then showed a dramatic improvement in performance, with a result of just 563 #/cm^3. Subsequently, a competitor 8 cordierite DPF ("Comp.8_Cord.") was installed, driven for about 200 km, and also delivered very good results (1854 #/cm^3). These road test results clearly indicate that aftermarket DPFs may require a period of conditioning before reaching their optimal filtration efficiency.

The final test conducted on the Peugeot 308 involved a forced regeneration of the DPF. After installing one of the aftermarket cordierite DPF filters, the particle number emissions were measured using the PNC device, resulting in a high value of 2 205 387 #/cm^3.

Subsequently, a forced regeneration procedure was performed at an authorized service. According to the manufacturer's diagnostic software, the regeneration process (Fig. 15) lasted approximately 1.5 hours and consisted of three identical cycles:

– 1st cycle: 35 min (7 min at 3000 rpm, remaining time at idle)
– 2nd cycle: 35 min (7 min at 3000 rpm, remaining time at idle)
– 3rd cycle: 35 min (7 min at 3000 rpm, remaining time at idle).

Immediately after the regeneration process, a follow-up PNC measurement showed that PN emissions had dropped below the 250,000 #/cm^3 limit, with a result of 173,172 #/cm^3. This demonstrates that forced regeneration has a measurable positive effect on the functional performance of the DPF.

3.2. CT scan analysis of filter structure and internal damage in DPF

An OEM diesel particulate filter removed from a Peugeot 308, provided by one of our customers, was found to exhibit elevated particle number emissions despite being a genuine component. The filter had a mileage of approximately 139,000 km at the time of inspection. This unit had previously been inspected and diagnosed by an authorized service center, after which it was replaced due to performance degradation. The filter featured a cylindrical geometry with a diameter of 5.66 inches, a length of 6 inches, and a cell density of 200 CPSI (cells per square inch), resulting in an approximate volume of 2.5 liters. According to the service report, the total soot load (i.e., particulate matter that can be removed through thermal regeneration) was measured at 1.65 g/l. In contrast, the ash content, which accumulates over time and cannot be removed by standard regeneration processes, represented about 82% of the total solid deposits within the DPF. Further inspection revealed that the filter was also physically damaged, with a visible crack in the ceramic structure. This combination of high ash loading and mechanical failure indicates an advanced stage of filter degradation and a significant reduction in soot storage capacity, ultimately justifying the need for replacement.

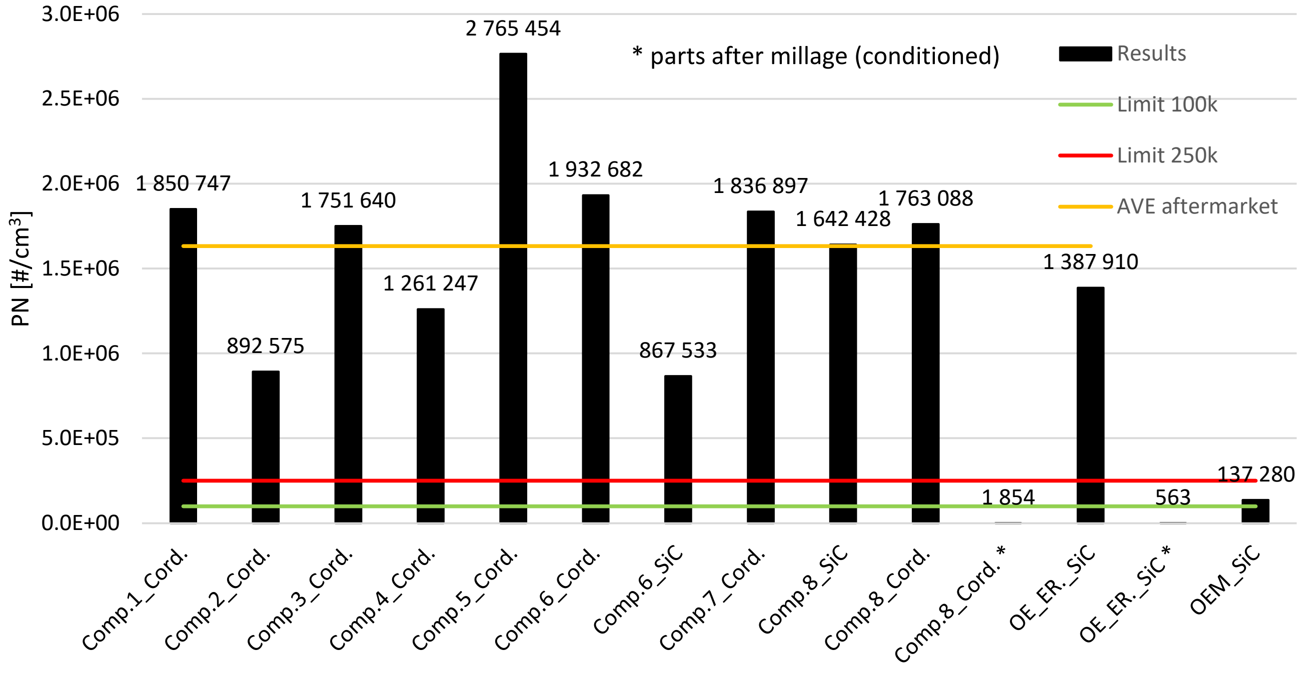

Fig. 14. PN emission results in a Peugeot 308 for different DPF filters from the aftermarket and original equipment

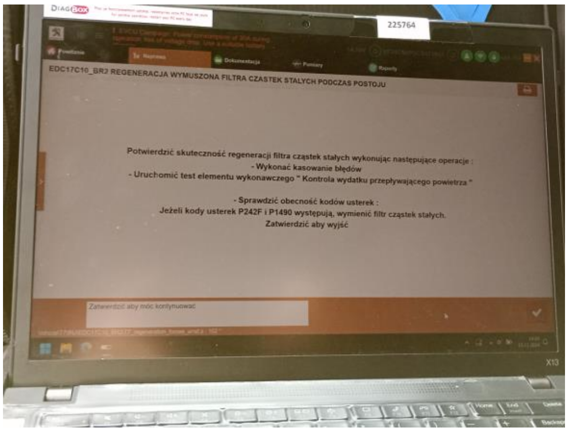

Fig. 15. Forced and stationary DPF filter regeneration by an authorized service

Following the installation of a new aftermarket DPF in the Peugeot 308, and after approximately two years of vehicle operation (covering a total distance of 33,000 km), the particle number emissions were remeasured using the PNC device. The recorded value reached 1 850 747 #/cm^3, indicating a significant deterioration in filtration performance.

To investigate the internal condition of the filter's core, the DPF was sent for X-ray computed tomography scanning at the CTLAB X-ray Computed Tomography laboratory, part of the Central European Institute of Technology. The CT scan was carried out using a GE Phoenix v|tome|x L240 tomograph, allowing for a non-destructive, high-resolution analysis of the filter's internal structure.

Computed tomography of the DPF revealed multiple transverse cracks in the lower part of the DPF filter (Fig. 16), a characteristic sign of "ring-off cracks", which commonly occur in diesel particulate filters [11, 19].

This type of damage usually happens when the DPF regeneration process doesn't occur properly. If the filter is clogged and the exhaust gases aren't hot enough, regeneration starts only at the front (inlet) of the filter. A heat wave then slowly moves toward the outlet. Because the rear part of the filter is still blocked with soot, it gets very hot. After some time, the high temperature at the outlet can also trigger regeneration from the rear side. Now, two heat waves travel toward each other – one from the front and one from the outlet. Meanwhile, the front of the filter stays relatively cool due to the incoming exhaust gases. This creates a strong temperature difference inside the filter. When the two heat zones meet (approximately one-third of the filter length from the rear), the thermal stress is so high that it causes the ceramic filter to crack – a failure known as "ring-off cracks".

The primary cause appears to be thermal stress generated during uncontrolled or interrupted regeneration processes. This typically occurs when the filter is heavily loaded with soot and regeneration initiates irregularly, creating intense localized heating. The resulting thermal gradients induce mechanical stress within the ceramic structure, leading to transverse cracks (ring-off cracks). Additional contributing factors may include:

- unplanned interruption of the regeneration process, such as turning off the engine while it's operating at high rpm
- the end-of-life condition of the DPF, where the filter becomes filled with non-burnable ash. This reduces flow and regeneration efficiency, leading to overheating
- poor engine condition or improper usage, such as excessive oil consumption or frequent short-distance driving, can contribute to excessive soot loading and regeneration difficulties.

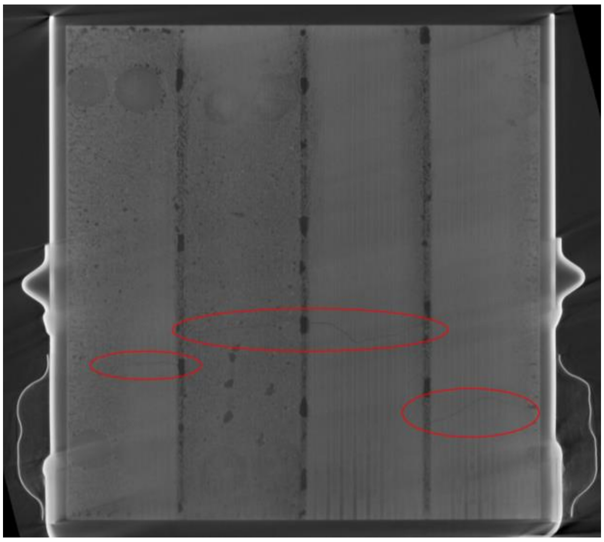

Fig. 16. Computer tomography of the DPF filter in the housing

The cracks likely resulted from a combination of excessive soot accumulation, irregular regeneration, and extended thermal gradients, all of which contributed to structural damage of the ceramic DPF filter.

After performing the CT scan of the DPF, the filter housing was cut for visual inspection of the internal damage. As shown in Fig. 17, a full circumferential crack was

Fig. 17. The filter after removing it from the housing

confirmed, and the filter unexpectedly split into two separate parts upon removal from the surrounding support mat.

The vehicle owner reported that the car was mainly driven on very short trips, typically around 3 km and occasionally up to 10 km. Additionally, the driver was unaware of when DPF regeneration cycles occurred. This strongly suggests that regeneration processes were either unsuccessful or early interrupted, which is a known cause of ring-off cracks.

In this case, the increased particulate number emissions recorded by the PNC device were caused by structural cracks in the DPF, which were confirmed both through computed tomography scanning and after cutting the filter housing. In addition to the high emissions, visual inspection showed significant smoke, a dirty exhaust outlet, and a noticeable unpleasant odor coming from the tailpipe.

In addition to the DPF filter that exhibited high PN emissions, a small cubic sample from both an OEM (SiC) filter (Fig. 18) and an aftermarket (cordierite) filter (Fig. 19) was sent to the CTLAB X-ray Computed Tomography facility at the Central European Institute of Technology. The purpose of this supplementary analysis was to examine the internal structure of the filters (wall thickness and porosity). This investigation aimed to explain why the OEM filter exhibited compliant PN emission levels immediately after installation in the vehicle, whereas the aftermarket DPF required initial conditioning to reach acceptable emission levels.

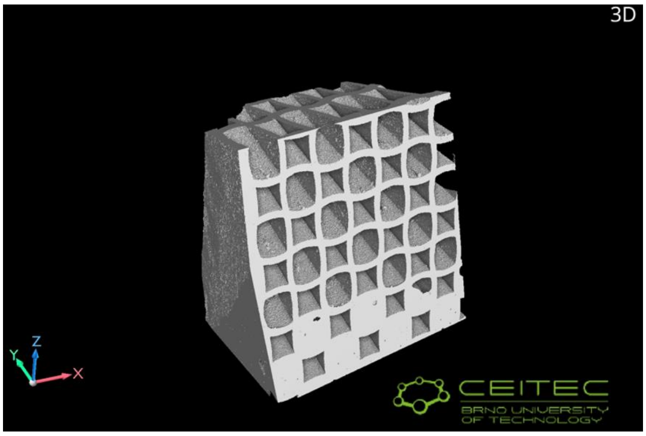

Fig. 18. 3D scan of a section of an OEM filter

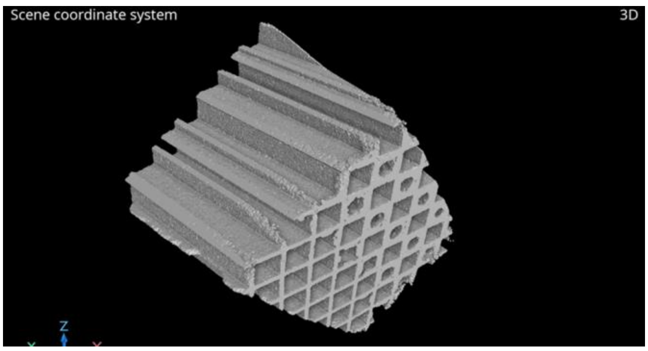

Fig. 19. 3D scan of a section of an aftermarket filter

Figure 20 shows the honeycomb structure of the OEM SiC filter, which features a relatively uncommon channel geometry. In contrast, Fig. 21 presents the more typical honeycomb structure of an aftermarket cordierite filter. A comparison of both structures indicates that the wall thickness of the OEM filter is 0.38 mm, while the aftermarket filter has a thinner wall of 0.31 mm – approximately 18% thinner. This reduced wall thickness likely contributes to lower particle filtration efficiency.

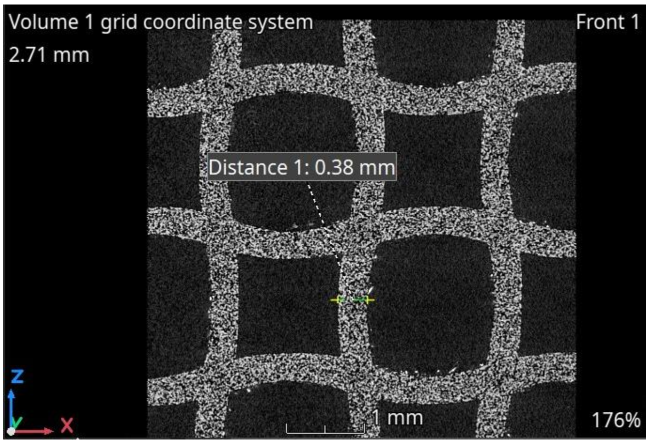

Fig. 20. Structure and wall thickness for OEM DPF SiC filter

Additionally, the OEM filter walls appear denser, with smaller pore sizes, whereas the aftermarket filter shows greater porosity (higher percentage of open space within the porous wall structure). This increased porosity improves the flow of exhaust gases and, consequently, allows more solid particles to pass through the filter wall.

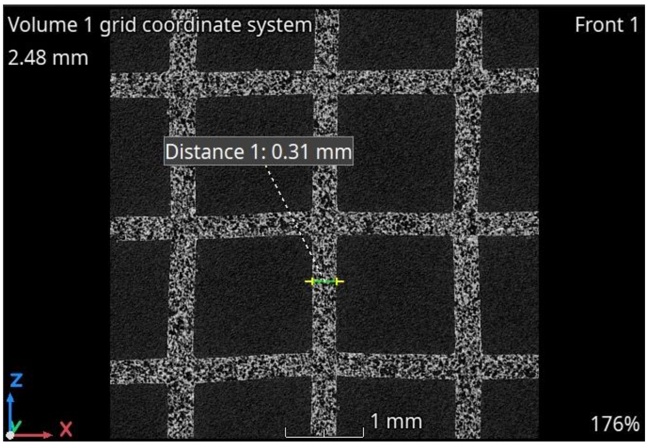

Fig. 21. Structure and wall thickness for Aftermarket DPF Cordierite filter

Figure 22 (OEM filter) and Fig. 23 (aftermarket filter) show magnified CT scan images of the filter walls and their pores. Several representative pore diameters are indicated, ranging from small pores of approximately 0.01 mm to larger ones around 0.06 mm. A visual comparison shows that the OEM filter contains a greater number of smaller pores, whereas the aftermarket filter exhibits larger pores.

Figures 24 and 25 present the pore diameter distributions for the OEM and aftermarket filters, respectively. Each histogram illustrates the frequency of pore sizes observed in the samples. The red solid line represents the fitted normal distribution, while the green dashed line corresponds to the log-normal distribution. These plots were generated using MATLAB, based on measurements extracted from CT scan image data.

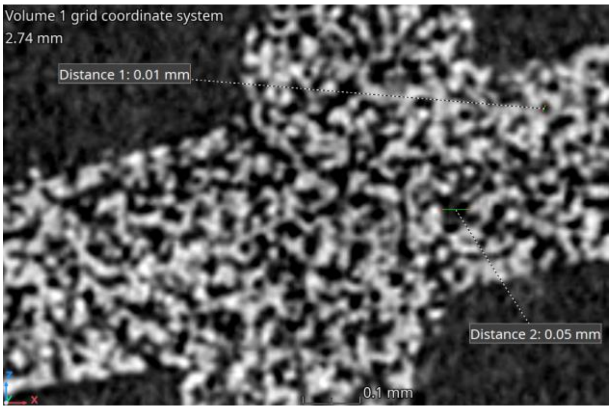

Fig. 22. OEM filter wall – magnified pore structure

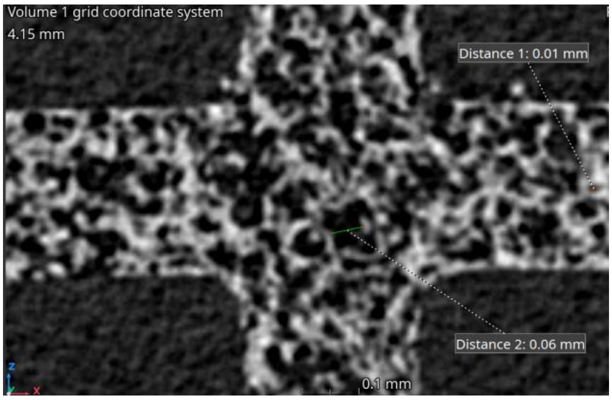

Fig. 23. Aftermarket filter wall – magnified pore structure

The OEM filter exhibits a more homogeneous pore structure, characterized by a narrower pore size distribution and reduced variability in pore diameters. In contrast, the aftermarket filter shows a broader pore size distribution, including a noticeable presence of larger pores. Such characteristics may suggest reduced efficiency in capturing fine particulate matter, although they could also result in lower flow resistance (i.e., lower pressure drop) across the filter.

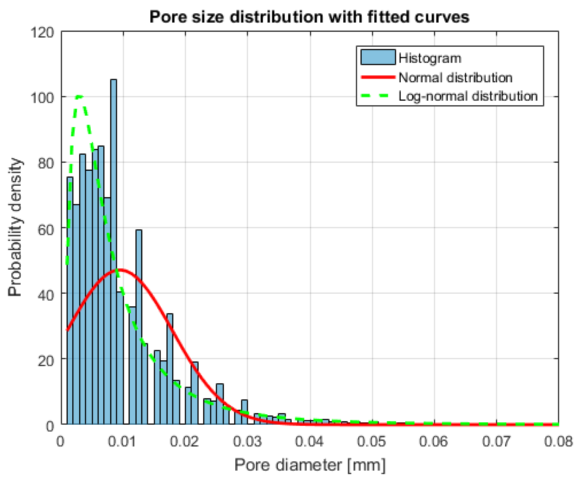

Fig. 24. Pore size distribution – OEM filter section

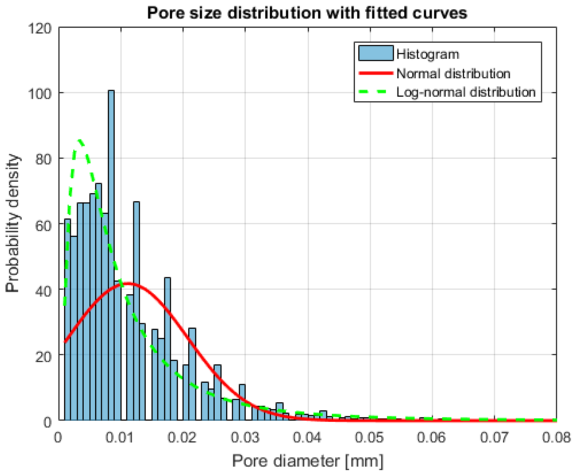

Fig. 25. Pore size distribution – aftermarket filter section

Based on this analysis, the mean pore diameter was calculated to be 9.5 μm for the OEM filter and 11.1 μm for the aftermarket filter. The porosity of each filter was determined by calculating the ratio of total pore volume to total sample volume, expressed as a percentage. According to this approach, the OEM filter exhibited a porosity of 39.5%, while the aftermarket filter showed a higher porosity of 45.5%.

As a result, the new aftermarket filter shows higher PN emissions during the initial phase. However, after a short conditioning period, the larger pores begin to fill with particulate matter, which enhances the filter's ability to trap particles and reduces emissions to levels compliant with regulatory limits.

4. Summary and conclusion

The conducted tests on vehicles with different emission standards demonstrated that particle number counters (PNC) are highly effective tools for determining the presence and proper functioning of diesel particulate filters, as well as for identifying their failure. In contrast, traditional opacity meters used to assess particulate matter (PM) emissions in the past often failed to accurately detect faulty or missing DPFs. Vehicles not equipped with DPFs – typically those compliant with emission standards lower than Euro 5, were unable to meet the new, stricter particle number (PN) limits during inspections when tested using PNC devices.

Further testing with the Peugeot 308 confirmed that aftermarket DPFs do not appropriately reduce PN emissions immediately after installation. Only vehicles equipped with original DPFs (OEM) consistently met the regulatory PN limits. One of the key factors influencing this outcome is the structural difference between filters, particularly wall thickness and porosity, which significantly affect filtration efficiency. However, the present study provides an initial comparison between OEM and aftermarket diesel particulate filters based on a limited number of samples. While the structural differences observed, such as variations in porosity and wall thickness, may suggest potential factors influencing filtration efficiency and PN emissions, the conclusions drawn should be considered preliminary.

To strengthen these findings and minimize overinterpretation, further comparative analyses are planned, including a larger sample size encompassing both OEM and aftermarket DPFs made of cordierite and SiC. This will include expanded CT imaging for evaluating structural and performance related differences between filter types and manufacturers.

New aftermarket DPFs require initial conditioning before they can reliably meet the PN limits during MOT testing using PNC devices. PN measurements should not be conducted immediately after DPF installation, as unconditioned filters may not yet be effective in trapping particulate matter.

Conditioning of aftermarket DPF filters can be achieved through a forced regeneration process, which is time-consuming, or through a relatively short driving period. Internal tests showed that after just a few kilometers of driving, the filters began functioning correctly and complied with the regulatory PN limits. Nevertheless, to ensure reliable performance and reduce variability caused by factors such as vehicle age, engine size, load, and fuel consumption, a minimum recommended distance of 60–100 kilometers should be covered before performing periodic technical inspections (PTI) using PNC devices.

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Nomenclature

CPC	condensation particle counter
CT	computed tomography
DC	diffusion charging
DPF	diesel particulate filters
OEM	original equipment manufacturer
PM	particulate matter
PN	particle number
PNC	particle number counter
PTI	Periodic Technical Inspections
SiC	silicon carbide
SPN	solid particle number

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