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Performance Assessment of an Advanced Diesel Particulate Filter for Euro 7 Heavy-Duty Vehicles

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Abstract

The Euro 7 standard for Heavy-Duty (HD) vehicles introduces stricter Solid Particle Number (SPN) emission limits by reducing In-Service Conformity (ISC) thresholds from 9.8×10^{11} #/kWh to 9.0×10^{11} #/kWh and lowering the minimum detectable particle size from 23 nm (SPN_{23}) to 10 nm (SPN_{10}). SPN emissions are excluded from active regeneration of Diesel Particulate Filters (DPFs), but passive regeneration during ISC testing remains a regulated condition for HD vehicles. These stricter regulations underscore the pressing need for advanced DPF technologies to ensure compliance under real-world operating conditions. In this study, a Euro VI Step E HD vehicle was evaluated on an HD chassis dynamometer using a predefined real-world ISC testing route to assess SPN emissions during passive regeneration of soot-loaded DPFs. Two SPN instruments, one downstream of the DPF and one downstream of the subsequent Selective Catalytic Reduction (SCR), allowed for a parallel characterization of the DPF performance and the net SPN increase observed across the SCR system. The tests indicate that passive regeneration in Euro VI vehicles can lead to SPN_{10} emissions as high as 23×10^{11} #/kWh with current technology DPFs. However, the advanced DPF technology limited weighted DPF-out SPN_{10} emissions to 1.2×10^{11} #/kWh, below the net increase observed across the SCR system (2.3×10^{11} to 2.9×10^{11} #/kWh), even during passive regeneration events, presenting a feasible pathway for achieving compliance with future emission standards.

Keywords: DPF; passive regeneration; solid particle number; 10 nm; Euro 7

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1. Introduction

The tightening of emission standards in the European Union (EU) has driven substantial reductions in automotive exhaust emissions over the years [1,2]. These advancements have been made possible through the continuous development of emission control systems, which remain vital in meeting increasingly stringent regulatory targets [3]. Among these systems, particulate filters have become essential components in both gasoline and diesel vehicles, particularly since the introduction of Solid Particle Number (SPN) limits within the EU regulations [4,5].

The recently adopted Euro 7 Regulation [6] introduces a modest 8% tightening (from 9.8×10^{11} #/kWh to 9.0×10^{11} #/kWh) of the SPN limits for In-Service Conformity (ISC) testing. The regulation, however, lowers the minimum detectable particle size threshold

from 23 nm to 10 nm. This change effectively tightens the emission budget further, as it now controls nanoscale particles at the tailpipe that were previously uncontrolled. For diesel vehicles, this shift to 10 nm requires control of particles generated within Selective Catalytic Reduction (SCR) systems [7–11], which have been reported to contribute up to 3×10^{11} #/kWh [12], i.e., 50% of the World Harmonized Transient Cycle (WHTC) dynamometer certification cycle limit, or one-third of the ISC limit. Consequently, the development of advanced filter technologies, either to directly target particles associated with the SCR system or to enhance the filtration efficiency of engine-out particles, is crucial in addressing these emerging challenges and ensuring compliance with the new regulatory framework [13,14].

Diesel Particulate Filters (DPFs) demonstrate exceptional particle number reduction potential, particularly as soot accumulates on their walls [15–17]. However, the accumulated soot must be periodically removed to prevent excessive back pressure build-up and, more critically, to avoid extreme exothermic reactions during soot oxidation that could damage the filter itself [18–20]. Currently, all systems in European HD vehicles rely to some extent on passive regeneration of the filter using catalysts to promote soot oxidation (primarily with NO_2) at temperatures encountered during regular vehicle operation. Whereas certain vehicles function predominantly via passive regeneration, others depend on periodic active control of exhaust gas temperature for DPF regeneration.

Under the regulation, cycle-averaged criteria pollutant emissions may exceed the regulated limits during tests that include an active regeneration event [21], provided that the average over the intervals between successive regenerations remains within the prescribed limits. This methodology is limited to engine dynamometer testing conducted over the regulated WHTC and applies only to gaseous pollutants and Particulate Matter (PM) mass [21]. SPN emissions are excluded from this procedure, as are all regulated emissions from on-road testing, where an active regeneration event invalidates the entire test [22].

In contrast to active regeneration, passive regeneration is treated as normal operation under the regulation. Accordingly, exceedances of SPN limits are not permitted, whether in test-cell measurements or during ISC testing. During passive regeneration, the soot cake is not always uniformly oxidized. Microscope images have revealed that, during oxidation, islands of soot cake can form, separated by areas where the filter wall is exposed [23–26]. Because the soot-free sections of the DPF wall are more permeable than the soot-covered areas, aerosol preferentially flows through these clean regions. This channeling raises the local through-wall (wall-normal) velocity above that of a uniformly clean filter, and the elevated velocity further reduces filtration efficiency [13]. As a result, passive regeneration can produce excessive SPN emissions, which can surpass those observed during active regeneration events [12,14].

The primary objective of this study is to characterize the SPN emissions of a Euro VI Step E truck during passive regeneration under ISC-relevant conditions. This vehicle was evaluated under similar conditions in an earlier study [12], enabling a direct comparison after substantially higher accumulated mileage. The present work extends that earlier study in several important respects. First, the earlier study did not focus on soot-loaded filters as a dedicated test condition, but rather included a single soot-loaded test to highlight the significance of soot-loaded passive regeneration for PN control. By contrast, the present study focuses specifically on this operating regime. Second, the same vehicle was re-evaluated after approximately 150,000 additional kilometers, allowing assessment of whether the net tailpipe SPN increase across the downstream SCR system changed with vehicle age. Third, the DPFs tested in the present study were brand new and ash-free, while preloaded with soot, enabling comparison with earlier data obtained using a

filter with 20,000 km accumulated mileage, i.e., close to the 25,000 km minimum mileage required before ISC testing. This comparison provides insight into the extent to which ash accumulation near the regulatory minimum mileage can enhance filtration efficiency, and therefore how much additional engineering margin it may offer for current-technology filters under passive-regeneration conditions. Fourth, whereas the earlier study evaluated an advanced filter concept [4] designed for the substantially more stringent filtration targets associated with the European Commission's initial Euro 7 proposal and based on a hierarchical wall microstructure [27,28], the filters tested here were optimized for the final Euro 7 regulation through a uniform microstructure optimization approach.

Two Original Equipment Manufacturer (OEM) filters and two Euro 7 filters were preloaded with 2.5 g/L of soot on an engine dynamometer and subsequently installed on the truck for emission characterization. Measurements were conducted on a chassis dynamometer, as it provides tighter control over operating conditions between repetitions and therefore improved repeatability. Two SPN instruments of identical design, each capable of simultaneous 10 nm and 23 nm measurements, were installed upstream and downstream of the SCR, enabling accurate quantification of DPF performance as well as the particle emissions generated within the SCR.

2. Materials and Methods

2.1. Test Vehicle

The vehicle tested was a 4 × 2 tractor powered by a 13-L Euro VI Step E-certified diesel engine, delivering a rated output of 500 hp. In accordance with Regulation 595/2009 [29], the reference work (W_{ref}) over the World Harmonized Transient Cycle (WHTC) was calculated to be 34 kWh. At the start of the test campaign, the truck had an accumulated mileage of approximately 200,000 km. The tests were conducted using commercially available diesel fuel compliant with EN590 specifications, along with commercial diesel exhaust fluid (DEF). The engine was operated with 5W/30 lubricating oil recommended by the manufacturer.

2.2. Particulate Filters

Two OEM cordierite DPFs were specifically procured for this study. Additionally, two advanced High Filtration Cordierite 2.1 (HFC2.1) filters (Corning Inc., Painted Post, NY, USA) of identical size and cell density (18 L, 300 cpsi) were prepared for the study using the original canning. The HFC2.1 technology features an advanced microstructure with a smaller mean pore size and a narrower pore size distribution compared to conventional Euro VI filters, offering improved filtration efficiency. Both the OEM and HFC2.1 filters were washcoated with an equivalent oxidation-catalyst-based coating technology. All filters were brand new, with no ash accumulation, and were pre-loaded with soot at a level of 2.5 g/L on an engine dynamometer bench at Corning Inc. using a 15 L HD diesel engine operating under steady state conditions. The soot loading progress was monitored using an AVL Micro Soot Sensor (MSS) [30], and the final soot mass was verified gravimetrically. To minimize interference from condensed water, the filters were weighed at 200 °C. The achieved soot loading ranged from 2.45 to 2.65 g/L across the four filters (Table 1). Two nominally identical filters of each type (OEM and HFC2.1) were included to examine the consistency of the observed trends across repeated tests.

2.3. Test Cell

All measurements were conducted at the Heavy-Duty (HD) vehicle laboratory of the Joint Research Centre (JRC) of the European Commission, located in Ispra, Italy. The climatic test cell is equipped with a four-wheel-drive, two-axle roller chassis dynamometer. All tests were carried out at a consistent ambient temperature of 23 °C.

Table 1. Overview of the test sequence for the four evaluated filters, including the gravimetrically determined soot load and the sampling positions of APC1 and APC2 in each test. For each filter type, "#1" and "#2" indicate the test sequence.

Day	Filter	Soot Load [g/L]	APC_1	APC_2
1	OEM #1	2.57	SCR out	DPF out [1]
2	OEM #2	2.47	DPF out	SCR out
3	HFC2.1 #1	2.65	DPF out	SCR out
4	HFC2.1 #2	2.61	SCR out	DPF out

[1] Measurement lost due to communication problems.

2.4. Test Setup

Two sampling probes were installed to enable simultaneous measurements of SPN emissions from two locations: the outlet of the DPF (upstream of the SCR) and directly at the outlet of the SCR (which is also the tailpipe emissions). The EFM was positioned downstream of the second sampling probe, with the entire exhaust system subsequently vented.

2.5. Measurement Instrumentation

Two Advanced Particle Counters (APC Model 489—AVL GmbH, Graz, Austria), each equipped with a 10 nm internal Condensation Particle Counter (CPC) and a 23 nm external CPC, were used for the measurement of SPN emissions [31]. In the APC, the exhaust was first diluted using a chopper diluter operating at 150 °C directly at the sampling location and then thermally processed in a Catalytic Stripper (CS) maintained at 350 °C [32]. Downstream of the CS, a simple mixer diluter cooled the thermally treated aerosol, bringing it within the operational temperature range of the two CPCs. One APC (APC_1) used CPCs manufactured by TSI (TSI Incorporated, Shoreview, MN, USA), while the other (APC_2) featured CPCs manufactured by AVL. The Particle Concentration Reduction Factor (PCRF) was set to 3500 in APC_1 and 3000 in APC_2. These relatively high PCRF values were chosen to ensure that the measured particle concentrations remained within the calibrated linearity range of the CPCs. Each APC sampled through a 0.5-m-long (4 mm inner diameter) stainless steel line heated to 90 °C. Although APC_1 and APC_2 used CPCs from different manufacturers, both systems complied with the applicable regulatory specifications; swapping their sampling positions during the test campaign was used to minimize any persistent instrument-to-instrument bias.

The truck's aftertreatment system was instrumented with thermocouples and pressure sensors to monitor temperatures and pressures at key locations, including the turbocharger outlet and the inlet and outlet of the DPF and SCR system. Data from these sensors, along with Electronic Control Unit (ECU) parameters such as engine speed, torque, and fuel consumption, were recorded using a dedicated data logger (UniCAN 3, CSM GmbH, Filderstadt, Germany). Additionally, the exhaust flow rate was measured using a 4-inch Semtech Exhaust Flow Meter (EFM) (Sensors, Inc., Saline, MI, USA).

All relevant signals used for emissions evaluation, including exhaust flow, ECU parameters, and particle number concentrations, were acquired within the laboratory automation system. Additional APC outputs were recorded externally to access instrument-specific parameters. The temporal alignment between particle number and exhaust-flow signals was verified once for each measurement configuration by examining dedicated distinct transient features during a warm up phase, and the corresponding delay was then implemented in the automation system and applied consistently to all recordings for that configuration. A post-check of each test dataset further confirmed that the applied delay corresponded closely to the maximum cross-correlation between the exhaust-flow and

particle-number signals. A sensitivity analysis showed that a residual misalignment of ±2 s affected the cycle-weighted emission results by less than approximately ±7%.

2.6. Test Protocol

2.6.1. Test Cycles

The passive regeneration emissions of the truck were characterized using the speed and slope trace of an on-road ISC cycle (Figure 1) for N3-class vehicles on the chassis-dyno [33]. Although it was performed in the laboratory, the other cycle requirements are compliant with European Euro VI Step E Regulation [34]. It has a total duration of 9267 s, with the first 27.1% representing urban driving, the next 26.4% rural driving, and the final 46.5% highway driving, with average speeds of 22.9 km/h, 58.8 km/h, and 79.8 km/h, respectively. All tests were conducted with a simulated payload on the dynamometer, corresponding to a gross vehicle weight of 29 tons. The total work over the ISC cycle for this payload was 225 kWh, equivalent to 6.6 × W_{ref}, which falls within the range required by the regulation of 4 to 8 × W_{ref}.

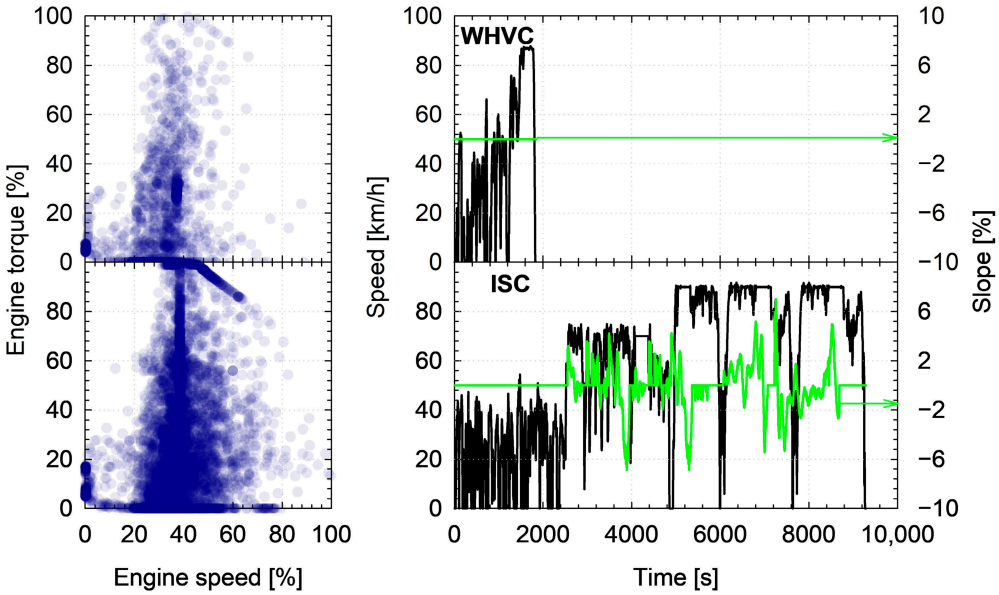


Figure 1. Operating engine maps (**left**) and speed (in black)/slope (in green) profiles (**right**) of the WHVC (**top**) and ISC (**bottom**) test cycles. Engine speed is normalized over the range from idle to maximum speed. ISC = In-Service Conformity; WHVC = World Harmonized Vehicle Cycle.

To ensure comparable SCR conditions at the start of each ISC cycle, the vehicle was conditioned at the end of each cycle with two repetitions of the World Harmonized Vehicle Cycle (WHVC). The WHVC is a chassis dynamometer implementation of the type-approval engine dynamometer cycle (World Harmonized Transient Cycle—WHTC) and was performed with the same payload and with a hot engine. A short highway driving segment was conducted prior to the first WHVC, while the second WHVC was performed shortly after the first.

2.6.2. Test Sequence

The vehicle was initially conditioned with two hot WHVCs and then soaked overnight for at least 8 h. At the start of each measurement day, the preloaded filter was installed prior to running an ISC cycle. Table 1 provides an overview of the test sequence. To ensure that the quantification of the urea-related SPN increase observed across the SCR system was not influenced by potential differences in the overall counting efficiencies of the two APCs, the sampling positions of the two APCs were swapped during the tests.

2.7. Evaluation Methodology

The concentrations reported by the APCs were adjusted using the PCRF and CPC calibration slopes. First, the concentrations and exhaust flows were normalized to the same conditions (0 °C and 1 atm). The two signals were then time-aligned and subsequently multiplied to calculate the instantaneous emission rates in particles per second (s^{-1}). Brake power was determined using the engine speed and torque data provided by the ECU.

The Moving Average Window (MAW) methodology was employed to calculate emissions in accordance with European regulations [6,34]. The evaluation process started once the coolant temperature surpassed 30 °C. The moving average windows were generated by increments of 1 s, with each window length determined to ensure the brake work within the window matched W_{ref}. In our tests, the elapsed time from the coolant first exceeding 30 °C to reaching 70 °C was less than 10 min. Therefore, the cold-start segment consisted of windows starting with coolant temperature between 30 °C and 70 °C. The remaining MAWs constituted the hot-start segment. All MAWs were included in the analysis since the average power across them exceeded 10% of the rated power. The cold-start emission results were determined using the 100th percentile of the cold-start MAWs, while the hot-start results were based on the 90th percentile of the hot-start MAWs. Under Euro VI Step E, this MAW methodology is applied to SPN_{23} and the result is compared with the applicable ISC threshold, whereas under Euro 7, the same methodology is applied to SPN_{10} and the result is compared with the Euro 7 threshold. Accordingly, the regulated emission results presented here were compared against the emission factor corresponding to the applicable Euro VI Step E conformity factor ($1.63 \times 6 \times 10^{11} = 9.78 \times 10^{11}$ #/kWh) and against the Euro 7 emission limit (9.0×10^{11} #/kWh).

Pressure Drop Normalization

The pressure drop across the filters, monitored in real time using dedicated pressure sensors, was normalized to a reference condition of 1250 kg/h flow rate and 200 °C temperature using the Euler-Reynolds number approach [35]. Neglecting second-order effects, the Euler number represents a nondimensional pressure drop, while the Reynolds number represents a nondimensional flow rate. Consequently, the product of the Euler and Reynolds numbers should remain constant under different exhaust conditions unless the filter's permeability has changed (e.g., due to the consumption of the soot cake). For the calculation of exhaust-gas properties, the exhaust was approximated as air. Gas density and viscosity were determined using the mean of the inlet and outlet DPF pressures and a representative gas temperature based on a 25%/75% weighting of the inlet/outlet DPF temperatures. This weighting was used as a practical approximation of the effective bulk filter temperature, accounting for the thermal mass of the substrate. Similarly, the average velocity through the filter was calculated from the volumetric flow rate and filter volume using the same representative pressure and temperature conditions.

3. Results

3.1. SPN_{23} Emission Performance

Figure 2 summarizes the SPN_{23} results for all four filters. The 100th percentile SPN_{23} emissions downstream of the DPF were low in all available DPF-out measurements, remaining at or below 3×10^{10} #/kWh. This outcome is consistent with expectations, given the high filtration efficiency of the soot cake deposited on the soot-loaded filters [36–38]. Nonetheless, the 100th percentile of the SPN_{23} emissions at the tailpipe were more than an order of magnitude higher averaging at approximately 2×10^{11} #/kWh. Hence, the dominant SPN contribution for soot-loaded DPFs is associated with the SCR system.

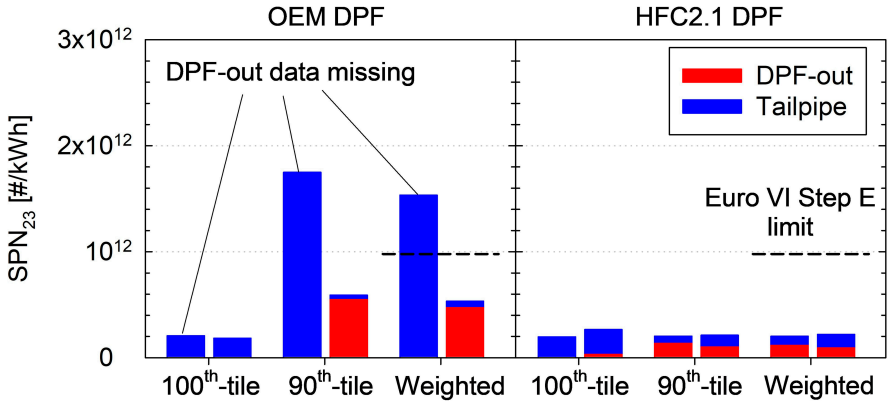


Figure 2. Summary of SPN_{23} emissions evaluated using the MAW methodology and compared with the applicable Euro VI Step E ISC threshold, for the OEM (**left**) and Euro 7 (**right**) filters. Results for the two filters of each technology are shown separately; within each result category, the bars are ordered as filter #1 followed by filter #2. Red bars represent emissions at the outlet of the DPF, highlighting the actual performance of the filter. Blue bars indicate emissions downstream of the SCR, reflecting the downstream urea-related particle contribution. The dashed lines illustrate the applicable SPN_{23} limit for the weighted ISC result. DPF = Diesel Particulate Filter; OEM = Original Equipment Manufacturer; SCR = Selective Catalytic Reduction.

A substantial increase in the 90th percentile SPN_{23} results was observed with the OEM DPF. The measured levels ranged between 6×10^{11} and 17×10^{11} #/kWh across the two test repetitions. In comparison, the corresponding figures for the two tests with the HFC2.1 DPF were 2×10^{11} and 2.1×10^{11} #/kWh. In all cases, the net particle number increase downstream of the DPF ranged between 0.5×10^{11} and 1×10^{11} #/kWh, indicating significant SPN slip during passive regeneration. These results demonstrate that the HFC2.1 technology is capable of maintaining 90th percentile DPF-out SPN_{23} emissions below 1.5×10^{11} #/kWh, under passive regeneration conditions. The weighted SPN_{23} emissions were 5.5×10^{11} #/kWh and 15×10^{11} #/kWh for the OEM DPF, compared to 2×10^{11} #/kWh and 2.2×10^{11} #/kWh for the HFC2.1 DPF. Conclusively, under the tested conditions, one of the two repetitions with the OEM DPF exceeded the regulatory PN conformity factor of 1.6 (equivalent to 9.78×10^{11} #/kWh), whereas the emissions with the HFC2.1 DPF remained at approximately 20% of the emissions threshold.

Previous tests conducted on the same vehicle with a 3 g/L soot-loaded OEM filter, after accumulating 20,000 km of mileage, revealed similarly high SPN_{23} slip over the same test cycle [12]. The 90th percentile SPN_{23} emissions (excluding particles formed downstream of the DPF) reached 21×10^{11} #/kWh when measured downstream of the DPF, while the weighted SPN_{23} result was 18×10^{11} #/kWh. These findings indicate that excessive PN slip during passive regeneration can be repeatedly observed under the tested conditions. In general, ash accumulated on the filter forms a cake layer that, over time, enhances the DPF's filtration efficiency. However, the good agreement between the emissions measured with fresh filters in the current campaign and with the 20,000 km filter in the previous campaign suggests that the ash deposited on the filter after the minimum required 25,000 km for ISC testing is insufficient to effectively control SPN slip during passive regeneration.

3.2. SPN_{10} Emission Performance

Figure 3 summarizes the SPN_{10} results for all 4 filters. Again, the 100th percentile results were dominated by urea-related particles reaching levels as high as 3.4×10^{11} #/kWh, with DPF out levels being substantially lower than tailpipe levels, due to the high filtration efficiency of the soot cake.

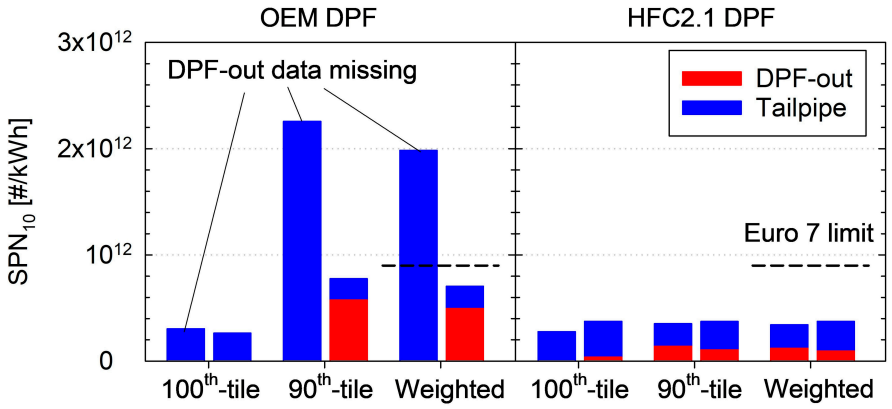


Figure 3. Summary of SPN_{10} emissions evaluated using the MAW methodology and compared with the Euro 7 limit, for the OEM (**left**) and Euro 7 (**right**) filters. Results for the two filters of each technology are shown separately; within each result category, the bars are ordered as filter #1 followed by filter #2. Red bars represent emissions at the outlet of the DPF, highlighting the actual performance of the filter. Blue bars indicate emissions downstream of the SCR, reflecting the downstream urea-related particle contribution. The dashed lines illustrate the Euro 7 SPN_{10} limit for the weighted ISC result. DPF = Diesel Particulate Filter; OEM = Original Equipment Manufacturer; SCR = Selective Catalytic Reduction.

Passive regeneration led to even higher results for SPN_{10} than for SPN_{23} with the OEM DPF filters, with the 90th percentiles being 7.8×10^{11} and 23×10^{11} #/kWh, and the weighted average results 7.0×10^{11} and 20×10^{11} #/kWh, respectively. On the other hand, the HFC2.1 results remained at similar levels with the 100th percentiles, leading to weighted SPN_{10} emissions of 3.4×10^{11} and 3.7×10^{11} #/kWh, with ~70% of them forming downstream of the DPF.

4. Discussion

4.1. Confirmation of Passive Regeneration

Figure 4 compares the real-time traces of inlet DPF temperatures and normalized pressure drops through the filters at 1250 kg/h flow rate and 200 °C (Section Pressure Drop Normalization). A sharp reduction in normalized pressure drop is observed starting at approximately 6400 s where the peak temperature is reached. The normalized pressure drop decreases from about 2 kPa to ~1 kPa for the OEM DPF and ~1.2 kPa for the HFC2.1 DPF by the end of the test. This reduction reflects a steady increase in filter permeability, which is consistent with the consumption of the soot cake. The pressure-drop trends were broadly similar across the available tests, suggesting comparable regeneration behavior for all four filters. The slightly lower normalized pressure drop observed with the first OEM DPF may be attributed to the 10 °C higher peak temperatures recorded or could be linked to test-to-test variability. The approximately 20% higher normalized pressure drop observed at the end of the test with the HFC2.1 filters aligns with the expected clean filter tradeoff, which is associated with the enhanced filtration efficiency of this Euro 7 technology DPF. The higher normalized pressure drop observed for the HFC2.1 filters is consistent with the general tradeoff between filtration efficiency and pressure drop. However, because the detailed properties of the OEM filter are not known and the present study was not designed to evaluate this tradeoff quantitatively, the observed difference is not interpreted further here.

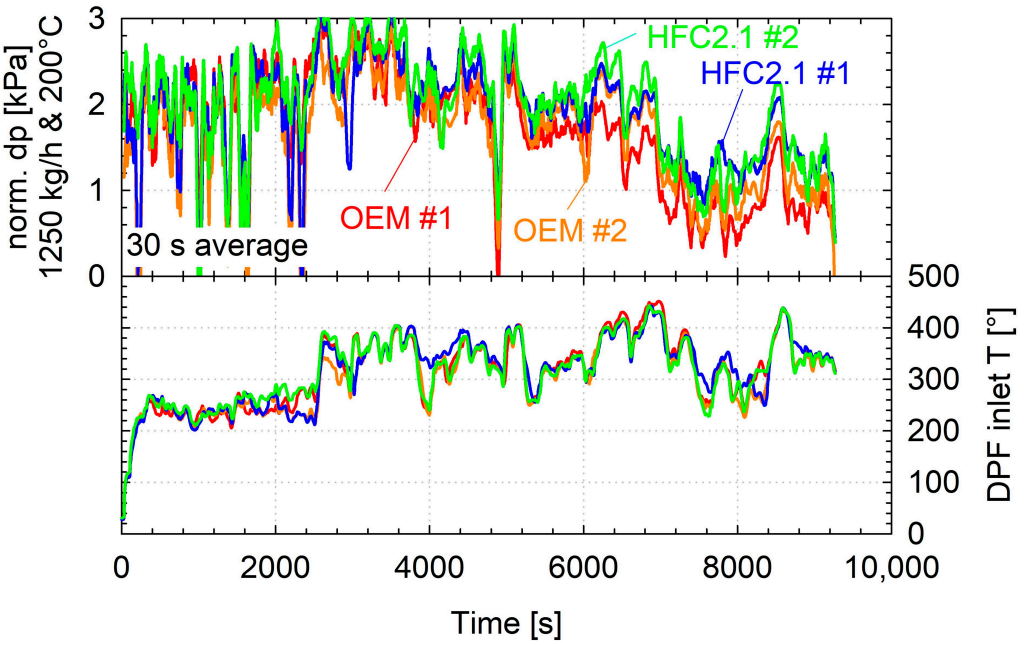


Figure 4. Evolution of the normalized pressure drop across the DPF (**top**) and inlet DPF temperature (**bottom**) during the ISC test cycle. Normalized pressure drops were calculated using the Euler-Reynolds number methodology and referenced to conditions of 1250 kg/h flow rate and 200 °C temperature. To facilitate comparisons, a 30-s moving average was applied to the normalized pressure drop data. DPF = Diesel Particulate Filter; OEM = Original Equipment Manufacturer; HFC = High Filtration Cordierite.

4.2. SPN_{10} Slip During Passive Regeneration of Euro VI Technology DPF

Figure 5 provides an overview of SPN_{10} emissions during the two ISC tests conducted with the OEM DPFs. The SPN_{10} traces at the outlet of the DPF indicate significant particle slip beginning at approximately 6400 s, with emissions remaining at elevated levels until the end of the test (~9300 s). The onset of slip coincides with the sharp decrease in normalized pressure drop observed in Figure 4, linking the phenomenon to the passive oxidation of soot.

The MAW results provide a more precise quantification of the changes in SPN_{10} emission levels. Prior to the onset of slip, SPN_{10} emissions are predominantly composed of particles formed downstream of the DPF (see difference of Tailpipe and DPF-out curves). These urea-related particles exhibit relatively stable emission levels throughout the test, ranging between 2.3×10^{11} and 2.9×10^{11} #/kWh, while DPF outlet emissions remain confined to less than 4×10^{9} #/kWh during this period. Passive regeneration leads to a sharp increase in SPN_{10} emissions downstream of the DPF, while particles forming downstream of the DPF continue to contribute at consistent levels (~2×10^{11} #/kWh). Peak tailpipe emissions during the tests reached 34.2×10^{11} #/kWh and 9.7×10^{11} #/kWh for the two OEM filters. The magnitude and timing of the observed SPN10 increases are consistent with findings from previous studies [14] on passive regeneration. Yet, the more aggressive regeneration behavior observed in the tests of the first DPF, as indicated by the sharper decrease in the normalized pressure drop (Figure 4), may suggest a higher regeneration efficiency that can also result in higher SPN slip [14].

4.3. SPN_{10} Slip During Passive Regeneration of Euro 7 Technology HFC2.1 DPF

Figure 6 gives an overview of SPN_{10} emissions during the two ISC tests performed with the HFC2.1 DPFs. The elevated SPN emissions observed at the outlet of the second HFC2.1 filter at the start of the cycle are most likely attributed to wear on the sealing gaskets

used to install the filter inside the aftertreatment box. The same gasket was reused across all tests, and some tearing was observed when the filter was removed at the end of this last test. This damage likely resulted in a minor slip of soot particles from the periphery of the filter. The gradual reduction in SPN_{10} emissions over the first ~3000 s likely reflects an improvement in the sealing, which may be partially attributed to the thermal expansion of the canned parts inside the aftertreatment box. Although this interpretation was not directly verified, any potential leakage appears limited, as start-up SPN_{10} levels were roughly an order of magnitude lower than the SCR-related SPN contribution (Figure 3) and is best viewed as a minor caveat that does not materially affect the main conclusions on SPN slip during passive regeneration.

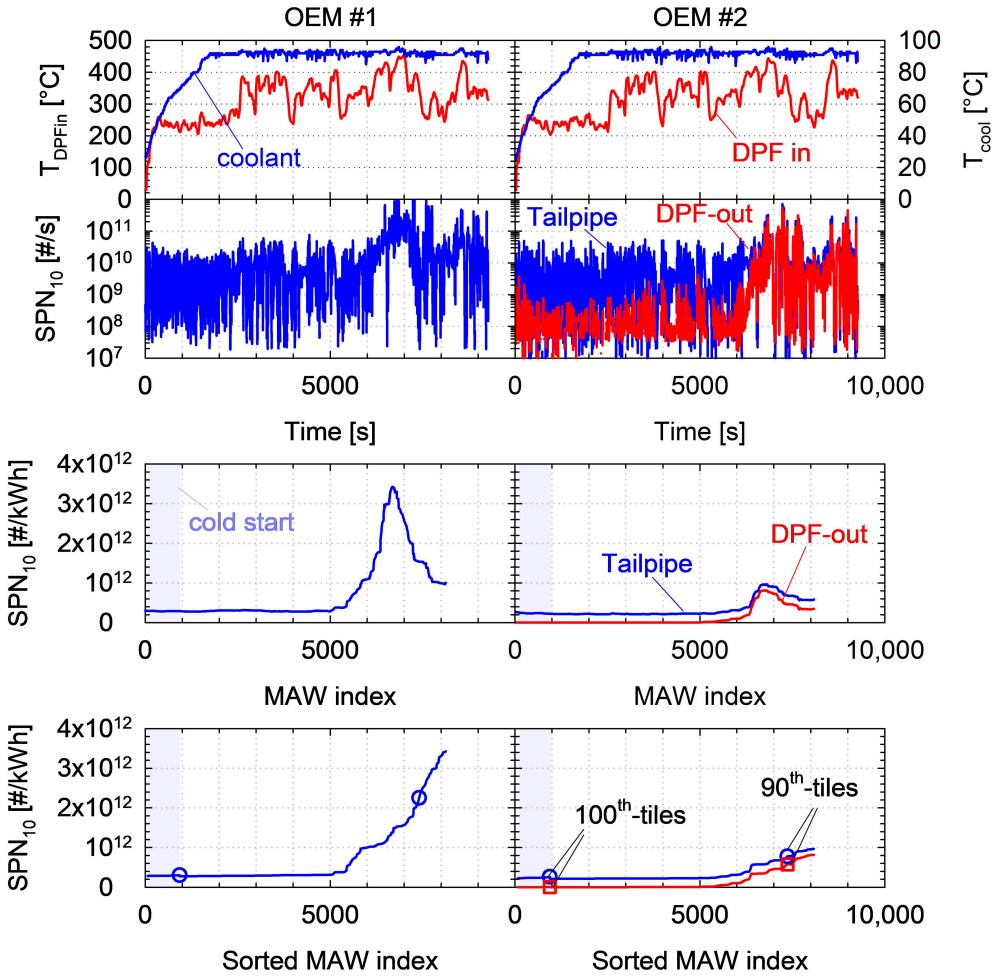


Figure 5. Comparison of SPN_{10} real-time emission rates (2nd row), valid MAW (3rd row), and sorted MAW (bottom row) during the two ISC tests with the OEM DPF. Temperatures at the inlet of the OEM DPF, along with ECU readings of coolant temperature, are shown in the top figures. The shaded colored area at the beginning of the tests illustrates the cold phase of the cycles, as defined in the Euro 7 regulation. The dots in the bottom figures represent the 100th percentiles of the cold-start (shaded blue area) section and the 90th percentile of the hot section; the corresponding numerical values are provided in the Supplementary Materials (Tables S1 and S2). DPF = Diesel Particulate Filter; ECU = Electronic Control Unit; ISC = In-Service Conformity; MAW = Moving Average Window; OEM = Original Equipment Manufacturer; SCR = Selective Catalytic Reduction.

Similar to the OEM DPF tests, the onset of SPN slip was observed at approximately 6400 s. However, the actual emission levels were significantly lower, with the peak MAW SPN_{10} emissions downstream of the DPF lying at 1.9×10^{11} #/kWh and 2.1×10^{11} #/kWh for the two HFC2.1 filters. These levels are comparable to the SCR-related SPN contribution.

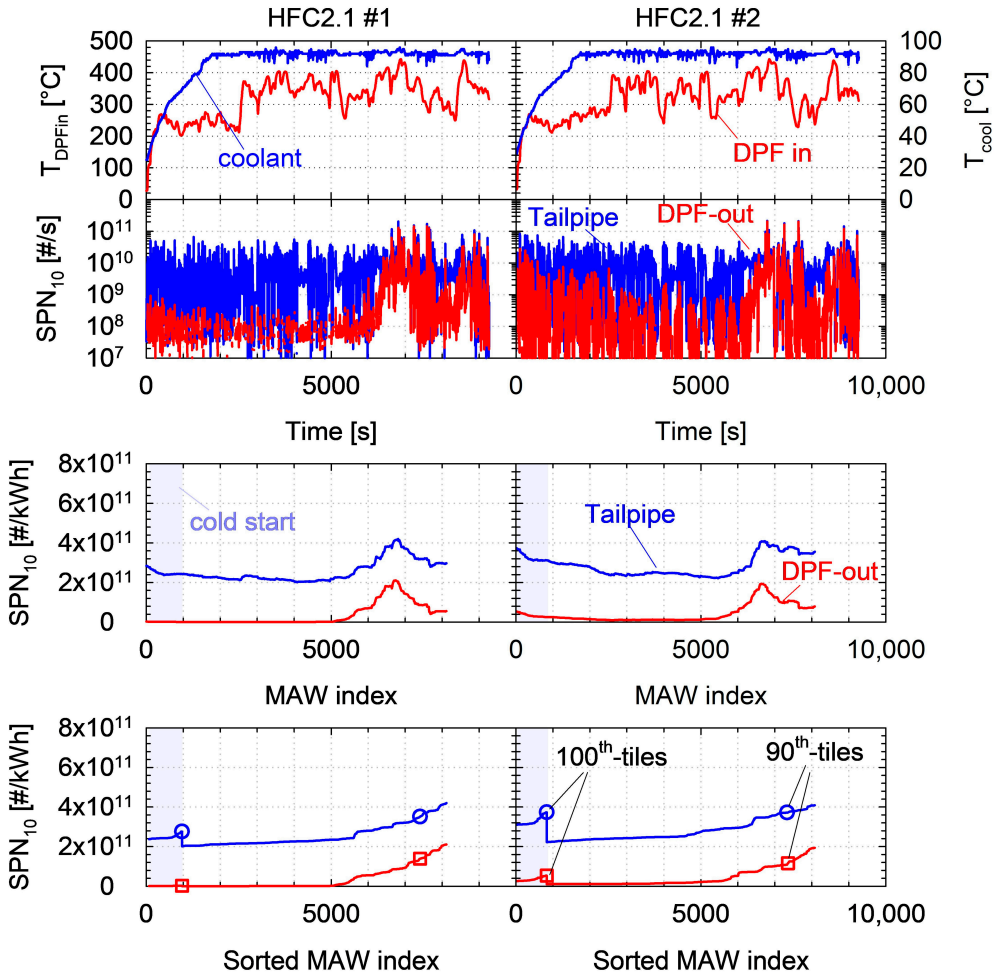


Figure 6. Comparison of SPN_{10} real-time emission rates (2nd row), valid MAW (3rd row), and sorted MAW (bottom row) during the two ISC tests with the Euro 7 DPF. Temperatures at the inlet of the DPF, along with ECU readings of coolant temperature, are shown in the top figures. The shaded colored area at the beginning of the tests illustrates the cold phase of the cycles, as defined in the Euro 7 regulation. The dots in the bottom figures represent the 100th percentiles of the cold-start (shaded blue area) section and the 90th percentile of the hot section; the corresponding numerical values are provided in the Supplementary Materials (Tables S1 and S2). DPF = Diesel Particulate Filter; ECU = Electronic Control Unit; ISC = In-Service Conformity; MAW = Moving Average Window; OEM = Original Equipment Manufacturer; SCR = Selective Catalytic Reduction.

4.4. Relevance of Passive Regeneration on European Truck Fleet

The effect of operating conditions on the magnitude of SPN slip during passive regeneration has been extensively studied in the literature [13,14]. It has been shown that the magnitude of the slip depends on exhaust conditions, specifically temperature and the ratio of NOx to soot mass (NOx-to-Soot Ratios NSR), as well as the state of the DPF prior to testing [13]. At NSRs above 150 and average temperatures exceeding 300 °C, a soot-loaded DPF has been observed to produce higher SPN emissions compared to tests starting with a clean filter, even when as much as 2–3 g/L of soot remains on the filter. This behavior suggests that non-uniform soot distribution exposes sections of the wall microstructure to the exhaust, causing a significant portion of the flow to pass through these high-permeability areas [23]. Elevated temperatures and increased NO_2 levels inhibit soot accumulation, resulting in prolonged periods of high SPN slip.

Figure 7 compares the NSR and exhaust temperature of the test truck, as determined in our previous campaign [12], with those of another Euro VI Step E-certified truck equipped with an active regeneration system and tested previously under the same cycle and payload

conditions [39]. The results shown correspond to the highway segment, where passive-regeneration leading to SPN slip is expected to occur. In both campaigns, soot concentrations were measured with an AVL Micro Soot Sensor sampling at the turbocharger outlet.

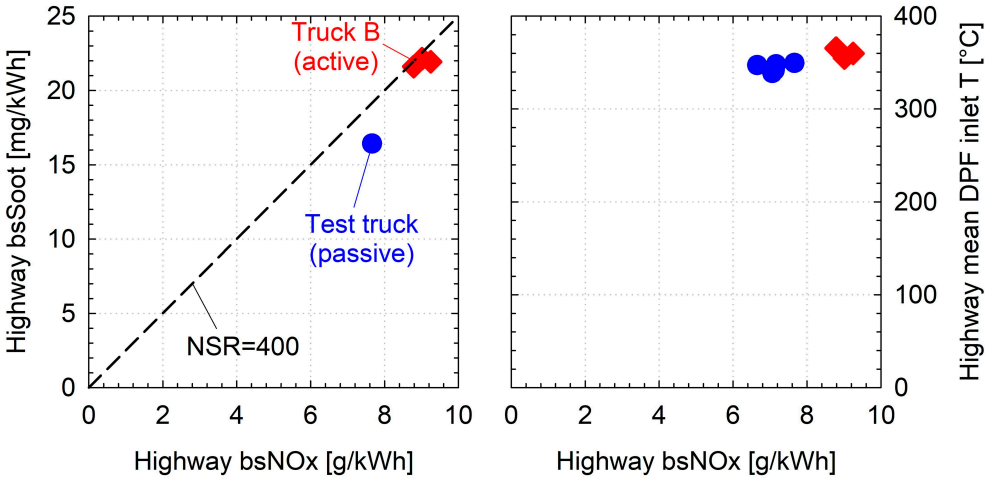


Figure 7. Comparison of highway brake-specific NOx emissions (bsNOx), brake-specific soot (bsSoot) emissions, and average temperatures at the inlet of the Diesel Particulate Filter (DPF) for the test truck (this study and [12]) and a Euro VI Step E truck equipped with an active regeneration system, tested previously under the same cycle [37]. The guideline on the left panel represents the NOx-to-Soot Ratio (NSR) of 400.

Both trucks were found to operate at similar NSRs of approximately 400:1, and similar average DPF inlet temperatures (330 to 360 °C) during the highway segment. These findings indicate that the conditions evaluated in the present study are not unique to a predominantly passive regeneration system, but are also encountered in a Euro VI Step E truck equipped with active regeneration. Since active-regeneration systems are designed to operate at higher soot loads (up to 5 g/L or higher), such conditions may actually be encountered more frequently and may therefore be even more relevant.

5. Conclusions

Euro VI and Euro 7 technology Diesel Particulate Filters (DPFs) were pre-loaded to 2.5 g/L soot and installed on a Euro VI Step E homologated heavy-duty truck for testing on a chassis dynamometer using an ISC test cycle compliant with regulatory requirements for real-world driving emission measurements. During the highway section of the cycle, the prevailing exhaust conditions consistently triggered passive regeneration across all tests. With the OEM Euro VI DPFs, weighted tailpipe SPN_{23} emissions reached up to 15×10^{11} #/kWh, exceeding the Euro VI Step E PN conformity threshold of 9.78×10^{11} #/kWh. Although one OEM DPF-out SPN_{23} trace was unavailable, the available measurements indicate that these elevated tailpipe levels were primarily associated with substantial DPF slip during passive regeneration, while the net SPN increase across the SCR system remained comparatively small. In contrast, the Euro 7 technology DPF maintained weighted DPF-out SPN_{10} emissions below 1.2×10^{11} #/kWh, while weighted tailpipe SPN_{10} emissions were 3.4–3.7 $\times 10^{11}$ #/kWh.

Particles associated with the SCR system are predominantly in the sub-23 nm range and therefore contribute more to SPN_{10} than to SPN_{23}. In addition, when passive-regeneration emissions are dominated by soot slip, the shift from SPN_{23} to SPN_{10} adds the 10–23 nm fraction of the soot size distribution, increasing the measured PN by about 30% in the present data. Together, these effects reduce the available compliance margin under Euro 7 and increase the importance of higher upstream filtration efficiency.

The exhaust conditions observed during aggressive highway driving were found to be similar to those also observed in a Euro VI Step E truck equipped with an active regeneration system. This indicates that the conditions identified here are not unique to predominantly passive systems. Since active-regeneration systems typically operate at higher soot loads (up to 5 g/L), such conditions may be particularly relevant for these vehicles with respect to passive-regeneration SPN slip.

This study has identified a demanding operating condition that warrant attention from enforcement authorities and should inform the design of Euro 7-compliant vehicles. At the same time, it demonstrated that advanced DPF technologies are capable of effectively controlling SPN emissions, even under challenging conditions associated with passive regeneration events.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/vehicles8090213/s1, Table S1: Summary of SPN_{10} and SPN_{23} emissions at the outlet of the DPF, evaluated using the MAW methodology; Table S2: Summary of SPN_{10} and SPN_{23} emissions at tailpipe, evaluated using the MAW methodology.

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Conflicts of Interest: A.M. (Athanasios Mamakos) and D.R. are employed by Corning GmbH. The HFC2.1 DPF evaluated in this study served as a demonstrator of a commercial technical solution developed by Corning Inc. The opinions expressed in this manuscript are those of the authors and should not in any way be considered to represent an official opinion of the European Commission.

Abbreviations

The following abbreviations are used in this manuscript:

APC	Advanced Particle Counter
CPC	Condensation Particle Counter
CS	Catalytic Stripper
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
EFM	Exhaust Flow Meter
EU	European Union
HD	Heavy Duty
HFC2.1	High Filtration Cordierite 2.1
ISC	In Service Conformity
JRC	Joint Research Centre
MAW	Moving Average Window

MSS	AVL Micro Soot Sensor
OEM	Original Equipment Manufacturer
PCRF	Particle Concentration Reduction Factor
PM	Particulate Mass
SCR	Selective Catalytic Reduction
SPN	Solid Particle Number
SPN10	Solid Particle Number above 10 nm
SPN23	Solid Particle Number above 23 nm
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle
Wref	Reference work over WHTC

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