

PN Emissions from Heavy-Duty Diesel Engine with Periodic Regenerating DPF

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ABSTRACT

Periodic increases of PN, PM, and regulated gases associated with DPF regeneration from a heavy-duty truck equipped with a diesel particulate filter (DPF; non-SCR truck) and from a heavy-duty diesel engine equipped with a DPF and a urea-SCR (SCR engine) were investigated. Both met Japanese 2009 regulations. From both exhausts, PN emissions two orders of magnitude higher than the European legislation limit were observed in the regeneration cycle, and these emissions gradually decreased in subsequent cycles. This can be explained by the relation between the filtering efficiency and the amount of loaded soot in the DPF. No emissions particular to regeneration, such as soot fragments, were observed. In some cases, higher PN emissions were observed from the SCR engine. This may be because of the difference in DPF performance, but there is a possibility that some particles were produced in the urea-SCR system. NO_x emissions from the SCR engine increased during regeneration because of the increase in engine out NO_x emissions in order to lower the regeneration temperature and the drop in NO_x removal efficiency of the SCR system due to the high exhaust gas temperature. Certification values of PM and PN were calculated as the weighted averages of periodic changes. The contributions of the first three cycles, starting from regeneration, to PN were 99 % for the non-SCR truck and 88 % for the SCR engine. These suggest that PN emissions in normal conditions have almost no effect on the certification values. In the PM measurement, the effect of tunnel blank was high.

CITATION: Yamada, H., "PN Emissions from Heavy-Duty Diesel Engine with Periodic Regenerating DPF," *SAE Int. J. Engines* 6(2):2013, doi:10.4271/2013-01-1564.

INTRODUCTION

Particles emitted from diesel engines have been regulated because of their toxicities. It is known that these particles are carcinogenic and cause damage especially to the respiratory system [1, 2]. In June 2012, the International Agency for Research on Cancer judged diesel exhaust to be carcinogenic [3]. Undertaking to reduce such hazardous species from diesel engines, manufacturers have been equipping almost all recent diesel vehicles with wall-flow Diesel Particulate Filters (DPFs). These are quite effective in reducing the particle emissions in diesel exhaust, and the filtering efficiency is usually more than 90 % [4, 5]. It is difficult to measure the particles after the DPF based on Particulate Mass (PM), which is the traditional filter weighing method [6]. In addition, particles of 10 to 100 nm in diameter are considered to be more toxic than other larger particles [7, 8]. From this point of view, the European Union (EU) has introduced a new regulation method based on the Particle Number (PN) in exhaust emissions from light-duty vehicles [9]. This regulation is also going to be applied to heavy-duty vehicles

(engines) in 2014 [10]. This is because PN has higher sensitivity, especially to small particles, than PM because this technique is not a mass-based method but is based on a count of the number of particles in exhaust gas. In addition, PN can be used to evaluate DPFs because it has sufficient sensitivity to measure the exhaust from DPFs [11, 12].

As discussed above, wall-flow DPFs exhibit quite high filtering efficiency. However, during normal operation, the particles are not oxidized into non-toxic species; they are just trapped and stored in the DPF. An increase of the trapped particles causes higher pressure loss at the DPF, which lowers the engine thermal efficiency [13]. To avoid this drop in efficiency, trapped particles are oxidized periodically by increasing the temperature in the DPF during the regeneration period. The regeneration intervals and periodic changes in the pressure drop strongly affect the engine performance. There have been some studies that examined the soot loading process in the DPF [14,15,16]. During the regeneration period, it is known that the filtering efficiency decreases because of the disappearance of a soot cake layer, which plays an important role in the soot trapping process in the

DPF [17]. In regulations, certification values of vehicles with DPFs under periodic regeneration are not the result of a single test, but are the averaged result during a period that includes the appearance of DPF regeneration [18, 19]. Thus, measuring the exhaust emissions during regeneration is essential for accurately evaluating DPFs. However, only a few studies have examined PN emissions during regeneration. Giechaskiel et al. [20] measured the PN during regeneration from a light-duty diesel vehicle. The particle emissions during regeneration were two orders of magnitude higher than those under normal conditions, but most of the increase was due to volatile particles. In PN measurement, volatile particles are eliminated before counting. Therefore, they concluded that the effect of regeneration on PN measurement is not so high. The effect was only a slight increase due to the drop in filtering efficiency resulting from a reduction in the amount of loaded soot by oxidation. On the other hand, Iorio et al. [21] measured the particle emissions from a heavy-duty engine during regeneration with a method that differs from the one used in the PN measurement system, and they observed solid particle emissions that were detectable with the PN measurement system. They concluded that there is a possibility that fragments of soot are emitted in the oxidation process during regeneration.

In this study, we examined periodic changes of PN, PM, and regulated gas emissions associated with DPF soot loading conditions and the appearance of regeneration. Examples of the most recent types of heavy-duty trucks and heavy-duty engines available on the Japanese market were tested with a chassis dynamometer and an engine bench, respectively. The effect of regeneration on NO_x emissions from an engine equipped with an SCR system downstream of the DPF is also discussed. In addition, the effects of regeneration and tunnel blank on the certification values of PM and PN, calculated as the weighted average during the periodic changes, are also discussed.

EXPERIMENTAL

Non-SCR Truck Tests

In this study, we examined PN, PM, and regulated gases from a heavy-duty truck that meets the Japanese 2009 regulations. These regulations are almost equal to the Euro VI regulations. Details of engine specifications are listed in Table 1. The after-treatment system of this vehicle consisted of a diesel oxidation catalyst (DOC) and a DPF. There was no after-treatment for NO_x reduction. The gross vehicle weight (GVW) was 13290 kg. In this paper we call this truck the “non-SCR truck”.

The truck was set on the chassis dynamometer, and all exhaust gas was introduced to a constant volume sampler (CVS), where it was diluted with filtered air. Figure 1 shows the experimental setup of this test. THC, NMHC, CO, NO_x , and CO_2 were measured using a MEXA-7500DEGR (Horiba). PM was trapped after secondary dilution. We used

a TX40 filter with a diameter of 70 mm, although EPA recommends use of a Teflon filter instead of TX40 for PM measurements from engines with DPFs [22]. These measurement systems meet the requirements of standard type approval tests in Japan. PN was measured with a MEXA-1000 SPCS (Horiba). This device measures only solid particles by eliminating volatile particles by hot dilution and has sensitivity to particles larger than 23 nm. These procedures are defined in relevant EU regulations for PN measurement [23]. Details are shown in Fig. 2.

Table 1. Specifications of tested non-SCR truck.

Manufacturer	Isuzu
Engine Type	4HK1-TCH
Max. Power (kW / rpm)	177 / 2600
Max. Torque (Nm / rpm)	706 / 1600
Displacement (L)	5.193
Numbers of Cylinders	Inline 6
Emission Level	2009 JP
After-Treatment	DOC, DPF
Type of Vehicle	Dump Truck
GVW(Kg)	13290

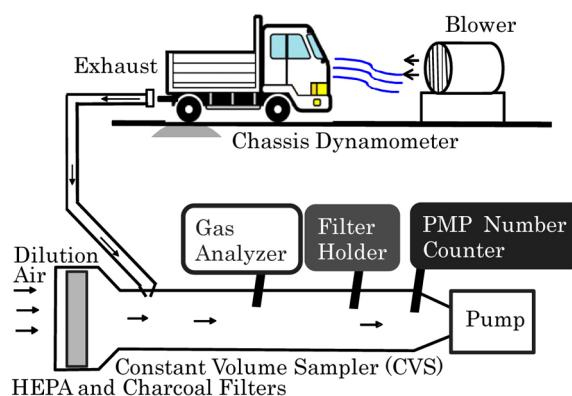


Figure 1. Experimental setup for non-SCR truck test.

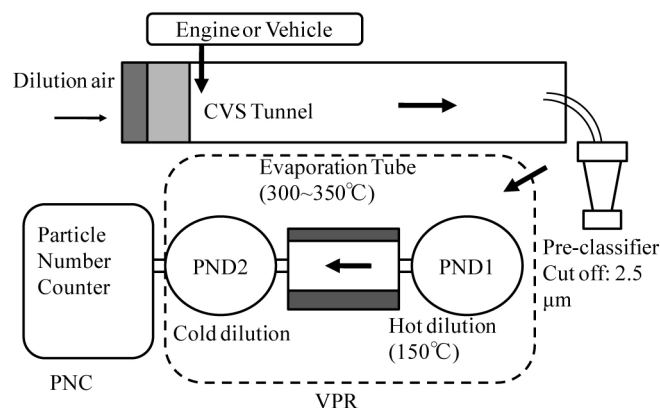


Figure 2. Schematic illustration of PN measurement system

The test schedule is listed in Table 2. The tests were conducted over 5 days. Before starting the first test on day 1, active regeneration was performed to clear the DPF. During the tests, JE05 mode operation without preconditioning procedures was repeated at 10-minute intervals. In total, 38 tests were performed, and we observed regeneration twice, on Day 3 and Day 5. They occurred in the 15th and the 21st tests after the former regeneration. Although we measured PN in every test, PM and regulated gas emissions were measured in selected tests only, which are shown with capital letters in Table 2.

Table 2. Test schedule of non-SCR truck experiments.

	1	2	3	4	5	6	7	8	9
Day1	h	h	h	h	h	h	h		
Day2	c	h	h	H	h	h			
Day3	c	h	h	h	H	h	h	h	
Day4	c	H	h	h	H	h	h	h	h
Day5	c	h	H	H	H	H	H	h	

c : JE05 cold mode without regulated emission measurement

h : JE05 hot mode without regulated emission measurement

H : JE05 hot mode with regulated emission measurement

h : JE05 hot mode without the regeneration measurement

H : JE05 hot mode with the regeneration measurement

SCR Engine Tests

In addition to the non-SCR truck tests, engine bench tests were also conducted. The specifications of the tested engine are listed in Table 3. The displacement of this engine was almost twice as large as that of the tested vehicle. This engine also met the Japanese 2009 regulations. The engine had a urea- SCR system for NO_x reduction and a DPF. We call this engine the “SCR-engine”.

Table 3. Specifications of tested SCR engine.

Manufacturer	Hino
Engine Type	E13C <ET-XIII>
Max. Power (kW / rpm)	279 / 1800
Max. Torque (Nm / rpm)	1912 / 1100
Displacement (L)	12.913
Numbers of Cylinders	Inline 6
Emission Level	2009 JP
After-Treatment	Urea-SCR, DPF

The emissions from the SCR engine were introduced to the same CVS used for the non-SCR truck tests. The instruments used for the SCR engine measurements were also the same as those used for the non-SCR truck tests, except for the PN measurement system. This time, we used an AVL particle counter (AVL). This device also meets the requirements of PN measurement, and equivalency of the

data to the Horiba system was confirmed. In the SCR engine tests, we selected the WHTC mode for the test cycle, and we repeated this mode at 10-minute intervals. The test schedule for the SCR engine is shown in Table 4. Tests were conducted over 11 days, and 96 tests were performed in total. Similar to the non-SCR truck tests, an active regeneration was performed before starting the first test on day 1. During the tests, we observed regeneration four times. Regeneration appeared every 21 or 22 tests. In these experiments, regulated gas emissions were measured in all tests; however, PM was measured in selected tests only, shown with capital letters in Table 4. Some ammonia emissions from the SCR engine were measured under conditions without regeneration using an FTIR system (Horiba, MEXA 4000 FT). However, emissions were below the detection limit (2 ppm).

Table 4. Test schedule of SCR engine experiments.

	1	2	3	4	5	6	7	8	9	10	11	12
Day1	H	H										
Day2	C	h	h	H	h	h	H	h				
Day3	C	h	h	H	h	h	H	H				
Day4	C	H	H	H	h	h						
Day5	C	h	h	h	h	h	h	H				
Day6	C	h	h	H	h	h						
Day7	C	H	H	H	H	H	H	H	H	H		
Day8	C	h	h	h	h	H	h	h	h	H	h	h
Day9	C	h	H	H	H	H	h	h	h	H	h	h
Day10	C	h	h	h	H	h	h	h	H	h		
Day11	C	H	H	H	H	H	H	H	H	H		

C : Cold test with PM measurement

H : Hot test with PM measurement

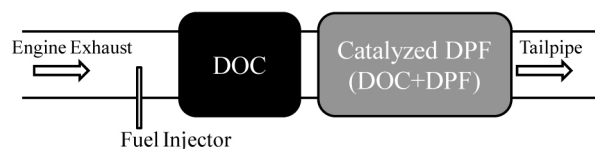
h : Hot test without PM measurement

H : Hot test with regeneration

Fig. 3 schematically illustrates the after-treatment systems provided in the non-SCR truck and the SCR engine. The non-SCR truck had a diesel oxidation catalyst (DOC) upstream of the DPF. In addition, an oxidation catalyst was also contained in the surface of the DPF. A fuel injector for starting regeneration was attached to the exhaust piping. The SCR engine had a DPF system (DOC + DPF) upstream of the SCR system. The SCR system consisted of a urea injector, an SCR catalyst, and a DOC for ammonia slip. This engine did not have a fuel injector in the exhaust piping. Thus, fuel injection for starting regeneration was performed by injectors in the cylinders. In the experiments with the SCR engine, two sampling probes of the exhaust gas analyzer were attached. One was located upstream of the whole after-treatment system to measure engine out emissions. Another was located downstream of the after-treatment system to measure the tailpipe emissions. The exhaust gas temperature was monitored after the SCR system; therefore, temperatures

observed during the DPF regeneration were somewhat low compared with the temperatures measured at the DPF.

Non-SCR truck



SCR engine

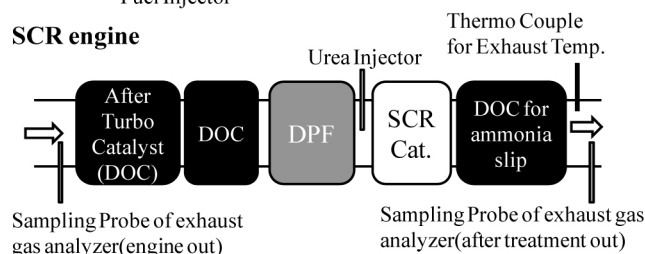


Figure 3. Schematic illustration of after-treatment systems with non-SCR truck and SCR engine.

RESULTS AND DISCUSSION

Periodic Changes of Non-SCR Truck Emissions

Figure 4 shows the gas emission results for the non-SCR truck as a function of the number of test cycles after the appearance of regeneration. The points located on the vertical axes and shown with closed symbols indicate the results for the cycles in which regeneration appeared. In the case of THC, NMHC, and CO₂, relatively high emissions were observed in the regeneration cycles. This was due to the fuel supply from the engine for increasing the DPF temperature to allow the regeneration. CO₂ emissions in the regeneration cycles were almost 10 % higher than in the other cycles. In addition to the increased fuel injection for starting regeneration, conversion of loaded soot in the DPF to CO₂ might have contributed to this increase. On the other hand, no differences were observed between cases with and without regeneration for NO_x and CO. For all species, the number of cycles after regeneration had no effect on the measurements in the non-regeneration cycles. This suggests that the emissions do not depend on the DPF condition, that is to say, how much soot is loaded.

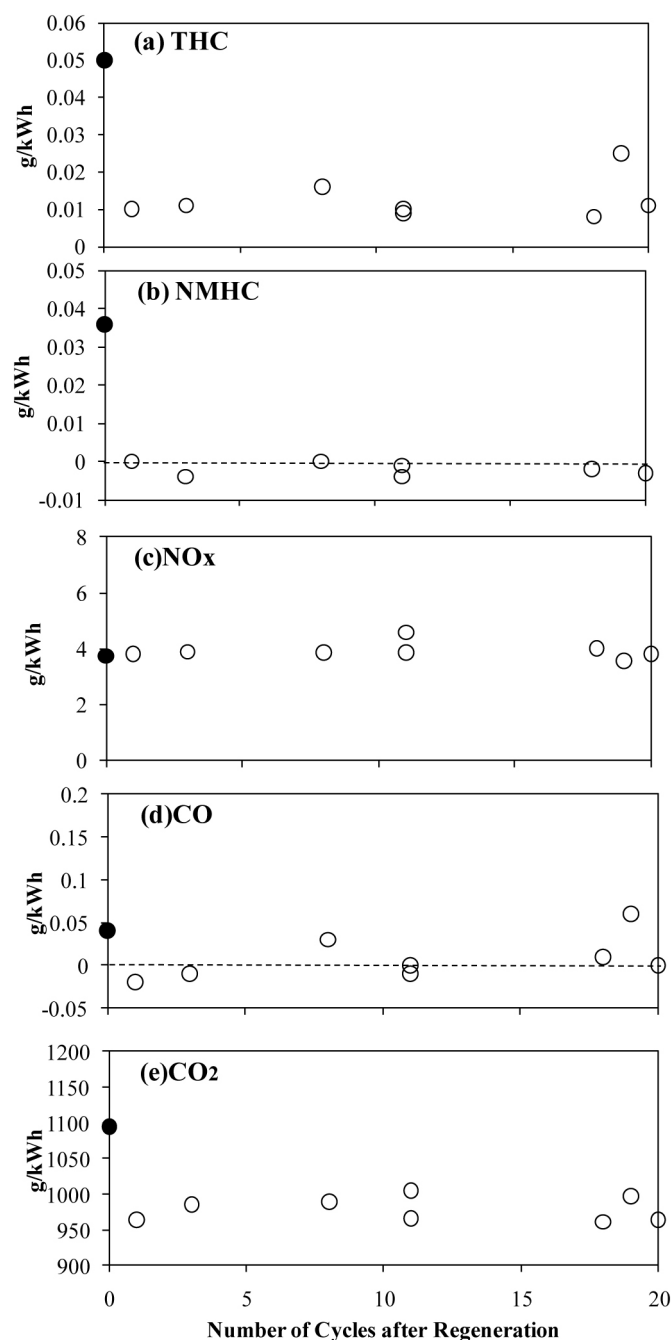


Figure 4. Emissions of THC (a), NMHC (b), NO_x (c), CO (d), and CO₂ (e) from non-SCR truck as a function of the number of cycles after regeneration. Closed symbols indicate the results in the cycle with regeneration.