The Process of Diesel Particulate Filter Regeneration under Real Driving Conditions

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Abstract. The global automotive industry is actually facing complex challenges to ensure solutions that reduce transportation related environmental impact. Because of this, solutions were created to reduce exhaust gas emission, like for example DPF [1]. This study was conducted to examine the process of Diesel particulate filter automatic active regeneration during on-road mileage accumulation of Diesel passenger cars. The Diesel test vehicles used in this study were equipped with Diesel oxidation catalysts (DOC), lean NOx trap (LNT, only one vehicle type) and two types of Diesel particulate filter: DPF and FAP (French: filtre à particules) as aftertreatment systems, and satisfied either the Euro 5 or the Euro 6 emissions standards, depending on the vehicle. The test vehicles’ mileage before testing was at least 30 000 km. The soot accumulated during normal use of the vehicles on various types of routes. Collected and processed data were obtained over a distance of 15 000 km. During soot accumulation and DPF regeneration, many parameters from the electronic control unit (ECU) were recorded, i.e. vehicle velocity, engine speed, accumulated soot mass, differential pressure and temperatures at the inlet and outlet of the DPF. The distance covered during the soot accumulation phase depended on the driving conditions, and was sometimes as high as 850 km. During the regeneration process, the temperature at the DPF inlet sometimes rose above 500 °C, and above 600 °C at the outlet, and the differential pressure sometimes reached over 250 mbar.

1. The presentation of the research objects and their characteristics

1.1. The introduction to Diesel Particulate Filter

The Diesel Particulate Filter is made of a honeycomb-shaped ceramic body that has been covered with silicon carbide or aluminium titanite. The ceramic inset contains many small channels that are alternately opened and closed, separated by filter walls (see Figure 1). The porous filter walls are coated with a substrate of metal oxide for example aluminium oxide. On this substrate are layer of the precious metal platinum and palladium, which functions as a catalytic converter. Over engine’s work the exhaust gas flows through the intake channels porous filter walls to the outlet channels, living the particles (soot and ash).

To avert the particulate filter from becoming stoppered with soot particles it must regenerate regularly. During the process of regeneration the soot which have collected in the filter are burned. The regeneration of the particulate filter can perform in the following stages:

- Passive regeneration – during this type of regeneration the soot is continuously burned without engine management system influence. This mostly happens when the engine is operated on high loads and exhaust gas temperature reach as high as 500°C.
Active regeneration – before this type of regeneration the soot has accumulated to some level in the filter. Low engine load (i.e. under urban driving) produces too low an exhaust gas temperature for the passive regeneration. As soon as a level of the accumulated soot reach the limit value active regeneration is inducted by the engine management system. The soot particulates are burned (oxidized) at an exhaust gas temperature of 600°C; because of that, the process of active regeneration requires additional fuel post-injections.

Regeneration trip by customer – if the load condition of the Diesel Particulate Filter reaches the limit and there will be no conditions to make active regeneration (driving only on extremely short trips) after some time the DPF warning lamp in the dash panel insert lights up. To perform this regeneration the vehicle must be driven for a short period at steady speed without turning off the engine.

Service regeneration – this regeneration is performed only in the workshop when the Diesel Particulate Filter loading reach 100%.

The table shown below presents the ranges of occurrence each types of Diesel Particulate Filter regeneration depending on the soot accumulated. Soot accumulation above 100% requires replacement of the filter with the new one.

**Table 1.** The ranges of occurrence each types of regeneration [2].

| Activity                   | Passive regeneration | Active regeneration | Regeneration trip by customer | Service regeneration | Filter destroyed |
|----------------------------|----------------------|---------------------|-------------------------------|----------------------|------------------|
| DPF load                   | Up to 40%            | Up to 67%           | Up to 89%                     | Up to 100%           | Above 100%       |

1.2. The research objects

A total of 3 types of vehicles were tested, each of them had 2 identical car. Both the test types vehicles were homologated in the EU and were hence developed to meet the prevailing EU regulations. The test vehicles were all in sound mechanical condition meeting the Euro 5 or Euro 6 standards. Key characteristics of the test vehicles are presented in Table 2. All were unmodified and operating in full accordance with the manufacturer’s instructions in terms of tire pressure, engine oil type, etc. Since this study represents the process of Diesel Particulate Filter regeneration, the fuel type is of no particular importance here. Standard, commercially Diesel B7 fuel was used – the same fuel for all mileage accumulation.
### Table 2. Key characteristics of the type test vehicles.

| Parameter                  | Type 1 | Type 2 | Type 3 |
|---------------------------|--------|--------|--------|
| Vehicle type              | PC     | PC     | PC     |
| Engine type               | CI, DI, TC | CI, DI, TC | CI, DI, TC |
| Approx. displacement [dm³] | 2.4    | 2.0    | 1.6    |
| Number of cylinders [-]   | 5      | 4      | 4      |
| Exhaust emission standard | Euro 5 | Euro 6 | Euro 5 |
| Aftertreatment system type| DOC + DPF | DOC + DPF | DOC + DPF (FAP) |
| Transmission type, number of gears | M, 6 | M, 6 | M, 5 |
| Approx. mileage at start of testing [km] | 115 000 | 35 000 | 160 000 |

Notes: PC – passenger car; DI – direct injection; TC – turbocharged; CI – compression ignition; DOC – Diesel oxidation catalyst; DPF – Diesel particulate filter; M – manual;

#### 1.3. The comparison of the test vehicles’ aftertreatment systems

The tested vehicles were equipped with two types of aftertreatment systems. The first, featured in two types of test vehicles, was a Diesel oxidation catalyst with Diesel Particulate Filter system; the second was again a Diesel oxidation catalyst, but with a “wet” Diesel Particulate Filter (FAP, French: filtre à particulates).

The figure shown below presents the exact aftertreatment system featured in type 2 vehicles (a very similar system was also featured in type 3 vehicles). The exhaust gas flows from the turbocharger through the Diesel oxidation catalyst to the Diesel Particulate Filter, and next – depending on the engine load – a portion flows through the EGR valve and EGR cooler, and the rest of the gas flows to the exhaust pipe. In the figure below, temperature and pressure measurement locations are shown.

![Figure 2. DOC and DPF aftertreatment system [3].](image-url)
The principle of operation of a "wet" Diesel Particulate Filter is very similar to that of a "normal" (or "dry") DPF. The main difference is in the construction of the fuel supply system (figure 3). In the fuel tank an injector for the additive is located (figure 3). The composition of the additive is a mixture of light oils and cerium oxide (properties of cerium oxide: particle size 0.1-0.5 µm, concentration 10-25 ppm) [4]. The purpose of using this additive is a reduction in the regeneration temperature to a level of 400°C. Depending on the fuel level and time of refueling, the engine ECU controls the amount of injected additive, which then mixes with the fuel while driving. After the fuel burns in the engine, the cerium oxides covers the soot particles, lowering the temperature required for them to be burned. Unfortunately, following that cerium particles settle in the filter, slowly causing its irreversible destruction.

Figure 3. The construction of fuel supply system in the exhaust aftertreatment system with FAP [5].

2. The process of the research
The data were collected under real driving conditions. The vehicles were driven on different routes (urban, extra-urban, mountain and motorway) during the whole year (summer and winter ambient conditions) doing a total over 15 000 km of mileage accumulation per vehicle. The engine oil and oil filter were changed many times.

3. The research results
The charts shown below present results of the progress of the process of Diesel Particulate Filter active regeneration. During all mileage accumulation many regenerations occurred, to point 3 in this paper was chosen one full active DPF regeneration.

The first chart (figure 4) presents DPF loading in terms of regeneration process. The type 2 vehicles always perform active regeneration to a level of about 20%. The type 3 vehicles were accumulated soot maximum to 5-6 g (figure 5), but during most of mileage accumulation time were performed short passive regenerations. Due to low soot accumulation for this vehicles type, time of DPF regeneration is the shortest (figure 6).
Figure 4. The Diesel Particulate Filter regeneration process.

Figure 5. The characteristic values before and after Diesel Particulate Filter regeneration.

Figure 6. The time of the Diesel Particulate Filter regeneration process.
Figure 7. The Diesel Particulate Filter inlet temperature over the regeneration process.

Figure 8. The Diesel Particulate Filter inlet temperature over the regeneration process.

Figure 9. The Diesel Particulate Filter outlet temperature over the regeneration process.
Figure 10. The Diesel Particulate Filter outlet temperature over the regeneration process.

Figure 11. The temperature at the end of tailpipe over the regeneration process.

Figure 12. The differential pressure over the Diesel Particulate Filter regeneration process.
Figure 13. The differential pressure over the Diesel Particulate Filter regeneration process.

Figure 14. The coolant temperature over the Diesel Particulate Filter regeneration process.

The temperature on the inlet of Diesel Particulate Filter for type 3 vehicles was higher than theoretical should be, and reached 600°C (figure 7, 8). The lower DPF inlet temperature was for type 1 of test vehicles. The DPF outlet temperature was recorded only for 4 cars, and was much higher than on inlet (more than 600°C) (figure 9, 10). The temperature at the end of tailpipe during DPF regeneration is very high and can reach 350 °C (figure 11). The highest differential pressure was for type 1 vehicle, all data of the differential pressure during DPF regeneration are on the figure 12 and 13. The coolant temperature was on the standard level (figure 14).

4. Conclusion
After analysing the collected data of active Diesel Particulate Filter regeneration (figure 15, 16) the following conclusion can be drawn:

- The type 1 vehicles collects soot to average level about 28 g, and always regenerates filter to the empty state. Average distance covered to accumulate soot to level of active regeneration is 710 km. The best result obtained for this type of vehicles is 857 km of distance per one DPF regeneration.
The type 2 vehicles collects soot to average level about 22 g, and mostly regenerates filter to level about 5-6 g. After reach this value the regeneration is automatically stopped. Average distance covered to accumulate soot to level of active regeneration is 426 km.

- The type 3 vehicles collects soot to average level about 5 g, and always regenerates filter to the empty state. Average distance covered to accumulate soot to level of active regeneration is 309 km.

**Figure 15.** The average accumulated soot in the Diesel Particulate Filter.

**Figure 16.** The distance covered over the Diesel Particulate Filter regeneration process.

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