

# On Road Durability and Performance Test of Diesel Particulate Filter with BS III and BS IV Fuel for Indian Market

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## ABSTRACT

The future emission regulation (BS V) in India is expected to create new challenges to meet the particulate matter (PM) limit for diesel cars. The upcoming emission norms will bring down the limit of PM by 80 % when compared to BS IV emission norms. The diesel particulate filter (DPF) is one of the promising technologies to achieve this emission target. The implementation of DPF system into Indian market poses challenges against fuel quality, driving cycles and warranty. Hence, it is necessary to do a detailed on-road evaluation of the DPF system with commercially available fuel under country specific drive cycles. Therefore, we conducted full vehicle durability testing with DPF system which is available in the European market to evaluate its robustness and reliability with BS III fuel ( $\leq 350$ ppm sulfur) & BS IV ( $\leq 50$ ppm sulfur) fuel under real Indian driving conditions. The testing was performed on several vehicles with instrumented DPF systems and data acquisition hardware for city and highway cycles. At periodic intervals, the oil and fuel samples were collected and analyzed. Also, the emissions levels in all vehicles were regularly checked over the Modified Indian Driving Cycle (MIDC) on a chassis dynamometer. Throughout the testing parameters like temperature profile inside filters (diesel oxidization catalyst (DOC) and DPF), pressure drop across filter, soot loading and few signals from engine ECU were monitored and recorded. This paper presents the test set ups and results of field trials conducted on DPF fitted vehicles using BS III and BS IV fuel.

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## INTRODUCTION

In India the share of diesel engine passenger cars is continuously growing. This is mainly due to their superior fuel economy and subsidies for diesel fuel. Diesel engines produce large amounts of particulate matter and Nitrous Oxide (NOx). Diesel particulate matter (DPM) is made of number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, soil or dust particles and allergens (such as fragments of pollen or mold spores). These particles in diesel exhaust are of special concern due to their respirable size. The particles less than 10 microns in diameter pose the greatest problem because they can get deep into human lungs and some may even get into the bloodstream. Larger particles are of less concern, although they can cause irritation to eyes, nose and throat. The upcoming stringent emission regulation (BS V) in India, aiming to address the above concerns will create new challenges to meet the PM limit not only in terms of mass but also in terms of particle numbers (PN) for diesel cars.

The significant PM reductions over the years were achieved with a combination of engine design optimization, availability of refined fuels, and the use of exhaust after treatment devices. The reduction of PM via combustion optimization is limited by combustion efficiency

and fuel economy. Hence, after treatment system is one of the promising technology to control PM from diesel cars. Diesel particulate filter can reduce PM by more than 95% from exhaust gas.

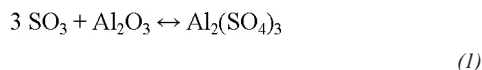
Currently, Mercedes-Benz uses Silicon Carbide (SiC) based catalyzed Diesel Particulate filters (cDPF) exclusively for passenger car applications. The main advantages of the catalytic coating are to reduce the activation energy for soot oxidation and to suppress secondary emissions (CO & HC) during DPF regeneration.

Diesel particulate filter performance is highly influenced by sulfur content in the diesel fuel and driving pattern. During the combustion, sulfur is oxidized to form sulfur dioxide (>95%) primarily and small portion of sulfur trioxide (2 -5 %) both being acid components. SO<sub>3</sub> is readily hydrolyzed to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and it combines with water in the exhaust gas to form a mist which is exhausted as a part of the fine diesel PM.

SO<sub>3</sub> and sulfuric acid will easily react with platinum (Pt) and palladium (Pd) precious metals which are incorporated within catalytic converter (DOC & DPF) to form sulfates that are not catalytic and not desirable substance within a catalyst (catalytic converter poisoning). The sulfate can be removed (de-poisoning)

from the substrate when it gets exposed to temperatures in the range of 650 to 700°C and in the process can degrade the original physical character and function of catalytic components (Pt & Pd) [2].

The sulfur compounds present in exhaust gas can also combine with the wash coat layer of the catalyst. In the oxidizing atmosphere and in the presence of platinum (intensive oxidation of SO<sub>2</sub>) large amounts of sulfur are deposited on the Al<sub>2</sub>O<sub>3</sub> layer following the reaction.



This reaction is very intensive at low temperatures and it precedes inversely at temperatures above 700°C [6].

Driving pattern is another important factor that needs to be considered while developing DPF system because it directly influences the oil dilution. Low average driving speed and longer idling duration are major concerns in developing countries like India. These factors will lead to longer regeneration duration, which means, post injection duration becomes longer and this phenomenon will lead to higher oil dilution. While injecting fuel very late in the combustion cycle the temperature and pressure in the combustion chamber are much lower. This usually results in incomplete fuel vaporization and fuel impingement on the cylinder liner. The result is that the fuel dilutes the engine oil which adversely affects engine wear, due to the lowering of the oil's viscosity. A typical design consideration is to allow oil dilution up to 10%.

In this paper, the impact of fuel quality (sulfur) and driving pattern on DPF regeneration behavior (temperature during regeneration, regeneration interval & duration), oil dilution and product durability are discussed based on durability test data.

## ON-ROAD DPF DURABILITY TESTING

The most realistic and straightforward approach to validate DPF performance and robustness is On-road DPF durability testing. Although it is time consuming and expensive, it gives realistic data with respect to fuel quality and driving pattern. Regeneration behavior and thereby oil dilution levels can be accurately monitored with selection of appropriate test cycles.

During the durability testing, the DPF undergoes repeated soot loading and regeneration cycles. DPF loading generally occurs when the rate of soot accumulation exceeds the rate of soot oxidation (e.g.: Passive regeneration). Soot accumulation in the DPF causes an increase of the pressure drop across the DPF filter which subsequently leads to higher pumping losses and fuel consumption. Therefore, the active regeneration must be done when the soot loading reaches a certain level.

Daimler AG has exclusively developed a DPF system for European market which cannot be directly used in India due to the different duty cycles and high sulfur ( $\leq 350\text{ppm}$ ) fuel. Hence, it is necessary to do country specific on-road DPF durability testing with respect to commercially available fuel. It would be a more realistic approach to validate DPF performance and robustness.

The objective of the project is to validate the DPF system which is available in the European market with BS III fuel under real Indian driving conditions to ensure the temperatures inside DOC and DPF are well within the safety limits.

## Specifications of Test Vehicles and Aftertreatment System

Durability test was carried out in India on 4 test vehicles; all of which were equipped with instrumented DOC & DPF, temperature and pressure measurement module (ES420, M-Thermo & M-Sens), ECU interface module (ES953) & data logger (ES720). Details about the test vehicles are given in [table 1](#).

**Table 1. Test vehicle details**

| Vehicle | Engine | Duty cycle  | Distance, km | Fuel        |
|---------|--------|-------------|--------------|-------------|
| A       | OM642  | City        | 30000        | BS III / IV |
| B       |        | Extra urban | 60000        |             |
| C       | OM642  | City        | 30000        | BS III      |
| D       |        | Extra urban | 60000        |             |

All test vehicles were equipped with state-of-the-art V6 diesel engines. The engine specifications are given in [table 2](#). These vehicles were equipped with different exhaust after treatment systems. Vehicle A and B had oxidation catalyst and cDPF closely in one canning. In other two vehicles (C and D) diesel oxidation catalyst were located in closed coupled position directly after turbocharger and cDPF was located slightly away from DOC due to the packaging constraints. However, According to test bed results, the difference in exhaust system architecture does not have much deviation in exhaust gas temperature profiles with respect to different duty cycle. Hence, the change in exhaust system architecture does not have much impact on A, B, C and D vehicle test results.

**Table 2. Engine Specification**

|                                 |                                                                                           |
|---------------------------------|-------------------------------------------------------------------------------------------|
| Engine Type                     | OM642                                                                                     |
| Number of Cylinders             | V6                                                                                        |
| Bore x Stroke (mm)              | 83 x 92                                                                                   |
| Displacement (cm <sup>3</sup> ) | 2987                                                                                      |
| Compression Ratio               | 15.5 : 1                                                                                  |
| Maximum Power                   | 195 kW @ 3800 rpm                                                                         |
| Maximum Torque                  | 620 Nm @ 1600-2400 rpm                                                                    |
| Lube Oil type                   | MB 229.5 (SAE 0W- 40)                                                                     |
| Fuel Injection system           | Common Rail Direct Injection                                                              |
| Charge System                   | Variable geometry turbocharger                                                            |
| Emission Control                | Close-coupled Diesel Oxidation Catalyst (DOC), catalyzed Diesel Particulate Filter (cDPF) |
| Emission level                  | Euro 5                                                                                    |

Diesel particulate filter details are given in table 3. A 2.44L catalyzed DPF was used for on vehicle durability test. The filters were made by silicon carbide (SiC) material coated with platinum and palladium catalyst. The main advantages of the catalytic coating are to reduce the activation energy for soot oxidation, to suppress secondary emissions (CO & HC) during filter regeneration. In addition, it supports soot oxidization (Passive regeneration) at around 300°C exhaust gas temperature with the help of DOC generated NO<sub>2</sub> and also it provides higher thermal stability.

Table 3. DPF specification

| Vehicle | Material | Cell Density (CPSI) | Wall thickness | Volume | Pt : Pd |
|---------|----------|---------------------|----------------|--------|---------|
| A       | SiC      | 270                 | 10 mm          | 2.44 L | 2 : 1   |
| B       |          |                     |                |        |         |
| C       |          | 271                 |                |        |         |
| B       |          |                     |                |        |         |

### Instrumentation and Data Acquisition

Test vehicles were equipped with an instrumented DOC and DPF to monitor temperature profile inside DOC & DPF throughout the field trials. All filters were equipped with 8 K-type thermocouples with diameter varying from 0.75 mm to 1.5 mm. The pressure drop across DPF was obtained from vehicle differential pressure sensor as well as from dedicated pressure sensor. Special care has been taken during the installation of the pressure sensor and the thermocouples to avoid early sensor damage due to the harsh operating environment and vibration during the vehicle operation. The typical test setup is shown in figure 1.

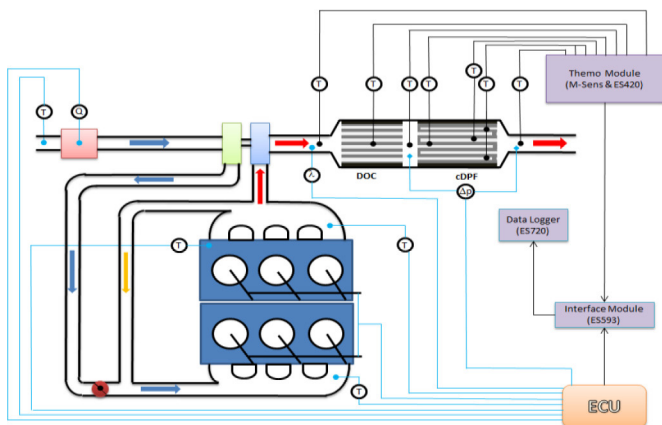


Figure 1. Typical test set-up used during durability test

Usually the highest temperature during regeneration is observed at the rear side of DPF and the highest radial temperature gradient is observed close to the skin of the DPF. Hence, it is necessary to place more thermocouples at the rear of the filter. It is also very important to monitor the temperatures in the DOC. Sometimes it witnesses highest temperature during the regeneration period. Upstream and downstream of DOC and DPF temperatures were also monitored. The thermocouple locations in the axial and radial directions are shown in

figure 1. The temperature information was sent to ETAS data logger (ES720) via Ipetronik M-Thermo (16Ch) module. Apart from the temperatures, pressure signals were also measured before and after DPF to verify the consistency of vehicle  $\Delta p$  sensor. A snapshot of an instrumented DPF with 8 thermocouples and pressure sensors is shown in figure 2.

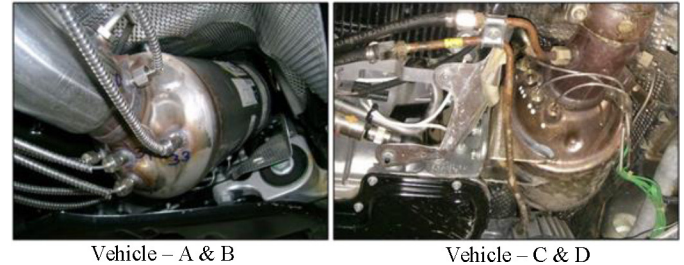


Figure 2. Snapshot of instrumented DPF with thermocouples

Other ECU variables like DPF regeneration duration, regeneration interval, vehicle speed, engine speed, fuel injection parameters (pilot, main, & post), lambda etc. were recorded via ETAS interface module (ES593).

### Derivation of Driving Cycles for DPF Validation

Test cycle or driving pattern selection is important for validation of DPF as it has an influence on regeneration interval, regeneration duration and thereby oil dilution. In order to validate the DPF in worst case driving profile with harsh accelerations and stop-and-go bumper to bumper traffic, an appropriate city cycle fulfilling the criteria was selected. Average driving speed and frequent idling are major concerns in city driving cycle. This impacts regeneration duration and DPF temperatures.

The main challenge in selecting city cycle was to cover the target distance within specified period of time and without violating the driving pattern. The average speed was to be maintained below 18kmph, overtaking and rash driving was prohibited. The vehicles were fitted with GPS in order to monitor the route followed by the vehicle and to inform or instruct the driver in case of any deviations.

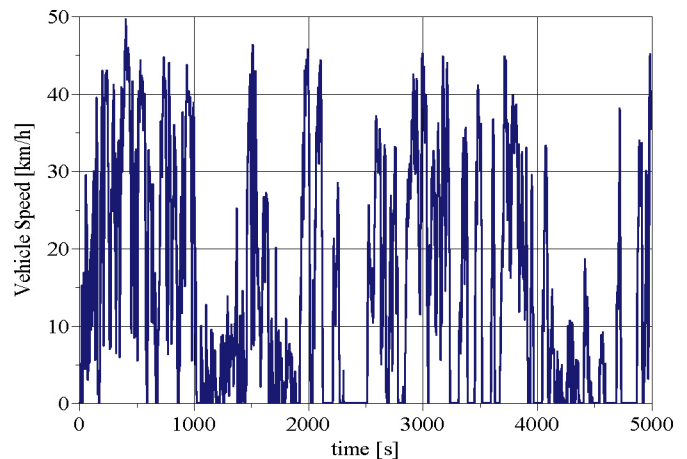


Figure 3. Typical city driving cycle

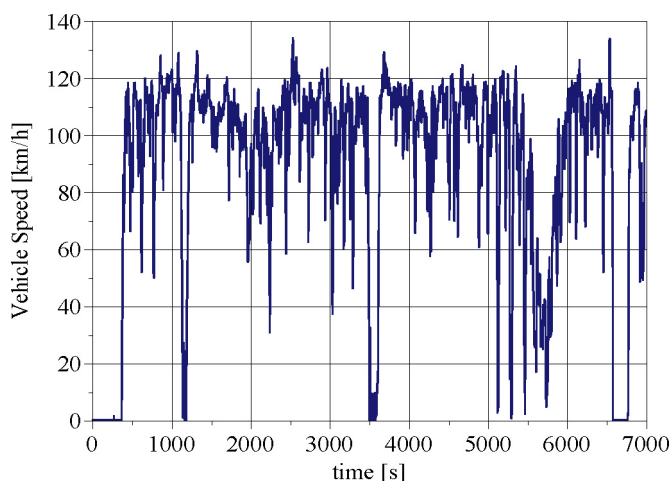


Figure 4. Typical extra urban driving cycle

Extra urban driving cycle is not as critical as city driving cycle since the exhaust temperatures are generally high enough to execute the passive regeneration and the exhaust flow rate is also higher which enables better regeneration performance. However, these profiles create few challenges for active regeneration, such as engine over run conditions with oxygen rich exhaust flow when the vehicle is approaching a traffic jam on a highway or rapid change in engine speed from rated rpm to idling (Drop to Idle). Typical city and extra urban driving profiles are as shown in figure 3 and 4.

## VEHICLE OPERATION

Durability testing on all vehicles was conducted at Pune and Bangalore in India. The tests were conducted under different duty cycles to obtain the diesel particulate filter performance data under wide range of practical driving conditions. The duty cycle was defined in such a way so as to represent the typical customer vehicle driving pattern in real world. City duty cycle consisted of 366 cycles and each cycle covered 95 km. Extra urban driving cycle consisted of 100 cycles and each cycle covered 600 km. The average vehicle speed observed during the city driving cycle trials was 15 - 20 km/h. In extra urban driving cycle the average speed observed was around 60 - 65 km/h. Details of test vehicles are given in table 1. BS III & BS IV certified fuel was used for vehicle A and B durability testing. These vehicles were running without any change in the calibration (same as European market calibration). Durability testing of these vehicles was conducted within and around Pune, India. The distance covered was around 30,000 km and 60,000 km in city and extra urban driving cycles respectively.

Based on A and B vehicle durability test results, re-calibration was done at Germany and new calibration data was used for C and D vehicles durability test. From the test results of A and B vehicles it was clear that DPF crack occurred due to the usage of BS III fuel. Hence, only BS III certified fuel was used for C and D vehicle's durability testing. The tests were mainly conducted in and around Bangalore, India.

Oil dilution is another critical parameter which needs to be monitored at periodic intervals to safeguard the engine against wear. In Indian driving conditions, the regeneration duration is expected to be longer as compared to Europe due to low average speed and longer idling duration. Hence, it is very important to monitor the oil dilution level periodically during durability testing. Oil samples were collected at periodic intervals of 2500 km and 5000 km in city and highway cycles respectively and samples were analyzed to ensure that oil dilution does not exceed the prescribed safe limits. BS III fuel samples were collected from various fuel stations across India to analyze the sulfur content and adulteration (if present) in fuel.

Mass emission test was conducted before starting the durability test as per Modified Indian driving cycle (MIDC) after instrumentation and filter installation on the test vehicles to assess the initial pollutants (CO, HC, NO<sub>x</sub> & PM) levels. At the end of durability test mass emission test was conducted again to check the impact of sulfur on DOC and DPF performance.

## TEST RESULTS AND DISCUSSIONS: A AND B VEHICLES

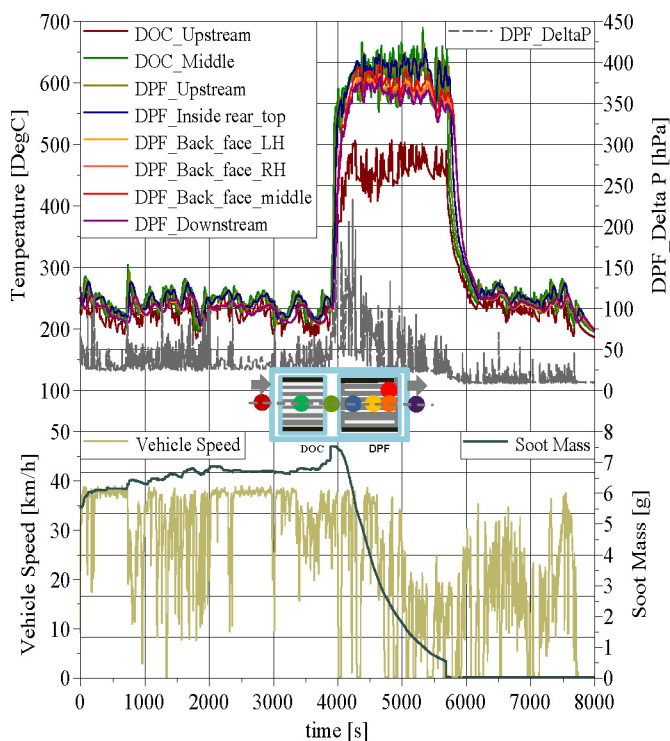


Figure 5. Controlled regeneration in city cycle (Vehicle-A)

The aim of durability test results presented here is to show the behavior of diesel particulate filter during regeneration under real driving conditions with European standard calibration. Figure 5 shows the exhaust gas temperature profile in DOC and DPF with BS IV fuel under city driving conditions. The vehicle speed, soot burning rate and pressure difference ( $\Delta P$ ) across DPF are shown in figure 5. It can be clearly observed that, during the normal operation mode, the exhaust temperature varies from 200°C to 300°C. However, during the regeneration mode (from 3900 to 5800 seconds), the exhaust gas temperature has elevated to 700°C. This is achieved by increasing post injection quantity and timing. These are two basic principle.