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INVESTIGATION OF MULTI-CYLINDER DIESEL ENGINE TO MEET FUTURE INDIAN EMISSION NORMS*

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Abstract– Direct injection diesel engine offers the benefit of better fuel economy over gasoline engine. Diesel engine with electronic control of high pressure, multiple injections per cycle, 4 valves per cylinder, turbocharged with intercooled, cooled EGR or SCR and DPF have now become the key features to meet the upcoming emissions in India.

This paper describes the work done on multi-cylinder diesel engine to meet the requirements of Bharat stage 5 emissions and has the potential to meet Euro6 emission norms. Vehicle simulation model developed by using AVL cruise software was used to find out the engine steady state speed-load point's equivalent to Bharat stage 5 emission test cycle. Engine emission development was done on test bench using these speed-load points. Engine was optimized with new hardware, namely piston bowl with reduced compression ratio, high capacity EGR cooler and turbocharger to attain the desired emission level. Diesel oxidation catalyst and coated diesel particulate filter (cDPF) loading were optimized to reach Bharat stage 5 emission norms. Vehicle with Selective Catalyst Reduction (SCR) with average 60% conversion efficiency has the potential to meet Euro6 norms.

Keywords– Diesel particulate filter, emissions, EGR, oxides of nitrogen, particulate, selective catalyst reduction

1. INTRODUCTION

Passenger vehicles equipped with diesel engines have become popular in automotive applications because of the fuel economy benefits they offer. Currently, Bharat stage 4 (BS4) emission norms are applicable in metros and other major cities of India, whereas Bharat stage 3 (BS3) emission norms are followed in the rest of India. The Indian government has proposed Bharat stage 5 (BS5) emission norms, but their implementation date is under discussion due to 10 ppm low sulfur diesel fuel availability which is essential for BS5 norms to avoid poisoning of oxidation catalyst and coated diesel particulate filter. The proposed BS5 emission norms are equivalent to European Euro 5 emission norms [1]. Table 1 shows the comparison between these two norms for passenger vehicle of N1, class 3 category.

From Table 1, it can be seen that a reduction of about 28% in NOx and 93% in PM emissions is required to meet BS5 emissions. The two most effective methods of reducing NOx emission are cooled Exhaust Gas Recirculation (cEGR) and Selective Catalyst Reduction (SCR) [2-4]. Between the two, the cEGR method became more popular because of its ease of design, adaptation and control. Initially the automotive engine was designed for hot EGR to control NOx emissions. However, there was a limitation of NOx-soot tradeoff with hot EGR. Cooled EGR became more popular due to its better NOx and soot tradeoff. Cooled EGR has become a universal solution for much less NOX and soot trade-off where there

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is no possibility of urea infrastructure available for SCR as an alternate solution. The SCR [5] method, on the other hand, is less popular, because it involves high cost and more calibration effort; besides, at present, the infrastructure available in India for urea filling stations is either limited or nil. In cylinder particulate matter can be reduced by effective utilization of air swirl motion in piston bowl by maintaining fuel spray hitting the plane below the bowl throat, increase in rail pressure, optimization of pilot quantity, its separation and main injection timing. However, they cannot reduce the in-cylinder particulate matter to the extent of meeting BS5 requirements without after-treatment system. Reduction of particulate matter by more than 98% is possible by using (cDPF) catalyzed particulate filters [6-7].

Table 1. Bharat stage 4 and 5 and Euro 6 Emission Norms for Passenger vehicle

Emission Norms	CO (mg/km)	HC+NOx (mg/km)	NOx (mg/km)	PM (mg/km)	PM number (Nb/km)
BS4	740	460	390	60	NIL
BS5	740	360	280	5	$6 \times 10^{\wedge 11}$
%	No change	22	28	93	PM count
Euro6	740	215	125	4.5	$6 \times 10^{\wedge 11}$

Table 2 shows the engine and vehicle specifications used for experimentation.

Table 2. Engine and Vehicle Specifications

Engine	Base Engine specifications	Experimental Engine specifications
	2.2L, Inline, 4 Cylinder, DOHC, HSDI Diesel	2.2L, Inline, 4 Cylinder, DOHC, HSDI Diesel
Compression Ratio	16.5 : 1	15.2: 1
Rated Power	103 kW	103 kW
Max Torque	320 Nm	320 Nm
Rated Speed	4000 rpm	3750 rpm
Injection System	Common Rail, Bosch Generation 2,1600 bar	Common Rail, Bosch Generation 2, 1600 bar
Air System	VGT Gen 3 Turbocharger	Gen 3.5 VGT Turbocharger
EGR system	Normal Cooled EGR with pneumatic actuation EGR Valve	Intake throttle+ High pressure EGR cooler with bypass & electrical actuated EGR valve
After-treatment system	Diesel Oxidation catalyst	DOC+ cDPF for BS5 DOC+ cDPF + SCR for Euro6
Emission	Bharat stage 4	Bharat stage 5 / Euro 6(estimated)
Vehicle specifications	Sport Utility Vehicle	Sport Utility Vehicle
Tyre dynamic rolling radius	0.331 m	0.331 m
Vehicle Mass	1860 kg	1860 kg

The engine was mounted on AVL make transient test Bench, equipped with Horiba 7100 D emission analyzers, smart sampler, Cameo and INCA interface and high speed data acquisition system for real time measurement of temperature, pressure and flow. AVL Indiset was used for measurement of heat release and cylinder pressure. Figure 1 shows the test bench setup used for engine testing. Base engine was tested for full load performance and power, torque, bsfc main injection timing, pilot quantity and pilot separation were recorded. Base engine was modified and converted into experimental engine. The following modifications were carried out in the base engine for emission development.

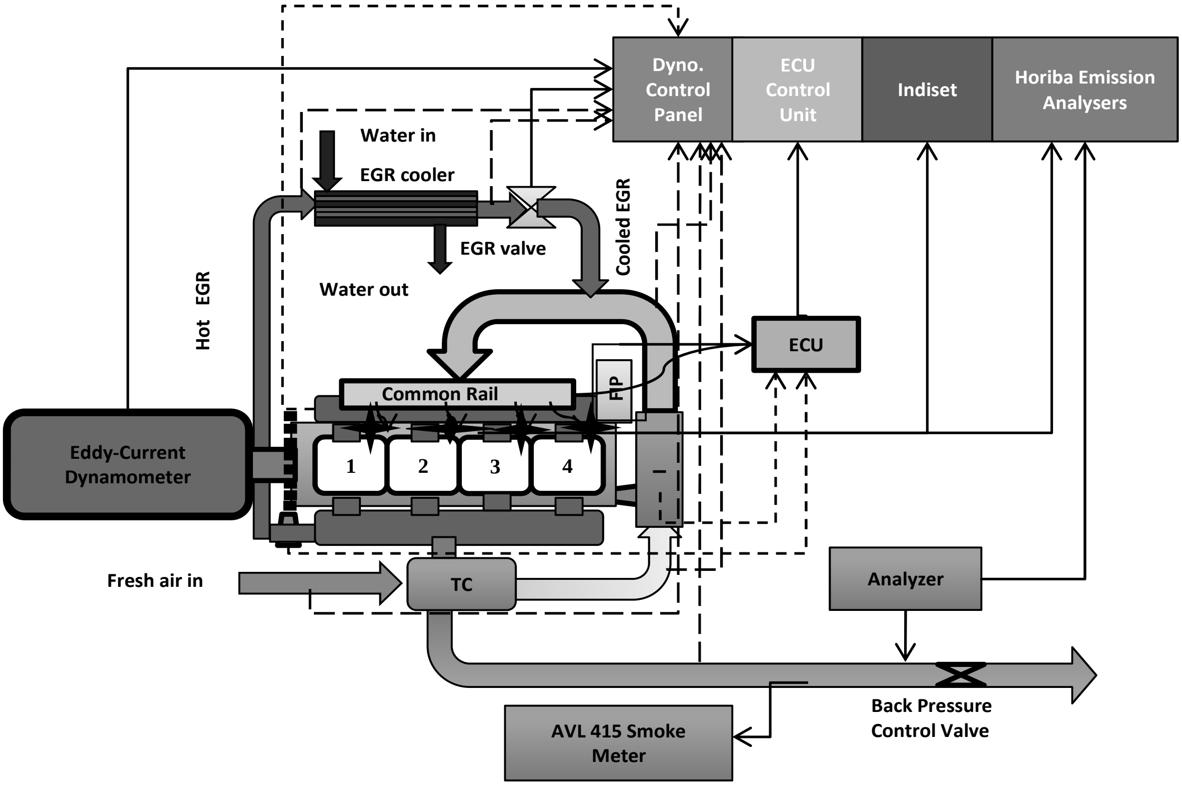

Fig. 1. Test bench setup for experimental engine

a) Compression ratio

Base engine compression ratio of 16.5:1 has been modified to 15.2:1 compression ratio without affecting starting of the engine in cold condition and cylinder peak firing pressure below limit of 160 bar. The compression ratio has been modified by scaling the 16.5:1 combustion chamber. The reduced compression ratio lowers the end compression temperature, reduces pumping losses and also reduces compression work.

b) Seven holes Injector

The selection of the injector is purely based on the spray-bowl swirl matching with 40 to 50% of hitting plane from the top face of the piston. Six holes injector has been replaced with seven holes and the spray cone angle changed from 148 to 152 degrees to hit spray in new piston crown at 40% of bowl depth with optimized main injection timing for effective utilization of air and fuel mixing as shown in Fig. 2. Injector protrusion was adjusted such that its spray will hit below the bowl radius of the combustion chamber to avoid wall impingement.

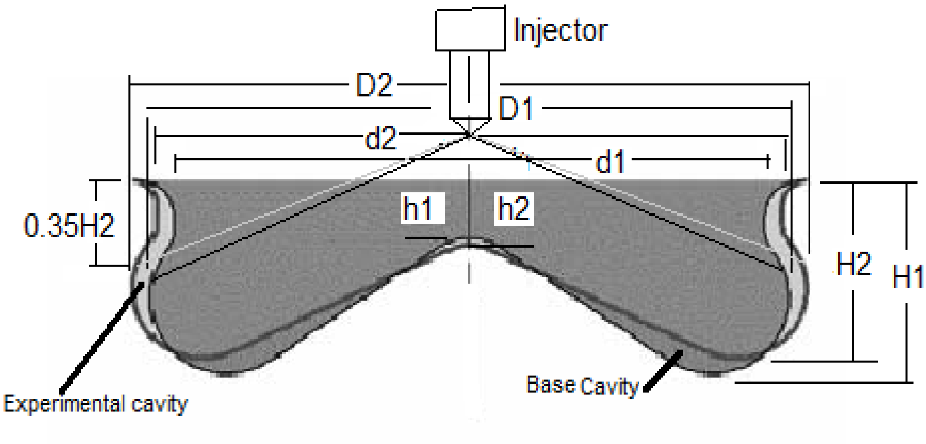

Fig. 2. Piston crown and injector spray comparison of base and experimental engine

c) Turbocharger

VGT turbocharger with generation 3.5 (lower cartridge assembly weight by 2 % and 'S' shape turbine vane in place of straight vane) was matched to meet higher air flow and boost pressure requirement over a wider range of load and speed conditions. This has helped in adjusting air excess ratio at various operating conditions of engine.

d) EGR cooler

The EGR is a prime technology for reducing NOx emissions. Adapting the cooler in the EGR path further reduced the NOx emissions by lowering the combustion temperature. EGR cooler capacity was increased from 4.5 kW to 10 kW for effective cooling of EGR gas and provision of uncooled exhaust gas in certain operating conditions. Refer to Fig. 3 for a comparison between base engine EGR system and experimental engine EGR system.

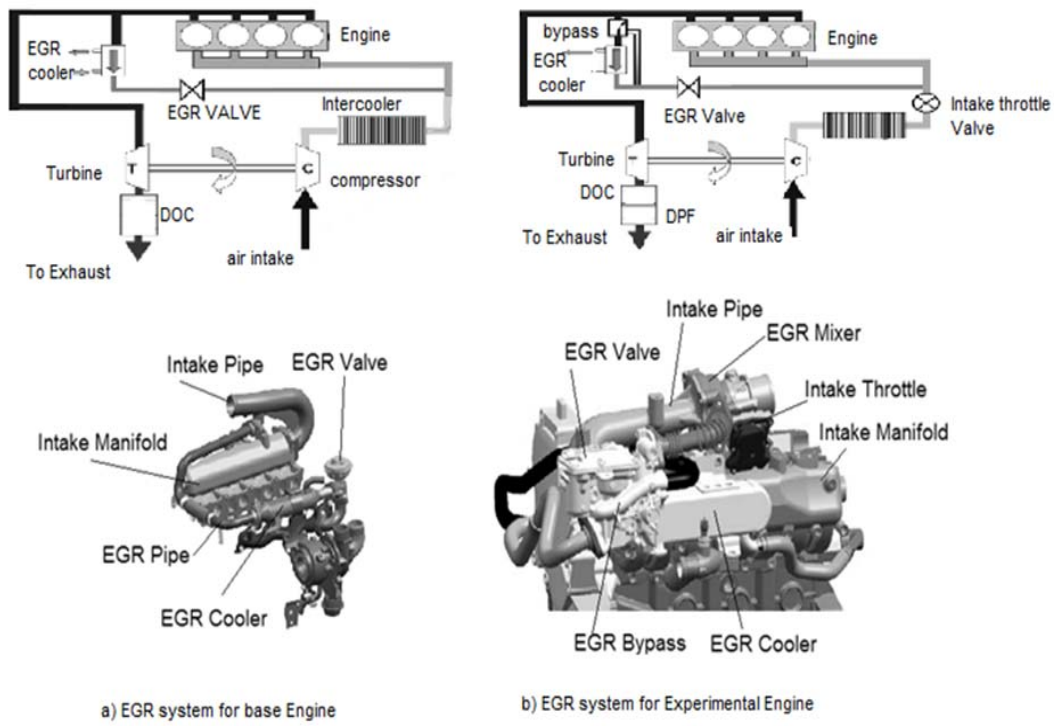

Fig. 3. EGR System layout of base and experimental engine

e) EGR mixer

EGR mixture was used in intake pipe to improve mixing of exhaust gas with air and to maintain uniformity of the mixture from cylinder to cylinder. This enabled 94 % achievement of the uniformity index. Intake throttle was introduced to increase and control EGR rate effectively.

f) Diesel oxidation catalyst

Diesel oxidation catalyst was replaced with single canned diesel oxidation catalyst and catalyzed silicon carbide (SIC) particulate filter, which were fitted in a closed couple to the engine. Loading of coating was optimized during engine testing on test bed and on chassis dynamometer.

g) Engine friction

Piston top ring tension was reduced by 5 %. Oil control ring contact area was reduced to 13 %. Due to these changes, engine frictional torque was reduced to 3 Nm at 1000 engine rpm and 5 Nm and 3750 rpm. Reduced engine friction has benefited in 0.2 % bsfc reduction.

3. METHODOLOGY

This paper describes the work done for emission development of 4-cylinder diesel engine and vehicle to meet the proposed BS5 emission norms, besides demonstrating its potential to meet European Euro 6 norms, assuming 60% SCR efficiency. The step-by-step procedure followed for engine emission development to meet BS5 norms is given below (please refer to the flow chart shown in Fig. 4)

a) Vehicle simulation model and predicting steady state 14-mode points, using AVL Cruise software.
b) Developing full load performance with new engine hardware, matching with base engine.
c) Optimizing hot emission of engine on steady state test bench with 14-mode speed-load points.
d) Testing vehicle hot emission on chassis dynamometer and comparing it with engine 14-point emission results.

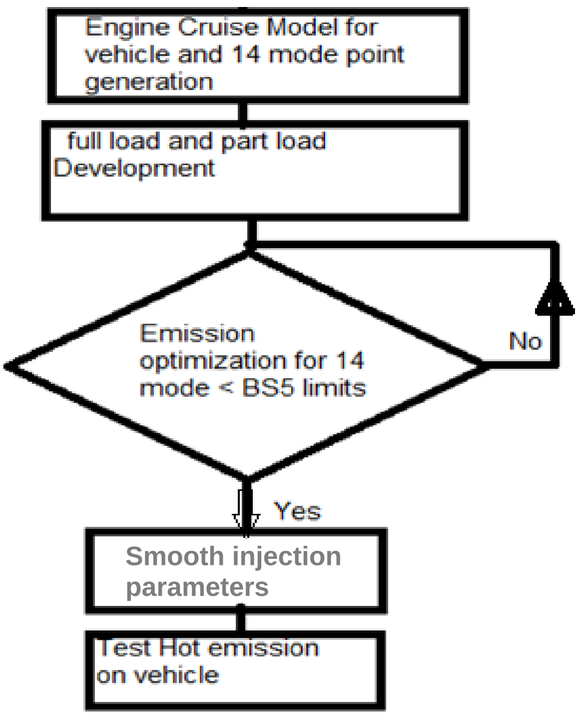

Fig. 4. Flowchart of BS5 emission development process

a) Steady state speed- load points generation using AVL cruise model

During the emission test cycle the engine operates at different speeds and load points based on gear box ratio, axle ratio, rolling radius and reference mass of vehicle. The exact operating points of engine were found by using vehicle simulation model using AVL Cruise software [8]. By running the vehicle cruise model as per NEDC cycle, 14 steady state speed-load points were obtained with weightage factors. These 14 mode points, which represent equivalent steady state speed- load points of BS5 emission cycle, were used for engine development on test bench.

b) Full load Performance development of engine on test bench

The engine was tested with new turbocharger, injector and piston bowl. Injection parameters, such as fueling quantity, main injection timing, boost pressure, pre-pilot1 quantity and pre-pilot 1 separation were optimized to match the power of base engine.

c) Hot Emission measurement on Engine dynamometer with 110 °C mode points

Engine was warmed up to reach oil temperature of 110 °C and coolant temperature of 90 °C. The engine was tested at each speed-load point. The emission results, compiled in an excel base program, were converted from ppm to g/km and compared with the values of hot emission target for engine bench.
The experiments were so designed as to optimize each speed-load point by varying the injection parameters like main injection timing, injection pressure, pilot quantity, EGR rate, pilot separation and boost pressure, to ultimately optimize the NOx-soot trade-off. AVL Cameo interference with INCA software was used to run the engine with different operating parameters and, at each point, optimum parameters were selected. All optimized results were analyzed by Excel program and it was confirmed that they were below the legislation limits. Figure 5 shows full pilot injections strategy made available in engine calibration software for development, and Table 3 shows actual injection strategy used during engine emission development at part load condition.

Table 3. Injection strategies for BS5 emission optimization

Mode No.	Engine speed rpm	Engine Torque Nm	PI1 $mm^{\wedge 3}$	PI separation micro sec	PO1 $mm^{\wedge 3}$	PO1 separation micro sec
1	1000	4	1.5	1200	-	-
2	1704	56.7	2	1000	-	-
3	2038	14.8	2	1000	-	-
4	1811	16.7	2	1100	-	-
5	1375	34.8	1.5	1200	-	-
6	1261	23.9	1.5	1200	-	-
7	1711	110.9	2	1000	3	2000
8	2005	112	2	1000	3	2000
9	1430	91.9	2	1000	3	2000
10	1004	50.3	2	1200	-	-
11	1152	77.2	2	1100	-	-
12	2295	137	2	1000	3	2000
13	2210	199.1	2	1000	3	2000
14	2048	72.1	2	1000	3	2000

Optimized injection parameters of 14-mode points were smoothed over the entire range of engine speed-load conditions, after which it was reconfirmed that the 14-mode emissions were within the set target of engine out emissions. The engine was tested with DOC+cDPF test samples I, II and III at 14-mode emission tests in hot condition. DOC+cDPF test sample loadings are as shown in Table 4.

Table 4. Substrate sample loading on DOC and cDPF used for testing

Test Sample	DOC loading	cDPF Loading
Sample I	50 : Platinum	10 (Platinum : Palladium ratio 2:1)
Sample II	70 : platinum	15 (Platinum : Palladium ratio 2:1)
Sample III	90 : Platinum	20 (Platinum : Palladium ratio 2:1)

Though the results of all the three samples were within the BS5 limits, there was scope to reduce precious metal loadings. Sample I with minimum loading of precious metal was selected.

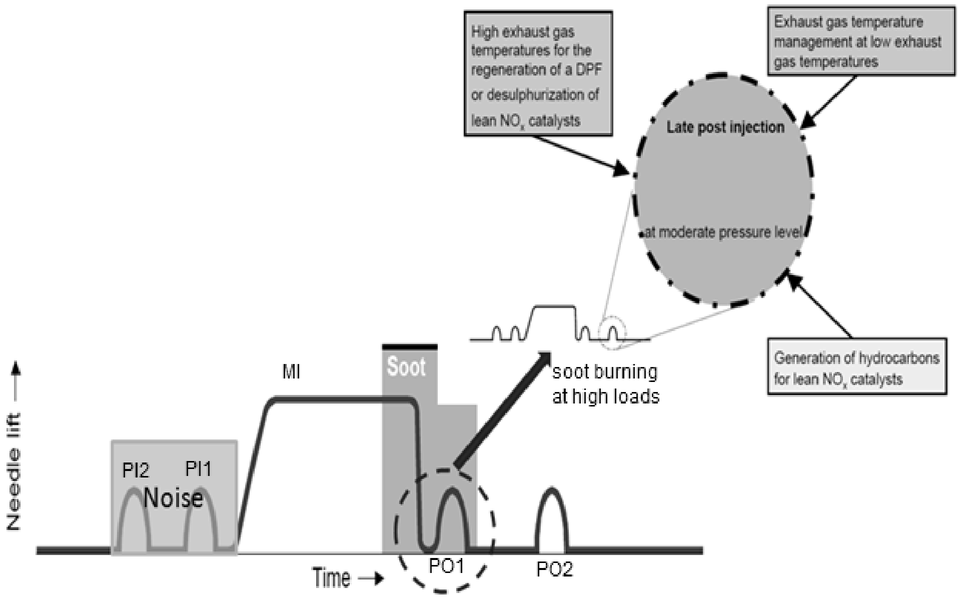

Fig. 5. Main and pilot injection strategy for experimental engine

d) Hot emission testing on chassis dynamometer

Vehicle fitted with DOC+ cDPF in exhaust system was warmed up on chassis dynamometer by running it with three extra urban driving (EUDC) cycles. Hot emission test was conducted as per the test cycle of Bharat stage 5.

4. RESULTS

a) 14 mode steady state points obtained from AVL cruise software are shown in Table 5.

Table 5. 14 mode points for Engine emission development

Points	Speed rpm	Torque Nm	Weightage factor %	Power kW
1	1000	4	29.1	0.4
2	1704	56.7	10.1	10.1
3	2038	14.8	8.3	3.2
4	1811	16.7	7.2	3.2
5	1375	34.8	6.1	5.0
6	1261	23.9	5.1	3.2
7	1711	110.9	4.5	19.9
8	2005	112	3.8	23.5
9	1430	91.9	3.7	13.8
10	1004	50.3	3.3	5.3
11	1152	77.2	2.5	9.3
12	2295	137	2.2	32.9
13	2210	199.1	1.7	46.1
14	2048	72.1	1.2	15.5

b) Full load performance

Figure 6 shows the comparison of power, torque, bsfc and main injection timing, pre-pilot 1 quantity and separation of base and experimental engine. Brake-specific fuel consumption of experimental engine was reduced to 0.2 % by optimization of advance timing pilot1, quantity pilot1 separation and engine friction reduction by tangential forces of piston ring, besides, oil control ring contact area was reduced. To achieve the same power with better bsfc, the experimental engine required more advanced main injection timing, pre-pilot 1 quantity above 2000 engine rpm and pre-pilot 1 separation, as compared to what the base engine required. This could be because of the fact that lower compression ratio increases ignition delay period in modified engine.

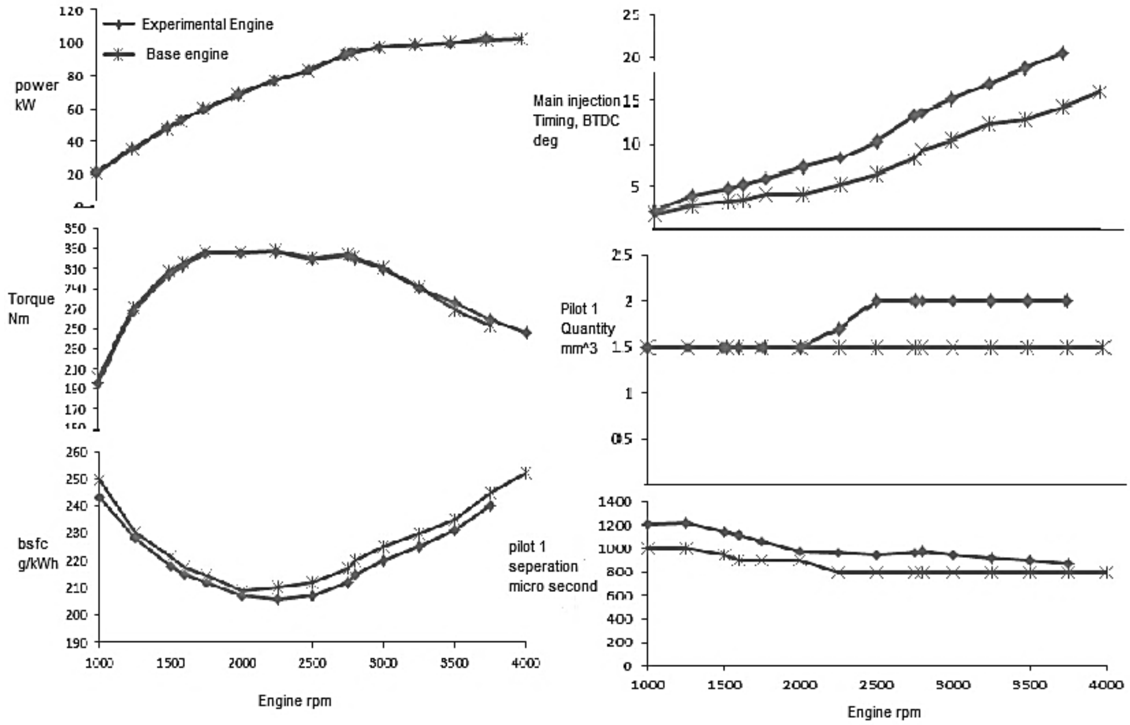

Fig. 6. Full load power comparison of base and experimental engine

c) 14 mode emissions

Figure 7 shows 14-mode optimized engine out emission results for W_NOx and W_GSoot in g/hr. A series of optimization tests were conducted at 14-mode points, and the best test results of test nos. 5, 9 and 13 were plotted against each mode for discussion. The results of Test no. 5 were optimized for NOx. However, soot and CO emissions were deteriorated and out of limit. Optimization of emission parameters was done by swinging main injection timing and EGR rate for mode point nos. 7, 8, 12 and 13, where soot and CO emission were high. Additional 3 mm^^{3} post injection quantity was injected at 12 degrees after top dead center to burn soot without a significant increase in NOx. Refer to Fig. 8 for soot, CO, HC and bsfc variations at point no.7 in g/hr. A similar trend was noticed for mode point nos. 8, 12 and 13, though not shown here. The remaining mode points were optimized with pre-pilot 1 injection only. Optimum point was selected based on minimum bsfc. The emission results were compared with test bed target as defined in Table 6. Please refer to Fig. 9 for a comparison of 14-mode NOx versus soot and CO, and for fuel consumption in kmpl of test nos. 5, 9, and 13. Though both trial nos.9 and 13 met engine out emissions, trial no. 9 gave better fuel consumption. Hence, trial no. 9 emission results were considered final engine out emission results for after-treatment loading optimization. Summary of 14 mode test results was compiled and is as shown in Table 6.

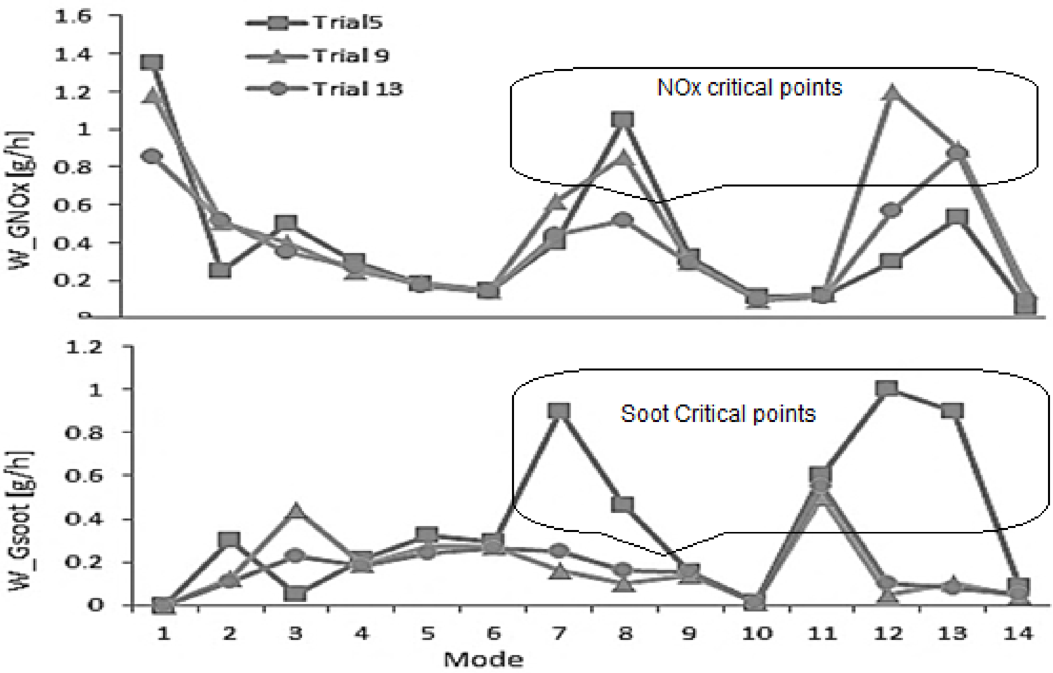

Fig. 7. Engine out 14 mode W_GSoot and W_GNOx emissions at 3 trials

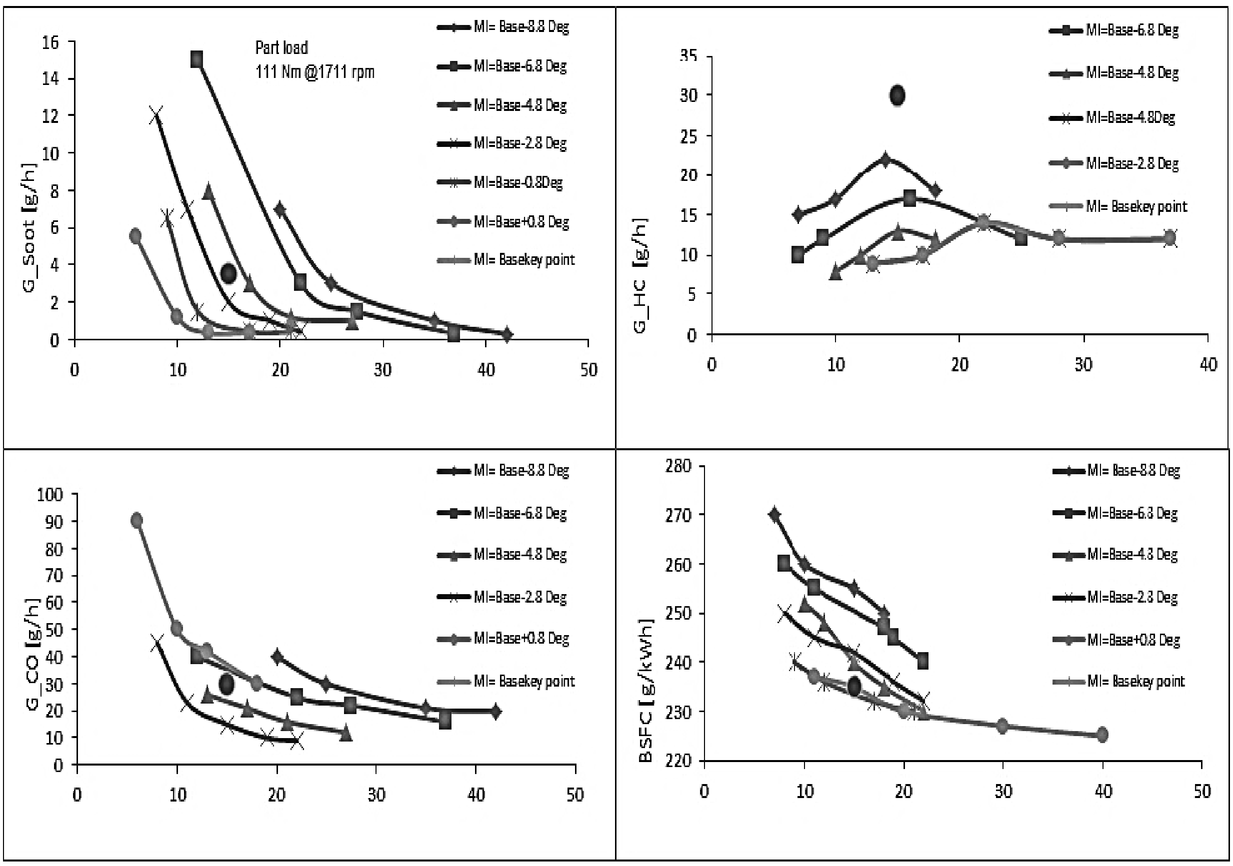

Fig. 8. Engine out emission optimization at mode No 7 for experimental engine

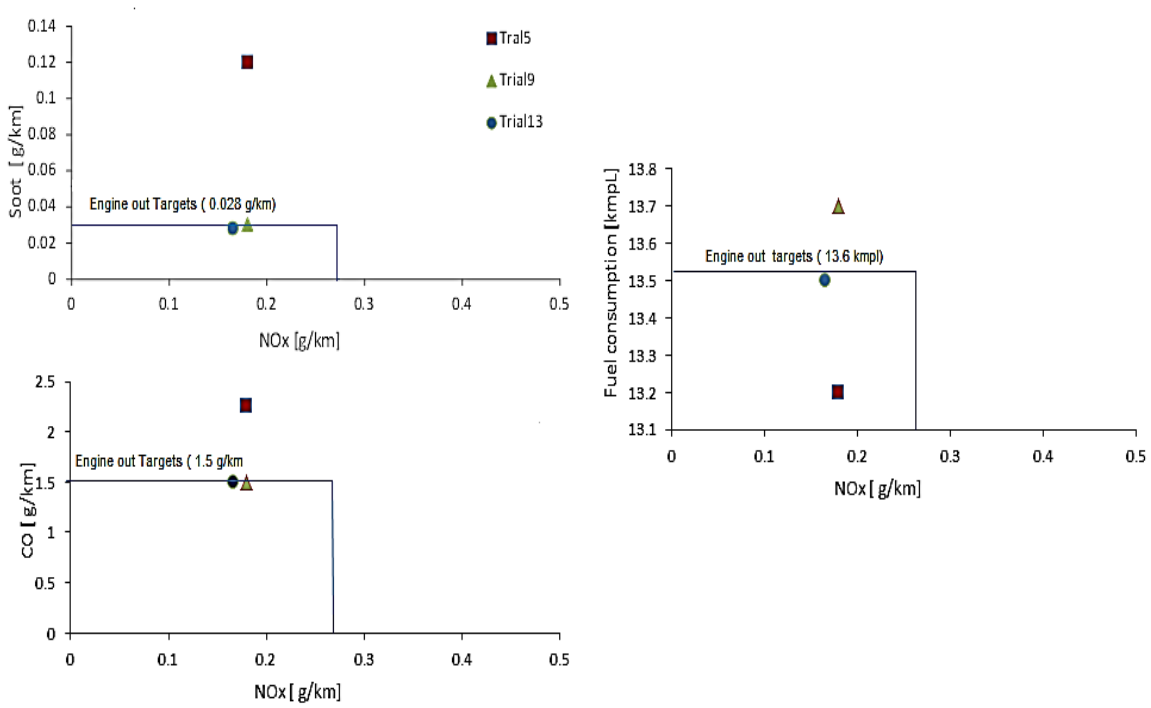

Fig. 9. Hot engine out emission soot and NOx at 14 mode points of experimental engine

Table 6. Hot emission results comparison of 14 mode engine and vehicle

	Hot Emissions [m g/km]				
Combination of test condition	NOx	HC+NOx	PM	CO	HC
14 mode results on Engine out	181	261	2.78	1500	80
Vehicle Emission results	192	278	2.98	1397	86
% difference (Engine to vehicle)	-6.1	-6.5	-7.3	6.9	-7.5
Engine Bed Target	210	260	2.80	1500	-
After- treatment efficiency	NIL	NIL	90%	80%	80%
14 mode results on Engine with sample 1	167	197	278	290	30
Vehicle Emission results with sample 1	177	203.7	3.0	267	26.7
% difference (Engine to vehicle)	-6.0	-3.4	-7.3	7.9	11.0
Proposed Bharat stage 5 limits	280	350	4.5	740	-
SCR efficiency (assumed)	60%	60%	-	-	-
Bharat stage 6 / Euro 6 emissions	125	215	4.5	740	-
Vehicle out NOx emissions (calculated)	78	81.4	3.0	267	3.7

d) Hot emission on chassis dynamometer

The emission results of 14-mode point engine tail pipe test bench were compared with the vehicle's tailpipe hot emission results. Three test samples showed a correlation between the 14-mode engine test bench and chassis dynamometer results of engine tail pipe emission in hot condition (as shown in Fig. 10). The accuracy of the results for NOx and particulates was close to 95 %. Diesel oxidation catalyst loading was optimized by testing different platinum loadings for DOC and platinum / palladium loadings for coated particulate filter. The results obtained with various DOC and DPF loadings during vehicle tail pipe emissions tested on chassis dynamometer are shown in Fig. 11. Samples with I, II, III platinum for DOC and I, II, III with 2:1 Pt /Pd ratio were used for testing. Sample I was selected based on minimum loading and similar emission results as shown in Fig. 11.

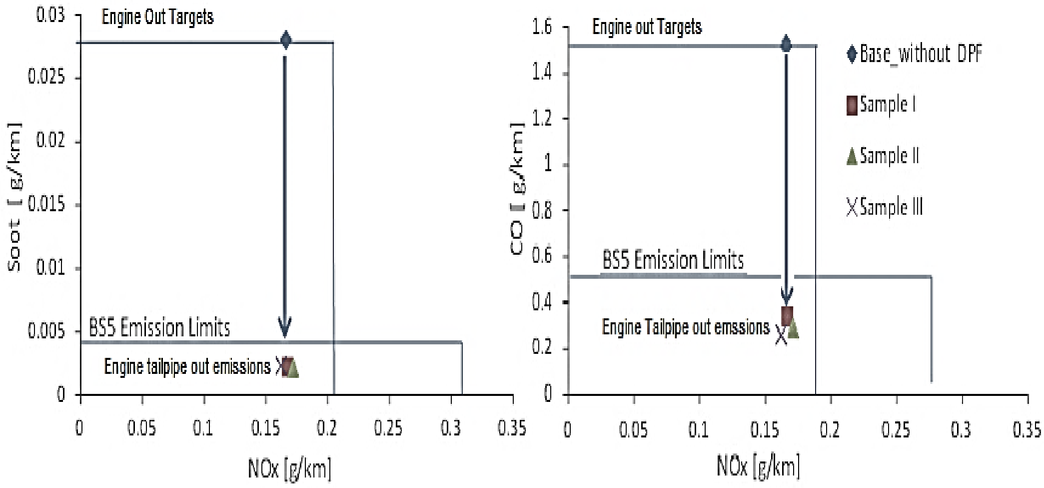

Fig. 10. Hot engine tailpipe out soot and NOx emission at 14 mode of experimental engine

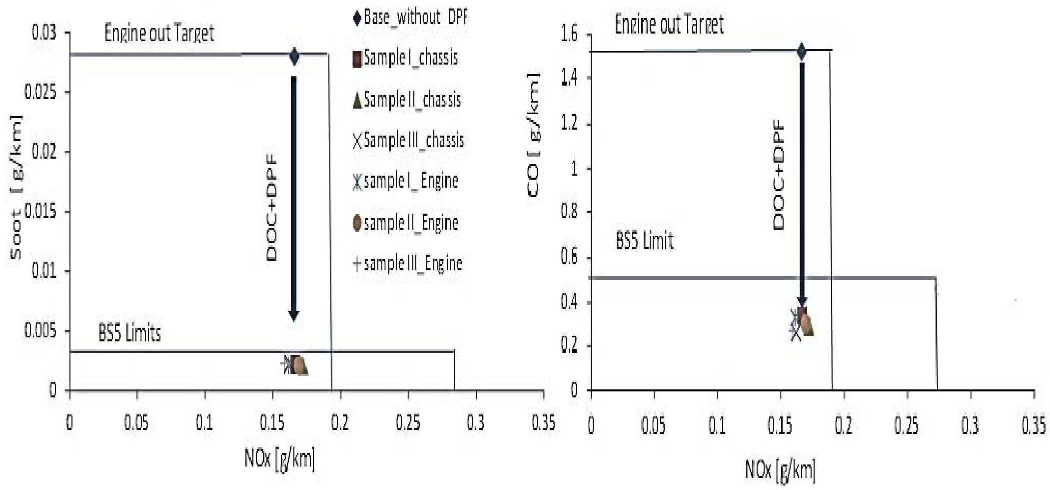

Fig. 11. Hot Engine tail pipe out14 mode emission and vehicle tailpipe out emissions with three samples

5. DISCUSSION

The effect of air excess ratio was studied for NOx and soot formation at various engine speed and part load conditions. At 1710 rpm, EGR rate was increased to control NOx without increase in soot emissions at different part load conditions (as shown in Fig. 12). NOx emission at part load condition increased with increase in air excess ratio due to the availability of more oxygen which reacted with nitrogen to form NOx at high temperature in combustion. The trade-off between the formations of NOx and soot at air excess ratio of 1.55 to 1.45 was found to be optimum. Soot emission at part load condition increases with decrease in air excess ratio due to paucity of oxygen, which led to incomplete combustion. In very light load conditions and with high EGR rate, the rate of soot rise was found to increase drastically with reduced air excess ratio due to high turbulence. Hence, for best NOx-soot trade-off, air excess ratio was adjusted to 1.55 for loads < 50% and to 1.45 for loads > 50 % and above. The NOx-soot trade-off of the engine was optimized for other speed and load conditions covering the entire range of speed and load.

High torque points of 14 mode, (as shown in Table 5) soot and NOX emissions were reduced simultaneously with little penalty of fuel consumption using post pilot injection. [9- 11] In the common rail diesel engine, multiple injections are possible before the main injection (pre- pilot injection) and after (post pilot injection) (as shown in Fig. 5). In this case, pre-pilot1 (PI1) injection of 1.5 mm^3 was injected at 1000 micro-seconds before main injection, and post-pilot1 injection of (PO1) 3 mm^3, 2000 micro-seconds after top dead center. The post-injection helped burning of the soot, which would have been produced by main injection during the later part of combustion when the temperature and pressure would have come down because of piston movement. Post-injection helped in maintaining the temperature of combustion gases at a level they can burn the later part of soot and release the heat. The effect of increase in post-injection quantity, at 12 degrees after TDC, on NOx and soot is shown in Fig. 13. The increase in post-injection quantity resulted in simultaneous reduction of soot and NOx because of increase in combustion temperature following rapid release of heat. However, cylinder pressure started reducing due to piston starting move towards bottom dead center resulting in soot burning without increase in NOx emissions but its effect on fuel consumption was adverse. Based on fuel consumption deterioration, pilot quantity of 2 to 4 mm^3 was found to be the acceptable range. The engine NOx-soot trade-off was further optimized by varying the main injection timing swing , EGR rate at each point, pre- and post-pilot1 quantities at all 14-mode points with loads of more than 50 Nm; 14-mode points with torque less than 50 Nm were optimized only with pre-pilot1 quantity, separation and variations in main injection timing and EGR rate. After optimizing all the 14-mode points, the injection timing, EGR rate, pilot quantity, and pilot separations were smoothed over the entire range of engine speed and load points.

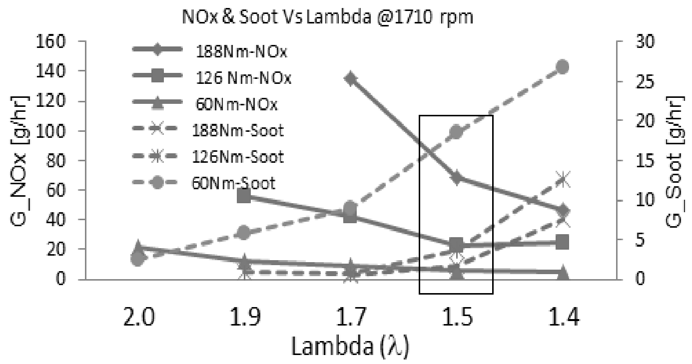

Fig. 12. Effect of lambda on soot and NOx emissions at part load condition @ 1710 rpm

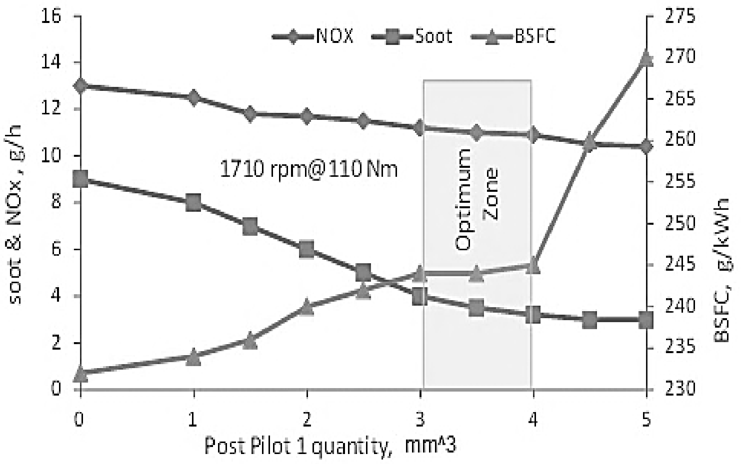

Fig. 13. Simultaneous soot and NOx reduction by early post injection

Optimized 14-mode hot emission tests result no. 9 from engine dynamometer and chassis dynamometers were compared for NOx, THC+NOx , CO and particulate matter, and the results are presented in Table 6. THC+NOx and CO results are within 5 %, and those of particulate (soot) emissions within 4 %. However, HC emissions varied by 16.6 %, which may be due to variations in the warm up conditions of the engine and the vehicle during the test. However, the results were well within the Bharat stage 5 emissions.

While optimizing the engine, it was found that by incorporating SCR system in after-treatment system with NOx conversion efficiency of 60% , the emissions were within the levels of Bharat stage 6 / Euro 6 (as shown in Table 5). The emission results were acceptable and the selected hardware and combustion parameters were considered appropriate for continuing further development work on vehicle for cold correction, drivability, cold starts, and regeneration calibration of DPF.

Best in-cylinder NOx-soot trade-off shows that control of particulate emissions requires coated diesel particulate filter to reach BS5 standards. Engine out CO and THC results show that diesel oxidation catalyst is required to control CO and THC to the extent of satisfying BS5 emission norms.

6. CONCLUSION

Engine design and development are complex processes. Use of engine simulation software tool would be helpful in early prediction of engine performance and in selecting the operating speed and load points for optimization.

Good correlation was noticed between steady state engine bench and chassis dynamometer in terms of NOx, PM and CO emissions. However, due to changes in engine warm-up conditions between steady state and chassis dynamometer tests, CO and THC emissions were not close to the steady state.

In-cylinder optimization of NOx-soot trade-off, turbocharging, common rail with flexible injection control, cooled EGR, diesel oxidation catalyst for CO and THC control and particulate control require diesel particulate filter to comply with BS5 emission norms, and SCR for BS6 / Euro 6 emissions.

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ABBREVIATIONS

BS4	Bharat Stage 4 Emissions
BS5	Bharat Stage 5 Emissions
cEGR	Cooled Exhaust Gas Recirculation
EGR	Exhaust Gas Recirculation
cDPF	Coated Diesel Particulate Filter
DOC	Diesel Oxidation catalyst
NOx	Oxides of Nitrogen
CO	Carbon Monoxide
THC	Total Hydrocarbon
PM	Particulate Matter
NEDC	New European Driving Cycle
CR	Compression Ratio
VGT	Variable Geometry Turbocharger
INCA	Integrated Calibration and Acquisition
DOHC	Double Overhead Camshaft
HSDI	High Speed Direct Injection
Pt	platinum
Pd	palladium
PO1	post pilot injection 1
PI1	pre-pilot injection 1
SCR	Selective Catalyst Reduction
rpm	revolution per minute

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