OPTIMISATION OF THE 2.2 LITER HIGH SPEED DIESEL ENGINE FOR PROPOSED BHARAT STAGE 5 EMISSION NORMS IN INDIA

by

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Direct injection diesel engine combustion system offers improvements in performance and fuel economy benefits. Four valves per cylinder, turbocharged and intercooled diesel engine became trustworthy for automobile application. Electronic diesel control, use of common rail with increase in injection pressures, and flexibility in injection control has changed the image of diesel engine. Evolutions in piston crown shape, intake ports with different swirl level helped to enhance mixing of air and fuel for better performance and emissions.

Paper describes the work done on 4 cylinder diesel engine, upgraded to BS5 (Bharat stage 5) emission norms with 20% power increase. A systematic approach of engine development was fallowed. Engine performance prediction was done using AVL Boost software. Boost Model was validated with existing engine cylinder pressure. Combustion parameters have been varied to predict higher power. Vehicle model has been build using AVL cruise software and used to obtain steady-state load- speed points. Engine emission development has been done on engine test bench. Typical hardware like piston crown, turbocharger, exhaust gas re-circulation system with exhaust gas re-circulation cooler and various combustion parameters were tested and optimized. Suitable after-treatment system was selected and optimised for precious metal loading to reach Bharat stage 5 emissions.

Key words: *coated diesel particulate filter, emissions, exhaust gas re-circulation, oxides of nitrogen, particulate matter*

Introduction

To control air pollution from diesel vehicle, it was necessary to improve fuel consumption and reduce emissions. At present Bharat stage 4 (BS4) emission norms is applicable in major cities of India. Indian government has proposed Bharat stage 5 (BS5) emission norms which are similar to European Euro5 emission norms and tentatively shall be introduced from 2015. Table 1 shows the comparison of BS4 and BS5 emission norms.

Table 1. Comparison type BS4 and BS5 emission norms for N1 class 3 of vehicle

Emission norms	CO [gkm^{-1}]	HC + NO$_x$ [gkm^{-1}]	NO$_x$ [gkm^{-1}]	PM [gkm^{-1}]	PM [Nbkm^{-1}]
BS4	0.74	0.46	0.39	0.06	NIL
BS5	0.74	0.36	0.28	0.0045	$6 \cdot 10^{-11}$
% change	No change	22	28	93	–

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Significant reduction of NO_x (28%) and PM (93%) emissions were required to meet BS5 as compared to BS4 emission norms. Effective method for NO_x emission reduction from diesel engine was use of cooled exhaust gas re-circulation (cEGR) and selective catalyst reduction (SCR) [1, 2]. Cooled EGR method became more popular in automotive engines due to ease of design, adaptation and calibration. Selective catalyst reduction has become less popular due to high cost, more calibration effort and limited or no infrastructure is present in India for urea filling stations. Particulate matter can be reduced in-cylinder by effective utilization of air-fuel mixing and optimization of combustion parameters. However it was not possible to control in-cylinder particulates completely and meet BS5 emissions without after-treatment system. Particulate reduction more than 90% was possible with (cDPF) coated particulate filters used [3].

This paper describes the development work done on 4 cylinder diesel engine and vehicle to meet BS5 emission norms proposed in India. Step by step process of emission development has been established while doing this development. Engine simulation model was developed using AVL Boost software [4]. This model was validated with base engine test parameters and used for parametric study. This has helped to select engine hardware for testing. Engine operates at different speed and load points based on gear box ratio, axle ratio, dynamic rolling radius and reference mass of vehicle during emission test cycle. Exact operating points of engine have been found out by vehicle simulation model using AVL Cruise software [5]. Fourteen steady-state speed-load points were obtained with budget factors by running cruise model as per BS5 emission cycle. These 14 points were represents equivalent steady-state speed-load points of BS5 emission cycle and was used for engine development on test bench.

Engine and vehicle specification for experimentation

Following design modifications have been done in base engine and converted it to experimental engine for emission development:

– Compression ratio has been reduced from 18.5 to 16.5. This has helped lowering initial temperature of charge and work done during compression.

– Six holes injector has been replaced with seven holes and increase hydraulic flow to 16%. The spray cone angle was changed from 148 to 152 degree to hit spray in new piston crown at 35% of bowl depth with optimized main injection timing for effective utilization of air and fuel mixing as shown in fig. 1

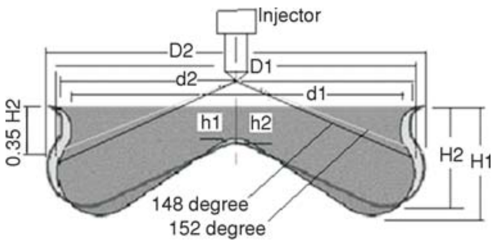


Figure 1. Piston crown and injector spray modification

– VGT turbocharger straight vanes replaced with "S" vane generation 3.5 with turbine and compressor efficiency has been matched to meet higher air flow and boost pressure at all load and speed condition. This has been helped in adjusting desired air excess ratio at various operating conditions of engine.

– Exhaust gas re-circulation (EGR) cooler capacity has been increased from 4.5 kW to 8 kW for effective cooling of EGR gas. In some operating conditions of engine exhaust gas by-pass without cooling has been kept. Refer fig. 2 comparison of base EGR system and experimental engine EGR system.

– EGR mixture has been used in intake pipe to improve mixing of exhaust gas with air and uniform mixture between cylinders to cylinder. With EGR mixer uniformity index has been achieved 94%.

– Diesel oxidation catalyst has been replaced with single canned diesel oxidation catalyst and coated silicon carbide particulate filter (cDPF) fitted in closed coupled to engine. Loading of coating has been optimized during testing of engine on test bed and on chassis dynamometer. Table 2 shows base engine and vehicle specification with power and torque upgrade from BS4 to BS5 emission.

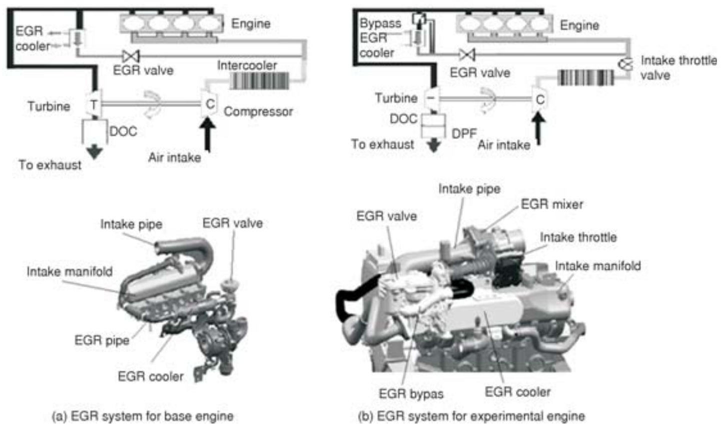


Figure 2. EGR system for base and experimental engine

Table 2. Engine and vehicle specification

Engine type Mahindra make	Base engine specifications	Experimental engine specifications
	2.2L, Inline, 4 cylinder, DOHC, HSDI diesel	2.2L, Inline, 4 cylinder, DOHC, HSDI diesel
Compression ratio	18.5 : 1	16.5: 1
Rated power	88 kW	103 kW
Torque	280 Nm	330 Nm
Rated speed	4000 rpm	3750 rpm
Injection system	Common rail, Bosch,1600 bar	Common rail, Bosch, 1600 bar
Air system	VGT Gen. 2 turbocharger	VGT Gen. 3.5 turbocharger
EGR system	Normal cooled EGR vacuum operated EGR valve	Intake throttle + high pressure EGR cooler with bypass, electrical operated EGR valve
After-treatment system	Diesel oxidation catalyst	DOC+ cDPF
Emission	Bharat stage 4 (BS4)	Bharat stage 5 (BS5)
Vehicle specifications	SUV	SUV
Gearbox	Manual transmission with 5 forward + 1 backward	Manual transmission with 5 speed + 1 backward
Axle ratio	4.1	4.1
Rolling radius	0.331 m	0.331 m
Unladen vehicle mass	1680 kg	1680 kg

Methodology

Methodology for performance and emission development was as follows.

– Engine simulation model using AVL Boost software and validation with base engine.
– Parametric study on simulated engine model and performance prediction.
– Vehicle simulation model and prediction of 14 mode speed-load points using AVL Cruise software.

– Full load performance development.
– Hot emission optimization on engine for steady-state test bench as per 14 mode speed load-points.
– Optimizing vehicle for hot tailpipe emission on chassis dynamometer.
– Optimization for catalyst loading and cDPF loading on engine and vehicle.

Engine boost model by use of AVL Boost software

Base engine simulation model has been developed on computer using AVL Boost software [4]. Figure 3 shows AVL Boost model of engine used for parametric study and full load performance prediction.

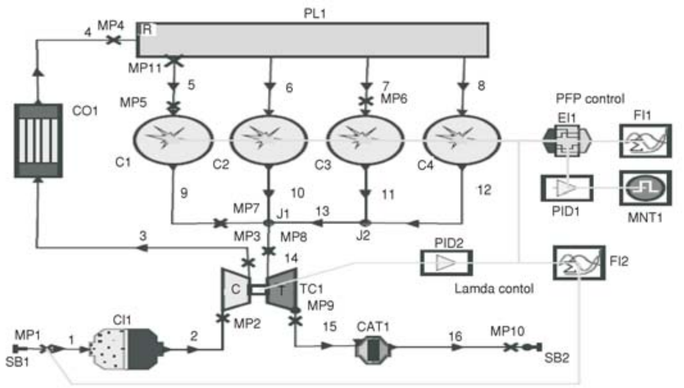


Figure 3. Engine simulation model developed using AVL Boost software

While creating engine simulation model, following constraint were applied on boost model. Engine cylinder peak firing pressure limit has been increased from 13500 kPa to 15500 kPa. Maximum exhaust gas temperature limit has been increased from 700 to 760 °C considering limit of new turbocharger material. Engine oil temperature has been relaxed from 125 to 135 °C. Maximum turbocharger speed was relaxed from 190000 rpm to 210000 rpm. Pressure before turbocharger limit has been reduced from 230 kPa to 200 kPa. Boost model performance has been compared and validated with base engine parameter. This validated Boost model has been used for parametric study to predict the target engine full load performance.

Parametric study on AVL Boost engine model

Air flow and fuel flow has been varied by keeping injection parameters same as base engine. Peak firing pressure was exceeding set limit of 15500 kPa. Hence compression ratio of engine from 18.5 reduced to 16.5 and run boost model with same parameters. Peak firing pressure was found to be within the targets, however, exhaust gas temperature was exceeding to set target of 760 °C. Injection timing has been advanced and injector hydraulic through flow has been increased 16% to maintain the exhaust temperature below 760 °C. with this change, boost model output were matching the set target of power, torque, and brake specific fuel consumption (BSFC). From boost input selection of hardware like piston crown with 16.5 compression ratio, turbocharger with high air flow in line with boost results and injector with high through flow were selected for experimental engine. When actual engine tested for full throttle performance, actual results were matching with boost results within ±5%. Figure 4 shows comparison of simulation cylinder pressure and actual cylinder pressure at full load 1500 rpm and 3750 rpm. Boost model has been validated at two speed of full load performance.

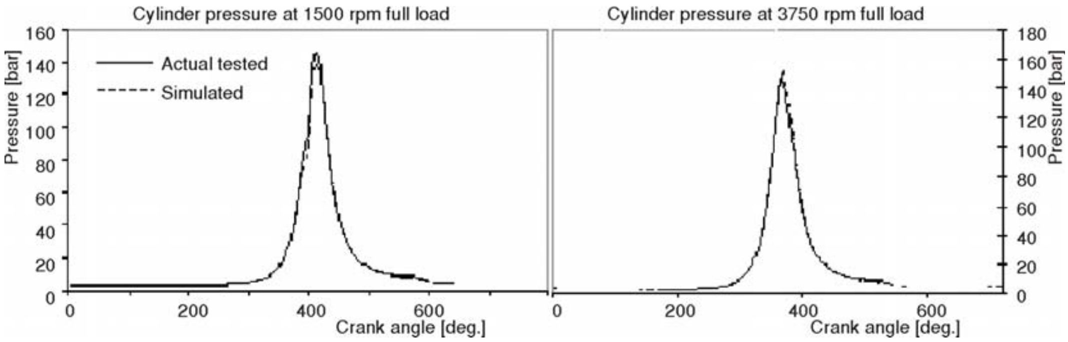


Figure 4. Cylinder pressure comparison at base and experimental engine at full load 1500 and 3750 rpm

Vehicle simulation model and prediction of 14 mode speed-load points using AVL Cruise software

Vehicle model has been generated in AVL Cruise software [5]. Input to the cruise model were vehicle parameters like, mass of vehicles, gear box ratios, efficiency of transmissions, rolling resistance of vehicle, axle ratio and dynamic rolling radius of tyre. Cruise model was run with NEDC cycle. Power required for driving of the vehicle in NEDC cycle at various vehicle speed/ gears were recorded.

Cluster of speed-load points at which vehicle operate at maximum time were defined as key points and weightage was given based on time duration at that point. These 14 mode steady-state speed-points were equivalent to NEDC cycle. Excel base program has been developed to convert engine raw emission g/h to g/km (gram per kilometer). Table 3 shows engine speed, power, torque, percentage weightage of 14 mode points generated.

Table 3. Steady state 14 mode points equivalent to NEDC cycle

Points	Speed [rpm]	Load [Nm]	Budget 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

Full load performance development of engine on test bed

Experimental set-up

Engine was mounted on AVL make, Hi Dynamic Test Bench, equipped with Horiba 7100 D emission analyzers, Smart sampler, Cameo and INCA interface and high speed data acquisition system for real time measurements temperatures , pressures and flows measurements. AVL Indi-com was used for measurement of heat release and cylinder pressure. Figure 5 show test bed set-up used for experiment.

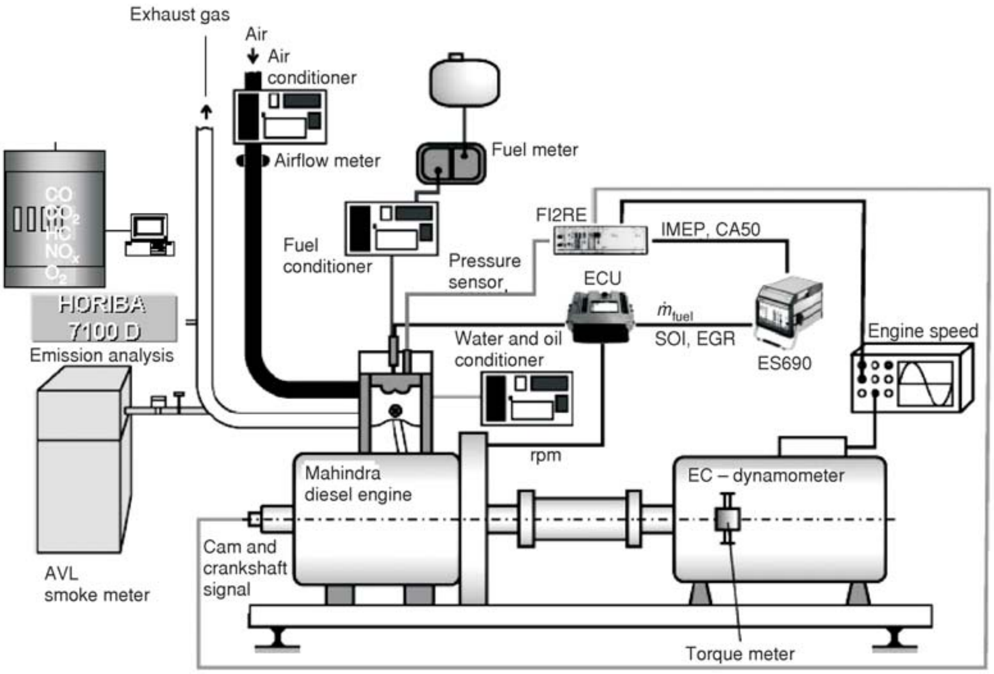


Figure 5. Test bench set-up for experimental engine testing

Full load performance

Engine has been tested with new turbocharger, injector with 16% high hydraulic through flow and piston crown with 16.5 compression ratio (CR). Injection parameters has been varied like, fueling quantity, main injection timing, boost pressure, pre-pilots quantity and pilot separation to achieve power to 103 kW and 3750 rpm and maximum torque 330 Nm and 1600-2800 rpm.

Figure 6 shows comparison of power, torque, BSFC, main injection timing and pilot quantity of base and modified engine. Brake specific fuel consumption of modified engine has been reduced to 4 g/kWh by optimization of advance timing, pilot1 quantity, pilot1 separation, reducing pressure before turbocharger from 230 kPa to 200 kPa. Piston ring friction was also reduced by reducing tangential forces of oil control ring. Modified engine was required more advance main injection timing, pilot 1 quantity above 2000 engine rpm and pilot 1 separation as compared to base engine to achieve same power and with better BSFC.

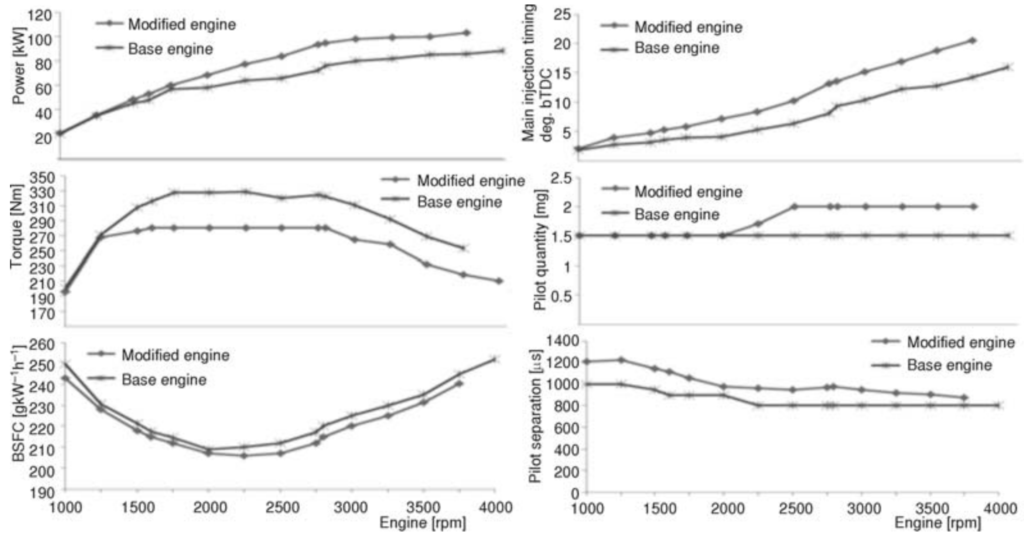
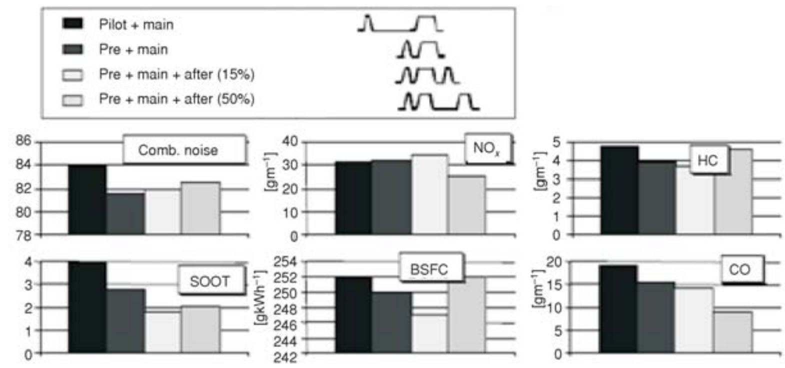


Figure 6. Full load performance comparison of base and experimental engine

Hot emission optimization on engine for steady-state test bench as per 14 mode speed load-points

Engine was warmed to reach oil temperature 110 °C and coolant temperature to 90 °C. Engine has been tested at each speed and load points as shown in tab. 3 and raw emissions in ppm has been recorded. Emission results have been converted from ppm to g/km using Excel program. Design of experiments has been conducted 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 optimize NO_x-soot trade-off. AVL Cameo interference with INCA software had used to run engine with different operating parameters and optimum parameters were selected at each point. All optimized results have been analyzed by Excel program and confirmed that it below BS5 limits. Optimized injection parameters of 14 mode points were smoothened over entire engine speed and load condition. After smoothening of injection parameters, 14 mode emissions were re-confirmed below set target. If not, re-optimization and smoothing of emission parameters were done until it was within defined targets. Figure 7 shows pilot injections strategy created for use of pre-pilot, post pilot, and pilot separa-

Figure 7. Injection strategy of main, pilot injection quantity and pilot separation for emissions, noise and BSFC



tion effectively and was used during engine developments to meet BS5 emissions. Figure 8 shows engine 14 mode emissions, smoke main injection timing and pilot quantities comparison of base (BS4) and experimental engine (BS5). Engine was optimized for best soot and NO_x trade-off by optimized injection timing, high EGR rate, and CO and HC emissions observed to be more compared to BS4. CO and HC emissions were controlled by using closed coupled DOC + DPF with optimum platinum/palladium loading and brought within the BS5 emission limits. More EGR rate, more pilot 2 quantity and separations was required in mode 3 and more 8 to control the engine out NO_x at these light load points.

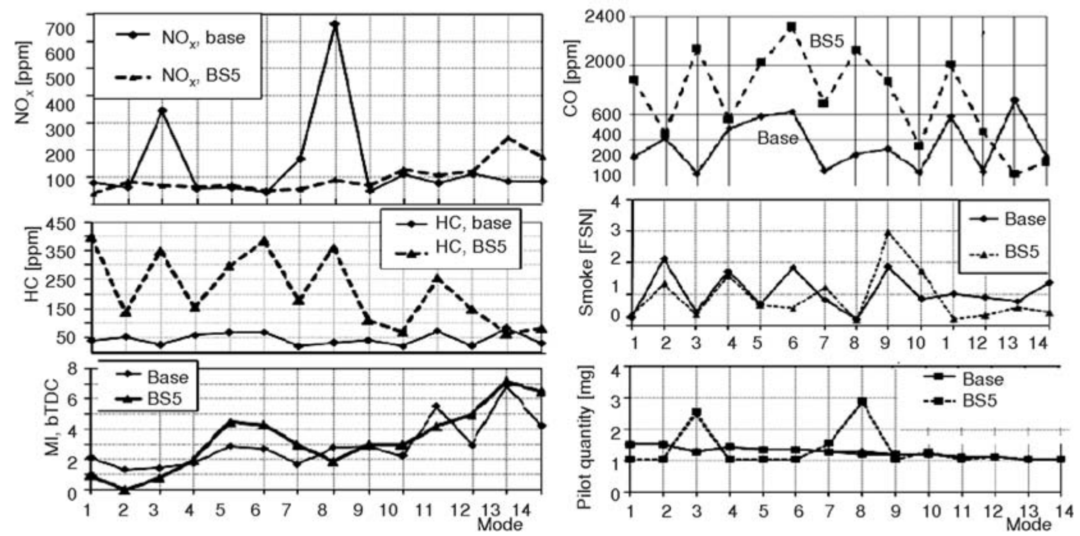


Figure 8. Engine out emission comparison of base and experimental engine

Optimizing vehicle for hot tailpipe emission on chassis dynamometer

Engine has been tested with DOC + cDPF test samples I, II, and III at 14 mode emission test results in hot condition. Refer tab. 4 for DOC + cDPF test sample loadings. Results of all three samples were within the BS5 limits and conversion efficiency of CO, HC, and soot emission by all three samples was similar. Sample I with minimum loading of precious metal was selected. Emission test has been taken on vehicle in hot condition with NEDC test cycle. Emission results of engine test bench and vehicle has been compared.

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

Test sample	DOC	cDPF
I	30 (Pt/Pd ratio 2:1)	10 Pt
II	60 (Pt/Pd ratio 2:1)	15 Pt
III	90 (Pt/Pd ratio 2:1)	20 Pt

Figure 7 shows co-relation between engine bench and vehicle emissions in hot condition. Results were matching for NO_x and particulates emissions within ±5% accuracy. By applying correction maps with respective temperature in injection parameters, cold emission were matched, conducting series of emission test on vehicle, emission were achieved well within margin.

Optimization for catalyst loading and cDPF loading on engine and vehicle

Diesel oxidation catalyst loading has been optimized by testing different platinum/palladium loading for DOC and platinum loading for coated particulate filter. Figure 9 shows emission results with different DOC + cDPF samples tested on chassis dynamometer. Samples with I, II, and III platinum/palladium for DOC with 2:1 Pt/Pd and platinum for DPF was used testing. Based on cold vehicle emissions lower precious metal loading for DOC and DPF has been selected. Work related to calibration of soot mass loading in DPF and its regeneration strategy has not been discussed in this paper.

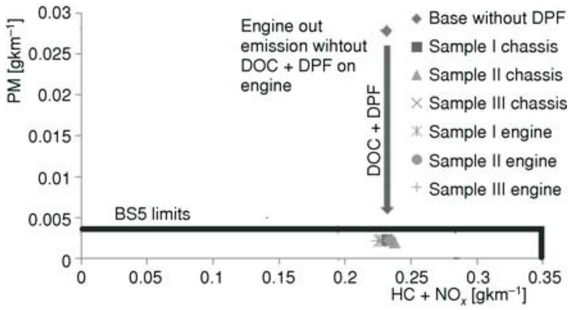


Figure 9. Engine out and chassis out hot emission co-relation

Results and discussions

Engine Boost model and actual test results were compared at two full load points namely 1500 rpm and 3750 rpm and it was matching within ±5 %. Engine bench emission results and vehicle emissions has been compared for NO_x, HC + NO_x, PM, and HC in hot conditions. NO_x emissions were matching within 3%. HC + $NO_{\pm x}$ results were matching within ±5%. Particulate emissions were within ±4%. CO emissions were also comparable and within ±5%. However HC emissions were within 16.6% accuracy. This might be due to difference in warming condition of engine on test bench and on vehicle. Vehicle HC emissions has been more than engine test bench. Table 5 shows engine test bench and vehicle tail pipe emissions in hot condition. Results were comparable and gave the confidence that hardware and combustion parameters selected has been correct.

Table 5. Hot emission results comparison of 14 mode and vehicle tested on chassis dynamometer

	Hot emissions [gkm^{-1}]				
Engine/vehicle	NO_x	HC + NO_x	PM	CO	HC
14 mode results on engine (sample I)	0.207	0.237	0.00232	0.375	0.03
Vehicle emission results (sample I)	0.213	0.248	0.00241	0.394	0.035
% difference in emissions	2.9	4.6	3.9	5.0	16.6
Engg. target	0.238	0.297	0.0038	0.629	0.05
Bharat stage 5 limits	0.28	0.35	0.0045	0.740	–

Conclusions

BS5 emissions compliance required following modification in engine combustion system and tuning of combustion parameters.

Piston crown with shallow, re-entrant type cavity, reduced depth, increased diameter, and compression ratio reduction from 18.5 to 16.5 is required to control NO_x emissions.

Injector, with number of holes matching with intake swirl and correct protrusion and spray hitting plane gives best mixing characteristic to achieve low NO_x-soot tradeoff.

Higher capacity EGR cooler with provision of EGR by-pass, EGR mixer and intake throttle to achieved best uniformity of air and exhaust mixture and accurate rate of EGR to reach best NO_x-soot trade-off. Higher capacity turbocharger with VGT helped achieving better air fuel ratio at various operating condition. Use of closed coupled DOC + DPF was must to meet particulate and CO emission below BS5 norms. Use of engine and vehicle simulation model helped prediction of engine performance and selecting critical engine hardware's before engine goes in test bench.

Very good correlation has been seen for NO_x, PM, and CO emissions of engine at steady-state and on vehicle. However HC correlations were not very good. This might be due to vehicle warm up conditions would have been slightly different than engine on test bench.

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Acronyms

BSFC – Brake specific fuel consumption
BS4 – Bharat stage 4 emissions
BS5 – Bharat stage 5 emissions
cEGR – cooled exhaust gas recirculation
CR – compression ratio
EGR – exhaust gas recirculation
cDPF – coated diesel particulate filter
DOC – diesel oxidation catalyst
DOHC – double overhead camshaft
HSDI – high speed direct injection
INCA – integrated calibration and acquisition
NEDC – new European driving cycle
PM – particulate matter
Pt – platinum
Pd – palladium
VGT – variable geometry turbocharger

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