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SIMULATION AND OPTIMIZATION OF HSDI DIESEL ENGINE FOR SUV TO MEET BHARAT 4 EMISSION NORMS IN INDIA

Huikun ,Zhang. Department of Mechanics,China

Research Article

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ABSTRACT

Diesel engines with direct injection provide advantages in terms of performance and fuel efficiency. Utilizing performance prediction software lowers development costs, effort, and engine tuning time. AVL Boost software was used in the current investigation to anticipate basic engine performance. Real engine test data were used to verify this model. This model is used in parametric research to forecast future performance. The Bharat stage 4 emission test cycle's 14 modes steady state speed-load point engine was predicted using AVL Cruise software. On an engine test bed, these 14 modes were used for emission optimization. Emission optimization was achieved by using the design of experiment approach. Combustion parameters are optimized using CAMEO software based on INCA. To compare engine out hot emissions with vehicle chassis dynamometer hot emissions, the Xcel basic software was created. This method shortens the time needed to create engine and vehicle emissions.

Keywards : BSFC, BMEP, CO, DOC, EGR, SUV

INTRODUCTION

The contemporary automotive industry needs to improve diesel engine performance and emissions because of upcoming strict CO2, noise, and emission regulations. India has amended the test cycle to reduce the maximum speed from 120 km/h to 90 km/h, however it has partly adopted European standards with the same emission limit. Indian road conditions are the basis for the Bharat stage emission standards.

In the current effort, engine performance and vehicle emission development were completed for the Bharat stage 4 standards, which were implemented in India's main cities and metropolitan areas starting in April 2010.The rest of India continues to adhere to Bharat Stage 3 standards. To lessen the growth of emissions time, [3] Before the prototype was constructed, the engine performance was predicted using AVL BOOST simulation software. AVL Cruise software [4] was used to generate 14 constant mode points of engine speed and load condition, which approximate the real emission test cycle when the vehicle was tested on the chassis dynamometer for emissions, in order to shorten the time it took to create emissions.

Following engine optimization for emissions at 14 mode points, the vehicle underwent further testing in a chassis dynamometer.

This test approach shortens the chassis dynamometer's principal emission development time.

The engine runs at various speeds and load points during the emission test cycle depending on the vehicle's reference mass, tire radius, transmission ratio, and axle ratio. Optimizing the vehicle's engine overall and meeting pollution standards got more difficult. Therefore, using AVL Cruise software, a methodical strategy was created to transform the emission cycle into 14 steady state critical points with a time weightage factor.

Before engines existed, AVL Boost software was used to forecast engine performance. Before the engine is actually tested on a dynamometer, the Boost Model engine provides a reasonable level of confidence in achieving the target engine performance. To achieve the intended engine full load performance, a parametric research was conducted using this engine Boost model.

Optimizing common rail injection settings and choosing appropriate hardware, such as piston bowl shape, turbocharger, and EGR with cooler, were key components of performance development work on the test platform.

On the test bed, 14 mode points, engine part load optimization, and injection parameter smoothing were carried out. EGR rate, injection timing, pilot injection, and other important parameters were measured on a steady state test bench.

After the base was established, the vehicle's engine was fitted, and additional work on the chassis dynamometer began. To achieve the required emissions, the EGR rate and oxidation catalytic converter loading were tuned during the chassis dynamometer test.

This approach may shorten the time needed to develop engine emissions and lower testing expenses.

ENGINE AND VEHICLE SPECIFICATION USED FOR EXPERIMENETATION

Base engine and vehicle specifications are shown in Table 1. Bharat stage 4 emission standards and full load performance targets for the power boost to 103 kW rating were retained for future development.Table1: Engine and vehicle specification for experimental setup.

Engine Type	Base Engine specifications	Upgraded Engine specifications
	2.2L, Inline, 4 cylinders, DOHC, HSDI Diesel	2.2L, Inline, 4 cylinders, DOHC, HSDI Diesel
Compression Ratio	18.5 : 1	16.5: 1

Rated Power	88 kW	103 kW
Rated Speed	4000 rpm	3750 rpm
Injection System	Common Rail, Bosch Gen 2	Common Rail, Bosch Gen 2
Air System	VGT Gen 2 Turbocharger	Gen 3.5 ‘S’ vane VGT Turbocharger
Emission	Bharat stage 3	Bharat stage 4
Vehicle specifications	SUV	SUV
Gearbox	Manual Transmission with 5 forward+ 1 backward	Manual transmission with 5 speed + 1backward
Axle ratio	4.1	4.1
Rolling radius	0.331 m	0.331 m

METHODOLOGY

In order to fulfill Bharat stage 4 emission standards, the engine and vehicle's performance and emissions were upgraded using the following methods.

3.1 AVL Boost software is used to simulate and validate a thermodynamic engine model using a basic engine.
3.2 Parametric analysis of engine models using AVL Boost software to forecast engine performance at full load
3.3 Using AVL Cruise simulation software, steady state 14 mode speed-load points and their weighting factor are generated.
3.4 Engine testing and full load performance development on a steady state test bench
3.5 Hot emission development on the engine according to 14 mode speed load points for a steady state test bench.
3.6 Using the engine dynamometer's 14 mode point data to verify the vehicle's hot emission optimization on the chassis dynamometer.

Cold correction was used and industry standard practices were adhered to for further vehicle calibration work after the successful correlation of hot emissions on the engine and vehicle. such as summer and winter calibration, as well as features related to comfort and driveability that were not included in the current scope of this research.

Thermodynamic Engine simulation model by use of AVL BOOST software

AVL Boost software was used to create the base engine simulation model on a computer [3]. The model's performance output was evaluated and compared to that of the basic engine. The intended engine full load performance objective of 103kW was predicted using a parametric analysis using this verified Boost model. The AVL Boost engine model, which is utilized for parametric analysis and full load performance prediction, is seen in Figure 1.

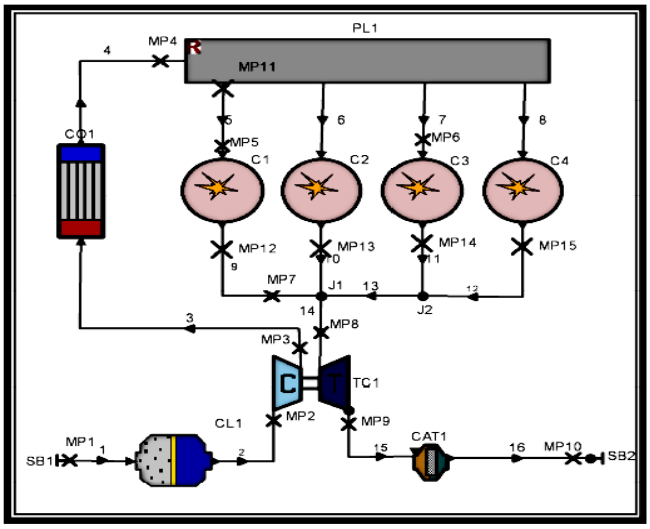


Fig. 1: AVL Boost model for experimental engine

The engine's design and thermal boundary conditions enforced the following useful boundary conditions during the creation of the boost model. The maximum engine cylinder pressure was 155 bar. Due to turbocharger material constraints, the maximum exhaust gas temperature was set at 760 degrees Celsius. The temperature of the engine oil was permitted to reach 130 degrees Celsius. The maximum turbine speed permitted was 2,10,000 rpm. Prior to the turbocharger, the maximum pressure was 2300 mbar. At full load and full speed, the engine noise objective was maintained at 97 dBA. Based on the engine valve train's design and operating restriction, the maximum permitted engine speed was limited to 4750 rpm.

Parametric study on AVL Boost Engine Model

The engine's full load performance was estimated for all speed-load conditions between 1000 and 4000 rpm while maintaining a maximum cylinder pressure of 155 bar. The full load comparison between the Boost simulated and real engine test results is shown in Figure 2.

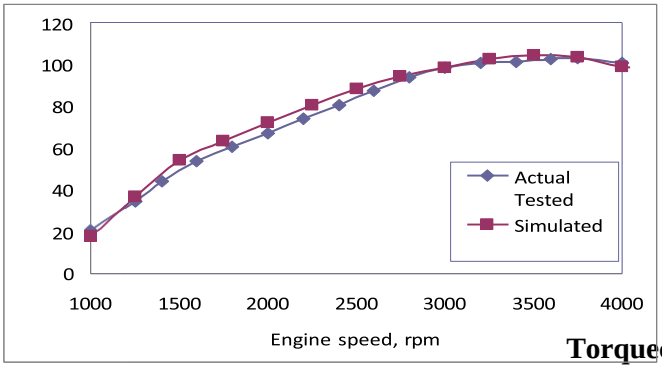


Fig. 2: Engine Full load performance comparison of simulated and actual tested results.

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Figure 3 displays the predicted engine torque and the actual engine test results, which matched 96% of each other. The actual test results are somewhat lower since the engine's turbocharger air flow was found to be lower.

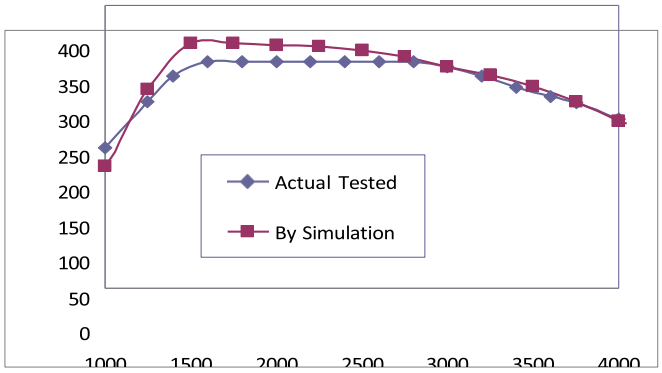


Fig. 3: Engine Torque comparison of Actual tested and simulated results.

Figure 4 displays both the simulated findings from the AVL Boost model and the actual tested engine's brake-specific fuel consumption. The simulated and real test results matched. Due to the boost model's reduced assumptions, real results are somewhat greater than expected in every speed.

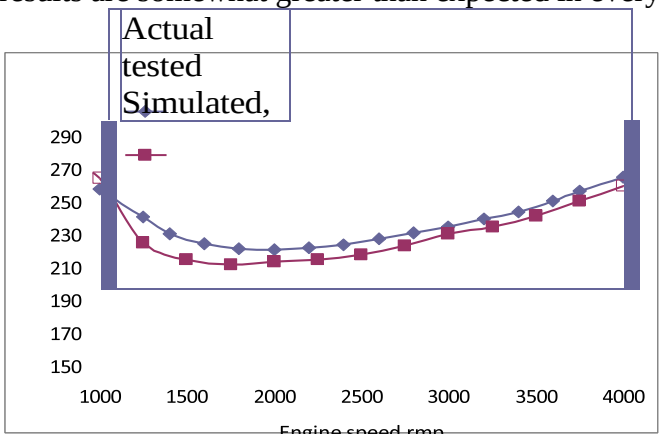


Fig. 4:Engine power and BSFC vs engine speed in both simulated and real-world tests.

Simulated and real engine test results at various engine full load operating speeds are shown in Figure 5. With the exception of 4000 rpm, the simulated findings indicate a greater temperature than the real one. This is made feasible by the boost combustion model's reduced assumptions. As a consequence, the findings did not match the real test results.

Fig. 5: Comparison of real tested and simulated findings for exhaust temperature vs engine speed The combustion noise comparison between the real tested engine and the boost simulation results is shown in Figure 6. The real engine combustion noise was around 3 dBA lower than the boost simulated results at higher speeds above 2000 rpm, and the boost results matched the lower engine speed.

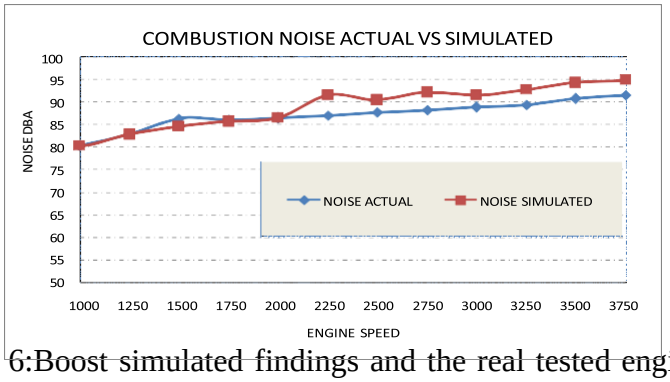


Fig. 6:Boost simulated findings and the real tested engine's combustion noise are compared. Based on improved combustion characteristics, the predicted cylinder pressure closely matches the actual test results.

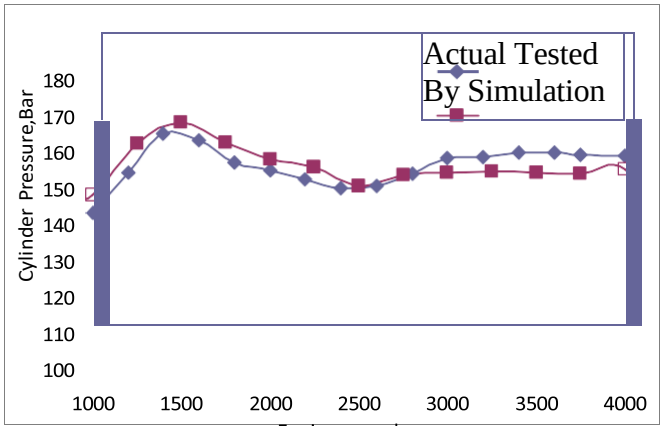


Fig. 7: Combustion Noise comparison of actual tested engine and Boost simulated results.

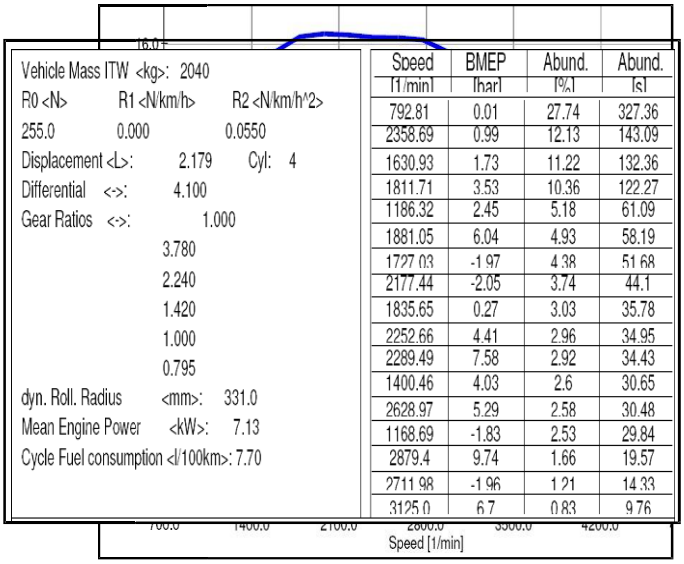
Generation of 14 mode steady state points for hot emission development on Engine dynamometer by use of AVL Cruise software

New approach was suggested in this work .Transient emission cycle was converted in to 14 mode steady state speed-points with time weightage factor by use of AVL Cr ise software [4]. Excel base program was developed for conversion of engine out raw emission PPM to gram per

kilometer. Table 2 and figure 8 shows engine speed, BMEP, percentage weightage of 14 mode points generated by use of AVL cruise software.

Fig. 8: AVL Cruise prediction for 14 steady state mode speed-load points.

Table 2: Steady state 14 mode points for engine testing on test bed



Speed [1/min]	BMEP [bar]	Abund. [%]	Abund. [s]
792.81	0.01	27.74	327.36
2358.69	0.99	12.13	143.09
1630.93	1.73	11.22	132.36
1811.71	3.53	10.36	122.27
1186.32	2.45	5.18	61.09
1881.05	6.04	4.93	58.19
1727.03	-1.97	4.38	51.68
2177.44	-2.05	3.74	44.1
1835.65	0.27	3.03	35.78
2252.66	4.41	2.96	34.95
2289.49	7.58	2.92	34.43
1400.46	4.03	2.6	30.65
2628.97	5.29	2.58	30.48
1168.69	-1.83	2.53	29.84
2879.4	9.74	1.66	19.57
2711.98	-1.96	1.21	14.33
3125.0	6.7	0.83	9.76

3.4. Full load Performance development of engine on test bed

Experiments were conducted on engine mounted on AVL make Hi Dynamic Test Bench equipped with Horiba 7100 D emission analyzers, Smart sampler, Cameo and INCA interfaceand hi speed data acquisition system for real time measurements all temperatures , pressures and flows measurements. AVL Indi master for measurement of heat release and cylinder pressure measurements. Figure 9 show test bed setup used for Experiment.

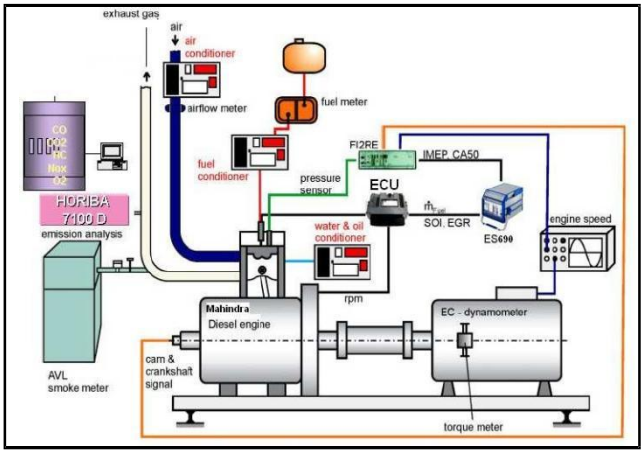


Fig. 9: Test bench setup for Experiment

The underlying engine's design was altered to satisfy full load performance requirements. [1] To change the compression ratio from 18.5 to 16.5, a piston with a re-entrant bowl has a new form with greater

cavity volume and depth. Variable geometry turbochargers (VGTs) with straight vanes were swapped out for VGT turbochargers with "S"-shaped vanes to satisfy increased air flow requirements.[2] In order to regulate NOX emissions and particle trade-off during part load conditions without increasing smoke and particulates, an EGR cooler was used to cool exhaust gas and feed cooled EGR. The Bosch Generation 2 common rail fuel injection technology remains unchanged. To accommodate the new improved combustion bowl, the injector hydraulic through flow and spray cone angle have been altered. To fit the new combustion chamber design, injector protrusion is re-optimized [5, 6]. In order to reduce the impact of compression ratio on start ability in cold weather, glow plugs were made mandatory. The engine power and torque attained are compared to baseline performance in Figure 9.

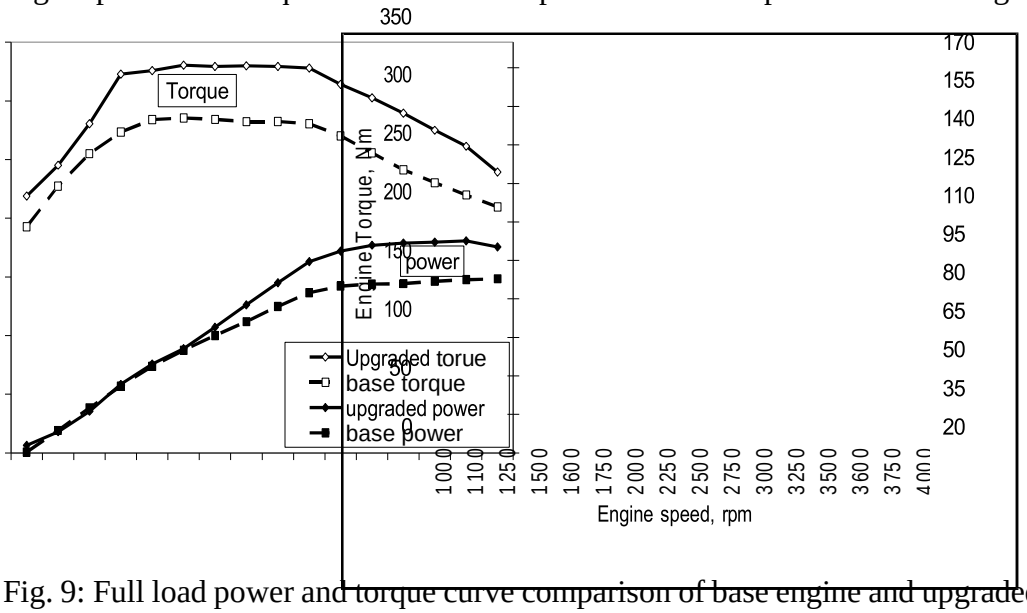


Fig. 9: Full load power and torque curve comparison of base engine and upgraded engine

Figure 10 shows the pilot injection strategies used in optimization of full load performance of engine at various speeds. Advantages of using pilot injection help in engine NVH characteristic of engine and increase in power output of engine due to premixed combustion.

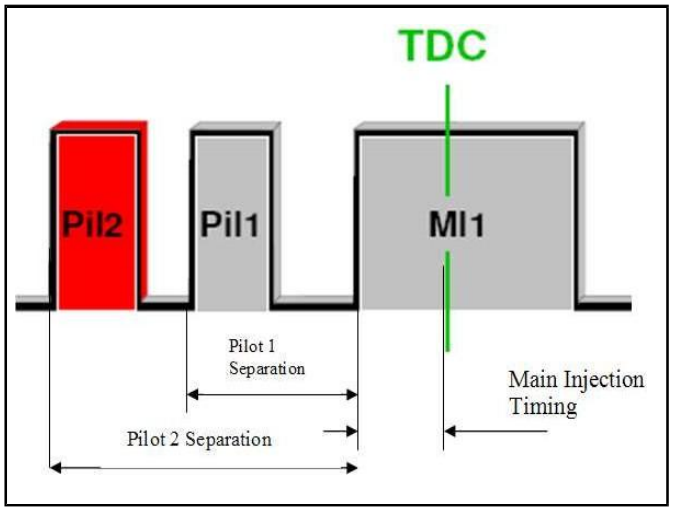


Fig.: 10: Main injection and Two pilot injection strategies for full load performance and emission optimization.

3.5 Hot Emission development on Engine dynamometer

After starting the engine, the coolant and oil temperatures were adjusted to 97 and 90 degrees Celsius, respectively. Every speed, load, and row of engine emissions were recorded while the engine was running. These emissions were entered into an Excel sheet where a software was created to convert engine out emissions from ppm or g/hr to g/km, and the results were compared to the Bharat stage 4 emission laws' limit value. In order to achieve optimal NOx-smoke trade-off and manage CO and HC emissions, experiments were designed to optimize each point by adjusting injection parameters such as injection time, injection pressure, pilot amount, EGR rate, pilot separation, and various boost pressures. The engine was run at several operating points using AVL Cameo interfaced with common rail INCA software, and the best settings were chosen at each crucial point.

Using an Excel base program, every optimized key point data was examined to see whether or not the optimized results were within legal bounds. The PPM level of NOx was optimized by raising the EGR rate. When an engine was optimized for Bharat stage 4 emission standards without an EGR cooler, it was found that smoke levels significantly increased. In order to manage NOx and smoke levels and meet Bharat stage 4 emission requirements, an EGR cooler with a cooled EGR rate was used. Engine output NOx, CO, HC, and smoke at 14 mode points optimized from BS3 to BS4 emissions are shown in Figures 10, 11, 12, and 13. Even though CO and HC emissions were greater than those of BS3, they were nonetheless below legal limits because to the use of closed-coupled DOC with increased platinum loading.

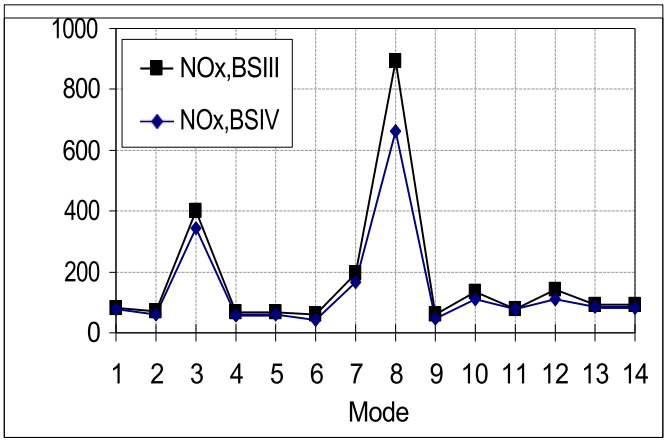


Fig 10: Engine out NOx emission at 14 mode points

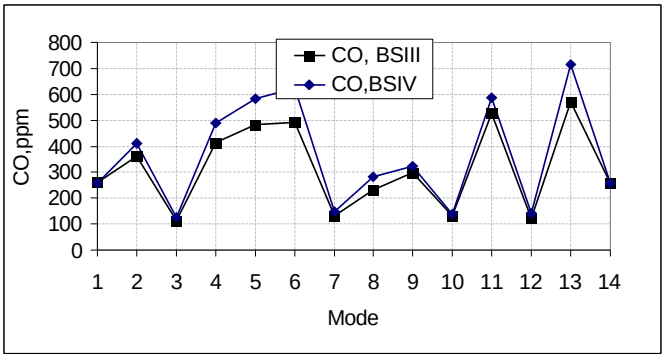


Fig 11: Engine out CO emissions at 14 mode points

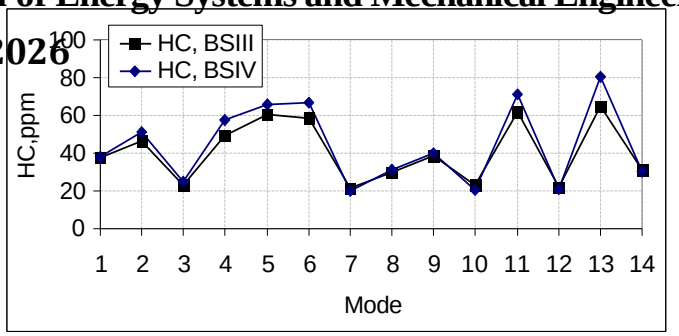


Fig 12 : Engine out HC emissions at 14 mode points

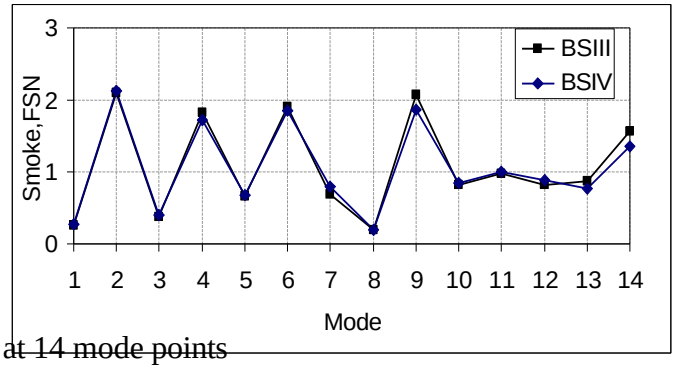


Fig 13: Engine out smoke at 14 mode points

Figure 14 and 15 shows various engine performance parameters for 14 mode points.

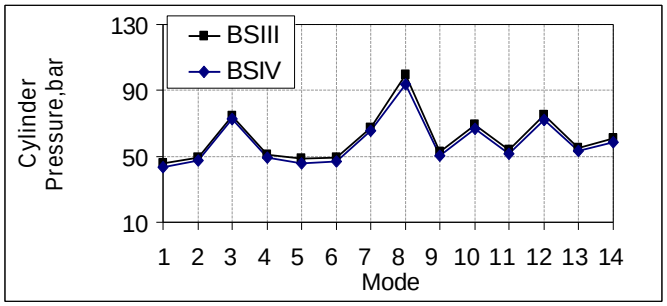


Fig 14: Cylinder pressure at 14 mode point

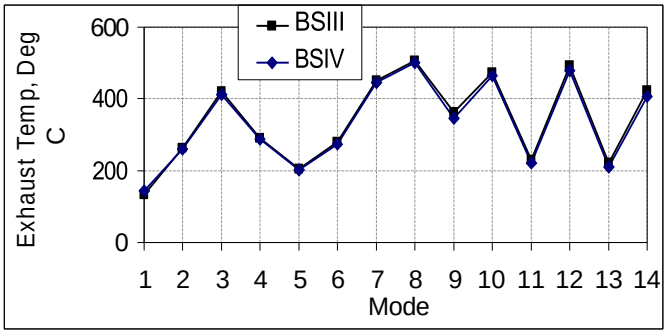


Fig 15: Exhaust temperature at 14 mode points
Figure 16, 17, 18 and 19 shows main combustion and injection parameters.

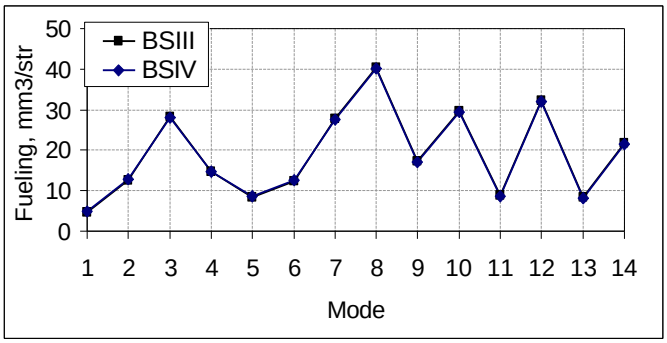


Fig 16: Engine fueling at 14 mode points

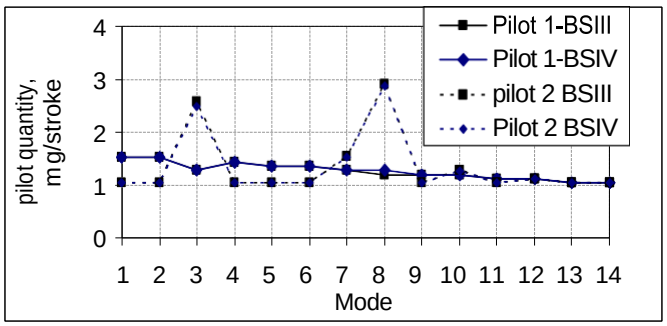


Fig. 17: Pilot 1 and 2 quality at 14 mode points

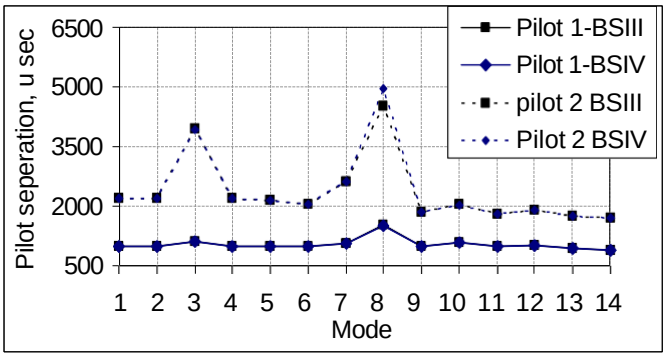


Fig.18: Pilot 1 and 2 separation at 14 mode points

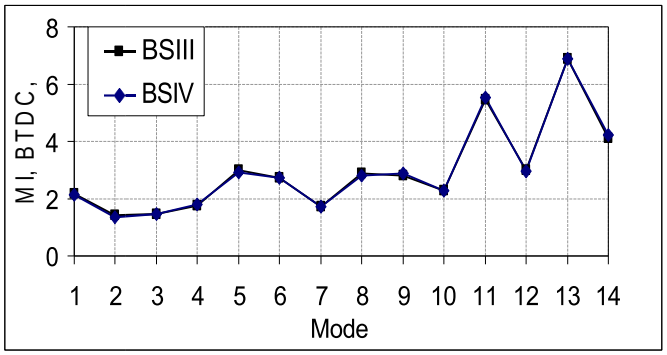


Fig. 19: Main injection timing at 14 mode points

To manage the engine out NOx at these low load locations, more pilot 2 quantity and separations are usually needed in mode 3 and more 8. In order to achieve smooth engine operation in terms of noise and drivability, optimal injection parameters of 14 critical points are smoothed across the full engine speed load condition once hot emissions are satisfied with suitable engineering margins. To make sure that engine out emissions are still within the engineering goals, hot emissions were measured once more after the injection parameters were smoothed at the full engine speed load situation. If not, optimize and smooth again until emissions fall below engineering limits. When the car is cold started at 20 degrees Celsius, Bharat stage 4 emissions must be satisfied. In order to get the same engine output emissions, the engine coolant and oil temperatures were changed at 40 degrees Celsius on the test bed using cold adjustments.

3.6. Chassis dynamometer testing and optimization of hot emissions and comparison with engine dynamometer 14 key point findings.

The engine was installed on the vehicle to establish a link between engine emissions and the hot emissions of the chassis dynamometer test results after it had been tuned for 14 mode points, additional component load points, and injection parameter smoothing. The Horiba chassis dynamometer with AVL-made emission analyzers for testing is seen in Figure 20.

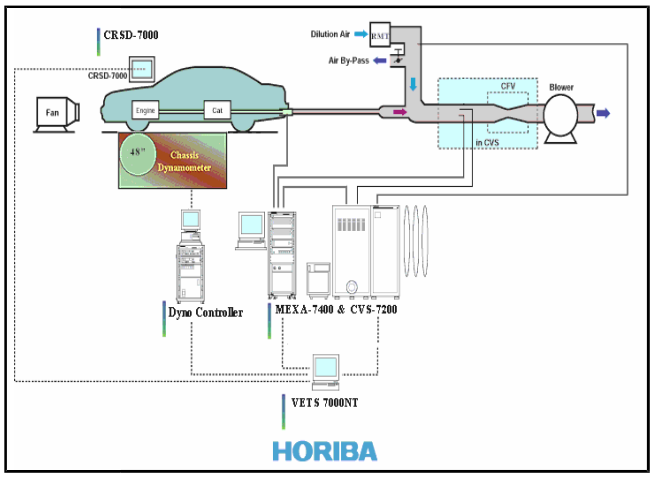


Figure 20: Chassis dynamometer test setup for vehicle Emissions

Before taking emission test, vehicle was wormed up on chassis dynamometer by running it with three

EUDC cycle. Hot emission test was conducted on chassis dynamometer as per test cycle defined in Bharat stage 4 emission norms. Figure 21, 22, 23 and 24 shows online traces of CO, NOx, HC and smoke emissions plotted in real time scale during the test cycle.

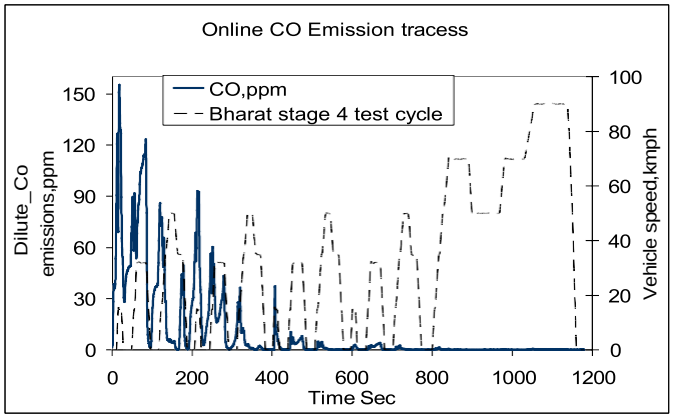


Fig. 21: Online Traces of Dilute CO Emission during Hot Emission Test Cycle

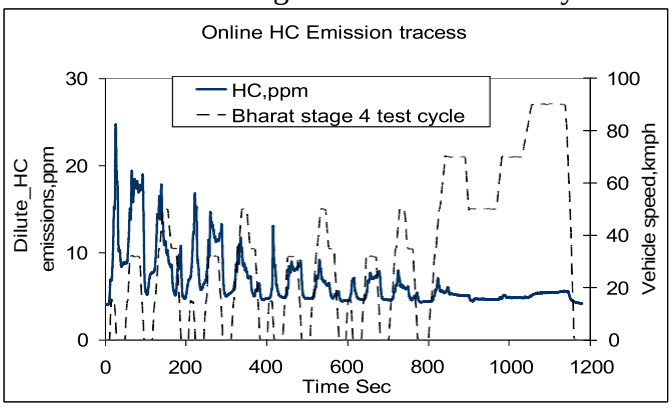


Fig 22: Online traces of Dilute NOx Emission during hot emission test cycle

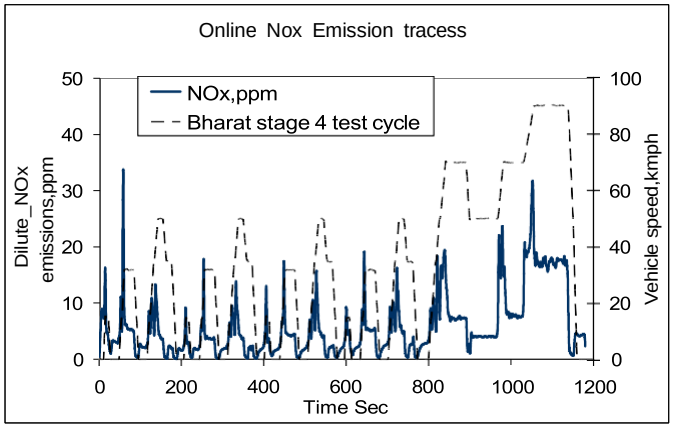


Fig. 23: Online traces of Dilute HC Emission during hot emission test cycle

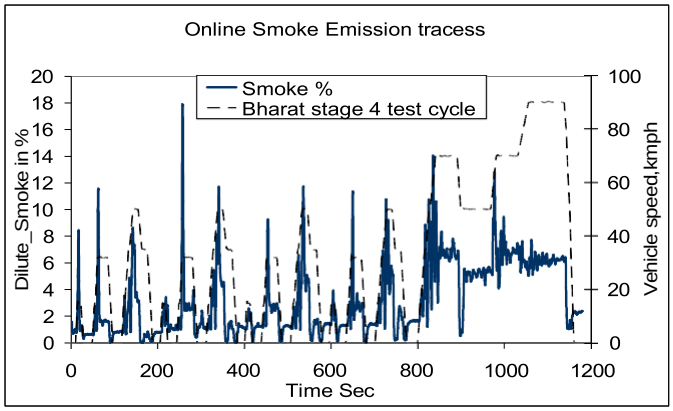


Fig. 24: Online Traces of Dilute Smoke Emission during Hot Emission Test Cycle

IV RESULTS AND DISCUSSSIONS

4.1 AVL Boost simulation and real test results are correlated

A parametric research and boost simulation revealed that maintaining a peak firing cylinder pressure of 155 bar requires reducing the compression ratio from 18.5 to 16.5. The findings of the simulation and the actual engine tests matched.The simulated boost pressure and real test results at full load at 3750 rpm and 1500 rpm are compared in Figures 25 and 26.

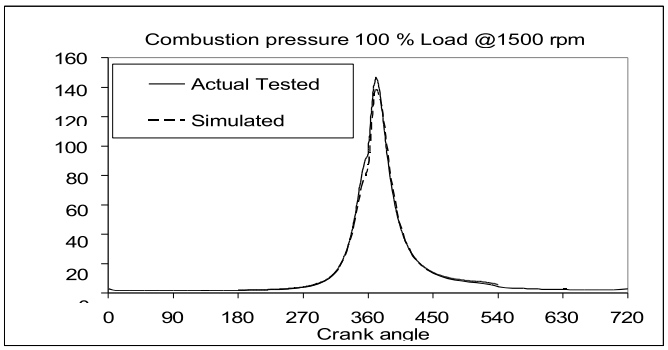


Fig 25: Cylinder Pressure comparison at Full load @ 3750 rpm for actual and simulated results

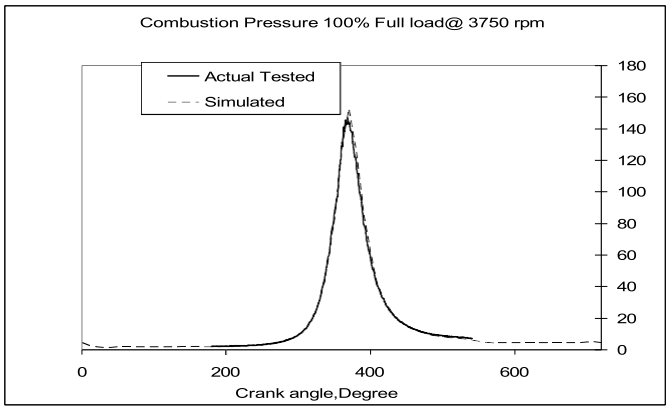


Figure 26: Cylinder Pressure comparison at Full load @ 1500 rpm for actual and simulated results

Engine 14 mode hot emission and vehicle hot emission of chassis dynamometer results.

14 The results of engine dynamometer and chassis dynamometer mode emission tests were compared for PM and HC+NOX for Bharat stage 4 emission standards and hot engine out objectives. When compared to the data from the chassis dynamometer, the HC+NOx readings are within 6%. Test bed and chassis dynamometer vehicle emissions are under 10% of particulate (soot) emissions. The engineering test bed objectives for CO and HC emissions are met. The use of an appropriate oxidation catalyst on a chassis dynamometer helps optimize the vehicle's CO and HC emission margins, which vary significantly. As is customary, further adjustments were made to the injection settings, EGR rate, and catalytic converter loading on the car.

Table No 3: Hot emission results comparison of 14 mode and vehicle tested on chassis dynamometer

	Hot Emissions [g/km]				
Engine /vehicle	Nox	HC+Nox	Soot (PM)	CO	HC
14 mode Emission results	0.343	0.396	0.044	0.375	0.053
Vehicle Emission results	0.333	0.391	0.042	0.402	0.058
% difference	2.915	1.279	4.762	6.716	9.434
Engine out target	0.360	0.420	0.050	0.550	0.060
Bharat stage 4 limits	0.390	0.460	0.060	0.740	-

Table 3 and figure 27 shows the hot emission test of 14 mode and chassis dynamometer. Results were comparable and give the confidence of selected hardware and combustion parameters to proceed further for work on chassis dynamometer.

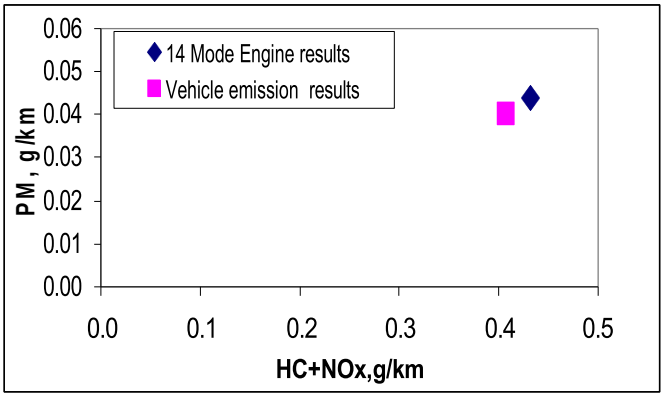


Fig. 27: HC+NOx verses particulate hot emission results

CONCLUSIONS

The process of designing and developing engines is complicated. Due to the complexity of engine characteristics such common rail, EGR cooler, next generation boosting system, etc., there is no quick cut in development to fulfill future ultra low emission standards.

The conclusions that follow are based on these developments.
5.1 Before an engine is put on a test bed, the use of simulation tools aids in the early prediction of engine performance and the selection of crucial engine hardware.
5.2 By optimizing the engine on stable points on the test bench, a significant amount of vehicle emission development time on chassis dynamometers may be decreased.
5.3 If one engine is used in several cars or if there are multiple vehicle variations to comply with the same emission regulations, this strategy is particularly helpful.
5.4 Significant development cost savings and infrastructure overload may be avoided.
5.5 It is feasible to build a single engine and apply it to several vehicle variations that meet the same emission standards.
5.6 NOx and soot emissions from the steady state and hot chassis dynamometer showed a very strong association.
5.7 Correlations between HC and CO are not seen. This is mostly caused by the catalyst's temperature and conversion efficiency.

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