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Effect of Injection Parameters on Steady State Emission of a Common Rail Diesel Engine

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Abstract—*This paper discusses the effect of injection parameters in the steady state emission of a common rail diesel engine. Test conducted on a 3. 3L engine with a focused objective to minimize the engine out emission levels for the pollutants as Particulate Matter, Oxides of Nitrogen, Hydrocarbon and Carbon Monoxide. In the tradeoff between PM and NOx, role of Injection Pressure (Rail Pressure) and Start of Injection (Main Injection Timing) is analyzed.*
On commercial vehicle application the emission testing is carried out on engine dynamometer and raw emission is measured through the 13 Mode cycle. Emission limits from BS II (Bharat Stage II) to Bharat Stage III and Bharat Stage IV level are stringent, these emission limits demand lowered value of raw exhaust emissions from the engine. The test procedure based on the 13 mode cover engine operating zone through various part load and full load speed load points, this is based on the vehicle application. The initial work for optimization of the individual modes covered the study of changes in the 13Mode ESC test over the earlier R49 – 13 Mode cycle used for measurement of BS II emission compliance.
Combustion optimization is achieved through the iterations of the injection timing, injection pressure and application of pilot injection at part load mode points. These test iterations are focused on individual modes and the combined effect of the optimized set of parameters is tested on a complete 13 Mode cycle. .

1. INTRODUCTION

Reduction in engine out emission and ensuring the engine performance with best possible BSFC are the two important aspects focused during the combustion development of a diesel engine. With the advances in the fuel injection equipment technology, availability of the higher fuel injection pressure is the main advantage. It also gives the flexibility in precise setting of the injection parameters as injection pressure, start of injection, introduction of pilot injection and the pilot injection separation. Electronic fuel injection control also enhances the ability to set the operating injection parameters based on the engine speed and torque condition. Selection of these parameters can be varied based on the fuel quantity for a particular speed point. This can also be opted for a steady state and transient behaviour of the engine. Application of the common rail system for engine advancement presents opportunity to reduce the engine out emission and at the same time can benefit through fuel economy.

Advantage of the common rail system is to change and use the selective set of injection parameters for a specific steady state of the engine, which includes introduction multiple injection, setting the precise start of injection, controlling the injection duration based on the optimized output results of emission as well as engine overall performance for power, torque and best possible level of BSFC.

2. EMISSION TEST PROCEDURE

As the commercial vehicle has the engine dynamometer emission testing, the exhaust gases out of engine are measured through the emission analyser and PM sampling unit. Engine is run through various operating mode points of speed and % of torque, which is derived from the standard test procedure.

For Bharat stage II the 13 mode cycle used for commercial vehicle application engine is R49 cycle. R49 cycle has 13 Mode points which cover a low idle point, 6 Modes for maximum torque and maximum (rated power), these mode points are derived on a standard calculation of part load and full load to cover the part load and full load of the engine operating zone. Whereas for Bharat stage III onwards the 13 mode cycle is more enhance to cover in detail operating zone of the engine, reaching more closure to the actual engine behavior on a commercial vehicle duty cycle. 13 Mode ESC used for BS III and BS IV is derived on selection of A, B, C speeds and these speed points are calculated from the N_{hi} and N_{low} of the engine power curve. It is derivation of the engine operating points between the 70% of maximum power speed and the lowest speed at 50% of the maximum power observed on lower side of power curve.

The R49 test is performed on an engine dynamometer operated through a sequence of 13 speed and load conditions. The cycle has 3 low idle modes and 5 Modes each for maximum power and maximum torque speed. Exhaust emissions measured at each mode are expressed in g/kWh. The final test result is a weighted average of the 13 modes. The test cycle is as shown in Fig. 1

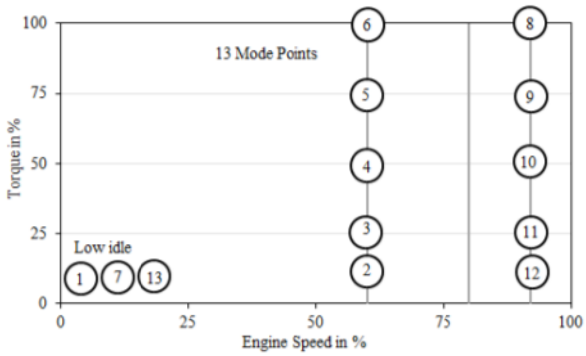

Fig. 1: R49 Emission Cycle

13 Mode ESC test cycle is a 13-mode, steady-state procedure that replaced the R-49 test for BS III and BS IV emission testing. The engine is tested on an engine dynamometer over a sequence of steady-state modes The specified speed shall be held to within ±50 rpm and the specified torque shall be held to within ±2% of the maximum torque at the test speed. Emissions are measured during each mode and averaged over the cycle using a set of weighting factors. Particulate matter emissions are sampled on one filter over the 13 modes. The final emission results are expressed in g/kWh.

Engine operating speed range is the range which represents the engine speed and torque used on vehicle during field application. This range lies between the low and high speed point.

Low speed (N_{lo}) is the lowest engine speed where 50% of the declared maximum power occurs and High speed (N_{hi}) is the highest engine speed where 70% of the declared maximum power occurs. Based on these two speeds A, B and C speeds are calculated.

Speed A = $N_{lo} + 25\% (N_{hi} - N_{lo})$

Speed B = $N_{lo} + 50\% (N_{hi} - N_{lo})$

Speed C = $N_{lo} + 75\% (N_{hi} - N_{lo})$

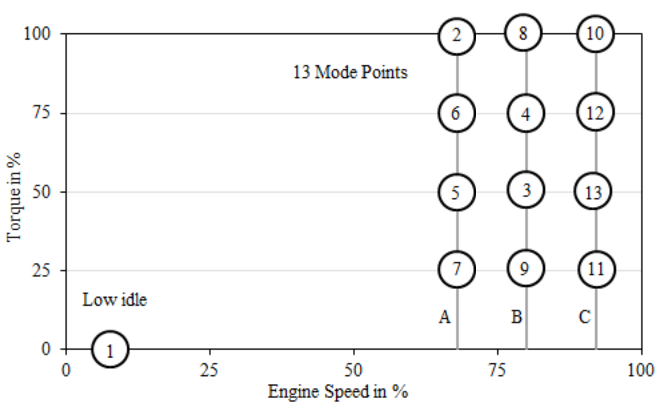

Fig. 2: 13Mode ESC Emission Cycle

As seen in the Fig. 1 and Fig. 2, 13 Mode ESC test covers the operating zone of the engine through various speed - load, part load points.

The present work involves emission optimization, dictated by ESC test applicable to the engines to be used on Light Commercial Vehicles. A step by step approach was adopted to meet the performance and emission targets. Initial work involved study of the 13 Mode ESC test standard and calculation of the A, B and C speed for the engine, which was followed by the injection parameters optimization.

3. EXPERIMENTAL SETUP

The experiments are conducted on engine with a dynamometer controller, interface with emission analyzer and Particulate sampler for conducting the test and data acquisition. All the trials were conducted with low sulphur reference diesel and conditioned air. Fig. 3 shows the experimental setup.

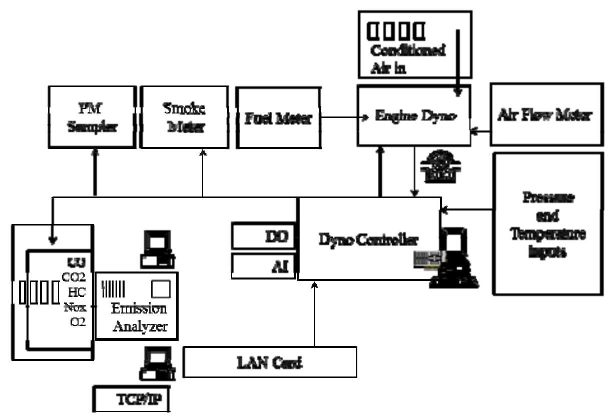

Fig. 3: Schematic of Experimental Setup

As seen in setup the engine has the input from fuel meter, air flow meter and engine dynamometer controller, whereas the output of the exhaust gas is routed to the emission analyzer, PM sampler and smoke meter.

4. ENGINE AND TEST DESCRIPTION

3. 3L engine with 1600 bar common rail injection system is tested with this setup and the individual modes are tested with the iterations for the parameters as injection pressure, start of injection, introduction of pilot injection and optimizing the pilot separation.

Table 1: Engine specifications

Engine Type	4 Stroke, 4 Cylinder, CI
Bore x Stroke	96 x 115 mm
Displacement	3. 3L
Rated Power	82 kW@ 2800 rpm
Aspiration	Turbocharged with intercooler
Fuel Injection System	Common Rail

5. METHODOLOGY

The methodology involved study of the mode points based on the weightage factor of the 13 Mode ESC test cycle, which is targeted to give a weighted average test result combined tested in a 13 Mode cycle.

As given in Table. 2, Mode number 3, 4 and 9 has the 10% weightage in the 13 mode test cycle so selected as the priority to optimize for the engine out emission. These mode points contributed to the weighted average test result. As the 13 mode emission test is a planned set of experiments, in which all focused injection parameters of are varied over a specified range.

Table 2: 13 Mode weightage

Mode	Engine Speed	Load, %	Weight %	Time Min
1	Low idle	0	15	4 Min
2	A	100	8	2 Min
3	B	50	10	2 Min
4	B	75	10	2 Min
5	A	50	5	2 Min
6	A	75	5	2 Min
7	A	25	5	2 Min
8	B	100	9	2 Min
9	B	25	10	2 Min
10	C	100	8	2 Min
11	C	25	5	2 Min
12	C	75	5	2 Min
13	C	50	5	2 Min

This gives a systematic data and optimised value of the resulted emission when compared with a complete set of test. Mathematically, such a complete set of experiments ought to give desired results. In many cases, particularly emissions in which optimisation, based on trade-offs is required, the method does not point to the best optimised setting of parameters, but gives only the interactive relation of these parameters with each other.

Taguchi Method based on orthogonal array experiments gives much-reduced variance for the experiment with optimum settings of control parameters. Orthogonal Arrays(OA) provide a set of balanced experiments and also streamline the data analysis for optimum results. Three injection variables as injection pressure (RP), Start of injection (SOI) and Pilot Separation (Sep) with three levels each RP1, RP2, RP3, SOI 1, SOI 2, SOI 3, Sep1, Sep2 and Sep3 are selected at each of the 10 Modes. The full load points are not iterated with pilot injection 'On' state.

Table 3: Orthogonal array

Sr	Injection Pressure (RP) 'bar'	Start of Injection 'Deg BTDC'	Pilot Separation 'µs'
1	X-120	Y+1	Z-200
2	X-120	Y	Z
3	X-120	Y-1	Z+200
4	X	Y+1	Z-200
5	X	Y	Z
6	X	Y-1	Z+200
7	X+120	Y+1	Z-200
8	X+120	Y	Z
9	X+120	Y-1	Z+200

With reference to Table 2, at iteration number 1, injection pressure RP is set to level1, SOI to level 1and Pilot separation to level 2. In this sequence the combination of these three parameters is iterated in such a way that optimum level for engine out emission pollutants as CO, HC, NOx and PM is obtained. As the iterations progressed through various modes the base level value of the injection pressure, start of injection in degrees of crank angle and pilot separation in microseconds is varied. As the pilot separation is the illustration of the start of injection timing separated from the main injection timing, which varies based on change in the engine speed.

6. TEST DETAILS AND ANALYSIS OF RESULTS

Iterations are carried out individual modes, from which one mode is explained as mode number 9 with 2150 rpm and 80Nm torque. This is the B speed, 25% of torque with weightage factor of 10 %.

Table. 4 Mode 9 Details

Speed rpm	Torque Nm	Injection Pressure bar	SOIDeg BTDC	Sep µs
2150	80	920	5. 2	1720

Table 5: Levels of injection parameters for mode 9

Level	RP	SOI	Sep
1	800	4. 2	1520
2	920	5. 2	1720
3	1040	6. 2	1920

Base level of this iteration is set at 920 bar injection pressure with start of injection at 5. 2 Deg BTDC and pilot separation of 1720 µs.

The different values of RP, MI and Sep at the selected mode, which have been selected for further investigation, are given in Table 4. On the basis of signal to noise ratio the results are plotted for each emission pollutants individually, this is analyzed on the basis of the smallest is the best value, of minima principle. Where the output function, n = - 10 Log_{10}(mean of sum of squares of measured data). As shown in the Fig. 4, HC emissions are lower at SOI 3 and Sep 1. This trend is observed with CO emission also, as shown in Fig. 5.

There is no significant variation in CO and HC ppm based on the iterations of injection pressure from RP1 to RP 3, whereas considerable variation is seen on the NOx ppm with increase in injection pressure, this change is better for NOx level, In case of smoke the first level injection pressure (RP1)shown optimum results.

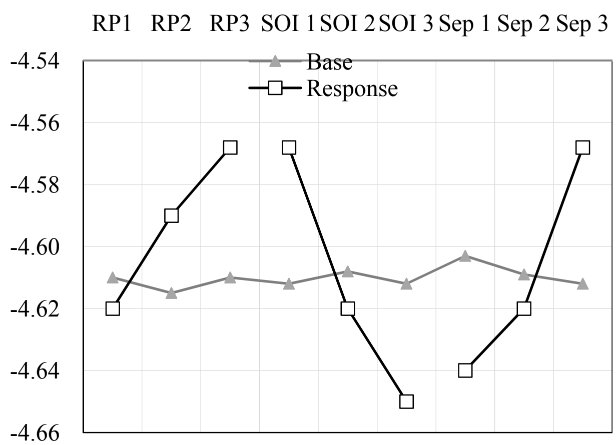

Fig. 4: HC response curve

The response for HC and CO together has suggested the emission trade off can be obtained by operating the engine at mode number 9 with 2nd level of injection pressure, 3rd level of start of injection, and 1st level of pilot separation.

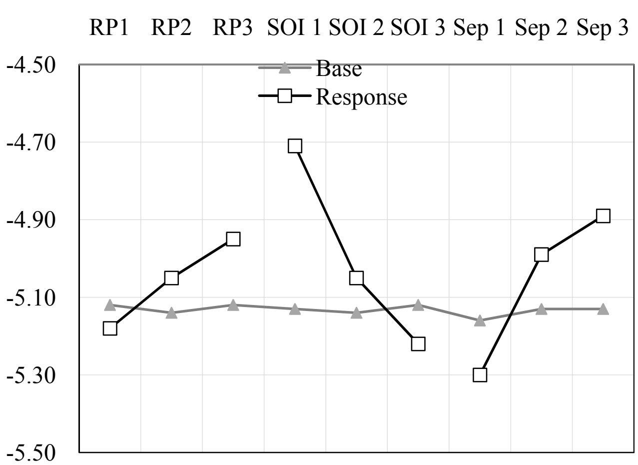

Fig. 5: CO response curve

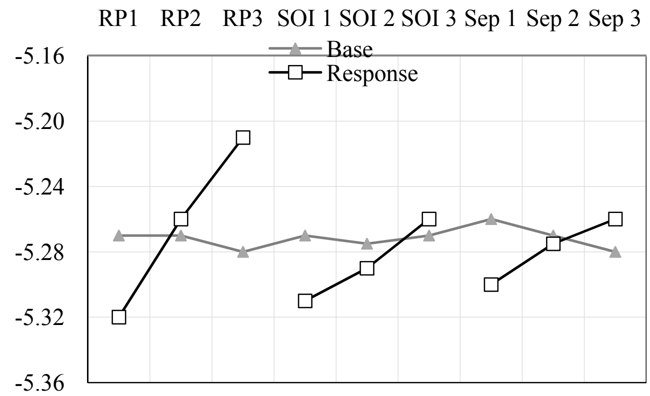

Fig. 6: NOx response curve

With these iterations of a mode point, similar process for the injection pressure selection and setting the start of injection with pilot separation for the optimum engineout emission level is carried out at remaining part load points.

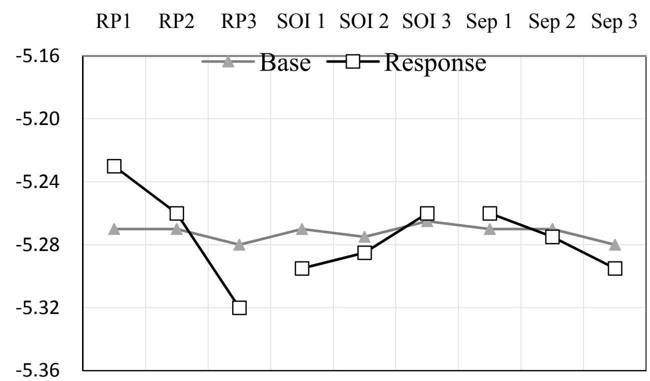

Fig. 7: Smoke response curve

The emission result values for the base test and test conducted after the DOE values is compared in Fig. 8, marginal increase in the smoke value is seen through the test, but still it does not contribute to weighted average result of particulate matter.

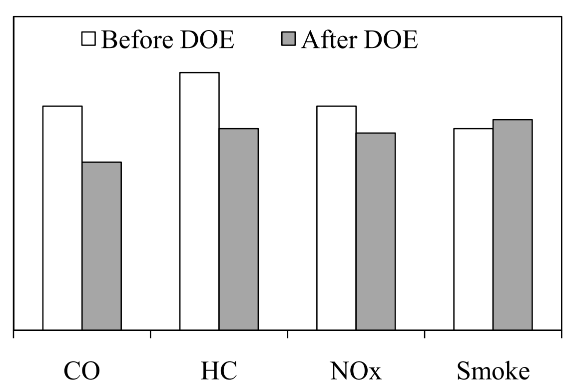

Fig. 8: Emissions before and after DOE

7. SUMMARY

- Design of experiment with selected injection parameters and the statistical analysis gave understanding for the trend of the optimum combustion and emission reduction.
- Considerable reduction in actual testing time is achieved. As on completion of one mode, the results were used as base iteration for the part load modes of same speed point.
- Effect of injection parameters on emission pollutants at individual mode found to be consistent within ± 3%, as compared to complete 13Mode cycle test.
- Pilot injection helps in bringing down NOx with a less effect on smoke values. Optimized pilot separation value directed the quantity just outside the bowl. This helps the main injection in start of the combustion
- When the injection pressure and start of injection is optimized together the trade-off between NOx and PM can be achieved with overall reduction of all emission pollutants.

8. NOMENCLATURE

RP : Rail Pressure (Injection Pressure)
SOI : Start of injection
CO : Carbon Monoxide
HC : Hydrocarbons
NOx : Oxides of Nitrogen
PPM : Particles Per Million
TDC : Top Dead Center
BTDC : Before Top Dead Center

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