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Emission Optimization for Diesel Engine by DOE Model to Comply with BS III Norms

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Abstract

This paper discusses calibration of electronically controlled common rail diesel engine by Design of Experiments (DOE). DOE method accomplishes modelling and optimization with MINITAB tool. This paper presents DOE based experiments to investigate the effect of total fueling, pilot fueling, pilot separation, injection timing, rail pressure on performance and emissions without change in engine hardware of base engine. A 320 kW 8.9L in-line 6 cylinder non-emmisionized was chosen as base engine. By modified calibration emission the NOx by 18.03 %, CO by 2.60 % & increasing the particulate matter by 31.08 % and achieved BSFC is better orcomparable than best calibration. Due to commercial competition the paper remains mute on specific values of performance and emission of base as well as modified engine for defense application.

Keywords: *Design of Experiments, Emission Optimization, Injection Parameters*

1. Introduction

With the advent of electronic unit injector for diesel engine fuelling parameters can be easily programmed and adjusted to achieve optimized power and emissions. Brien Fulton et al (1993) investigated effect of injection timing on performance, combustion and emission Injection timing retard offers one of the best solutions for meeting exceedingly restrictive BSNOx emissions requirements. Injection timing retard decreases power, efficiency, and increases smoke emissions. However, reductions in BSNOx emissions are much greater than deterioration of the other operating parameters. Penalties of retarded timing become more prevalent at reduced loads, where BSNOx emissions decrease. In diesel engines optimization of engine out emissions and fuel consumption requires experimental investigation of effects of different injection strategies as well as of large engine variables, such as scheduling of pilot and after pulses, rail pressure and air to fuel ratio. Andrea Emilio Catania et al (2008) found increase in Rail Pressure was found to be effective means to improve fuel charge premixing due to fine atomizing of fuel leading to decrease in soot formation due to lower equivalence ratio & proper dwell time between pilot and main injection resulted in reduction of CO and no detoriation in Nox than in basline engine.

Praveer Jain et al (2016) selected various engine parameters for optimization and to meet BS-III emission norms.The variables choosed was swirl ratio, FIP timing, turbocharger, optimised by DOE model and NOx emission was mainly affected by fuel injection timing (65.019 % contribution) and swirl ratio (22.547 % contribution). Increase in advance played a vital role as it increased the combustion temperature thereby producing higher NOx. Due to high number of testing conditions involved full factorial approaches are not viable whereas Design of Experiments techniques has demonstrated to be a valid methodology. Balaji Mohan et al (2013) effect of injection pressure, injection timing, injection strategies. Increasing injection pressure, in general, results in increased thermal efficiency and better fuel consumption and less CO,HC and smoke emissions, however with higher NOx Ultra high injection pressures results in reduction of soot emissions mainly attributed by better spray atomization and air entrainment, however leads to increased NOx and BSFC. Very high injection pressures also have significant effect on soot particle size distribution.

In current study a common rail six cylinder in-line diesel engine, 8.9L total displacement for heavy duty truck application was used to perform experiment. A DoE-based method is applied to improve the trade-off between oxide of nitrogen (NOx) and particulate (PM) hydro carbons (HC) and smoke by a fine calibration of injection strategy including the rail pressure, main injection timing, pilot injection separation , total fuelling, pilot injection quantity.

2. Engine Characteristics and Experimental Preparation

Main features of the engine are stated in the Table 1. The engine is heavy duty diesel engine turbocharged with intercooled aspiration with no after treatment. Investigation is recorded in steady operating conditions: the engine was operated on ESC (European steady state cycle) ELR (European load Response), Full Throttle Performance.

Table 1. *Engine Specifications*

Engine Type	6 cylinder in-line 8.9L
Bore x Stroke	114 mm x 144.5 mm
Max. Power	450 HP @ 2200 rpm
Peak Torque	1627 Nm @ 1300 rpm
Fuel System	BOSCH Common Rail Direct Injection
Turbocharger	Variable Geometry Turbocharger
Injector	Solenoid Operated Injector

For each operating point, all information of the engine, including periphery condition characteristics, control parameters, emission parameters are recorded. The experimental facilities are listed in Table 2.
Also for measurement of emissions from exhaust gas Non-Dispersive Infrared (0-3000 ppm) for measuring CO, Flame Ionization Detector (0-10000 ppm) for measuring HC, Chemiluminescence Detector (0-10,000 ppm) for measuring NOx was used.

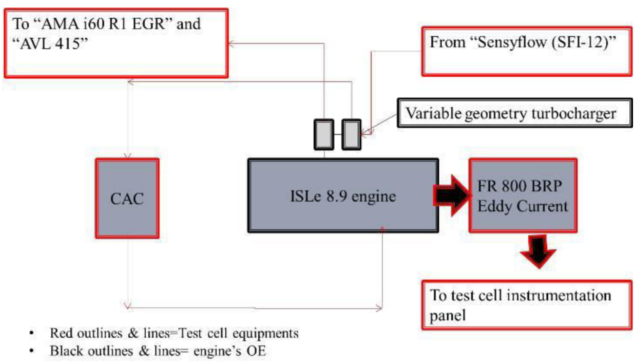

Fig. 1 *Test Cell Set up at ARAI*

3. Selection of A,B & C speed for ESC cycle

The engine speeds are defined as follows
The high speed n_{hi} is determined by calculating 70 % of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi} .
The lowest speed n_{lo} is determined by calculating 50 % of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo}.
A,B and C speed are calculated as,
$A = n_{lo} + 0.25(n_{hi} - n_{lo})$
$B = n_{lo} + 0.50(n_{hi} - n_{lo})$
$C = n_{lo} + 0.75(n_{hi} - n_{lo})$

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.

3. DOE Development Procedure

DoE allows to manipulate the independent variables and see the effect on the dependent variables. In other words it is used to find cause and effect relationship and optimize the output.
Half factorial method was used for DoE model. 2^n optimized combinations were formed where n is number of independent variables. Here the number of independent variables are 6, therefore 32 combinations for each mode was the optimized output by MINITAB.

Table 2. *Test Cell Specifications*

SN	Parameter	Make	Model Name
1	Dynamometer	APICOM	FR800 BRP Eddy Current
2	Fuel Flowmeter	APICOM	Orbit-e
3	Emission System	AVL	AMA i60 R1 EGR
4	Particulate System	AVL	SPC 472
5	Conditioned Air System	KS Engineers	IACU3000
6	Air Flow Meter	ABB	Sensyflow (SFI-12)
7	Opacimeter	AVL	S439-03
8	Smoke Meter	AVL	415

3.1 Procedure description

The experiment was designed in the following steps:
Define the test plan, development of statistical model, generate suitable calibration, experimental measurement its optimization and finally validation of the optimized calibration in detail.

3.2 Problem specification

After the baseline determination of the existing calibration the thermal and mechanical limits' margins for the engine was found to be well within the acceptable limit. Maximum and minimum range for the independent variables were specified from which the optimum value was calculated.

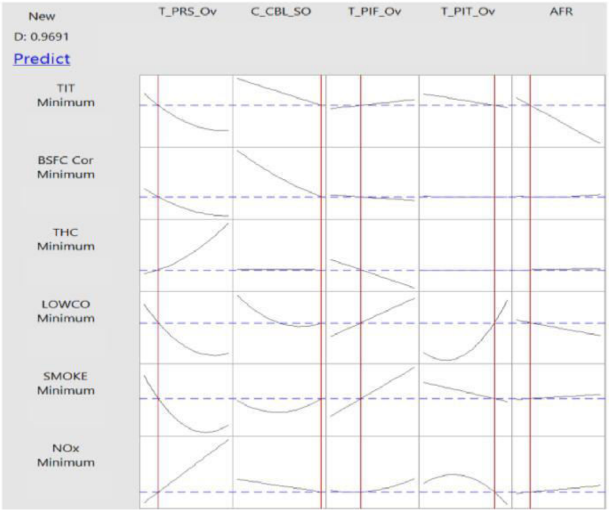

Fig.2 *DoE Plot for B 75 Speed*

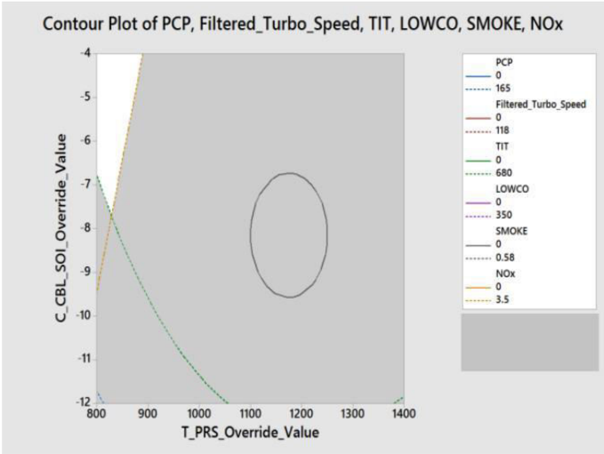

Fig.3 *Contour Plot for B75 Speed*

Table 3. DoE Index

Operation Points	13
DoE Method	Full Factorial
DoE Points	32 per mode
Optimization Object	Nox, PM, HC, CO, Smoke, Turbo inlet Temperature ,Peak Cylinder Pressure, BSFC
Optimization Constraints	Rail Pressure, SOI, Pilot Injection, Pilot Separation, AFR, Total Fuelling

4. Experimental DoE Solution

The general test procedure operated for this test is
1. Perform engine warm up
2. Set boundary conditions at rated 2200 rpm
3. Record performance and emission for each speed
4. Engine is allowed to stabilize for 4 mins before logging each data point.
5. The boundary conditions are allowed to freefall after initial setting

Table 4. Boundary Conditions at Rated Point

Parameter	Value
Intake manifold pressure (kPa)	200 ± 10
Intake manifold temperature (°C)	48 ± 2
Charged air cooler ΔP (kPa)	11.5 ± 0.5
Exhaust back pressure (kPa)	9.5 ± 0.5
Air intake restriction (kPa)	3.74 ± 0.1
Fuel inlet temperature (°C)	39 ± 1
Fuel return temperature (°C)	75 ± 2
Coolant outlet temperature (°C)	88 ± 2

4.2 DoE Plots

DoE Plots are shown in Fig.2 and Fig.3 for speed B and load 75% load. Similar plots were obtained for A, B & C speed and 100%, 75%, 50%, 25% load. Optimal point from these plots were found and base calibration was modified

5. Result & Discussion

Start of injection, Rail Pressure, Air to fuel ratio was captured over full throttle performance (FTP) & ESC test. The comparison for the various injection parameters for base calibration and new calibration is discussed below.

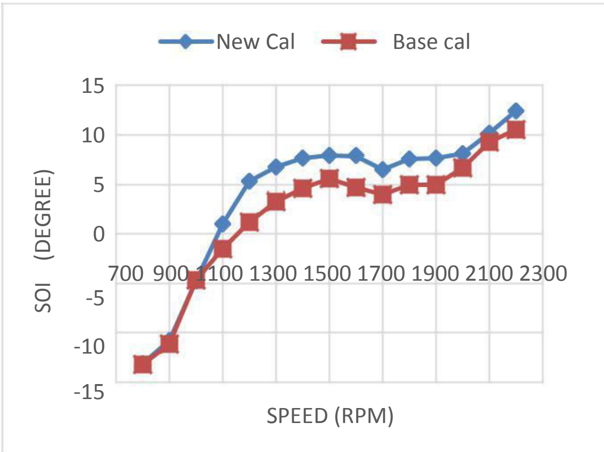

Fig4. *Speed Vs Start of Injection*

Start of injection was retarded than base calibration to get NOx advantage as shown in Fig. 4. Figm5. shows comparison of rail pressure where rail pressure was increased at lower speeds and was decreased at higher speed than base calibration.

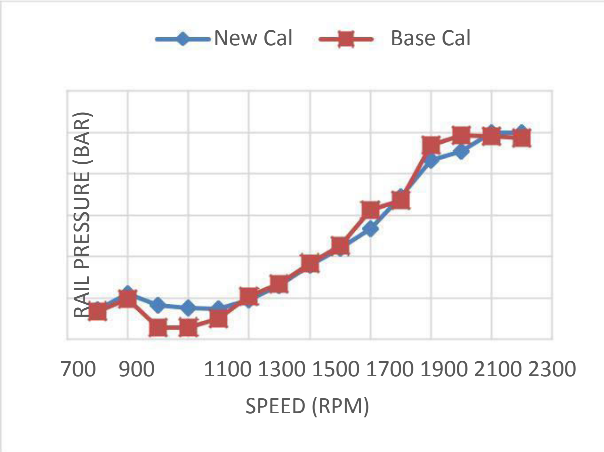

Fig 5. *Speed vs Rail Pressure (bar)*

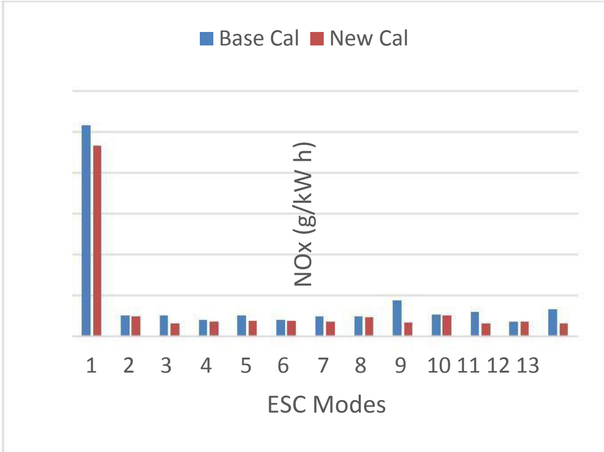

Fig 7. *BSNOx Comparison for 13 Mode ESC*

Figure 6. shows the comparison for air to fuel ratio for new calibration and base calibration. Air to fuel ratio was kept slightly on higher side for lower speed and on higher side than base calibration.

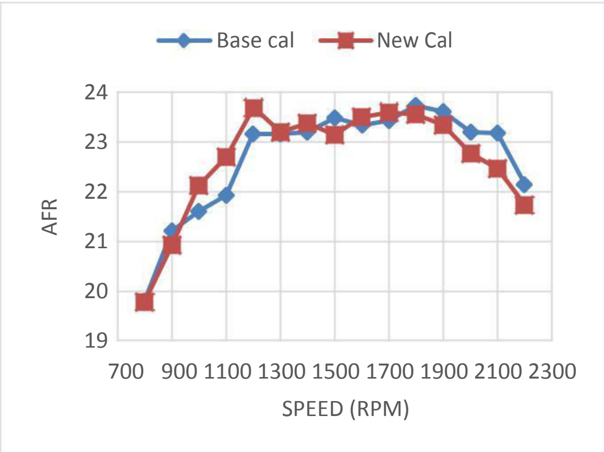

Fig 6. Speed Vs Air to Fuel Ratio

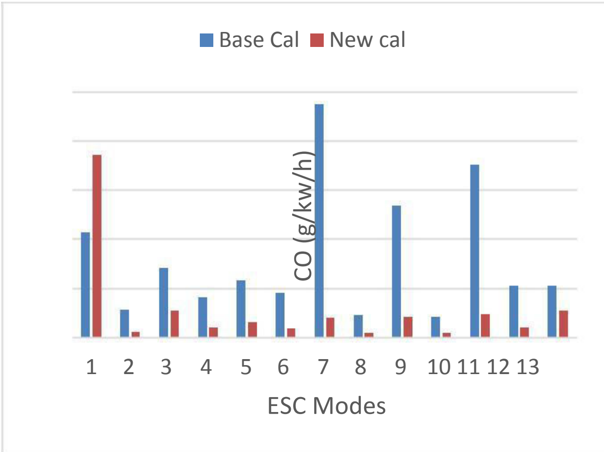

Fig 8. *BSCO Comparison for 13 mode ESC*

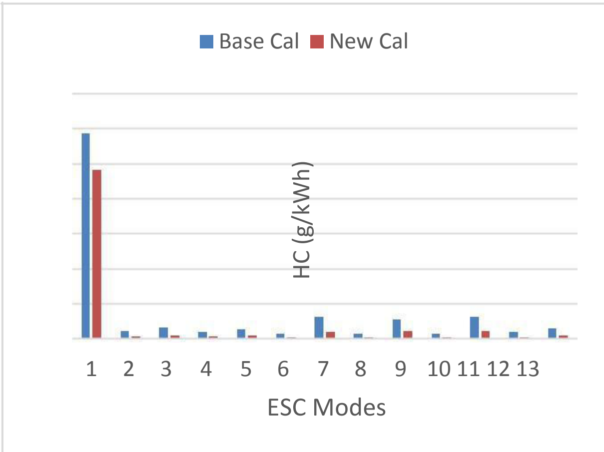

Fig 9. *BSHC Comparison for 13 mode ESC*

Fig.7 shows BSNOx comparison for each mode of 13 modes of ESC cycle. By implementing new calibration decrement in NOx at each mode is seen. Final value of NOx is calculated by weighted average method, where the weights are defined by European Stationary Cycle. Similarly Fig 8. shows BSCO comparison for each mode and it is seen significant decrease in CO at each mode. Fig. 9 shows BSHC comparison for all ESC cycle which also shows decrease in HC than base calibration values. With the new calibration mechanical and thermal limits i.e turbo inlet temperature & peak cylinder of the engine were within limits. Fig.12 shows comparison of BSFC comparison over FTP where BSFC with new calibration is better or comparable with the base calibration BSFC.

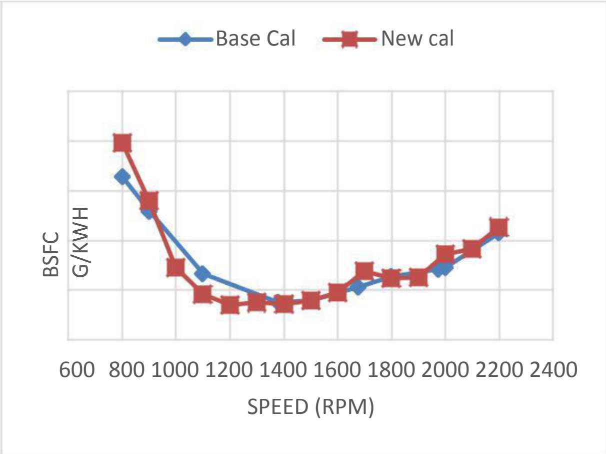

Fig. 12 Speed Vs BSFC

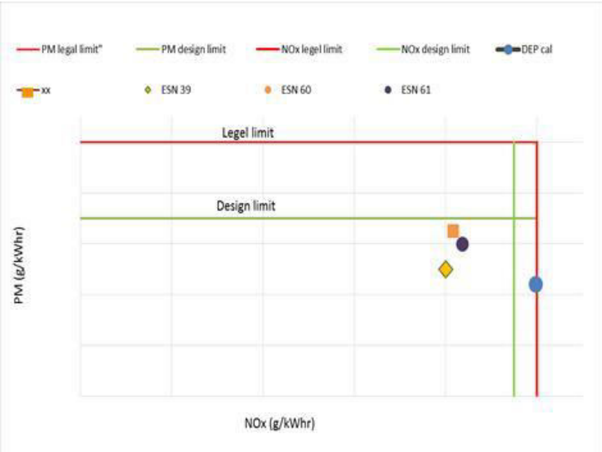

Fig. 11 *Three Engine Emission Consistency Result*

By weighted average method final values of NOx, PM, HC, CO were calculated from ESC. Three engine are tested to prove emission result consistency.All three engines NOx, PM, HC, CO & smoke are found within BS III norms and design limits as shown in Fig. 11

6. Conclusions

1. BSFC achieved with this calibration was better or comparable than base calibration.

2. Three engine consistency was tested to prove emission robustness with the new developed calibration.

3. Critical time period for NOx formation is when gas temperature burned are max i.e. between the start of combustion & shortly after occurrence of peak cylinder pressure, as injection timing was retarded, it reduced the temperature in the cylinder and gave benefit in NOx by 18.03 %

4. As timing was retarded, combustion process was retarded with it reducing the combustion temperature & efficiency thus increasing the particulate matter by 31.08 %

5. Ignition delay decreases the with retarded timing and reduces the amount of fuel injected into the cylinder during ignition delay thus decreasing the CO by 2.60 % as CO formation is function of air to fuel ratio.

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