Optimization of Fuel Injection Parameters for Meeting Euro III Exhaust Emission Norms on a Heavy Duty Diesel Engine Using Taguchi Technique


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Abstract

In pursuit of high power density, improved fuel economy and low emission developments in combustion technologies, advanced electronic fuel injection, refined engine and injection parameters have been going on. Understanding engine and injection parameters and their effects on exhaust emissions is vital to provide correct direction to these efforts.

The scope of this work was to optimize the influence of injection parameters on regulated emission constituents of diesel exhaust to meet Euro III emission norms on a heavy duty diesel DI engine. Design of Experiments (DOE) and Taguchi technique were used to identify the influence of parameters cam velocity, nozzle through flow, nozzle tip protrusion into the combustion chamber and number of spray orifices on emission levels were studied. Based on the DOE results, levels of these parameters were found with which Euro III emissions targets were met consistently and in totality. The analysis results were validated through tests.

Key Words: Injection parameters for Euro III, Taguchi technique, L, Orthogonal Array, Analysis of Means (ANOM), Signal-to-noise ratio (S/N), Analysis of Variance (ANOVA).

1. INTRODUCTION

The remarkable progress in compression ignition engine, to its present form and diversity, has brought the diesel engine to technological forefront. Its high efficiency with lean combustion, resulting in minimum fuel consumption, has made the diesel engine a subject of intense research. This research, in a constant quest to tap maximum power density with minimum fuel consumption, has been a moving target for all combustion engineers.

Last decades witnessed continuous attempts to enhance diesel engine power and torque per unit displacement, and simultaneously reduce specific fuel consumption and emissions [1]. The focus of achieving this objective is through the process of fine tuning fuel injection equipment like injection pumps and nozzles [1-7] together with improvements in combustion technologies [3-5] [8-9]. This is accomplished by injecting as much fuel as the engine can digest at a given engine speed and load, to achieve constant pressure combustion without excessive increase in combustion pressure, smoke and emissions.

The demand on diesel engines in late 1980's resulted in the birth of a new area of application "very high speed DI diesel engines" [2, 10-16]. High speed IDI diesel engines which ruled passenger car market are now replaced by DI technology due to its superior emission, fuel consumption and driveability [1]. Concerns on noise in DI diesel engines were addressed by injection rate shaping, use of two spring injectors, multiple pilot and post injections using common rail technology and better understanding of engine acoustics [1][17-18]. Very high speed DI diesel engine today has become the undisputed leader and its potential is enhanced using advanced electronic fuel injection technologies [1][3-4].

Driving factors propelling countries worldwide to witness rapid growth in diesel engine development include:

- Demand for better engine performance and fuel economy.
- Growing awareness of harmful effects of engine exhaust.
- Refinement in federal laws controlling emission regulations around the world.
- Legislations controlling noise, vibration and harshness characteristics.

Market demand for better power and fuel economy, together with legal demand for lower emission compliance, set mutually conflicting and challenging targets for automotive engineers. Dynamic market trends for power fuel consumption and emission, since 1989, are shown in Figure 1 [15]. These goals, by nature, impose tradeoffs within which the engine is optimized. Typical tradeoffs include:


Emission tradeoff: NOx-Pm, NOx-Soot, NOxHC.

Emission Performance tradeoff: NOx-Power, Smoke-Torque, NOx-Injection timing.

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Emission Performance tradeoff: NOx-Power, Smoke-Torque, NOx-Injection timing.

2. AIM AND OBJECTIVES

The present work is aimed at establishing the influence of injection parameters on regulated emission constituents of engine exhaust to meet Euro III emission norms on a heavy duty diesel DI engine. This was accompanied by enhancing the raw engine performance of an existing Euro II compliant heavy duty diesel engine.

To identify the fuel injection parameters, and their operating levels, that will meet the emission goals, Design of Experiments and Taguchi technique were used. The results of these experimentation were analyzed using following techniques:

- Analysis of means (ANOM).
- Analysis of signal-to-noise ratio (S/N).
- Analysis of Variance (ANOVA).

Simultaneous study of multiple injection parameters using orthogonal arrays for studying the effects of control factors on emission response was in contrast to conventional combustion development utilizing one-factor-at-a-time experimentation.

To enhance the engine performance by exploiting engine
design to produce maximum torque and power per unit displacement, without significant increase in smoke at constant combustion pressure, new engine performance parameters for Euro III compliant engine were proposed (Table 1).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Euro II</th>
<th>Euro III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>6 Cylinder, Inline, Water cooled with Turbocharger and Intercooler</td>
<td></td>
</tr>
<tr>
<td>Rated Power</td>
<td>96kW@2400 rpm</td>
<td>132kW@2400 rpm</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>440Nm@1800 rpm</td>
<td>600Nm@1400 rpm</td>
</tr>
<tr>
<td>Capacity</td>
<td>5.68 Liter</td>
<td></td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>97 mm x 128 mm</td>
<td></td>
</tr>
<tr>
<td>R_c</td>
<td>19.1</td>
<td>17.5 : 1</td>
</tr>
<tr>
<td>Idle speed</td>
<td>650 ± 50 rpm</td>
<td></td>
</tr>
<tr>
<td>Fly up speed</td>
<td>2800 ± 50 rpm</td>
<td></td>
</tr>
<tr>
<td>Swirl</td>
<td>2.2 AVL</td>
<td>2.0 AVL</td>
</tr>
<tr>
<td>Application</td>
<td>Heavy Commercial Vehicle (Bus, truck)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Existing Euro II and proposed Euro III engine performance parameters

For emission target, the goal set was to meet the Euro III emission targets with safety margins as defined in European emission regulation 1999/96/EC [14]. These, for diesel powered heavy duty vehicles of gross vehicle weight greater than 3.5 tons (GVW> 3.5 tons) are given in Table 2.

<table>
<thead>
<tr>
<th>Emission Parameter</th>
<th>Euro II Limits</th>
<th>Euro III Limits</th>
<th>Euro III Targets</th>
<th>Safety margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx (g/kWh)</td>
<td>7.00</td>
<td>5.00</td>
<td>4.500</td>
<td>8%</td>
</tr>
<tr>
<td>CO (g/kWh)</td>
<td>4.00</td>
<td>2.10</td>
<td>1.785</td>
<td>15%</td>
</tr>
<tr>
<td>HC (g/kWh)</td>
<td>1.10</td>
<td>0.66</td>
<td>0.561</td>
<td>15%</td>
</tr>
<tr>
<td>PM (g/kWh)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.085</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 2: Euro II and Euro III emission regulations and safety margins

To guarantee reliable results on subsequent engines due to environmental variations, safety margins for each emission component were defined based on past experience in similar applications. The objective was to achieve emissions lower than Euro III engineering margins.

For a robust design, it was important to identify the variables affecting the emission response and deciding the direction in which to vary them. Following an exhaustive literature survey several such variables were identified and categorized.

3. IDENTIFICATION OF CONTROL FACTORS

Injection parameters whose effects on engine performance were evaluated directly formed this class of variables. These parameters significantly affect response (exhaust emissions components) and create the basic need for experimental investigation [10]. Among fuel injection variables surveyed in literature, those outlined in Table 3 were optimized assuming 2 and 3 levels for linear and quadratic loss function models respectively.

In the experimental investigation, variables cam velocity, nozzle through flow, nozzle tip protrusion in combustion chamber and number of spray orifices of nozzles were used to control injection parameters.

These injection parameters included injection rate, injection pressures at pump and injectors, injection duration, spray penetration, spray velocity, atomization etc. Injection parameters affected by the four control parameters are presented in Table 4.

Table 3: Control factors and their levels.

<table>
<thead>
<tr>
<th>Control Factors</th>
<th>Affected Injection parameter</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cam Velocity</td>
<td>Injection rate.</td>
<td>f(NOx,HC,PM)</td>
</tr>
<tr>
<td>Nozzle through flow</td>
<td>Injection pressure at pump.</td>
<td>f(Nozzle, HC)</td>
</tr>
<tr>
<td>Nozzle tip protrusion</td>
<td>Spray jet targeting.</td>
<td>f(Nozzle, HC, PM)</td>
</tr>
<tr>
<td>No. of spray orifices</td>
<td>Injection pressure at nozzle</td>
<td>f(Soot, HC)</td>
</tr>
<tr>
<td></td>
<td>Injection duration.</td>
<td>f(Soot, HC)</td>
</tr>
<tr>
<td></td>
<td>Spray velocity.</td>
<td>f(Soot, HC, PM)</td>
</tr>
</tbody>
</table>

Table 4: Control factors affecting injection parameters and effects on engine performance

4. BACKGROUND FACTORS

In addition to control factors, several injection variables and design features of injection systems affect emission levels. Since these were not included in this study, these variables were held constant or at a specified level throughout the investigation to keep their influence constant. Phadke [11] emphasized the fact that these factors could be specified freely by engineers, and their settings or levels can be selected and defined to minimize sensitivity of product's response (exhaust emissions) to all noise factors or uncontrolled variables.

4.1 CONTROLLABLE BACKGROUND FACTORS

In this investigation, engine testing was carried out in controlled condition to minimize the influence of background factors on the results. Air entering the engine was conditioned using Sea Level Altitude Simulation System (SLASS), fuel temperature, exhaust back pressure, sulfur content in fuel, intercooler temperature, oil temperature, etc. were maintained within the specified limits simulating the engine operation on the vehicle.

Dynamic injection timing : Held constant & optimized.
Diesel fuel type: <500 ppm Low "S" Euro III
Fuel inlet temperature: 40±3 °C
Exhaust back pressure : Max 60±5 mm Hg
Intercooler outlet temperature : 47±3 °C
Water outlet temperature : 85±5 °C
Lubricant oil temperature : Max 100 °C
Relative humidity: 50±1 %
Inlet air temperature: 25±1 °C

4.2 BACKGROUND FACTORS HELD CONSTANT

Following variables which are not of primary interest of study, but influence the engine emissions were held constant
- Engine and engine parameters (Bore, stroke, capacity, power, torque, compression ratio)
- All nozzles used were Valve Covered Orifice (VCO), conical spray orifice with hydro erosion type having constant spray orifice location, constant spray cone angle
- Discharge tubing diameter
5. UNCONTROLABLE NOISE FACTORS

Variables that affect engine emissions but were not controlled because of cost or difficulty are termed as Noise factors. These factors fall into three categories: external, unit-to-unit variation and deterioration of product.

To reduce the influence of noise factors, randomization, as suggested by Hahn [10] was introduced. Randomization involves in this work was sequence of preparing experimental units, namely, the injection pump and nozzles, assigning treatments like assigning the experimental factors to orthogonal arrays, running order of the emission tests, recording the measurements etc.

During execution of this project, parallel development work of turbocharger and intercooler was planned. The objective was to increase the airflow characteristics of turbocharger for lower PM emission and obtain low pressure drop across intercooler for lower specific volume of air resulting in better fuel economy. Since use of turbocharger and intercooler was subjected to unplanned changes during experimentation, they were treated as external noise.

6. SYSTEM CONSTRAINTS AND BOUNDARIES

6.1 INJECTION SYSTEM CONSTRAINTS

High cam velocities used in the DI injection pumps (1.55s/m and 1.6m/s) are desirable for achieving high injection pressures (Max 1200 bar) and high injection rates (28.5 and 30.0 mm³/std/°Cam) especially for a high speed heavy duty DI application as reported by Max Straubel and Klaus Krieger [2].

Higher cam velocities over small cam angles translate to high cam acceleration. This, together higher element pressures (Max 800 bar) reduce durability and lead to increased drive torque (Max 11.5Nm) of the injection pump. In order to guarantee reliable working life of injection system, constraints on injection pressures at the pump and injector end were imposed with limitation of drive torque.

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Magnitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump limits</td>
<td>Element pressure = 800 bar</td>
</tr>
<tr>
<td></td>
<td>Drive Torque = 115 Nm</td>
</tr>
<tr>
<td>Injection</td>
<td>Injector end pressure = 1200 bar</td>
</tr>
<tr>
<td>limits</td>
<td>Injector duration = 36° Crank</td>
</tr>
<tr>
<td></td>
<td>Injection begin (Max advance) = 14° BTDC</td>
</tr>
<tr>
<td></td>
<td>Injection begin (Max retard) = 5° ATDC</td>
</tr>
</tbody>
</table>

Table 5: Injection system constraints

Injection timing and injection duration play an important role in engine performance. To ensure fuel temperature is raised to auto-ignition point and total mass of fuel injected participates in combustion process and translates to useful power, fuel is injected slightly in advance before compression TDC. If ignition timing is too advanced, combustion gases expand when the piston is still approaching TDC. Expansion takes place against compression work leading to loss of useful power. This leads to high temperatures and combustion pressures and increases NOx and knocking tendency. While high speeds and loads favor advanced begin, smooth engine operation with low combustion noise at part loads, favors retarded timing. Excess retardation results in unburnt or partially burnt fuel due to low temperatures and results in higher HC, PM and smoke with poor fuel economy. For safe engine operation, preliminary combustion optimization was carried out to evaluate ignition limits (injection timing and duration) beyond which engine performance and emissions deteriorate. These thresholds are presented in Table 5.

7. INTERACTION AND THEIR EFFECTS

In an experiment, if the effect of response of one variable depends on the condition of another variable, the variables are said to interact.

Gerald J Hahn [10] emphasizes that the purpose of designing the experiment is not only to study the effect of control factors on response but also to obtain information about the interaction among primary control factors. This is accomplished by varying control factors simultaneously in contrast to changing these factors one at a time. If the predicted experimental conclusions are not reproducible in confirmatory runs, the possible causes according to [12] are:

- Strong interactions between control factors.
- Presence of strong noise factors.
- Experimental errors.

Interactions in experimental designs can be categorized into two groups.

- Interaction between control factors and noise factors relating to robustness of the system.
- Interaction between control factors themselves diminishing additivity of factorial effects.

In an experiment, interaction between control factors causes inconsistent effects and the results therefore cannot be easily predicted, reproduced or controlled. To overcome this, traditional methods of counteracting interaction use fractional or full factorial experimentation. Robust design treats interaction between control factors and noise factors by evaluation of signal-to-noise ratio to achieve robustness.

Taguchi [12] emphasizes taking advantage of interactions, however moderate of insignificant, during development to make systems robust. He recommends use of any of the five countermeasures to counteract interaction using robust design:

- Proper determination of project scope.
- Use of additive output response.
- Proper selection of control factors and their levels.
- Use special orthogonal arrays (and).
- Use of signal-to-noise ratios (S/N).

The intent of using these countermeasures is to minimize control factor interactions and ensure that control factor effects are stronger and dominant than interaction effects resulting in reproducible experiments. Among all the countermeasure techniques listed, signal-to-noise (S/N) ratio is the most popularly used technique as it addresses all aspects of noise -- internal (control factor interactions) and external (control factors with external environment or noise). The S/N ratio is given by:

\[
S/N = \frac{2}{n} \sum_{i=1}^{n} \left( \frac{y_i^2}{n} \right)
\]

Dr. Taguchi's philosophy recommends maximizing S/N ratio to maximize useful output energy and simultaneously minimize all harmful output energies. Traditional approaches emphasize minimizing only few harmful output energies and therefore address only partially the system responses. The S/N technique, on the other hand, addresses both useful output and harmful output and is therefore a complete approach. S/N ratio countermeasure addresses interaction in any form as harmful output. This technique was used to overcome interaction.

Since exhaust emissions are harmful, ideally "zero" emission is expected. The quality characteristic of exhaust emission response follows smaller-the-better type. The Signal-to-noise ratio (S/N or \( \eta \)) follows the relationship:

\[
\eta = -10 \log_{10} \left( \sum_{i=1}^{n} \frac{y_i^2}{n} \right)
\]
8. SELECTION OF ORTHOGONAL ARRAY

Selection of cam velocity, number of nozzle spray orifices at 2 levels and nozzle through flow, nozzle tip protrusion into the combustion chamber at 3 levels results in following parameters for DOE.
Total degrees of freedom: \( \Sigma D = (D_1)_a + (D_2)_a + (D_3)_a + (D_4)_a \)
Total degrees of freedom: \( \Sigma D = 1 + 2 + 2 + 1 = 6 \)
Minimum number of experiments: \( \Sigma D + 1 = 6 + 1 = 7 \).

Minimum of 7 fractional factorial experiments were necessary to evaluate effect of experimental factors and their levels on response as defined in Table 3. The nearest orthogonal array that can be used for experimentation is \( L_7 \).

<table>
<thead>
<tr>
<th>Factor</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>Cam</td>
<td>Nozzle</td>
<td>Nozzle</td>
<td>Number</td>
</tr>
<tr>
<td></td>
<td>velocity</td>
<td>through</td>
<td>tip protrusion</td>
<td>spray orifices</td>
</tr>
<tr>
<td>No.</td>
<td>m/s</td>
<td>cc/30s</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A1</td>
<td>B1</td>
<td>C1</td>
<td>D1</td>
</tr>
<tr>
<td>2</td>
<td>A1</td>
<td>B2</td>
<td>C2</td>
<td>D2</td>
</tr>
<tr>
<td>3</td>
<td>A1</td>
<td>B3</td>
<td>C3</td>
<td>D3*</td>
</tr>
<tr>
<td>4</td>
<td>A2</td>
<td>B1</td>
<td>C2</td>
<td>D3*</td>
</tr>
<tr>
<td>5</td>
<td>A2</td>
<td>B2</td>
<td>C3</td>
<td>D1</td>
</tr>
<tr>
<td>6</td>
<td>A2</td>
<td>B3</td>
<td>C1</td>
<td>D2</td>
</tr>
<tr>
<td>7</td>
<td>A3*</td>
<td>B1</td>
<td>C1</td>
<td>D2</td>
</tr>
<tr>
<td>8</td>
<td>A3*</td>
<td>B2</td>
<td>C2</td>
<td>D1</td>
</tr>
<tr>
<td>9</td>
<td>A3*</td>
<td>B3</td>
<td>C3</td>
<td>D1</td>
</tr>
</tbody>
</table>

Table 6: \( L_7 \) orthogonal array with dummy technique

\( L_7 \) orthogonal array shown in Table 6 [13] advocates systematic changes of many control factors simultaneously. This ensures reliable and independent study of main interaction effects. Since only 2 levels, each of cam velocity and number of spray orifice, were considered for experimentation, dummy level technique was used to modify the standard \( L_7 \) orthogonal array to accommodate 2 level factors. "*" represents a dummy treatment where \( A_3 = A_1 \) and \( D_3 = D_1 \).

9. EXPERIMENTAL INVESTIGATIONS - ESC tests

As defined in test procedure in emission directive 1999/96/EC [14] for Euro III, all precautions were taken before start of emission test to ensure reliable and repeatable measurements. Test conditions were maintained before emission sampling of each ESC test. Test apparatus, engine and its exhaust systems were conditioned till stabilization of temperatures and pressures were achieved followed by recording the operating parameters and their influence on emissions.

9.1 ESC EMISSION TEST RESULTS

ESC emission tests were conducted for 9 experiments as defined by \( L_7 \), orthogonal array and emission response characteristics NOx, CO, HC and PM were measured. These emission results are presented in Table 7. It was observed from Table 7 that CO and HC emission were relatively easier to meet due to presence of higher concentrations of oxygen in intake air during diesel combustion. CO and HC emission of 9 experiments were significantly lower than engineering targets set for Euro III. Comparing NOx and PM similarly, indicated that they were within Euro III limits close to engineering targets. Therefore meeting NOx-PM limits was the challenging task in this investigation program.

Investigations [3][4][5] reveal NOx and PM are inversely proportional, increase of one emission component leads to reduction of the other. This relationship between NOx and PM in 9 experiments of \( L_7 \) orthogonal array are presented pictorially in Figure 2.

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helps lower PM emission at the cost of increased NOx emission. In contrast, higher nozzle through flow shortens the injection duration, lowers flame temperature and combustion pressures and favors NOx emissions. These effects can be clearly interpreted from the overall trends of NOx and PM emission in the main effect plots.

- Neither too high nor too low values of nozzle tip protrusion into combustion chamber are desirable. While excessive protrusion of nozzle tip into combustion bowl increases the tendency of combustion chamber wall wetting, reduced spray penetration and resulting in partially burned fuel due to wall quenching effects leading to poor emission. Inadequate nozzle protrusion results in spray jets being targeted on piston crown above the combustion bowl leading to poor emissions. 1.5 mm nozzle tip protrusion into the combustion bowl was found to be most optimum of different levels experiment.

10.2 SELECTION OF OPTIMUM FACTOR LEVELS

Use of following combinations of injection parameters presented in Table 8 with NOx-PM tradeoff timing would result in lowest NOx, CO, HC and PM respectively. These conclusions are inferred from main effect plots in Figure 3 by studying each control factor and its level necessary for producing lowest emission for each exhaust component.

10.3 PREDICTION OF EMISSION RESULTS

One of the primary reasons for using robust design was to predict the exhaust emission response of the engine with defined control factors and their levels through analysis of data, thereby saving precious time and resources and quickly converge at the results. Using the combination of control factors and their levels necessary for producing lowest NOx, CO, HC and PM respectively the response characteristics of the system with NOx-PM tradeoff timing was predicted. These results and injection parameters required to produce them are presented in Table 8.

The predicted emission results are ranked based on severity, importance of emission component. Factors like margins to meet Euro III engineering limits, criticality of NOx-PM tradeoff, low criticality of CO and HC emission were considered for ranking.

Table 8: Injection parameters and their predicted emission responses

It can be inferred from Table 8 and Figure 4 that minimum NOx configuration does not meet Euro III PM limits and thereby the project objective. Since CO and HC engineering limits can be met with any combination of injection parameters, ranking of predicted emission results was carried out based on NOx-PM tradeoff. The injection parameter responsible for producing lowest PM emission also significantly reduces NOx and therefore ranked first.

11. ANALYSIS OF SIGNAL TO NOISE RATIO (S/N)

During the course of experimentation, simultaneous development of turbocharger and intercooler took place.
change in turbine diameter of turbocharger was done in order to improve airflow characteristics at high engine speeds and loads with intent of improving PM emission. Likewise, the intercooler development resulted in lower pressure drop across the intercooler leading to lower specific volume and lower temperature at intercooler outlet. Consequently, higher mass of compressed air per unit volume resulted due to increase in mass density of air, altering the emission characteristics, particularly NOx-PM.

Since these changes were unplanned, difficult, expensive to control and beyond the scope of this investigation, but at the same time drastically influenced emissions, they were considered as noise. Other noise factors during experimentation like deterioration of the engine,

Gradual drift of measuring instruments, etc. were considered less important and ignored, considering the short time line for development and frequency of preventive maintenance of measuring instruments. Possibility of interacting control factors is also a form of internal noise. Therefore Dr. Taguchi [11] proposes use of signal-to-noise ratio as countermeasure to overcome both internal and external noise for recommending optimum control factor and their levels by studying both the main effects and signal-to-noise ratio. Results of this analysis are presented in Figure 5.

11.1 INFERENCES FROM ANALYSIS OF MEANS

The objective function is to maximize signal-to-noise ratio, therefore the optimum factor is the one which produces the highest value of signal to noise ratio in the experimental region.

- Factors A1=1.55m/s cam velocity, B2=4600cc/30s through flow, C1=1.5mm nozzle tip protrusion and D2=7 orifice nozzle would give highest signal to noise ratio for NOx response. In other words, use of these factors and levels would result in lowest NOx under influence of noise. During experimentation, variation of turbocharger and intercooler were considered as noise. Hence combination of these injection parameters can be used in criticality of NOx emissions.

- As seen in analysis of means, use of control factor combination A1, B2, C1 and D2 for low NOx emission would result in predicted PM emission out of Euro III limits and hence this combination was no longer a viable option for meeting Euro III norms.

- On the other hand, control factors A2=1.60m/s cam velocity, B1=4400cc/30s through flow, C1=1.5mm nozzle tip protrusion and D1=6 orifice nozzle have highest S/N ratio when PM emissions are concerned. Hence this combination and levels of control factors are more robust to influence of noise than other factor levels and form an optimum combination for low PM emissions. In addition to producing low PM, predicted values of NOx, CO and HC are lower than the Euro III engineering targets (refer Figure 4). Hence, it was decided to use A2, B1, C1 and D1 for confirmation run and validation of analysis.

12. ANALYSIS OF VARIANCE (ANOVA)

Different control factors (cam velocity, nozzle through flow, nozzle tip protrusion, number of sprays orifices) affect NOx, CO, HC and PM to different degrees. The relative magnitude of factor effects can be judged from Figure 5 that gives average signal-to-noise ratio of each factor level.

In order to quantify and get a better feel of relative effect of different factors, estimate the error variance and prediction error, the results were analyzed further by decomposition of variance called ANOVA. Results of this analysis are presented in Table 9.

- Referring to sum of squares column in Table 9, number of nozzle spray orifices makes significant contribution of 39.8% to the total sum of squares of NOx emission. Nozzle tip protrusion into combustion bowl and cam velocity contributes 27.5% and 20.0% to total sum of squares for NOx emission. Similarly, number of nozzle orifices and cam velocity contribute 91.8% and 6.5% respectively for total sum of squares for PM emission. Nozzle through flow and nozzle tip protrusion together make only a negligible contribution to total sum of squares for PM emission.

- Larger the contribution to the total sum of squares, the larger is the ability of the factor to influence the signal-to-noise ratio. This analysis reveals that number of nozzle orifices influences NOx emission significantly, followed by factors like nozzle tip protrusion and cam velocity which influence the signal-to-noise ratio by almost equal amounts. Both number of nozzle orifices and cam velocity similarly have significant influence on PM emissions and their signal-to-noise ratios.

- The magnitude of factor effect relative to error variance can be judged from calculated F-ratio. The larger the F-ratio, the larger the factor effect is compared to error variance. Also the larger the F-ratio, the more important the factor is to that quality characteristic. On these lines, the control factors are ranked in descending order of their influence on signal-to-noise ratio for each exhaust emission component.
control factors and their levels (A2, B1, C1, D1) are the ones responsible for producing lower emissions and contribution from errors to emission response is minimized.

![Figure 6: Validation and consistency test results.](image)

13. INFERENCES - VALIDATION AND CONSISTENCY

It can be inferred from Figure 6 that, emission results of optimized configuration of injection parameters A2, B1, C1 and D1 indeed produce emission results within Euro III engineering targets.

- Averaged emission components from consistency tests indicate that the objective of meeting Euro III emissions with more than 8% margins on NOx and 15% margins on CO, HC and PM have been realized comfortably. In fact 11.5% margins on NOx, 61.5% margins on CO, 76.5% margins on HC and 23% margins on PM emissions have been achieved compared to the Euro III limits.

- Consistency tests indicate that injection parameters and their levels used and emission measurements are repeatable and reliable for meeting Euro III exhaust emission norms with safe engineering margins.

- The predicted emission results through analysis, and averaged emission results achieved by experimentation, are in close proximity with each other. This demonstrates that design of experiments and Taguchi technique are powerful tools which, when used properly, can meet the project objectives effectively and efficiently.

- The experimental error between predicted emission components and actual measurements of emissions are 1.65% for NOx, 7.5% for CO, 8.8% for HC and 6.8% for PM. This is a relatively small percentage compared to contribution by the injection parameters. This indicates that a major contribution to the project has been through correct selection and use of injection parameters.

- This project has demonstrated yet another case of successfully achieving the target objectives using design of experiments and Taguchi techniques in automotive domain, reinforcing the fact that these techniques are an indispensable part of robust design.

14. ENHANCEMENT OF ENGINE PERFORMANCE

Using the finalized injection parameters, engine performance characteristics were tuned. Factors $A_2 = 1.6$ m/s, $B_1 = 4400$ cc/30s, $C_1 = 1.5$ mm and $D_1 = 6$ orifice nozzles were used and injected fuel quantities and dynamic begin of injection were tuned to achieve target torque and power, low SFC, low smoke over entire speed and load range of the engine. Figure 7 presents comparison of Euro II performance and enhanced Euro III performance characteristics. It is noticed from enhanced Euro III engine performance that the torque and power over the full load range have is increased. Low
end power was increased by 30% for better driveability and acceleration performance, in addition power at maximum torque speed (volumetric efficiency zone) and at rated speed were increased by 33% and 38.5% for better load carrying capacity and facilitate higher vehicle speed. Further overall reduction in full load fuel consumption was achieved by reducing SFC by a maximum 10.6%.

![Graph](image)

**Figure 8: Euro II to III trends in engine parameters and injection systems**

- Saturation tradeoffs between NOx-PM-SFC have to be simultaneously studied so that engine does not suffer from excess emission or poor fuel consumption.
- Carefully planned and tailored orthogonal arrays, DOE and Taguchi technique, with clearly set objectives, significantly helps engineers to investigate problems and quantify effects of experimental factors in a short time frame economically.

The scope of this investigation was restricted to meet Euro III emissions. With worldwide emission regulations getting stringent every day, possibilities of meeting Euro IV emission norms and beyond, with modifications on engine and injection systems can be further explored with exhaust gas after treatment strategies and common rail systems.

**16. REFERENCES**


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