# Combustion and Emission Based Optimization of Turbocharged Diesel Engine Run on Biodiesel using Grey-Taguchi Method

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***Abstract-***in this work it is attempted to optimize the combustion parameters such as instantaneous heat release (IH), cylinder Pressure (P) and rate of change of pressure per degree crank angle (dP/do)) and the emissions characteristics such as $NO_x$ and Smoke of a turbocharged direct injection (DI) compression ignition (CI) engine alternatively run on pure biodiesel (B100), diesel and biodiesel-diesel blend (B20) applying Grey Taguchi method (GTM). GTM is used to convert multi variables into a single objective function. The process environment comprising three input parameters (speed of the engine, load and type of fuel) were used in this case. The design of experiment (DOE) was selected on an orthogonal array based on $L_9$ ($3^3$). The Optimum Parameters were found on the basis of Grey Relational Grade (GRG) and signal to noise (SN) ratio using GTM. The resulted optimum combination of the input parameters was used to get maximum possible values of IH, P and least possible values of $NO_x$, smoke & dP/do. The higher values of IH and P measure the better performance of the engine, while lower values of $NO_x$, smoke and dP/do are the ultimate objectives of the study. According to the results It was revealed that B100 fuel, 1800 rpm speed and 10% load offer the optimum combination for the desired performance of the engine along with reduced pollutants. Analysis of Variance (ANOVA) based on a software Minitab 16 was used to get the most significant input parameter keeping in view responses. Fuel type and engine load were found to be the dominant factors with 48.16% and 43.18% impact on the output parameters, respectively. Finally the results were validated using Artificial Neural Network (ANN) through Mat lab.

***Keywords-***Biodiesel, Turbocharged, Diesel Engine, Grey Taguchi Method,ANN, SN Ratio, GRG

## I. INTRODUCTION

Heat engines are deemed to be an indispensable part of modern life style owing to the dependence of smaller vehicles used in transport and agricultural equipment's in the past few years, so energy crisis and ever tighter emission standards have been the potential threats to this efficient, robust and unmatched prime mover. As a result scientists and researchers have converged their attentions for the survival of this technology by introducing not only alternative fuels but also to emission controlling Strategies. Since diesel engines and fossil fuels are considered to be the backbone of Agriculture and Transport sector especially for developing countries. The different types of heat engines came in to practice out of which diesel engine is mainly used in agriculture, The economic growth of Pakistan is mostly dependent on agriculture so diesel engines and fossil fuels plays a dominant role . Agriculture and energy are related to each other, so rapid energy consumption and environmental problems caused by emissions of petroleum vehicles are dangerous. These emissions contribute to global warming, Ice melt down due to large carbon deposits in environment. Kyoto protocol and Copenhagen conference (2009) is expected to control the greenhouse gas concentration in atmosphere [i].

It is well known that a turbocharged direct injection diesel engine shows more fuel efficiency when biodiesel was used. It has already been reported that combustion of the engine can be improved due to the increased combustion pressure. Also break specific Fuel Combustion (BSFC), maximum combustion pressure. And Injection angle was increased while BSEC, maximum rate of pressure rise, ignition lag and premixed combustion were decreased [ii]. Carbonylisis emission analysis of turbocharged diesel engines on the basis of different operating fuels i.e. diesel, biodiesel and biodiesel-diesel blends revealed maximum Break Specific Exhaust (BSE) at low load that decreases with the increase in load [iii]. Reference [iv] tested different blends of Jatropha biodiesel in a single cylinder four stroke diesel engine in order to check the performance and emission properties on the basis of parameters such as brake thermal efficiency, bmep, bsfc, exhaust gas temperature. It was concluded that BJ10 and BJ20 have better emission behavior as compared to other blends and are close to diesel. According to [v] investigated the effect of injection timing, fuel quantity per fuel pulse, and injection rate on the exhaust gas emissions like Nitrogen Oxide. It was observed that among all these factors fuel injection has special importance in air fuel mixing and combustion of the mixture, so will determine the exhaust emissions. It was found that $NO_x$ emissions can be controlled by controlling injection timing and rate. The percentage contributions of different engine operating parameters on engine noise, emission and BSFC was found by Taguchi based Analysis of Variance. Reference [vi] Performed experiments to check the effect of fuel injection timing, Exhaust gas recirculation and fuel injection pressure to control the Nitrogen Oxides of a stationary Diesel Engine using Crude rice bran oil (methyl ester) as fuel. It was observed that there is a reduction in NOx emission without any marked rise in the smoke concentration. Reference [vii] observed that it is really important to cut down the $NO_x$ by some inside sources. There were many solutions but the most practical one were EGR, water injection or Fuel water emulsion, they brought the combustion temperature down which reduced the $NO_x$ Values. But with the above method they faced the problem of BSFC and soot formation. So they used multiple simulation method for the above said there methods, the experiments were performed on heavy duty diesel engine at various working conditions. In above said method engine performance and emission was observed with special attention given to fuel and sot formation. At the end of their work it were concluded that $NO_x$ reduction is most attractive at 30% of fuel water emulsion considering both BSFC and soot formation in mind. Reference [viii] studied the effect of castor biodiesel on the performance end emissions of a diesel engine using Castor biodiesel produced by Tran's esterification in an acid base catalyzed system. The highest value obtained was 82.5%, smoke test was performed and it was observed that B40 has minimum smoke. Performance test of diesel engine shown that BSFC of blended biodiesel engine was increased significantly; Engine power was same for diesel fuel and B20. B20 shown best combustion with minimum PM, CO and HC as compared to diesel engine.

The effect of biodiesel on emission and efficiency of stationary diesel engine with the help of Rapeseed biodiesel blends has been studied experimentally; the results of this study were compared to the similar experiments performed by other researchers. It was observed that BSFC was not showing large changes with different blend, $CO_2$ emissions were reduced for blended fuels, by increasing the biodiesel concentration the engine temperature increased as a result $NO_x$ concentrations, Power and heat release rate was also increased. The results obtained in this experiment cannot be related to the moving engines, so biodiesel is useful for farmers from economic and environmental point of view [ix]. The extracted bio diesel from different kinds of fish can be used to study combustion, performance and emission of a diesel engine. Following blends B25, B75, and B100 were used for experimentation and results shown that BSFC and brake thermal efficiency is higher for B100 than pure diesel. The peak combustion pressure for above said blends was lower than pure diesel, the flue gases temperature were lower for B100 than pure diesel at different operating conditions. At full load B100 produced higher smoke, $NO_x$, CO and HC as compared to pure diesel [x]. Reference [xi] performed experiments on a multicylinder (4 cylinders) DI diesel engine fuelled with biodiesel and its blends (20.40,60,80 by volume of biodiesel) to examine the emission properties of the engine operating at various loads (25, 40, 65, 80%) and 2000 RPM. Biodiesel was obtained from waste frying oil. CO and HC emissions were higher at low engine speeds and lower at high speeds, $NO_x$ and $CO_2$ were increased with the increase in load, in blended fuel CO and HC concentration was reduced due to better combustion and $NO_x$ was increased due to higher combustion temperature. Buyukkaya, et al [xii] worked on the combustion, performance and emission of a diesel engine using three different blends B5, B20 and B70 obtained from neat rapeseed oil. It was observed that biodiesel produced less amount of smoke (up to 60%), greater BSFC (up to 11%) compared to diesel.B5 and B100 produced less CO emissions (9 and 32%) as compared to diesel, Observing the combustion it was concluded that ignition delay was decreased for pure biodiesel and its blends, combustion behavior of biodiesel and its blends is closely related to pure diesel.

The application of Taguchi and Grey relational analysis, to find out the optimum level and optimum performance of the diesel engine operated by different blends of Thumba biodiesel was investigated. Factors involved were Thumba biodiesel blend, CR, Nozzle opening pressure and injection timing each parameter having 3 levels. $L_9$ orthogonal array was used to arrange the data of performance and emission of the engine. S/N ration and grey relational analysis were used. The optimum combination came out to be 30% Thumba, CR 14, 250 bar pressure and 20 degrees injection angle. Thermal efficiency was maximum and BSFC was minimum at this combination along with minimum emissions [xiii]. According to [xiv] used Turpentine as alternative fuel for a diesel engine, Turpentine has low cetane number so cannot be used individually blends of turpentine were used. So it was tried in this work to replace diesel fuel by turpentine at maximum concentration. As multiple parametric optimization was involved so taguchi method was used, so no of experiments were reduced. ANOVA was used to show the % effect of each parameter on the needed parameter. The optimum combination was 40T, 29 degrees BTDC and 180 bar pressure, Brake thermal efficiency was increased by1-2% at optimum level, there was slight increase in $NO_x$, smoke was reduced by 50% and Co was also decreased at Optimum combination.

Artificial Neural Network (ANN) is a modeling tool used for the optimization and prediction of the data for different engineering problems like in manufacturing IC engine optimizations etc. In the optimization of combustion emissions and performance of a diesel engine the experimental data is used for the training and testing purpose. In some problems some statistical tools are linked with ANN to get optimum combination and later on ANN predict the output parameters at that combination. It has been accurately used to optimize and predict the different parameters of the IC engines [xv-xviii].

Extensive research into the mechanism governing diesel combustion and emission has already been done. However in spite of many studies being conducted in the area of diesel combustion and emission, these process are still not well understood due to the complex interrelationship that exist between combustion system parameters and injection system parameters. The exhaust gases of a diesel engine strictly depend upon the combustion phenomenon, combustion process is highly dependent on combustion chamber and the injection system of the engine. Whenever we have the problems where output is dependent on many factors (variables, inputs) Taguchi method is used for design and analysis purpose which reduces the loss of time and economy by running the process using all possible combinations of values of those variables.

By carefully selecting certain combinations it is possible to find their individual effects. Conventional Taguchi method is not sufficient in handling multiple objective optimizations in single purpose function. Grey analysis based Taguchi method which has more prominent applications is used to solve problems like that. Once we have the optimal combination Minitab software will be used to perform the analysis of variance, the dependency of the each input parameter can be checked and we will chose the most significant parameter by measuring the percentage contribution. Artificial Neural Network tool given in Mat lab to find out the desired output parameters at the given optimal combination.

## II. EXPERIMENTAL SETUP & METHDOLOGY

### *A. Experimental Setup*

The engine used for the experimentation purpose was a Turbocharged, 4 cylinder, DI compression ignition engine having intercooling connected to a test bench shown in fig 1.Further properties of the engine are given below

Bore and stroke length, 110 and 125 mm respectively

Displacement volume and compression ratio are 4752 $cm^3$ and 16.8:1 respectively

There are 6 nozzle holes in the injector and each of 0.23 mm diameter

The rated power and maximum Torque of the engine is 117/2300 (KW/rpm) and 580/1400 (N.m/rpm) respectively

There was no modification done on this engine during experimentation.

Following three fuels were used during experimentation

1. Pure diesel fuel
2. Pure Biodiesel (B100)
3. A blend of biodiesel and diesel having 20% biodiesel and 80% diesel (by volume) designated by B20

The properties of the fuels are given in Table.1

The following parameters were collected from the test bench during experiments

Load and speed from Electrical dynamometer (SCHENCK HT 350)

Crank Angle from Kistler corporation 2613A sensor)

Instantaneous heat release (IH) from Combustion analyzer (DEWE-5000)

Instantaneous Pressure (P) in cylinders from (Kistler 6125B, Peizo-electric sensor)

Rate of Change of Pressure per degree crank angle (dP/do CA)

$NO_x$ Analyzer (Pier burgAMA 4000)

Smoke Opacimeter (AVL 439)

### *B. Methodology*

The methodology used in this research is shown in the Fig 2.

### *C. Data Collection*

The experimental setup shown in Fig.I is used to find out the input data for further study we have taken the readings of Smoke, $NO_x$, Heat release, pressure per Degree crank angle and cycle pressure at nine different operating conditions

### *D. Grey Taguchi Method*

Taguchi method is used for the optimization of the experimental parameters when we are dealing with fewer trials. The number of trials depends upon the number of factors contributing to the experiments; higher number of parameters will give large number of trials for a given experiment, so it will require more time and money for experiment [xix].

Simple taguchi method was used for the optimization of a single parameter so optimization of multi parameters is a tough task than a single one. A grey based Taguchi method is used in this research incorporating the signal to noise ratio analysis [xx].

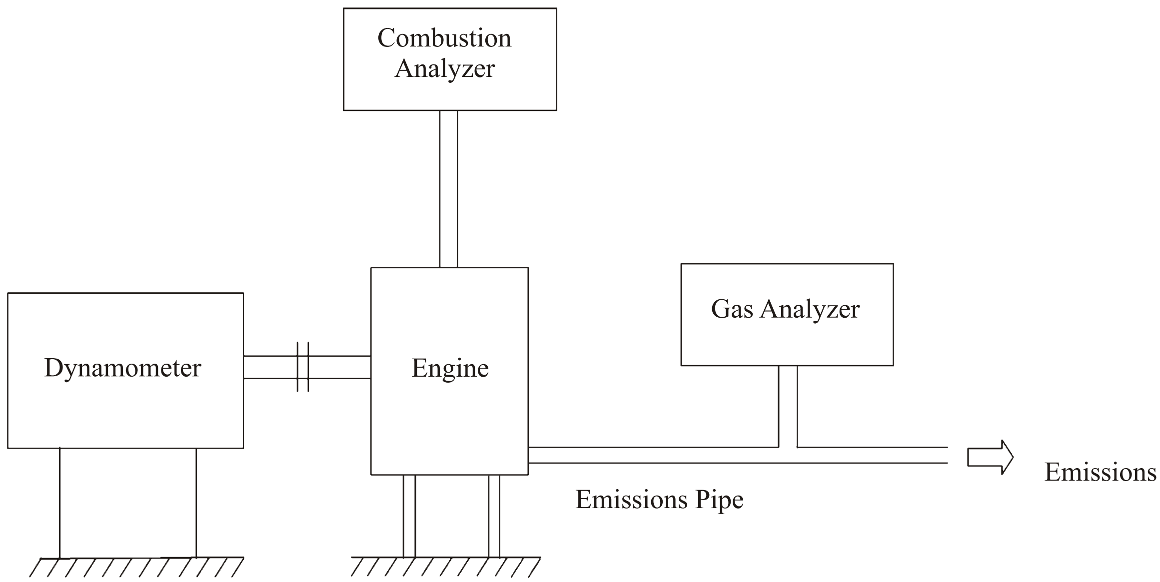


Fig.1. Experimental Setup

TABLE I
PROPERTIES OF THE FUELS

| Properties | B100 | B20 | D | Standards[a] |
|---|---|---|---|---|
| Oxygen % by weight | 11.33 | n/a | 0 | Element analysis |
| Hydrogen % by weight | 11.91 | n/a | 13.08 | SH/T 0656-98 |
| Carbon % by weight | 76.83 | n/a | 86.92 | SH/T 0656-98 |
| Sulfur (mg/L) | 25 | n/a | 264 | SH/T 0253-92 |
| Lower Calorific value (MJ/kg) | 37.3 | 41.57 | 42.8 | GB/T 384 |
| Viscosity ($mm^2/s$) at 20 ºC | 8.067 | 4.020 | 3.393 | GB/T 265 |
| Density ($kg/m^3$) | 886.4 | 845.1 | 834.8 | SH/T 0604 |
| Cetane number | 60.1 | n/a | 51.1 | GB/T 386-91 |

[a] Chinese standard

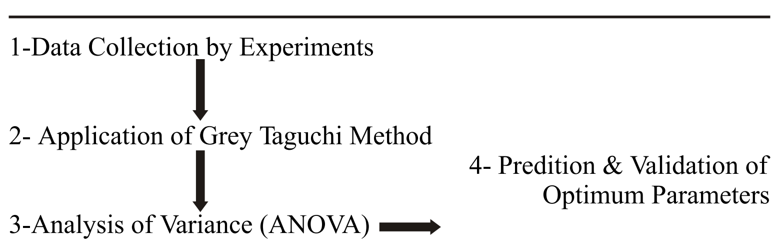


Fig. 2. Structure of Grey Taguchi Method

*E. Selection of Input Factors*

The input factor which effect the combustion and emission of the given engine are found with the help of experimentation. In this work we are using speed of the engine, type of fuel and load as the input factors and each of these factors has three levels which are given in Table II.

*F. Orthogonal Array Design*

After selecting the input parameters the orthogonal array is prepared according to the number of parameters and their level, so the OA used in this work is based on $L_9(3^3)$ is given in table 3. This table gives the total number of experiments carried out and their corresponding combination of the input parameters.

TABLE III
ORTHOGONAL ARRAY DESIGN

| Run No | Type of Fuel (A) | Speed (B) | Load C |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

Once we have the OA the experiment is carried out according to the combinations given in the table 2 in order to find the output parameters.

*G. Normalization of Data*

The grey relational generation normalizes the output data. The Normalization of the data can be done by the different equations coming forward.

If we want to maximize our required output response then "the larger the better" criteria is used given below

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

Here $X_i$ (k) is the value after the grey relational formation and min $Y_i$ (k) is the minimum value, max Yi (k) is the maximum value of the comparable sequence $Y_i$ (k) for the kth response.

If we are interested in the minimization of the response data then "The larger the Better "criteria is used given below

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (2)$$

After Normalization of the data Quality Loss factor is estimated for each response using the equation given below

$$x_0(k) - x_i(k) \quad (3)$$

Here $X_0$ (k) is the ideal sequence of the responses

*H. Grey Relational Coefficient Generation*

The GRC is used to show the relation between the two sequences [ideal sequence $X_0$ (k) and $X_i$ (k), i = 1, 2, 3……9]. The grey relational Coefficient is given below

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \quad (4)$$

Here $\Delta_{oi} = \| x_0(k) - x_i(k) \|$ = Difference between absolute value $X_0$ (k) and $X_i$ (k), $\Delta_{min}$ and $\Delta_{max}$ are the minimum and maximum values of the $\Delta_{oi}$ (k) sequence; ψ is the distinguishing coefficient.

$0 \le \psi \le 1; \Delta_{\min} = \forall j^{\min} \varepsilon i \forall k^{\min} \| x_0(k) - xj(k) \| =$ The smallest value of $\Delta_{oi}$

*I. Grey Relational Grade Formation*

The grey relational grade is computed by taking the average of grey relational coefficient as given below.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (5)$$

*J. S/N Ratio Formation from GRG*

This ratio is calculated using Higher the better Criterion given below.

$$\text{SN (Higher the Better)} = -10\log\left(\frac{1}{t}\sum_{i=1}^{i}\frac{1}{y_i^2}\right) \quad (6)$$

Here "t" is the number of measurements for the given run; $Y_i$ is the value of the ith run.

*K. Analysis of Variance (ANOVA)*

Analysis of variance is done to check the most significant and least significant input factor by calculating the sum of squares, Mean square of the Average S/N ratios and the percentage contribution of each input factor.

## III. RESULTS & DISCUSSION

The response parameters corresponding to their orthogonal array are given in Table IV

The instantaneous heat released during combustion has a strong effect on the exhaust emission as we know that higher the combustion temperature high the concentration of $NO_x$. The cylinder pressure has a positive effect on the combustion of the engine high pressures will give us efficient combustion. The rate of Change of pressure per degree crank angle It is well known that smoke formation is mainly due to the lack of oxygen content which is normally the case for all diesel engines and even worse when the air to fuel ratio decreases. From experimentation it has been observed that smoke values increases as the load on the engine increases and 100% loaded engine has maximum smoke value.

The NOx is mainly due to the cylinder temperature during combustion and the locally available oxygen, so with the increase in biodiesel content $NO_x$ value increases [xxi]. $NO_x$ formation often takes place while the combustion in the combustion chamber is in the starting phase of the rapid burning owing to the great increase in the temperature in the combustion vicinity [xxii]. Zeldovich or thermal reaction consisting of three reactions generates NO having high temperature due to the burned gases left by the flame front. The chemical reactions involved are [xxiii]

$$O + N2 \leftrightarrow NO + N2$$

$$N + O2 \leftrightarrow NO + O$$

$$N + OH \leftrightarrow NO + H$$

The rate of Pressure rise (dP/d° CA) is the load applied due to combustion on the cylinder head and block [ii]. Once we have the response/output parameters according to the orthogonal array we can further apply the Rey Taguchi method.

The Normalization of this data is done by equation. (i) And (ii) which is given in table.5, after normalization the quality loss factor is calculated using equation (iii) and given in Table VI

Once we have the quality loss estimate then we can find the grey relational Coefficient and GRG using equation (IV) and (v). GRC & GRG are given in Table VII

Signal to Noise ratio is calculated using the GRG using equation (VI) and given in the Table VIII

TABLE VIII
S/N RATIO

| Run | GRG | S/N Ratio |
|---|---|---|
| 1 | 0.55489157 | -5.115837466 |
| 2 | 0.564487357 | -4.966915609 |
| 3 | 0.55192529 | -5.162394112 |
| 4 | 0.554670406 | -5.119300101 |
| 5 | 0.678963918 | -3.363066096 |
| 6 | 0.777843448 | -2.182156038 |
| 7 | 0.657911825 | -3.636646153 |
| 8 | 0.656431275 | -3.656214719 |
| 9 | 0.554854843 | -5.116412383 |

Average S/N ratios are given in Table IX

Once we have the average S/N ratio we can find the combination of the input parameters for optimum combustion and emission parameters by just plotting the graph between Levels of each factor and their Average S/N ratio. These plots are given below in Fig. 3

By observing the above plot the optimum combination came out to be A2B2C1-which is 100% pure biodiesel, 1800 rpm speed and 10% load on the engine. So when engine will be operated at this combination it will give optimized value of combustion and emission.

*L. Analysis of Variance (ANOVA)*

The ANOVA is performed by software named as Minitab 16, which is statistical tool. This tool checks the dependency of the response factors on the input variables [xxiv]. Here it takes the S/N ratio of the response as the input and gives us the sum of square, mean square, F value and the percentage contribution of each input factor to response values at optimum combination. The table.10 shows the Minitab calculations.

The Table X shows that factor which is having higher F-Value is the most significant one because it is contributing more to the response values at the optimum combination. Here type of the fuel is the most significant having 48.16% contribution and load is the second significant factor having 43.177% contribution while speed of the engine is least significant having 8.66% contribution. So response parameters will be mostly depending on type of fuel and load.

*M. Prediction of Output Response using ANN*

The response parameters are predicted at the optimum combination using artificial neural network tool present in Mat lab, the predicted and experimental response values at the optimum combination obtained above are given in Table XII. The best result for the prediction using ANN is obtained at 30 neurons

If we look into Fig. 4 we can see that there is a very small difference between the experimental and ANN based predicted results of the response parameters.

The pictorial view of the ANN prediction and response validation is given in annexure 1.

## IV. CONCLUSIONS

Current study addresses the optimization of turbocharged diesel engine on the basis of combustion and emissions responses using GTM. The engine was operated alternatively on B100, Diesel and B20 while three input factors were speed, type of fuel and load on the engine. The effort was made to get maximum value of P and IH, minimizing the smoke, $NO_x$ and dP/do. Following are the key findings of this work.

- There were 3 input factors and three levels of each factor giving the best combination on the basis of $L_9$ (3×3) OA.
- GTM was selected as a better option owing to its better handling of the factors involved.
- It was revealed corresponding to maximum values of combustion, $NO_x$ and smoke were at their peaks.
- On the other side if focus was on the minimization of emissions then combustion was not efficient
- On the basis of optimization it was found that better combustion and emission occurred during a combination of A2B2C1 (B100, 1800 rpm and 10% load on the engine)
- The Analysis of Variance of the input parameters at the optimum combination revealed that type of fuel is the most significant parameter showing 48.16% influence on response values whereas engine speed revealing the minimum effect of 8.66%.
- The results were successfully predicted and validated through ANN method.

The $NO_x$ during this optimum combination was slightly higher due to better combustion of pure biodiesel but remained within the limits. However combustion parameters like IH and P were reflected to be at their best.

TABLE II
EXPERIMENTAL FACTORS AND THEIR LEVELS

| Control Variables | Code | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Type Of Fuel | A | B-20 | B-100 | Diesel |
| Speed (rpm) | B | 1400 | 1800 | 2300 |
| Load ( % ) | C | 10 | 50 | 100 |

TABLE IV
RESPONSE PARAMETERS

| OA | | | OP | | | | |
|---|---|---|---|---|---|---|---|
| Type of Fuel | Speed (RPM) | Load (%) | dP/do (bar/°CA ) | Smoke (1/m) | NOx (ppm) | P (bar) | IH (%) |
| B-20 | 1400 | 10 | 4.3153933887 | 0.0620000000 | 235.6585714286 | 61.6294053231 | 99.9999977654 |
| B-20 | 1800 | 50 | 3.8285284936 | 0.0483333333 | 579.1052380952 | 89.5961307837 | 99.9999995120 |
| B-20 | 2300 | 100 | 3.2575687529 | 0.1740000000 | 557.0000000000 | 104.2792712103 | 99.9999987393 |
| B-100 | 1400 | 50 | 4.7447000000 | 0.0143333333 | 975.0000000000 | 89.3599000000 | 100.0000000000 |
| B-100 | 1800 | 100 | 3.2310124859 | 0.0383333333 | 887.0000000000 | 115.1535713317 | 100.0000016536 |
| B-100 | 2300 | 10 | 2.3502296302 | 0.0740000000 | 165.0000000000 | 74.2244611595 | 100.0000040684 |
| Diesel | 1400 | 100 | 3.5762439570 | 0.2210000000 | 1027.0000000000 | 116.1922609361 | 100.0000053901 |
| Diesel | 1800 | 10 | 3.3062552424 | 0.0633333333 | 235.0000000000 | 64.9547953486 | 100.0000033759 |
| Diesel | 2300 | 50 | 3.9259014726 | 0.1190000000 | 314.0000000000 | 94.3216997614 | 99.9999979013 |

TABLE V
NORMALIZATION OF THE RESPONSE DATA

| Smaller the Better | | | Larger-the-better | |
|---|---|---|---|---|
| dP/d° CA | Smoke (1/m) | NOx (ppm) | P (bar) | IH (%) |
| 0.179290843 | 0.769354839 | 0.9180295 | 0 | 0 |
| 0.382619688 | 0.835483871 | 0.519599492 | 0.512559784 | 0.22907589 |
| 0.62106897 | 0.227419355 | 0.545243619 | 0.781664842 | 0.127724964 |
| 0 | 1 | 0.060324826 | 0.508230267 | 0.293075283 |
| 0.632159635 | 0.883870968 | 0.162412993 | 0.98096343 | 0.50994451 |
| 1 | 0.711290323 | 1 | 0.230835716 | 0.826662212 |
| 0.487980999 | 0 | 0 | 1 | 1 |
| 0.600736086 | 0.762903226 | 0.918793503 | 0.060946041 | 0.73583434 |
| 0.341953919 | 0.493548387 | 0.827146172 | 0.599167585 | 0.017828701 |

TABLE VI
QUALITY LOSS ESTIMATE

| dP/do CA | Smoke (1/m) | NOx (ppm) | P (bar) | IH (%) |
|---|---|---|---|---|
| 0.820709157 | 0.230645161 | 0.0819705 | 1 | 1 |
| 0.617380312 | 0.164516129 | 0.480400508 | 0.487440216 | 0.77092411 |
| 0.37893103 | 0.772580645 | 0.454756381 | 0.218335158 | 0.872275036 |
| 1 | 0 | 0.939675174 | 0.491769733 | 0.706924717 |
| 0.367840365 | 0.116129032 | 0.837587007 | 0.01903657 | 0.49005549 |
| 0 | 0.288709677 | 0 | 0.769164284 | 0.173337788 |
| 0.512019001 | 1 | 1 | 0 | 0 |
| 0.399263914 | 0.237096774 | 0.081206497 | 0.939053959 | 0.26416566 |
| 0.658046081 | 0.506451613 | 0.172853828 | 0.400832415 | 0.982171299 |

TABLE VII
GREY RELATIONAL COEFFICIENT & GRG

| Grey relational coefficients (Distinguishing Coefficient =0.6) | | | | | GRG |
|---|---|---|---|---|---|
| dP/do CA | Smoke (1/m) | NOx (ppm) | P (bar) | IH (%) | |
| 0.4223243 | 0.722330097 | 0.879803451 | 0.375 | 0.375 | 0.55489157 |
| 0.492861593 | 0.784810127 | 0.555349609 | 0.55175447 | 0.437660988 | 0.564487357 |
| 0.612913455 | 0.437132785 | 0.568851738 | 0.733195921 | 0.40753255 | 0.55192529 |
| 0.375 | 1 | 0.389692586 | 0.549566435 | 0.459093008 | 0.554670406 |
| 0.619936946 | 0.837837838 | 0.417366043 | 0.969248069 | 0.550430694 | 0.678963918 |
| 1 | 0.675136116 | 1 | 0.438223526 | 0.7758576 | 0.777843448 |
| 0.539559126 | 0.375 | 0.375 | 1 | 1 | 0.657911825 |
| 0.600441977 | 0.716763006 | 0.880790191 | 0.389849879 | 0.69431132 | 0.656431275 |
| 0.476930066 | 0.542274052 | 0.77634344 | 0.599500967 | 0.379225688 | 0.554854843 |

TABLE IX
AVERAGE S/N RATIO

| | Factors | | |
|---|---|---|---|
| Levels | A | B | C |
| 1 | -5.081715729 | -4.623927906 | -3.6514027 |
| 2 | -3.554840745 | -3.995398808 | -5.0675427 |
| 3 | -4.136424418 | -4.153654178 | -4.0540355 |

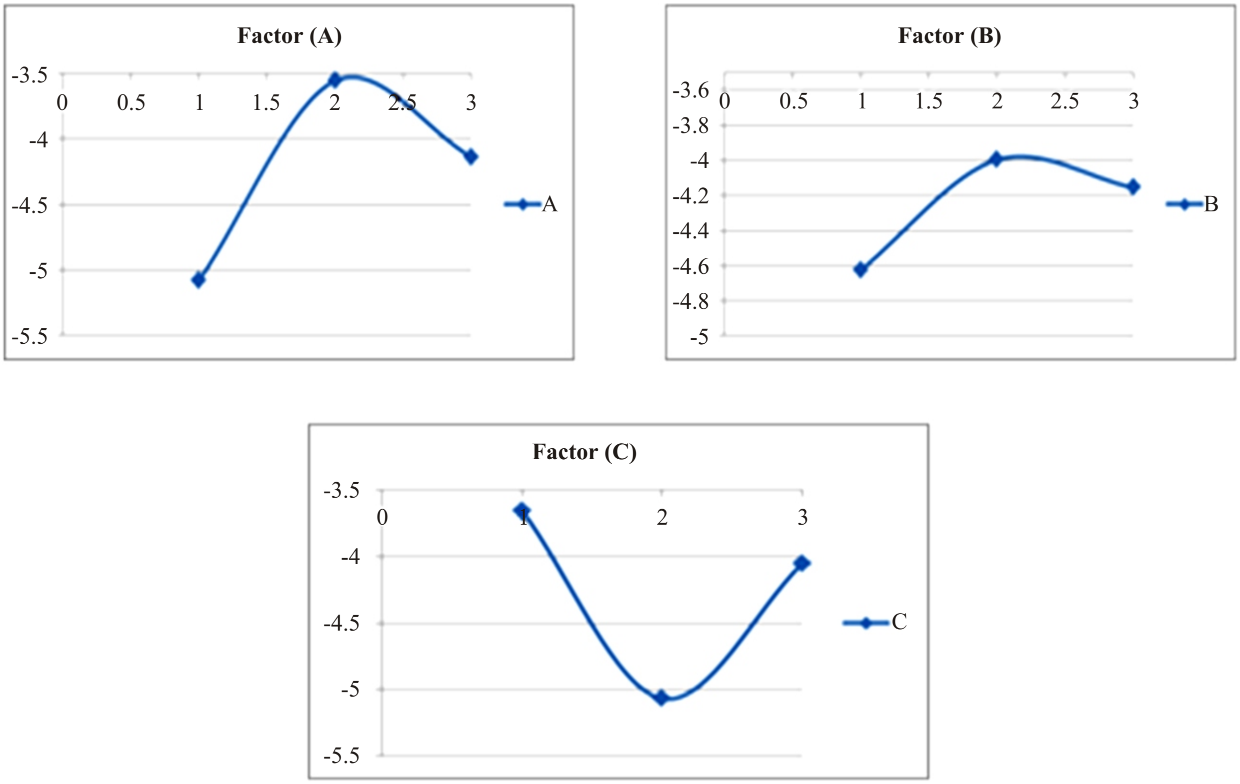


Fig. 3. Average S/N ratio Plot

TABLE X
ANOVA PERFORMED BY MINITAB.16

| Factors | Levels 1 | Levels 2 | Levels 3 | DF | Sum of square (SS) | Mean Square (MS) | Mean Square (MS) | F-Value | P-Value | Contribution % |
|---|---|---|---|---|---|---|---|---|---|---|
| A | -5.081715729 | -3.554840745 | -4.1364244 | 2 | 3.5632 | 1.7816 | 1.7816 | 1.79 | 0.359 | 48.15655747 |
| B | -4.623927906 | -3.995398808 | -4.1536542 | 2 | 0.6413 | 0.3206 | 0.3206 | 0.32 | 0.757 | 8.665801708 |
| C | -3.651402741 | -5.067542698 | -4.0540355 | 2 | 3.1948 | 1.5974 | 1.5974 | 1.6 | 0.384 | 43.17764083 |
| Error | | | | 2 | 1.9942 | 0.9971 | 0.9971 | | | |
| Total | | | | 8 | 9.3933 | 3.6996 | 3.6996 | | | 100 |

TABLE XII
EXPERIMENTAL & BASED ANN RESPONSE VALUES

| Response Factors | Experimental | ANN Based |
|---|---|---|
| dP/do | 3.381497999 | 4.8258 |
| Smoke | 0.042333333 | 0.05573 |
| $NO_x$ | 224.6666667 | 233.4223 |
| P | 64.19553495 | 63.4433 |
| IH | 100.0000029 | 100 |

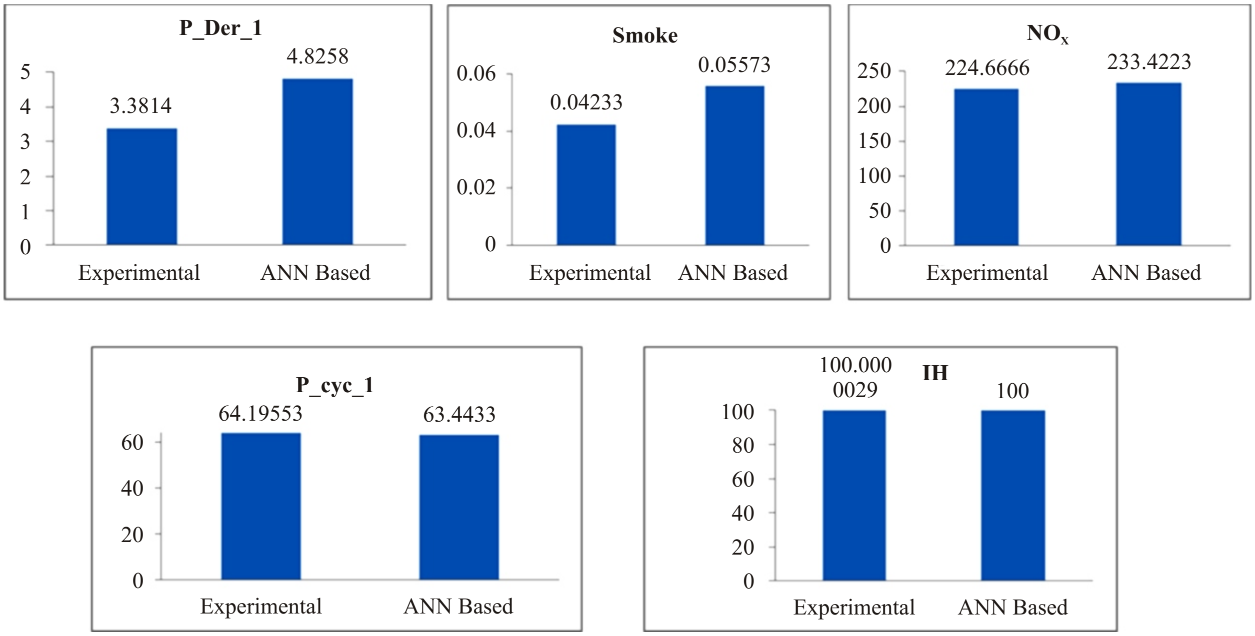


Fig. 4. Comparison between ANN and Experimental Response Values

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ANNEXURE I

ANN TRAINING AND VALIDATION