Optimization of Diesel Engine Performance by Taguchi Grey Relational Analysis using Fuel Blends

A. Naresh Kumar, K. Madhu Babu, B. Prasanth Kumar, S. Kiran Kumar, P. S. Kishore

Abstract: In this present investigation an attempt was made to explore the effect of fuel injection timing (FIT), fuel injection pressure (FIP), Load and exhaust gas recirculation (EGR) for various fuel blends (Palm oil, Cotton seed oil, n-Butanol) as input parameters on SFC, BTE, CO, HC, NOx and with a minimum number of experiments. In order to reduce the experimental efforts, Taguchi’s L27 orthogonal array was employed for design of experiments. An algorithm involving the combination of grey relational analysis with Taguchi technique was proposed for the optimization of engine emission and performance. The optimum combination for more brake thermal efficiency is obtained for n-butanol-IT of 27th bTDC-IP of 200 bar- EGR of 10% load percentage of 100. At the same time optimum combination for minimum nitrogen oxide emission is obtained for CSO-IT of 190 bTDC-IP of 220 bar-EGR of 20 percentage- load percentage of 50. The optimum combination considering all the output parameters was obtained using grey relational analysis and output values for optimum combination was also calculated experimentally. Based on ANOVA, engine load be the most influencing factor (Contribution of load was 57.8 %) for the selected objective of improvement in BSFC and BTE with lesser penalty on emissions (HC, CO, NOx) based on equal weight ages.

Index Terms: Biodiesel, Palm oil, Cotton seed oil, n-Butanol, Injection pressure, Injection timing, Exhaust gas recirculation (EGR), Engine Load, Grey relational analysis, Taguchi optimization, ANOVA

1. INTRODUCTION

Increasing cost of fossil fuel due to depletion of current energy resources, stricter legislative emission standard due to increased environmental concerns are the major concerns for searching complimentary renewable fuels. Oil is world’s primary source for energy and chemicals, with a current demand of about 12 million tonnes per day and it is expected to reach 16 million tonnes per day by 2030. At present, 30% of the global oil consumption is for transport sector and it is expected to increase by 60 % till 2030. The available reserves of oil and gas will last only for less number of years respectively as per current utilization factor.

With increasingly stricter emission norms, there is a need to search and find ways of using complementary fuels, which are renewable and less polluting. Biofuel become the best source of alternative renewable energy amongst the possible alternatives for reducing emission worldwide. Moreover early inventors of diesel engine proposed the use of vegetable oils for engine may seem insignificant today, but such oils may in course of time be as important as petroleum and the coal tar products of the present time. Several countries, including India, had already begun substituting conventional diesel with a certain amount of biodiesel. Biodiesel is a clean burning renewable fuel made using natural vegetable oils and fats. Biodiesel is made through a chemical process which converts oils and fats of natural origin into fatty acid methyl esters (FAME). Biodiesel is intended to be used as a replacement for petroleum diesel fuel, or can be blended with petroleum diesel fuel in any proportion. Biodiesel does not require modifications to a diesel engine to be used. Biodiesel is simple to use, biodegradable, nontoxic, and essentially free of sulphur and aromatics. Biodiesel obtained from the feedstocks such as jatropha, rapeseed, soybean, sunflower, palm, Mustard, Cotton-seed, Lin-seed and jatropha are some of the popular biodiesel currently considered as complementary fuels for diesel. Many researchers are focusing on oils obtaining from seeds as they are non-edible. However there are certain limitations of biodiesel which include injector coking and trumpet formation on the injectors, more carbon deposits, oil ring sticking and thickening and gelling of the engine lubricant oil. Currently different techniques are used in compression ignition (CI) engines for emission reduction and performance improvement while replacing diesel with biodiesel. While considering replacement of diesel with biodiesel, it is vital to investigate the effect of parameters such as; injection pressure (IP), injection timing (IT), different additives and use of exhaust gas recirculation (EGR) in order to improve engine performance for compensating the limitations of biodiesel fuels. It is equally important to identify significant parameters amongst the above parameters. The use of additive in biodiesel fuel is inalienable for improving fuel properties, thereby improving engine performance and emission. The use of oxygenated liquid additives, in general, improves the flash point, pour point and viscosity of the biodiesel fuel. The extent of improvement depends on the % of additives. Various researchers have investigated the potential of different biodiesels in CI engines. Singh P et al. (2010) investigated on hybrid fuels consisting of coconut oil.
The experimental results show that the efficiency of the hybrid fuels is comparable to that of diesel. As the viscosity of the hybrid fuels decreased and approached that of diesel, the efficiency increased progressively towards that of diesel. The exhaust emissions were lower than those for diesel, except carbon monoxide emissions, which increased. Sanjid A et al. (2014) investigated the performance, emission characteristics on Mustard biodiesel (MB).

During engine performance test MB10 and MB20 showed 8-13% higher BSFC and 5-6% lower BTE compared to B0. By contrast, MB blends produced 7-8% less BP and 6-8% less engine torque compared to B0. Engine emission and noise test showed 9-12% higher NOx, 24-42% lower HC, 19-40% lower CO and 2-7% lower noise emission for MB blends compared to diesel. Senthilraja R et al. (2016) have conducted experiments to evaluate the effects of diesel, ethanol, Cotton Seed Oil Methyl Ester (CSOME) and Compressed Natural Gas. The experiments were carried out using various fuel blends and Compressed Natural Gas in normal engine mode and dual fuel engine mode. The test fuels were blends of Diesel, Ethanol and Cotton Seed Oil Methyl Ester. The results indicated that, Nitrogen oxide (NOX) emissions, Carbon dioxide (CO2) emissions decreased at all loads for fuel blends and exhaust emissions with CNG. Nagaraja S et al. (2016) tested corn oil methyl ester (COME) in compression ignition engine. The results give clear information that COME has low exhaust emissions and increase in performance compared to D100 without any modifications. It gives better performance, which is nearer to the obtained results of D100. Specific fuel consumption (SFC) of B100 at the full load condition is found to be 4% lower than that of D100. The maximum brake efficiency (BTE) of B100 is found to be 8.5% higher than that of the D100 at full load. Also, the maximum BTE of part load for different blends is varied from 5.9% to 7.45% which is higher than D100. Ganapathi P et al. [2014] described an experimental study of using pongamia pinnata oil as a fuel in diesel engine. In this study the effect of using pongamia pinnata oil-diesel fuel blends (B10, B20) on the engine performance, exhaust emission have been experimentally investigated. Pongamia biodiesel shows lower heat release rate during premixed burning phase compared to diesel. The experimental result showed that the carbon monoxide, hydrocarbons with increase in both specific fuel consumption and brake thermal efficiency. From the in-depth literature survey, it was observed that no research has been done in optimizing palm oil, cotton-seed oil and n-butanol using various parameters such as injection timing, injection pressure and Exhaust gas recirculation. Therefore the present research focusses on Taguchi grey relational analysis (GRA) to optimize various parameters and thereby decreasing both time and cost. Five different factors such as fuel, load, injection pressure, injection timing and EGR was taken. For each factor three different levels are taken as shown in Table.1. The performance and emission variables such as brake thermal efficiency, specific fuel consumption, brake thermal efficiency, oxygen content, carbon monoxide, nitrogen oxide, smoke and hydro carbons were investigated. These performance and emission parameters of all biodiesel blends were optimized by using GRA to obtain the best combination of input variables.

### Table 1. Factors with their levels

| Factors | 1            | 2            | 3            |
|---------|--------------|--------------|--------------|
| A       | FUEL         | Palm Oil     | Cotton Seed Oil | n-Butanol  |
| B       | FIP          | 180bar       | 200bar       | 220bar     |
| C       | FIT          | 19° btdc     | 23° btdc     | 27° btdc   |
| D       | EGR          | 10%          | 15%          | 20%        |
| E       | LOAD         | 50%          | 75%          | 100%       |

### II. METHODOLOGY

The work performed can be divided into following steps:-

1. Biodiesels were prepared using Transesterification process.
2. Fuel properties were analysed for biodiesels.
3. Blends were prepared for all oils i.e. Palm oil, Cotton-seed oil and n-Butanol.
4. Taguchi orthogonal array based on number of factors and their levels were developed by using MINITAB 18.
5. Evaluation of performance and emission characteristics of biodiesel blends on diesel engine were done by taking the orthogonal array as a reference.
6. GRA technique was then applied to get best optimum combination of input variables.
7. Finally performance and emission characteristics for the optimum combination obtained was also checked experimentally to validate the technique applied.

### III. EQUIPMENT USED FOR THE EVALUATION OF ENGINE PERFORMANCE

A four stroke, single cylinder variable compression ratio diesel engine was used for the present study. The performance and emission were evaluated on the variable compression ratio diesel engine using various blends of diesel and biodiesel as a fuel. The experiments were conducted at the constant speed of 1500rpm at various loads, fuel injection pressure, fuel injection timing and exhaust gas recirculation. The compression ratio can be varied by using tilting cylinder block without stopping the engine. The arrangement for measurement of airflow, fuel flow, temperatures and load provided. Air box, manometer, fuel tank, fuel measuring unit, transmitters for air and fuel flow measurements, engine indicator and process indicator has been assembled separately on panel box. The flow of cooling water and calorimeter was controlled with rotameter. Load cell sensor was used to vary the load on eddy current dynamometer which is coupled to the engine. Lab view based Engine Performance Analysis software package “Enginesoft” is provided for on line performance evaluation. The schematic diagram of experimental setup and specification of the engine was shown in Fig.1 and Table.2.
In this study, Taguchi’s DOE method is used to find out the optimal combinations of engine operating parameters, i.e., engine operating load, fuel injection pressure, exhaust gas recirculation and fuel injection timing, to maximize the BTE and \( \text{O}_2 \) and to minimize the BSFC and emissions (Smoke HC, NOx and CO). In the parametric design of the Taguchi method, first quality characteristics and design parameters (i.e., engine operating parameters) are identified, and then the number of levels for engine operating parameters and possible interactions between the engine operating parameters are estimated. The levels of design parameters for this study are shown in Table 1 (TOA design). The experiments were done and conducted based on the orthogonal array. In the orthogonal array, all the factors of the experiment and their responses vary simultaneously according to orthogonal array design values instead of one factor. The Taguchi approach can be used to analyse several factors with a minimum number of experiments.

### 4.2 Signal to Noise ratio of output parameters

#### Fig. 2. S/N for BTE

![S/N for BTE](image)

**Table 2. Performance at optimal combination of BTE**

| BTE | \( \text{O}_2 \) | SFC | NOx | HC | SMOKE | CO  |
|-----|----------|------|-----|----|-------|-----|
| 34.07 | 5.98 | 0.26 | 1201 | 151 | 71.4 | 0.396 |

In Fig. 2, it was observed that the maximum brake thermal efficiency is observed at n-Butanol fuel, 27° btdc injection timing, 200bar fuel injection pressure, 10% Exhaust gas recirculation and at 100% load. Similarly for Fig. 3, the oxygen content is maximum at n-Butanol fuel, 23° btdc injection timing, 180 bar fuel injection pressure, 10% exhaust gas recirculation and 50% load. In Fig. 4, the specific fuel consumption is maximum at CSO fuel, 27° btdc injection timing, 220 bar fuel injection pressure, 20% exhaust gas recirculation and 50% load. Similarly for Fig. 5, the NOx is minimum at cotton seed oil fuel, 19° btdc injection timing, 200 bar fuel injection pressure, 20% exhaust gas recirculation and 50% load. Similarly for Fig. 6, the CO is minimum at n-Butanol fuel, 23° btdc injection timing, 200 bar fuel injection pressure, 10% exhaust gas recirculation and 50% load. Similarly for Fig. 7, the CO is minimum at n-Butanol fuel, 19° btdc injection timing, 200 bar fuel injection pressure, 10% exhaust gas recirculation and 50% load.
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Table 3. Performance at optimal combination of O2

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 24.57| 13.02| 0.33| 456 | 18  | 22.4  | 0.041|

Table 4. Performance at optimal combination of SFC

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 32.47| 6.04 | 0.24| 1084| 239 | 82.4  | 0.494|

Table 5. Performance at optimal combination of HC

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 26.37| 10.41| 0.33| 578 | 19  | 31.5  | 0.121|

Table 6. Performance at optimal combination of NOx

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 22.5 | 11.32| 0.33| 262 | 29  | 27.6  | 0.043|

Table 7. Performance at optimal combination of SMOKE

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 28.05| 10.51| 0.29| 967 | 33  | 21.3  | 0.034|

Table 8. Performance at optimal combination of CO

| BTE  | O2  | SFC | NOx | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 34.07| 5.98 | 0.26| 1201| 151 | 71.4  | 0.396|
4.2. Grey Relational Analysis

Grey relational analysis (GRA) is multi response optimization technique has been applied for evaluating the performance of a variety of complex application with meagre information. It is widely used for measuring the degree of relationship between sequences by grey relational grade. This method can effectively solve the problems that are uncertain or incomplete or which involve system with incomplete information, using system relational analysis, model construction, forecasting and decision analysis. The grey system theory has been successfully used in various fields, including industry, agriculture, economics, mechanical and civil engineering. The objective of optimization is to make the difference between the objective sequence and the standard sequence as small as possible that is the smaller the grey difference degree the better the results. However when the response variables in the problem are conflicting to each other for e.g. if brake thermal efficiency is having higher-the-better (↑) quality characteristic and NOx is having smaller-the-better (↓) Quality characteristic then the grey relational analysis gives the best single parametric condition that shows improved performance. As two extremes, means that all of its information is known and a black system means that no information, the GRA identifies the (grey/hidden) values between 0 and 1, which may not be possible in other techniques. If there are multiple response variables, for the same conditions of independent variables, the optimum parameter cannot be found by Taguchi method because Taguchi method provides separate optimum parametric conditions for each response variable. However, Grey relational analysis ranks the experiment based on the increasing order of their grey relational grade (GRG) which is used for identifying the most influencing factor affecting the response variables. In the present case, the problem has seven output variables which need to be minimized by choosing appropriate conditions. Hence, it is necessary to convert multi-objective problem into a single objective problem using grey relational analysis.

Table 9. Input factors and their levels (L27 orthogonal design matrix of experimental data)

| No. | Fuel   | IT | FIP | EGR | LOAD | BTE | O2  | SFC | NOx | HC   | Smoke | CO |
|-----|--------|----|-----|-----|------|-----|-----|-----|-----|------|-------|----|
| 1   | Cotton | 19 | 180 | 10  | 50   | 26.98 | 12.68 | 0.32 | 403 | 26   | 33.5  | 0.039 |
| 2   | Cotton | 19 | 180 | 10  | 75   | 30.24 | 9.72  | 0.28 | 537 | 88   | 54.6  | 0.094 |
| 3   | Cotton | 19 | 180 | 10  | 100  | 30.68 | 5.46  | 0.28 | 552 | 135  | 91.3  | 0.435 |
| 4   | Cotton | 23 | 200 | 15  | 50   | 28.68 | 12.5  | 0.3  | 821 | 104  | 27.1  | 0.094 |
| 5   | Cotton | 23 | 200 | 15  | 75   | 31.63 | 9.83  | 0.27 | 1009 | 159  | 42.1  | 0.149 |
| 6   | Cotton | 23 | 200 | 15  | 100  | 33.27 | 5.36  | 0.26 | 947 | 214  | 82.2  | 0.733 |
| 7   | Cotton | 27 | 220 | 20  | 50   | 26.58 | 11.16 | 0.32 | 586 | 31   | 34.3  | 0.042 |
| 8   | Cotton | 27 | 220 | 20  | 75   | 28.6  | 7.42  | 0.3  | 570 | 79   | 59.1  | 0.125 |
| 9   | Cotton | 27 | 220 | 20  | 100  | 28.58 | 2.33  | 0.3  | 373 | 168  | 100   | 2.296 |
| 10  | LPO    | 19 | 200 | 20  | 50   | 27.03 | 11.9  | 0.32 | 280 | 25   | 36.5  | 0.043 |
| 11  | LPO    | 19 | 200 | 20  | 75   | 32.04 | 8.3   | 0.27 | 301 | 75   | 52.9  | 0.118 |
| 12  | LPO    | 19 | 200 | 20  | 100  | 31.03 | 2.97  | 0.28 | 246 | 157  | 100   | 1.584 |
| 13  | LPO    | 23 | 220 | 10  | 50   | 27.05 | 12.57 | 0.32 | 813 | 110  | 25.1  | 0.098 |
| 14  | LPO    | 23 | 220 | 10  | 75   | 30.47 | 10.05 | 0.28 | 1047 | 171  | 46.9  | 0.154 |
| 15  | LPO    | 23 | 220 | 10  | 100  | 32.47 | 6.04  | 0.27 | 1084 | 239  | 82.4  | 0.494 |
| 16  | LPO    | 27 | 180 | 15  | 50   | 27.05 | 11.82 | 0.32 | 920 | 66   | 55.8  | 0.077 |
| 17  | LPO    | 27 | 180 | 15  | 75   | 32.06 | 8.72  | 0.27 | 1064 | 94   | 70.7  | 0.121 |
| 18  | LPO    | 27 | 180 | 15  | 100  | 31.12 | 4.42  | 0.28 | 952 | 161  | 89.8  | 0.847 |
| 19  | Butanol| 19 | 220 | 15  | 50   | 26.5  | 12.32 | 0.33 | 352 | 19   | 22.6  | 0.042 |
| 20  | Butanol| 19 | 220 | 15  | 75   | 30.35 | 9.13  | 0.29 | 432 | 81   | 42.4  | 0.092 |
| 21  | Butanol| 19 | 220 | 15  | 100  | 32.31 | 4.52  | 0.27 | 392 | 150  | 89.8  | 0.734 |
| 22  | Butanol| 23 | 180 | 20  | 50   | 26.27 | 12.11 | 0.33 | 642 | 111  | 31.9  | 0.112 |
| 23  | Butanol| 23 | 180 | 20  | 75   | 29.03 | 8.88  | 0.31 | 735 | 166  | 48.4  | 0.168 |
| 24  | Butanol| 23 | 180 | 20  | 100  | 31.38 | 4.57  | 0.28 | 646 | 228  | 82.9  | 0.727 |
| 25  | Butanol| 27 | 200 | 10  | 50   | 30.05 | 12.51 | 0.29 | 967 | 33   | 26.3  | 0.034 |
| 26  | Butanol| 27 | 200 | 10  | 75   | 33.48 | 9.63  | 0.26 | 1259 | 80   | 40.7  | 0.063 |
| 27  | Butanol| 27 | 200 | 10  | 100  | 34.07 | 5.98  | 0.26 | 1201 | 151  | 71.4  | 0.396 |

The stepwise procedure of GRA optimization, shown in the flowchart (as shown Fig. 4), is used to solve the above formulation.

Step 1: Grey relational generation

A linear normalization of the output values in the range between zero and unity is also called as the grey relational generation. The “smaller-the-better” (see Eq. 1) and “larger-the-better” (see Eq. 2) are the characteristics of the original sequence, and they are used to compare levels in the grey relational generation (GRGn). The original sequence was normalized using following Eqs. 1 and 2

\[ y(k) = \frac{y(k) - y(k)}{\text{max}(k) - \text{min}(k)} \]  

\[ y(k) = \frac{y(k)}{\text{min}(k)} \]  

where y(K) is the value after the grey relational generation, maxy(k) is the largest value of y(k), miny(k) is the smallest value of y(k) for the Kth response. The normalized data after grey relational generation is presented in Table 1.

Step 2: Calculation of grey relational coefficients

GRCs for all the sequences expresses the relationship between the ideal (best = 1) and actual normalized. If the two sequences agree at all points, then their grey relational coefficient is 1. The Grey relational coefficient was calculated using Eq. 3.
$$\delta\text{min} + \psi \cdot \delta\text{max}$$

$$\epsilon(k) = \frac{\delta_i + \psi \cdot \delta_{\text{max}}}{\delta_{\text{min}} + \psi \cdot \delta_{\text{max}}} \quad \ldots\ldots\ldots\ldots(3)$$

Step 3 Calculation of grey relational grade (GRG)

After calculating the Grey relational coefficients, the overall grey relational grade was calculated using Eq. 4. Higher value of GRG represents desirability level.

$$\Delta i = \sum_{k=1}^{n} W_k \cdot \zeta(k) \quad \ldots\ldots\ldots\ldots(4)$$

Where $W_k$ is the weighting value for each grey relational coefficient ranging from 0 to 1 and the sum of $W_k$ is always equal to 1.

**Table 10. Grey Relational Generation**

| S.NO | BTE  | O2   | BSFC | NO X  | EGR  | SMOKE   | CO   |
|------|------|------|------|-------|------|---------|------|
| 1    | 0.063408 | 1    | 0.142857 | 0.845015 | 0.968182 | 0.859173 | 0.99779 |
| 2    | 0.494055 | 0.71401 | 0.714286 | 0.686364 | 0.586563 | 0.973475 |
| 3    | 0.55218  | 0.302415 | 0.714286 | 0.697927  | 0.472727 | 0.112403 | 0.822723 |
| 4    | 0.287979 | 0.982609 | 0.428571 | 0.432379  | 0.613636 | 0.94186  | 0.973475 |
| 5    | 0.677675 | 0.724638 | 0.857143 | 0.246792  | 0.363636 | 0.740862 | 0.94916  |
| 6    | 0.89432  | 0.292754 | 1       | 0.30997   | 0.113636 | 0.229974 | 0.690981 |
| 7    | 0.010568 | 0.85314 | 0.142857 | 0.664363  | 0.945455 | 0.848837 | 0.996463 |
| 8    | 0.277411 | 0.491787 | 0.428571 | 0.680158  | 0.727273 | 0.528424 | 0.95977  |
| 9    | 0.274769 | 0     | 0.428571 | 0.87463   | 0.322727 | 0       | 0     |
| 10   | 0.070013 | 0.924638 | 0.142857 | 0.966436  | 0.972727 | 0.820413 | 0.996021 |
| 11   | 0.731836 | 0.576812 | 0.857143 | 0.945706  | 0.745455 | 0.608527 | 0.962865 |
| 12   | 0.598415 | 0.061836 | 0.714286 | 1       | 0.372727 | 0       | 0.314766 |
| 13   | 0.072655 | 0.989372 | 0.142857 | 0.440276  | 0.586364 | 0.96777  | 0.971706 |
| 14   | 0.524439 | 0.745894 | 0.714286 | 0.209279  | 0.309091 | 0.686047 | 0.94695  |
| 15   | 0.788639 | 0.358454 | 0.857143 | 0.172754  | 0       | 0.22739  | 0.79664  |
| 16   | 0.072655 | 0.916908 | 0.142857 | 0.33465   | 0.786364 | 0.571059 | 0.98099  |
| 17   | 0.734478 | 0.617391 | 0.857143 | 0.192498  | 0.659091 | 0.378553 | 0.961538 |
| 18   | 0.661891 | 0.201932 | 0.714286 | 0.30306   | 0.354545 | 0.131783 | 0.640584 |
| 19   | 0     | 0.965217 | 0     | 0.89536   | 1       | 1       | 0.996463 |
| 20   | 0.508587 | 0.661836 | 0.571429 | 0.816387  | 0.718182 | 0.744186 | 0.974359 |
| 21   | 0.767503 | 0.211594 | 0.857143 | 0.855874  | 0.404545 | 0.131783 | 0.690539 |
| 22   | 0.009247 | 0.944928 | 0     | 0.609082  | 0.581818 | 0.879845 | 0.966401 |
| 23   | 0.334214 | 0.63285 | 0.285714 | 0.517275  | 0.331818 | 0.666667 | 0.944297 |
| 24   | 0.64465  | 0.216425 | 0.714286 | 0.605133  | 0.05    | 0.22093  | 0.693634 |

In present study, equal weightages are given to every output variable, the ranking is given based on ‘larger is better’, the grey relational grades for all the 27 sets along with their ranking are shown in Table 13.

Step 4 Generation of best combination

Until now the information present is incomplete, so it needs a best combination among the complete information (which is unknown). Therefore the matrix is generated by summing up the grey relational grades of each factor and their levels separately into a matrix as shown in Table 13.
| S.NO | BTE   | O2    | BSFC | NO X | EGR    | SMOKE | CO   |
|------|-------|-------|------|------|--------|-------|------|
| 1    | 0.348046 | 1     | 0.368421 | 0.763376 | 0.940171 | 0.780242 | 0.995599 |
| 2    | 0.497045 | 0.63614 | 0.636364 | 0.63511 | 0.614525 | 0.547383 | 0.949622 |
| 3    | 0.527526 | 0.417507 | 0.636364 | 0.623385 | 0.486726 | 0.360335 | 0.738251 |
| 4    | 0.412534 | 0.966387 | 0.466667 | 0.468331 | 0.564103 | 0.722727 | 0.369509 |
| 5    | 0.608032 | 0.64486 | 0.777778 | 0.398976 | 0.443548 | 0.333333 | 0.421858 |
| 6    | 0.825518 | 0.414166 | 1    | 0.420158 | 0.360656 | 0.393693 | 0.618033 |
| 7    | 0.335698 | 0.772965 | 0.368421 | 0.598346 | 0.901639 | 0.767857 | 0.992976 |
| 8    | 0.409648 | 0.495927 | 0.368421 | 0.763376 | 0.940171 | 0.766158 | 0.987179 |
| 9    | 0.408069 | 0.333333 | 0.466667 | 0.799526 | 0.42471 | 0.333333 | 0.333333 |
| 10   | 0.349654 | 0.869018 | 0.368421 | 0.937095 | 0.948276 | 0.735741 | 0.992105 |
| 11   | 0.650903 | 0.541601 | 0.777778 | 0.902048 | 0.662651 | 0.56087 | 0.930864 |
| 12   | 0.554579 | 0.347665 | 0.636364 | 1    | 0.443548 | 0.333333 | 0.421858 |
| 13   | 0.350301 | 0.979186 | 0.368421 | 0.471821 | 0.547264 | 0.93932 | 0.946444 |
| 14   | 0.512525 | 0.663037 | 0.368421 | 0.38738 | 0.419847 | 0.614286 | 0.904077 |
| 15   | 0.702878 | 0.438003 | 0.777778 | 0.37672 | 0.333333 | 0.392893 | 0.710874 |
| 16   | 0.350301 | 0.857498 | 0.368421 | 0.429055 | 0.700637 | 0.538248 | 0.963373 |
| 17   | 0.653149 | 0.566502 | 0.777778 | 0.382408 | 0.594595 | 0.445853 | 0.928571 |
| 18   | 0.596581 | 0.385188 | 0.636364 | 0.417732 | 0.36508 | 0.365439 | 0.58179 |
| 19   | 0.333333 | 0.934959 | 0.333333 | 0.826939 | 1    | 0.992976 |
| 20   | 0.50433 | 0.596542 | 0.538462 | 0.731408 | 0.639535 | 0.661538 | 0.95122 |
| 21   | 0.682597 | 0.388076 | 0.777778 | 0.776245 | 0.456432 | 0.365439 | 0.617695 |
| 22   | 0.335401 | 0.900783 | 0.333333 | 0.561219 | 0.544554 | 0.80625 | 0.937034 |
| 23   | 0.428895 | 0.576602 | 0.411765 | 0.50879 | 0.428016 | 0.6    | 0.899761 |
| 24   | 0.584556 | 0.389537 | 0.636364 | 0.558742 | 0.344828 | 0.390909 | 0.620066 |
| 25   | 0.484946 | 0.968195 | 0.538462 | 0.412627 | 0.887097 | 0.912736 | 1    |
| 26   | 0.865143 | 0.629179 | 1    | 0.333333 | 0.643275 | 0.681338 | 0.975 |
| 27   | 1    | 0.435789 | 1    | 0.346562 | 0.454545 | 0.442286 | 0.757535 |
Table 12. Grey Relational Grades and Ranks for each set

| Exp No. | Grey relational grade | Rank | Exp No. | Grey relational grade | Rank |
|---------|-----------------------|------|---------|-----------------------|------|
| 1       | 0.742264              | 4    | 15      | 0.533211              | 22   |
| 2       | 0.645169              | 11   | 16      | 0.601076              | 16   |
| 3       | 0.541441              | 20   | 17      | 0.621265              | 15   |
| 4       | 0.674782              | 8    | 18      | 0.488514              | 22   |
| 5       | 0.634614              | 13   | 19      | 0.774505              | 1    |
| 6       | 0.576031              | 19   | 20      | 0.660433              | 9    |
| 7       | 0.676843              | 7    | 21      | 0.580608              | 17   |
| 8       | 0.581236              | 16   | 22      | 0.631224              | 14   |
| 9       | 0.442712              | 23   | 23      | 0.550546              | 20   |
| 10      | 0.742901              | 3    | 24      | 0.503572              | 21   |
| 11      | 0.718102              | 6    | 25      | 0.743437              | 2    |
| 12      | 0.533911              | 21   | 26      | 0.732466              | 5    |
| 13      | 0.657536              | 10   | 27      | 0.633816              | 12   |
| 14      | 0.591073              | 17   |         |                       |      |

Table 13. Average Grey Relational Grade

| LEVEL | A | B          | C          | D          | E          |
|-------|---|------------|------------|------------|------------|
| 1     | 0.612789 | 0.659926   | 0.591675   | 0.646713   | 0.693841   |
| 2     | 0.609732 | 0.594733   | 0.665562   | 0.623537   | 0.637212   |
| 3     | 0.645624 | 0.613485   | 0.610907   | 0.597894   | 0.537091   |

The maximum values in each column are highlighted such that at each factor the best level is obtained. From above matrix the best combination obtained is A3 B1 C2 D1 E1

A3: Fuel is n-Butanol
B1: FIT is 19° btdc
C2: FIP is 200 bar
D1: EGR is 10%
E1: load at 50%

Table 14. Performance at optimal combination in GRA

| BTE  | O₂  | SFC | NOₓ | HC  | SMOKE | CO   |
|------|-----|-----|-----|-----|-------|------|
| 34.07| 13.2| 0.33| 456 | 18  | 22.4  | 0.041|

V. CONCLUSION

In the present investigation, an attempt was made to explore the effect of Fuel injection pressure (FIP), fuel injection timing (FIT), exhaust gas recirculation (EGR) and Load and for various fuel blends (Cotton Seed Oil1, Palm oil, n-Butanol) as input parameters on SFC, BTE,O₂, CO, HC, NOx and Smoke output variables with minimum number of experiments. In order to reduce the experimental...
efforts, Taguchi’s L27 orthogonal array was employed for design of experiments. Following major conclusions are drawn based on the investigation:

5.1 Taguchi Analysis

The optimal combinations which are obtained are of single objective each of fuel blends, Fuel injection timing, Fuel injection Pressure, Exhaust Gas Recirculation, Load are shown below.

### Table.15. The optimal combinations for all parameters

| Parameters | FUEL     | FIT       | FIP       | EGR    | LOAD    |
|------------|----------|-----------|-----------|--------|---------|
| BTE        | n-Butanol| 27° btdc  | 200 bar   | 10%    | 100%    |
| O2         | n-Butanol| 23° btdc  | 180 bar   | 10%    | 50%     |
| SFC        | LPO      | 27° btdc  | 200 bar   | 10%    | 100%    |
| CO         | n-Butanol| 19° btdc  | 200 bar   | 10%    | 50%     |
| HC         | n-Butanol| 19° btdc  | 200 bar   | 20%    | 50%     |
| NOx        | CPO      | 19° btdc  | 220 bar   | 20%    | 50%     |
| Smoke      | n-Butanol| 23° btdc  | 200 bar   | 10%    | 50%     |

The maximum Brake thermal efficiency is observed is 34.07%, maximum Oxygen Content is 13.3 ppm, Specific Fuel Consumption is 0.24, Nitrogen Oxides is 262 ppm, Hydro Carbon are of 19 ppm, Smoke Opacity is about 21.3%, and Carbon Mono oxide is of 0.041 ppm.

5.2 Grey Relational Analysis

The optimal combination of the input parameters of the CI engine operated on n-Butanol at 19° btdc fuel injection timing, 180 bar fuel injection pressure, 10% exhaust gas recirculation, 50% load.

Table.16. Optimal Combination Obtained in GRA

| Fuel     | FIT       | FIP       | EGR    | LOAD    |
|----------|-----------|-----------|--------|---------|
| n-Butanol| 19° btdc  | 200 bar   | 10%    | 50%     |

Table.17. Performance at optimal combination in GRA

| BTE | O₂ | SFC | NOx | HC | SMOKE | CO |
|-----|----|-----|-----|----|-------|----|
| 34.07 | 13.2 | 0.33 | 456 | 18 | 22.4   | 0.041 |

- Based on ANOVA, Engine Load was the most influencing factor (Contribution of load was 57.8%) for the chosen objective of improvement in BTE and BSFC with lesser penalty on emissions (CO, HC, CO₂, NOx and Smoke) based on equal weight ages.
- With minor modifications in existing diesel engine, n-Butanol diesel blend can be used without much compromising with performance while restricting emission.
- The experimental confirmation test reveals that Taguchi grey relational analysis (TGRA) technique is suitable for multi-objective optimization problem on engine performance and emission.

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AUTHORS PROFILE

A.Naresh Kumar, Assistant Professor, Department of Mechanical Engineering, Lakireddy Balireddy College of Engineering, Mylavaram, India. Email: nareshkumarakula@gmail.com

K.Madhu Babu, Assistant Professor, Department of Mechanical Engineering, Sree Vahini Institute of Science & Technology, Tiruvuru, India. Email: k.madhu681@gmail.com

B.Prashanth Kumar, Assistant Professor, Department of Mechanical Engineering, Sree Vahini Institute of Science & Technology, Tiruvuru, India. Email: prashanthbadisa123@gmail.com

S.Kiran Kumar, Professor, Department of Mechanical Engineering, Sree Vahini Institute of Science & Technology, Tiruvuru, India. Email: kirankumar.sureddy@gmail.com

P.S.Kishore, Professor, Department of Mechanical Engineering, Andhra University Visakhapatnam, Indian. Email: porinivaskishore@gmail.com