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Combined influence of supercharging, EGR, biodiesel and ethanol on emissions of a diesel engine: Proposal of an optimization strategy

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ABSTRACT

There are several abatement technologies used for emissions, especially NO_x emissions, from Diesel engines. Exhaust Gas Recirculation (EGR) system and alternative blend fuels are leading among the common methods used. Although the EGR provides remarkable reduction in NO_x emissions, has negative effects on other emissions and engine performance. Among the alternative fuels, biodiesel and ethanol are preferred for being renewable. Chemical properties make these fuels feasible to be used in diesel blends at various ratios. Utilizing these fuels with diesel fuel in blends on engines provide improvements in engine performance parameters and emissions characteristics. However, biodiesels with oxygen content increase NO_x emissions in particular. Eventually, utilizing different methods together is beneficial to optimize for the most convenient utilization ratios and conditions regarding all the emissions from engine. In this study, utilizing supercharging, EGR, biodiesel at various ratios and introducing ethanol fumigation through intake manifold of a DI diesel, and the most convenient engine operation conditions and ratios of the factors are determined through optimization using Taguchi method regarding engine brake specific heat consumption and emissions. Experiments are conducted regarding to orthogonal series L16 ($4^2 \times 2^2$) with the combinations of factor and levels. Effect degrees of factors are determined through variation analysis. As a conclusion, factors evaluated in combination under different engine operating conditions, and factors and levels minimizing brake specific heat consumption and emissions, NO, smoke, HC, CO and CO_2, are stated.

1. Introduction

Global energy demand is supplied by fossil fuel resources, substantially. However, growth of world population at an increasing rate and increase in energy demand of the developing industries worldwide causes rapid depletion of resources. On the other hand, utilization of fossil fuels causes damage to the environment. Therefore, legislative regulations on emissions are changing continuously. In this situation, turning to renewable and sustainable energy resources is inevitable [1,2]. In this context, utilization of ethanol fuel, produced from vegetables or animals, stands out [3].

Biodiesel is one of the potential fuels to be used on diesel engines [1]. Utilization of biodiesels on diesel engines has become widespread [6], because vegetable oils are renewable, biologically degradable, free of toxic materials, and have low emission profile, except NO_x [4,5]. In some countries, biodiesel addition into commercial diesel fuel is a legal obligation.

Ethanol is another alternative fuel used in diesel engines. Ethanol is a renewable fuel, produced by fermentation of carbohydrates using enzymes as catalysts. Corn, sugar cane, wheat, potato, rice, rye and various fruits can be used as carbohydrate sources [7]. Ethanol utilization reduces some emissions, since ethanol is free from sulfur and heavy metals, unlike diesel fuel, has a smaller molecular structure, and has oxygen content [8–12].

One of the worse problems is the negative effect of diesel engines on the environment with NO_x emissions. NO_x production takes place at high combustion chamber temperatures at the presence of oxygen [13]. NO_x emissions can be reduced by Exhaust Gas Recirculation (EGR). By redirecting some exhaust gasses back into the cylinder, charge in the combustion chamber is diluted, and as a result, peak combustion temperatures, so the amount of NO_x,

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are reduced [14–16]. But, increasing EGR ratio above a threshold worsens engine performance parameters, and so, the specific fuel consumption increases [17–19]. Therefore, to control performance and emissions, both, combined implementations can be effective and successive. Hereby, besides alternative fuel utilization, EGR and supercharging applications parameter optimization of the mentioned should be done, as a whole.

Efe et al. [22] investigated effects of using blends of biodiesel, from corn, sunflower, soybean, canola and hazelnut oils, and diesel fuel on Diesel engine, experimentally. Experiment resulted in 20% biodiesel fraction blend fuel giving the best engine performance and for hazelnut oil. Also, testing various oil biodiesel-diesel fuel blends, increase in specific fuel consumption in comparison to standard engine data is stated. Ayhan et al. [20] tested diesel and sunflower oil methyl ester blend fuel on a Diesel engine and studied engine brake power, specific fuel consumption and emissions. And, indicated, B20 blend giving the optimum results compared to standard engine data among B10, B20 and B50 blends. Also pointed, significant decrease in HC, CO and smoke emissions, but increase in NO emission. And added, increasing biodiesel fraction in blend fuel caused increase in specific fuel consumption compared to standard engine data. Karabas [21] experimentally investigated the effect of using tobacco seed oil biodiesel blend fuels, B10, B20 and B50, on a Diesel engine for engine performance and emission characteristics. And reported, higher specific fuel consumption and NO_x emissions, and lower HC, CO and smoke emissions, in comparison to diesel fuel. Manigandan et al. [20] conducted experimental studies using blend fuel, consist of corn oil methyl ester, pentanol and titanium at various fractions, at various speeds and loads. Significant reductions in CO, HC and smoke emissions are reported for using blend fuel consist of 25% corn oil methyl ester, 50% diesel fuel, 20% pentanol and 5% titanium, namely M25D50P20T5, compared to diesel fuel.

Jamrozik [12] conducted experimental studies on a direct injection Diesel engine to investigate effects of using ethanol and diesel fuel blend fuels on performance and emissions. Alternating alcohol fractions in the blend between 0 and 40%, reported improvements in engine performance by using diesel ethanol blend fuels throughout the mentioned range, CO emissions were reduced by 38%, whereas THC and CO_2 emissions remained virtually unchanged, but NO_x emissions increased. Ghadikolaei et al. [23] analyzed comparatively performance and emissions on a Diesel engine using diesel-biodiesel-ethanol blend using fumigation. To compare different fuel modes, a blend with constant fractions by volume of 80% diesel, 5% biodiesel and 15% ethanol is used. To the test results, in fumigation mode, CO_2, CO and HC emission increased, but NO_x and NO emissions decreased. And, in general, smoke emission is determined to be increased in comparison to standard engine. Pradelle et al. [24] studied experimentally performance and combustion characteristics of a Diesel engine using diesel-biodiesel-ethanol blend fuels. In engine tests, blend fuels used are obtained by adding ethanol in fractions of 0% up to 20% into B15 fuel. The test results of the various blend fuels are presented in comparison to B7E0, consisting of 7% biodiesel, 0% ethanol and 93% diesel, blend fuel. A 2% increase in specific fuel consumption is reported corresponding to each 5% increase in ethanol fraction. It is suggested to be caused by the decrease in blend fuel volume and the decrease in heating value. Shamun [25], testing on a Diesel engine using ethanol in high amounts, 30% ethanol fraction, reported significant decrease in NO_x emissions. And, added HC and CO emissions to be higher than diesel fuel for using ethanol at low loads.

In Exhaust Gas Recirculation (EGR) applied studies, worsening in engine performance and increase in HC, CO and smoke emission, but decrease in NO_x emissions are observed [14,26–28]. He et al. [27] added alcohol at different fractions, 15% ethanol, 15% butanol and 40% butanol, into diesel fuel, and also applied EGR on a Diesel engine, and to investigate combustion properties and changes in emissions at high load conditions, experimentally. And concluded that, at moderate alcohol fraction and EGR ratios improvements in engine performance and emissions can be achieved, in common. Verma et al. [28], using dual fuel (diesel and biogas) on a Diesel engine at different EGR ratios and compression ratios studied engine performance and emissions experimentally. During testing, 5%, 10% and 15% EGR ratios are used. Inducing EGR into engine at low loads resulted in a slight increase in engine efficiency and decrease in NO_x emissions. Also, at high loads and increasing EGR ratios decrease in engine efficiency is reported.

In this study, engine tests are designed as suggested in Taguchi method. In this method, instead of conducting all the test in the factorial combination, just a factorial combination of orthogonal series is determined for the optimal emission characteristics and tested [41]. Reviewing the literature within this context, Taguchi design of experiments method is chosen by many researchers [29,33–39] to reduce time and costs. In the literature [29–31] optimization of various engine input parameters to sustain the best engine emissions are performed by Taguchi method. Ansari et al. [32] investigated engine performance and emissions of a Diesel engine using various biodiesel blend fuels by Taguchi method. As a result, input parameters are optimized for the best engine performance and emissions. Wu et al. [33] studied combustion characteristics by Taguchi method on an EGR applied Diesel engine run on Liquefied Petroleum Gas (LPG) and diesel-biodiesel blend fuel and stated the optimum operating factors. Wu and Wu [34] investigated engine emissions and combustion properties on a single cylinder engine using diesel and biodiesel blends and induction of H_2 at various fractions and EGR into inlet manifold at various fractions, and determined the best combinations of input parameters by Taguchi method. Also, time savings of 67% is pointed out during tests by using L9 orthogonal series of Taguchi method.

Reviewing the literature, the following information is concluded. Biodiesel utilization in engines improves engine performance parameters and emissions, but NOx, at different amounts, instead increases NOx emissions. And, ethanol decreases CO emissions, but increases NO_x emissions, while do not effect HC and CO_2 emissions. EGR decreases NO_x emissions, significantly, but deteriorates rest of the engine parameters, particularly under high EGR rates. However, differences in test results are observed regarding differences in testing conditions in the studies. In the literature, in any study using different fuels and emission reductions techniques, comprehensively, like in this study is reported. In this study, factors are chosen considering improvements provided by different alternative fuels, supercharging and EGR. With EGR utilization, NO emission reduction is predicted. And with biodiesel, ethanol and supercharging utilization, improvements on deteriorated emissions remaining and specific fuel consumption are aimed. In comparison to standard engine data, reductions in all the emissions and specific fuel consumption are intended. For this reason, the effects of using alternative fuel blends and ethanol fumigation as alternative fuels and EGR at various rates and supercharging on specific fuel consumption and emissions for a diesel engine operating at various loads and engine speeds are investigated experimentally. Taguchi method is used for the design of experiments. The optimum factor levels of parameters are evaluated using the Signal/Noise (S/N) ratios suggested by Taguchi method. Variation analysis is used to evaluate the effect of different factor levels on specific fuel consumption and emissions characteristics.

2. Materials and methods

2.1. Biodiesel production

The biodiesel fuel used in experiments was produced from corn oil by transesterification method in laboratory. Alcohol, and catalyst used in transesterification process were methyl alcohol and KOH (potassium hydroxide), respectively. At first, KOH catalyst was dissolved in alcohol. In the meanwhile, corn oil was placed in a mixing container and its temperature was brought to 60 °C, constant. Afterwards, alcohol and catalyst mixture was transferred into a closed reaction container. And, corn oil was added into the mixture to react. When reaction completed, denser glycerin sunk at the bottom was taken away. Distilled water was added into fuel to remove the remaining catalyst and alcohol in extracted biodiesel. At the end of process, biodiesel and distilled water were dissolved, and water in the biodiesel was vaporized. Properties of the biodiesel used in the experiments are given in Table 1.

2.2. Ethanol fumigation

In the experiments, ethanol with 99% purity by Merck was used. In the experiments, ethanol was injected into the intake manifold at ratios of 10%, 15% and 20% by mass. Beforehand, to evaluate the required ethanol quantities regarding the specified ethanol ratios, on an experiment stage, fuel consumption duration was determined by conducting experiments without using ethanol. Also, prior to engine experiments, ethanol injection quantity of injector at 3 bar was examined. For this reason, injected alcohol quantity for the applied pulse duration was determined through a series of experiments. Mass flow rates of injected ethanol were determined for the injection ratios, considering required fuel consumption rates. And, next experiment stage was followed for implementation. At first, corresponding experiment stage was conducted without ethanol and load value measured from dynamometer force arm was recorded. During ethanol injection stage, delivered fuel rate was reduced according to the required ethanol ratio. Corresponding ethanol quantity for the required ethanol ratio was injected through the injector managed by electronic control unit. Quantity of fuel injected through injector was measured by a precision scale of 0.001 g resolution. A separate injector with solenoid control was mounted on the intake manifold for ethanol injection. Ethanol quantity, injection duration and start of injection signals are sent by electric control unit. Injector started operation at 5°CA aTDC, during intake process. Properties of fuels used in the experiments are given in Table 1.

2.3. Application of EGR

During the experiments EGR is applied to the engine at different ratios, 10%, 15% and 20%. Initial experiment steps are performed without EGR application. And in the meanwhile, CO_2 levels are measured. EGR ratios are calculated from measured CO_2 values. The amount of exhaust gas induced into inlet manifold is calculated from Eq. (1).

Table 1
Properties of fuels used in experiments.

Property	Diesel	COME-Biodiesel	Ethanol
Density (15 °C)	0.82−0.86	0.87−0.88	0.78−0.79
Cetane number	49	>55	11
Kinematic viscosity mm^2/s, (40 °C)	2.5−3.5	4.3	1.1
Flash point (°C)	>55	>100	425
Lower heating value (kJ/kg)	42,640	39,576	27,423

$$\mathrm{EGR}(\%) = \frac{\left[(\mathrm{CO_2})_{\text{intake manifold}} - (\mathrm{CO_2})_{\text{ambient}}\right]}{\left[(\mathrm{CO_2})_{\text{exhaust manifold}}\right]} \times 100 \qquad (1)$$

An additional connection pipe is arranged to transfer a fraction of the engine combustion products, exhaust gases, back into the inlet manifold. Also, an EGR cooler to cool the exhaust gasses, leaving the exhaust manifold, and a multiturn valve to adjust EGR ratio is placed on the connection line.

2.4. Application of supercharging

Experiments are conducted with natural aspiration, without supercharging (1 bar), and with supercharging at 2.1 bar (absolute pressure). By means of supercharging, denser air is delivered into the engine cylinder. Supercharging unit is composed of an electric motor and a compressor. In which, the compressor is primed by the electric motor. Supercharging pressure is set through an inverter to adjust electric motor speed to the required. A controlling valve, denoted by 1 in Fig. 1, is located between the surge tank and the inlet manifold in order to engage/disengage the supercharging unit. To engage the supercharging unit, the controlling valve denoted by 3 is closed to stop direct air intake, and valves denoted by 4 and 5 are opened to engage the supercharging unit. As a result, intake air is directed into the supercharging unit first, and then into the inlet manifold.

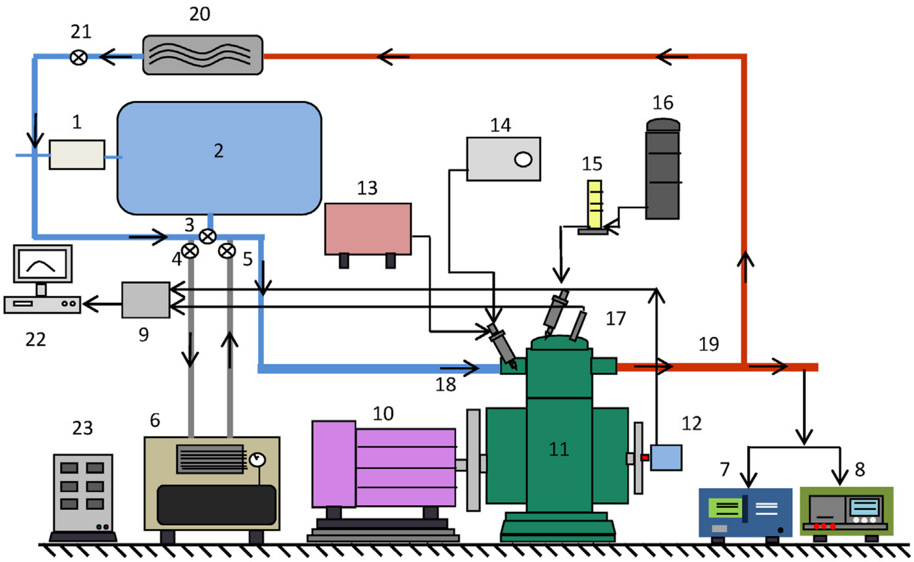
2.5. Test stand

In the experiments, a water cooled, DI single cylinder Diesel engine is used. Technical specifications of the test engine are given in Table 2.

Before the experiments, engine is warmed, run at partial loads for a period, in order to sustain the engine temperatures to stabilize. Moreover, test rig is equipped with water and oil conditioning units. Thus, water and oil temperatures are kept constant at 85 °C during the experiments. The test engine is loaded with a hydraulic dynamometer of 50 kg load capacity, and engine power output is measured with an S type load cell of 0.1 N precision attached to the dynamometer force arm. NiCr−Ni type thermocouples are used for all the temperature measurements. At first, experiments are done to determine optimum injection timing, as a result, it is specified as 29°CA. Bosch BEA 060 emission analyzer is used for NO, HC, CO, CO_2 emissions and Bosch BEA 070 emission analyzer is used for smoke emission. Fuel consumption is measured volumetric flowmeter system. A surge tank and air flowmeter are used for air consumption measurement. Kistler 6061 B model pressure transducer and Kistler 5011 B model charge amplifier are used for in-cylinder pressure measurement. National Instrument AI-16E-4 model data acquisition card is used for acquiring data through single channel at 500 kHz rate and Koyo TRD J1000-RZ model encoder with 1000 pulse/revolution is used for angular position measurement. Experiments are conducted at 1600 and 2400 rpm engine speeds and at 40%, 60%, 80% and 100% loads. Engine tests are conducted according to L16 orthogonal series, proposed by Taguchi method. Engine Test rig is illustrated in Fig. 1. Instrumentations used are given in Table 3 with technical data, including resolutions.

2.6. Design of experiments by taguchi method

In Taguchi method, to determine changes on performance characteristics by factors mean, standard deviation and in addition S/N (Signal/Noise) performance statistics are used. S/N ratios reveal sensitivity of performance characteristics under study on external



1	Air-flow meter	9	Amplifier	17	Pressure sensor-In-cylinder
2	Surge tank	10	Hydraulic dynamometer	18	Fresh charge
3	Control valve-Surge out	11	Test engine	19	Exhaust gas
4	Control valve-SC in	12	Encoder	20	EGR cooler
5	Control valve-SC out	13	Ethanol fumigation system	21	Valve-4
6	Supercharging system	14	Electronic control unit	22	Computer
7	Emission analyzer	15	Fuel flow meter	23	Monitoring
8	Smoke meter	16	Fuel tank		

Fig. 1. Engine test stand.

Table 2
Technical specifications of test engine, Super Star make diesel engine.

Quantity	Unit	Value
Piston bore	mm	108
Stroke	mm	100
Number of cylinders		1
Stroke Volume	dm^3	0.92
Brake Power, at 2200 rpm	kW	13
Injector Opening Pressure	bar	225
Injection Timing	°CA, bTDC	29
Compression Ratio		17
Maximum Speed	rpm	2500
Cooling Type		Water
Injection Type		Direct Injection
Piston Type		Bowl in Piston

factors, that are uncontrollable and influence results. In common, high S/N ratios are targeted for experiments. Large S/N ratios indicate low loss. For large system responses “larger the better” function, for small system responses “Smaller the better” function and for reducing system response variability “Nominal the best” function can be chosen. S/N ratios proposed by Taguchi are explained regarding the three conventional conditions. In this study, specific energy consumption and emissions were calculated using “smaller is better”, since the target values were required to be low.

Parameter design is the most important aspect of Taguchi method. The essential aim of the parameter design is to specify factors and levels that influence quality variable (performance parameter) target value and that can optimize target value. The two significant features in parameter design are robust design and orthogonal arrays. Degree of freedom is rather important in determining the orthogonal array. In statistics, degree of freedom represents the number of variables used in statistical data calculations. After determining factors, the number of levels and degrees of freedom for the experimental study, orthogonal array is specified, and then experiments are done with respect to the array specified. Underlying orthogonal experiment designs are provided by Taguchi method. The design plans are standardized, and can be

Table 3
Technical data of instrumentations used in experiments.

Measurements	Unit	Range	Instrumentation	Resolution
Engine speed	rpm	0–9999	Digital tachometer	1 rpm
Temperature	°C	0–1000	Thermocouple	1 °C
Fuel consumption	ml	0–100	Volumetric measurement device	50 ml measurement container
Brake force	N	0–100	S type load cell	0.01 N
Charge air flow	g/s	0–100	Electronically controlled air mass flowmeter	0.01 g/s
Carbon monoxide (CO)	%	0–15.0	Bosch BEA 060	Vol. 0.03%
Carbon dioxide (CO_2)	%	0–20.0	Bosch BEA 060	Vol. 0.5%
Hydrocarbon (HC)	ppm	0–20000	Bosch BEA 060	5% of measured value
Nitrogen oxide (NO)	ppm	0–2000	Bosch BEA 060	5% of measured value
Smoke opacity	%	0–100	Bosch BEA 070	1%
In-cylinder pressure	bar	0–300	Kistler 6061-B	−26.09 pC/bar and ± 0.3%
Crankshaft angular position	°CA	0–360	Koyo TRD J1000-RZ	1000 pulse/rev

used for experiment designs directly.

Controllable factors and levels investigated are listed in Table 4.

The specified factors and levels can be given as, biodiesel fractions are 4 levels, B0, B10, B20 and B50; ethanol fumigation fractions are 4 levels, E0, E10, E15 and E20; EGR ratios are 4 levels, EGR0, EGR10, EGR15 and EGR20; engine loads are 4 levels, 40%, 60%, 80% and 100%, charging pressures (absolute pressure) are 2 levels; SC1 and SC2.1 and engine speeds are 2 levels, 1600 rpm, for maximum brake torque, and 2400 rpm for maximum brake power. Planning experiments with full factors, involving numerous tests, has a negative effect on time and costs. To fulfill this study in full factorial test design, each test should be repeated 1024 times. Using Taguchi, the number of tests reduces to 16 tests. By means of planning orthogonal experiments in Taguchi design of experiments, testing for multiple factors and levels becomes possible by conducting a few numbers of tests. Orthogonal series is matching levels of a factor at trial stage to the levels of the rest of the factors [38]. In this study, specifying 4 factors by 4 levels and 2 factors by 2 levels, the data is input to Minitab software. And, an adequate orthogonal series, corresponding to factors and levels, is obtained. Orthogonal series, expressed as L16 (4^3) (2^1), is given in Table 5.

Regarding to Table 5, 16 random tests with 3 repetitions are conducted. Brake Specific Heat Consumption (BSHC) data are calculated using the engine test results. Emission characteristics for NO, HC, CO_2, CO and smoke emissions are measured by emission analyzers. Parameters are specified as a result of the experimental studies conducted with 3 repetitions, and the mean values evaluated are used in analyses. Ternary fuel blend composed of fuels with different density and heating values is used in the experiments. Therefore, S/N values are calculated for BSHC data to present contributions of fuels into fuel economy, instead of brake specific fuel consumption. And similarly, to compare natural aspiration and supercharged conditions, emissions (NO, HC, CO and CO2) data in ppm and vol% units are converted into g/kWh unit and analysis are done.

The most important distinguishing feature of Taguchi method from conventional design of experiments methods is the Signal to Noise (S/N) ratio utilized to evaluate performance criterion [42]. Therefore, adequate S/N ratios are determined for brake specific heat consumption and emissions of NO, HC, CO_2 and smoke. And, since the least values are intended, “the smaller is better” approach is used to determine BSHC and emission characteristics. The figures are prepared using this S/N ratio. In using “Smaller is better” formula, the maximum for numerical value of S/N ratio regarding observation values represents the minimum condition, in fact. For this reason, the considered formula, proposed by Taguchi, for the calculations has great importance. And it is worth noting the considered formula, while reading the figures. In this study, minimizing all the parameters is aimed. Therefore, the S/N ratio, providing the minimum values for each parameter, of the level with highest numerical value represents the optimum for corresponding factor. S/N ratios are calculated using Eq. (2).

The smaller is better;

Table 4
Factors and design levels.

Symbol	Factor	Level 1	Level 2	Level 3	Level 4
A	Load [%]	40	60	80	100
B	Biodiesel [B%, mass]	0	10	20	50
C	Ethanol [E%, mass]	0	10	15	20
D	EGR [EGR%]	0	10	15	20
E	Speed [rpm]	1600	2400	–	–
F	Supercharging [SC,bar]	1	2.1	–	–

Table 5
L16 orthogonal experimental setup.

Test No	Factors A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	2	2	2	1	2
3	1	3	3	3	2	1
4	1	4	4	4	2	2
5	2	1	2	3	2	2
6	2	2	1	4	2	1
7	2	3	4	1	1	2
8	2	4	3	2	1	1
9	3	1	3	4	1	2
10	3	2	4	3	1	1
11	3	3	1	2	2	2
12	3	4	2	1	2	1
13	4	1	4	2	2	1
14	4	2	3	1	2	2
15	4	3	2	4	1	1
16	4	4	1	3	1	2

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{2}$$

where, n, y_i and I are number of repetitions, measured data and the number of design parameters in the orthogonal series, respectively, under the same circumstances at a trial.

S/N ratios of BSHC and emission characteristics are investigated. As a result, the optimum combinations are determined and variational analysis (ANOVA) is performed to specify percentage effects of factors. Eq. s 3–7 are used in the variational analysis.

$$SS_T = \left[\sum_{i=1}^{N} (S/N)i^2\right] - \frac{T^2}{N} \tag{3}$$

$$SS_A = \left[\sum_{i=1}^{K_A} \left(\frac{A_i^2}{n_{Ai}}\right)\right] - \frac{T^2}{N} \tag{4}$$

$$v_{total} = N - 1 \tag{5}$$

$$V_{factor} = \frac{SS_{factor}}{\vartheta_{factor}} \tag{6}$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \tag{7}$$

SS_T is the total sum of squares, N the total number of experiments SS_A is the sum of squares for factor A, K_A is the number of factor A levels, Ai is the ith level value of factor A and n_{Ai} is the number of factor A levels, T is the sum of S/N ratios for the experiments and ϑ is the degrees of freedom, V_{factor} is variation of factor, SS_{factor} is the sum of squares for factor and F_{factor} is the F ratio for factor. In the Taguchi methods, confidence interval of 90–99% in variational analysis is sensible. Design of experiments are constituted regarding to the mentioned confidence limits.

3. Research findings

3.1. Brake specific heat consumption

In Fig. 2, Changes in S/N values of factors and levels for brake specific heat consumption is presented. Optimum BSHC is obtained at 80% load, for B10 biodiesel blend fuel and E20 ethanol ratio, EGR0

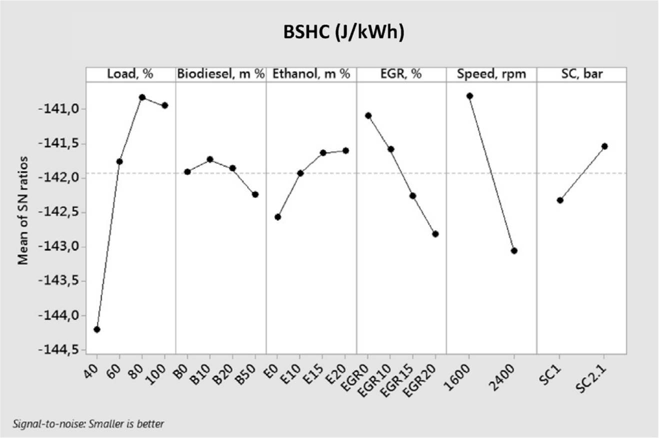


Fig. 2. S/N ratios of factor levels for BSHC.

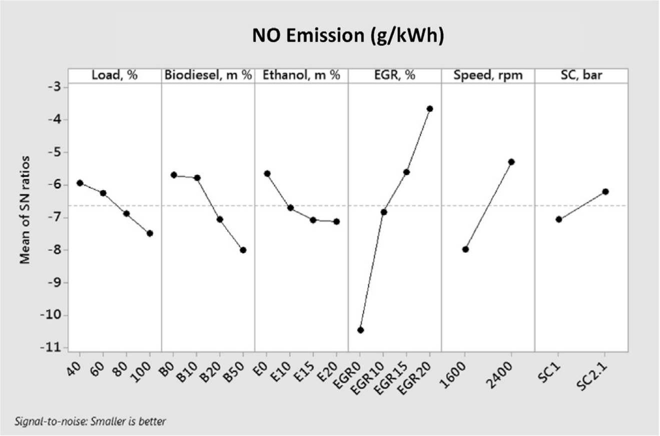


Fig. 3. S/N ratios of factor levels for NO emission.

(without EGR), at 1600 rpm and SC2.1 (supercharging at 2.1 bar). And, the best combination corresponds to A3-B2-C4-D1-E1-F2 (Load:80%-Biodiesel:10%-Ethanol:20%-EGR:0%-Speed:1600rpm-SC:2.1 bar).

Engine load increases with the fuel quantity delivered. Brake specific heat consumption is defined as conversion efficiency of fuel to power. Calculated BSHC data are shown in Fig. 2 with respect to load. And, the minimum BSHC is obtained under 80% load condition. Considering deviations in energy consumption related to the biodiesel utilization, the minimum BSHC is obtained close to 10% biodiesel blend fuel. The decrease in energy consumption for the blend fuel containing 10% biodiesel can be explained by the increase in combustion quality due to oxygen content in biodiesel.

Above 10% biodiesel fraction, fuel consumption increases compared to diesel fuel, proportional to the biodiesel content percentage in blend fuel. Considering changes in energy consumption due to ethanol utilization, brake specific heat consumption decreases as the injected ethanol ratio increases. As a result, the minimum energy consumption is obtained for E20 ethanol ratio. In the literature, the range of ethanol utilization ratios is proposed as 5–20% [11,12,23,40–44]. In EGR utilization, energy consumption deteriorates as the EGR ratio increases. Moreover, cylinder charge becomes richer as the EGR ratio increases, resulting in worsening of combustion. At 1600 rpm BSHC is the lowest. And as the engine speed increases, consumption duration of fuel contained in the same volume decreases, in other words, brake specific heat consumption increases due to more fuel consumption. The optimum heat consumption is obtained with supercharging.

3.2. Emissions characteristics

Changes in S/N ratios of factor levels for NO emission are presented in Fig. 3. The optimum NO is obtained for 40% load, diesel fuel (B0), without ethanol injection (E0), with 20% EGR ratio (EGR20), at 2400 rpm and supercharging at 2.1 bar (SC2.1). So, the best combination corresponds to A1-B1-C1-D4-E2-F2 (Load:40%-Biodiesel:0%-Ethanol:0%-EGR:20%-Speed:2400rpm-SC:2.1 bar).

The reaction of oxygen and nitrogen at high temperatures results in formation of NO emission. As seen in Fig. 3, the minimum NO emission is obtained with diesel fuel. And, NO emission increases as the biodiesel fraction in the blend fuel increases.

Biodiesel addition into engine fuel increases NO emissions for all the blend ratios. Moreover, increase in NO emission gets higher as the blend ratio increases. The reason for higher NO emission is the 8–12% excess oxygen in biodiesel fuel, as stated for the formation of NO emissions in Zeldovich mechanism [45–47]. Also, in cylinder temperatures increase as the combustion efficiencies increase due to biodiesel utilization, and results in high NO emissions. In fact, emission species are affected by engine operating conditions and control parameters. The test engine used in this study has a mechanical type diesel fuel injection system and tests are conducted with constant SOI timing (advance angle). And, variation in engine speed affects emission amount. At full load condition, in-cylinder air-fuel ratio decreases, as a result in-cylinder charge becomes a richer mixture. As the engine load increases, NO emissions increase with increase in temperature and change in air excess ratio. At full load condition, reduction of air in charge causes a richer mixture. In this case, increase in biodiesel amount supplies more oxygen to react. Thus, NO reaction increases [48,49].

NO emissions increase with ethanol fumigation at various ratios in the diesel engine [50]. In a conventional diesel combustion, NO emissions forms, mostly, in the lean zones of flame occurring at premixed combustion phase. NO formation mechanism depends on temperature, local oxygen concentration and reaction period. In comparison with diesel fuel, ethanol has a higher boiling temperature, but has a lower heating value. For stoichiometric diesel combustion in-cylinder temperatures decrease due to high latent heat of vaporization, however, at high engine loads temperatures increase due to richer fuel with ethanol fumigation and NO emissions increase. Moreover, due to the high combustion speed of Diesel-ethanol blend fuel, greater air demand is required. So, more NO emission is seen in the exhaust gasses [51–54].

Also, NO emission decreases as the EGR ratio is increased. In the case of recirculated exhaust gases, the peak temperature decreases, since some of the combustion heat is absorbed by the recirculated exhaust gases, causing extra reduction in NO emission. Moreover, decrease in combustion rate causes retarding of the location maximum heat release, and so, the maximum in-cylinder temperature decreases. In this case, further decrease in NO emission occurs. At high speeds, as is known, formation of NO emission reduces due to deterioration in combustion and inadequate advance timing. In this study, engine tests are conducted at two speeds, 1600 and 2400 rpm. Comparing results of experiments done at 1600 rpm and 2400 rpm, less NO is observed at high speed, 2400 rpm, as seen in Fig. 3. Moreover, NO emission decreases as a result of supercharging. In supercharging the same fuel mass flow rate as in standard engine data condition is used. However, intake of air in the engine is more than the required for combustion reactions, so, due to increase in EAR results in absorption of heat by the excessive air. Eventually, in-cylinder temperatures decrease compared to standard condition. Although, the amount of intake air in the cylinder is a factor that influences NO emission, less NO emission is obtained with supercharging, because reaction rates are reduced at low temperatures.

In Fig. 4, in-cylinder pressure measured (a) vs crank angle and in-cylinder temperature calculated vs crank angle are shown for factor levels minimizing NO emissions in comparison with standard engine data. As seen in the figure, considering the experiments done, in-cylinder temperature obtained for optimum factor levels, at 40% load, B0, E0, EGR20, 2400 rpm and SC2.1, is reduced gradually as crank angle increases compared to the standard engine data, at 40% load, B0, E0, EGR0, 2400 rpm and SC1. This situation is an indication of reduction in NO emissions.

In Fig. 5, smoke emissions (opacity) vs factor levels are shown. The optimum smoke emission is obtained for 40% load, B50 biodiesel blend fuel, E0 (without ethanol injection), EGR0 ratio (without EGR), 2400 rpm and SC2.1 supercharging. So, the best combination corresponds to A1-B4-C1-D1-E1-F2 (Load:40%-Biodiesel:50%-Ethanol:0%-EGR:0%-Speed:2400rpm-SC:2.1 bar).

Effects of factor levels on smoke emission can be studied from Fig. 5. Smoke emission increases as load increases. Although, the diesel engines are run with higher EARs, compared to gasoline engines, smoke emissions are formed depending engine operational conditions. Formation of local rich mixture at some regions, owing to inadequate mixture formation of in-cylinder air-fuel charge is the cause of this situation, [20]. Regarding to biodiesel utilization a small reduction in smoke emission is observed, compared to standard engine data condition. By increasing biodiesel fraction, further reductions are obtained. The oxygen content in biodiesel causing formation of a leaner charge mixture can be reasoned for the change. Moreover, ethanol injection causes increase in smoke emissions. Increase in smoke emissions are similar to increase in ethanol fraction. An essential factor in smoke emission formation, not sustained in this case, is the adequate oxygen amounts for the oxidation of carbon and hydrogen atoms at satisfactory temperatures. And also, the lower heating value of ethanol is less than biodiesel blend fuel, and as a consequence of fumigation, the oxygen amount inducted in the cylinder is reduced are both considered to participate in the acceleration of smoke formation mechanism. Smoke emission increases with EGR and as the EGR ratio increases. The optimum EGR is obtained at without EGR application. EGR reduces the oxygen concentration in cylinder, and causes reduction in flame temperature, and as a result smoke emission is increased. Smoke emission is lower at 1600 rpm. As engine speed is increased to 2400 rpm, smoke emission increases, the reason is considered to be the decrease in volumetric efficiency, inadequate time for air and fuel mixture formation and evaporation of fuel. In conclusion, smoke emission formation increases at high speeds. However, smoke formation is reduced with supercharging. Therefore, in diesel engines, the change in excess air ratio due to directing extra air into the cylinder is considered to be the prominent factor for the change in smoke emission. As a result of supercharging, extra air is supplied into the cylinders, including throughout the whole load and speed ranges, and similarly, more fuel can be delivered into the cylinders. In conclusion, combustion efficiency is improved, and thus, the smoke emission is decreased.

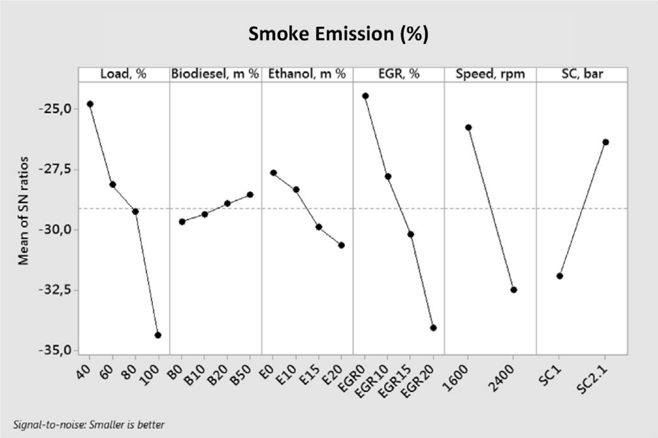
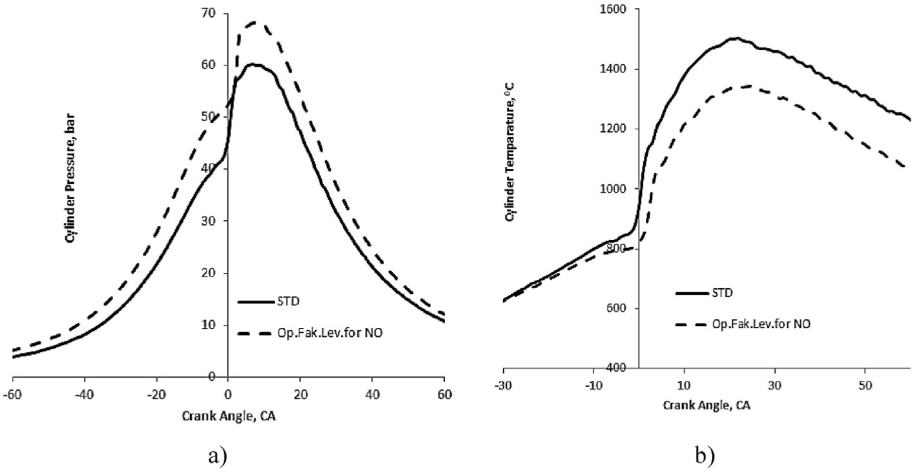


Fig. 5. S/N ratios of factor levels for smoke emission.

In Fig. 6, change in S/N data with factors and levels for HC emission are presented. The optimum HC emission is obtained for 40% load, B50 biodiesel blend fuel, E0 ethanol (without injection), EGR0 ratio (without EGR), 1600 rpm and SC2.1 supercharging. The best combination corresponds to A1-B4-C1-D1-E1-F2 (Load:40%-Biodiesel:50%-Ethanol:0%-EGR:0%-Speed:1600rpm-SC:2.1 bar).

Changes in HC emissions with factor levels can be seen in Fig. 6. The lowest HC emission is obtained at 40% load condition. HC emissions increase as the load is increased. Utilizing biodiesel blend fuels, reduction in HC emission level compared to standard engine data is observed. Since inadequate oxygen concentration is a factor in HC emission formation, with using biodiesel blend fuels increases oxygen concentration and results in improved combustion



a) b)

Fig. 4. In-cylinder pressure (a) and temperature (b) versus crank angle for standard engine data and optimum factor levels.

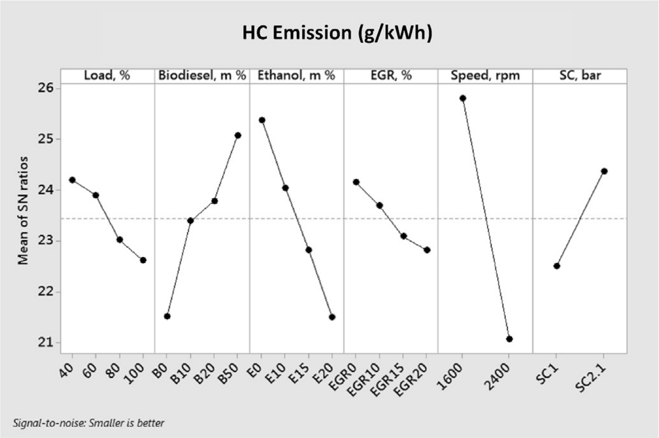


Fig. 6. S/N ratios of factor levels for HC emission.

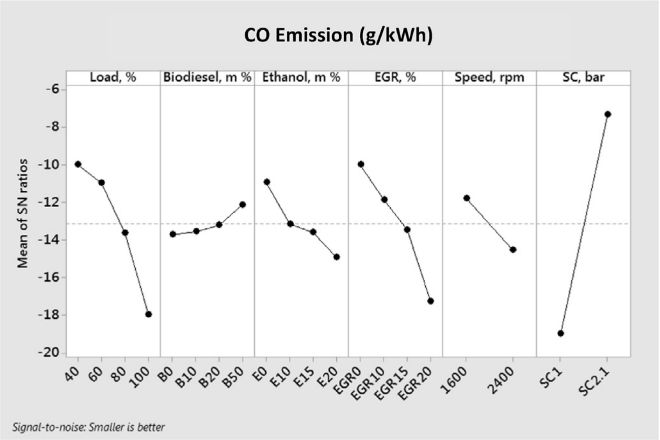


Fig. 7. S/N ratios of factor levels for CO emission.

efficiency, and so, HC emission decreases in return. Moreover, cetane number of biodiesel is greater than diesel fuel, so as considered, the HC emission decreases, compared to standard situation, as the biodiesel fraction in the blend fuel increases.

Furthermore, HC emission increase with ethanol injection. Tutak et al., stated using some alcohol added blend fuels cause slightly higher HC emission. The reasons are the longer ignition delay period of alcohols and also low cetane number of alcohols causing separation in blend fuels. Also, formation of HC emission in low temperature regions, such as cylinder wall, is pointed. Therefore, increase in HC emission with ethanol percentage can be explained by local temperature reductions in the cylinder due to low lower heating value of ethanol. HC emission increases with EGR utilization and further increases occur as the EGR ratio increases. The reason is the deterioration of combustion owing to EGR utilization. Accumulation of unburnt hydrocarbons grows with the deteriorating combustion. The optimum hydrocarbon emission is obtained at 1600 rpm. At 2400 rpm higher HC emission is observed. The optimal HC emission is obtained for supercharging at 2.1 bar. Using supercharging, lower HC emission is obtained compared to standard engine data condition. HC emissions in Diesel engines are known to occur in local lean regions in the fuel spray, developed through evaporation of fuel. Oxidation reactions accelerate with supercharging, owing to the increase in temperature at start of combustion and decrease in actual fuel-air ratio, compared to natural aspirated Diesel engine. Thus, improvement in combustion results in reduction of HC emission.

In Fig. 7, changes by factors and levels effecting CO emission is presented. Optimum CO emission is obtained for 40% load, B50 biodiesel blend fuel, E0 ethanol injection, EGR0 ratio, 1600 rpm and SC2.1 supercharging. The best combination corresponds to A1-B4-C1-D1-E1-F2 (Load:40%-Biodiesel:50%-Ethanol:0%-EGR:0%-Speed:1600rpm-SC:2.1 bar).

Changes in CO emissions with factors and levels are presented in Fig. 7. The lowest CO emission is obtained at 40% load. CO emission increases as engine load is increased. The prominent factor in CO emission formation is the oxygen deficiency in combustion chamber. Oxygen deficiency can be observed over the whole combustion chamber or at only some regions. Resulting increase in CO emissions occurs [17]. CO emission decreases with biodiesel utilization in comparison to standard condition. The maximum reduction observed is close to B50 blend fuel. CO emission is a by-product of incomplete combustion.

Therefore, CO emission is reduced using biodiesel, as considered, which increases oxygen concentration, and causes engine running on a leaner charge. On the other hand, CO emission decreases as ethanol fraction is increased. CO emission formation occur at low in-cylinder temperatures and with low oxygen concentration. As is known, decrease in CO emission is expected as oxygen content in fuel increases. However, CO emission increases with ethanol addition. As reasoned, lower heating value of ethanol is lower than diesel fuel and biodiesel blend fuel that favors CO formation. For conditions without EGR, the lowest CO emissions are obtained, and as EGR ratio is increased CO emission increases. With EGR, recirculated exhaust gases into cylinders reduces oxygen concentration in the charge, and causes worsening of combustion, and consequently, CO emission increases. CO emissions at 1600 rpm is observed to be less than 2400 rpm. CO emission increases as engine speed is increased. Excess air ratio is increased by using supercharging systems in Diesel engines, compared to standard engine data, due to induction of extra air into cylinder. Therefore, lower CO emission is observed with supercharging.

In Fig. 8, changes in CO_2 emissions with factor and levels are presented. The optimum CO_2 emission is obtained at 40% load, B0 biodiesel fraction (only diesel), E0 ethanol fraction (without ethanol injection), EGR0 (without EGR), at 1600 rpm and SC2.1 (supercharging at 2.1 bar). The best combination corresponds to A1-B1-C1-D1-E1-F2 (Load:40%-Biodiesel:0%-Ethanol:0%-EGR:0%-Speed:1600rpm-SC:2.1 bar).

Studying Fig. 8, CO_2 emission changes with load, biodiesel fraction, ethanol fraction, EGR ratio, engine speed and

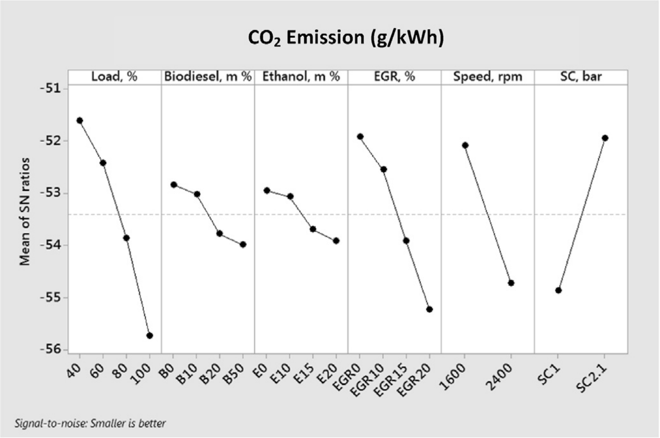


Fig. 8. S/N ratios of factor levels for CO_2 emission.

Table 6
Variational analysis results for BSHC.

	Factors	Degree of Freedom	Sum of Squares, *SS*	Average of squares, V	^{F}theory
BSHC	A – Load [%]	3	29,6353	9,8784	139,25
	B – Biodiesel [%]	3	0,567	0189	2,66
	C – Ethanol [%]	3	2,4072	0,8024	11,31
	D – EGR [%]	3	6,8259	2,2753	32,07
	E – Speed [rpm]	1	20,4059	20,4059	287,64*
	F –Supercharging [bar]	1	2,4479	2,4479	34,51
	Error	1	0,0709	0,0709	
	Total	15	62,3602		

Confidence interval of *95%, **99%, ***99.99%.

supercharging as seen. CO$_2$ emission measured in exhaust increases as load is increased. Similarly, CO$_2$ emission increases as biodiesel fraction, ethanol fraction or EGR ratio increases. CO$_2$ emission observed at 2400 rpm is higher than 1600 rpm. With supercharging improvement in CO$_2$ emission is obtained.

3.3. *Analysis of variation*

In Table 6, effects of factors on BSHC from variational analysis results are presented. While, engine speed has an influence of 95% confidence interval upon BSHC, load, biodiesel fraction, ethanol fraction, EGR ratio and supercharging have slight, but sensible, influences.

In Table 7, variational analysis results for the changes in NO, smoke, HC, CO and CO$_2$ emissions with factors are presented.

Apparently, EGR and engine speed have more influence on NO emission than the rest of the factors. Nevertheless, influences of the remaining factors are sensible. Also, engine speed and supercharging have more influence on smoke emission than the rest of the factors. Load and EGR have more influence on smoke emission, compared to biodiesel and ethanol addition. However, influences of the remaining factors are sensible. Influence of engine speed on HC emission is more than the rest of the factors. Biodiesel, ethanol and supercharging have more influence on HC emission, compared to load and EGR. However, influence of load and EGR are also sensible. Supercharging has more influence on CO emission than the rest,

Table 7
Variational analysis results for emission characteristics.

	Factors	Degree of Freedom	Sum of Squares, *SS*	Average of squares, V	^{F}theory
NO	A – Load [%]	3	5711	1904	0,18
	B – Biodiesel [%]	3	14,784	4928	0,46
	C – Ethanol [%]	3	5763	1921	0,18
	D – EGR [%]	3	98,224	32,741	3,07
	E – Speed [rpm]	1	28,924	28,924	2,71
	F –Supercharging [bar]	1	2957	2957	0,28
	Error	1	10,661	10,661	
	Total	15	167,025		
Smoke	A – Load [%]	3	189,31	63,103	1,85
	B – Biodiesel [%]	3	2825	0,942	0,03
	C – Ethanol [%]	3	22,783	7594	0,22
	D – EGR [%]	3	197,225	65,742	1,92
	E – Speed [rpm]	1	181,836	181,836	5,32
	F –Supercharging [bar]	1	123,691	123,691	3,62
	Error	1	34,196	34,196	
	Total	15	751,867		
HC	A – Load [%]	3	6544	2181	0,93
	B – Biodiesel [%]	3	25,904	8635	3,66
	C – Ethanol [%]	3	33,064	11,021	4,68
	D – EGR [%]	3	4312	1437	0,61
	E – Speed [rpm]	1	90,124	90,124	38,23
	F –Supercharging [bar]	1	13,979	13,979	5,93
	Error	1	2357	2357	
	Total	15	176,284		
CO	A – Load [%]	3	153,013	51,004	13,11
	B – Biodiesel [%]	3	6,12	2,04	0,52
	C – Ethanol [%]	3	33,095	11,032	2,84
	D – EGR [%]	3	115,007	38,336	9,86
	E – Speed [rpm]	1	30,514	30,514	7,85
	F –Supercharging [bar]	1	545,822	545,822	140,34
	Error	1	3889	3889	
	Total	15	887,46		
CO$_2$	A – Load [%]	3	39,299	13,0996	11,24
	B – Biodiesel [%]	3	3812	1,2706	1,09
	C – Ethanol [%]	3	2713	0,9044	0,78
	D – EGR [%]	3	26,182	8,7273	7,49
	E – Speed [rpm]	1	27,956	27,9564	23,98
	F –Supercharging [bar]	1	34,247	34,2474	29,37
	Error	1	1166	1,1659	
	Total	15	135,376		

*%95, **%99, ***%99.99 confidence interval.

but also influence of biodiesel and ethanol fractions are sensible. Engine speed and supercharging have more influence on CO_2 emissions than the rest of the factors. Load and EGR have more influence on CO_2 emission compared to biodiesel and ethanol fractions, although the effect of biodiesel and ethanol fractions are sensible.

3.4. *Tests for validation*

The optimum NO emission is obtained for 40%-B0-E0-EGR0-2400-SC2.1 combination. The given combination is not present among the orthogonal series experiment steps. NO emission corresponding to the given combination is obtained 0.294 g/kWh as a result of experiments done for verification. Mean NO emission obtained for standard engine, corresponding to 40%-B0-E0-EGR0-2400-SC1, is 1.93 g/kWh Comparing standard engine data and Taguchi optimized results, 84.8% improvement is obtained for Taguchi optimization.

4. Conclusion

In this study, using Taguchi design of experiments method, changes in engine parameters, specific fuel consumption and emission characteristics at various biodiesel fractions, ethanol fractions, EGR ratios and charging pressure, are investigated for a Diesel engine running at various loads and speeds. In conclusion, as determined, engine load and engine speed at various biodiesel, ethanol, EGR and supercharging levels have influence on SFC and emission characteristics. Overall results are listed in the following.

- Using Taguchi design of experiments method is considered to be effective in evaluating the optimum BSHC and emission characteristics.
- The optimum SFC results are obtained for 80% load, B10 biodiesel blend fuel, E20 ethanol, EGR0 (without EGR), 1600 rpm and SC2.1 (supercharging at 2.1 bar). In comparison to standard engine data for running under the same speed and load condition, 10% reduction in BSHC is obtained for operation under the optimum factor levels.
- The optimum NO emission results are obtained for 40% load, with diesel fuel (B0), without ethanol (E0), at 20% EGR rate (EGR20), at 2400 rpm engine speed and at 2.1 bar supercharging pressure (SC2.1 bar). Using factor levels for the optimum NO condition reduction by 84.8% is obtained compared to experiment conditions.
- As observed, in-cylinder pressures increase using combination of factors and levels optimizing NO emission results compared to standard data. And, in cylinder temperatures decrease compared to standard data for pressures measured with optimum factors.
- The optimum smoke, HC and CO emissions are obtained for 40% load, B50 biodiesel blend fuel, E0 (without ethanol injection), EGR0 (without EGR), 1600 rpm and SC2.1 (supercharging at 2.1 bar). Running engine with the optimum factor levels at determined and 1600 rpm and 40% load, causes reductions in smoke, HC and CO emissions at about 85%, 40% and 75%, respectively, in comparison to standard engine data condition.
- The optimum CO2 emission is obtained for 40% load, B0 biodiesel blend fuel (diesel fuel only), E0 (without ethanol), EGR0 (without EGR), 1600 rpm and SC2.1 (supercharging at 2.1 bar). Compared to standard engine data condition, 33% reduction in CO2 emission is obtained with running engine at the condition on optimum factor levels.
- In this study, considerable savings in time and cost for experiments are obtained using Taguchi statistical experimental design method. In the case of full factorial experimental layout, to obtain optimum levels of factors measurements from 1024 points are required for a single run. Using Taguchi fractional factorial experimental design method, results with high accuracy is obtained with only measurements from 16 points. Factors levels are optimized for the parameters, and the results are consistent with the full factorial experiment results. As a conclusion, Taguchi method is approved to be an effective and a pretty functional method for studying the effects of factors with various levels, such as engine emission characteristics under various conditions.

Credit author statement

We would like to inform you that all authors have contributed to the preparation of the manuscript. The study was prepared with the contribution of all authors, both in the conduct of experimental studies and in the writing of the manuscript, literature research, drawing and interpretation of the figures, writing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

aTDC	After top dead center, CA
B10	Biodiesel fraction 10% mass
bTDC	Before top dead center, CA
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct injection
E10	Ethanol fraction 10% mass
EAR	Excess Air Ratio
EGR	Exhaust Gas Recirculation
EGR10	Exhaust gas recirculation fraction 10%
HC	Hydrocarbon
LPG	Liquefied Petroleum Gas
NO	Nitrogen oxide
S/N	Signal to Noise ratio
SC0	Charging pressure atmospheric
SC2.1	Supercharging absolute pressure 2.1 bar
BSHC	Brake specific heat consumption, J/kWh

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