



Optimization of Parameters Affecting the Performance and Emissions of a Spark Ignition Engine Fueled with n-Pentanol/Gasoline Blends Using Taguchi Method

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Abstract

As operating factors play an important role in engine emissions and performance, it is important to explore the simultaneous impact of various operating factors on engine performance and emission responses. Taguchi method was used in order to determine the suitability of using n-pentanol in spark ignition engine and to determine the optimum operating conditions with fewer experiments instead of many experiments. Engine load, n-pentanol percentage and ignition advance were selected as engine operating variables. Three different levels were determined for each of the selected engine variables and an experimental design was created using the Taguchi method. Taguchi method proposed $L_{27} (3^3)$ orthogonal array experimental design for three different variables with three different levels. According to the graphs of signal-to-noise ratio obtained with Taguchi design, simultaneous optimum results of all responses were generally determined as high n-pentanol percentage, average ignition advance and average load. According to results, Taguchi design method is an effective method with the aim of defining the impact rates of engine operating parameters and to optimize engine operating variables for best engine performance and emissions.

Keywords Taguchi · N-pentanol · Ignition advance · Gasoline · Spark ignition engine

Abbreviations

Adj- R^2	Adjusted R^2 value
ANOVA	Analysis of variance
BSFC	Brake specific fuel consumption
bTDC	Before top dead center
<i>BTHE</i>	Brake thermal efficiency
CO	Carbon monoxide
CO ₂	Carbon dioxide
DOE	Design of experiment
<i>F</i> -value	Value of <i>F</i> -test
HC	Hydrocarbon
NO _x	Nitrogen oxides
<i>P</i> -value	Probability value

Pred- R^2	Predicted R^2 value
R^2	Correlation coefficient
S/N	Signal to noise
SS	Sum of squares
OA	Orthogonal array
O ₂	Oxygen

1 Introduction

Air pollution is increasing rapidly due to the increasing number of vehicles with the unavoidable population growth worldwide [1–5]. In addition, due to the epidemic that the whole world has faced, especially in recent months, people prefer to use individual vehicles instead of public transportation. In parallel with the increasing number of vehicles, energy consumption is also increasing rapidly [6–10]. For this reason, it has become necessary to use cleaner, renewable fuel to reduce the air pollution caused by internal combustion engine vehicles and to meet the increasing energy demand [11, 12]. Many different alternative fuels have been used in internal combustion engines for years. In spark ignition engines, the use of alcohols as alternative fuel is in

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a wide range [13–15]. While low carbon alcohols such as ethanol and methanol were used in the beginning, today high carbon alcohols are mostly preferred. High carbon alcohols have some advantages over low carbon alcohols, such as better ignition quality, high energy density and the ability to mix easily with conventional fuels [16–18]. The use of n-pentanol, which is one of the high carbon alcohols group, as an alternative fuel has become very interesting by researchers in recent years [19–21].

In the search for alternative fuel, it is also extremely important to determine the suitability of a fuel for use in internal combustion engines and to determine the optimum operating conditions. Before the development of computer technologies, numerous tests might be needed to determine the suitability of alternative fuels [22]. In particular, it is not efficient to test alternative fuels that are very difficult to obtain or can only be obtained in small quantities. For these reasons, with the developing computer technologies, optimization techniques that can simulate a large number of experiments with less experimentation have started to be used [23–25]. Thanks to these techniques, it can be determined with high accuracy whether a fuel can be an alternative to internal combustion engines in less time and with less cost. Taguchi is one of these optimization techniques. Taguchi design, one of the design of experiments-based techniques, is an optimization method that reveals which of the selected input variables is more effective and has the ability to determine the optimum levels of all variables [26, 27].

In the literature, Taguchi has been successfully used to get optimum variables to operate the engine and found convenient for the reduction in time for the process. Ansari et al. [28] used Taguchi design method to examine the effects of selected engine variables on diesel engine performance and exhaust emission responses which is operating with biodiesel fuel blends. In order to determine optimum engine performance and emissions, they determined the biodiesel ratio, injection timing and injection pressure as engine variables. Optimum conditions determined as 30% biodiesel

ratio, 15° bTDC injection timing and 200 bar injection pressure. Rai and Sahoo [29] made the designs of their experiments using the Taguchi method in their study, in which they selected compression ratio, engine load and mixing ratio as engine operating parameters. According to their results, they achieved optimum working conditions as 17 compression ratio, 10 kg engine load and 30% biodiesel ratio. Uslu [30] carried out an optimization study using the Taguchi design method in a diesel engine where diethyl ether ratio, palm oil ratio, injection advance and engine load were selected as engine variables. Generally, it achieved optimum performance responses at low levels of diethyl ether, palm oil and spray advance, and high levels of engine load. Optimum emission responses were achieved at low levels of diethyl ether and engine load, and high levels of palm oil ratio and injection advance.

Although there are many studies on the use of n-pentanol in diesel engines, there are limited studies on its use in gasoline engines. In addition, attention has not yet been paid to determine the optimum operating conditions of a spark ignition engine using n-pentanol/gasoline mixtures by optimization techniques. In this study, it is aimed to determine the optimum engine conditions in which the best emission and performance values can be obtained in a gasoline engine using n-pentanol/gasoline fuel blends using Taguchi method.

2 Materials and Methods

In this study, the experiments were designed with Taguchi method in order to determine the most suitable usage conditions of n-pentanol in gasoline engines. The parameters affecting engine performance and emissions were selected as n-pentanol percentage, ignition advance and engine load. It was found appropriate to use three different levels for the selected parameters, and accordingly, experimental design was carried out with Taguchi method.

The accuracy of the device and the uncertainty analysis of the measured values are essential to ensure the measurement accuracy. In addition, uncertainty analysis is needed as standard conditions in the test environment can be affected by various factors such as environmental factors. The measured values of the uncertainty of the different variables are shown in Table 1. The overall uncertainty was calculated as follows:

Table 1 Uncertainties of various factors

Measurement items	Percentage uncertainty
Load measurement	± 1.3
Injection advance	± 1.86
BTHE	± 0.74
BSFC	± 1.45
CO	± 0.52
CO ₂	± 1.5
O ₂	± 2.14
NO _x	± 1.23
HC	± 1.0

Table 2 Parameters and levels affecting engine performance and emissions

Variables	Levels		
n-pentanol percentage (vol.%)	0	10	20
Engine load (kW)	2.27	3.78	5.30
Ignition advance (°bTDC)	10	14	18



$$\begin{aligned}
 \text{Overall uncertainty} &= \text{squareroot of} \left[(\text{uncertain of load})^2 + (\text{uncertain of injection advance})^2 + (\text{uncertain of BTHE})^2 \right. \\
 &\quad + (\text{uncertain of BSFC})^2 + (\text{uncertain of CO})^2 + (\text{uncertain of CO}_2)^2 \\
 &\quad \left. + (\text{uncertain of O}_2)^2 + (\text{uncertain of NO}_x)^2 + (\text{uncertain of HC})^2 \right] \\
 &= \text{squareroot of} \left[(1.3)^2 + (1.86)^2 + (0.74)^2 + (1.45)^2 + (0.52)^2 + (1.5)^2 + (2.14)^2 + (1.23)^2 + (1.0)^2 \right] \\
 &= \pm 4.173\%
 \end{aligned}$$

Taguchi is a design method used to determine the optimized parameter combinations with a minimum number of experiments, reduce experimental errors and process variety, and determine experimental conditions with orthogonal arrays in order to ensure reproducibility of experiments. In Taguchi method, it is accepted that there are two basic tools for design of experiments (DOE): Orthogonal array (OA) and signal-to-noise (S/N) ratio. OA is a type of generic fractional factorial design that takes into account a selected combination of multiple levels, multiple factors to save time and cost for experimentation. The S/N ratio in Taguchi designs is a robustness measure used to describe control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). The S/N ratio measures how the response varies with the nominal or target value under different noise conditions. Higher values of the S/N ratio define control factor settings that minimize the effects of noise factors.

Different S/N ratios can be used, such as "smaller is better", "larger is better" and "nominal is best" depending on the purpose of the experiment. In the Taguchi design in this study, "larger is better" is used for brake thermal efficiency (BTHE), while "smaller is better" types are selected for brake specific fuel consumption (BSFC) and all emissions. S/N ratios are given as follows with Eq. (1) and (2), respectively.

Larger is better;

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

Smaller is better;

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

where n is the number of experiments, i is the number of design factors and y_i is the response factor.

In this study, n-pentanol percentage, engine load and ignition advance were chosen as variables affecting BTHE, BSFC, carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbon (HC), oxygen (O₂) and nitrogen oxides (NO_x) emissions. To examine the effect of each variables on the responses, it is scheduled to test the engine with the three

levels shown in Table 2, among the selected factors. Three different levels of selected input variables were determined as 0%, 10% and 20% for n-pentanol percentage, 2.27, 3.78 and 5.30 kW for engine load and finally 10, 14 and 18° bTDC for ignition advance.

The appropriate DOE put forward by Taguchi depending on the three different variables selected as parameters affecting engine performance and emissions and three different levels of these three variables was determined as L₂₇ (3 ^ 3) OA. The DOE created according to the determined L₂₇ OA is shown in Table 3.

Experimental fuels were prepared according to the experimental design determined by Taguchi and experiments were carried out at the specified engine load and ignition advance values. Using the experimental results obtained, a design model was created with Taguchi. S/N ratios from the created model were determined separately for each performance and emission response. In addition, analysis of variance (ANOVA) was applied to determine the proportional effects of the selected variables. ANOVA is a statistically decision-making tool to detect differences in the average performance and helps testing the significance of all main factors [31, 32]. ANOVA evaluates the significance of one or more variables by comparing the response factor tools at various factor levels. ANOVA is also called a linear statistical analysis as the response is a linear function of the factors involved in the experiment [33, 34].

In addition, R^2 , adjusted R^2 (Adj- R^2) and predicted R^2 (Pred- R^2) values, which are important indicators to evaluate the performance of the model created, were calculated with the following equations.

$$R^2 = 1 - \left[\frac{SS_{\text{residual}}}{SS_{\text{residual}} + SS_{\text{model}}} \right] \tag{3}$$

$$\text{Adj.}R^2 = 1 - \left[\left(\frac{SS_{\text{residual}}}{df_{\text{residual}}} \right) / \left(\frac{SS_{\text{residual}} + SS_{\text{model}}}{df_{\text{residual}} + df_{\text{model}}} \right) \right] \tag{4}$$

$$\text{Pred.}R^2 = 1 - \left[\frac{\sum_{i=1}^n (e - 1)^2}{SS_{\text{residual}} + SS_{\text{model}}} \right] \tag{5}$$

Table 3 Experimental layout by Taguchi L_{27} OA design

Trial	n-Pentanol percentage (%)	Engine load (kW)	Ignition advance ($^{\circ}$ bTDC)	BTHE (%)	BSFC (kg/kWh)	CO (%)	CO ₂ (%)	HC (ppm)	O ₂ (%)	NO _x (ppm)
1	0	2.27	10	23.79	0.33	0.77	14.76	155.36	1.18	637.55
2	0	3.78	10	27.42	0.3	0.44	15.01	153.27	1.16	1033.18
3	0	5.30	10	33.7	0.24	0.36	15.22	135.00	1.03	1310.70
4	0	2.27	14	23.94	0.34	0.64	15.01	185.80	1.05	772.20
5	0	3.78	14	33.29	0.24	0.39	15.11	140.11	1.10	1148.22
6	0	5.30	14	34.78	0.23	0.38	15.15	126.60	1.05	1323.20
7	0	2.27	18	25.09	0.32	0.67	15.09	215.57	0.84	695.86
8	0	3.78	18	33.35	0.24	0.44	15.28	166.67	0.81	1088.33
9	0	5.30	18	35.15	0.22	0.37	15.40	182.60	0.79	1441.20
10	10	2.27	10	23.1	0.35	0.69	15.16	155.67	0.83	670.56
11	10	3.78	10	30.81	0.26	0.41	15.40	145.82	0.80	946.00
12	10	5.30	10	33.03	0.24	0.35	15.54	135.00	0.68	1232.18
13	10	2.27	14	25.92	0.33	0.97	15.00	190.56	0.98	672.33
14	10	3.78	14	30.1	0.3	0.46	15.37	168.78	0.87	996.78
15	10	5.30	14	33.14	0.25	0.32	15.49	218.50	0.61	1293.38
16	10	2.27	18	27.75	0.31	0.59	15.21	191.22	0.87	663.44
17	10	3.78	18	31.71	0.26	0.49	15.21	193.44	0.80	1108.33
18	10	5.30	18	33.34	0.24	0.41	15.40	152.67	0.65	1331.11
19	20	2.27	10	26.36	0.24	0.32	15.48	239.89	0.65	1307.89
20	20	3.78	10	30.8	0.26	0.38	15.33	153.00	0.80	1036.50
21	20	5.30	10	34.18	0.32	0.57	14.87	155.33	1.25	640.56
22	20	2.27	14	24.78	0.23	0.34	15.17	143.67	1.08	1336.22
23	20	3.78	14	33.19	0.26	0.41	15.11	146.11	0.98	1177.11
24	20	5.30	14	34.58	34	0.58	14.81	157.11	1.22	730.67
25	20	2.27	18	27.56	0.21	0.37	15.22	197.73	0.91	1455.36
26	20	3.78	18	32.11	0.27	0.43	15.06	157.50	1.07	1197.70
27	20	5.30	18	40.38	0.31	0.59	15.00	192.64	1.03	749.09

$$e - 1 = \frac{e_i}{1 - h_{ii}} \quad (6)$$

where *residuals* indicate the quantity of variety not described in the response, *model* indicates how much variety is described in the model with the general model test for significance, *sum of squares* (SS) is changes between the overall average and the amount of variety described by the source. e_i is residual for each observation left from the model, $e - 1$ is a deletion residue that tries to guess i th observation with a model without the i th study and with the resulting model, h_{ii} is the force of the run in the model.

3 Results and Discussion

In present study, ANOVA was employed to identify the influence ratios of selected engine variables on engine emission and performance responses. The ANOVA results for

BTHE, BSFC, CO, CO₂, HC, O₂ and NO_x are shown in Table 4. S/N ratio graphs showing graphical representation of variation response characteristics related to various control parameter levels are also given below for performance and emission responses.

In accordance with Taguchi method, the S/N ratio is the measure of the impact of noise fraction on performance. Both average and variation in S/N ratio have been considered, and a larger S/N ratio indicates better performance of the system.

3.1 Effect of Process Variables on Performance

S/N ratio graphs for BTHE and BSFC, which are considered as performance responses, are shown in Figs. 1 and 3, respectively. When S/N ratio graphs are examined, it is seen that the optimum engine variable levels for BTHE are 20% n-pentanol percentage, 5.30 kW engine load and 18 $^{\circ}$ bTDC ignition advance. On the other hand, optimum values

Table 4 ANOVA for all engine responses

Factors	DF	SS	F-value	p-value	Percentage contribution (%)
<i>BTHE</i>					
A-pentanol percentage	2	55.15	13.24	0.041	10.91%
B-engine load	2	253.47	86.15	0.000	50.14%
C-ignition advance	2	150.12	46.43	0.007	29.69%
Error	20	46.83			9.26%
Total	26	505.57			100.00%
<i>BSFC</i>					
A-pentanol percentage	2	423.93	163.52	0.000	38.70%
B-engine load	2	192.80	73.34	0.000	17.60%
C-ignition advance	2	401.15	144.18	0.000	36.62%
Error	20	77.56			7.08%
Total	26	1095.43			100.00%
<i>CO</i>					
A-pentanol percentage	2	1.12035	45.6	0.000	22.07%
B-engine load	2	0.7286	31.88	0.000	14.35%
C-ignition advance	2	2.92304	112.45	0.000	57.58%
Error	20	0.30409			5.99%
Total	26	5.07608			100.00%
<i>CO₂</i>					
A-pentanol percentage	2	7.4711	134.34	0.000	50.45%
B-engine load	2	3.3932	61.02	0.000	22.91%
C-ignition advance	2	3.6408	65.47	0.000	24.58%
Error	20	0.30409			2.05%
Total	26	14.80919			100.00%
<i>HC</i>					
A-pentanol percentage	2	4157	303.368	0.000	19.52%
B-engine load	2	3014.9	206.748	0.000	14.16%
C-ignition advance	2	13,568.5	736.38	0.000	63.71%
Error	20	556.4			2.61%
Total	26	21,296.8			100.00%
<i>O₂</i>					
A-pentanol percentage	2	0.511963	9.2432	0.000	59.61%
B-engine load	2	0.065096	1.49	0.25	7.58%
C-ignition advance	2	0.270252	5.28	0.000	31.47%
Error	20	0.011474			1.34%
Total	26	0.858785			100.00%
<i>NO_x</i>					
A-pentanol percentage	2	380,902	86.8	0.000	18.94%

Table 4 (continued)

Factors	DF	SS	F-value	p-value	Percentage contribution (%)
B-engine load	2	1,115,982	195.75	0.000	55.50%
C-ignition advance	2	398,873	94.71	0.000	19.84%
Error	20	114,930			5.72%
Total	26	2,010,687			100.00%

for BSFC were found 0% n-pentanol ratio, 3.78 kW load and 18 °bTDC ignition advance. While the maximum level of n-pentanol percentage is optimum for BTHE, the minimum percentage of n-pentanol is optimum for BSFC. Increasing the BSFC due to the smaller lower calorific value of n-pentanol compared to gasoline caused the percentage of 0% to be optimum. On the other hand, 20% n-pentanol percentage has emerged as optimum for BTHE, as it improves combustion thanks to the oxygen content it contains will increase BTHE. The increase in the ignition advance had a positive effect for both performance variables. BTHE increased and BSFC decreased as the maximum pressure approached closer to the upper dead point with increasing ignition advance. Also, getting more air/fuel mixture into the engine with increased engine load will increase not only BTHE but also BSFC. Thus, the lowest level of engine load is optimum for the BSFC, while the highest level for BTHE is optimum.

In addition to the optimum variable levels, the representation of the degree of influence of the variables is given in Figs. 2 and 4 for BTHE and BSFC, respectively. Engine load was the most effective variable for BTHE with a ratio of 50.14%, while the percentage of n-pentanol was for BSFC with 38.7% according to the distribution of effect degrees (Figs. 1, 2, 3, 4).

3.2 Effect of Process Variables on Exhaust Emissions

S/N ratio graphs for CO, CO₂, HC, O₂ and NO_x evaluated as emission responses are shown in Figs. 5, 7, 9, 11 and 13, respectively. Optimum n-pentanol percentage was obtained as 20% for CO, HC and O₂, 10% for NO_x and 0% for CO₂. As the ratio of n-pentanol, which contains oxygen, in the mixture increases, the rate of complete combustion increases, so an increase in O₂, a decrease in CO and HC is expected. S/N ratio graphs also gave results that support this expectation. As the complete combustion rate increases, the conversion ratio of carbon atoms to CO₂ increases, so the lowest n-pentanol level has been optimum for CO₂. The optimum n-pentanol level of NO_x was found to be 10% since the amount of oxygen in the mixture higher than the optimum

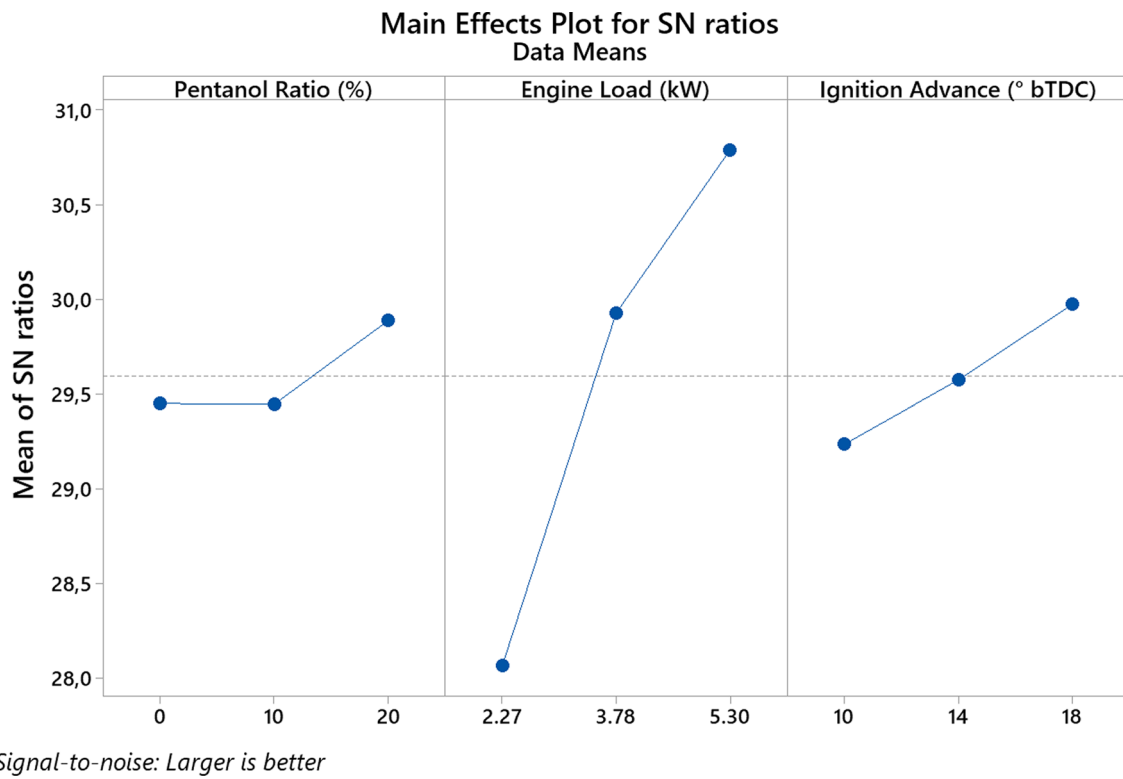
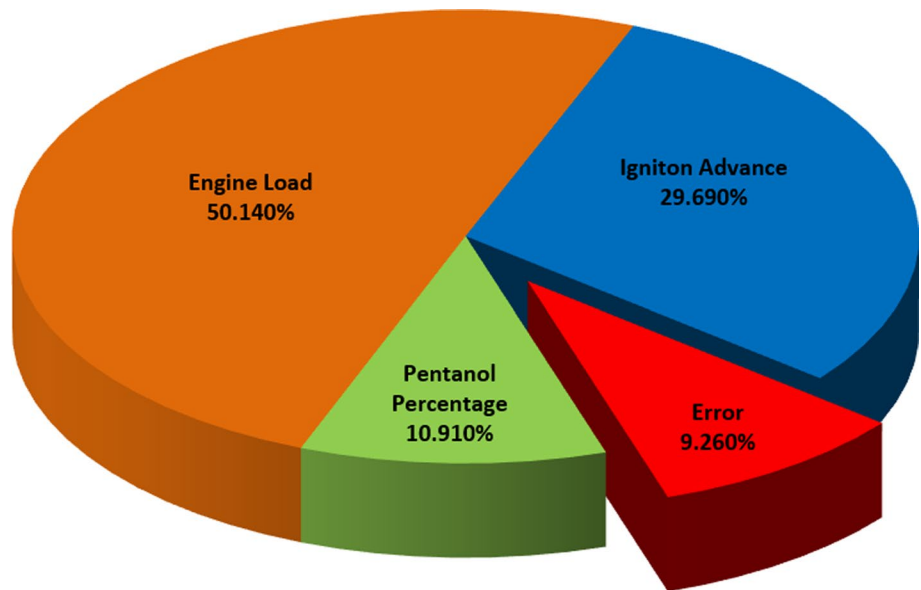


Fig. 1 S/N values of variables for BTHE

Fig. 2 The impact rates of variables and error on BTHE



level with a n-pentanol ratio of more than 10% will cause the NO_x to increase again.

Optimum engine load levels were found to be 5.30 kW, which is the maximum engine load level for CO, HC and O₂, while the minimum level for CO₂ and NO_x was 2.27 kW.

When examined in terms of ignition advance, optimum results were obtained as 14 ° bTDC for CO and HC, 10 ° bTDC as the lowest level for CO₂ and NO_x and 18 ° bTDC as the highest level for O₂. As the ignition advance increases, the temperature inside the cylinder will increase

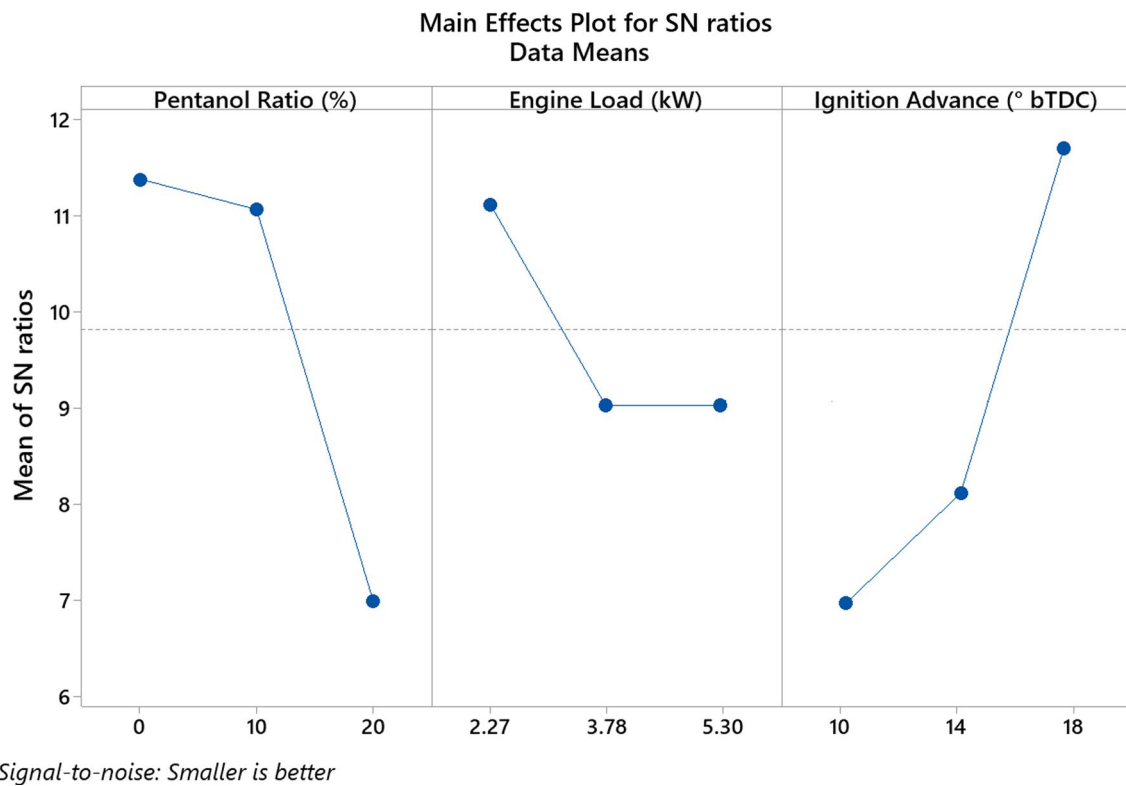
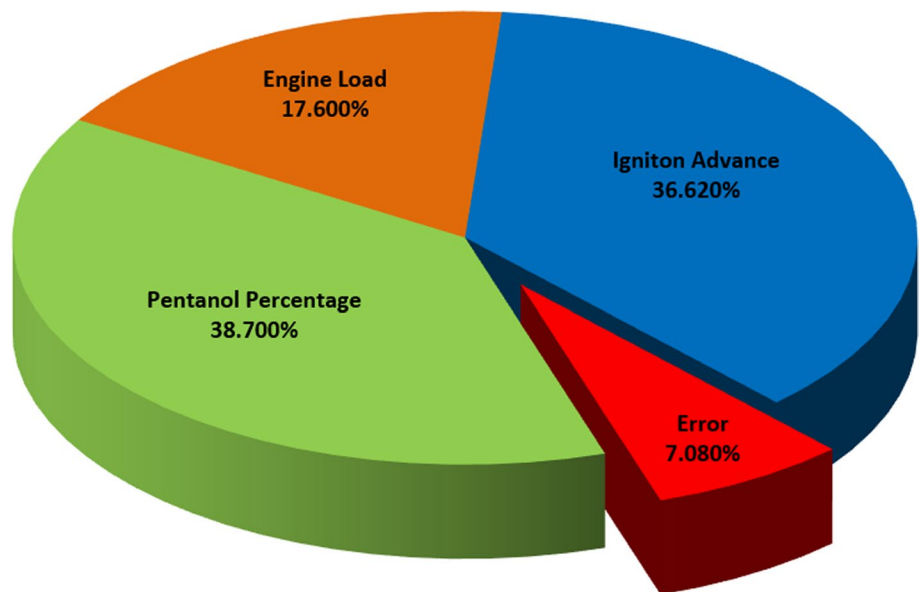


Fig. 3 S/N values of variables for BSFC

Fig. 4 The impact rates of variables and error on BSFC



as higher-pressure levels will be reached. Therefore, low ignition advance for NO_x , which is a function of temperature, will be the optimum level. On the other hand, if the

ignition is delayed too much, the average ignition advance level was obtained optimally for CO and HC, as the risk of incomplete combustion at the end of the expansion stroke

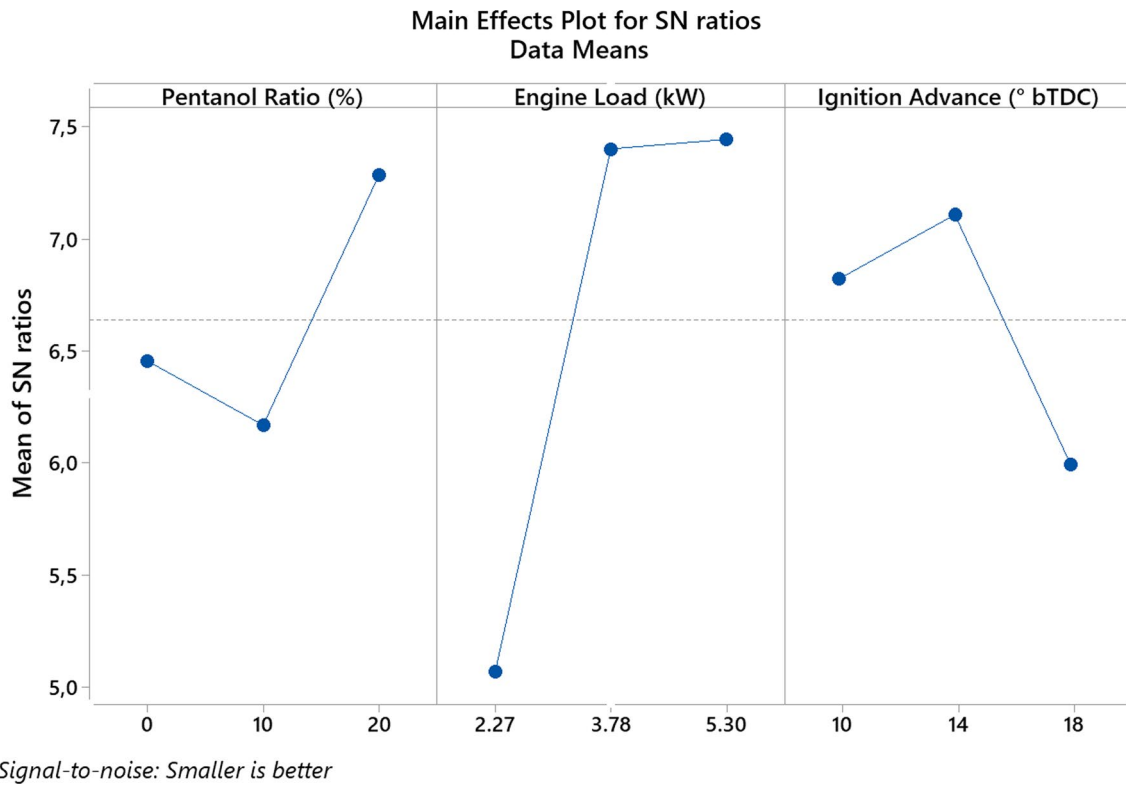
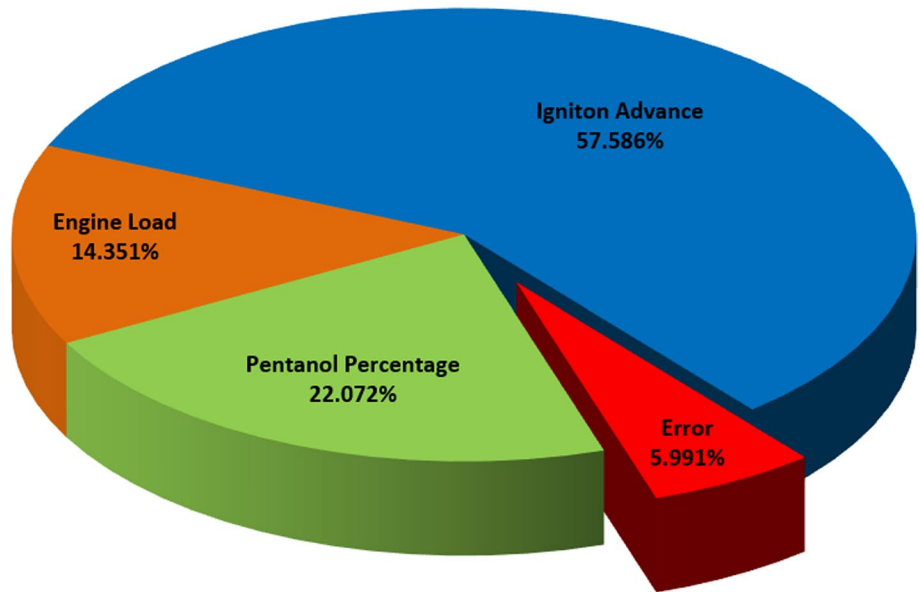


Fig. 5 S/N values of variables for CO emissions

Fig. 6 The impact rates of variables and error on CO emission



would increase. Also, although the possibility of incomplete combustion began to emerge at the maximum ignition advance level, the best results for O₂ emission were obtained at the maximum ignition advance level, thanks to the oxygen content of n-pentanol.

Figures 6, 8, 10, 12 and 14 show which engine variables are more effective for CO, CO₂, HC, O₂ and NO_x, respectively. While the ignition advance was the most effective for CO and HC, the n-pentanol percentage was found to be the most effective variable for CO₂ and CO₂. For NO_x, the

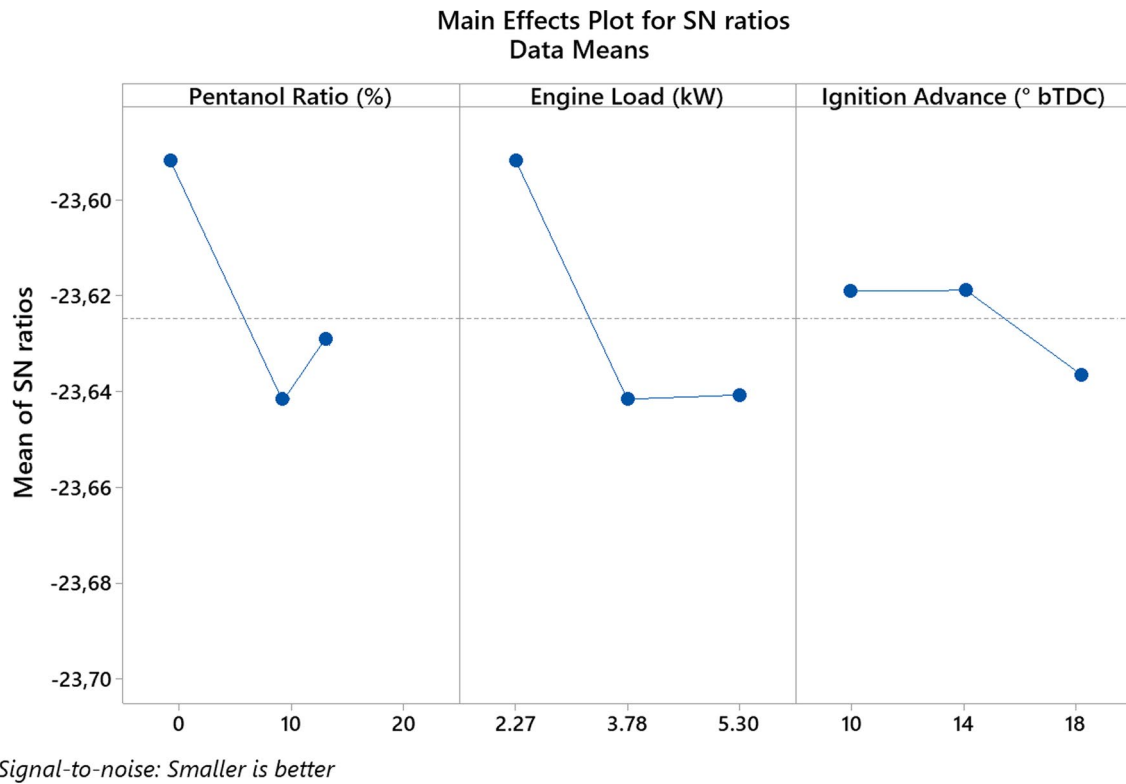
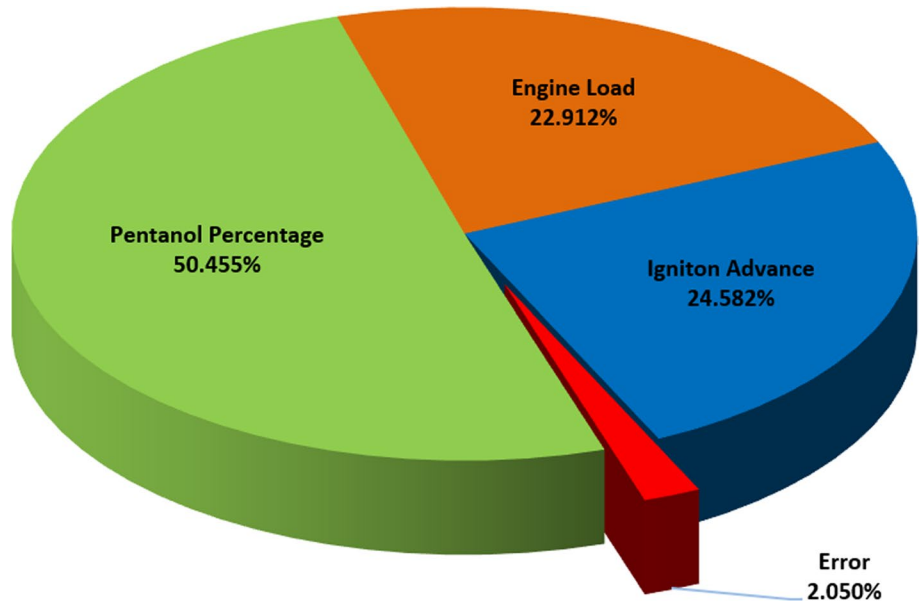


Fig. 7 S/N values of variables for CO₂ emissions

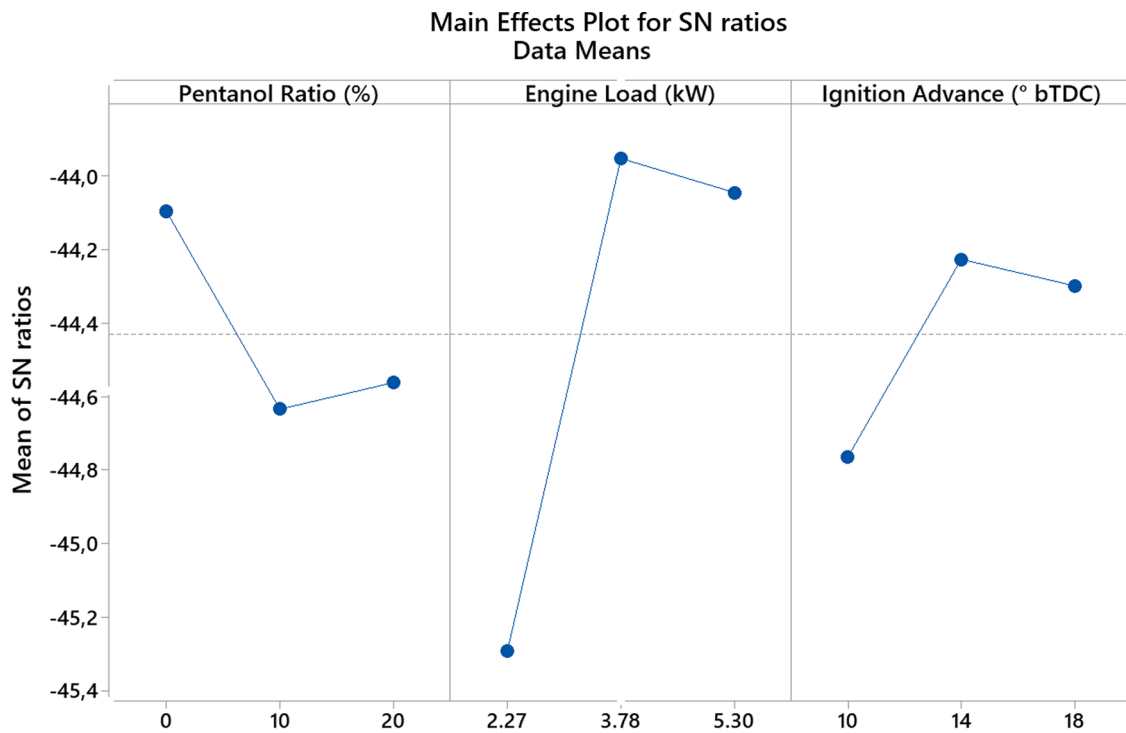
Fig. 8 The impact rates of variables and error on CO₂ emission



engine load was determined to be the most effective variable (Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14).

4 Conclusions

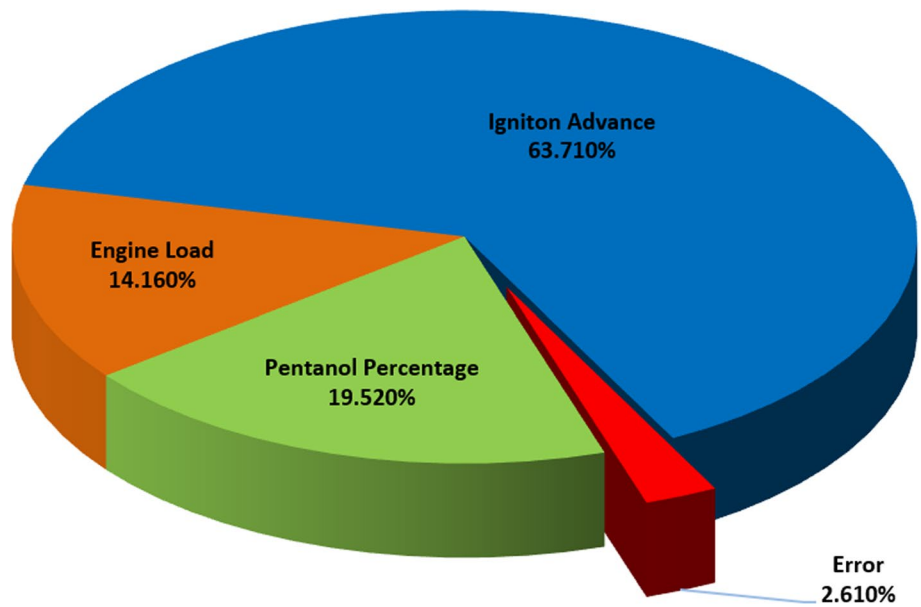
In this study, it is aimed to optimize engine operating parameters and determine the effect degree of parameters in order



Signal-to-noise: Smaller is better

Fig. 9 S/N values of variables for HC emissions

Fig. 10 The impact rates of variables and error on HC emission



to obtain optimum performance and emissions in spark ignition engine using n-pentanol/gasoline fuel mixtures. The results obtained are listed below:

- For the n-pentanol percentage, the optimum level was obtained as 20% for BTHE and 0% for BSFC, which are considered as performance responses. In terms of emissions, it was found to be the highest level of 20% for CO, HC and O₂, 0% for CO₂ and 10% for NO_x.

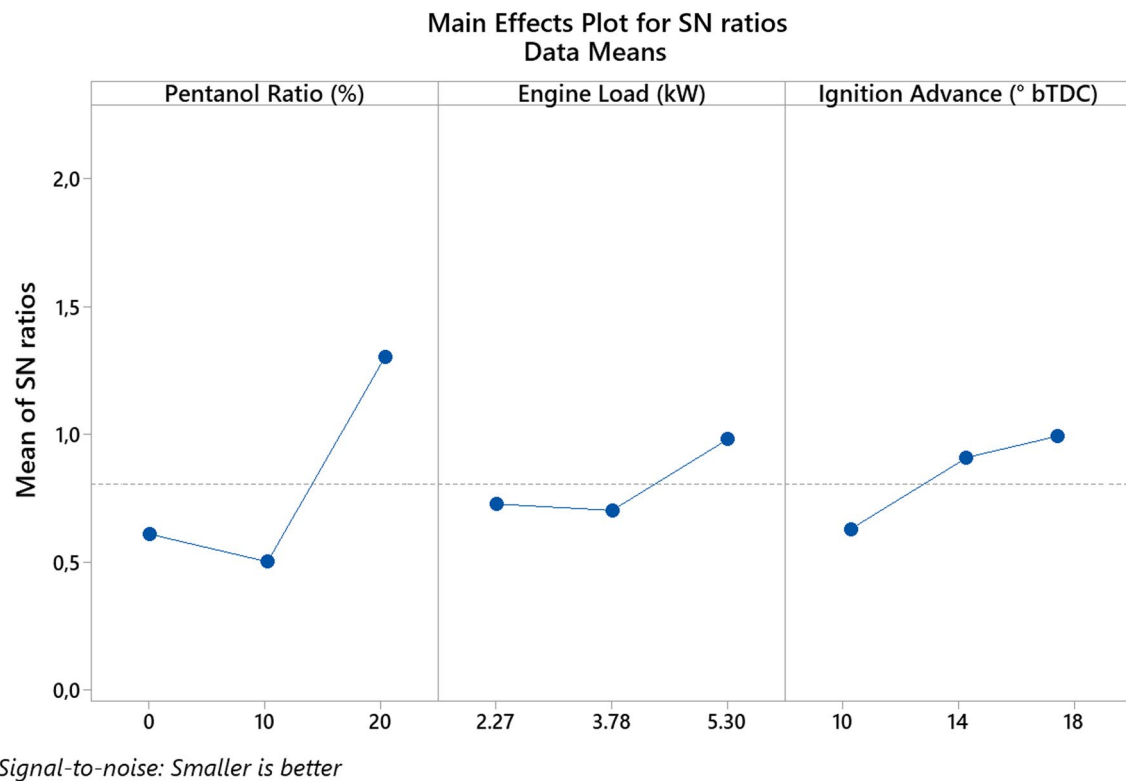
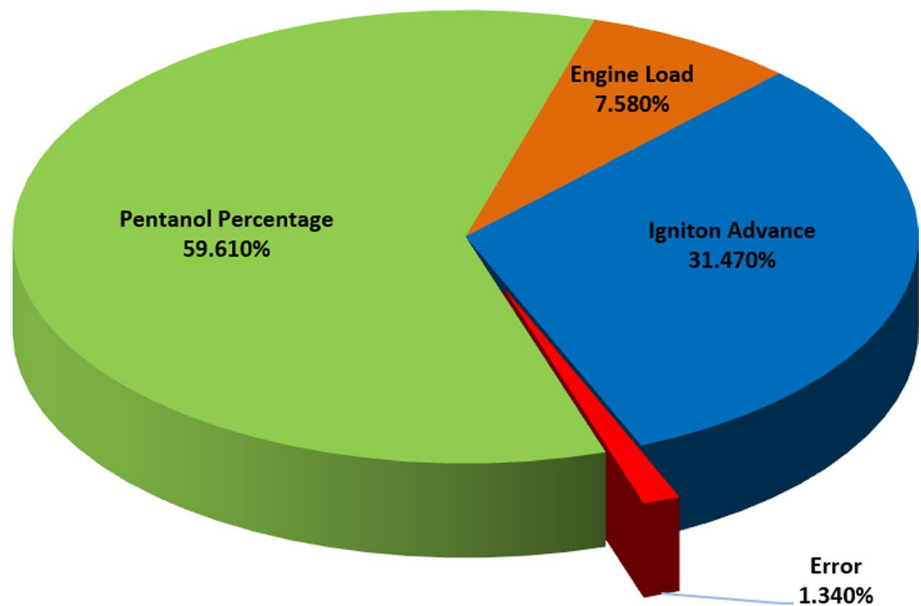


Fig. 11 S/N values of variables for O₂ emissions

Fig. 12 The impact rates of variables and error on O₂ emission



- In the evaluation made in terms of engine load, the highest engine load level of 5.30 kW was obtained as the optimum value for BTHE, CO, HC and O₂. On the other hand, the lowest level of 2.27 kW for BSFC, CO₂ and NO_x has been determined as optimum.
- Optimum levels of ignition advance were obtained as 18 ° bTDC for both performance responses. In addition, it was found to be 14 ° bTDC for CO and HC, 10 ° bTDC for CO₂ and NO_x, and 18 ° bTDC for O₂.

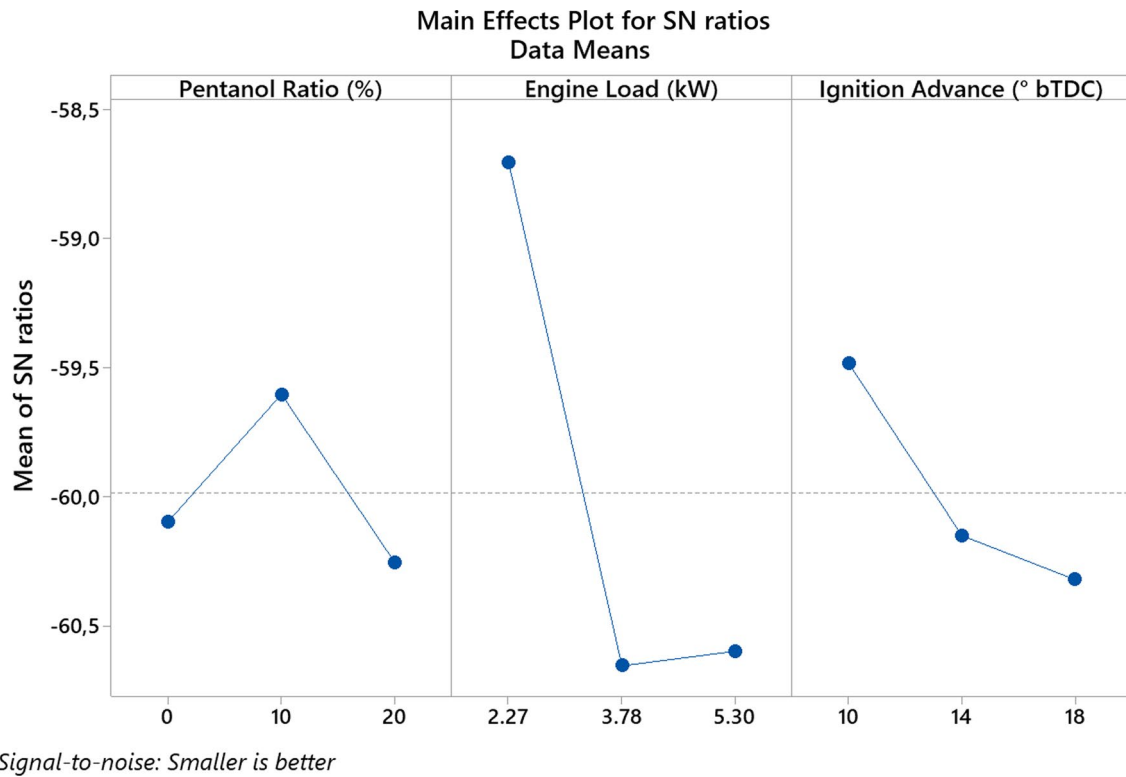
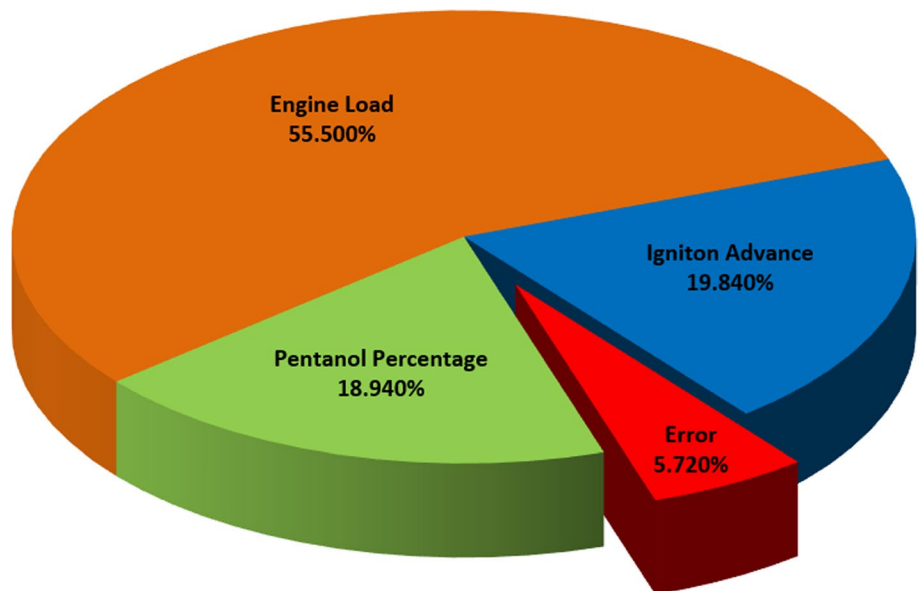


Fig. 13 S/N values of variables for NO_x emissions

Fig. 14 The impact rates of variables and error on NO_x emission



- In evaluating the most effective engine variables on performance and emission responses, the most effective variable on BTHE and NO_x was determined as engine load. For BSFC, CO₂ and O₂, the n-pentanol percentage was determined to be the most effective, while the igni-

tion advance for CO and HC was found to be the most effective variable.

Based on the results obtained from the study, it was concluded that pentanol can be used successfully as an alternative fuel or fuel additive for the gasoline engine. In addition,

in this study, it is thought that determining the n-pentanol ratio and engine variables levels that should be used for high performance and low emission when n-pentanol is used in spark ignition engine will shed light on future studies.

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Data Availability The data used and/or analyzed throughout the present study are available from the authors on reasonable request.

Declaration

Conflict of interest The authors pointed out that there is no potential conflict of interest.

Ethical approval The authors declared that no animal and human studies are presented in this manuscript and no potentially identifiable human images or data are given in this research.

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