Hindawi
International Journal of Chemical Engineering
Volume 2024, Article ID 8707726, 12 pages
https://doi.org/10.1155/2024/8707726

Research Article

Response Analysis of an Experimental Study on the Effect of Speed and Premixed Fuel Ratio on Performance and Emissions in RCCI Engine

Habtamu Deresso Disassa,[1] **Venkata Ramayya Ancha**,[2] **Ramesh Babu Nallamothu**,[1] **Bisrat Yoseph**,[3] **and Getachew Alemayehu**[1]

[1]*Department of Mechanical Engineering, Adama Science and Technology University, Adama, P.O. Box 1888, Ethiopia*
[2]*Department of Mechanical Engineering, Jimma University Institute of Technology, Jimma, P.O. Box 378, Ethiopia*
[3]*Department of Mechanical Engineering, Defense Engineering College, Bishoftu, P.O. Box 1014, Ethiopia*

Correspondence should be addressed to Habtamu Deresso Disassa; habtamu.deresso@astu.edu.et

Received 19 April 2023; Revised 12 December 2023; Accepted 21 December 2023; Published 4 January 2024

Academic Editor: Yanqing Niu

Even though CI engines are more efficient than SI engines due to their ability to operate at a greater compression ratio, a leaner charge, and lower throttle losses, they have higher PM and nitrogen oxide emissions. The induction system modification with fuel port injection is used as a parameter in RCCI engine operations for controlling emission through in-cylinder charge reactivity and combustion phasing. By varying the amount of hydrous bioethanol in the premixed fuel injection ratio, the engine's performance and emissions are greatly affected. In this study, an experimental investigation of a triple-fuel RCCI engine running on port-injected gasoline-bioethanol blend and direct-injected diesel fuel was conducted. Taguchi's experimental design method was employed to assess the impact of various independent variables utilizing three set levels and two factors with the L9 orthogonal array. From the findings, the delta value shows the highest average response for each factor. Engine speed has the largest effect on the signal-to-noise ratio (SNR) with the (delta value of: 10.7446, rank = 1), and the delta value of 38.96, rank = 1, has the largest effect on the response of means at engine speeds of 3000 rpm. The premixed fuel ratio of G25BE75 (delta: 87.30, rank = 1) has the largest effect on the standard deviation. The lines are not parallel in all emission and performance cases except for Tb and CO_2, which are close to parallel. The best means in engine speed and premixed blended fuel ratio were NOx, CO, HC, and brake power. At 3000 rpm, the speed had the larger main effect plots of SNR. The premixed fuel ratio of G25BE75 had higher main effect plots for means and standard deviations. The residues appear to have been dispersed normally based on a straight line by using a normal probability plot. The data are normally distributed, as demonstrated by the normal probability plot, and the factors had an impact on the response. Conferring to the experiment result, a high engine speed and higher ethanol content in the RCCI premixed fuel are preferred for reducing nitrogen oxides (NOx) and carbon dioxide (CO_2), while unburned hydrocarbons (UHCs) and carbon monoxide (CO) showed a slight increase.

1. Introduction

Ecological pollution and the world energy crisis force investigators to find renewable, hygienic energy sources and advanced combustion technologies [1]. Many advanced low-temperature combustion (LTC) technologies, such as HCCI [2], PCCI [3], PPCI [4], and RCCI [5, 6], respectively, have been proposed to improve the combustion efficiency and reduce emissions of internal combustion engines. The RCCI combustion, which belongs to the dual-fuel mode, regulates the ratio of two fuels with different reactivity, of which one is injected through the port and the other is directly injected to control the ignition and combustion process [7]. Hence, the RCCI has received widespread attention. Due to the higher compression ratios [8], leaner charges [9], and lower throttle losses [10], spark ignition engines and compression ignition engines are typically more efficient. However, the difficulty of CIE is their increased emissions of particulate matter (PM) and NOx. Under the present and upcoming legislation, vehicles must obey strict rules for both pollution and fuel efficiency [11]. These problems demanded the development of an advanced engine technology as well as an alternative fuel to fossil fuels that is both efficient and emits negligible emissions [12]. Several innovative CI combustion methods have been investigated to reduce emissions in a cylinder while retaining higher thermal efficiency [13]. To address future demands for cleaner and more efficient power plants, the majority of current techniques are classified as LTC engines [14, 15]. It was found that RCCI combustion was able to operate with low NO_x and soot emissions [16], even though it still needs further investigation, with higher indicated efficiency. However, due to load extension limitations caused by high PRR, high UHC, and carbon monoxide emissions in crevice volumes, an inferior part-load performance and high load operation could not be achieved with power outputs comparable to those of a normal combustion compression ignition engine. The findings showed that RCCI was attained under the investigated test settings, and the key elements for the operation were revealed during the tests. Overall, the results show the viability of using diesel-ethanol [17] in compression ignition engines with RCCI combustion [18]. They recommended conducting further studies at various speeds to broaden how the engines with wet-ethanol PFI operate. In addition, a durability study is recommended as a part of the future research to assess these technologies over a longer period, and future analyses should additionally include PM and HC to maintain the integrity of the study [11]. MPRR, extensive HC and CO emissions in crevice volumes, and poor part-load performance put limits on load extension. However, the majority of earlier studies are conducted on ethanol, gasoline, NG, and CNG, with each alone as a low-reactivity port-injected fuel, and tested under RCCI engine operations. Nevertheless, a research gap arises due to several studies conducted with premixed alcohol or petrol fuel alone having high CO and UHC emissions as stated by Pan et al., 2021 [19]. Higher CO and UHC emissions from the unique fuel RCCI experimental results showed that it is possible to simultaneously achieve ultra-low engine-out emissions of NOx and PM and lower CO and UHC as Žvar Baškovič et al. [20] indicated. Therefore, it is of great importance to test ethanol-gasoline blends in an up-to-date LTC concept of the RCCI, which enables its use for injection into the intake manifold. This is due to ethanol's advantage of the cooling effect and its oxygen content in composition to reduce oxygen deficiency in the engine at the time of combustion. In this regard, the combustion, performance, and emissions of the diesel engine fueled with EGB and diesel at high premix ratios are investigated in the present study. The intention of this study is also to use sustainable ethanol for fossil energy replacement with innovative RCCI engines to reduce NOx and PM and to find the operating condition for lower CO and HC (Gharehghani et al.) [21, 22].

The results of the experiments are analyzed to establish the minimum emissions and higher performances; estimate the contributions of individual parameters to the response by using the Taguchi method; and show the response under optimum conditions by investigating the main effects of each parameter. The main effect plot for the SNR is the engine speed, and for means and standard deviation, the main effect plots are the premixed fuel ratio at G25/E75. According to the result, CO and UHC emissions are reduced at G50E50 which is unusual in RCCI engines, and NOx and CO_2 are reduced at a blend ratio of G25E75 fuel.

2. Materials and Methodology

2.1. Experimental Design. Even though there are many widely used orthogonal arrays, each array is suited for a specific amount of independent design variables and levels [23]. The most effective way to experiment to examine the impact of various independent variables each of which has three set levels and two factors is to use a L9 orthogonal array [24]. The relationship between speed and the characteristics of the fuel is a typical example of an interaction. To properly reveal all factors influencing performance and emission characteristics, the common orthogonal arrays help define the bare minimum of tests necessary [25]. Baseline experiments were conducted on a horizontally mounted, 4-stroke, naturally aspirated, 0.309-liter, water-cooled, single-cylinder, directly injected diesel engine having the specifications shown in Table 1. The fuel with the physiochemical properties of fuels shown in Table 2 is supplied to the engine through direct injection, and a hydrous bioethanol-gasoline fuel blend is injected into the intake manifold by port fuel injection (PFI). As a consequence of the forced parameters, it was decided to employ performance and emission process factors, such as engine speed and premixed gasoline-bioethanol blend ratios, to assess the effects of the test samples on the emission properties. The experimental findings are displayed in Table 3. The engine setup test rig with the data acquisition system was directly coupled to the dynamometer found at Jimma University Institute of Technology (JiT) as shown in Figure 1. The second experiment was carried out on the same engine that had been modified for the RCCI engine to improve efficiency and reduce emissions. For the port fuel injection system controlling mechanism, an Arduino board electronic microcontroller is used for controlling the injection volume of the blended fuel. The performance and emission characteristics of blends and diesel fuels are investigated by using maximum loads (80%), varying engine speeds, and fuel ratios as variables to assess the combustion phase, at which the efficiency is the highest. The study employed an 80% one-stage direct-injection technique for diesel fuel and 20% fuel blends for PFI. Experiments are performed at constant engine load, varying speeds, and different premixed fuel ratios in both RCCI and baseline combustion engine modes. The experiments were limited to a minimum engine speed of 1600 and a maximum engine speed of 3000 rpm due to the excessively unstable RCCI engine combustion at higher rpm. The premixed ratio (r_p) is defined as the ratio of port-injected fuel energy to the total fuel energy injected, as shown in the following equation [26]:

Table 1: Engine model and specifications.

Engine type, company	EA300-E2-NB, Kubota
No of cylinder and stroke	1 and 4 stroke
Bore * stroke	75.0 * 70.0 mm
Output power at 3,000 rpm	5.1 KW
Swept volume	0.309 L
Connecting rod ratio	0.25
Noise level	95 dB (A)
Compression ratio	23
Maximum speed	3000 rpm

Table 2: Physiochemical properties of fuels.

Properties	Ethanol	Gasoline	Diesel
Auto ignition temperature (°C)	420	300	—
Flashpoint (°C)	13	45	93
Density at 15°C	0.79	0.720	0.840
Adiabatic FT @ (25°C)	2234	2289	2600
Molecular weight	46	(95–120)	198–202
Reid vapor pressure (KPa)	17	41–65	—
Cetane number	7	17	54.6
Latent heat (KJ/kg)	904	380–500	904
RON	106	Min 92	CN-48
MON	89	81–89	—
LHV (MJ/kg)	26.8	42.4	42.5
Total sulfur (% wt)	—	Max 0.05	—
FBP temperature (°C)	—	Max 225	380

Table 3: L9 Experimental results of the engine emissions and performance.

Speed	PMF-ratio	NOx	CO	CO_2	HC	BT	BP	SNR	LSTD	STD	Mean	CV
2200	0	41	0.251	4.04	21	14.16016	3.28355	−25.9286	2.73238	15.369	13.9558	1.10129
2200	25/75	36	0.512	2.62	53	15.18555	3.5058	−28.6084	3.06736	21.485	18.4706	1.16321
2200	50/50	37	0.73	2.34	30	15.23438	3.84225	−26.2357	2.73921	15.475	14.8578	1.04152
2600	0	92	0.677	4.79	23	14.16016	3.87003	−31.8714	3.54794	34.742	23.0829	1.50509
2600	25/75	38	2.692	1.94	313	14.16016	3.84225	−42.2028	4.81697	123.59	62.2724	1.98466
2600	50/50	69	0.92	2.49	34	15.18555	4.52167	−30.1249	3.27898	26.549	21.0195	1.26305
3000	0	152	1.058	6.41	48	14.11133	4.51805	−36.3127	4.07015	58.566	37.6829	1.55417
3000	25/75	33	4.537	3.85	510	14.16016	4.52167	−46.3923	5.3162	203.61	95.0115	2.14299
3000	50/50	115	1.652	3.64	50	14.16016	4.43393	−34.2491	3.80119	44.754	31.481	1.42163

Engine speed in rpm and the premixed fuel ratio in percent volume; NOx and HC emissions are in particulate per million; CO and CO2 are in percent volume; BP is the brake power in kW and BT is the brake torque in N-m. SNR: signal-to-noise ratio; LSTD: least square standard deviations; STD: standard deviation; CV: coefficients of variance.

$$r_p = \frac{m \times (\mathrm{LHV})_{\mathrm{GBE}}}{M \times (\mathrm{LHV})_D + m \times (\mathrm{LHV})_{\mathrm{GBE}}}, \tag{1}$$

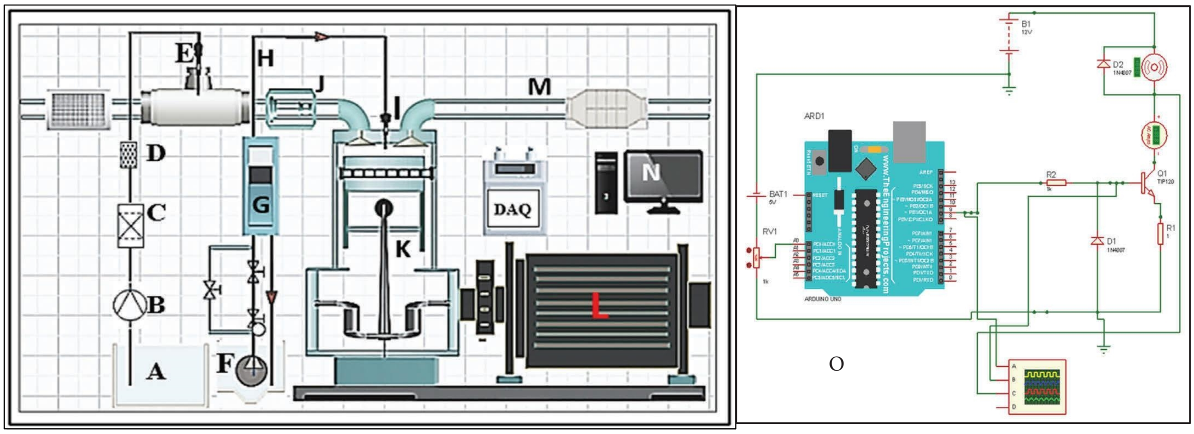
where M and m are the mass flow rates of primary and secondary fuels, respectively, and LHV is the lower heating value of the respective fuels. Where D is diesel fuel, GBE is gasoline-bioethanol blend r_p is the premixed ratio of G25BE75 and G50BE50 percent of the port injected fuel. The start of diesel fuel injection (SOI) timing was kept constant in all experiments at 14° CA bTDC.

3. Result and Discussion

The Taguchi experimental design method is preferred for optimization strategies to solve the drawbacks of multifactorial and full factorial designs that are connected to the outcomes that can be attained through extensive experimentation. The Taguchi technique is employed in this study to identify the key factors that make the greatest contributions to the variation in response parameters of interest. It recommends an orthogonal array for laying out the experiments which is a significant part. Instead of varying one factor at a time, all factors are varied simultaneously as per the design array and the response values are observed. It can evaluate several factors in a minimum number of tests. In this research, the Taguchi experimental design method uses the three set levels and two factors with the L9 orthogonal array.

3.1. Taguchi Analysis of Emission and Performance vs. Speed and Premixed Blended Fuel Ratio

3.1. Taguchi Analysis of Emission and Performance vs. Speed and Premixed Blended Fuel Ratio. Linear model analysis of the signal-to-noise ratio, means, and the standard deviation versus engine speed and premixed hydrous bioethanol fuel ratio; the main effect plot of signal-to-noise ratio, means,



A. Fuel tank B. Fuel pump C. Fuel filter D. Fuel meter E. PFI F. Blended F. Pump
G. Fuel gauge H. Diesel fuel line I. D. Injector J. Reactors K. Engine L. Dynamometer
M. E. Manifold N. Computer O. Controller P. Intake Manifold DAQ-Data acquisition system

Figure 1: Engine test rig setup and Arduino board microcontroller.

standard deviation; and the interaction plots, residual plots of SNR, means, and standard deviation are clearly shown in the subsequent sections.

The control factor settings that minimize the variability brought on by the noise factors are identified by the SNR. Minitab computes the average signal-to-noise ratio for each level of each control factor as well as the SNR for each combination of control factors. When the procedure selected the option when "larger is better" from the signal-to-noise ratios; the first option's experimental objective is to maximize the response with favorable data features according to the following equation:

$$\frac{S}{N} = -10 \times \log\left[\sum\left(\left(\frac{yi}{n}\right) \times \left(\frac{yi}{n}\right)\right)\right], \tag{2}$$

where y_i are the measured property values and n is the total number of experiments. In trials, to boost performance and emission, it was found that the two variables' engine speed and premixed gasoline-bioethanol blend ratio were the most effective ones. In linear model analysis, statistical significance refers to the determination of whether the estimated coefficient of the independent variable is different from zero, as shown in Table 4. The estimated model coefficients represent the relationships between the independent variables and the mean of the dependent variable, as shown in Table 5. In linear model analysis, the estimated model coefficients do not directly represent the standard deviations of the variables involved, as shown in Table 6.

Table 4: Estimated model coefficients for SNR.

Term	Coeff	SE coef	T	P value
Constant	6.3988	0.7713	8.296	0.001
Speed 2200	−5.7546	1.0908	−5.276	0.006
Speed 2600	0.7647	1.0908	0.701	0.522
PMF ratio	−3.7985	1.0908	−3.482	0.025
PMF ratio 25/75	2.9879	1.0908	2.739	0.052

PMF ratio: premixed fuel blend ratio; SNR: signal-to-noise ratio; SE coef: significant error coefficient; Coeff; coefficient; P: statistical significance; $S = 2.3139$; R-Sq = 92.05%; R-Sq(adj) = 84.09%.

Table 5: Estimated model coefficients for means.

Term	Coef	SE coef	T	P value
Constant	35.3149	5.528	6.389	0.003
Speed 2200	−19.5536	7.817	−2.501	0.067
Speed 2600	0.1433	7.817	0.018	0.986
PMF ratio	−10.4077	7.817	−1.331	0.254
PMF ratio 25/75	23.2699	7.817	2.977	0.041

$S = 16.5833$; R-Sq = 81.11%; R-Sq (adj) = 62.22%.

Table 6: Estimated model coefficients for standard deviation.

Term	Coeff	SE coeff	T	P value
Constant	60.460	14.17	4.266	0.013
Speed 2200	−43.017	20.04	−2.146	0.098
Speed 2600	1.167	20.04	0.058	0.956
PMF ratio	−24.234	20.04	−1.209	0.293
PMF ratio 25/75	55.768	20.04	2.783	0.050

$S = 42.5134$; R-Sq = 77.49%; R-Sq (adj) = 54.98%.

3.1.1. Linear Model Analysis: SNR vs. Speed and Premixed Fuel Blend Ratio. Analysis of variance (ANOVA): the major goal of the analysis is to pinpoint and investigate the significant variables that affect an internal combustion engine's performance and emission levels and also to determine the impact of the effective parameters on the quality characteristic. The total squared deviations of the overall mean are used in the analysis of variance. The effect of each experimental component can be divided based on its contribution and inaccuracy. The parameter with the highest mean square value is determined to be the most important one, and it affects the operation and emission characteristics of an internal combustion engine with the premixed fuels blend. Tables 7–9 present the ANOVA's findings. The percentage contribution of each of the design parameters is represented by p, and MS is the mean square of a component discovered by dividing its sum of squares and degrees of freedom. For each factor, the degree of freedom is 2. The second factor, speed, is therefore determined to be the most significant element that contributes to and influences the performance and emission characteristics of an RCCI internal combustion engine based on the analysis, which finds that it has the maximum mean square value. The degrees of freedom, successive sums of squares, mean square (MS), T-statistic from the MS, and p value can all be obtained from an analysis of variance. Analysis of variance (ANOVA) findings are presented in Table 7 is speed, in Table 8 is premixed blended fuel ratio, and in Table 9 is premixed blended fuel ratio is significant in SNR, means, and standard deviation, respectively. The analysis is deemed significant at a level of 5% with a 95% confidence level. The column of p values in this Table 7 shows which of the effective parameter is a crucial one and has the most impact.

3.1.2. Linear Model Analysis: Means vs. Speed and Premixed Fuel Blend Ratio.

3.1.3. Linear Model Analysis: Standard Deviation vs. Speed and Premixed Blended Fuel Ratio. Main effects plot: the signal-to-noise ratio, means, and standard deviations are just a few examples of the factors that the major effect plots display as they relate to the response characteristic. As a result, as shown in Figure 2, for the main effect plots of the signal-to-noise ratios, the speed had a larger main influence. The premixed blended fuel ratio, as seen in Figures 3 and 4, had a bigger main effect, according to the main effects plots for means and standard deviations. Individual standard deviations are used to calculate interval plots at the 95% confidence level of NOx and CO_2 to determine which premixed blend ratios of low-reactivity fuel have a significant effect on emissions and engine speed. Figures 5(a) and 5(b) clearly show the maximum NOx and CO_2 levels at all baseline and minimum at all 25/75 RCCI engine combustion modes.

Residual plots of SNR, means, and standard deviation: Figures 6–8 display the residual plots for SNRs, means, and standard deviations, respectively. A residual plot is a graph where the independent variable is on the horizontal axis and the residuals are displayed on the vertical axis. A linear regression model is adequate for the data if the dots in a residual plot are randomly distributed across the horizontal axis; otherwise, a nonlinear model is preferable. A linear model offers a respectable fit to the data, as evidenced by the residual plot's seemingly random pattern. Although there can be a small nonlinearity in the middle, the data seem to be mostly linear. Overall, for these data at this level, linear regression is adequate. Figure 6 displays the residual plot of S/N ratios. This design is used to check whether the model adheres to the analyses' underlying assumptions. The residual plots and each residual plot's interpretation are as follows:

(i) By using a normal probability plot, abnormality is found. The residues appear to be dispersed normally in an essentially straight line. The data are normally distributed, as demonstrated by the normal probability plot above, and the factors have an impact on the response, as seen in Figures 6–8.

(ii) Outliers, missing higher-order terms, and non-constant variance are found by using the residuals vs. fitted values display. Around 0, the residuals ought to be dispersed randomly. The residuals vs. fitted values plot shown above shows that the variance is consistent and that there are no outliers in the data.

(iii) The residuals' histogram plot aids in the identification of many peaks, outliers, and abnormalities. The histogram should roughly be bell-shaped and symmetric. The histogram of the residual points is depicted in the abovementioned plot, and it is seen that it is roughly symmetric and bell-shaped.

(iv) The plot of residuals versus order helps in detecting the time dependence of residuals. The residuals should exhibit no clear pattern. The abovementioned residuals versus order plot indicated the random pattern of the residuals.

Delta value shows the difference between the highest average response values for each factor. According to the present investigation, speed has the largest effect on the signal-to-noise ratio with the delta value of 38.96, rank=1, and has the largest effect on the response table of means with the delta value of 38.96, rank = 1. The premixed fuel ratio (delta: 87.30, rank = 1) has the largest effect on the standard deviations, but (delta: 84.87, rank = 2) has the lowest effect on the standard deviations in all options as is shown in Table 10. The box plots of brake power and brake torque at a 95% confidence level are shown in Figures 9(a) and 9(b), and both are inversely proportional to each other.

Table 7: Analysis of variance (ANOVA) for SNR.

Source	DOF	SS	Adj SS	Adj MS	*F*	*P* value
Speed	2	175.80	175.80	87.901	16.42	0.012
PMF-ratio	2	72.04	72.04	36.021	6.73	0.053
Residual error	4	21.42	21.42	5.354		
Total	8	269.26				

DOF: degree of freedom; SS: sum of the square; Adj SS: adjusted sum of square; Adj MS: adjusted mean square.

Table 8: Analysis of variance (ANOVA) for means.

Source	DOF	SS	Adj SS	Adj MS	*F*	*P* value
Speed	2	2277	2277	1138.7	4.14	0.106
PMF ratio	2	2446	2446	1222.9	4.45	0.096
Residual error	4	1100	1100	275.0		
Total	8	5823				

Table 9: Analysis of variance for standard deviations.

Source	DOF	SS	Adj SS	Adj MS	*F*	*P* value
Speed	2	10810	10810	5405	2.99	0.161
PMF ratio	2	14075	14075	7038	3.89	0.115
Residual error	4	7230	7230	1807		
Total	8	32114				

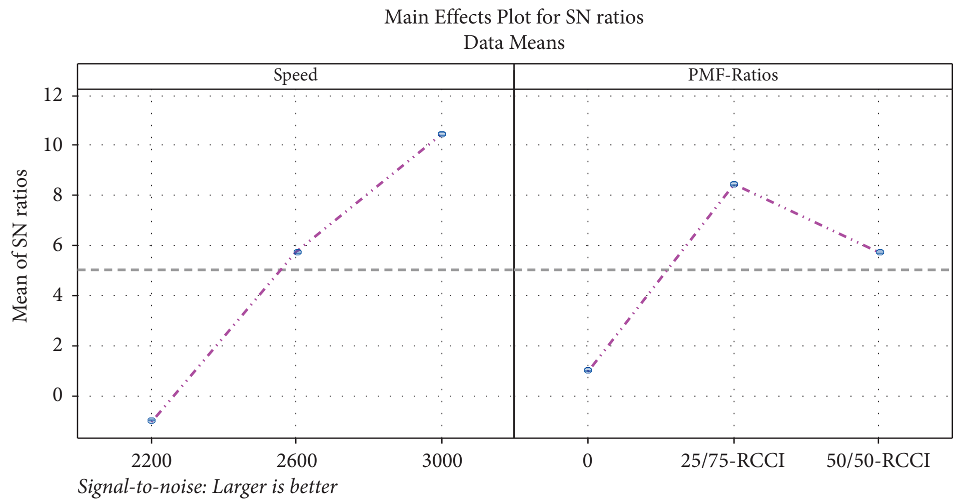


FIGURE 2: Main effect plots for SNR.

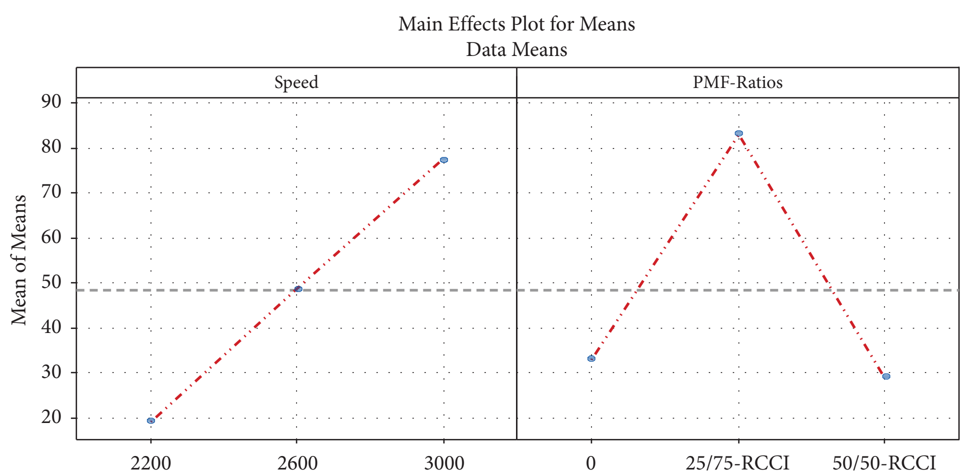


FIGURE 3: Main effect plot for means.

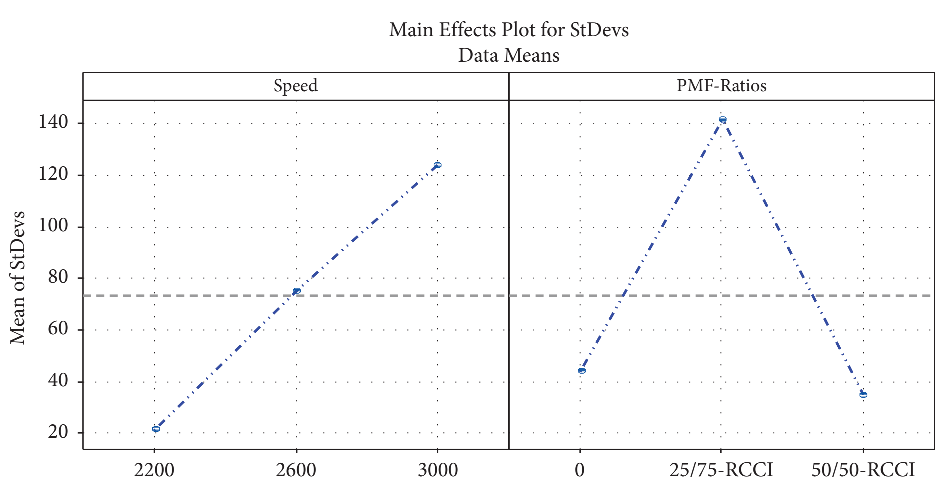


FIGURE 4: Main effect plot for standard deviations.

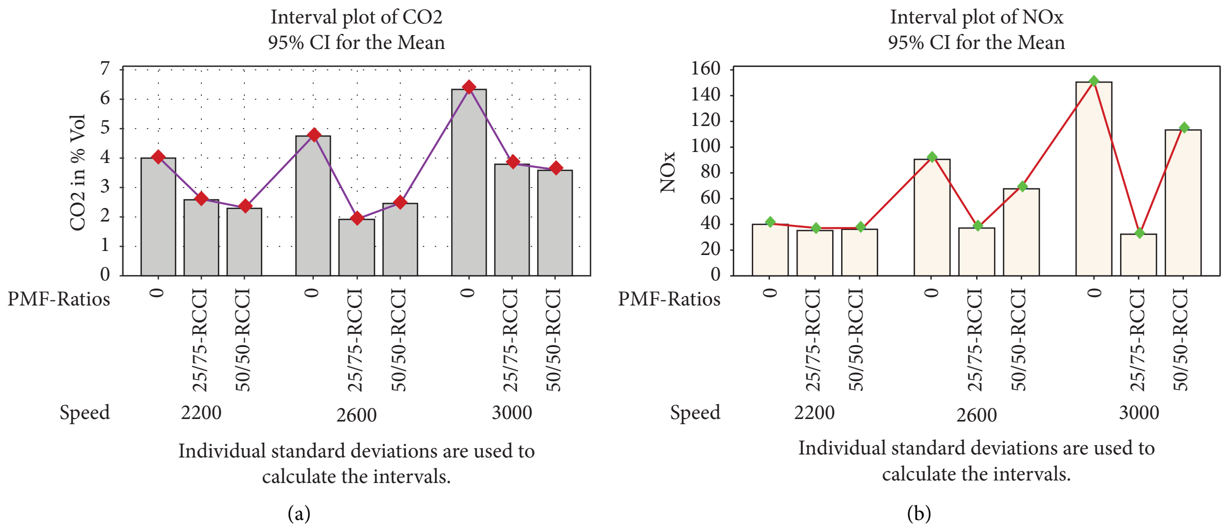


Figure 5: Interval plot of (a) NOx and (b) CO_2, which shows significant details of emissions.

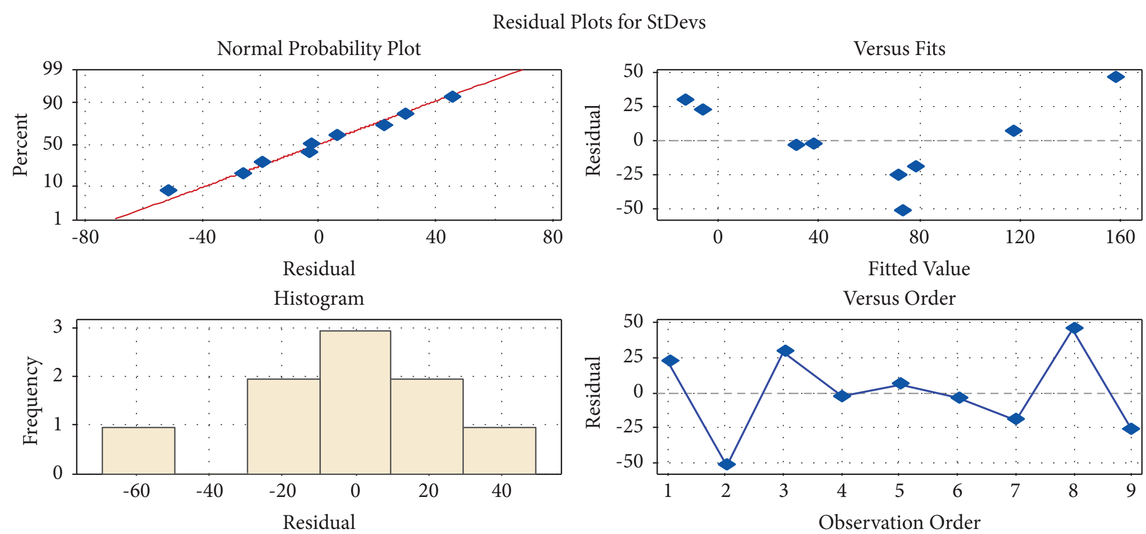


Figure 6: Residual plots for SNR.

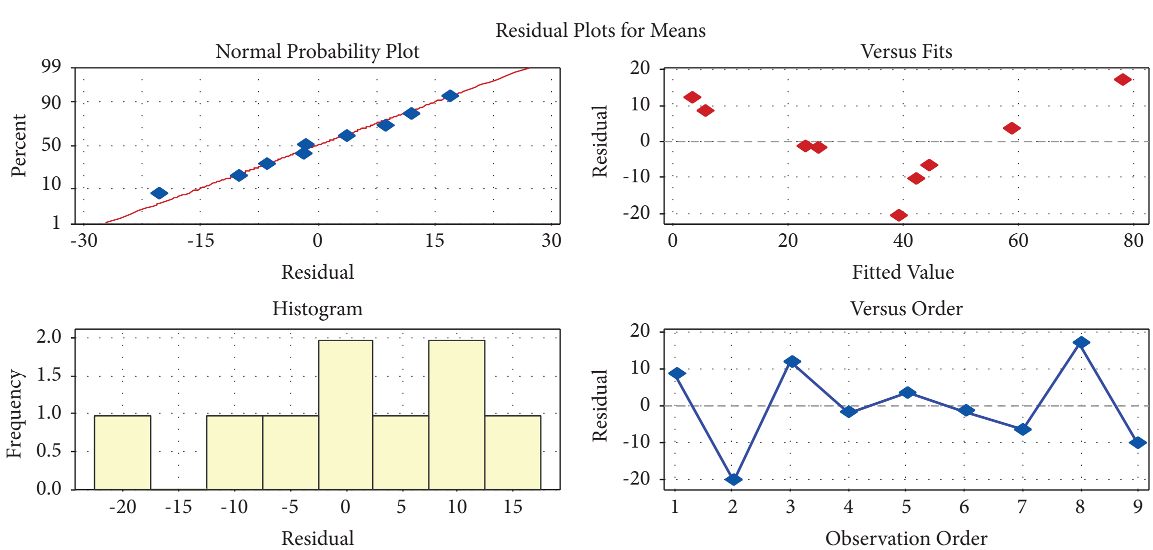


Figure 7: Residual plots for means.

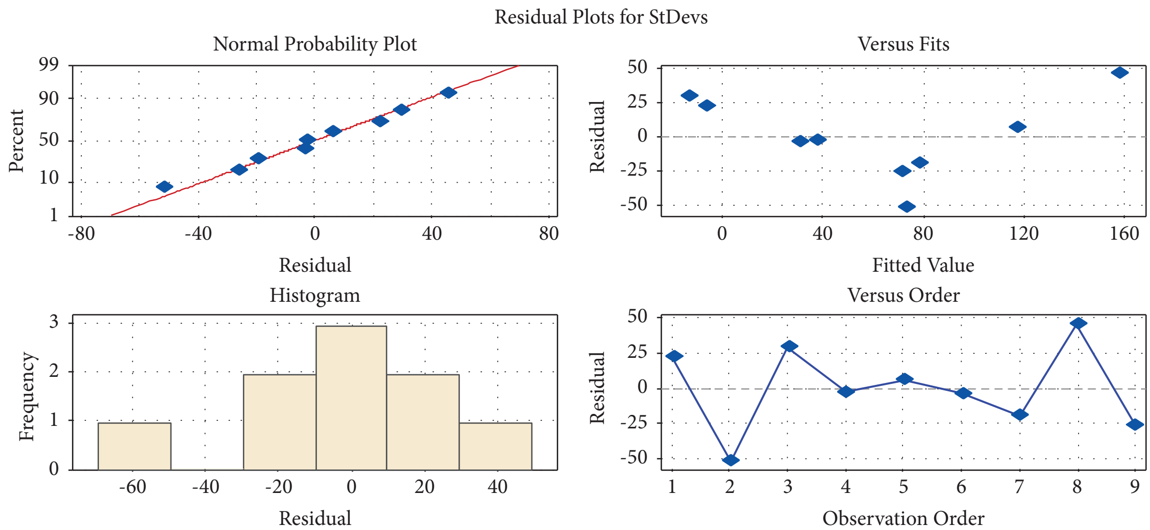
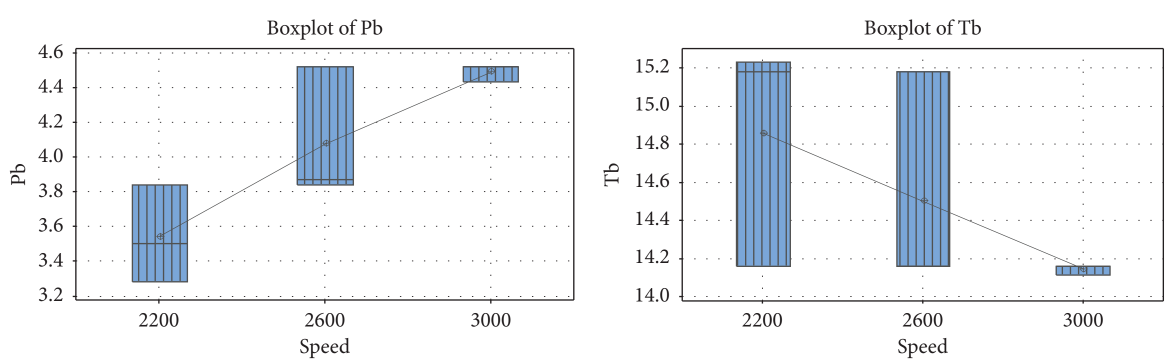


Figure 8: Residual plots for standard deviations.

Table 10: Response table for SNR, means, and standard deviation with the selected option "larger is better."

Response table for SNR			Response table for means			Response table for STD		
Level	Speed	PMF-ratio	Level	Speed	PMF ratio	Level	Speed	PMF ratio
1	0.6441	2.6002	1	15.76	24.91	1	17.44	36.23
2	7.1634	9.3867	2	35.46	58.58	2	61.63	116.23
3	11.3887	7.2094	3	54.73	22.45	3	102.31	28.93
Δ	10.7446	6.7865	Δ	38.96	36.13	Δ	84.87	87.30
Rank	1	2	Rank	1	2	Rank	2	1



(a) (b)

Figure 9: The box plots of (a) brake power and (b) brake torque at the 95% confidence level.

Table 11: Engine combustion, performance, and emission results and validations.

Ref	Parameters	Results								Baseline and RCCI
		CP	HRR	RI	GIE	NOx	Soot	UHC	CO	
[19]	↑ Rp G-D RCCI	↑	↑	—	↑	↓	↓	↑↑	↓	Diesel-gasoline RCCI
[27]	Peak load-MCP	↑↑	—	—		↓	↓	↑	↑	Diesel-alcohol RCCI
[28]	Peak load	↑			↑	↓	↓	—	—	
[29]	Improving the PR of NG	—	↓	↓		↓	↓	↑	↑	Diesel-RCCI (NG/CNG/H_2)
[30]	60CNG energy share	—	—	↑	↑	↓	↓	↑	↓	
Current work	G25E75-RCCI	↑↑	↑↑	—	≈	↓↓	↓↓CO2	↑	↑	At 3000 rpm (GE blend)
	G50E50-RCCI	↑	↑	—	↑	↓	↓ CO_2	≈	↓	At 2200 and 2600 (GE blend)

D: diesel fuel; DI: direct injected; Rp: premixed ratio; G-D: gasoline diesel; MCP: maximum cylinder pressure; NG: natural gas; CNG: compressed natural gas; ↑↑: maximum; ↑: increased; ≈: average; ↓: reduced; G25E75 or G50E50: a blend ratio for the RCCI engine combustions for present investigation; Ref: referees; GIE: growth-indicated efficiency.

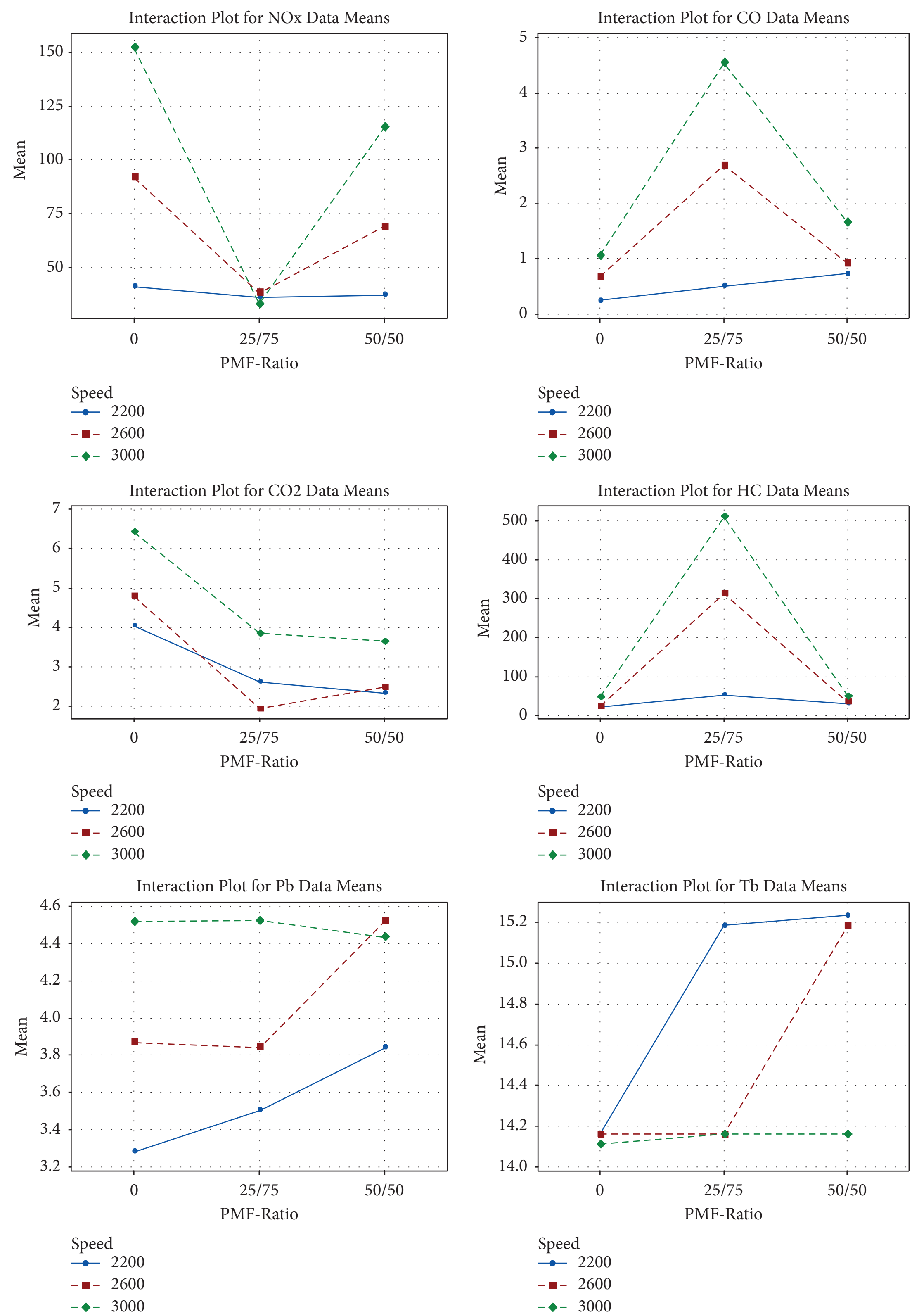


Figure 10: Interaction plot for emissions and performances.

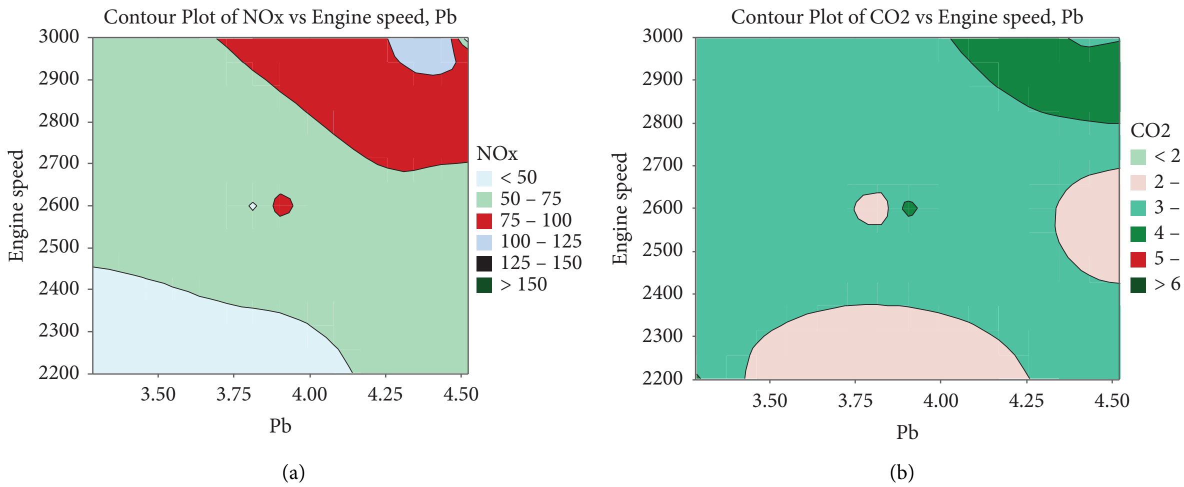


Figure 11: The contour plot of (a) NOx and (b) CO_2 of CDC and RCCI emission.

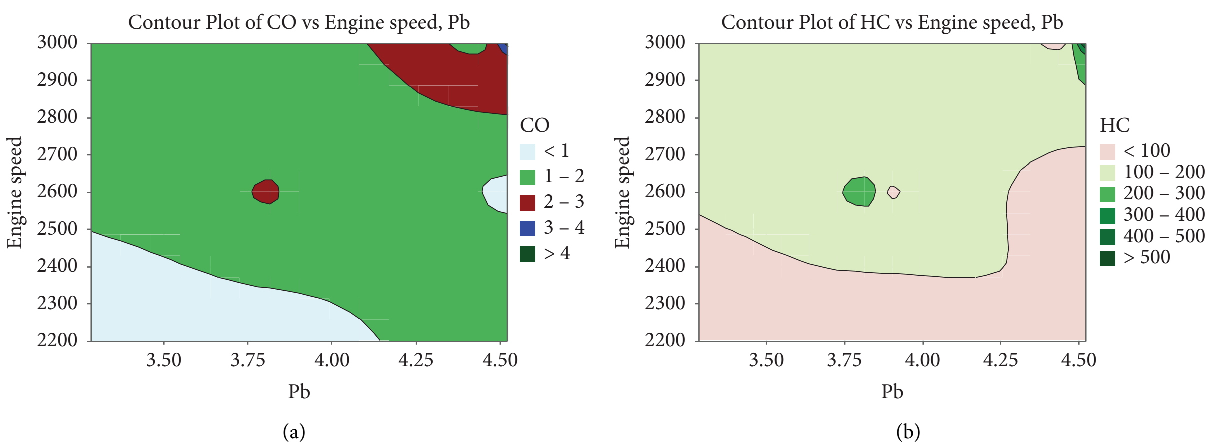


Figure 12: The contour plot of (a) CO vs. speed and (b) UHC vs. speed of CDC and RCCI emission.

The comparative analysis of the previous work with the current investigation and its novelty is shown in Table 11. The lower carbon monoxide level at the blend ratio of G50E50 is unusual in other RCCI Engines.

3.1.4. Interaction Plots for NOx, CO, CO_2, HC, Tb, and Pb. The Minitab forms an interaction plot by plotting for two factors the characteristic average for each combination of factor levels. So, for two factors with three levels each, Minitab plots six points that represent the six possible combinations. The levels of one factor are indicated on the horizontal axis, whereas different colored lines and symbols indicate the levels of the other factor. If the lines are parallel to each other, then there is no interaction between the two factors. If the lines are not parallel to each other, then there is an interaction between the two factors. In these results, Tb and CO_2 lines are parallel, which means that the effect of one factor on the response variable is consistent across different levels of the other factor. This implies that the factors do not interact, and their effects on the response variable are independent of each other. As shown in Figure 10, NOx, CO, HC, and Pb had the strongest means in engine speed and premixed blended fuel ratio. The lines for NOx, CO, HC, and Pb are not parallel, which indicates an interaction effect. This means that the effect of one factor on the response variable depends on the level of the other factor. In this case, it is important to further analyze the nature of the interaction and interpret the results accordingly. The gasoline-ethanol (25/75) blend and the speed of 3000 rpm show more impact relative to all the others due to the cooling effects and oxygen contents of the ethanol improving combustion efficiency that creates variation as shown in each graph.

3.1.5. Contour Plots of Performance and Emissions. The focal issues from the diesel engines are NOx and PM emissions. The contour plots of nitrogen oxides (in ppm) from the exhaust of the engine are minimum at the lower brake power and engine speed, while carbon dioxide (in % vol) emission seems to be lower at low speed and maximum at lower brake power but maximum at higher speed and higher brake power as shown in Figures 11(a) and 11(b).

Figures 12(a) and 12(b) show the contour plots of carbon monoxide and unburned hydrocarbon emission in percentage volume versus engine speed, respectively. The CO is maximum (3-4% vol) and lower at speeds below 2500 rpm and brake power below 4.2 kw, which is less than 1% vol. Unburned hydrocarbon in less than 100 ppm emission at below 2500 rpm in all engine brake power and 100-200 ppm in all speeds is observed to be greater at the engine speeds of more than 2500 rpm.

4. Conclusions

An experimental investigation of a triple-fuel RCCI engine running on a port-injected hydrous bioethanol-gasoline blend and direct-injected diesel fuel was conducted. According to the investigation, the following conclusions are drawn:

(1) The delta value shows the highest average response values for each factor. The engine speed having a (delta value of: 10.7446, rank = 1) has the largest effect on the SNR, and delta 38.96, rank = 1, has the largest effect on the response for means at engine speeds of 3000 rpm. The premixed fuel ratio of G25BE75 (delta: 87.30, rank = 1) has the largest effect on the standard deviation.

(2) The interaction plot between the two factors in NOx, CO, HC, and brake power had the strongest means except brake torque and CO_2, in speed and premixed blended fuel ratio.

(3) The speed had the larger main effect plots for SNR at the engine speed of 3000 rpm that is to mean higher engine speed and higher ethanol contents have a good effect on the investigation. The premixed blended fuel ratio of G25E75 had the higher main effect plots for means and standard deviations.

(4) This shows that the fuel ratio of G25E75 premixed fuel and engine speed of 3000 rpm had the lowest oxides of nitrogen and CO_2 emissions at the modified RCCI engine and had the highest NOx emissions at the engine running with diesel fuel alone and vice versa for CO and HC emissions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Habtamu Deresso conceived, designed, conducted the experiments, analyzed data, and wrote the paper; Venkata Ramayya Ancha supervised, comprehended, analyzed, and edited the paper; Ramesh Babu Nallamothu and Bisrat Yosef prepared the material and collected the data. The manuscript's data were also anlalyzed and enhanced in figure quality by Getachew Alemayehu.

Acknowledgments

Adama Science and Technology University and Jimma University Institute of Technology (JiT) Center of Excellence are greatly acknowledged for their support, and Balewgize Amare Zeru (Ass Prof) is appreciated for his unreserved support at the experiment.

References

[1] J. Li, D. Wang, C. Zhuang, S. Gong, and S. J. P. Li, "Numerical investigation of the knocking combustion characteristics of the N-butanol/N-octanol RCCI engine," *Processes*, vol. 10, no. 10, p. 2142, 2022.

[2] N. Komninos, C. J. R. Rakopoulos, and S. E. Reviews, "Modeling HCCI combustion of biofuels: a review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1588–1610, 2012.

[3] Y. Zhao, E. Weibo, T. Niu, and J. He, "Study on combustion processes of a premixed charge compression ignition (PCCI) engine fueled with DME/diesel," *Journal of Physics: Conference Series*, vol. 1732, no. 1, Article ID 012154, 2021.

[4] D. Habtamu, A. V. Ramayya, N. R. Babu, S. Balkeshwar, and Y. Bisrat, "Investigation of Partially pre-mixed charge ignitions (ppci) engine mode," *Journal of Harbin Institute of Technology*, 2022.

[5] Y. Cui, Z. Zheng, M. Wen et al., "Optical diagnostics on the effects of reverse reactivity stratification on the flame development in dual-fuel combustion," *Fuel*, vol. 287, Article ID 119500, 2021.

[6] S. Pan, K. Cai, M. Cai et al., "Experimental study on the cyclic variations of ethanol/diesel reactivity controlled compression ignition (RCCI) combustion in a heavy-duty diesel engine," *Energy*, vol. 237, Article ID 121614, 2021.

[7] J. S. Rosa, M. E. S. Martins, G. D. Telli, C. R. Altafini, P. R. Wander, and L. A. O. J. F. Rocha, "Exploring the effects of diesel start of injection and water-in-ethanol concentration on a reactivity controlled compression ignition engine," *Fuel*, vol. 281, Article ID 118751, 2020.

[8] K. K. Sadabadi, *Modelling and Control of Combustion Phasing of an Rcci Engine*, Michigan Technological University, Houghton, MI, USA, 2015.

[9] J. Benajes, S. Molina, A. García, E. Belarte, and M. J. A. T. E. Vanvolsem, "An investigation on RCCI combustion in a heavy duty diesel engine using in-cylinder blending of diesel and gasoline fuels," *Applied Thermal Engineering*, vol. 63, no. 1, pp. 66–76, 2014.

[10] T. Duy Nguyen, T. Tran Anh, V. Tran Quang, H. Bui Nhat, and V. Nguyen Duy, "An experimental evaluation of engine performance and emissions characteristics of a modified direct injection diesel engine operated in RCCI mode," *AIMS Energy*, vol. 8, no. 6, pp. 1069–1087, 2020.

[11] K. Jagankumar, N. Prakash, C. Prasad, V. Shridhar, M. Dinesh Singh, and R. Sathyamurthy, "An experimental investigation on single cylinder RCCI engine fuelled with diesel/petrol," *Journal of Physics: Conference Series*, vol. 1706, no. 1, Article ID 012200, 2020.

[12] M. Mofijur, M. M. Hasan, T. Mahlia, S. A. Rahman, A. Silitonga, and H. C. J. E. Ong, "Performance and emission parameters of homogeneous charge compression ignition (HCCI) engine: a review," *Energies*, vol. 12, no. 18, p. 3557, 2019.

[13] Q. Tang, H. Liu, M. Li, C. Geng, and M. J. F. Yao, "Multiple optical diagnostics on effect of fuel stratification degree on

reactivity controlled compression ignition," *Fuel*, vol. 202, pp. 688–698, 2017.

[14] B. Tekgül, S. Karimkashi, O. Kaario et al., "Large-eddy simulation of split injection strategies in RCCI conditions," *Combustion Theory and Modelling*, vol. 26, no. 3, pp. 590–611, 2022.

[15] T. K. Sharma, G. A. P. Rao, and K. M. Murthy, "Homogeneous charge compression ignition (HCCI) engines: a review," *Archives of Computational Methods in Engineering*, vol. 23, no. 4, pp. 623–657, 2015.

[16] Z. Zheng, M. Xia, H. Liu, X. Wang, and M. J. E. Yao, "Experimental study on combustion and emissions of dual fuel RCCI mode fueled with biodiesel/n-butanol, biodiesel/2, 5-dimethylfuran and biodiesel/ethanol," *Energy*, vol. 148, pp. 824–838, 2018.

[17] Y. Wu, X. Zhang, Z. Zhang et al., "Effects of diesel-ethanol-THF blend fuel on the performance and exhaust emissions on a heavy-duty diesel engine," *Fuel*, vol. 271, Article ID 117633, 2020.

[18] D. Splitter, M. Wissink, D. DelVescovo, and R. Reitz, *RCCI Engine Operation towards 60% thermal Efficiency*, SAE International, Warrendale, PA, USA, 2013.

[19] S. Pan, K. Cai, M. Cai et al., "Experimental study on the cyclic variations of ethanol/diesel reactivity controlled compression ignition (RCCI) combustion in a heavy-duty diesel engine," *Energy*, vol. 237, Article ID 121614, 2021.

[20] U. Žvar Baškovič, R. Vihar, S. Rodman Oprešnik, T. Seljak, T. Katrašnik, and Tomaž, "RCCI combustion with renewable fuel mix – tailoring operating parameters to minimize exhaust emissions," *Fuel*, vol. 311, Article ID 122590, 2022.

[21] A. Gharehghani, M. M. Salahi, A. M. Andwari, M. Mikulski, and J. Könnö, "Reactivity enhancement of natural gas/diesel RCCI engine by adding ozone species," *Energy*, vol. 274, Article ID 127341, 2023.

[22] H. D. Disassa, V. R. Ancha, R. B. Nallamothu, and B. A. Zeru, "Experimental study on the effect of speed and port-injected fuel blend ratio on a reactivity-control compression ignition (RCCI) engine performance," *Energy Conversion and Management X*, vol. 20, Article ID 100448, 2023.

[23] H. Sheikhani, H. Ajam, and M. J. Ghazikhani, "Experimental investigation of minimum total irreversibility in non-premixed combustion of different multi-branch burners by Taguchi analysis," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 45, no. 1, p. 53, 2023.

[24] S. Yessian and P. A. Varthanan, "Optimization of performance and emission characteristics of catalytic coated ic engine with biodiesel using grey-taguchi method," *Scientific Reports*, vol. 10, no. 1, p. 2129, 2020.

[25] A. Pathak, P. Choudhury, and R. J. M. T. P. Dutta, "Taguchi-grey relational based multi-objective optimization of process parameters on the emission and fuel consumption characteristics of A VCR petrol engine," *Materials Today: Proceedings*, vol. 5, no. 2, pp. 4702–4710, 2018.

[26] V. B. Pedrozo, X. Wang, W. Guan, and H. Zhao, "The effects of natural gas composition on conventional dual-fuel and reactivity-controlled compression ignition combustion in a heavy-duty diesel engine," *International Journal of Engine Research*, vol. 23, no. 3, pp. 397–415, 2022.

[27] S. Molina, A. García, J. M. Pastor, E. Belarte, and I. Balloul, "Operating range extension of RCCI combustion concept from low to full load in a heavy-duty engine," *Applied Energy*, vol. 143, pp. 211–227, 2015.

[28] Y. Wang, M. Yao, T. Li, W. Zhang, and Z. J. A. E. Zheng, "A parametric study for enabling reactivity controlled compression ignition (RCCI) operation in diesel engines at various engine loads," *Applied Energy*, vol. 175, pp. 389–402, 2016.

[29] K. Poorghasemi, R. Khoshbakhti Saray, E. Ansari, S. M. Mousavi, and A. Zehni, "Statistical analysis on the effect of premixed ratio, EGR, and diesel fuel injection parameters on the performance and emissions of a NG/Diesel RCCI engine using a DOE method," *Proceedings of the Institution of Mechanical Engineers- Part D: Journal of Automobile Engineering*, vol. 236, no. 2-3, pp. 460–473, 2021.

[30] S. P. Wategave, N. Banapurmath, M. Sawant et al., "Clean combustion and emissions strategy using reactivity controlled compression ignition (RCCI) mode engine powered with CNG-Karanja biodiesel," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 124, pp. 116–131, 2021.