Progress in Engineering Application and Technology Vol. 2 No. 2 (2021) 790–809

PEAT

Homepage: http://penerbit.uthm.edu.my/periodicals/index.php/peat
e-ISSN : 2773-5303

Prediction of Performance and Emission of CNG-Diesel Dual Fuel Engine using Response Surface Methodology

Muhammad Syahir Shamsuddin[1], **Abd Fathul Hakim Zulkifli**[1]*

[1]Department of Mechanical Engineering Technology, Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600, Pagoh, Johor, MALAYSIA

*Corresponding Author Designation

DOI: https://doi.org/10.30880/peat.2021.02.02.072
Received 13 January 2021; Accepted 01 March 2021; Available online 02 December 2021

Abstract: Application natural gas for vehicle application through dual fuel system is well known. However, the conversion process especially for diesel engine application is challenging. In this study, the aim is to predict the performance and emission of CNG- diesel dual fuel engine using Response Surface Methodology (RSM). The test was performed between 1500 and 3500 rpm engine speed for each of CNG fraction between 0.00 % to 40.00 %. The evaluation of performance in term of brake torque, brake power and BSEC, while HC, CO and NOx was considered for exhaust emissions evaluation. Then, the prediction models were validated through confirmation test. Based on the RSM model, the performance of brake torque and brake power decreases with an increase of CNG substitution, while BSEC increase. As for exhaust emissions, both HC and CO increase greatly, while NOx emission decrease with an increase of CNG substitution. The confirmation test showed the prediction model is statistically significant. This concluded that, the dual fuel system engine shows an improvement in terms of NOx compared to the diesel engine. Hence, contributing to the efficiency of the conversion process for dual fuel system.

Keywords: Engine Performances, Exhaust Emissions, CNG-Diesel Dual Fuel, Response Surface Methodology

1. Introduction

Automobile is one of the major causes of global warming since they are the main contributor of carbon dioxide and other greenhouse gases [1]. The combustion process from the conventional fuel engines such as those which burn petrol and diesel fuel is causing continuing damage to the environment [2], [3]. Therefore, alternative fuels have become more increasingly important. A lot of alternative fuels have been taken account to substitute the conventional fuels and one of them is Compressed natural gas (CNG).

**Corresponding author: fathul@uthm.edu.my*

Malaysia has taken an action by launched the Malaysian National Green Technology Policy in 2009. According to the policy, the 'green technology' should minimize environmental degradation, lower greenhouse gas emission, and conserving energy and natural resources [4]. Recently, National Automotive Policy (NAP 2020) was launched in February 2020 with an objective to continue to pursue the objectives of NAP 2014 of transforming the competitiveness of the Malaysian automotive industry to face the global challenges. NAP 2014 objective is to develop Malaysia as the regional automotive hub in energy-efficient vehicles (EEV). The EEV is specified by the type of vehicle that meets a certain level of carbon emission or fuel consumption [5], [6].

Compressed natural gas (CNG) is the alternative fuels that contain a mixture of gas species, which is methane, as a primary component with ethane content and other hydrocarbon content [7]. CNG is the alternative fuels known as eco-friendly fuel that has the clean nature of combustion [8]. CNG able to produce low polluted emission and wide availability in a huge quantity worldwide. Previous study found that power generator CI engine installed with a CNG dual-fuel system will have a positive impact on its environment due to a reduction in exhaust emissions with little or no loss of performance [9].

According to the study done by [10], the experiment was using the single cylinder spark ignition (SI) engine in order to study the effect CNG into the spark ignition engine. The result shown that CNG produced 18.50 % less than power compared to gasoline. Another study stated that, the results disclose that CNG in public transportation can provide to the improvement of urban air, reduce harmful health effects and social costs of air pollution. It was observed that, CNG produce lower greenhouse gases as compared to the conventional gasoline and diesel vehicles. On average, the reduction of CO and HC emission are 8.00 -20.00 %, 20.00 -98.00 % and 40.00 -87.00 % respectively by CNG [11], [12].

Response surface methodology (RSM) is used to establish mathematical relationships between engine speed and CNG fraction as a variables and torque, power, BSEC, HC, CO and NOx as the responses. RSM is an effective and economical method for evaluating factors of experiment variables that produce an output of responses. Besides, the result acquired by RSM analysis will give excellent system performance for optimized datasets. This method required a fewer test and less time consuming that the real experiment study. These advantages lead to the widely used of this approach in many studies especially in the optimization of engine output in compression ignition (CI) engines [13].

In this study, the following investigations were carried out. In order to tackle the issues poses by conventional fuels that environment hazards due to its high emission and high pollutant emission, unstable energy price and also a non-renewability of the fuel. This study was to predict the performance and emission CNG-Diesel Dual Fuel engine using Response Surface Methodology (RSM). Besides, graphically present the characteristic of CNG-Diesel Dual Fuel Engine in term of performance and emission compared to diesel engine. After that, validate the established predicted model using confirmation test.

2. Materials and Methods

2.1 Experimental design

The Design Expert version 11 software was used to develop the experimental model RSM. In this study, RSM was used as the methodological approach. The RSM is a sequence of designed experiments to acquire an optimal response. In RSM, the input and output variables are denoted as $\mathrm{X}_1, \mathrm{X}_2 \ldots, \mathrm{X}_\mathrm{k}$ and (y), respectively. The approximation functions (y) for RSM are usually based on low-order polynomial models; first order (equation 1), second order (equation 2), and quadratic model (equation 3) [14], [15].

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \varepsilon \qquad Eq. 1$$

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad Eq. 2$$

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum_{i}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad Eq. 3$$

The data generated from the experimental work will be used in the software to evaluate the variance analysis (ANOVA) with the fitted statistical significance and fitness test (LOF) models. The evaluation is made, based on the probability value (p-value), Adjusted R^2 (R^2_{Ajd}) and Predicted R^2(R^2_{Pred}), and Adequate Precision (AP) values. Diagnostic plots and their respective contour plots and response surface profiles were acquired based on the two factors (engine speeds and CNG fraction) on the responses (brake torque, brake power, BSEC, HC, CO and NOx) [13].

2.2 Experimental Setup

Figure 1 is displayed the schematic diagram experiment setup for this study. Toyota Hilux 2.5 L common-rail diesel engine with a direct fuel injection system, four-cylinder (in-line), four-stroke was used as the test engine in this experiment. The engine specification is shows in Table 2.1. The engine converted into a dual fuel system by installing the diesel-CNG dual fuel conversion kits. No modification was made to the original diesel engine.

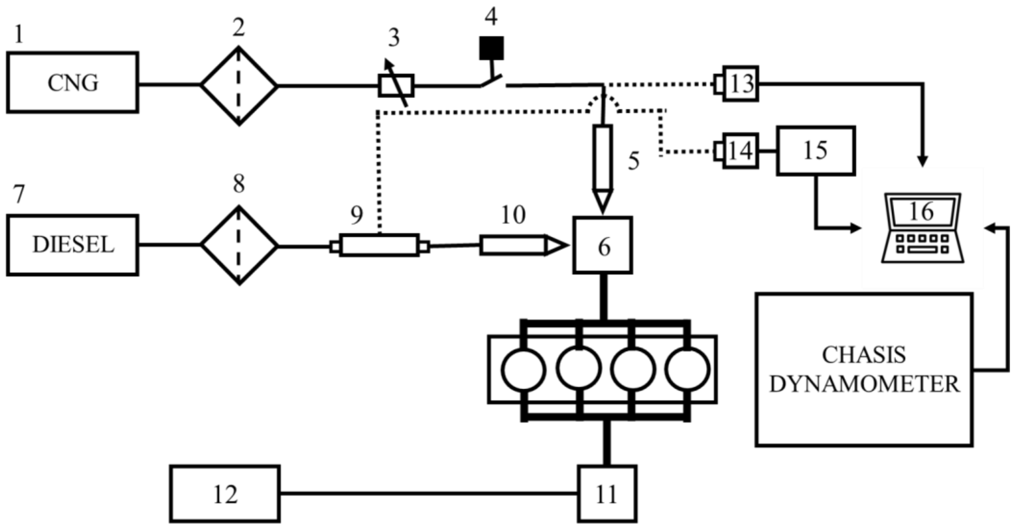


Figure 1: Schematic diagram of experimental setup

Table 1: The specification of Toyota Hilux 2.5 L common-rail direct injection diesel engine [16]

Engine Specification	Descriptions
Engine code	2KD-FTV
Bore x stroke	92.0 x 93.8 mm
Engine displacement	2494 cc
Compression ratio	17.4:1
Fuel injection system	Common rail direct injection
Maximum power	80 kW @ 3600 rpm
Maximum torque	325 Nm @ 2000 rpm

2.3 Fuel properties

Fuel resources provided for this study from the commercial refuelling station. Properties of test fuels is tabled in Table 2 and Table 3. In Malaysia, any standard Euro 2M diesel fuel contained 7 percent of palm methyl ester (PME) that complied with the Malaysian standard MS 2008.

Table 2: Properties of CNG test fuels [17]

Property	CNG
Gross heating value (MJ/Sm^3)	39.20
Specific gravity (compare to air)	0.6042
Flammability limit (%)	5-15
Compressibility	0.9977
Methane (vol.%)	93.07
Ethane (vol.%)	3.70
Propane (vol.%)	0.90
i-Butane (vol.%)	0.29
n-Butane (vol.%)	0.13
i-Pentane (vol.%)	0.07
C_{6+} (vol.%)	0.07
Nitrogen (vol.%)	0.68
Carbon dioxide (vol.%)	1.10

Table 3: Properties of Diesel test fuels [17]

Property	Diesel
Flash Point (PM, °C)	76
Kinematic viscosity (40°C)	3.21
Sulfur (mg/kg)	7.5
Cetane index	52
Density (15°C, kg/m^3)	831
Low heating value (MJ/kg)	43.15

2.3 Experiment procedure

The measurement was taken at five different CNG fraction which 0.00 %, 10.00 %, 20.00 %, 30.00 % and 40.00 %. The fuel fraction is monitored by using the OBD scan tool (Bosch KTS 570) for diesel and gas flow meter (Alicat Scientific M-250SLPM) is used for CNG. Each CNG substitution percent were tested at five engine speeds 1500, 2000, 2500,3000 and 3500 rpm. The hub type dynamometer (Dynapack 4WD chassis dynamometer) was used to determine the parameter of engine performance in terms of engine torque and power, while for brake specific energy consumption (BSEC) is calculated using equation 1. Besides that, the exhaust emission composition consists of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NOx) were measured using the Gas emission analyser by Anycar Autochek Gas & Smoke analyser. All the parameters were taken accordingly.

$$\text{BSEC} = \frac{(\dot{m}_{diesel} \times CV_{diesel} + \dot{m}_{CNG} \times CV_{CNG})}{brake\ power} \quad Eq.4$$

Where $\dot{m}$ = mass flow rate [kg/s]
CV = calorific value [MJ/kg]

The parameters were recorded, while engine was run in steady state condition. Where the engine is warmed at least five minutes and the temperature of coolant inside the engine reached varied from 85.00 °C and 90.00 °C. Besides, all engine speed for each test condition were using fourth gear (transmission ratio 1:1). The recorded average humidity is approximately 63.50 %, while the average ambient temperature is 29.83 °C. The reading of parameters was taken by controlling the gas throttle, where the engine speed was change from 1500 rpm to 3500 rpm with 500 rpm interval. In order to prevent human error, an in-house manufactured emulator is used to control the gas throttle. Then, the test continue for all the condition and the reading are taken.

3. Results and Discussion

3.1 Engine Performance

The analysis each model of engine performance were torque, power and brake specific energy consumption (BSEC). The ANOVA analysis of those model are presented as shown in Table 4, Table 5 and Table 6, respectively. The result from the ANOVA tables suggested the linear model for each model of engine performance. Every model has p-values for linear model less than 0.05, which proved that the model is significant. The lack of fit values is not significant in relation to the pure error where it is desirable. The pure error is the amount of difference between replicate runs. The Predicted R^2 is in reasonable agreement with the Adjusted R^2, where the difference is less than 0.2. The Adequate Precision (AP) measures the signal to noise ratio. A ratio greater than 4 is desirable and the model can be used to navigate the design space. The AP values for torque, power and BSEC model are greater than 4 and acceptable as a model.

The diagnostics plot for the torque model was depicted in Figure 2. The normal plot of residuals was presented in Figure 2 (a) and residuals versus predicted was presented in Figure 2 (b). The normal plot shows the data of residuals is following the straight line that interpreted as normally distributes and the residuals versus predicted plot indicates the data is randomly scatter. The contour plot (a) and the response surface profile (b) for the torque model are shown in Figure 3. The model shows high torque at low engine speed, while decreasing to higher speed due to the presence of CNG in the engine cylinder, better combustion was achieved. This leads to increasing engine speed yet; it would cause decreasing in engine torque. Mixture of Diesel and CNG could decrease the torque value as the increasing if engine speed. The equation for torque in the relationship between engine speed (A) and CNG fraction (B) shown in Equation 5.

$$\text{Torque} = 240.3868 - 0.0203368\text{A} - 0.45096\text{B} \quad Eq.5$$

Table 4: ANOVA table for torque

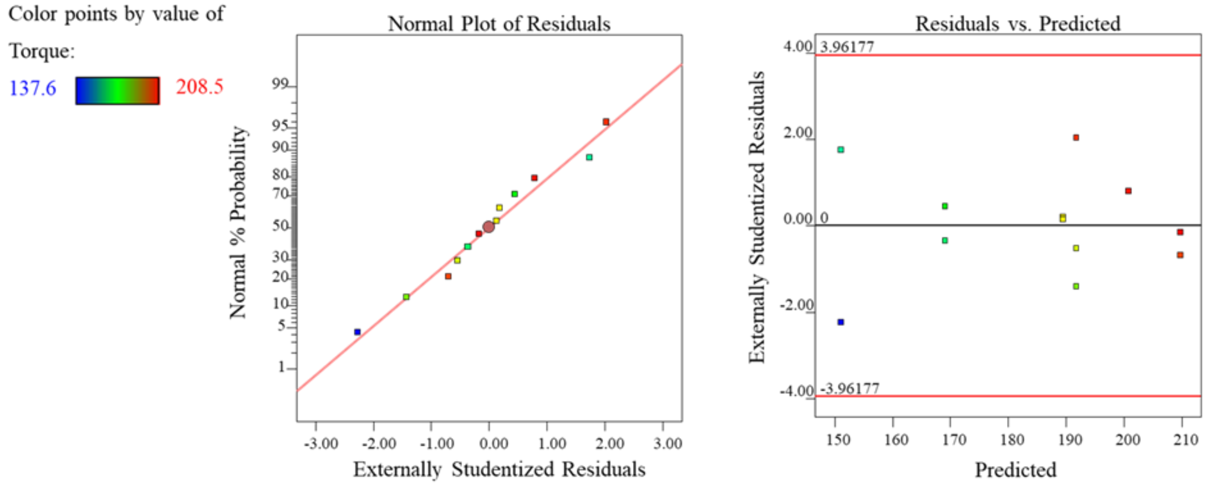
Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	4458.04	2	2229.02	26.97	0.0002	significant
A-Engine Speed	3946.43	1	3946.43	47.74	< 0.0001	
B-CNG Fraction	876.57	1	876.57	10.60	0.0099	
Residual	743.95	9	82.66			
Lack of Fit	76.90	3	25.63	0.2306	0.8720	not significant
Pure Error	667.05	6	111.18			
Cor Total	5201.99	11				
Std. Dev.		9.09		R^2		0.8570
Mean		184.67		Adjusted R^2		0.8252
C.V. %		4.92		Predicted R^2		0.7086
				Adeq Precision		12.9153

Table 5: ANOVA table for power

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	1928.18	2	964.09	114.55	< 0.0001	significant
A-Engine Speed	1739.38	1	1739.38	206.66	< 0.0001	
B-CNG Fraction	79.48	1	79.48	9.44	0.0133	
Residual	75.75	9	8.42			
Lack of Fit	22.73	3	7.58	0.8577	0.5120	not significant
Pure Error	53.02	6	8.84			
Cor Total	2003.93	11				
Std. Dev.		2.90		R^2		0.9622
Mean		43.50		Adjusted R^2		0.9538
C.V. %		6.67		Predicted R^2		0.9183
				Adeq Precision		22.3596

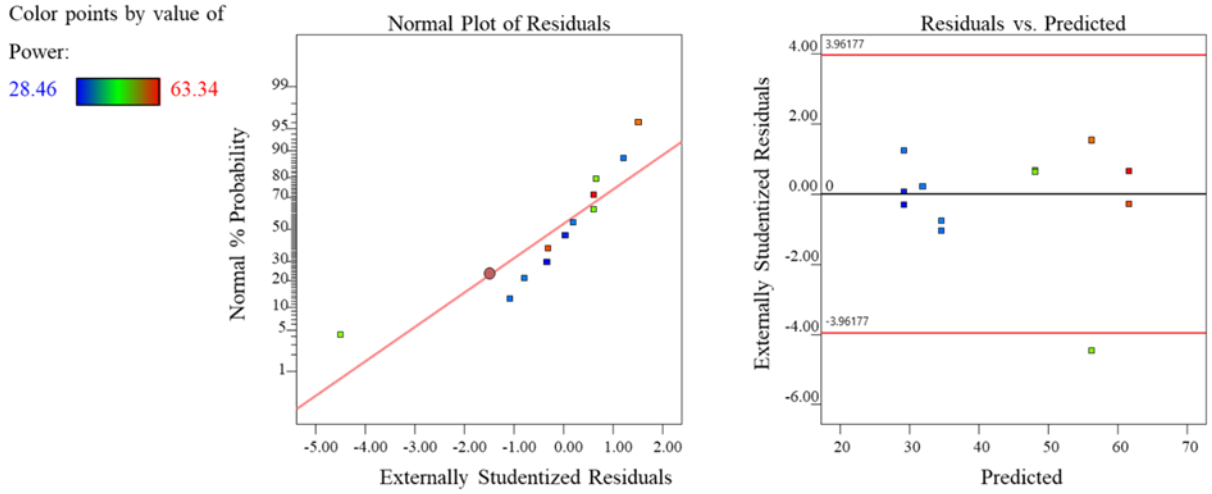
Table 6: ANOVA table for BSEC

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	21.86	2	10.93	22.44	0.0003	significant
A-Engine Speed	16.88	1	16.88	34.67	0.0002	
B-CNG Fraction	7.20	1	7.20	14.78	0.0039	
Residual	4.38	9	0.4870			
Lack of Fit	0.6909	3	0.2303	0.3742	0.7751	not significant
Pure Error	3.69	6	0.6154			
Cor Total	26.24	11				
Std. Dev.		0.6979		R^2		0.8330
Mean		11.04		Adjusted R^2		0.7959
C.V. %		6.32		Predicted R^2		0.6333
				Adeq Precision		12.3084



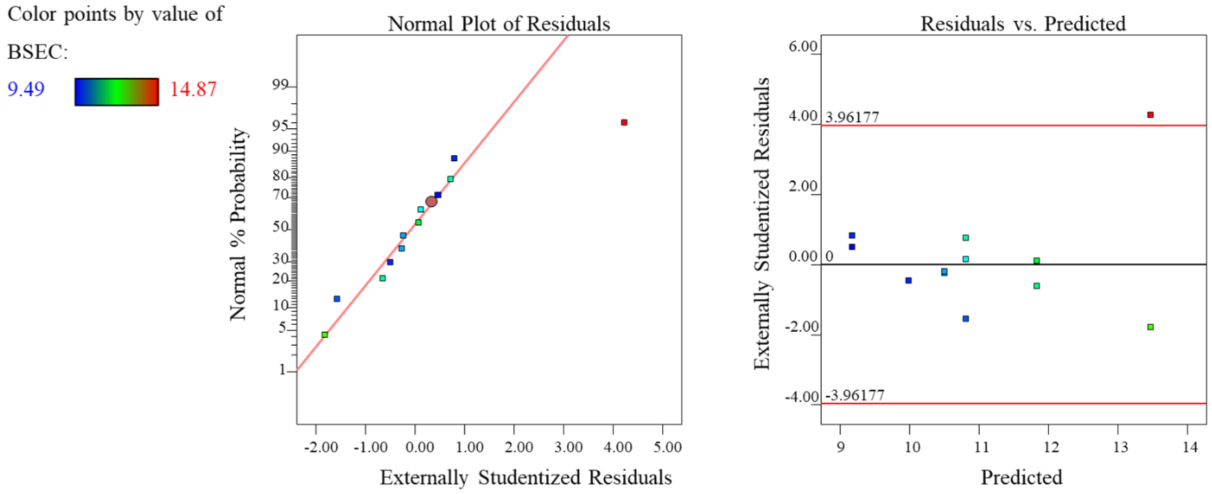
(a) (b)

Figure 2: Diagnostics plot for torque model (a) Normal Plot of Residuals (b) Residuals vs Predicted



(a) (b)

Figure 3: Diagnostics plot for power model (a) Normal Plot of Residuals (b) Residuals vs Predicted



(a) (b)

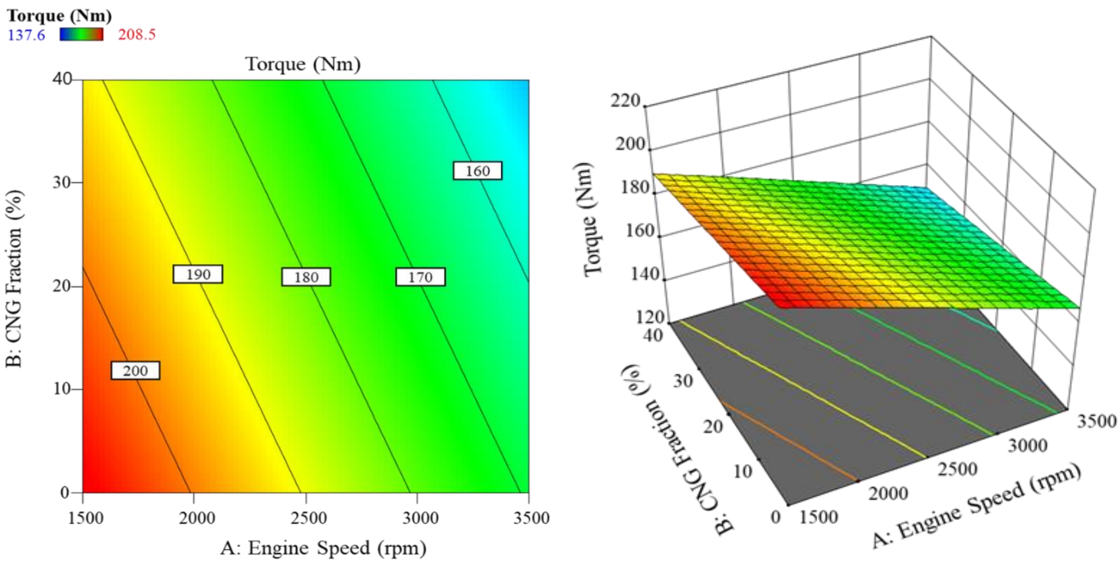
Figure 4: Diagnostics plot for BSEC model (a) Normal Plot of Residuals (b) Residuals vs Predicted

The diagnostics plots for the power model are presented in Figure 3. The normal probability plot in Figure 3 (a) shows the data of residuals is normally distributes and the residuals versus predicted is randomly scatter as presented in Figure 3 (b). It has indicated that the predicted model is statistically significant. The contour plot (a) and response surface profile (b) for the power model shown are in Figure 5. Based on Figure 6, when the substitution of CNG increase is causing a decreases of power produce by the dual fuel system. Power is directly proportional to torque, same as torque decrease with the increases of CNG fraction in fuel. Power also decreases as substitution of CNG increase. The prediction model's equation of power is presented in Equation 6.

$$\text{Power} = 14.487132 + 0.013501368\text{A} - 0.1357904\text{B} \quad \text{Eq. 6}$$

The diagnostics plots as shown in Figure 4 indicate that the predicted model is statistically significant where the residual is normally distributes in Figure 4 (a) Normal Plot of Residuals and the data is randomly scatter in Figure 4 (b) Residuals vs Predicted. Based on the contour plot (a) and its response surface profile (b) as presented in Figure 7, it shows that the engine is predicted to consume more energy as increasing of CNG fraction at all engine speed, resulting in less efficient production of usable power. The prediction model's equation of BSEC is presented in Equation 7.

$$\text{BSEC} = 7.1897778 + 0.0013301972\text{A} + 0.04085884\text{B} \quad \text{Eq. 7}$$



(a) (b)

Figure 5: The contour plot (a) and response surface profile (b) for the torque model

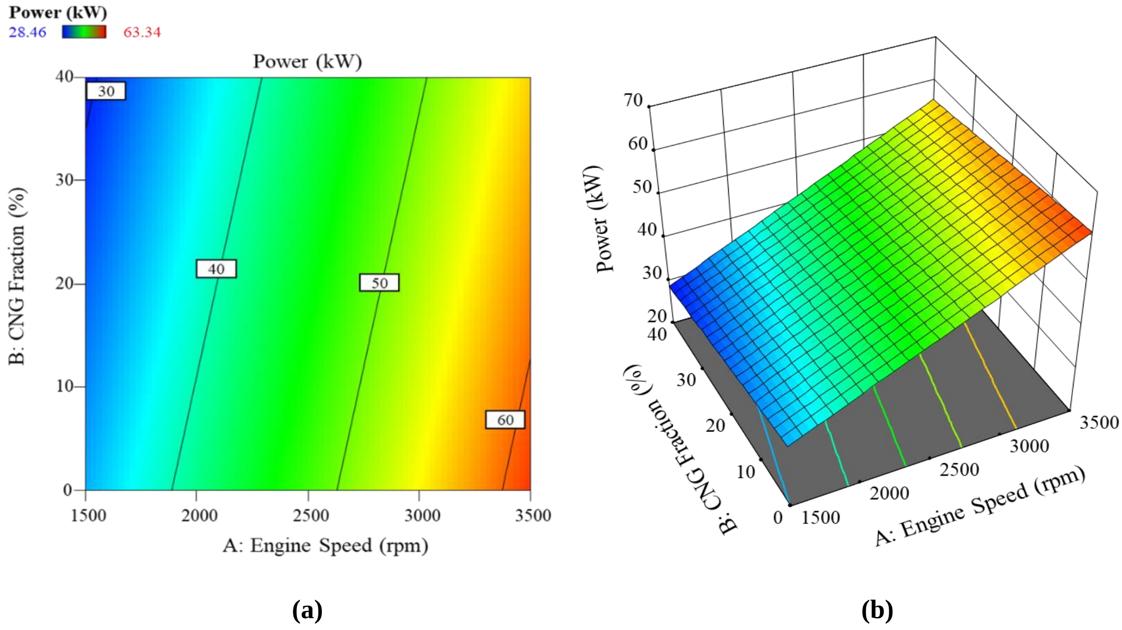


Figure 6: The contour plot (a) and response surface profile (b) for the power model

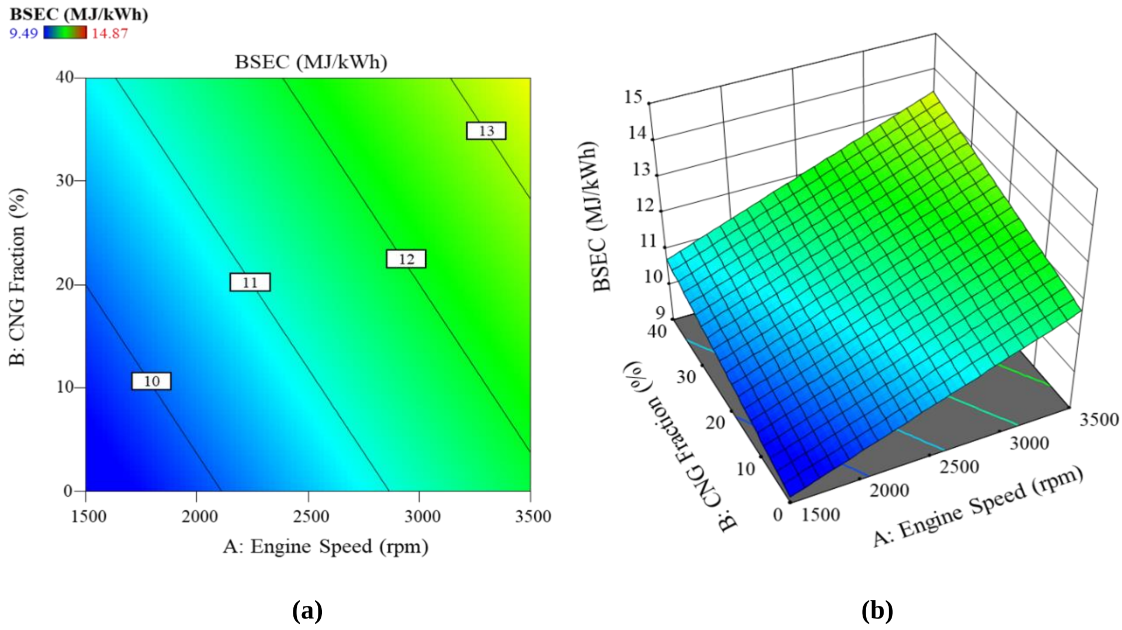
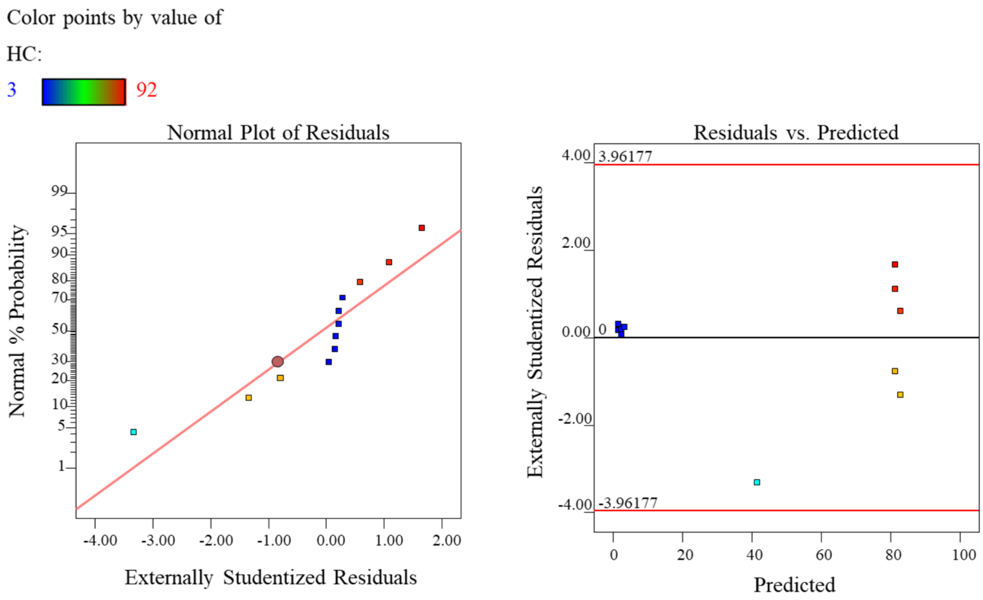


Figure 7: The contour plot (a) and response surface profile (b) for the BSEC model

3.2 Exhaust Emission

The diagnostics plots in Figure 8 shows the normal plot of the residuals did not follow the straight line but forming like an S-shaped curve. Besides, the residuals versus predicted plot shows the data is not randomly scatter but expanding like megaphone pattern. This has stipulated that the model transformation is required for HC model. Model transformation can be defined by the power function where it gives a scale satisfying the equal variance requirement of the statistical model. The transformation used the value of lambda (λ) in range -3 to +3.



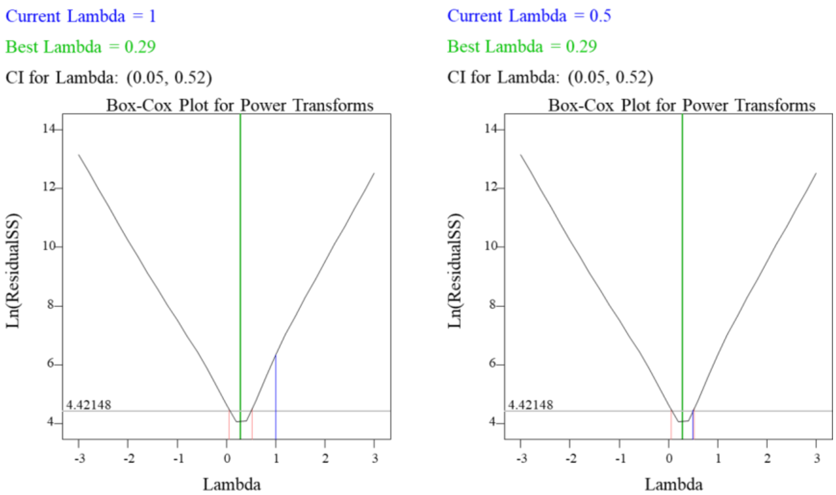
(a) **(b)**

Figure 8: Diagnostics plot for HC model (a) Normal Plot of Residuals (b) Residuals vs Predicted

Since model transformation is needed, the box-cox plot is used to determine the ideal power law transformation. Figure 9 (a) shows the box-cox plot for HC model. The current λ values equal to 1, while the confidence interval for λ values between 0.05 and 0.52. The recommended transformation is square root and gives the λ values equal to 0.5 as shown in Figure 9 (b).

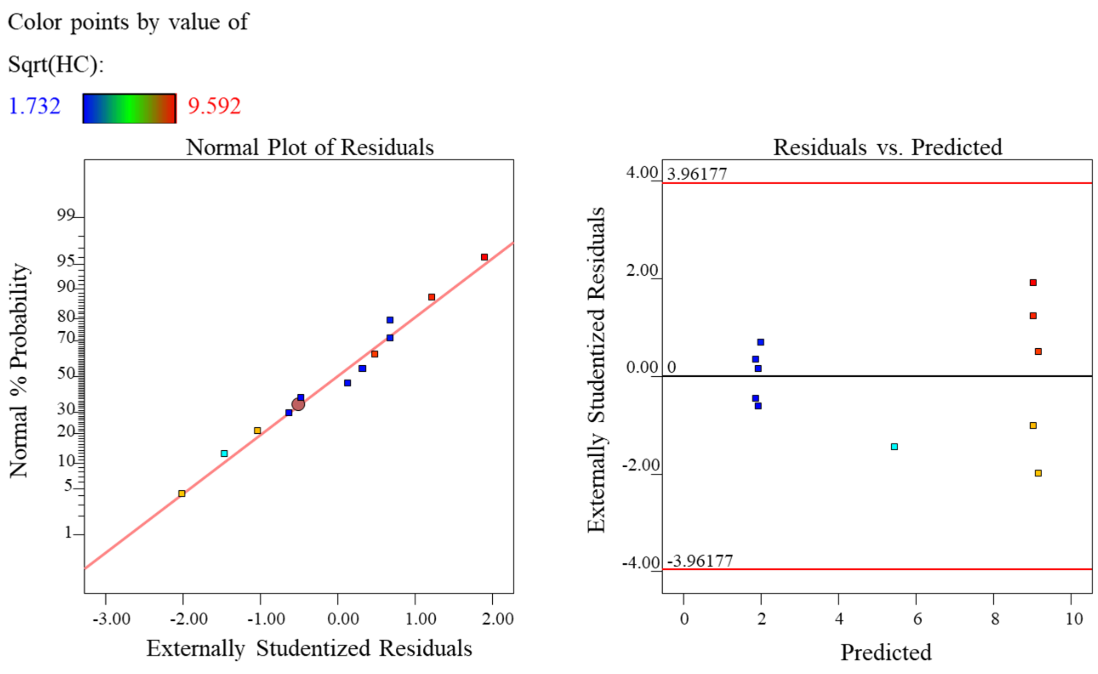
Then, the revised ANOVA for the HC emission model is shown in Table 7 and its predicted model is presented in equation 8. The ANOVA shows the revised HC model is statistically significant. The p-value for HC model is less than 0.05, the different between Adjusted R^2 and Predicted R^2 is less than 0.2, the AP values is greater than 4 and the LOF is insignificant, which are desirable for model. The revised plots show the normal probability plot is normally distributes and the residuals vs predicted data is randomly scatter as shown in Figure 10.

$$\mathrm{Sqrt(HC)} = 1.7935075737639 + 6.2732878031742e-05A + 0.17903955116717B \quad \text{Eq. 8}$$



(a) **(b)**

Figure 9: Box-Cox plot for Power Transformation (a) before transformation (b) after transformation for HC emissions model



(a) (b)

Figure 10: The re-diagnostics plot for HC emissions model (a) Normal Plot of Residuals (b) Residuals vs Predicted

Table 7: ANOVA table for HC

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	139.49	2	69.74	503.81	< 0.0001	significant
A-Engine Speed	0.0376	1	0.0376	0.2713	0.6151	
B-CNG Fraction	138.17	1	138.17	998.10	< 0.0001	
Residual	1.25	9	0.1384			
Lack of Fit	0.5178	3	0.1726	1.42	0.3257	not significant
Pure Error	0.7281	6	0.1214			
Cor Total	140.73	11				
Std. Dev.		0.3721		R^2		0.9911
Mean		5.22		Adjusted R^2		0.9892
C.V. %		7.12		Predicted R^2		0.9836
				Adeq Precision		39.1708

The diagnostics plots for CO emission model as shown in Figure 11 stipulate a similar finding as HC model where the residual is S-shaped curve pattern formed in Figure 11 (a) Normal Probability Plot and the data is not randomly scatter but expanding like megaphone pattern in Figure 11 (b) Residuals vs Predicted. Figure 12 (a) shows the box-cox plot for CO model. The confidence interval for λ values between -0.19 and 0.32 with the current λ values equal to 1. The recommended transformation is base 10 log and gives the λ values equal to 0 as shown in Figure 12 (b). The prediction model's equation of NOx is presented in Equation 9.

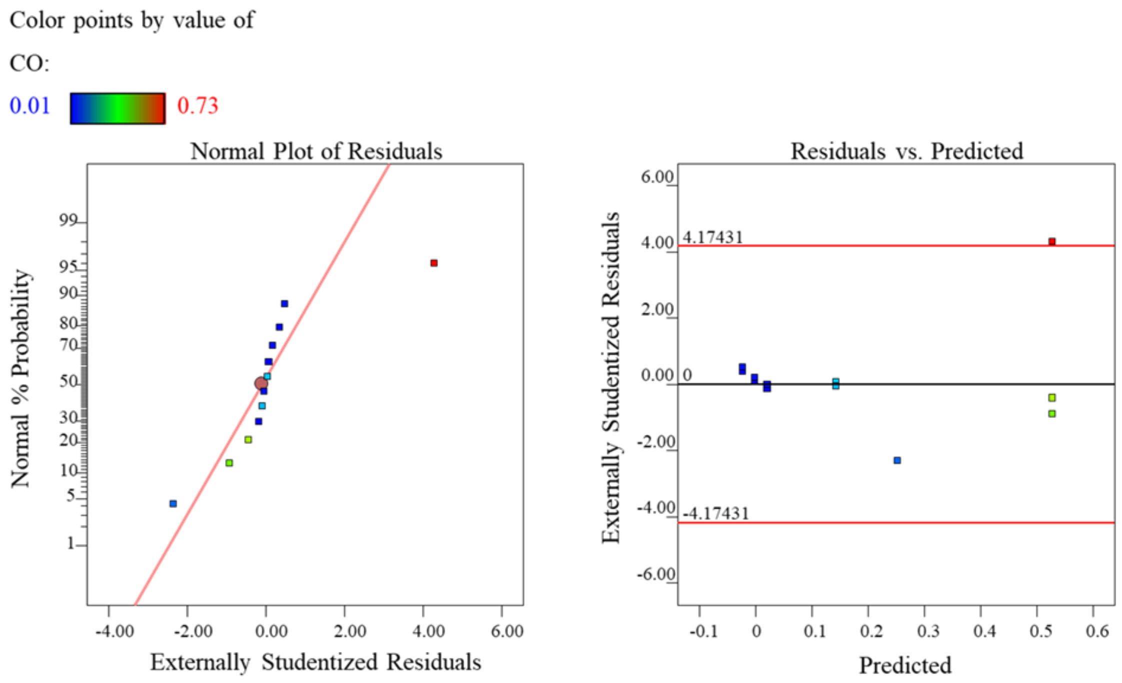
$$\mathrm{Log}^{10}(\mathrm{CO}) = -1.8628036980274 + 4.2059039555902e-06A \qquad \mathrm{Eq.\,9}$$

$$+0.050485442534874B - 7.2158929988942e-06AB$$

The revised ANOVA for CO emission model is presented in Table 8. The ANOVA for CO emissions model shows the two-factor interaction (2FI) model is suggested. The p-value for CO model is less than 0.0500 indicate model terms are significant. The Predicted R^2 of 0.9335, while the Adjusted R^2 of 0.9599 and the different between Adjusted R^2 and Predicted R^2 is less than 0.2. The AP values is 19.2573 indicates an adequate signal and the LOF is insignificant, which indicates the desired model. The revised plots of the normal probability plot and the residuals vs predicted are shown in Figure 13.

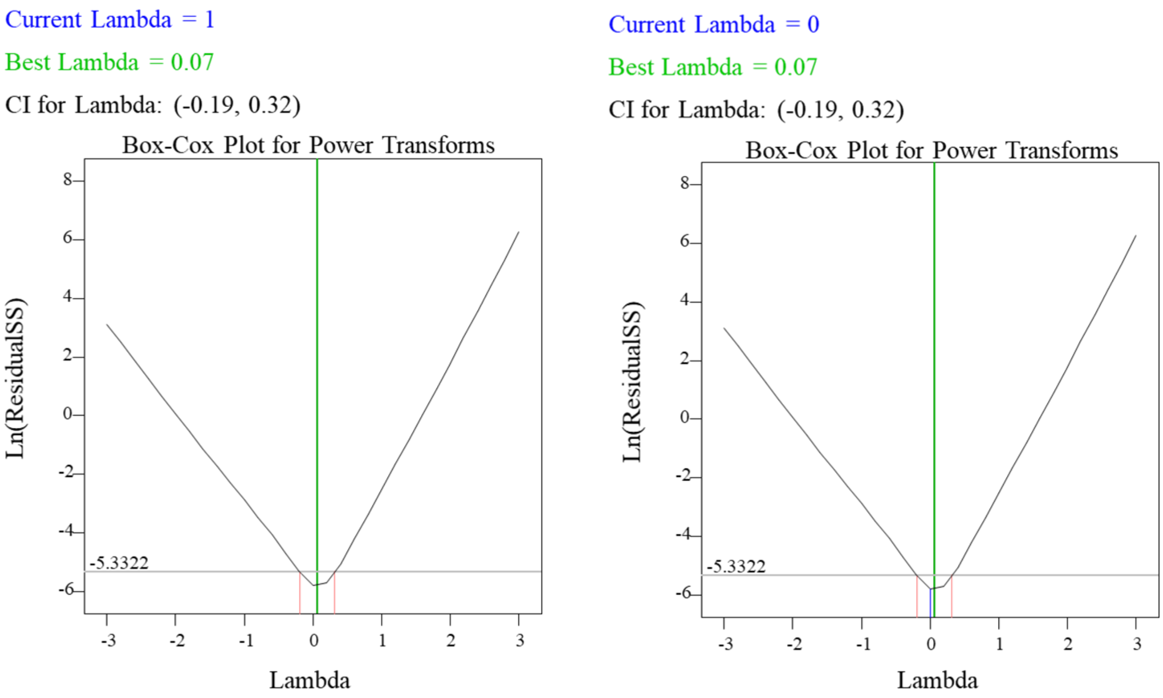
Table 8: ANOVA table for CO

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	5.42	3	1.81	88.75	< 0.0001	significant
A-Engine Speed	0.1862	1	0.1862	9.14	0.0165	
B-CNG Fraction	4.49	1	4.49	220.60	< 0.0001	
Residual	0.1824	1	0.1824	8.96	0.0173	
Lack of Fit	0.1629	8	0.0204			
Pure Error	0.0013	2	0.0007	0.0250	0.9754	not significant
Cor Total	0.1615	6	0.0269			
Std. Dev.		0.1427		R^2		0.9708
Mean		-1.22		Adjusted R^2		0.9599
C.V. %		11.68		Predicted R^2		0.9335
				Adeq Precision		19.2573



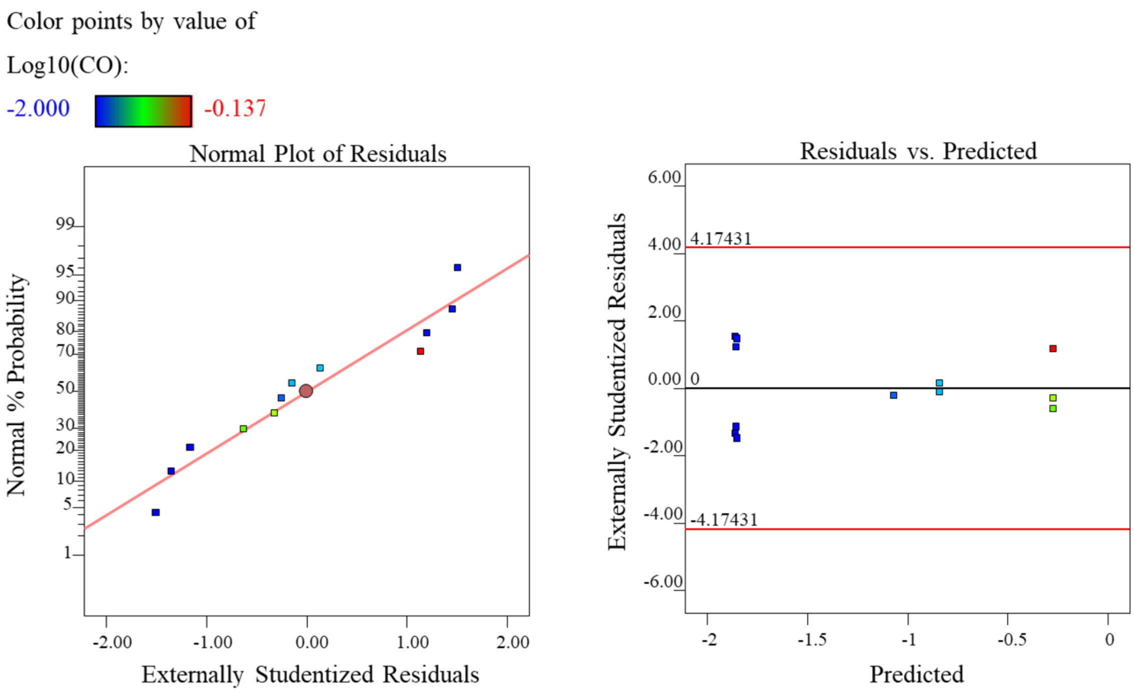
(a) (b)

Figure 11: Diagnostics plot for CO model (a) Normal Plot of Residuals (b) Residuals vs Predicted



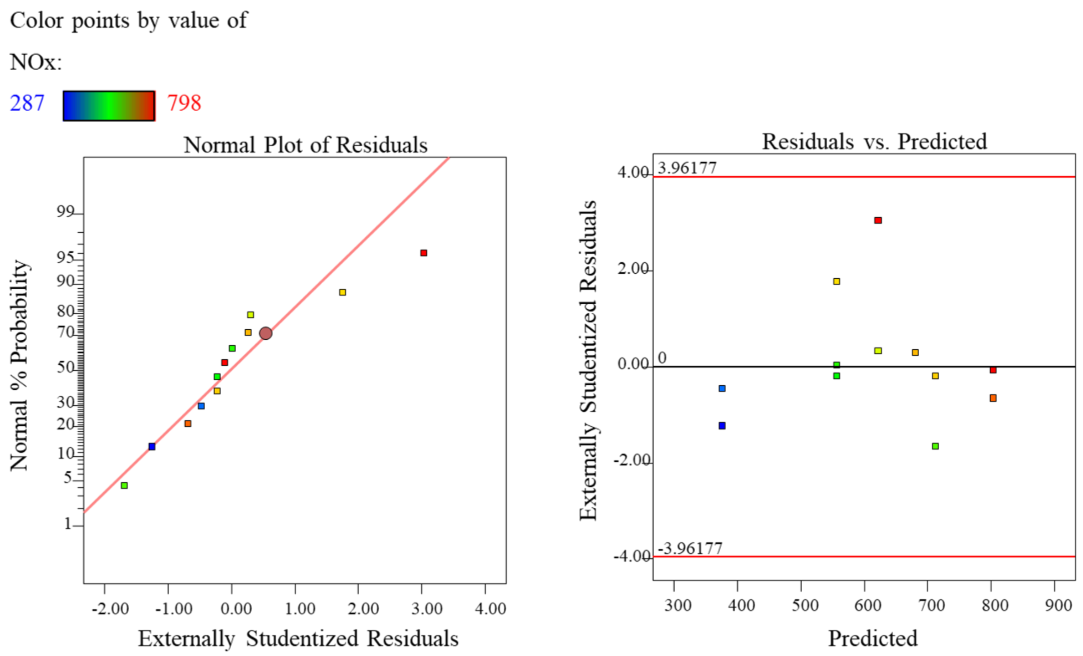
(a) **(b)**

Figure 12: Box-Cox plot for Power Transformation (a) before transformation (b) after transformation for CO emissions model



(a) **(b)**

Figure 13: The re-diagnostics plot for CO emissions model (a) Normal Plot of Residuals (b) Residuals vs Predicted



(a) **(b)**

Figure 14: Diagnostics plot for NOx model (a) Normal Plot of Residuals (b) Residuals vs Predicted

The diagnostics plots for the NOx model are presented in Figure 14. The normal probability plot in Figure 14 (a) shows the normality of residuals is normally distributes and the residuals versus predicted is randomly scatter as presented in Figure 14 (b). It has indicated that the predicted model is statistically significant. The prediction model's equation of NOx is presented in Equation 10.

$$\text{NOx} = 941.10160 - 0.090802A - 6.15352B \quad \text{Eq. 10}$$

The ANOVA for NOx emission model is presented in Table 3.6. The ANOVA for NOx emissions model shows the linear model is suggested. The p-value for NOx model is less than 0.0500 indicate model terms are significant. The Predicted R^2 of 0.5139, while the Adjusted R^2 of 0.6758, the different between Adjusted R^2 and Predicted R^2 is less than 0.2. The AP values is 9.1273 indicates an adequate signal and the LOF is insignificant, which indicates the model is statistically significant.

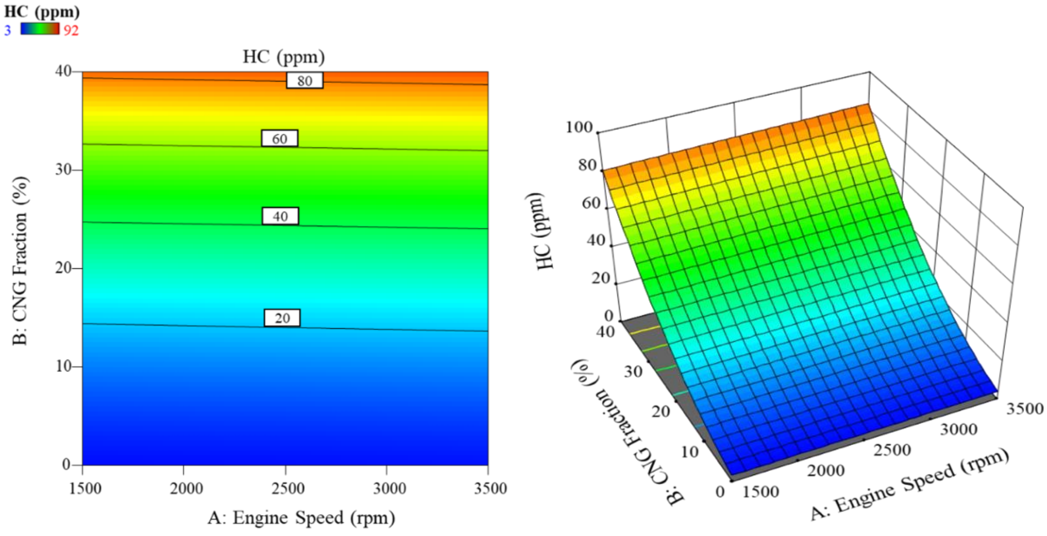
Table 9: ANOVA table for NOx

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	2.190E+05	2	1.095E+05	12.46	0.0026	significant
A-Engine Speed	78673.00	1	78673.00	8.96	0.0151	
B-CNG Fraction	1.632E+05	1	1.632E+05	18.58	0.0020	
Residual	79065.53	9	8785.06			
Lack of Fit	46518.87	3	15506.29	2.86	0.1267	not significant
Pure Error	32546.67	6	5424.44			
Cor Total	2.980E+05	11				
Std. Dev.		93.73		R^2		0.7347
Mean		616.42		Adjusted R^2		0.6758
C.V. %		15.21		Predicted R^2		0.5139
				Adeq Precision		9.1273

Figure 15 shows the contour plot (a) and the response surface profile (b) of the HC emissions model. The CNG fraction showed that the unburned fuel increased dramatically high due to substitution rate, most likely due to incomplete combustion of gaseous fuel. During the dual fuel combustion, a high amount of air (oxygen level) is required for complete combustion compared to diesel fuel. In term of engine speed, HC emissions not really affected by the engine speed:

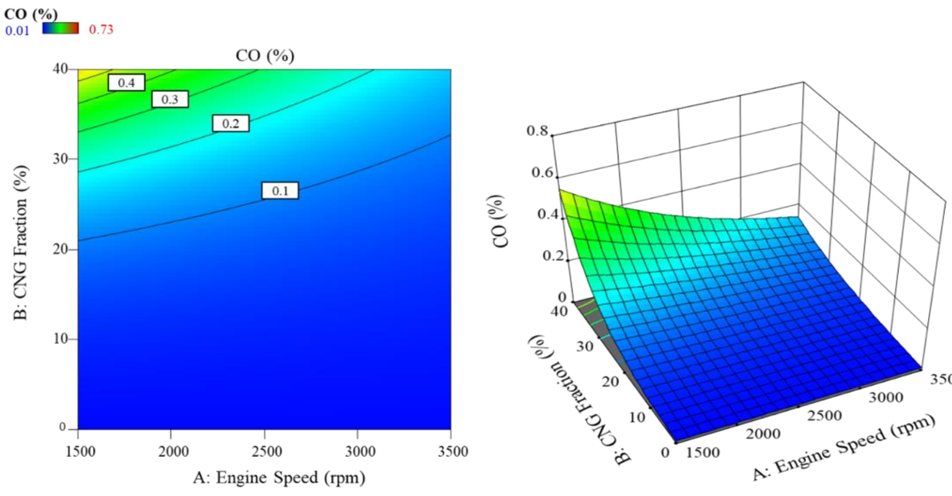
The contour plot (a) and the response surface profile (b) of the CO emissions model are shown in Figure 16. The figures proved that the CO emission emitted from the engine became higher in the presence of CNG in the fuel. CO was found decrease as the engine speed increase due to CO emission tend to increase when low temperature combustion (LTC) occurs.

Figure 17 shows the contour plot (a) and the response surface profile (b) of the NOx emissions model. The substitution of CNG has greatly decreased NOx formation because of it is greatly depends on high oxygen concentration. Due to the premixed combustion phase, the substitution of CNG has decreased the oxygen concentration. This is a major advantage because the post-treatment of this pollutant is very difficult for all engines with low content mixtures.



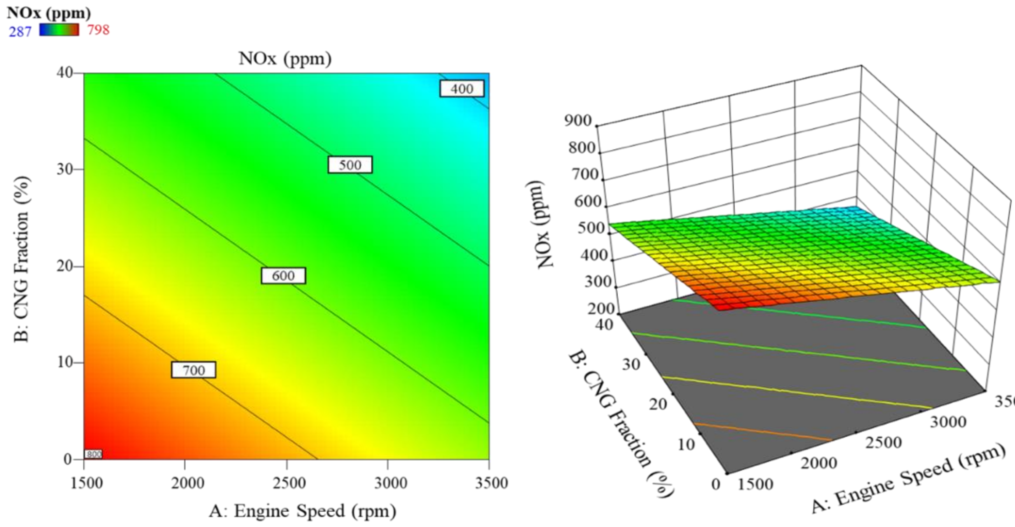
(a) **(b)**

Figure 15: The contour plot (a) and response surface profile (b) for the HC model



(a) **(b)**

Figure 16: The contour plot (a) and response surface profile (b) for the CO model



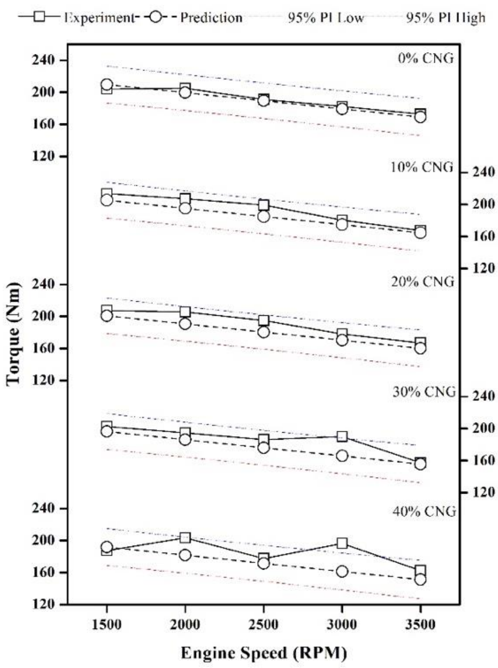
(a) **(b)**

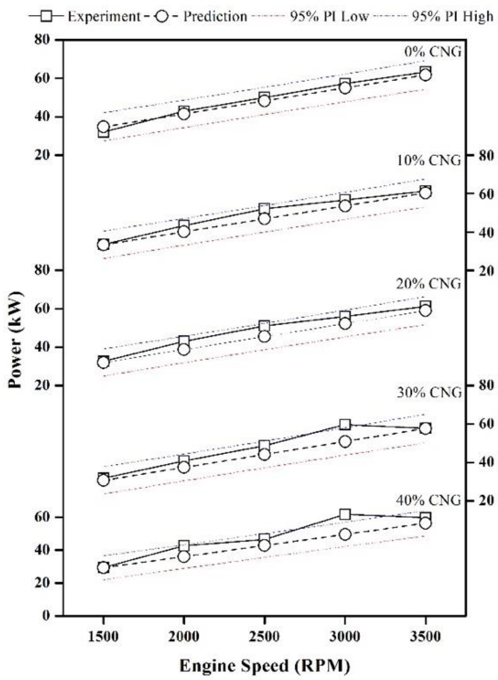
Figure 17: The contour plot (a) and response surface profile (b) for the NOx model

3.3 Model Validation

The confirmation test was made to validate the prediction model. In confirmation test, the prediction interval of the model was compared with the experiment data. The prediction interval is the statistical interval determined by the Design Expert software within 95.00 % confidence level. The prediction interval (PI) is presented by 95.00 % PI Low and 95.00 % PI High. The 95.00 % PI Low means the low value of the prediction interval that will contain the true value of an individual observation 95.00 % of the time, while 95.00 % PI High means the high value of the prediction interval. If the experiment data is inside the prediction interval then the model is confirmed. When the prediction model is confirmed, it is indicating that the developed model could predict well. All predicted models were tested at 0.00 %, 10.00 %, 20.00 %, 30.00 % and 40.00 % CNG fraction in range of 1500 rpm to 3500 rpm.

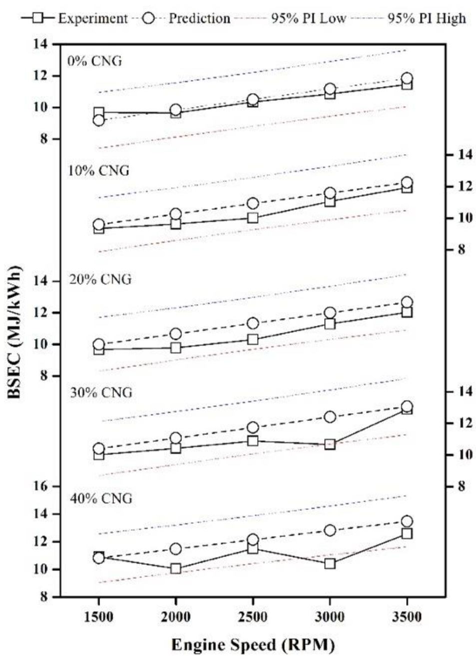
The validation for torque, power and BSEC prediction models are illustrated in Figure 18 (a), Figure 18 (b) and Figure 19 (a), respectively. The prediction values ware calculated by using Equation 1, 2 and 3. Two points are outside the prediction interval was observed for torque prediction model. One point at 30.00 % CNG substitution rate, during engine speed at 3000 rpm. Another points at 3000 rpm and CNG fraction at 40.00 %. The prediction model for power and BSEC are same as torque where two points are outside the prediction interval. One point at 3000 rpm and 30.00 % CNG fraction and another point at 3000 rpm and 40.00 % CNG fraction.

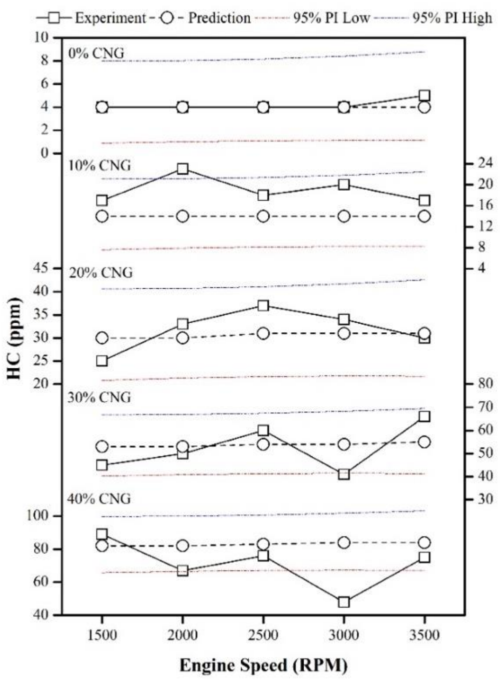




(a) **(b)**

Figure 18: Predicted versus experiment values for (a) torque prediction model (b) power prediction model





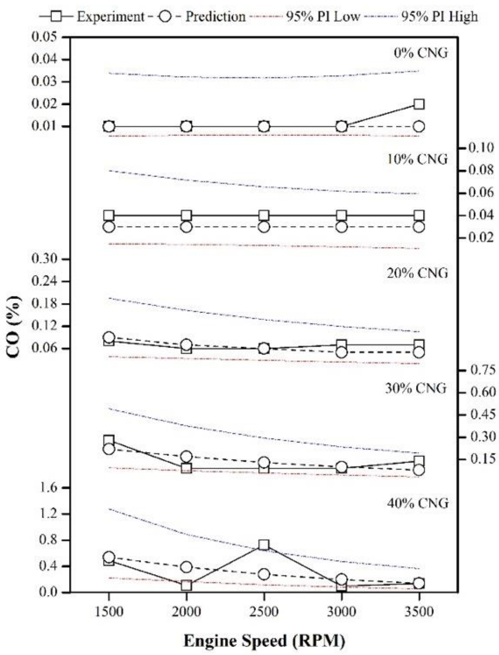
(a) **(b)**

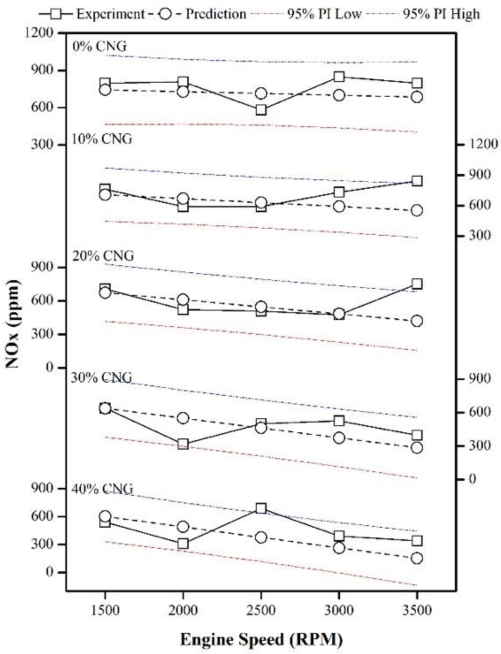
Figure 19: Predicted versus experiment values for (a) BSEC prediction model (b) HC prediction model

Figure 19 (b) shows the confirmation test for HC emission prediction model. The prediction values of model were determined using equation 4. For HC model, three points are outside the prediction interval was observed for HC prediction model. Two points at 3000 rpm of engine speed, during 30.00 % and 40.00 % CNG fraction, respectively. Another points at 2000 rpm and 10.00 % CNG fraction.

The confirmation test for CO prediction model is illustrated in Figure 20 (a). The prediction values of model were calculated using equation 5. The experimental results for CO were within the prediction interval, except for condition engine speed at 2000 rpm and CNG fraction at 40.00 % where the CO was observed at 0.11 % which is lower than prediction value, 0.16845 %.

The confirmation test for NOx is presented in Figure 20 (b). The prediction values were calculated using equation 6. The experimental results for power prediction model were within the prediction interval, except for condition engine speed at 2000 rpm and CNG fraction at 30.00 % where the NOx observed was outside the prediction interval and also other two points at 3500 rpm during 10.00 % and 20.00 % CNG fraction, respectively.





(a) **(b)**

Figure 20: Predicted versus experiment values for (a) CO prediction model (b) NOx prediction model

4. Conclusion

In this study, the aim was to investigate the performance and emission of CNG- diesel dual fuel engine, while comparing with the conventional diesel engine. From the results of this investigation, the following conclusions are drawn:

- The prediction model suggested for engine performances of torque, power and BSEC were linear model. As for exhaust emission models, both HC and NOx models also were suggested with linear model, while CO was predicted with 2 factor interaction (2FI). However, HC and CO models required model transformation due to the responses data did not met the residual assumptions. Residuals are assumed to be normally distributed with a constant variance.
- Based on the model graphs of contour plot and response surface profile, the performance of torque and power decreases with an increase of CNG substitution, while BSEC increase. This

might be so because of inefficient combustion occur at that operating condition. As for exhaust emissions, both HC and CO increase greatly, while NOx emission decrease with an increase of CNG substitution.

- From that, the performance of diesel engine is better than the DDF engine the exhaust emission of HC and CO, diesel engine has produced lower emission than DDF engine, while DDF engine produced lower NOx compared to diesel engine.
- The confirmation test was done for the model validation where the experiment data was compared to prediction models within its prediction interval. The prediction interval (PI) is presented by 95.00 % PI Low and 95.00 % PI High. If the experiment data is inside the prediction interval then the model is confirmed. As for torque, power, BSEC and CO, each have two points outside the prediction interval, while HC and NOx emission have three points outside the interval for both parameters. However, based on overall prediction models performance, the miss observations are acceptable.

Acknowledgement

The authors would like to thank the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia for its support.

References

[1] National Geographic, “The environmental impacts of cars, explained,” *NATIONAL GEOGRAPHIC*, 2019. [Online]. Available: https://www.nationalgeographic.com/environment/green-guide/buying-guides/car/environmental-impact/.

[2] S. Wasiu, S. Sulaiman, R. A. Aziz, and S. Azhar, “Effects of Different Injection Timings on the Performance and Emission Characteristics of the Direct-Injection Compressed Natural Gas Engine,” *International Journal of Applied Engineering Research ISSN*, vol. 13, no. 1, pp. 973–4562, 2018.

[3] A. A. A. Al-Saadi and I. Bin Aris, “CNG-diesel dual fuel engine: A review on emissions and alternative fuels,” *2015 10th Asian Control Conference: Emerging Control Techniques for a Sustainable World, ASCC 2015*, no. May, 2015.

[4] Malaysian Government, *National Policy on Green Technology*. 2009.

[5] M. Government, *NATIONAL AUTOMOTIVE POLICY (NAP) 2020*. 2020.

[6] M. R. A. Mansor, “EEV initiative: Paving the way for greener mobility in Malaysia,” *Journal of the Society of Automotive Engineers Malaysia, 2(2).*, 2018.

[7] M. M. Ismail, M. Fawzi, L. Theerayut, F. H. Zulkifli, S. A. Osman, and J. Taweekun, “Energy consumption and emissions of diesel-CNG dual fuel engine at high load operation,” *International Journal of Integrated Engineering*, vol. 12, no. 2, pp. 253–260, 2020.

[8] A. K. Singh, A. Sharma, and N. Kumar, “Performance and emission analysis of a CI engine in dual mode with CNG and karanja oil methyl ester,” *SAE Technical Papers*, no. September, 2014.

[9] T. Yusaf, P. Baker, I. Hamawand, and M. M. Noor, “Effect of compressed natural gas mixing on the engine performance and emissions,” *International Journal of Automotive and Mechanical Engineering*, vol. 8, no. 1, pp. 1416–1429, 2013.

[10] M. M. Tahir *et al.*, “Performance analysis of a spark ignition engine using compressed

natural gas (CNG) as fuel," *Energy Procedia*, vol. 68, pp. 355–362, 2015.

[11] M. I. Khan, T. Yasmin, and A. Shakoor, "International experience with compressed natural gas (CNG) as environmental friendly fuel," *Energy Systems*, vol. 6, no. 4, pp. 507–531, 2015.

[12] M. Saraswat and R. Gadi, "Assessment of Different Alternative Fuels For Internal Combustion Engine : A Review," *International Journal of Engineering Research & Management Technology*, vol. 2, no. 3, pp. 103–109, 2016.

[13] I. M. Yusri, R. Mamat, W. H. Azmi, A. I. Omar, M. A. Obed, and A. I. M. Shaiful, "Application of response surface methodology in optimization of performance and exhaust emissions of secondary butyl alcohol-gasoline blends in SI engine," *Energy Conversion and Management*, vol. 133, no. 2017, pp. 178–195, 2020.

[14] O. I. Awad *et al.*, "Response surface methodology (RSM) based multi-objective optimization of fusel oil -gasoline blends at di ff erent water content in SI engine," *Energy Conversion and Management*, vol. 150, no. July, pp. 222–241, 2017.

[15] N. Branch and A. Mechanzation, "INVESTIGATING THE EFFECTS OF BIODIESEL FROM WASTE COOKING OIL PERFORMANCE BY RESPONSE SURFACE METHODOLOGY," vol. 38, pp. 289–301, 2014.

[16] M. M. Ismail, F. H. Zulkifli, M. Fawzi, and S. A. Osman, "Conversion method of a diesel engine to a CNG-diesel dual fuel engine and its financial savings," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 8, pp. 5078–5083, 2016.

[17] Z. Abdul Majid, R. Mohsin, and A. H. Shihnan, "Engine performance and exhaust emission of diesel dual fuel engine fuelled by biodiesel, diesel and natural gas," *Jurnal Teknologi*, vol. 78, no. 6, pp. 59–67, 2016.