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Determination of a Spark Ignition Engine's Performance Parameters Using Response Surface Methodology

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Abstract

The combustion process in engines is highly influenced by the combined effect of various parameters. As far as the internal combustion engines are concerned, emission is the important parameters for which the other design and operating parameters have to be optimized. This paper studies the use of RSM (Response Surface Methodology) to optimize the performance parameters of a 4-stroke spark ignition engine. In this work, a description of the facilities developed for conducting experimental work on the test engine experiment was conducted. Theoretical evaluation, experimental evaluation, prediction of performance parameters using RSM and statistical evaluation of SI engine were performed. The study also explained how to build an analytical model for the complicated problem. The development of the incombustible gases concentration (part per million-ppm) as a function of engine speed (rpm), loading condition (%) and operating time (seconds) was done via 2^3 factorial designs of the experiment (DoE)and RSM. The results obtained from HC, CO and NO_x emission models showed that the engine speed, loading condition and time were found to have significant influence on the emission. The HC, CO and NO_x emission models have also proved positive response from the regression analysis of actual and predicted responses. In the error estimation with 95% confidence interval the equations are within the ranges. Thus, the response surface methodology provides useful information required for the experiment and also useful in predicting the response of engine parameters to engine emissions.

*Keywords:*Spark Ignition Engine, Performance, Parameters, RSM, Emission Model

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1. Introduction

Internal combustion engines have played an indispensable role in human society in a wide range of applications (industrial power generation, in powering automobile vehicles as well as electric generator for domestic purposes, etc.) due to their high reliability, low manufacturing cost and high power density. The two most common types of internal combustion engines are four-stroke spark ignition (SI) and compression ignition (CI) engines[8]. The number of spark ignition engines (electric generators) in Nigeria is increasing every day and the primary fuels which are used in these engines(gasoline and diesel) are derived from petroleum-based crude oil.

According to Zoran (2013) the spark ignition engines manufacturing industries is going through a period of rapid transformation. The impetus for innovation and development of advanced technologies is created by recognition of energy supply and climate change challenges, as well as awareness of market pressures and ever increasing consumers' expectations.Increased concern about rising fuel prices, limited petroleum supplies and greenhouse-gas emissions call for more advanced, efficient and cleaner spark ignition engines, SIE for industrial and domestic usages is louder than ever.

However, the world at large has been reported to be experiencing a serious problem due to pollutants from automotive exhaust gases and industrialization and increased rate of technological advancement have been found to be the causative factors. Cities around the world have become island of toxic chemicals from the unrestricted use of engine burning fossil fuels. Nigeria,among other countries, have recorded huge amount of causalities because of increase in the number of generators found in its environs [1]. Exhaust gases from internal combustion engines have adverse effect on human's life and properties. Some parameters which include engine load, engine speed, air-fuel ratio, volumetric efficiency, specific output, specific fuel consumption, thermal efficiency and heat balance, exhaust smoke and emissions, effective pressure and torque, power and mechanical efficiency are responsible for this incomplete combustion [7] and consequently affect the engine performance as well produce exhaust gases which have adverse effect on human health. The adverse effect of automotive exhaust is persuasive and difficult to measure.

Earlier studies show that the effect of injection system parameters has been investigated by the approach of ''varying one parameter at a time''. However the combustion process in engines are highly influenced by the combined effect of various parameters like air–fuel ratio and operating parameters like load and speed. Hence, a systematic multivariate study could only provide a clear and thorough knowledge on the combustion characteristics of the engine than the approach by one variable at a time study [4].

According to [6] as far as the internal combustion engines are concerned, the thermal efficiency and emission are the important parameters for which the other design and operating parameters have to be optimized. The most common optimization techniques used for engine analysis are response surface method, gray relational analysis, non-linear regression, genetic algorithm, and Taguchi method; Taguchi technique has been popular for parameter optimization in design of experiments.

Genetic Algorithm Optimization Approach

Genetic algorithm (GA) is an algorithm that simulates the natural evolution processes of creatures. The algorithm starts with a population of individuals representing different combinations of the operating parameters settings. An objective function is used to evaluate the quality of each individual and those with high qualities are selected as good solution with their attributes randomly combined to generate the next generation of individuals. Iterations of this process proceed until an optimal solution is found [8].

Although GA and engine modeling approaches have proven to be effective in optimization of engine operating parameters, their computational resource requirement is high and an insight into the effects and interactions of different operating parameters is not guaranteed [4].

Response Surface Methodology (RSM) Optimization Approach

Another method for optimization of engine operating parameters is RSM. It is useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [2]. RSM is a set of mathematical and statistical techniques seeking to optimize an objective function (or response) that is affected by multiple factors using design of experiments (DoE) methods and statistical analysis [3]. Instead of seeking the optimal solution within a large number of randomly generated candidates, RSM utilizes reduced and simplified experimental designs to gain a thorough understanding of the system as well as obtain the optimal combinations of operating parameters. It has been shown to be an effective and efficient tool for engine optimization that avoids extensive experimental testing and the need for a complicated CFD modeling process [8].

An advantage of RSM over other optimization methods such as GA is the capability of providing insights into the effects and interactions of different operating parameters while generating optimal outcome with a minimal number of experiments. The RSM approach was used in this research to optimize combustion and emissions in a diesel-hydrous ethanol RCCI engine as well as investigate the effects and interactions of key engine operating parameters[4].

RSM has been shown to be an effective and efficient approach for optimizing engine operating parameters where comprehensive physical understanding of their interactions have not been identified[8][4]used RSM to optimize the performance and emissions of a diesel engine fueled with diesel and biodiesel blend. The RSM models were shown to be capable of predicting brake specific energy consumption, brake thermal efficiency, CO, HC, NOX and smoke opacity and revealing the interactions between operating parameters such as injection pressure, injection timing and nozzle tip protrusion. In [8] a series of Design of Experiments (DoE) tests were conducted under each operating conditions to build statistical RSM models and derive optimal combinations of key engine parameters with reduced experimental time and resource costs.

In this work, the determination of performance parameters and analysed those incombustible particles through both the theoretical and experimental methods becomes necessary to further predict the performance and exhaust gas emissions of SI engine using Surface Response Method (SRM). The effort would pave the way for better control of engine operation and performance as well as extend the scope of application of spark ignition engine systems in an optimized manner.

The objectives of this investigation can be summarized as:

- Theoretical and experimental determination of the effect of some selected performance parameters on SI engine to obtain optimal overall performance and emissions output under selected engine operating conditions.
- Implementation of an optimization technique that could give global optimum parameters to achieve required performance and emission characteristics.
- Prediction of the performance parameters of SI engine using response surface methodology (RSM).

1. MATERIALS AND METHODS

In this work, a description of the facilities developed for conducting experimental work on the test engine experiment was conducted. Theoretical evaluation, experimental evaluation, prediction of performance parameters using RSM and statistical evaluation of SI engine were performed. The study also explained how to build an analytical model for the complicated problem. RSM designs are useful for investigating the nature of relationship between the response and factors. In practice, both the models and the parameter values are unknown, and subject to uncertainty on top of ignorance. Of course, an estimated optimum point need not be optimum in reality, because of the errors of the estimates and of the inadequacies of the model. Nonetheless, response surface methodology has an effective track-record of helping researchers improve products and services [2].

i. **Linear Regression Model Design:** The development of the incombustible gases concentration (part per million-ppm) as a function of engine speed (rpm), engine load (%) and operating time (seconds) was done via 2^3 factorial designs of the experiment and RSM. The functional relationship between exhaust gas response and independent variable according to [5] can be expressed as

$$E = C \times n_e^a \times l_c^b \times t_o^c \qquad (1)$$

The parameter or regression coefficient was later represented in linear form in terms of the logarithmic expression shown presented below

$$\ln E = \ln C + a\ln l_c + c\ln t_o \qquad (2)$$

The approximate true response surface over small region of independent variable space was presented by first order model in terms of the coded variables

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (3)$$

Where, ε represents the random error including effects like measurement error on response, background noise and the effect of other variables. The β in equation 3 is chosen so that the sum of square of the error ε is minimized.
The true response of surface roughness η on a logarithm scale with $x_o = 1$, x_1, x_2 and x_3 where the logarithm transformations of the engine speed, engine load and operating time β_o, β_1, β_2 and β_3 are parameters to be estimated.

$$\eta = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (4)$$

Then, predicted error

$$\hat{y} = y - \varepsilon = b_o + b_1 x_1 + b_2 x_2 + b_3 x_3.. \qquad (5)$$

Where $\hat{y}$is the estimated exhaust gas content, y is the exhaust gas content on logarithmic scale, ε experimental random error and b estimated value of β parameters. The b values are to be estimated by least square method using

$$b = (X^T X)^{-1} X^T y \qquad (6)$$

The variance covariance matrix of b is obtained by

$$x_1 = \frac{ln\, n_e - ln\, 3000}{ln\, 4000 - ln\, 3000} = 3.4761\, ln\, n_e - 27.8309 \qquad (7)$$

$$x_2 = \frac{ln\, l_e - ln\, 50}{ln\, 100 - ln\, 50} = 1.4427\, ln\, nl_c - 5.6439 \qquad (8)$$

$$x_3 = \frac{ln\, t_o - ln\, 2}{ln\, 10 - ln\, 2} = 0.6213\, ln\, t_o - 0.4307 \qquad (9)$$

Table 1: Level of the independent variables and coding identification

S/N	Level	Low	Centre	High
1	Coding	-1	0	1
2	Engine speed n_e (rpm)	2000	3000	4000
3	Loading condition l_c (%)	50	75	100
4	Operating time t_o (min)	2	6	10

Table 2: Experiment condition and the coding identification

Trial No.	Independent variable			Coding		
	Engine Speed (n_e)	Engine Load (l_c)	Operating time (t_o) (min)	X_1	X_2	X_3
1	2000	50	2	-1	-1	-1
2	4000	50	2	1	-1	-1
3	2000	100	2	-1	1	-1
4	4000	100	2	1	1	-1
5	2000	50	10	-1	-1	1
6	4000	50	10	1	-1	1
7	2000	100	10	-1	1	1
8	4000	100	10	1	1	1
9	3000	75	6	0	0	0
10	3000	75	6	0	0	0
11	3000	75	6	0	0	0
12	3000	75	6	0	0	0

Experimental Analysis: A 4-stroke cylinder horizontal shaft spark ignition engine coupled to a 2.5kVA alternator (electric generator) was used to conduct the experiments. The engine used run on 100% PMS. Table 1 shows the engine's specification for the engine used.

The materials and apparatus used for the experiment in this research include: Elepaq 2.5kVA electric generator, Nova 7460 series engine exhaust gas analyzer, Hydra PT-110 Non-contact laser Tachometer, Locally fabricated electric load simulator, Burette, Retort stand, Fuel tank, Hose, Petrol fuel, Fuel tank stand, Stop watch. The experimental analysis was carried out to determine the effect of engine load and engine speed on fuel consumption and exhaust gas emissions of SI engine.

Table 3: Engine Specifications

S/N	Parameters	Value	S/N	Parameters	Value
1.	Model	Honda	8.	Cycle	Four stroke
2.	Type	Air cooled, SI engine	9.	Maximum speed	5500 rpm
3.	Number of cylinder	1	10.	Maximum torque	7.4 Nm
4.	Bore –Stroke (mm)	60 x 42 mm	11.	Maximum power	2.5 Kw
5.	Connecting rod	78 mm	12.	Dimension	305 x 341 x 318 mm
6.	Displacement	118 cm^3	13.	Dry weight	13 kg
7.	Clearance volume	10.05 cm^3			

A locally fabricated electric load simulator which consist of twelve different light bulbs of 200W each and one light bulb of 100W (total of 2.5kW) wired in parallel, with every two bulbs sharing a switch, was used to allow easy loading and flexible testing. A schematic diagram of the load simulator is illustrated in figure 1. Three different engine speeds were also considered (low, medium and high) for the experiment. The actual speed in rpm was measured by using a hand hold PT-110 Non-Contact Laser Tachometer.

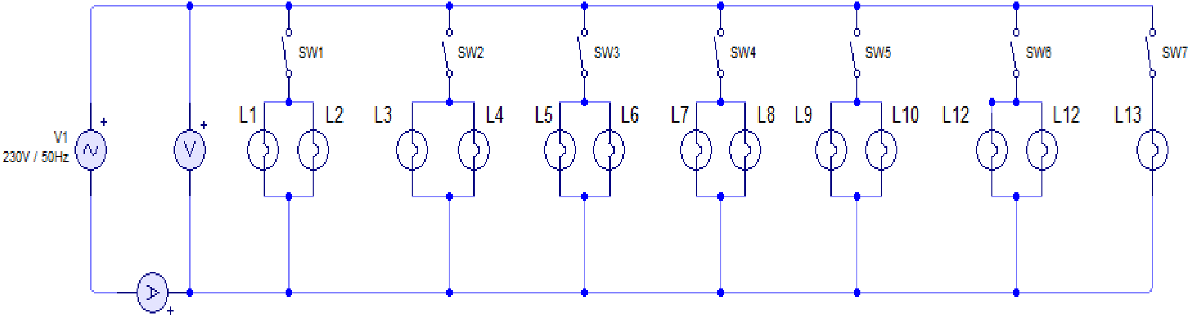


Figure 1: Circuit Diagram of the Load Simulator

Table 4: Stage setting for each of the different operating variable during the experiment

	Stages								
	1	2	3	4	5	6	7	8	9
Engine speed n_e (rpm)	1000	2000	2000	2000	2500	3000	3000	3000	3000
Loading condition l_c (%)	25	50	50	100	100	75	50	75	50
Operating time t_o (min)	2	6	10	2	10	6	2	6	2
	Stages								
	1	2	3	4	5	6	7	8	9
Engine speed n_e (rpm)	4000	4000	4000	4000	3000	2500	2000	2000	1000
Loading condition v_t (%)	50	50	100	100	75	50	75	35	25
Operating time t_o (min)	4	10	2	10	6	2	6	1	1

Exhaust gas emissions were also measured by using a portable NOVA 7460 series engine exhaust gas analyzer. The worst pollutant in the SI engine exhaust emissions is CO, NOx and HC which are the basic exhaust gas emissions of interest. The NOVA 7460 can measure concentrations of O_2, CO, CO_2, NO, NO_2 and HC.

Experimental procedures: Experiments were conducted at several stages with combination of loading condition (50, 75 and 100%) and engine speed from 2000 to 4000 rpm. There were 12 stages of combination and after 20 minutes, the engine and exhaust analyzer is warmed up before the performance test was run and the experiment starts and the data collected. The engine was run according to the stages earlier set while the engine speed (rpm) using Tachometer increases from 2000 to 4000, then decreases again till 1000 rpm as shown in table 4. The exhaust gas emissions readings of CO, NO_x and HC were later measured using NOVA exhaust gas analyzer and recorded at interval of two (2) minutes before each stage of operating time lapsed.

Results and Discussions

Experiments were conducted by varying parameters. During experimental investigation, the results of the exhaust gases (i.e. CO, NO_x and HC) were recorded as shown in table 5.

From the comparative evaluation of the experimental results for the different operating conditions, it is revealed that there is a great influence of the engine speed, loading conditions and operating time.

Linear regression model of emissions: The coefficients of the functions were obtained via the least square method while developing a regression model. Matlab 9.0 was later used in obtaining the parameter b (Table 6) in the formula,

$$b = (X^T X)^{-1} X^T y \qquad (10)$$

With present four coefficients, the estimated responses in linear form can be developed in model

$$\hat{y}_{HC} = 6.8213 + 0.3520x_1 - 0.06712x_2 - 0.000908x_3 \qquad (11)$$

$$\hat{y}_{CO} = 1.5435 + 0.3124x_1 - 0.4776x_2 - 0.001048x_3 \qquad (12)$$

$$\hat{y}_{NO_x} = 0.5639 + 0.1660x_1 - 0.06936x_2 - 0.005762x_3 \qquad (13)$$

Substituting the transform of each independent variable of equation (8), (9) and (10) into (11), (12) and (13), another set of equation written as $\boldsymbol{\hat{y}}$ = In E were formed. Therefore the estimated response of emission concentration, E in logarithmic functions is written as

$$ln(E_{HC}) = -2.5960 + 1.2236ln(n_e) - 0.09683\ ln(l_c) - 0.000564\ ln(t_o) \qquad (14)$$

$$ln(E_{CO}) = -4.4549 + 1.0859ln(n_e) - 0.6890\ ln(l_c) - 0.000651\ ln(t_o) \qquad (15)$$

$$ln(E_{NO_x}) = -3.6620 + 0.577\ ln(n_e) - 0.1000\ ln(l_c) - 0.003580\ ln(t_o) \qquad (16)$$

Transforming equation (14), (15) and (16) to exponential form, the emission concentration in percentage volume over the three selected parameters now become

$$E_{HC} = 0.07457\, {n_e}^{1.2236} \quad {l_c}^{-0.09683}\, {t_o}^{-0.000564} \qquad (17)$$

$$E_{CO} = 0.01162\, {n_e}^{1.0859} \quad {l_c}^{-0.6890}\, {t_o}^{-0.000651} \qquad (18)$$

$$E_{NO_x} = 0.02568\, {n_e}^{0.577} \quad {l_c}^{-0.1000}\, {t_o}^{-0.003580} \qquad (19)$$

Equation 18), (19) and (20) will now validate the emissions of HC, CO and NO_x as developed from least square method and DOE.

Table 5: Experimental results of exhaust emission concentration

Trial No.	Independent variable			Coding			Emission concentrations			$\hat{y} = \ln E$		
	n_e (rpm)	l_c (%)	t_o (min)	X_1	X_2	X_3	E_{HC} (ppm)	E_{CO} (ppm)	E_{NOx} (ppm)	HC	CO	NO_x
1	2000	50	2	-1	-1	-1	558.50	3.0134	1.3910	6.3253	1.1031	0.3300
2	4000	50	2	1	-1	-1	1304.26	6.3958	2.0750	7.1734	1.8556	0.7300
3	2000	100	2	-1	1	-1	522.25	1.8690	1.2978	6.2581	0.6254	0.2607
4	400	100	2	1	1	-1	1219.5	3.967	1.936	7.106	1.378	0.660

Table 6: Values of parameter β for regression model of HC, CO and NO_x

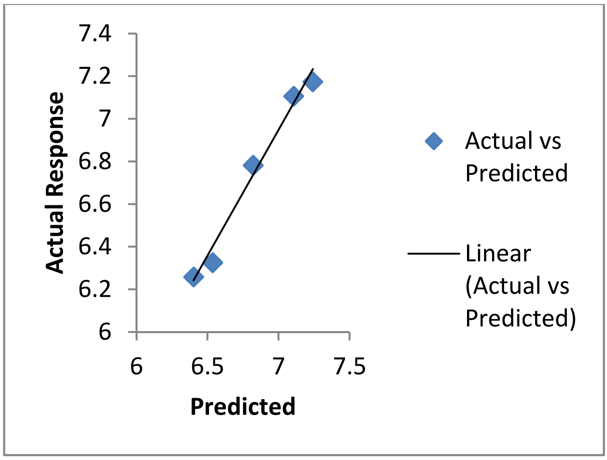
Parameters	Values of parameter HC	CO	NO_x
β_0	6.8213	1.5435	0.5639
β_1	0.3520	0.3124	0.1660
β_2	-0.06712	-0.4776	-0.06936
β_3	-0.000908	-0.001048	-0.005762

By using ANOVA and evaluated with 95% confidence limit to validate and analyze the model equations for further emission prediction.

Table 7: Comparison of actual emission values and predicted emission value

Trial No.	Independent variable			Coding			Emission Response in logarithmic form Predicted			Actual			Difference		
	n_e (rpm)	l_c (%)	t_o (min)	X_1	X_2	X_3	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x
1	2000	50	2	-1	-1	-1	6.5373	1.7097	0.4730	6.3253	1.1031	0.3300	0.2120	0.6066	0.1430
2	4000	50	2	1	-1	-1	7.2413	2.3345	0.8050	7.1734	1.8556	0.7300	0.0679	0.4789	0.0750
3	2000	100	2	-1	1	-1	6.4031	0.7545	0.3343	6.2581	0.6254	0.2607	0.1450	0.1291	0.0736
4	4000	100	2	1	1	-1	7.1071	1.3793	0.6663	7.1063	1.3781	0.6606	0.0008	0.0012	0.0057
5	2000	50	10	-1	-1	1	6.5355	1.7077	0.4615	6.3243	1.1050	0.3243	0.2112	0.6027	0.1372
6	4000	50	10	1	-1	1	7.2395	2.3325	0.7935	7.1725	1.8576	0.7242	0.0670	0.4749	0.0693
7	2000	100	10	-1	1	1	6.4013	0.7525	0.3228	6.257	0.627	0.2550	0.144	0.497	0.0678

It is found that error between the HC predicted responses and actual responses are small when x_1 and x_2 are positive that is shown in Table 7. The plot of actual response against predicted response of HC is presented in fig. 2. It was found that a regression value of 0.98 is obtained which is an indication that the relationship between actual and predicted responses is positive. Fig. 3 also showed a regression value of 0.83 which also shows positive relationship between actual and predicted response of CO emission.



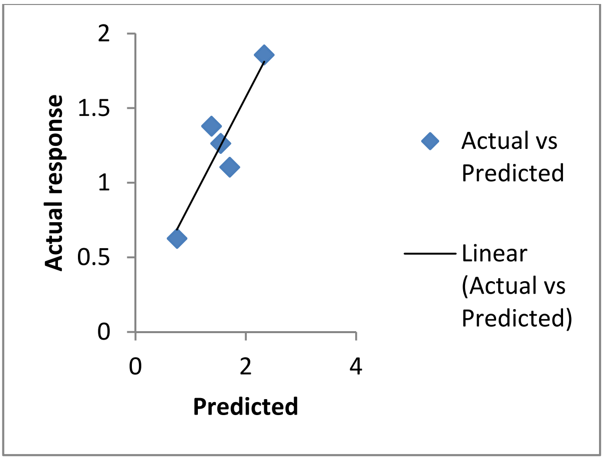


Fig. 2: Plot of Actual Response against Predicted for HC emission

Fig. 3: Plot of Actual Response against Predicted for CO emission

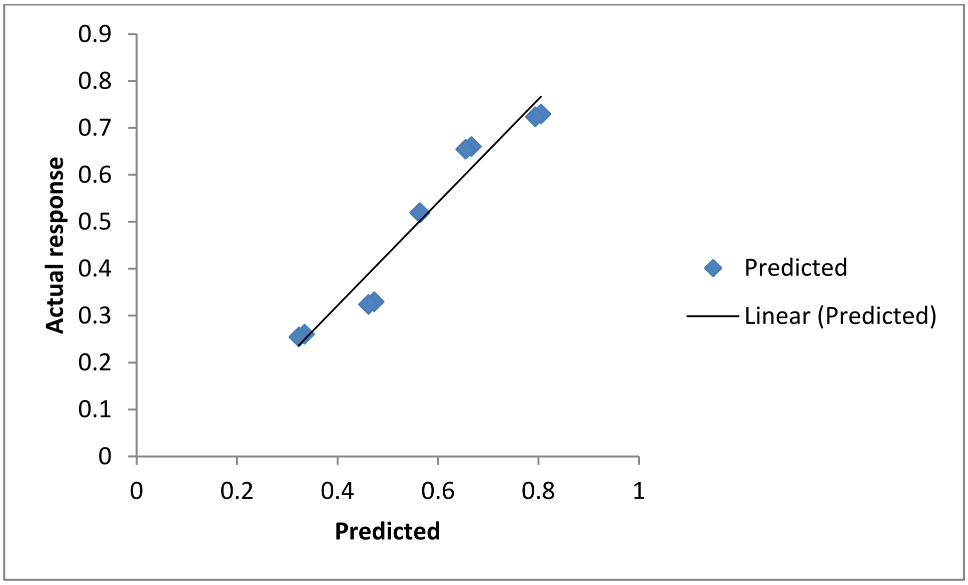


Fig. 4: Plot of Actual Response against Predicted for NO_x emission

The plot of actual response against predicted response of NO_x is presented in fig. 4. It was found that a regression value of 0.94 is obtained which is an indication that the relationship between actual and predicted responses is positive.

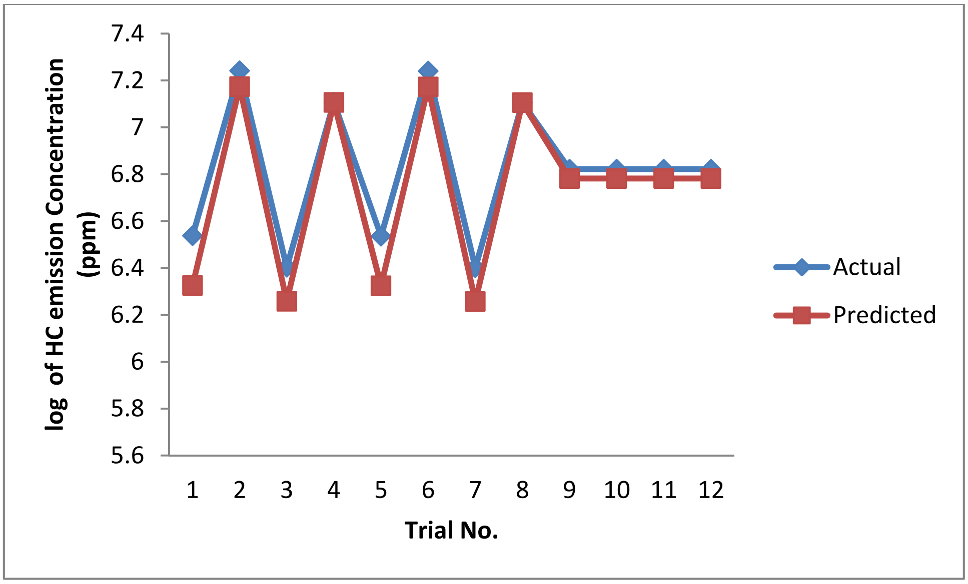


Fig. 5: Comparison between log of actual response and predicted response for HC emission

Fig. 5 – fig. 7 shows the comparison between the log of actual responses and predicted responses of HC, CO and NO_x emissions. It was found that the error in HC emission is less than 3.4%. Besides that, when x_1 and x_2 combinations are positive, the HC,CO and NO_x emissions are all within the lower and upper range at 95% confidence interval. These indicate the relevance or significance of the selected parameters to emission response.

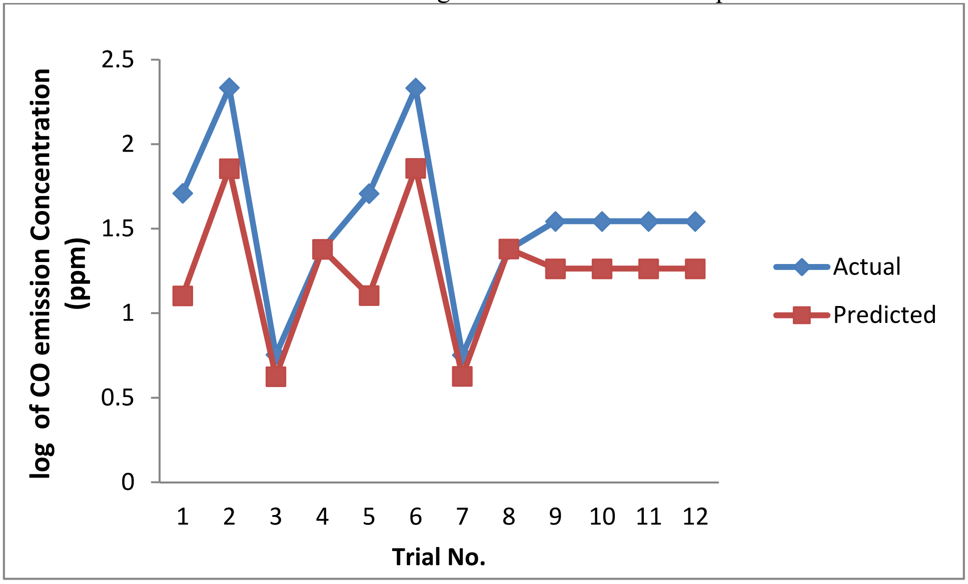


Fig. 6: Comparison between log of actual response and predicted response for HC emission

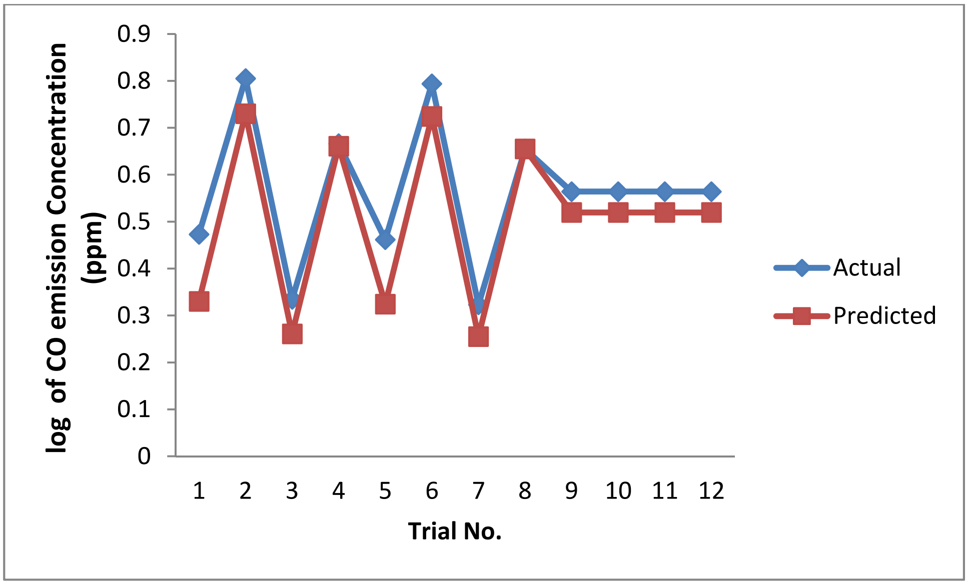


Fig. 7: Plot of Actual Response against Predicted for NO_x emission

Conclusion And Recommendation

Internal combustion engines played an indispensable role in human society in a wide range of applications due to their high reliability, low manufacturing cost and high power density. However, the combustion process in engines is highly influenced by the combined effect of various parameters. As far as the internal combustion engines are concerned, emission is the important parameters for which the other design and operating parameters have to be optimized. This study utilizes the most common optimization technique (response surface method) to further predict the performance and exhaust gas emissions of SI engine after theinvestigation of the effects of three operating parameters on the three emissions of SI engines using theoretical, experimental and RSM methods. The following conclusions can be drawn based on the various results obtained in this work; From HC, CO and NO_x emission models showed that the engine speed, loading condition and time were found to have significant influence on the emission. The HC, CO and NO_x emission models have also proved positive response from the regression analysis of actual and predicted responses. The HC, CO and NO_x emission models have also proved positive response from the regression analysis of actual and predicted responses. In the error estimation with 95% confidence interval the equations are within the ranges. Thus, the response surface methodology provides useful information required for the experiment and also useful in predicting the response of engine parameters to engine emissions. The effort would pave the way for better control of engine operation and performance as well as extend the scope of application of spark ignition engine systems in an optimized way.

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