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Analysis of Exhaust Emissions of Natural Gas Engine by Using Response Surface Methodology

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Abstract: Experiments were conducted to investigate the engine's emission at the different operating conditions. The tests were conducted by varying the engine speed, throttle opening and operating time. During the experimental investigation, the operating variables were varied (engine speed from 1500 to 2500 rpm; throttle percentage from 25 to 36% and operating time from 2.5 to 5 min) according to the experimental schedule set up. These emission models reveal the effects of each parameter's significance and adequacy for the design range which evaluated using ANOVA F-test. The effects of each parameter in emission response are studied through the response model. From the comparative evaluation of the experimental results for the different operating conditions, it is revealed that there is an influence of the engine speed, throttle position and operating time. From the analysis, it is concluded that emissions are more affected on engine speed and throttle position.

Key words: Emission, response surface, regression model, engine speed, throttle position, combustion kit

INTRODUCTION

The numbers of vehicles increases very fast, therefore the automotive engines such as Spark Ignition (SI) and diesel engine (CI) are becoming the major sources of urban air pollution. As a result, using automobile engines already become part of major cause for environment pollution and global warming. The combustion product emission from internal combustion engine contain nitrogen oxides (NO_x), carbon monoxides (CO), hydrocarbon (HC), particulates (PM) and aldehydes. All these pollutants gas are known to cause serious health problems and very harmful to environment. Exhaust gas with contain lead effect of human health such as reduce human mental ability, damage the blood, nerves and organs and raise the blood pressure. It is a worldwide concern for the environment of the acceleration of global warming and climate change by the emission of gases. The global, regional and national CO_2 emissions in the year 1996 and estimated that 77.5% of CO_2 emissions are emitted from liquid and solid fuels where as, 18.3% of CO_2 emissions are emitted from gaseous fuels burning. The energy used and emission in the industrial section in Malaysia are analyzed and found that the emissions of the entire sector are more in the year of 1998 compared to the year of 1988. The analysis shows that over all emission is about 5 times in the year of 1998 compared to that of 1988 (Saidur *et al*., 2007). Air pollution was a serious issue in Malaysia. Sureshkumar *et al.* (2008) investigated that transport vehicles greatly pollute the environment through emissions such as CO, CO_2, NO_x, SO_x, unburnt or partially burnt HC and particulate emissions. Fossil fuels are the chief contributors to urban air pollution and major source of green house gases (GHGs) and considered to be the prime cause behind the global climate change. Biofuels are renewable, can supplement fossil fuels, reduce GHGs and mitigate their adverse effects on the climate resulting from global warming. Saleh (2008) investigated that the exhaust emission from diesel engines is still a serious problem and an international concern has been raised for its control and restriction. Hence, in order to meet the environmental legislations, it is highly desirable to reduce the amount of NOx in the exhaust gas. Yao *et al.* (2008) investigated the effect of diesel/methanol compound combustion on diesel engine combustion and emissions. The results show that the diesel/methanol compound combustion system engine equipped with an oxidation catalytic converter has potential to reduce all emissions, including HC, CO, NO_x and PM, simultaneously. Zuo *et al.* (2008) investigated the emissions of the coal-bed gas engine. The CO emission is small at all the tested conditions, with a maximum value of 0.062%, while the HC emission is less than 380 ppm. The NO emission increases with the engine load but is less than 1800 ppm. Sarvi *et al.* (2008) investigated the operation of four stroke diesel engines in either propulsion or generator mode application has a strong influence on gaseous, smoke (soot) and particulates

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emissions. Tests were made with a supercharged after-cooled large-scale diesel engine burning mainly heavy fuel oil. Gaseous emissions (NO_x, CO, HC) were measured according to the IMO technical code, smoke (soot) emissions were determined optically and Particulate Matter (PM) was measured using a gravimetric impactor for five size fractions. Results show that the exhaust emission was also highly dependent on the engine turbocharger system, especially the by-pass control, but was not affected by waste gate control. Dorado *et al.* (2003) have tested a three cylinder, four stroke, 2500 cm^3 DI diesel engine with olive oil methyl ester and reported a constant combustion efficiency for methyl ester of olive oil and diesel, a slight reduction in brake specific fuel consumption (BSFC), reduction of 58.9% in CO, 8.9% in CO_2, 37.5% in NO and 32% in NO_x for olive oil methyl ester as compared to diesel. Utlu and Kocak (2008) investigated the effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. The emission tests are measured by using Gaco-SN gas analysis monitoring system. This device can measure CO (carbon monoxide), CO_2 (carbon dioxide), NO_x (oxides of nitrogen), O_2 (oxygen), SO_2 (sulfur dioxide) gases as ppm and mg Nm^{-3}. It is found that emission values are decreased as 17.14% CO, 1.45% NO_x. In the last 30 years legal regulations demanded and also gained distinct emission reductions. From the year 2005 onwards, spark ignition (SI)-engines, for instance, have to fulfill EU-4 limits with HC emissions being only 3% of the values of 1970 (Eichlseder and Wimmer, 2003). With increasingly strict international, national and other institutional legislations on emission, engine manufactures are developing new strategies and technologies to reduce exhaust gas emissions. Thus exhaust gas emission limits and tests producers for internal combustion engines have had a market impact upon the development of the engine and systems. Earlier design objective were mainly by efficiency, reliability and durability. These items are still of significant importance but have became secondary with respect to exhaust emission limits. Basically, very low emissions of internal combustion engines can be achieved either with exhaust gas after treatment or optimized combustion processes. There are many published works on the exhaust gas after treatment specially regulates hydrocarbon emission by catalysts equipment on internal combustion engine (Poulopoulos *et al*., 2001; Heneina and Tagomorib, 1999). Many steps have also taken to control emission by this process but exhaust gas after treatment system cannot lead to success alone. For the further development of traffic caused emissions and to full fill international standard, step should be taken on optimized combustion processes.

RSM is a collection of mathematical and statistical techniques widely used to determine the effect of several variables and to optimize different processes. The RSM has been successfully applied for optimizing conditions of various fields like aerodynamic noise (Hyosung *et al*., 2006), heat-transfer (Li *et al*., 2002), in food research (Varnalis *et al*., 2004) also but very few studies focused on the optimization of the exhaust emission on internal combustion engine.

The aim of the research is to study and develop analytical model equations for content the exhaust emission of a retrofitted CNG engine using RMS. To determine the model adequacy by using the F-test analysis of variance (ANOVA) and error estimation are used for checking the error. Base on experiment result, contours and response surface are plotted by using MATLAB 6.5 that show the combine effects of the engine parameters and each effect of the independent input variable to the output-response of emission.

MATERIALS AND METHODS

Here, a description of the facilities developed for conducting experimental work on a test engine. Experiments were conducted at Heat Engine Laboratory, Mechanical Engineering Department, University of Malaya in 2007. Response Surface Methodology (RSM) was introduced and explains how to build an analytical model or approximate function for the complicated problem. RSM is a collection of the mathematical and statistical technique for empirical model building to optimize a response (output variable) which is influenced by several independent variables (input variables).

Concept of response surface methodology: RSM consists of a group of mathematical and statistical techniques that can be used to define the relationship between the response and the independent input variable, either in alone or in combination on the process. The graphical perspective of mathematical model has led to the term Response Surface Methodology. The second step is to find out an appropriate mathematical model that is suitable and fit for the true function relationship between response and the set of independent variables. To get the suitable approximation to the true relationship, the low order polynomial in some region of the independent variables with little curvature is applied. The first order model is adopted when the response is well modeled by a linear function of the independent variables. With collecting the data from the proper experiment and use the least squared method, the model parameter can be estimated and check the adequacy and fitted model of the response surface; the analysis of variance (ANOVA) is used to analysis the response function and to determine the significance of each factor.

In generally, the response surface can represent in quadratic polynomial which include two variable; the design variable and state variable.

Design variable: $x_i(i = 1...n)$; State variable: $y = f(x_1...x_n)+\varepsilon$

where, ε is a random error includes effects such as measurement error on response, background noise and the effect of other variables. The quadratic polynomial equation normally expressed in polynomials, exponential or logarithm. The quadratic polynomials, the response surface which mention above can describe as follow with that n>k observation on the response variable are available and let say $y_1, y_2,....y_n$ is the observation of the response variable and x_{ij} is the regressor variable of each response y_i at level of variable-j.

$$y_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} + \varepsilon_i \quad i = 1, 2... n \tag{1}$$

The first order model is used to approximate the true response surface over small region of independent variable space. Therefore for the case of three variables in this experiment, first order model in term of the coded variables:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \tag{2}$$

With the least square method, β's in the Eq. 2 is chosen so that the sum of square of the error ε is minimized. The least square function is as below:

$$L = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{k} \beta_j x_{ij} \right)^2 \tag{3}$$

And to simply the equations, the model in terms may be written in matrix notation as:

$$\begin{aligned} L &= \sum_{i=1}^{n} \varepsilon_i^2 = \varepsilon^T \varepsilon \\ &= y^T y - 2\beta^T X^T y - \beta^T X^T X \beta \end{aligned} \tag{4}$$

Least square estimator must fulfill and satisfy the below condition.

$$\left.\frac{\partial L}{\partial \beta}\right|_{\hat{\beta}} = -2X^T y + 2X^T X\hat{\beta} = 0$$

Because $\hat{\beta}^T X^T y$ is a scalar matrix (1 x 1) and transpose of it also is a same scalar.

$$(X^T X)\ \hat{\beta} = X^T y \tag{5}$$

So, the least square estimator of $\hat{\beta}$ become the equation below with the matrix (X^TX) is nonsingular and symmetry.

$$\hat{\beta} = (X^T X)^{-1} X^T y \tag{6}$$

where, $(X^TX)^{-1}$ is the inverse of matrix (X^TX), X^T is the transpose of matrix X and the proper regression model is show below $\hat{y} = X\hat{\beta}$

And in scalar notation is:

$$\hat{y}_i = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_j x_{ij} \quad i = 1, 2... n \tag{7}$$

The difference between the observation y_i and fitted value $\hat{y}_i$ is a residual, $e_i = y_i - \hat{y}_i$, or in vector form is denoted by $e = y - \hat{y}$

Linear regression model design: The exhaust gas content concentration (ppm) as a function of engine speed (rpm), throttle position (%) and operating time (minutes) would develop through 2^3 factorial designs of the experiment and RSM. The function relationship between exhaust gas response and independent variable can be expressed as:

$$E = C n_e^a v_t^b t_o^c \tag{8}$$

The parameter or regression coefficient needs to find through least square method where Eq. 8 has been linear in the logarithmic form.

$$\text{In } E = \text{In } C + a\text{In } n_e + b\text{In } v_t + c\text{In } t_o \tag{9}$$

From Eq. 7 and 9 present the following linear mathematical model:

$$\eta' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{10}$$

where, η' is true response of surface roughness on a logarithm scale with $x_0 = 1, x_1, x_2$ and x_3 where the logarithm transformations of the engine speed, throttle position and operation time. β_0, β_1, β_2 and β_3 are parameters to be estimated. The predicted error:

$$\hat{y} = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{11}$$

where, $\hat{y}$ is estimated exhaust gas contents and y measured exhaust gas content on the logarithmic scale, ε experimental random error and b estimated value of β parameters. The b values are to be estimated by least square method. From Eq. 5 and 6 to estimate b values can be express as:

$$b = (X^TX)^{-1} X^Ty \tag{12}$$

The variance covariance matrix of b is obtained as follows:

$$\text{cov}(b_i,b_j) = C_{ij} = \sigma^2 (X^TX)^{-1} \tag{13}$$

Design of experiment: Designed experiment is applied to reduce the variant of each coefficient in the estimated responses. Most of the criteria for optimum designed experiment are associated with the mathematical model of the process. The 2^3 full factorial designs and first order composite with 3 coded levels leading to twelve sets experiments would be used and run it. Experiments have divided into two groups. The first eight experiment represented a factorial design where + and - notation are used to represent the high and low levels of the factors, respectively. The remaining four experiments represented the add center points to the cube which codes as 0. These dummy set experiments are used to evaluate the confident interval and pure error estimations (Montogomery, 2001). The matrixes of independent variables X for fitting model of 12 experiments is given as follows:

$$\begin{array}{cccccc} & x_0 & x_1 & x_2 & x_3 & \text{Trial No.} \\ & 1 & -1 & -1 & -1 & 1 \\ & 1 & 1 & -1 & -1 & 2 \\ & 1 & -1 & 1 & -1 & 3 \\ & 1 & 1 & 1 & -1 & 4 \\ & 1 & -1 & -1 & 1 & 5 \\ \mathbf{X} = & 1 & 1 & -1 & 1 & 6 \\ & 1 & -1 & 1 & 1 & 7 \\ & 1 & 1 & 1 & 1 & 8 \\ & 1 & 0 & 0 & 0 & 9 \\ & 1 & 0 & 0 & 0 & 10 \\ & 1 & 0 & 0 & 0 & 11 \\ & 1 & 0 & 0 & 0 & 12 \end{array}$$

For any regression models, the product of the constant term β_0 and the dummy variables x_0 are always taking value of 1 and thus the first column of X matrix of independent variables contains 1s in first 8 experiment and the rest 0s for the central experiment. The variables are coded according to the equation as below for statistical calculation:

$$x_i = \frac{X_i - X_0}{\Delta x} \tag{14}$$

where, x_i independent coded variable, x_0 is the independent variable real point at the center point and Δx step change value.

The central composite design with 12 experiments provided three levels for each independent variable as show in Table 1. The coding identification and the levels of the independent variables in this experiments were varied (engine speed from 1500 to 2200 rpm, throttle valve position from 25 to 36% and operating time 2.5 to 5 min).

Table 2 shows the experimental condition where 12 tests were run according to the combination of the independent variables. The experimental errors are taken into consideration in the center point of experiment design that is the trial test 9, 10, 11 and 12. The transform of each independent variables in equation were shown at below:

$$x_1 = \frac{\text{In}(n_e) - \text{In}(2000)}{\text{In}(2500) - \text{In}(2000)} = 4.4814\text{In}(n_e) - 34.0628 \tag{15}$$

$$x_2 = \frac{\text{In}(v_t) - \text{In}(30)}{\text{In}(36) - \text{In}(30)} = 5.4848\text{In}(v_t) - 18.6549 \tag{16}$$

$$x_3 = \frac{\text{In}(t_0) - \text{In}(3.5)}{\text{In}(5) - \text{In}(3.5)} = 2.8037\text{In}(t_0) - 3.5123 \tag{17}$$

Analysis of variance (ANOVA): Analysis of variance (ANOVA) is useful tool which helps the user to identify sources of variability from one or more potential sources, sometimes referred to as treatments or factors. ANOVA is a statistical method that makes a simultaneous comparisons between two or more means that can be tested to determine whether a significant relation exists between variables or not. There are few essential assumptions that are taken into consideration as randomness and independence errors, homogeneity of variance, population are normally distributed, experimental data are distribute randomly to treatment and the data homogenous. Adequacy of the fitted model is checked by ANOVA using Fisher F-test which had included calculation of sum of square, mean square and F-statistic.

Table 1: Level of the independent variables and coding identification

Level	Low	Centre	High
Coding	-1	0	1
Engine speed n_e (rpm)	1500	2000	2500
Throttle position v_t (%)	25	30	36
Operation time t_o (min)	2.5	3.5	5

Table 2: Experiment condition and the coding identification

	Independent variables			Coding		
Trial No.	Engine speed (n_e) (rpm)	Throttle position (v_t) (%)	Operation time (t_o) (min)	x_1	x_2	x_3
1	1500	25	2.5	-1	-1	-1
2	2500	25	2.5	1	-1	-1
3	1500	36	2.5	-1	1	-1
4	2500	36	2.5	1	1	-1
5	1500	25	5.0	-1	-1	1
6	2500	25	5.0	1	-1	1
7	1500	36	5.0	-1	1	1
8	2500	36	5.0	1	1	1
9	2000	30	3.5	0	0	0
10	2000	30	3.5	0	0	0
11	2000	30	3.5	0	0	0
12	2000	30	3.5	0	0	0

Table 3: Specification of the engine

	Specifications
Characteristic	Magna-12 levels, 4 cylinder and 4 stroke
Displacement (cc)	1468
Compression ratio	9.2
Bore (mm)	75.5
Stroke (mm)	82
Max. output (kw rpm^{-1})	64/6000
Carburetor	Down-draft 2 barrel

After that, hypothesis testing which involve comparisons of two populations and null applied to test the significant terms by comparing the F-ratio with the values found using the F-table.

Engine: A four stroke spark ignition petrol car engine is retrofitted to run with CNG as a fuel. The specifications of the engine are shown in the Table 3. Emission control system was closed crankcase ventilations system with PCV valve.

Instrumentations: In the experiment, the analyzer, sensors and control system are very important and play an important role in order to achieve high accuracy experiment data. The engine operation is control by the CP 128 Control Panel which located in the heat engine lab. The computer software used in this researched with the CP 128 control and monitoring system is called CADET 10. In CADET 10, the parameters setting such as engine speed (rpm), engine torque and throttle valve position are become the experiment input. The control panel have many data can be taken and had shown in the monitor screen, the data such as engine speed, torque, brake power, efficiency, air mass, exhaust exit temperature, water temperature and dynamometer eddy current. Dynamometer is an instrument that provides an external load to the engine and absorbs power from the engine. The eddy current electric dynamometer is use to measure torque and power over the engine operating ranges of speed and load. The cooling tower is use to cool the components of the engine such as cylinder head, engine block and dynamometer from overheating. The Bosch exhaust analyzer is used to measure the concentrations of hydrocarbon (HC) in ppm, carbon dioxides (CO_2) and carbon monoxides (CO) in percentage.

Table 4: Combustion kit specifications

	Specifications
Stage	1st stage -3.4 bar
	2nd stage -0.8 bar
	3rd stage -negative pressure
Model	Tartarini model RP/76 - M
Mixer	Remote extractor

Combustion kit: Combustion kit is an instrument which is very important in natural gas engine and specification are shown in Table 4. It uses to modify the spark ignition engine to natural gas engine. It allows the natural gas as fuels to mix with air intake and burn in combustion chamber. It is connected with a hose to the CNG, gas flow sensor and natural gas vessel. And the other end of it is connected to the carburetor. It is regulated the amount of natural gas goes into the carburetor. Control system is the time advance processor of model 529.

Experimental procedure: Experimental are conducted in several stage with combination of different throttle (25, 30 and 36%) and engine speed from 1500 to 2500 rpm. There have 12 stages of condition would be set and save in CADET 10. The data from control panel and exhaust emission of CO_2, CO in percentage and HC in ppm. After few minute the engine and exhaust analyzer is warmed up, then press F3 key for run the performance tests and starts the experiment. The engine is run according the stages that set earlier. The engine speed increased from 1500 to 2500 rpm and then decrease again till 1000 rpm which each stage condition is shown at Table 5. The emission reading of CO_2, CO and HC were recorded down at 15 sec before it each stage operating time finished.

Exhaust emission measurement: The set-up of exhaust emission analyzer is very important. The exhaust pipe

Table 5: Stage setting for each stage of the different operating variable during the experiment

	Stages								
	1	2	3	4	5	6	7	8	9
Engine speed (rpm)	1100	1500	1500	1500	1500	2000	2000	2000	2200
Throttle (%)	15	25	25	36	36	30	25	30	25
Operation time (min)	2	2.5	5	2.5	5	3.5	2	3.5	2
Stages	10	11	12	13	14	15	16	17	18
Engine speed (rpm)	2500	2500	2500	2500	2000	2000	2000	1500	1000
Throttle (%)	25	25	36	36	30	25	30	20	15
Operation time (min)	2.5	5	2.5	5	3.5	2	3.5	1	1

must be leakage proved. Exhaust measurement is more satisfied and less error occurs when engine is under warm condition. In preparation, check the probe hose for deterioration and clean the opening of tip of probe. Then check whether the pipe of probe and the filter along the pipe either have water condense or HC residues inside or not. After cleaning, make sure the environment of the lab is pollutant gas free. If no gas, the analyzer analysis system automatically adjusts with zero gas (ambient gas) within two and half minute. The exhaust gas probe is inserted into exhaust pipe with attach the probe to the pipe with a clamping device. After checking setup, the engine can be started to perform the measurement. The filter and pipe need to check time to time to make sure to prevent the water condense in the pipe and affect the accuracy of data. When experiments were ended and finished measurements, take out the probe and press the run key again to flush the ambient air for one minute. This flushing process is used to reduce the amount of the fouling and prevent premature aging of the analyzer. Then, press the run key again to end the flushing process and switch the power supply.

RESULTS AND DISCUSSION

Experiments were conducted by varying the difference parameters. During the experimental investigation, the results of the hydrocarbon, carbon monoxides and carbon dioxides concentration was recorded. Table 6 shows that emission is more when the engine speed and throttle position are 2500 rpm and 36%, respectively. On the other hand, emission is less when the engine speed and throttle position are 1500 rpm and 25%, respectively. 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, throttle position and operating time.

Linear regression model of emissions: To develop a regression model, the coefficients of function need to obtain through the least square method. With using the formula $b = (X^TX)^{-1} X^Ty$ and calculate in Matlab 6.5, the parameters b obtained and show in Table 7.

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

$$\hat{y}_{HC} = 4.5473 + 0.2630x_1 - 0.04396x_2 - 0.000674x_3 \quad (18)$$

$$\hat{y}_{CO} = 0.5535 + 0.2453x_1 + 0.3010x_2 + 0.00786x_3 \quad (19)$$

$$\hat{y}_{CO_2} = 2.1792 + 0.1428x_1 + 0.05762x_2 - 0.00336x_3 \quad (20)$$

Then with substitute the transform of each independent variable in Eq. 15, 16 and 17 into Eq. 18, 19 and 20. After combining all the independent variable, the new three Equations can be written as $\hat{y} = \ln(E)$ that refers from Eq. 8. So, the estimated response of emission concentration, E in the logarithmic function becomes the Equations as follow:

$$\ln(E_{HC}) = -3.5898 + 1.1787\ln(n_e) - 0.2411\ln(v_t) - 0.00189\ln(t_o) \quad (21)$$

$$\ln(E_{CO}) = -13.4431 + 1.0992\ln(n_e) + 1.6505\ln(v_t) + 0.02205\ln(t_o) \quad (22)$$

$$\ln(E_{CO_2}) = -3.7486 + 0.6400\ln(n_e) + 0.3161\ln(v_t) - 0.00941\ln(t_o) \quad (23)$$

Equation 21, 22 and 23 can transform to exponential form and can construct emission concentrations of HC in ppm, CO and CO_2 in percentage volume which as a function of engine speed, n_e(rpm), throttle position, v_t. (%) and operation time, t_o (min). The functions of emission are shown as below:

$$E_{HC} = 0.0276 n_e^{1.1787} v_t^{-0.2411} t_o^{-0.00189} \quad (24)$$

$$E_{CO} = 1.4512 \times 10^{-6} n_e^{1.0992} v_t^{1.6505} t_o^{0.02205} \quad (25)$$

$$E_{CO_2} = 0.02355 n_e^{0.64} v_t^{0.3161} t_o^{-0.0094} \quad (26)$$

Equation 24-26 as function which develops by using least square method and design of experiment are valid for emission of HC, CO and CO_2 under following condition:

Table 6: Experimental results of emission concentrations of HC, CO and CO_2

				Coding						$\hat{y}$ = In (E)		
Run	n_e (rpm)	v_t (%)	t_o (min)	x_1	x_2	x_3	E_{HC} (ppm)	E_{CO} (%)	E_{CO_2} (%)	HC	CO	CO_2
1	1500	25	2.5	-1	-1	-1	74	0.888	6.6	4.3041	-0.1188	1.8871
2	2500	25	2.5	1	-1	-1	122	1.72	10.0	4.804	0.5423	2.3026
3	1500	36	2.5	-1	1	-1	67	1.89	8.5	4.2047	0.6366	2.1401
4	2500	36	2.5	1	1	-1	119	2.77	10.3	4.7791	1.0189	2.3321
5	1500	25	5.0	-1	-1	1	79	0.965	7.0	4.3694	-0.0356	1.9459
6	2500	25	5.0	1	-1	1	120	1.68	9.8	4.7875	0.5188	2.2824
7	1500	36	5.0	-1	1	1	64	1.91	8.2	4.1589	0.6471	2.1041
8	2500	36	5.0	1	1	1	118	2.75	10.0	4.7707	1.0116	2.3026
9	2000	30	3.5	0	0	0	99	1.88	9.3	4.5951	0.6313	2.230
10	2000	30	3.5	0	0	0	102	1.77	8.8	4.625	0.5710	2.1748
11	2000	30	3.5	0	0	0	96	1.79	9.3	4.5643	0.5822	2.2300
12	2000	30	3.5	0	0	0	100	1.89	9.2	4.6052	0.6366	2.2192

Table 7: Values of parameter b for regression model for HC, CO and CO_2

	Values of parameter		
Parameters	HC	CO	CO_2
b_0	4.5473	0.5535	2.1792
b_1	0.2630	0.2453	0.1428
b_2	-0.04396	0.3010	0.05762
b_3	-0.000674	0.00786	-0.00336

$$1500 \le n_e \le 2500 \text{ rpm}$$

$$25 \le v_t \le 36 \text{ \%}$$

$$2.5 \le t_o \le 5 \text{ min}$$

By using the ANOVA and evaluated with 95% confidence interval for analyzed the model Equations, analysis shows that first order models are valid and adequate for further prediction.

Contour and surface plot: The emission of HC, CO and CO_2 is develop and is approximated the function which is influenced by the engine speed, throttle position and operating time.

$$E_{HC} = 0.0276 n_e^{1.1787} v_t^{-0.2411} t_o^{-0.00189}$$

HC emission model equation: The Eq. 24 is the first order HC emission model equation. The exponential power value of operation time is smallest compared to exponential power of engine speed and throttle position. That mean the operation time has a minor effect of the model and the engine speed is the main parameter that is influenced the HC model. The response surface from Fig. 1a for operation time 3.5 min, respectively indicated that emission concentration of HC is almost same and the contour plot for HC model below also indicated trend for different operating time almost similar. From Fig. 1a, the HC emission concentration increases with the decrement of engine speed and increment of throttle position. In Fig. 1b, for the HC response surface, the minimum emissions achieve when engine speed is low and throttle position large.

Co emission model equation:

$$E_{CO} = 1.4512 x 10^{-6} n_e^{1.0992} v_t^{1.6505} t_o^{0.02205}$$

The above Equation is the first order CO emission model equation. Through this equation, it is realized that the throttle position is the main contributor to the CO emission concentration, whereas the operation time is the minor effect. The contour plot and response surface in Fig. 2 are indicated that CO concentration has same trend at operation time ranging 3.5 min. CO concentration increases with increasing the engine speed and throttle position. Increment of time does not much effect on it. The minimum CO concentration can achieve when engine speed and throttle position is small.

CO_2 emission model equation:

$$E_{CO_2} = 0.02355 n_e^{0.6400} v_t^{0.3161} t_o^{-0.0094}$$

Equation 26 is the first order CO_2 emission model equation. Equation has lowest exponential power for operation time and the exponential power value of engine speed is highest. The operation time give less effect in CO_2 concentration and engine speed contribute more influence on it. From response surface and contour plot of CO_2 emission, the trend of response and contour plot of CO_2 are almost similar. Figure 3a and b shows not much changes with time, but CO_2 concentration increases with increasing the engine speed and throttle position. CO_2 is directly related to combustion of fuel. Increase CO_2 means better fuel combustion. This is mainly due to the increase of fuel conversion efficiency.

Model comparison of with actual/experimental: It is found that error between the HC estimated responses and actual responses are small that is shown in Fig. 4. The error for the HC emission is less than 11.2%. Besides that, almost all actual values for the HC emission are within the lower

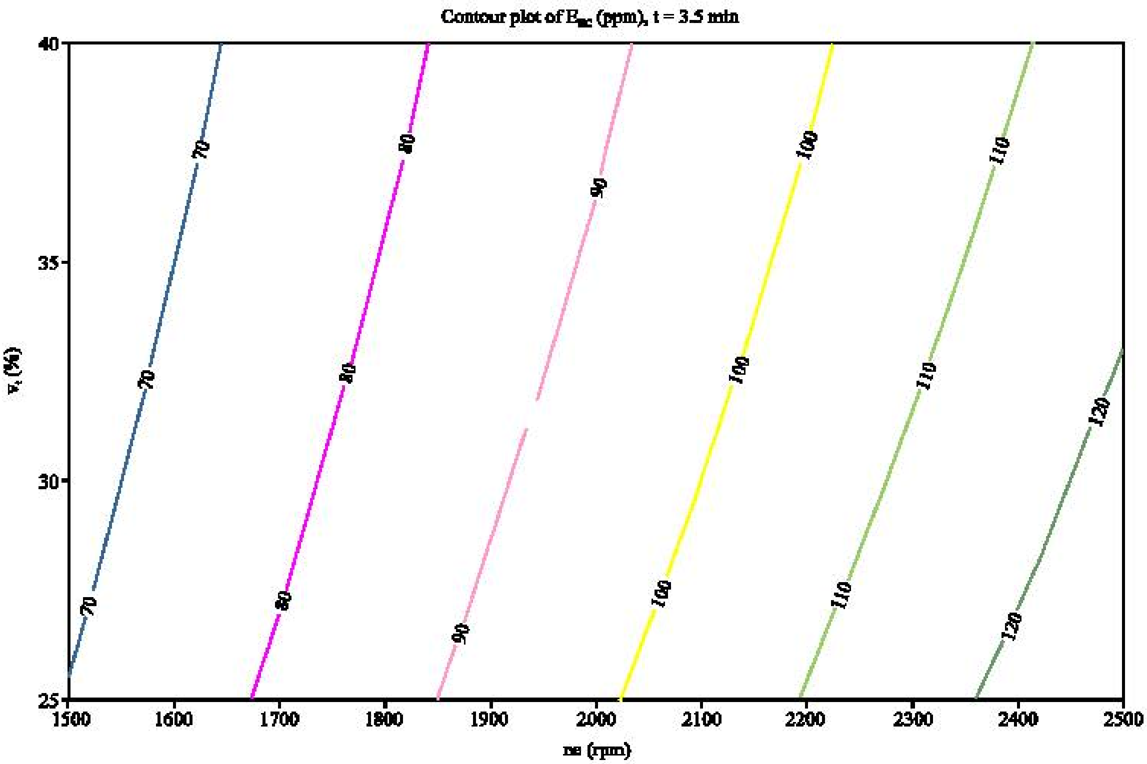

Fig. 1a: Contour plot of engine speed-throttle position plane at operation time 3.5 min for HC emission

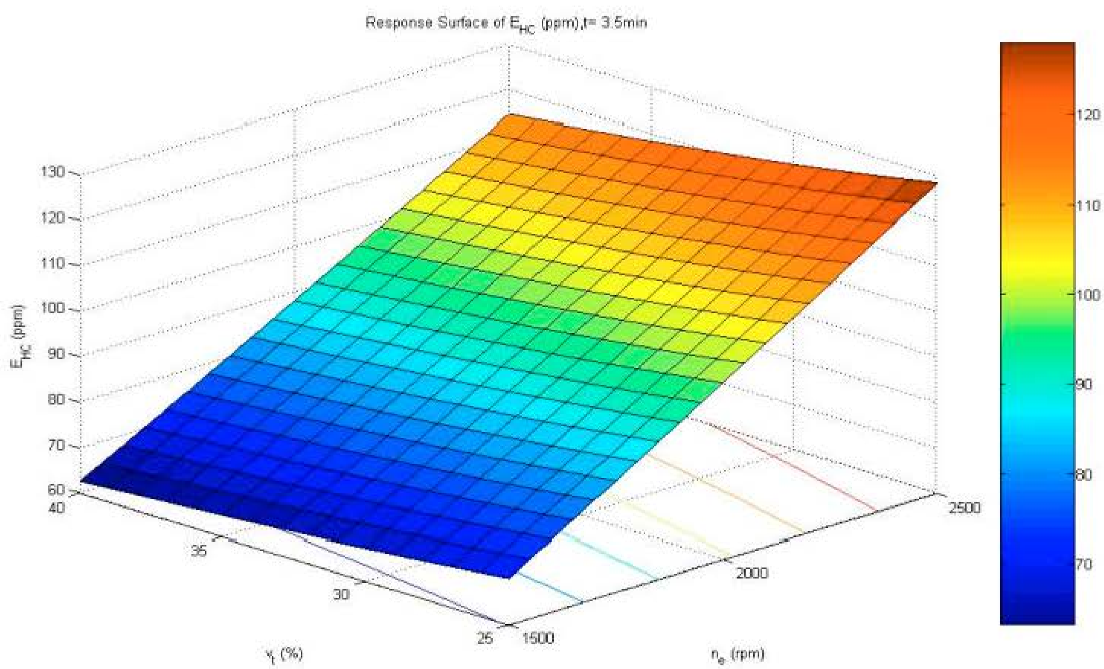

Fig. 1b: Response surface of HC emission in engine speed-throttle position plane at operation time 3.5 min

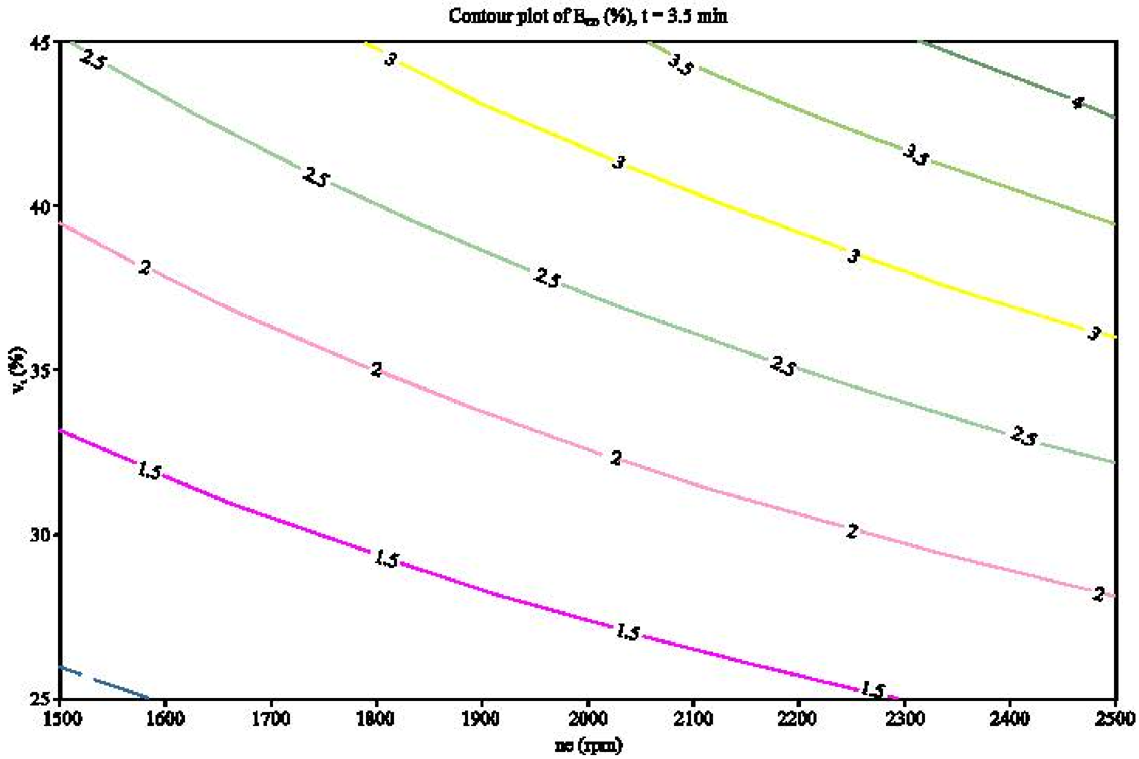

Fig. 2a: Contour plot of engine speed-throttle position plane at operation time 3.5 min for CO emission

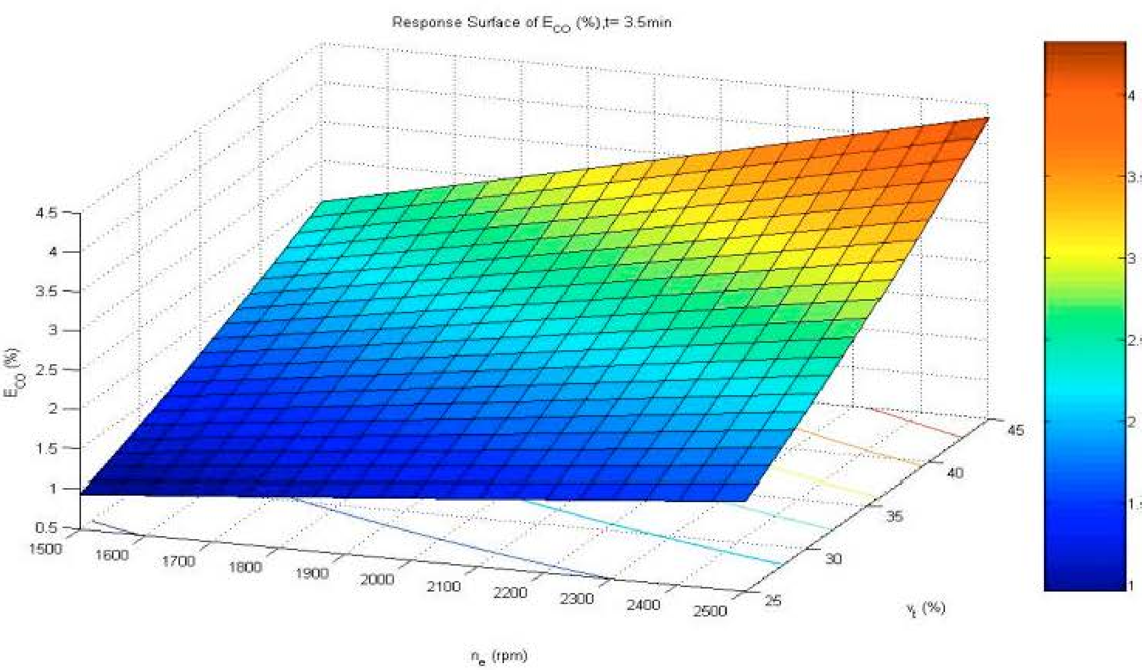

Fig. 2b: Response surface of CO emission in engine speed-throttle position plane at operation time 3.5 min

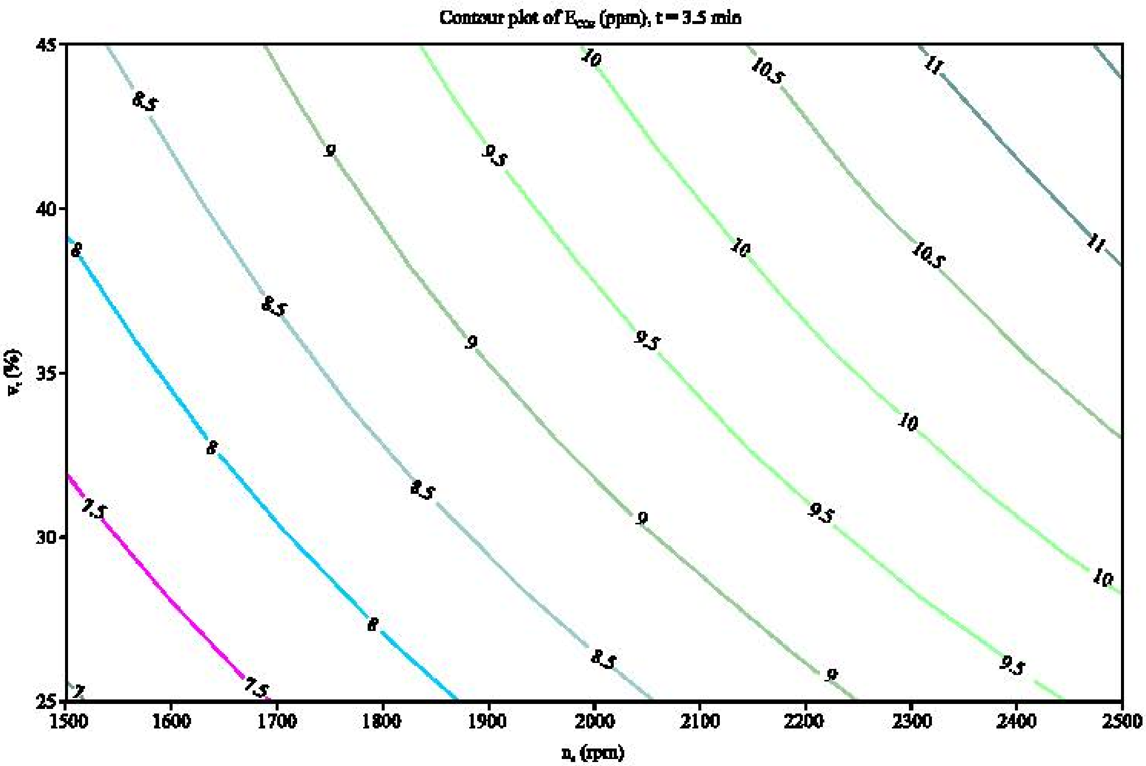

Fig. 3a: Contour plot of engine speed-throttle position plane at operation time 3.5 min for CO_2 emission

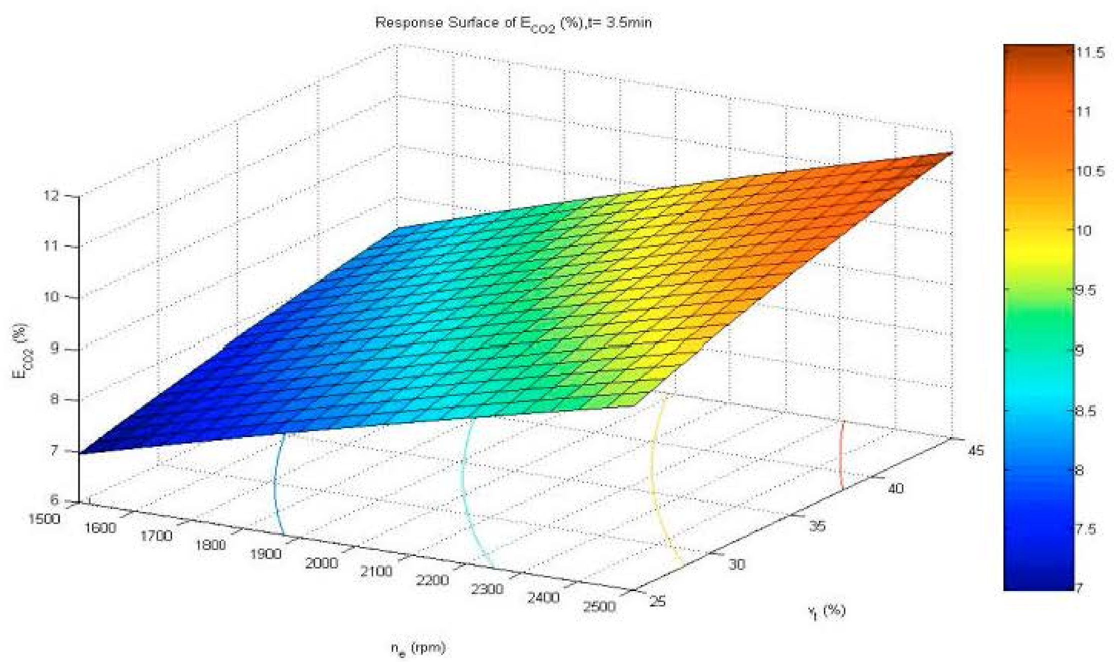

Fig. 3b: Response surface of CO_2 emission in engine speed-throttle position plane at operation time 3.5 min

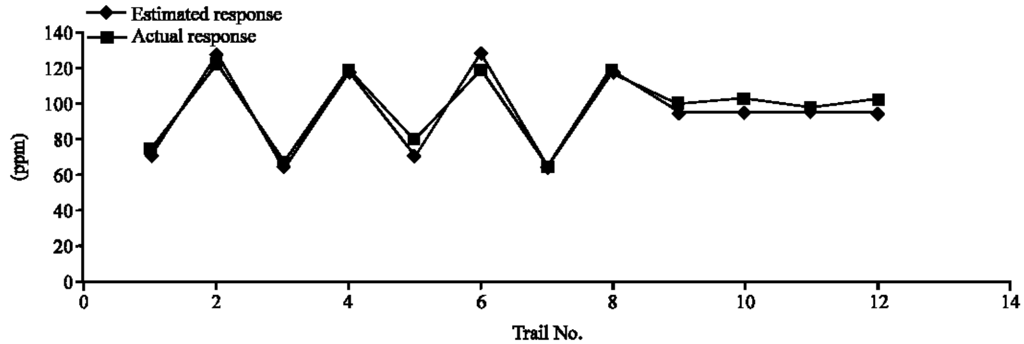

Fig. 4: Comparison between HC actual response and estimated response

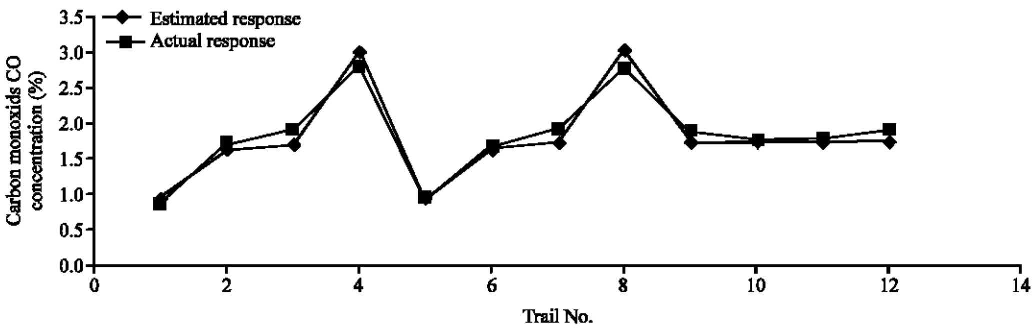

Fig. 5: Comparison between CO actual response and estimated response

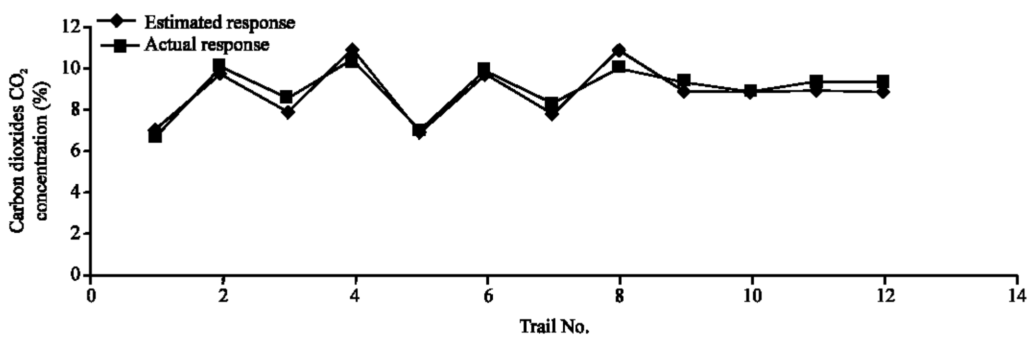

Fig. 6: Comparison between CO_2 actual response and estimated response

and upper range at 95% confidence interval. Therefore, HC regression model is suitable to use to predict at the design range. CO and CO_2 emission both models are suitable to use because CO and CO_2 actual responses are within the lower and upper range at 95% confidence interval that is observed from Fig. 5 and 6. Moreover, the errors between the actual and estimated responses for CO and CO_2 are relatively small which are less than 10.1 and 8.2%, respectively. Therefore, it is concluded that models are suitable to predict the emissions at the design studied range.

CONCLUSIONS

Through analysis of variance F-test, (ANOVA) and 95% confidence interval, the calculation of F-statistic value emissions models are larger than tabulated F-value. The test regression model has successfully proved that at least one independent or regression variable of nonzero coefficient. From HC, CO and CO_2 emission models, engine speed and throttle position are found significant influence on the emission, respectively. However, the operation time only give a small effect on the emission.

HC and CO_2 emission equations show the major effect of engine speed. On the other hand, CO emission is mostly effected by the throttle position. HC, CO and CO_2 emission models also proved that the regression model is adequate and linear at the range. In the error estimation with 95% confidence interval, the equations are within the ranges. Error of the regression models are insignificant and can be neglect. The dual response contour of the emission models which obtained in plane of two responses. The engine speed and throttle position are provided useful information about minimum attainable exhaust content. Through the contours investigation, emission output as a function of three independent variables can be improves and minimize. The response surface methodology provides useful information with using the small experiment. HC, CO and CO_2 regression model is suitable to predict and get the relevant information within the design range.

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