DEVELOPMENT AND VALIDATION OF EMISSION MODEL FOR A PETROL ENGINE USING RESPONSE SURFACE METHODOLOGY (RSM)

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ABSTRACT

Hydrocarbon emissions are generated from the presence of unburned fuel in the exhaust of a petrol engine. Liquid fuels contain 10 to 20 major species of hydrocarbon and some 100 to 200 minor species. Most of these species are found in the exhaust gas of a petrol engine. However, some of the exhaust hydrocarbons are not found in the parent fuel, but are hydrocarbons derived from the fuel whose structure was altered within the cylinder by incomplete chemical reaction. About 50% of the total hydrocarbons are emitted in this way. In this paper a mathematical model utilising the response surface methodology (RSM) has been developed for predicting the hydrocarbon (HC) emission from a petrol engine. The adequacy of the model has been investigated statistically by the analysis of variance (ANOVA) as well. Based on the response models, contours have been plotted in throttle-speed planes. For a given surface, these contours help to predict the setting parameters for minimum hydrocarbon emission.

Keywords : *ANOVA, Emission Model, Hydrocarbon, Petrol Engine, RSM*

NOMENCLATURE

b	Matrix of the parameter estimates
E_{HC}	Hydrocarbon (HC) emission (PPM)
P	Throttle position (%)
R^2	Regression
T	Operation time (min)
V	Engine speed (rpm)
X	Matrix of independent variables
X^T	Transpose of X
$(X^TX)^{-1}$	Inverse of (XTX)
y	Observed exhaust emission = $\ln E$
β	Parameters
ε	Experimental error

1. INTRODUCTION

More and more attention is being paid to the various environmental effects caused by the use of road traffic vehicles. Air pollution caused by CO, HC, NO and particulate matters are of major concern. For passenger and freight traffic, internal combustion engine is the favored propulsion system. Due to this wide range of use the entire emission, which required important developmental processes for its reduction in the past, and will also demand even greater ones in the future, is considerable. In the last 30 years legal regulations demanded and also gained distinct emission reductions. From the year 2005 onwards, passenger cars with spark ignition (SI)-engines, for instance, have to fulfill EU-4 limits with HC emissions being only 3% of the values of 1970 [1]. 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 optimised combustion processes. There have been many published works on the exhaust gas after treatment specially regulates hydrocarbon emission by catalysts equipped on internal combustion engine [2-4]. Lots of 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 optimised combustion processes.

Response surface methodology (RSM) is a collection of mathematical and statistical techniques widely used to determine the effect of several variables and to optimise different processes. The response surface methodology (RSM) has been successfully applied for optimising conditions of various fields like aerodynamic noise [5], heat-transfer [6], in food research [7] also but very few studies focused on the optimisation of the exhaust emission on internal combustion engine. Many research have also been done to analyse nitrogen-oxide [8-11], carbon-monoxide [12] emission from internal combustion engine. In this paper a mathematical model utilising the response surface methodology (RSM) has been developed for predicting the hydrocarbon (HC) emission of petrol engine. This study mainly focuses on few variables, which are throttle position, speed, and operation time of the petrol engine. The specifications of the engine are shown in Table 1. In this model a 2^3 factorial design is used to study the combined effect of throttle position, speed and operation time on the hydrocarbon (HC) emission.

2. RESPONSE MODEL AND ERROR ANALYSIS

If all of these variables (throttle position, engine speed and operation time) are assumed to be measurable, the response surface can be expressed as

$y = f(x_1, x_2 ... x_k)$ .... (1)

The goal is to optimise the response variable y. It is assumed that the independent variables are continuous and controllable by the experimenter with negligible error. The response or the dependent variable is assumed to be a random variable.

Say in a combustion process, it is necessary to find a suitable combination of throttle position ($x_1 = ln\ P$), speed ($x_2 = ln\ V$), and operation time ($x_3 = lnT$) that optimise exhaust emission ($y = ln\ E$), the observed response y as a function of throttle position, engine speed, and duration of combustion can be written as

$y = f(x_1, x_2 ... x_k) + \varepsilon$ .... (2)

where ε is a random error. If the expected response is denoted by $E(y) = \eta$, then the surface represented by $\eta = f(x_1, x_2, x_3)$ is called a response surface. It is required to find a suitable approximation for the true functional relationship between y and the set of independent variables x_i's. Usually a low order polynomial (first-order and second-order) in some regions of the independent variables is employed. The first-order model

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \quad \text{.. (3)}$$

and the second-order model

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon$$

for i < j .... (4)

are generally utilised in RSM problem. The β parameters of the polynomials are estimated by the method of least squares.

The matrix approach of solving Equation (3) or Equation (4) has been adopted in the present analysis. y is defined (n x 1) vector of observations on y, x is defined (n x p) matrix of independent variables, β to be a (p x 1) vector of parameters to be estimated, and ε is defined (n x 1) vector of errors Equation (3) or Equation (4) can be written in matrix form as

$y = \beta x + \varepsilon$ .... (5)

The least-square estimate of β is the value b which, when substituted into Equation (3) or Equation (4), minimises $\varepsilon'\varepsilon$. The normal equations can be expressed as

$(x^T x)\, b = x^T y$ .... (6)

where β is replaced by b matrix. If $(x^T x)$ is non-singular, the solution of the normal equations can be written as

$b = (x^T x)^{-1} x^T y$ .... (7)

where x^T is the transpose of the matrix x and $(x^T x)^{-1}$ is the inverse of the matrix $(x^T x)$. The response surface analysis is done in terms of the fitted surface. The main purpose of RSM is to ascertain the optimum operating regions for the system involving the independent variables.

A factorial design of experiment is one in which all levels of a given factor are combined with all levels of every other factor in the experiment. This design is necessary when interactions between the variables are to be investigated. Furthermore, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, giving conclusions that are valid over a range of experimental conditions. This is explained more in detail by Montgomery [13]. In using 2^k factorial designs, it is assumed that the k factors are coded to the standardised levels $\pm$ 1. Used presently is a 2^3 design to fit the first-order model:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$ .... (8)

The x matrix for fitting the model is

$$x = \begin{array}{cccc} \beta_0 & \beta_1 & \beta_2 & \beta_3 \end{array} \begin{vmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{vmatrix}$$

The first column of the x matrix of independent variables contains only 1s.This is the general convention for any regression model containing β_0 terms to be of the form $\beta_0 x_0$, where x_0 is a dummy variable always taking the value 1. The off-diagonal elements of $(x^T x)$ matrix are zero for this design. The 2^k design does not take into account the estimate of the experimental error unless some runs are repeated. The common method of including replication in the 2^k design is to augment the design with several observation at the centre (x_i=0, i=1, 2,…k). The inclusion of centre points to the 2^k design does not affect the regression coefficients (β_i)for i $\geq$ 1, but the estimate of β_0 becomes the grand average of all observations. Moreover, the centre points do not influence or change the orthogonal property of the design. [14-15].

A. ADEQUACY OF THE POSTULATED MODEL

In order to perform the analysis of variance, the total sum of square, $\sum y^2$, is usually partitioned into contributions due to 'regression term', 'the lack of fit' and 'pure error'. The sum of squares of individual items divided by their respective degrees of freedom gives the mean squares.

3. EXPERIMENTAL WORK

A. EXPERIMENTAL SET-UP

The specific operating conditions of the engine were programmed according to the CADET operating system.

B. DESIGN OF EXPERIMENT

Twelve experiments were performed to develop the first order mathematical model to investigate the combined effect of throttle positions, engine speed, and operation time, on HC emissions. Eight experiments represent a factorial design, while the remaining 4 represent repetition to estimate the pure error. The experimental design and conditions have been shown in Table 2. A factorial design of experiment is one in which all levels of a given factor are combined with all levels of every other factor in the experiment. This design is necessary when interactions between the variables are to be investigated. Furthermore, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, giving conclusions that are valid over a range of experimental conditions [14-15]. The level of independent variables and coding identifications used in this design are presented in Table 4. According to references [14-15] the transforming equations for eTwelve experiments were performed to develop the first order mathematical model to investigate the combined effect of throttle positions, engine speed, and operation time, on HC emissions. Eight experiments represent a factorial design, while the remaining 4 represent repetition to estimate the pure error. The experimental design and conditions have been shown in Table 2. A factorial design of experiment is one in which all levels of a given factor are combined with all levels of every other factor in the experiment. This design is necessary when interactions between the variables are to be investigated. Furthermore, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, giving conclusions that are valid over a range of experimental conditions [14-15]. The level of independent variables and coding identifications used in this design are presented in Table 4. According to references [14-15] the transforming equations for each of the independent variables are:h of the independent variables are:

$$x_1 = \frac{\text{In } P - \text{In } 43.3}{\text{In } 75 - \text{In } 43.3}\ , \quad x_2 = \frac{\text{In } V - \text{In } 1580}{\text{In } 2500 - \text{In } 1580}$$

$$x^3 = \frac{\text{In } T - \text{In } 2.8}{\text{In } 4 - \text{In } 2.8} \quad \text{.. (9)}$$

4. INSTRUMENTATION

A. DYNAMOMETER

The dynamometer is a device that provides an external load to the engine, and absorbs the power form the engine. The power is absorbed by dynamometer called the "brake horsepower." A hydraulic dynamometer or water brake was used in this experiment, which was constructed of a vane rotor mounted in a casing mounted to the rotating engine shaft. A continuous flow of water is maintained through the casing. The power absorbed by the rotor is dissipated in fluid friction as the rotor shears through the water. Adjusting the level of water in the casing varies the torque absorbed.

B. CADET SYSTEM

In this experiment we used an electronic control unite (ECU) for the engine that was tested. It is called the CADET system with CP 128 Control and Monitoring System, which is able to use with any computer having a serial interface.

C. EXHAUST EMISSION ANALYSER

The model for the exhaust analyser or combustion analyser was used for this experiment is BOSCH Combustion Analyser Model ETT 008.31. Hydrocarbon (HC), Carbon Dioxide (CO_2), Oxygen (O_2), and Carbon monoxide emission reading was appeared on the analyser screen.

5. RESULTS, DISCUSSION AND ANALYSIS

From the experimental results shown in Table 5, model Equation (10) has been developed using Eqs. (3) and (9).

The estimated HC emission based on the 12 experimental results (Table 5) in coded form is

$$\hat{y} = 6.9049 + 0.2126x_1 + 0.2689x_2 + 0.1846x_3 \quad \text{.................. (10)}$$

Equation (10) describing the HC emission model can be transformed using Equation (9) into the following form

$$E_{HC} = 1.8178P^{\,0.3869}\,V^{\,0.8859}\,T^{\,0.5176} \quad \text{... (11)}$$

The equation shows that the exhaust emission hydrocarbon increases with increases of the throttle position, speed and operation time. The engine speed has the most dominant effect on exhaust emission followed by the operation time and throttle position.

At higher engine speeds, there is less time per cycle. Combustions occurs over about same engine rotation (burn angle) at all speeds, so the time of combustion is less at higher speeds and combustions is not completed which leads high HC emission [16]. How ever, there is also less time for heat transfer per cycle, which means the engine runs hotter, and a hotter engine has a greater knock problem [17]. The result of this is that high temperature and pressure develop inside the cylinder. This high temperature evaporates engine oil but engine oil is heavier than fuel and remains unburned. So it escaped as unburned HC with exhaust gas. As high pressure continues to rise which increase the flow of unburned mixture into crevice volume (mainly volume between piston, piston rings and cylinder wall) and flame cannot reach there. This unburned mixture escape during exhaust stroke, which is the major source of hydrocarbon emission [17]. When an engine is operating at high speed and the throttle is suddenly closed to decelerate the automobile. The combination of a closed throttle and high engine speed will create a high vacuum in the intake system downstream from the throttle plate. With the high vacuum in the intake system, a very large exhaust residual will occur during valve overlap. This high exhaust residual causes poor combustion. Misfire is another common phenomenon when engine run at high speed. One misfire out of 1000 cycle gives exhaust emission of 1gm/kg of fuel and this is another source of unburned HC [16]. With increasing the throttle position, air fuel ratio (AF) became leaner. If AF is too lean, poorer combustion occurs, again resulting in HC emission. If the engine run over long period of time, the temperature of the engine also increase. This high temperature

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causes more HC emission that already mentioned.

Also, Figure 2 shows the response surface at the selected levels of operation time (2, 2.8 and 4 minutes) containing the throttle position and speed. These response surfaces were obtained utilising the MATLAB computer package. It can be seen from Figure 2 that the HC emission increase with an increasing in throttle position, and increases as speed increases. The analysis of variance of 95% has shown that the ratio of lack of fit to pure error was 5.09 whilst the F-statistics was 9.01 [18] shows in Table 5. Therefore, the model was adequate.

Table 1: Engine Specification

Characteristic	Magna - 12 valves, 4 cylinder, 4 stroke
Displacement (cc)	1,468
Compression Ratio	9.2
Bore, mm	75.5
Stroke, mm	82
Max. Output (DIN) ps/rpm net	87/6000
(KW/rpm)	(64/6000)
Carburetor	Down-draft 2 barrel
Exhaust system	- Closed crankcase ventilation system with PCV valve
	- Exhaust Gas Recirculation (EGR)
Stage	First stage-3.4 Bar
	Second stage-0.8 Bar
	Third stage-negative pressure
Regulator	Tartarini Model RP176-M
Mixer	Remote Extractor
Control	Time Advance Processor Model 529

Table 2: Engine Specification

Trial No.	Throttle Positon, P %	Speed,V rpm	Duration, t min	Coding x1	x2	x3
1	25	1000	2	-1	-1	-1
2	75	1000	2	1	-1	-1
3	25	2500	2	-1	1	-1
4	75	2500	2	1	1	-1
5	25	1000	4	-1	-1	1
6	75	1000	4	1	-1	1
7	25	2500	4	-1	1	1
8	75	2500	4	1	1	1
9	43.3	1580	2.8	0	0	0
10	43.3	1580	2.8	0	0	0
11	43.3	1580	2.8	0	0	0
12	43.3	1580	2.8	0	0	0

Table 3: Levels of independent variables for Proton petrol engine

Levels	Low	Centre	High
Coding	-1	0	1
Throttle, P (%)	25	43.3	75
Speed, V (rpm)	1000	1580	2500
Duration, T (min)	2	2.8	4

6. CONCLUSION

The first-order model equation derived from this study shows that engine speed has the most dominant effect on hydrocarbon emission, followed by the engine operation time and engine throttle position. This equation also indicates that there is no interaction between engine parameters on hydrocarbon emission and individual engine parameter can change the hydrocarbon emission level. But it is not possible to measure the amount of hydrocarbon emission changed for a unit change of individual engine parameter because the amount of hydrocarbon emission is not same at all running conditions. The resulting 95 per cent confidence intervals for the 12 tests indicate that a first-order equation is appropriate.

This study showed that response surface methodology is one of the suitable methods to optimise the best operating conditions of internal combustion engine to minimise exhaust emission. Satisfactory prediction equations were derived to predict HC emission from internal combustion engine using RSM to optimise the engine parameters. Therefore, the usage of response surface methodology may be highly recommended to predict the engine's emissions instead of having to undertake complex and time-consuming experimental studies. ■

Table 4: Experimental results

Trial No.	Response HC Emission, PPM	$ln(E_{HC})$
1	441	6.06
2	640	6.46
3	779	6.66
4	1108	7.01
5	628	6.44
6	980	6.88
7	1008	6.92
8	1716	7.45
9	1115	7.02
10	1410	7.04
11	1650	7.41
12	1435	7.27

Table 5: Analysis of Variance for Significance of Regression and Residual in Linear Model

Source of variance	Sum of Squares (SS)	Degrees of freedom	Mean Square (MS)	F Ratio (F)
Regression	1.2251	3	0.40837	4.35
Error or residual	0.7512	8	0.0939	
Lack of Fit	0.67198	5	0.134396	5.09
Pure Error	0.079218	3	0.026406	
Total	1.9763	11		

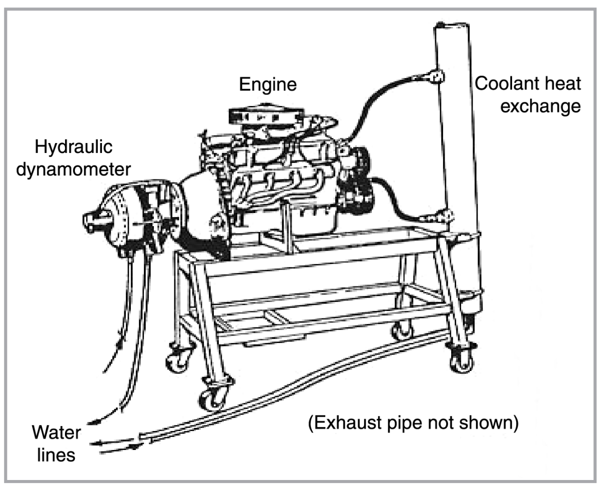

Figure 1: Experiment setup

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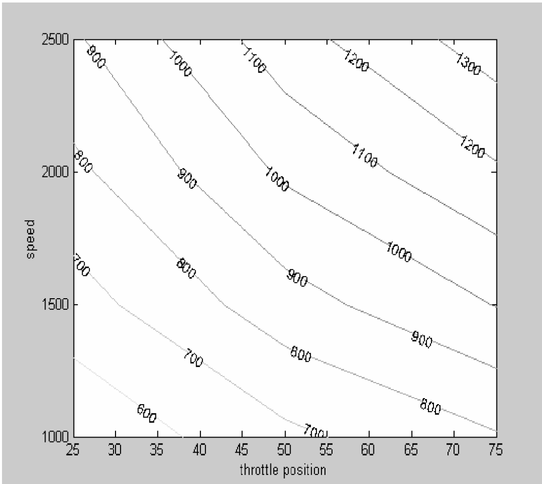
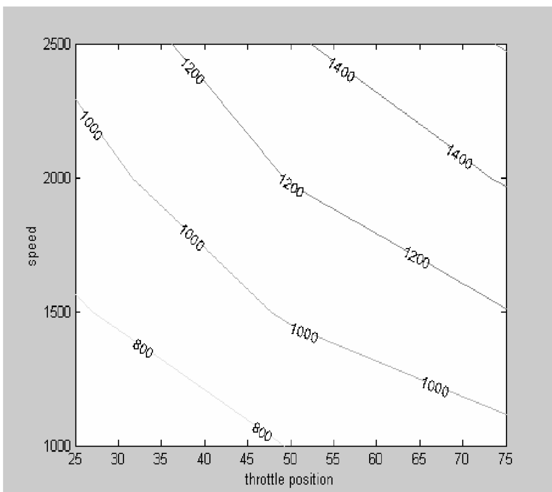


(a)



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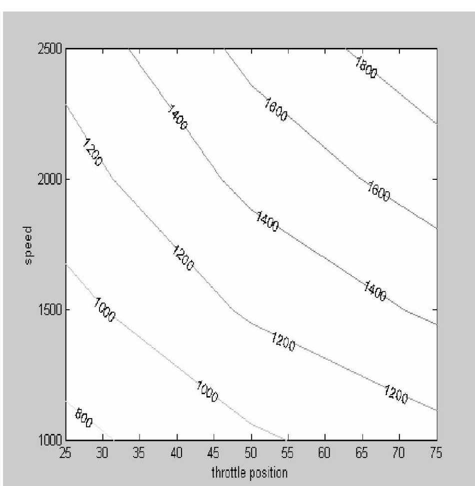

(c)

HC emission contours in the P-V plane for different operation times: (a) 2 minutes; (b) 2.8 minutes; (c) 4 minutes.

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