Experimental Optimization and Analysis of Intake and Exhaust Pipeline for Small Engine Motorcycle

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Abstract

In this paper, the investigation on the effects of intake and exhaust pipeline of a 125 cc small engine motorcycle is presented. The formal design of experiment (DOE) has been utilized to examine the significances of related parameters of pipelines. Four performance functions including the engine torque, fuel consumption, emission of CO and HC have been constructed by response surface methodology (RSM). The weighting strategy of four-objective optimization in six design cases was employed for analysis, comparison, and discussion. After some experimental investigations which provides some useful guidelines for intake and exhaust pipeline design. The proposed integrated process positively enhances the engine torque of overall speed and reduces the fuel consumption. The torque of low range speed can be particularly increased with the methodology presented in this paper. No clear evidence supports the polluted emission can be effectively deducted by modifying the intake pipeline system.

Key Words: Experimental Optimization, Design of Experiment (DOE), Small Engine, Motorcycle, Mechanical Design

1. Introduction

The motorcycle with 100 cc to 150 cc capacity is the most popular for personal transportation in Asia. How to enhance the output torque, reduce the energy expenses and eliminate the polluted emission always are desired goals and on going challenges. Figure 1 shows the characteristic diagram of a typical base engine's output torque against the range of speed. It shows that the output torque below 5500 rpm is obviously lower than that around 6500 rpm operating speed. From the theory of internal combustion engine, the larger torque indicates a higher power rate that induces lower specific fuel consumption (SFC) [1] under constant fuel flow rate. The low torque not only consumes fuel but also negatively effect the rider's comfort, particularly in the lower range speed. Thus, a small engine has a full-range high torque resulted in an expected characteristic curve can be represented in Figure 1.

In recent research and development there arise several new concepts to improve the efficiency of engines [2]. Based on such modern concept, the performance and functionality in the small engine of motorcycle requires the maximum power at lower range speed and the flat torque curve over a wide speed range. In the mean time, it desires the characteristics of fuel economy and the capability to satisfy current and foreseeable emission regulation. Several complicated and interacted factors influence the characteristics such as tuning and combustion [1]. Although the combustion is critical to the engine performance, the mechanical design of pipeline of air inlet and exhaust system has been recognized as very important to those performances. Deshmukh et al. [3] had performed experiments for parametric study of intake,

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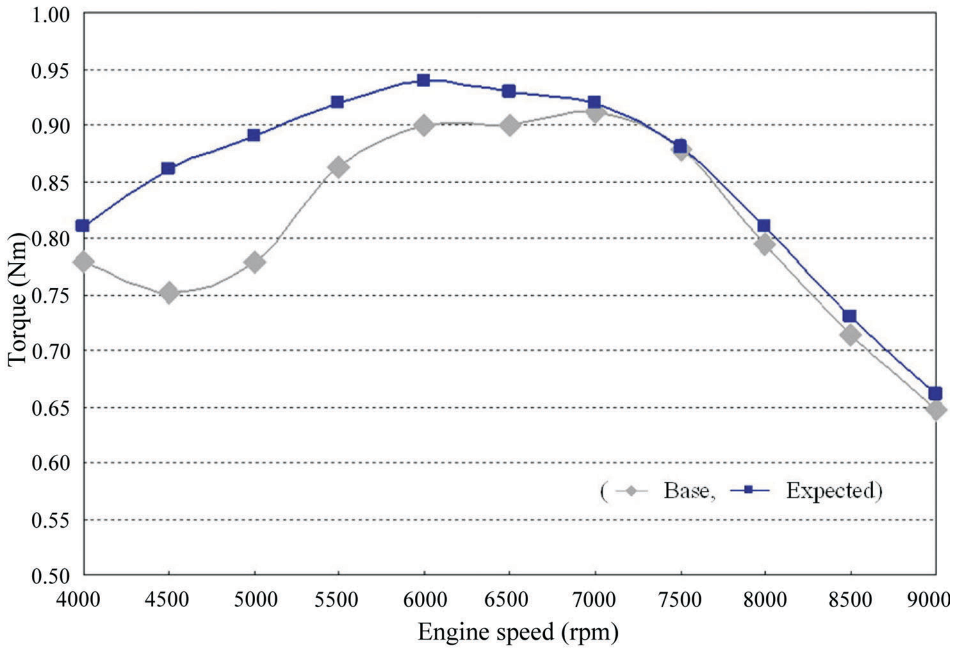

Figure 1. A typical fuel-load torque curve of small motorcycle engines.

exhaust valve timing, and exhaust pipe length. Jawad et al. [4] studied the inlet path design and throttle valve parameters to improve the tuning for a 600 cc engine. Blair et al. [5] investigated the magnifying effect of tuning by try-and-error to improve the output torque of a 4-stroke 400 cc engine. Mackey et al. [6] uses the software named Virtual 4-Stroke to simulate the tuning of a 4-stroke engine. The above three references indicate that the air exchange system is considerably effect the engine performance.

The work presented in this paper investigates the effects of intake and exhaust pipeline in a real 125 cc engine motorcycle produced by San Yang Industry. A formal design of experiment (DOE) has been applied to examine the significance of the parameters. Meanwhile, the response surface functions of performances can be established in terms of investigating parameters. Those performances corresponding to four design objectives are engine torque (T) of wide-range speed, brake specific fuel consumption (BSFC), emission of CO and HC. In this study, a particular interest focuses on promoting the output torque in low-speed range. Thus, the four design objectives contain the maximization of output torque and simultaneously minimize BSFC, CO and HC. In this paper, we presented six design cases of four-objective optimization and analysis with weighting strategy to examine the effects of various important rank of objectives. This study also investigates the effectiveness of exhaust pipeline to engine performance. Since the effect of exhaust system is less critical than that of intake section [3], a simple experiment and analysis has been executed that results in a applicable guideline for the exhaust pipeline design.

2. Analysis of DOE for Intake Pipeline

Figure 2 represents a conceptual configuration of air-inlet and outlet with surrounding devices. We adopted certain 125 cc motorcycle with fixed exhaust pipeline and investigated intake pipeline dimensions.

Figure 3 shows the top-view layout and front-view layout of a 125 cc base engine. It is noted that the work presented in this paper is independent to the type of carburetor of small engine. The intake pipeline of the base engine has length $\ell = 300$ mm and diameter $d = 35$ mm. The exhaust pipeline contains ℓ_C = constant, $\ell_V = 200$ mm and $d_a = d_b = 22.2$ mm. In order to examine the effect of intake air pipeline to the engine performances, we select length ℓ and diameter d as two design factors. Three level are selected for each factor such as 200 mm, 250 mm and 300 mm corresponding to length ℓ. Three levels of 25 mm, 30 mm and 38 mm are selected corresponding to diameter d.

The torque (T, kg · m), fuel consumption (g/(hrPS), BSFC), CO emission (%) and HC emission (ppm) are measured from 4000 rpm to 9000 rpm at each engine speed with 500 rpm interval. Those four performances are experimented by nine runs for each tested engine speed. The torque and BSFC are obtained from the dynamometer and then computed by a mathematical transformation. Figure 4 shows the characteristic curve of experimental engine torque. It can be seen that the highest output torque happens at the area of 6000 rpm. The plotting marks representing nine combinations of pipe-length/diameter and base engine.

Figure 5 shows the characteristic curves of BSFC against the engine speed. The fuel consumption is larger as engine speed is higher. The emission CO shown in Figure 6 seems to be oscillates as engine speed varies. Figure 7 shows that the characteristics of emission HC reduces as engine speed increases. The DOE shows that the different combinations of geometrical length and diameter of intake air pipeline interrelated to engine speed tremendously affect those performances. It is difficult to point out the most suitable length and diameter to promote those four characteristics from the analysis expressed in Figure 4 to Figure 7.

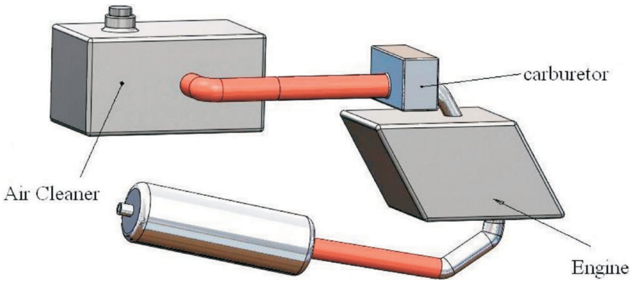

Figure 2. Engine intake and exhaust pipeline.

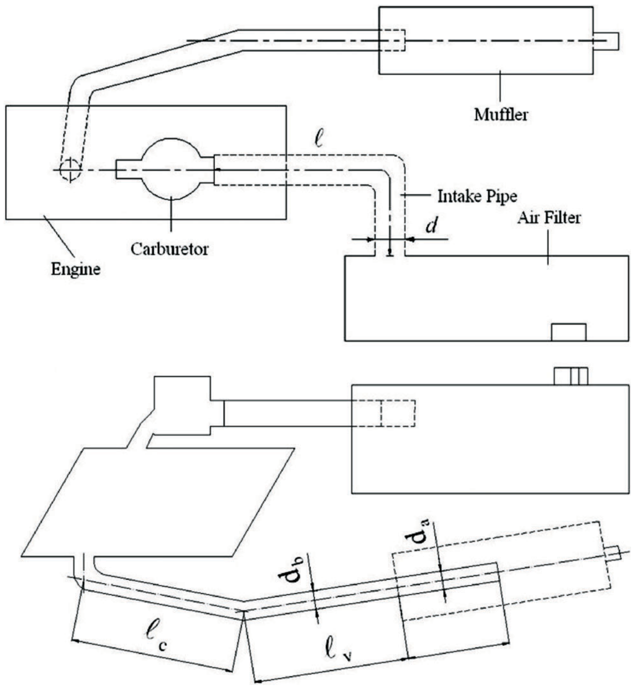

Figure 3. The top view and front view of base engine layout.

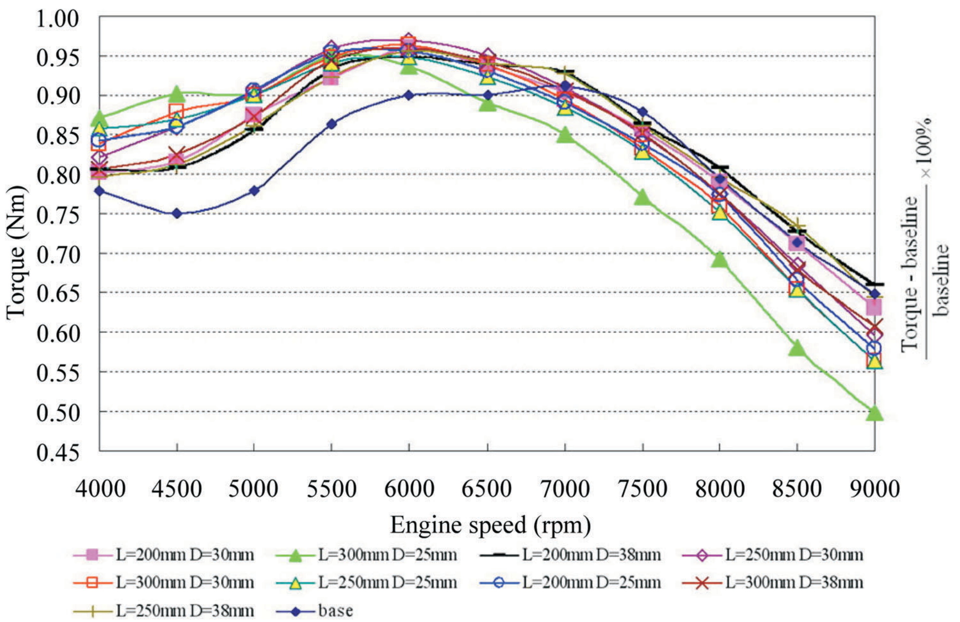

Figure 4. Characteristic curves of engine torque by DOE.

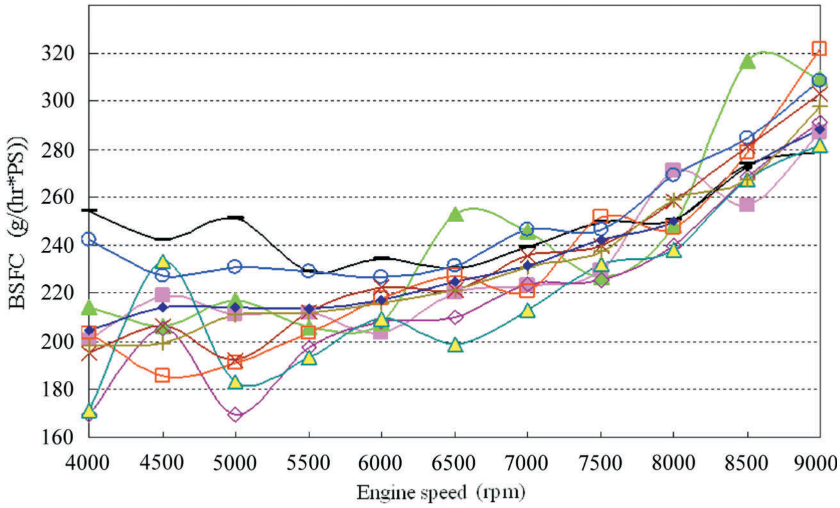

Figure 5. Characteristic curves of fuel consumption by DOE.

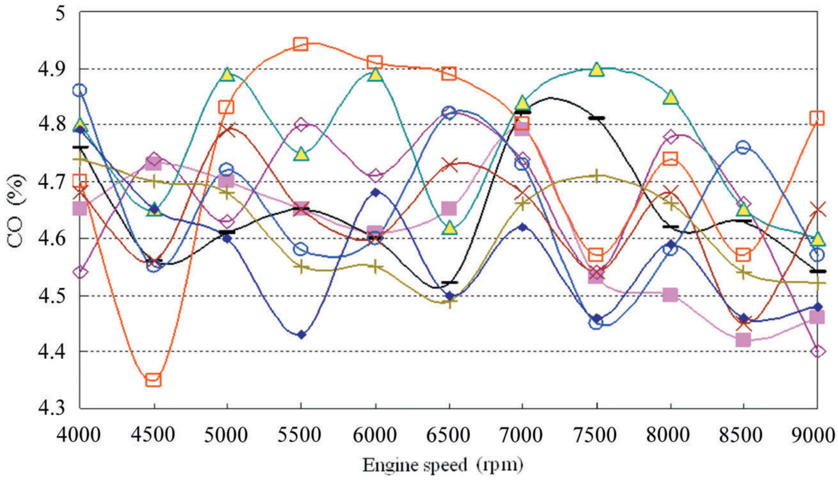

Figure 6. Characteristic curves of emission CO by DOE.

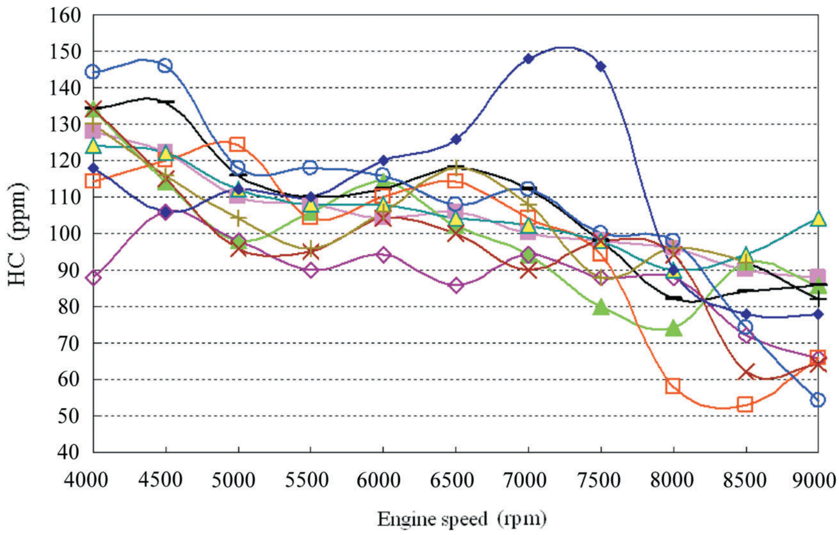

Figure 7. Characteristic curves of emission HC by DOE.

The analysis of experiments of Figure 4 shows that the pipe length at 4500 rpm and 7000 rpm, the pipe diameter in the range of 4000 rpm–5000 rpm and 6500 rpm–9000 rpm are significant to the torque. We can construct the response surface functions corresponding to individual characteristic at each experimental speed in terms of pipe length and diameter. For example, at the engine speed of 4000 rpm, we obtain $T_{4000}(\ell, d)$, $O_{4000}(\ell, d)$, $C_{4000}(\ell, d)$ and $H_{4000}(\ell, d)$ represented in Eq. (1) to (4) corresponding to torque, fuel consumption, CO and HC, respectively. Other similar response surface functions of performances in consequent speed can be obtained in similar manner.

$$T_{4000}(\ell, d) = 1.151 + 6.930E^{-4}\ell - 0.0249d - 2.558E^{-5}\ell d + 6.667E^{-7}\ell^2 + 4.359E^{-4}d^2 \quad (1)$$

$$O_{4000}(\ell, d) = 1445.57 - 6.919\ell - 24.49d - 0.0288\ell d + 0.0151\ell^2 + 0.511d^2 \quad (2)$$

$$C_{4000}(\ell, d) = 9.539 - 8.731E^{-3}\ell - 0.236d - 1.163E^{-6}\ell d + 1.667E^{-5}\ell^2 + 3.647E^{-3}d^2 \quad (3)$$

$$H_{4000}(\ell, d) = 905.122 - 9.451\ell + 30.184d + 0.0249\ell d + 0.0163\ell^2 - 0.579d^2 \quad (4)$$

3. Experimental Optimization of Intake Pipeline

The design variables are two experimental factors ℓ and d. The primary objectives in optimum design are engine torque required to be maximized; fuel consumption, CO and HC are required minimized simultaneously. Based on the important rank of each objective, six design cases associated to the primary enhancement of transmitted torque that can be formulated as design optimization for inlet-air pipeline.

Design 1. Maximize wide-range torque

This case focuses on promoting the overall torque because it is prior to all requirements in engine performance. The mathematical formulation is written as: Find ℓ, d that

$$\text{Max} \ \mathbf{F_1}(\ell, d) = (\sum_{i=1}^{11} T_{N_i}(\ell, d)) \quad (5)$$

where N_i represents 4000 rpm, 4500 rpm, ..., 9000 rpm ($i = 1, 2, ..., 11$). The design domain is within $200 \leqq \ell \leqq 300$ mm and $25 \leqq d \leqq 38$ mm. We substitute associated response surface function into Eq. (5) that can yield to the following.

$$\mathbf{F_1}(\ell, d) = (6.265 + 0.566\ell + 0.125d + 1.419E^{-5}\ell d - 2.933E^{-5}\ell^2 - 0.300d^2) \quad (6)$$

The optimum results are $\ell^* = 221.82$ mm and $d^* = 33.60$ mm. Those two values are intermediate within the design domain.

Design 2. Enhance the torque in low-speed range and promote wide-range torque

In order to increase the torque in low-range speed, a larger weighting coefficient ($w_1 = 0.7$) is adopted. This means the more importance in 4000 rpm to 6000 rpm than that of other speed ($w_2 = 0.3$). The mathematical formulation is written as: Find ℓ, d that

$$\text{Max} \ \mathbf{F_2}(\ell, d) = (w_1 \sum_{i=1}^{5} T_{N_i}(\ell, d)) + (w_2 \sum_{i=6}^{11} T_{N_i}(\ell, d)) \quad (7)$$

We substitute associated response surface function into Eq. (7) so that the function of $\mathbf{F_2}(\ell, d)$ can be rewritten as Eq. (8).

$$\mathbf{F_2}(\ell, d) = (6.265 + 0.057\ell + 0.125d + 1.419E^{-5}\ell d - 2.933E^{-5}\ell^2 - 0.0023d^2) \quad (8)$$

The optimum results are $\ell^* = 221.16$ mm and $d^* = 34.31$ mm. This result is similar to previous design case 1 with a little difference.

Design 3. Simultaneously optimize four performances

In this case, the engine torque must be maximized; meanwhile, the fuel consumption, CO and HC are simultaneously minimized. The mathematical formulation can be formulated as: Find ℓ, d that

$$\text{Min} \ \mathbf{F_3}(\ell, d) = -\sum_{i=1}^{11} T_{N_i}(\ell, d) + \sum_{i=1}^{11} O_{N_i}(\ell, d) + \sum_{i=1}^{11} C_{N_i}(\ell, d) + \sum_{i=1}^{11} H_{N_i}(\ell, d) \quad (9)$$

Since this formulation is a four-objective optimization problem and those objectives are different in units that arises numerically difficulty. It can be overcome by using the technique of normalization for each $T_{N_i}(\ell, d)$, $O_{N_i}(\ell, d)$, $C_{N_i}(\ell, d)$ and $H_{N_i}(\ell, d)$. For example, the torque of $T_{N_i}(\ell, d)$ can be normalized and rewritten as Eq. (10).

$$\hat{T}_{N_i}(\ell, d) = \sum_{i=1}^{11} \frac{T_{N_i}^{\max} - T_{N_i}(\ell, d)}{T_{N_i}^{\max}} = 4.016 - 0.01\ell - 0.154d \\ -1.758E^{-4}\ell d + 3.598E^{-5}\ell^2 + 0.0028E^{-4}d^2 \quad (10)$$

where $T_{N_i}^{\max}$ is the maximum value obtained in DOE during 4000 rpm to 9000 rpm. The optimum results are $\ell^* = 276.56$ mm and $d^* = 25.85$ mm. This result is much different from that obtained in previous two cases. It can be concluded that a larger diameter and shorter length of intake pipeline is hekpful to increase engine torque.

Design 4. Maximize wide-range torque with enhancing low-speed torque and reducing fuel consumption

The engine torque ($\hat{T}1_{N_i}(\ell, d)$) below 6000 rpm is desired promotion while the fuel consumption ($\hat{O}1_{N_i}(\ell, d)$) is simultaneously desired decreasing. Thus, a prescribed larger weighting $w_1 = 0.7$ for both torque and fuel consumption at lower speed is assigned. A smaller weighting $w_2 = 0.3$ for both torque and fuel consumption associated to other speed is selected. Thus, a four-objective optimization problem can be formulated as: Find ℓ, d and minimize the following form.

$$\mathbf{F_4}(\ell, d) = [w_1(-\hat{T}1_{N_i}(\ell, d) + w_2(-\hat{T}2_{N_i}(\ell, d)] \\ +[w_2\hat{O}1_{N_i}(\ell, d) + w_1\hat{O}2_{N_i}(\ell, d)] + \hat{C}_{N_i}(\ell, d) + \hat{H}_{N_i}(\ell, d) \quad (11)$$

where $\hat{T}2_{N_i}(\ell, d)$ and $\hat{O}2_{N_i}(\ell, d)$ represent normalized torque and fuel consumption in the range of larger than 6000 rpm. The final mathematical formulation can be transformed to Eq. (12) as following.

$$\mathbf{F_4}(\ell, d) = (40.424 - 0.463\ell + 2.103d + 7.715E^{-4}\ell d \\ + 7.964E^{-4}\ell^2 - 0.037d^2) \quad (12)$$

The optimum results are $\ell^* = 259.43$ mm and $d^* = 32.05$ mm. Obviously, this design is different from previous cases and it is a compromise result.

Design 5. Maximize wide-range torque with four individual weighting coefficients

The optimization problem can be formulated as: Find ℓ, d and minimize the following.

$$\mathbf{F_5}(\ell, d) = w_t(-\hat{T}_{N_i}(\ell, d)) + w_o\hat{O}_{N_i}(\ell, d) + w_c\hat{C}_{N_i}(\ell, d) \\ + w_h\hat{H}_{N_i}(\ell, d) \quad (13)$$

The individual weighting factor are prescribed as $w_t = 0.6$, $w_o = 0.2$, and $w_c = w_h = 0.1$ depending on designer's important consideration. It is noticeable that the highest important degree is engine torque. The fuel consumption shows the second important. The optimum results are $\ell^* = 276.93$ mm and $d^* = 25.33$ mm. This design has the similar result compared to design case 3.

Design 6. Maximize wide-range torque with compound-weighting strategy

We accumulate some experiences from previous cases and a compound-weighting optimization formulation can be written as: Find ℓ, d and minimize the following.

$$\mathbf{F_6}(\ell, d) = w_t[w_1(-\hat{T}1_{N_i}(\ell, d)) + w_2(-\hat{T}2_{N_i}(\ell, d))] \\ +w_o[\hat{O}1_{N_i}(\ell, d) + w_1\hat{O}2_{N_i}(\ell, d)] + w_c\hat{C}_{N_i}(\ell, d) + w_h\hat{H}_{N_i}(\ell, d) \quad (14)$$

where $w_t = 0.6$, $w_o = 0.2$, $w_c = w_h = 0.1$, $w_1 = 0.7$ and $w_2 = 0.3$. This case combines the features of design case 4 and case 5 so that a most balance result should be predictable. The optimum design are $\ell^* = 252.54$ mm and $d^* = 37.80$ mm. This result is compared to previous five cases that appear unique design. The consequent section will discuss above results graphically.

4. Optimum Characteristic Curves with Discussion

The above six design cases are plotted in Figure 8 to 11. All six cases below 6500 rpm result in increasing torque, as compared the base engine. The case 6 shows averagely low fuel consumption and polluted emission. Therefore, it is recommended as the best design for the performance improvement.

Table 1 shows four performances of low speed range and overall speed range for the design case 6 and base engine. Although the high torque requires higher fuel

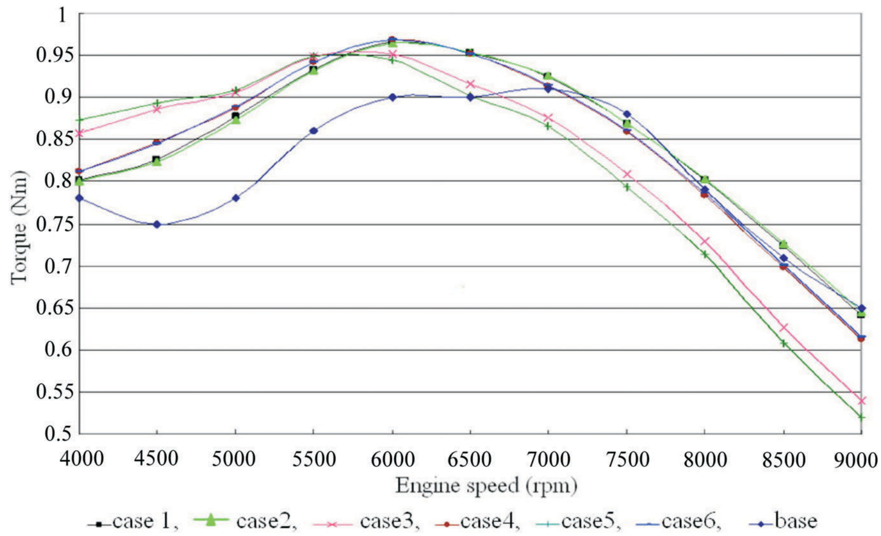

Figure 8. Six optimum designs of engine characteristic.

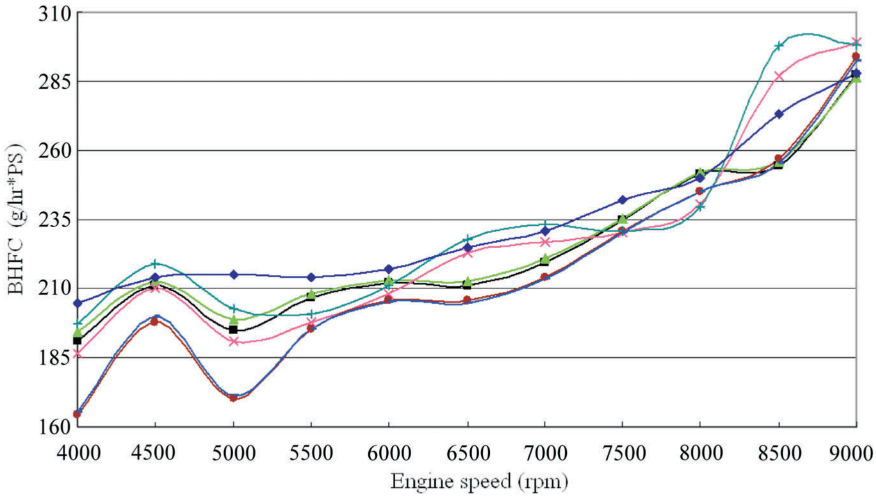

Figure 9. Six optimum designs of fuel consumption.

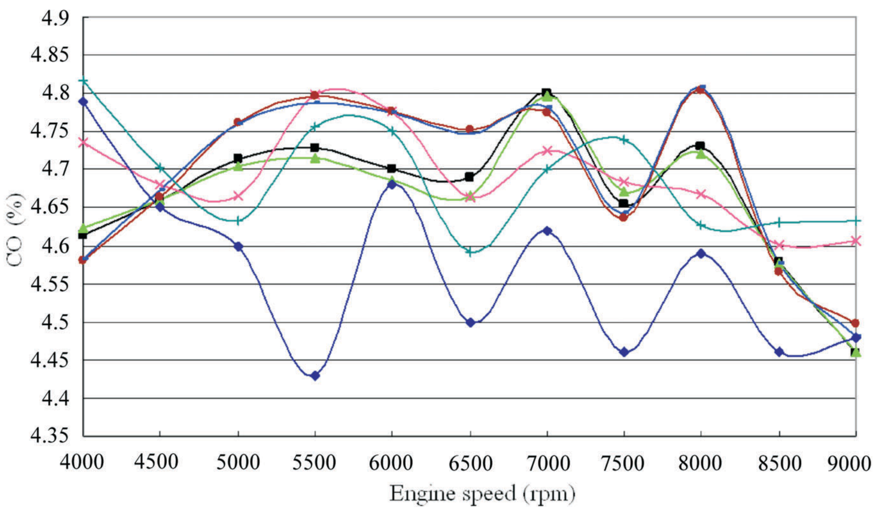

Figure 10. Six optimum designs of CO emission.

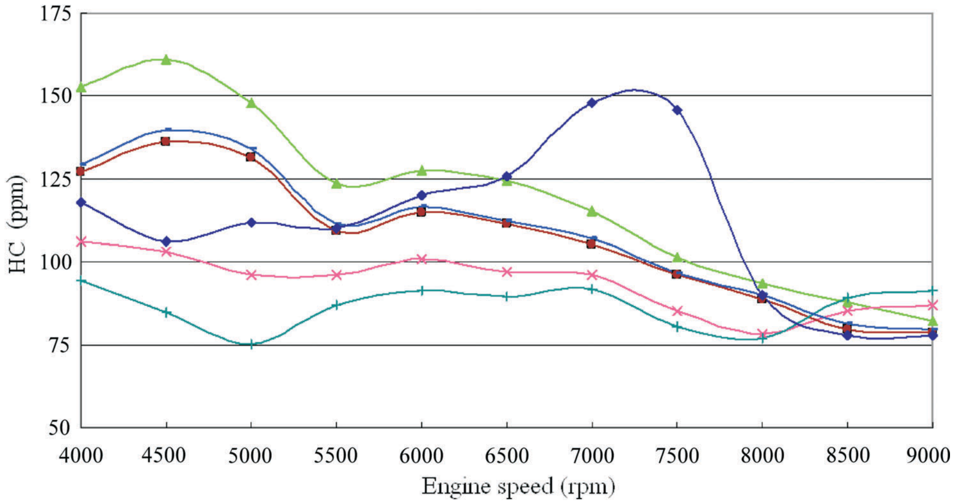

Figure 11. Six optimum designs of HC emission.

consumption; however, the optimum quantity can be obtained through this work. Emission CO is similar to that in base engine; the emission HC is reduced a little in overall speed range. Therefore, the emission generally shows non-sensitive to the size of intake air pipeline. Overall speaking, it can be concluded that the length and diameter of the intake pipeline are definitely critical to the engine torque and fuel consumption. For comparing the base engine of well engineering design, the proposed DOE based optimization still can increase about 10% improvement in the torque and fuel consumption. Another noted point is that the pipeline on a realistic base-engine is not geometrically straight that yield to lower torque than experiment at slow speed range.

5. Experimental Study of Exhaust Pipeline

From the previous description in Figure 3 shows that the portion of ℓ_V, d_a and d_b in exhaust pipeline can be re-design in the base engine. From the conclusion in reference [3] and [5] we learn that the length ℓ_V influences the engine performance and the performance can be enhanced by magnifying the diameter d_a. Thus, this study alters those of ℓ_V, d_b and d_a, by maintaining the intake pipeline, to examine the effects of exhaust pipeline. Therefore four experiments (A to D) are arranged, as shown in Table 2. Figure 12 and 13 show the characteristic curves corresponding to four performances in this experiment. The performances of torque (T) and BSFC is shown in Figure 12. The performances of emissions CO and HC is shown in Figure 13. The observation of experimental result indicates that the exhaust pipe length, pipe diameter and the magnification of diameter have no significant effects to engine performances. A little improvement can be reached by modifying the base pipeline to ℓ_V = 300 mm, d_b = 22.2 mm and d_a = 28.6 mm. We compare the effects of exhaust pipeline and intake pipeline obtained in this study for a small engine; those four performances in intake pipeline reflect more significance than exhaust pipeline. The similar conclusion also had

Table 1. The comparison of performances for design 6 and base engine

	rpm	Pipeline of design 6	Pipeline of base engine	%
Torque	4000~6000	4.45	4.07	9.34
(kg · m)	4000~9000	9.283	8.91	4.19
BSFC	4000~6000	937.44	1065	-11.98
(g/(hr*PS))	4000~9000	2379.1	2574	-7.57
CO (%)	4000~6000	23.57	23.15	1.81
	4000~9000	51.615	50.26	2.69
HC (ppm)	4000~6000	631.26	566	11.53
	4000~9000	1198.75	1232	-2.70

Table 2. Experiments arrangement of exhaust pipeline

Type	ℓ_v (mm)	d_b (mm)	d_a (mm)
Base	200	22.2	22.2
A	300	25.4	25.4
B	200	25.4	25.4
C	200	22.2	25.4
D	200	22.2	28.6

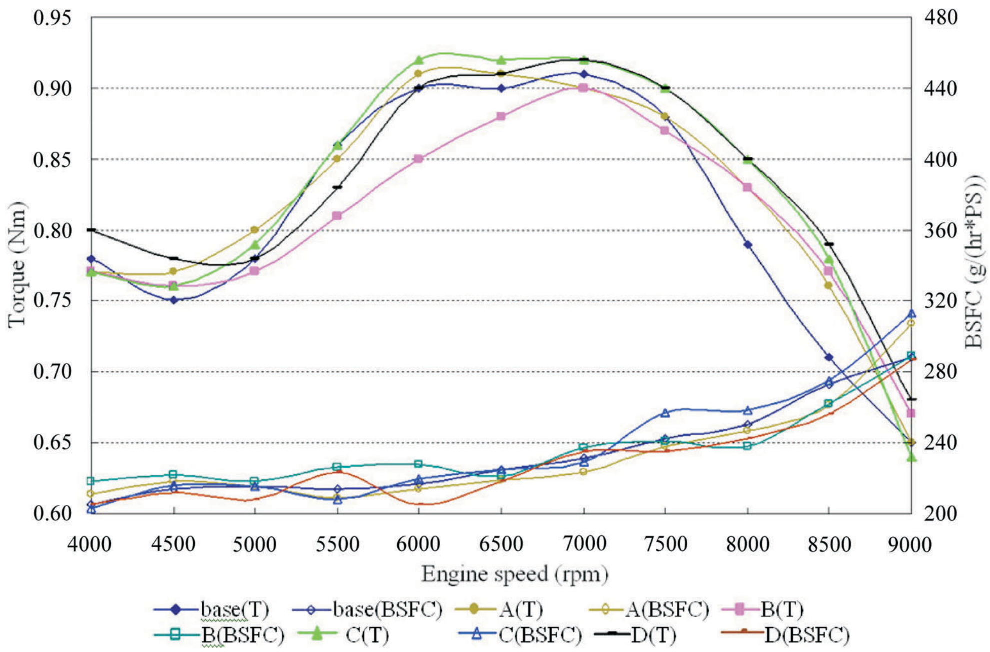

Figure 12. Torque and BSFC of the exhaust pipe.

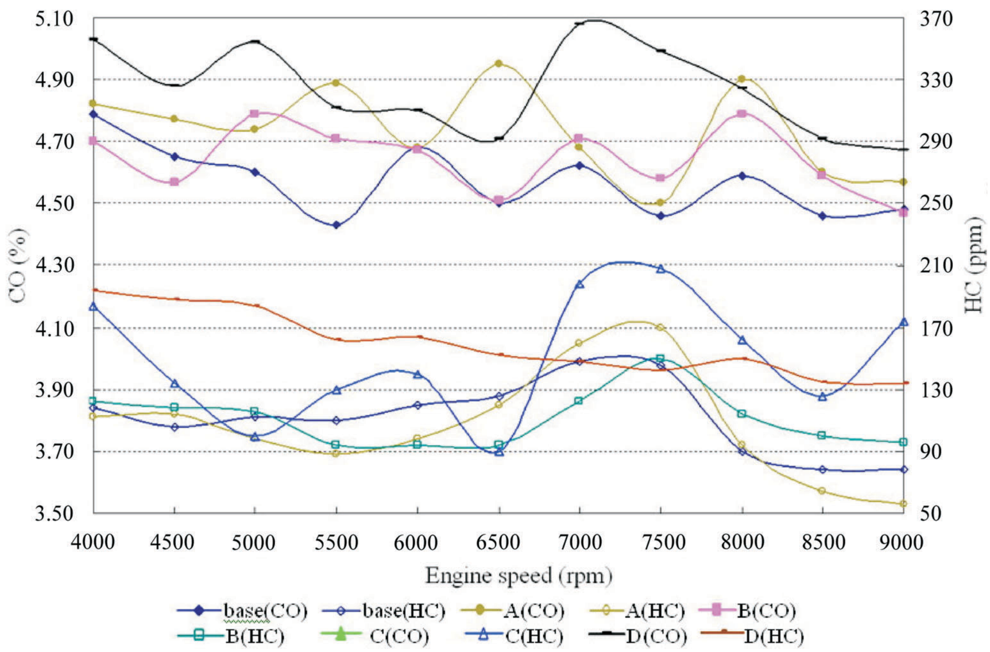

Figure 13. CO and HC of the exhaust pipe.

been obtained in Deshmukh's work [3].

6. Concluding Remarks

This paper proposes an integrated process utilizing design of experiment to build up explicit response surface functions to represent the complicate behaviors of engine torque, fuel consumption and emissions in terms of the geometrical dimensions of air pipeline system of a motorcycle. Six design cases containing four-objective optimization with weighting strategy are investigated and compared for obtaining the compromise designs. It shows that the engine torque of wide range speed can be enhanced as well as the fuel consumption can be reduced. Furthermore, the torque of low-speed range can be considerably increased to a higher value. There is no definite evidence supports the reduction of polluted emissions by modifying the intake pipeline. The study also shows the effect of exhaust pipeline that is not as significant as that of intake pipeline; however, the method of DOE still provides useful information for the improvement to exhaust pipeline effect.

Acknowledgement

The support received from the National Science Council, Taiwan under Grant No. NSC 98-2221-E-032-005, is gratefully acknowledged.

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Manuscript Received: Dec. 6, 2010
Accepted: Sep. 16, 2011