INTAKE AND EXHAUST INFLUENCE ON ENGINE PERFORMANCE

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Abstract

The intake and exhaust system shapes are very important factors in the gas exchange process of the internal combustion engines. That's why many investigations are related to the improvement of their geometry in order to maximize engine's performances or lower its emission values of the exhaust. Modern approach in such researches means use of numerical simulation codes, which give us individual geometry of several engine parts. After the production of numerically improved part, they must be tested and evaluated with the experiments.

The paper deals with the influence of the intake and the exhaust characteristic (diameters, lengths, shapes) on engine power, fuel consumption and emissions. The optimisation procedure together with the optimised measurements for the intake and the exhaust are also shown. For the simulations the AVL's program BOOST was used. It proved to be accurate enough for the four-stroke internal combustion engines in the course of our previous work.

1. Introduction

The intake and the exhaust systems have very important role in breathing ability of the internal combustion engine. Therefore their shapes, pipes lengths and diameters have crucial effect on engine's characteristics.

Modern search for the ideal intake and exhaust geometries includes use of engine simulation codes, which estimate engine's performance with good accuracy and can used for pre-designing various parts of internal combustion engine. The quest for ideal shape of engine parts requires numerous time-consuming trials and usually there are also several constraints, which have to be taken into consideration. To overcome these drawbacks, the engine simulation code can be connected with the optimisation program. Together they automatically perform the search for the optimum of the engine parts parameters.

The first step of design process of intake or exhaust system is model (or several models - different elementary geometry) creation in the simulation code pre-processor. That's followed by some trial runs in order to get basic information about the influence of the engine part parameters (selection of the most appropriate model). The results gained help us in the determination of the parameters value intervals, which are needed by the optimisation program. Finally we need the objective function (purpose of the optimisation) and constraints, which must be fulfilled during the optimisation. Then after defining initial values of the parameters (design variables), the optimisation process can start.

2. Engine model layout

In the course of our work AVL's programme Boost proved to be convenient for simulation of our four-cylinder four-stroke Honda engine. The connection with gradient-based optimisation programme iGO was also established.

The idea for the basic geometry of the intake and the exhaust system is shown on Figure 2.1.

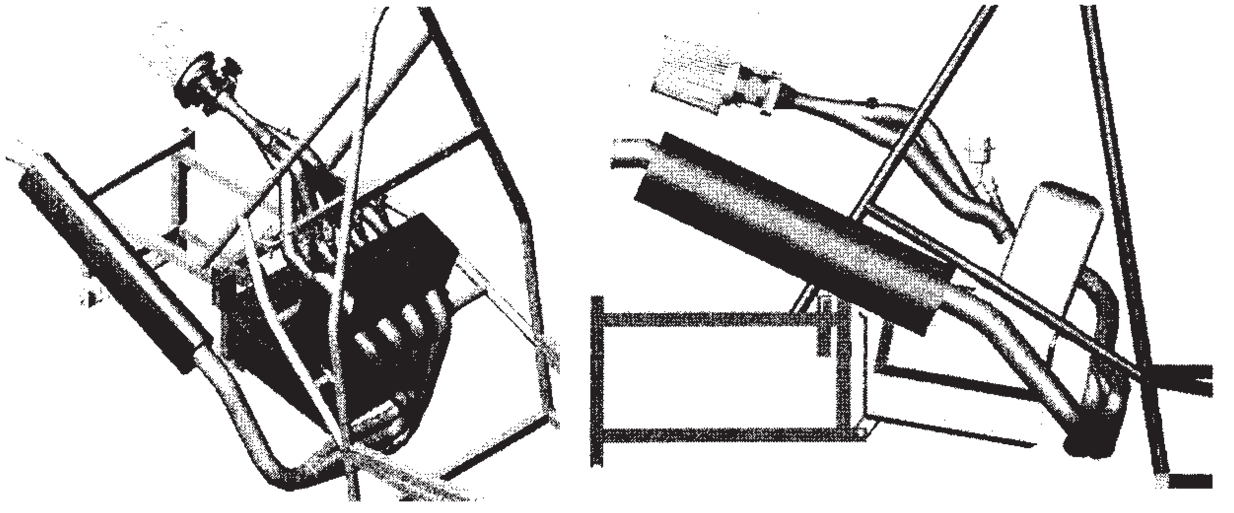
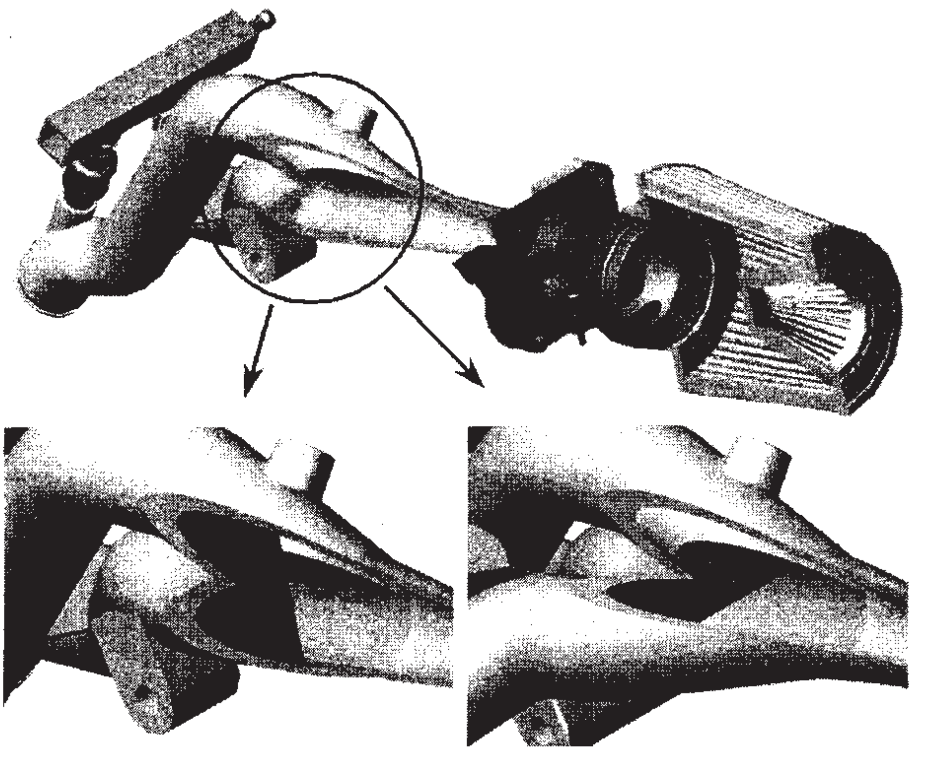


Figure 2. 1. Intake and exhaust system

Because of the pressure waves inside the intake and the exhaust system, the lengths of individual runners are very important. Connection between the secondary pipe and the primary pipes also influences on the conditions inside both systems. In our case the airflow from secondary pipe can be directly distributed into all for pipes (1-4 connection) or it can be firstly divided into two and then after defined distance in four primary pipes (1-2-4 connection). There are two possible 1-2-4 connections regards to firing order (1-2-4-3):

- connection between the primary pipes of the first and second cylinder (1-2,3-4),
- connection between the primary pipes of the first and fourth cylinder (1-4,2-3).

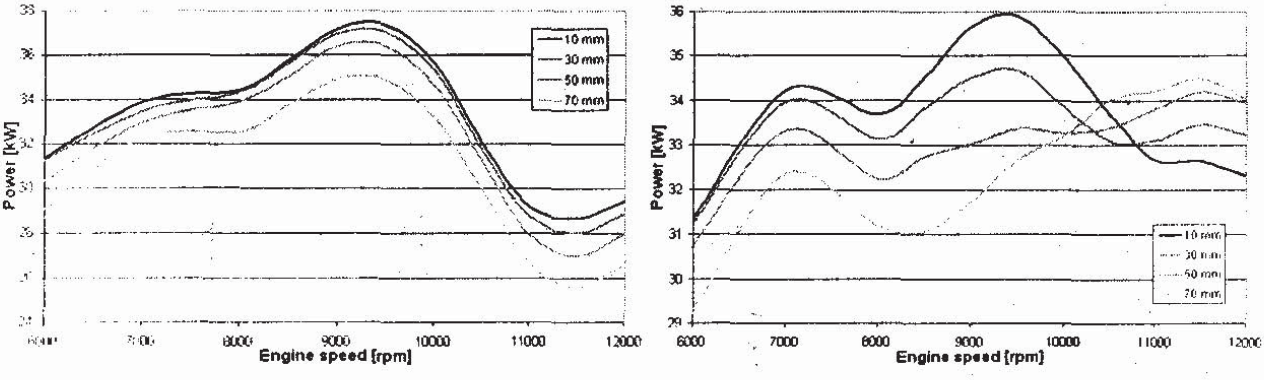
Both examples can be practically established with the use of barriers (Figure 2.2).



a.) 1-2,3-4 *b.) 1-4,2-3*

Figure 2. 2. Barriers for 12-34 and 14-23 connection in the intake system

Engine models were made in Boost for both examples. Calculations were performed for several barrier lengths; results are shown in Figure 2.3 and 2.4.



a.) 1-2,3-4 *b.) 1-4,2-3*

Figure 2. 3. Influence of barrier lengths on engine power (intake)

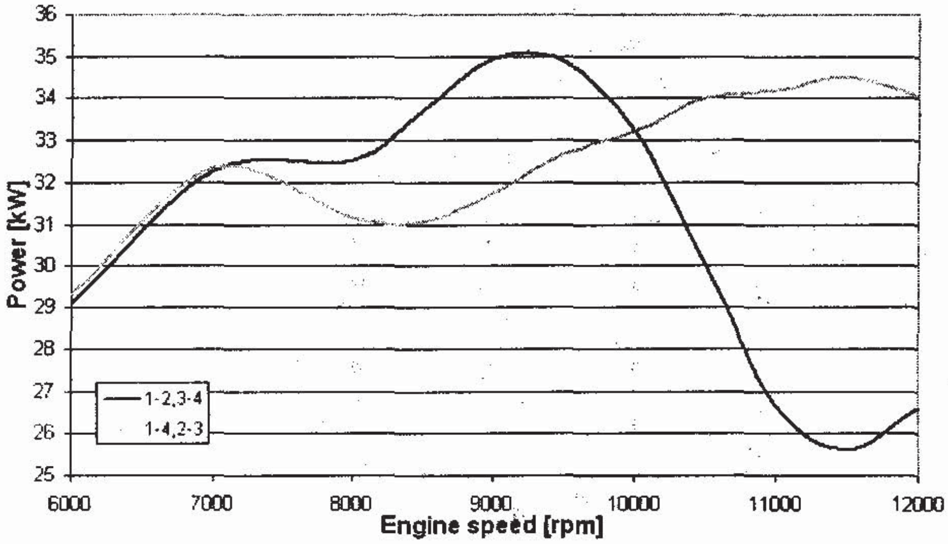


Figure 2. 4. Engine power in dependence of different connections (barrier length: 70mm)

As one can see the 1-2,3-4 connection is better between 7000 and 10000 rpm, while above 10000 rpm and overall the connection 1-4,2-3 is more appropriate and used for the optimisation process.

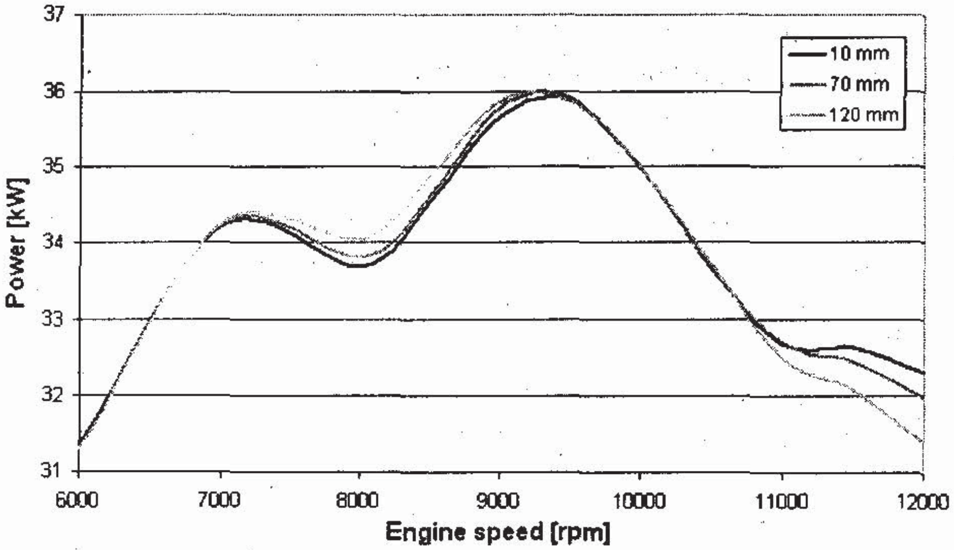


Figure 2. 5. Influence of barrier lengths on engine power (exhaust)

Similar conclusions can be made for the exhaust based on the calculations, which were performed for different pipe connections in the exhaust system. Figure 2.5 (1-4,2-3 connection) shows slight increase of power with longer barrier between 7000 and 10000 rpm, while engine power decrease in the area above 11000 rpm.
According to the obtained results 1-4,2-3 connections were selected for the intake and the exhaust system. Engine model layout in Boost pre-processor used for optimisation process is shown on Figure 2.6.

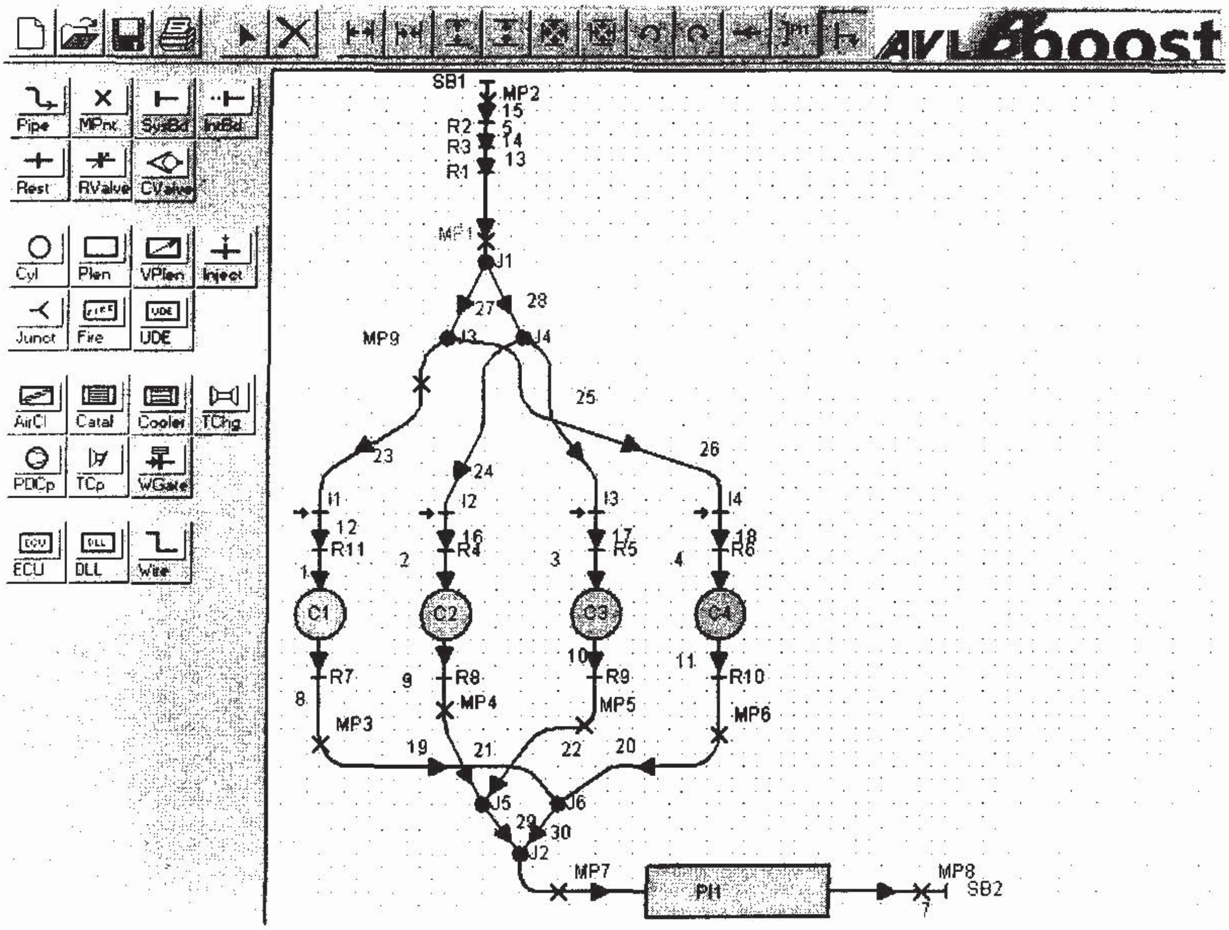


Figure 2. 6. Engine model layout

3. Optimisation procedure

Optimisation is an iterative process. In each iteration the optimisation program iGO runs the engine cycle simulation program Boost, acquires its output data and makes one call to the build-in optimiser. Programs can't be directly combined together, so simple ad-hoc wrapper programs had to be written to establish the communication (Figure 3.1).

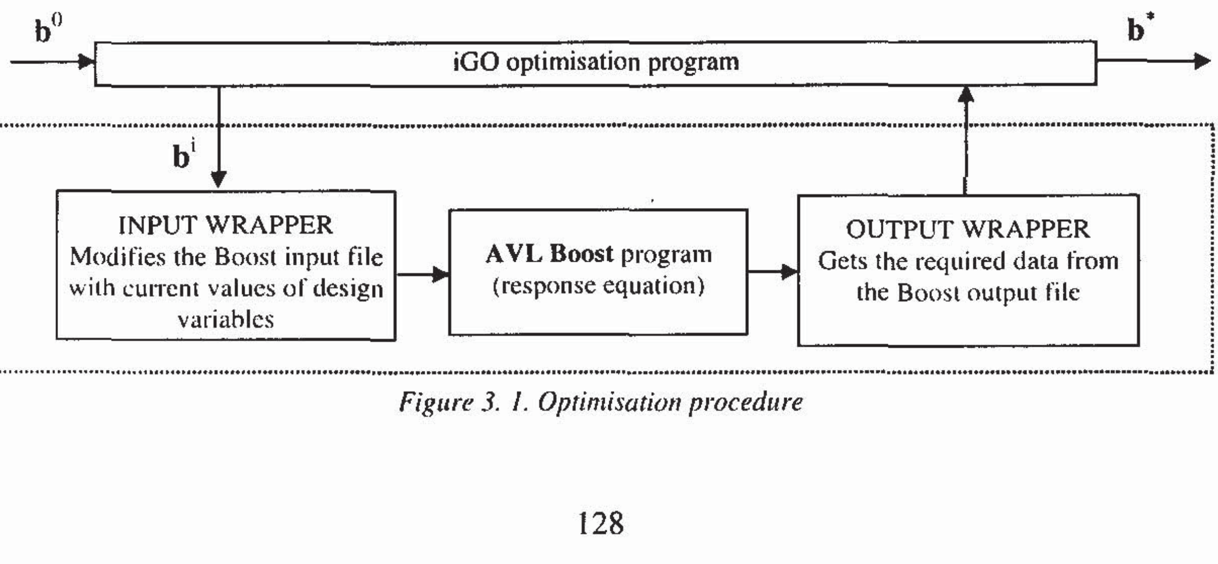


Figure 3. 1. Optimisation procedure

4. Optimal design formulation

For the formulation of the optimal design problem of the intake and exhaust system we have to define the objective function, the design variables with the boundary values and the constraints.

The main goal of our design process is the maximisation of the effective power in a wide range of engine speeds. This objective can be mathematically expressed as:

$$\min(-P_{e1},-P_{e2},\ldots,-P_{ez},\ldots,-P_{eN}),$$

where P_{ez} is the effective engine power corresponding to the z^{th} operating engine regime and N is the number of the operating regimes under consideration. Negative effective power values are used because of the nature of the optimal design process. The operating engine regimes are selected based on our experience only at full load at six ($N=6$) different engine speeds:

$$n[\min^{-1}] = \{7000,8000,9000,10000,11000,12000\}^T.$$

The next step is the selection of the design variables, which will be varied during the optimisation. In our case they are related to the primary pipe dimensions of the intake and the exhaust system and barrier lengths. The design variables together with the corresponding value intervals and initial conditions are given in Table 4.1.

Table 4. 1. Design variables

Design variable	Symbol	Initial value	Interval	Pipe number (Boost)
Intake pipe diameter [mm]	d_i	34	[30-50]	23, 24, 25, 26
Intake pipe length [mm]	L_i	356	[300-500]	23, 24, 25, 26
Intake barrier length [mm]	L_{ib}	10	[10-60]	27, 28
Exhaust barrier length [mm]	L_{eb}	10	[10-130]	29, 30
Exhaust pipe length [mm]	L_e	520	[400-600]	6

At the end the constraints must be defined. The shape of the intake system determines the minimal length of the primary pipes with regard to their diameters. Because of the omitted space the exhaust system length is also limited ($L_{e.\min}=400mm, L_{e.\max}=600mm$). Other constraints are related to the specific fuel consumption ($g_{e.\max}=380g/kWh$), the engine noise ($\xi_{\max}=110dBA$), which derives from the rules and the harmful emissions of NO_x ($\tau_{\max}=4.5g/kWh$). These constraints can be written as follows:

$$L_{\min}-L_i \le 0$$
$$L_{e.\min}-(L_e-L_{eb}) \le 0$$
$$(L_e+L_{eb})-_{e.\max} \le 0$$
$$g_{e.z}-g_{e.\max} \le 0 \quad z=1,2,\ldots,N$$
$$\xi_{e.z}-\xi_{e.\max} \le 0 \quad z=1,2,\ldots,N$$
$$\tau_{e.z}-\tau_{e.\max} \le 0 \quad z=1,2,\ldots,N$$

The requirements to minimise N objective functions, the selection of the design variables, the constraints and the appropriate response equation define the original design problem. Such a problem doesn't have a form suitable for the standard solution procedure and it must be transformed. Because of that an additional design variable ($b_{n+1}\in R$) is introduced. The objective function can be defined as

$$g_0=-b_{n+1}.$$

Furthermore the new constraint must be imposed

$$b_{n+1} - \frac{P_{e,z}}{\zeta_z} \leq 0,$$

where the symbol ζ_z denote suitable coefficients related to the desired effective power at different engine speeds ($\zeta_1 = \zeta_6 = 40, \zeta_2 = \zeta_5 = 41, \zeta_3 = \zeta_4 = 42$).
In our case the formulation of the optimal design consists of the objective function, 6 design variables and 27 constraints considering 6 different engine speeds.

5. Results

Our optimisation case was solved nicely in 7 iterations. Optimal design variable values are given in Table 5.1.

Table 5. 1. Design variables

Design variable	Symbol	Initial value	Optimised value
Intake pipe diameter [mm]	d_i	34	43,7
Intake pipe length [mm]	L_i	356	402,5
Intake barrier length [mm]	L_{ib}	10	11
Exhaust barrier length [mm]	L_{eb}	10	10,2
Exhaust pipe length [mm]	L_e	520	600

The diagram on Figure 5.1 shows engine power increase on the whole range of engine speed, so that the results of the optimised design are very satisfactory.

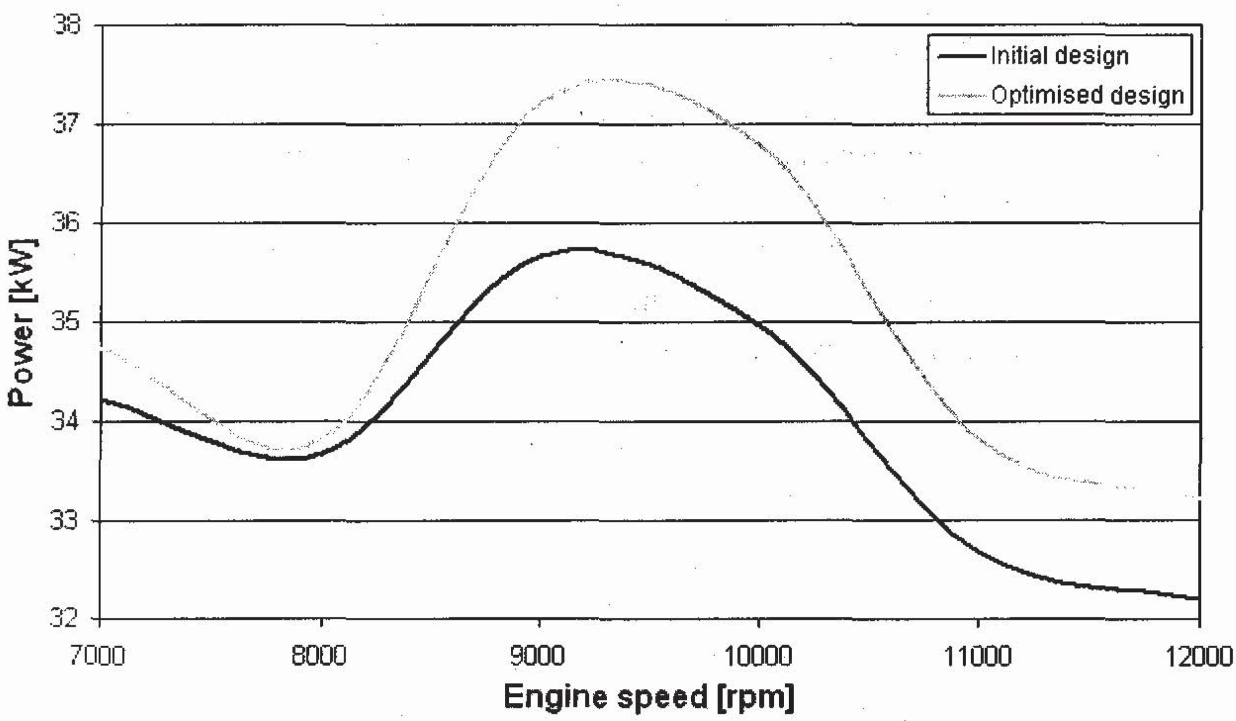


Figure 5. 1. Engine power increase

The average value of the effective power with optimised intake and exhaust system increased by 3 %, while it increased by 4 % between 9000 and 12000 rpm.

The specific fuel consumption is also better at all calculated engine speeds (Figure 5.2), the difference in engine noise is negligible, while NO_x emission is slightly higher only at 9000 rpm. All other values are lover than before (Figure 5.3).

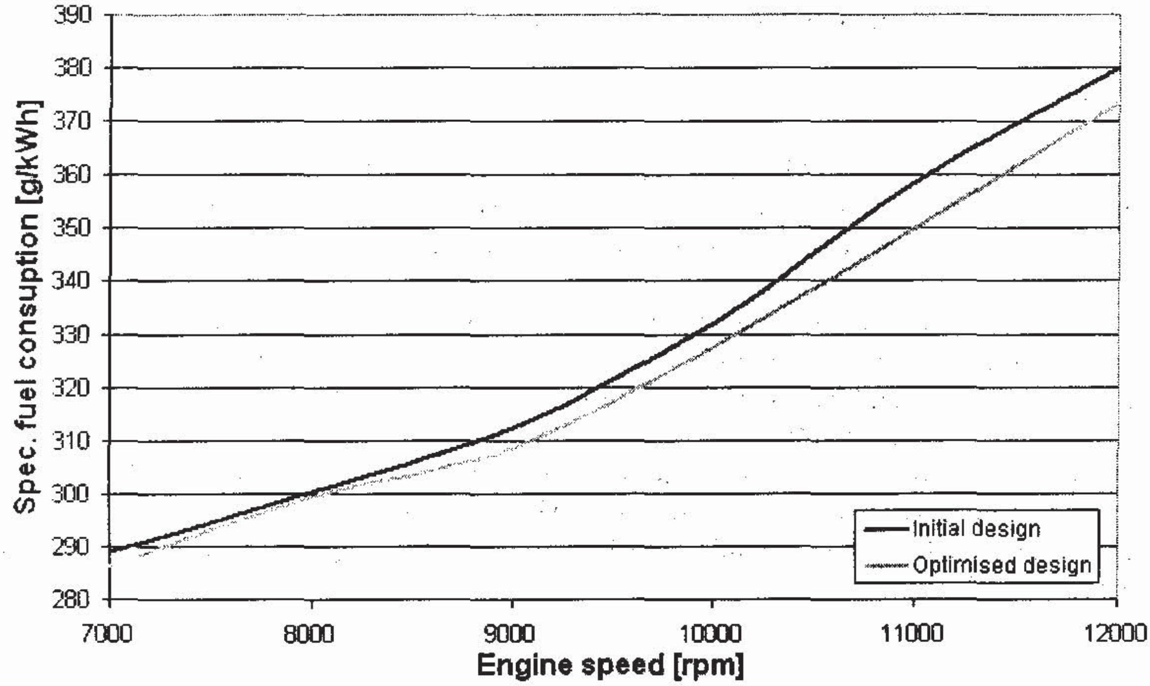


Figure 5. 2. Specific fuel consumption

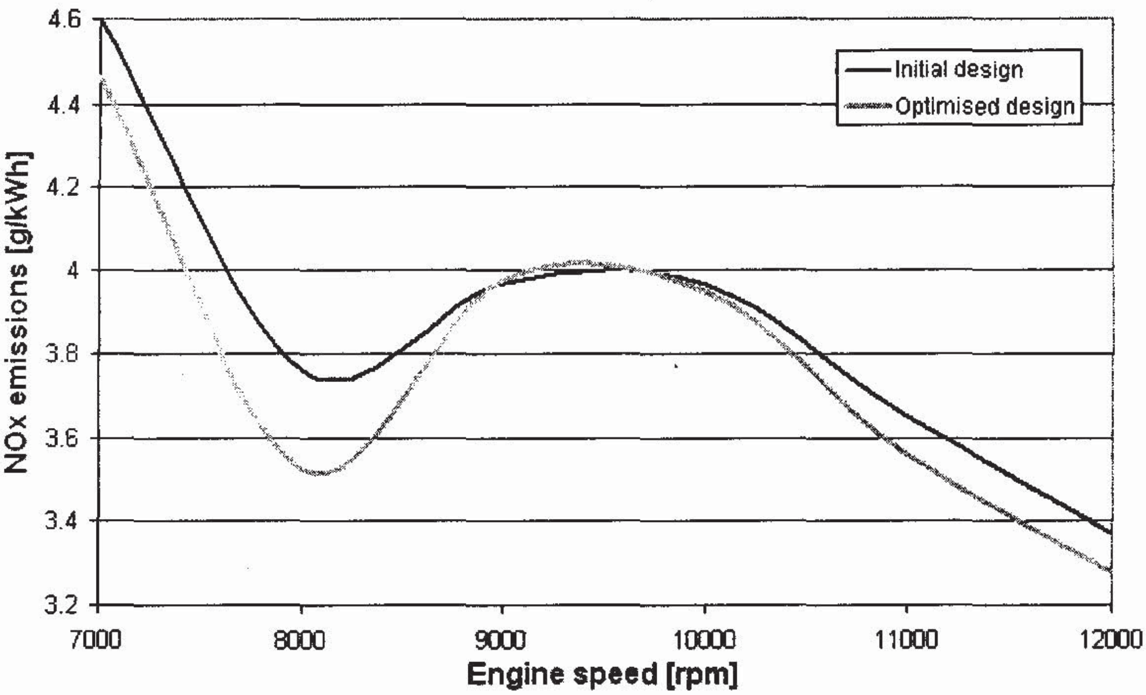


Figure 5. 3. NO_x emission

6. Conclusions

Influence of several intake end exhaust parameters on the engine characteristics is shown in the paper. Basic shape (1-2-4 or 1-4), lengths and diameters of primary and secondary pipes of intake and exhaust have major effect on engine performance, so they were used for the optimisation. The correlation between the engine simulation code Boost and the optimisation program iGO proved once again as an effective tool that provides a way for automatic search of the optimal shape of engine parts. The optimisation process can go in different directions; such as power increase, fuel consumption and noise minimisation or even modification of the engine in order to achieve the allowed and ever stricter emission values.

References

[1] Honda CBR600F, Shop Manual, Honda Motor co. ltd. 1990

[2] M. Kegl, B. J. Butinar, B. Kegl, An efficient gradient-based optimisation algorithm for mechanical systems, Comunications in numerical methods in engineering, 18:363-371, 2002

[3] V. C. Messa, Optimal design of the intake and exhaust system of a gasoline engine with special demands, Diploma work, Faculty of mechanical engineering Maribor, 2004

[4] P. Pogorevc, B. Kegl, Optimal design of the intake system, J. Kones 2003, Vol. 10, No. 1-2, Warsaw - Gdansk, 2003

[5] P. Pogorevc, Oblikovanje sesalnega razvoda s pomočjo računalniške dinamike tekočin, magistrska naloga, Fakulteta za strojništvo Maribor, 2003

[6] R. J. Tabaczinski, Effects of Inlet and Exhaust System design on Engine Performance, SAE 821577