# Sensitivity analyzes turbocharging variables for optimum engine performance

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**Abstract:** One dimensional model for a four cylinder V type turbocharged CNG engine has been developed and studied in detail using GT-POWER software [1]. The sensitivity analysis for a wide variety of parameters such as BMEP, BSFC, volumetric efficiency, turbocharger speed and compressor efficiency at different intake and exhaust of turbocharger unit conditions has been carried out for a specified engine with certain valve timings, injection timing and compression ratio at different engine speeds. For validation purposes the results are compared with experimental data available where 5 percent error has been achieved. The results obtained could be accurately used to predict and optimize a set of favorable performance conditions during SI engine development process and turbocharger selection also improved matching of parameters. GT-Power is a very powerful tool for simulating complete engines. However care must be taken when analyzing the results. The code only uses one direction and time, meaning that the flow will always be uniform in the cross sections. Whereas in many parts of the real engine the flow field is three dimensional and far from uniform in the cross-sections.

**Key words:** turbocharger, sensitive analyze, SI engine

| Nomenclature | | | |
|---|---|---|---|
| CA | crank angle | | |
| BMEP | brake mean effective pressure | | |
| BSFC | brake specific fuel consumption | | |
| K | Kelvin | | |
| CA | crank angle | | |
| **Variable name** | **Variable definition** | **Change extent** | **Reference value** |
| T-IN | Intake air temperature | Increasing 5 k | 289.95 k |
| P-IN | Intake air Pressure | Decreasing 0.1 bar | 0.8659 bar |
| IVO | Inlet valve opening | Increasing 3 degrees of CA | 345 CA |
| EVO | Exhaust valve opening | Decreasing 7 degrees of CA | 136 CA |
| NO-WG | No waste gate | --------- | With waste gate |
| AFR | Air fuel ratio | Decreasing 1 unit | 14.94049 |
| CR | Compression ratio | Increasing 1 unit | 9.8 |
| LRI | Intake runner length | Decreasing 8 mm | 103 mm |
| ICE-EFF | Intercooler efficiency | Increasing 10 percent | 0.84 |
| DRE | Exhaust runner diameter | Increasing 4 mm | 36mm |
| D-M | Muffler diameter | Increasing 5 mm | 50mm |
| DRI | Intake runner diameter | Decreasing 5 mm | 38mm |
| ADVANCE | Injection timing | Decreasing 2 degrees of CA | -14.700 degree of CA |

## 1. Introduction

A precise turbocharger selection could increase power output together with improved performance characteristics in an internal combustion engine. Using a turbocharger for a SI engine due to limitations many basic parameters has to be changed to achieve best efficiency possible. One-dimensional and three-dimensional simulation models are used to predict the performance of a newly designed engine to limit the number of steps, changes and modifications required during development of the prototyping and releasing an engine[2]. Zhang Wei-zheng et al. simulated the performance of a high power density diesel engine, analyzed the influencing factor and presented some key measures [3]. Zhang Shi-ying et al. used BOOST code to simulate the performance of a turbocharged DI diesel engine. The power, specific fuel consumption and emission of the diesel engine was predicted on

various operating condition [4]. XU Yuan-li et al. used BOOST code to simulate the performance of 4102ZQ diesel engine. Effect of compression ratio, injection timing, valve timing and exhaust system on power performance was put forward [5]. M. M. Abou Al-Sood presented simulation to investigate the effect of varying compression ratio on engine brake power and BSFC and torque and engine soot and NOx emissions. Optimum compression ratio was obtained on the different engine speeds [6,7]. Tim Lancefield used Wave code to simulate the effect of variable valve timing on the performance of a diesel engine. The optimum VVA was obtained on the different engine speeds and loads [8]. A.E. Catania et al. presented simulation to investigate how the boosting and exhaust pressures affected the performance of diesel engine on different engine speeds and loads [9]. Carlo Beatrice et al. analyze the compression ratio reduction in terms of emissions and combustion characteristics[10].

The study was performed using GT-Power to visualize how different parameters affected parameters such as efficiency, and break torque. Simulations were performed at steady state conditions. GT-Power is a one dimensional flow solver specifically tailored to simulate internal combustion engine flows, accounting for cylinder motion, combustion, gas composition, and temperatures among others. GT-Power calculates the flow motion in time using many different models for all parts of the engine. The models are mainly based on experimental empiricism and curve fitting from tabulated data.

The main question of this research is to find and sort the most important parameters which affected performance of an SI engine hence extended one-dimensional simulation of a turbocharged four-cylinder V-type SI engine has been carried out to study the effects of parameters such as compression ratio, intake temperature, intake pressure, valve timings, injection timing, air fuel ratio, diameter and length of inlet and exhaust runners, intercooler efficiency and waste gate application on performance of an SI engine by looking into engine metrics such as power output, fuel consumption, volumetric efficiency, turbocharger speed and compressor efficiency.
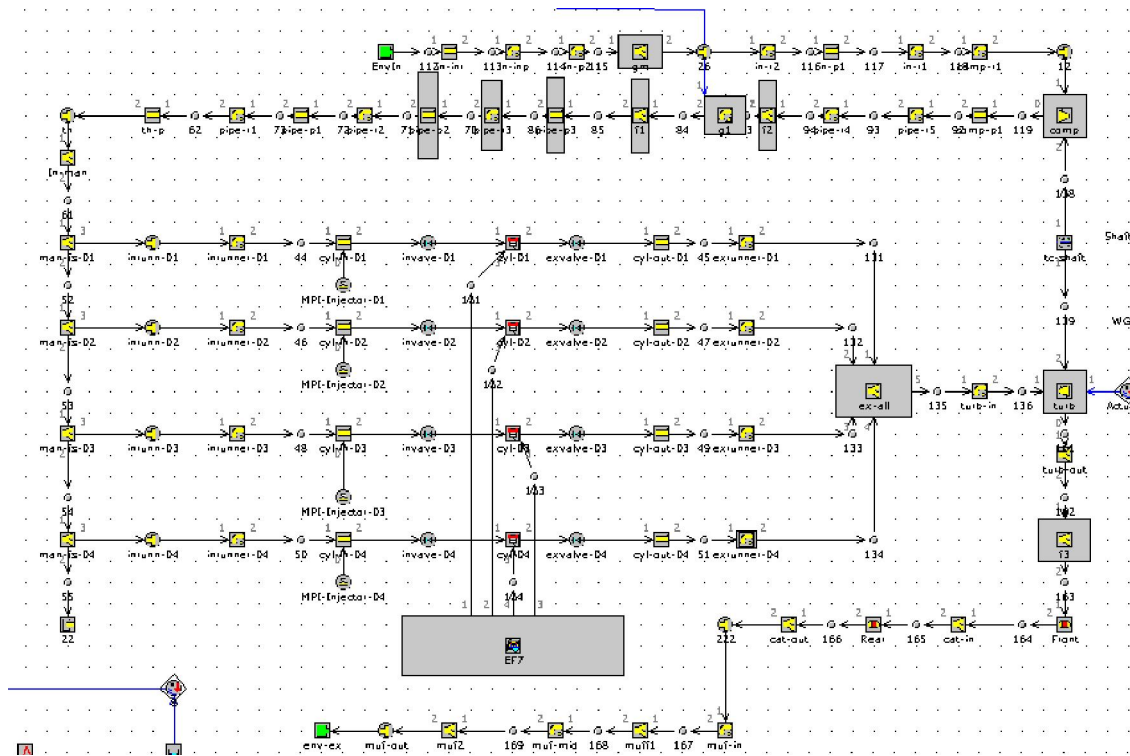
**2. Engine Simulation Model**


**Figure 1.** Turbocharged SI engine model

In the present work a specified engine simulation model has been used to study target parameters. The GT–Power software has been used to analyze the one-dimensional simulation and to estimate performance of the engine. GT-Power is a software developed by Gamma Technologies that can simulate an entire internal combustion engine. The programs main parts are the different pipes and flow splits that are used to build up the geometry. For the more specialized parts (e.g. cylinders, turbochargers, after-treatment devices

etcetera) the program uses models and tables to calculate the values needed (e.g. pressure, heat release, mass flow, efficiency, etc). To insure the accuracy of the model, results are compared with existing test data. Table 1 shows specifications of modeled engine.

**Table 1**. Engine specifications

| Bore | 78.6 |
|---|---|
| Stroke | 85.0 |
| Connecting Rod Length [mm] | 133.5 |
| Piston Pin Offset [mm] | 0.50 |
| Displacement/Cylinder [liter] | 0.412 |
| Number of Cylinders | 4 |
| Compression Ratio | 11.5 |
| IVC [CA] | 26ABDC |
| EVO [CA] | 25 BBDC |
| IVO [CA] | 15 ATDC |
| EVC [CA] | 15BTDC |

On the base of actual layout of a v-type four-cylinder SI engine, below configuration has been set up in GT-POWER software, figure(1).

The model has been tuned and adjusted to match the experimental results derived from test rig as accurately as possible for several operating conditions[4]. These tests had been carried out in IPCO company and in this research has been used for validatiing simulation results. In figures 2 to 5 simulation and the test data are compared at full load and when throttle valve is 25% opened. From the data achieved from these comparisons average validation percent obtained 5 percent.
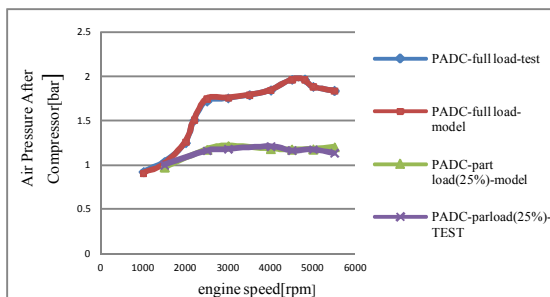


**Fig 2**. air pressure after compressor at full load and part load when throttle valve is 25%opened from simulation and test data

Application of turbocharger in a SI engine affects many parameters considering limitations of many parts due to metallurgic constrains; Any changes in parameters usually directly affects engine operation. To have the best setting and changes without hampering optimal performance possible; the performance parameters have to be identified and classified with the degree of their influential effects. Therefore sensitivity analysis has been carried out for

13 variables parameters of the engine which was identified and through following procedures has been ranked.
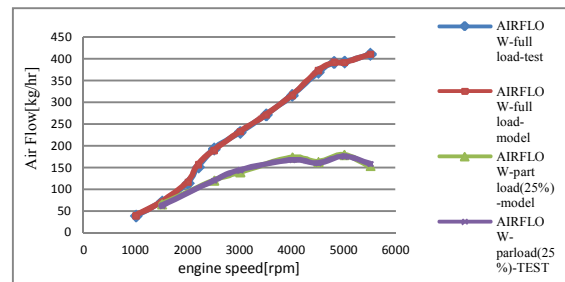


**Fig 3.** air flow at full load and part load when throttle valve is 25%opened- simulation and test data
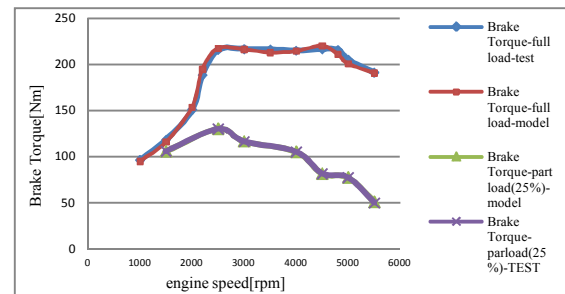


**Fig 4.** Brake torque at full load and part load when throttle valve is 25%opened -simulation and test data
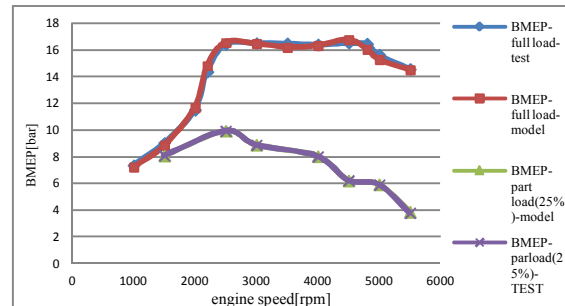


**Fig 5.** BMEP at full load and part load when throttle valve is 25%opened - simulation and test data

For conducting sensitivity analysis, equation (1) has been used.

$$S\% = \frac{\Delta F}{\Delta X} \times \frac{X_b}{F_b} \qquad (1)$$

In which s is degree of sensitivity, F is selected parameter, x is selected variable and index b shows base value.

In this approach variations from the same order in every variable assumed and it's effect on every selected parameter computed from the model and degree of sensitivity of each parameter respect to every variable calculated and compared to sort them.

## 3. Sensitivity Analysis of BMEP

Sensitivity analysis of BMEP for certain variables at different engine speed is shown in figure 6, within the engine operating speed of 1000 to 5500 rpm, the BMEP of the SI engine varies with the changes of every variable. Intake air temperature and Pressure changes has major effect on BMEP at low speed. But at intermediate speeds around 3000 rpm the presence of waste gate has more effect; also changes in the intake runner length and diameter, intercooler efficiency, exhaust runner diameter, injection timing and muffler diameter have negligible effect on BMEP. Air fuel ratio and compression ratio have almost same effect at all speed. Inlet and exhaust valves opening have relatively big effect on BMEP especially at low and high speeds.
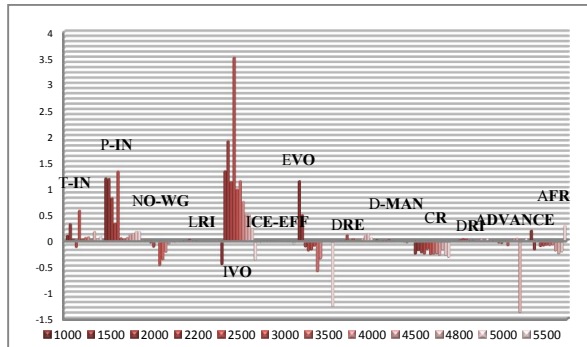


**Figure 6**. Sensitivity percentage of BMEP for various variables

By looking at the mean value of absolute sensitivity percent within the speed range for all variables, the greatest sensitivity of BMEP is with inlet valve opening compare to other parameters. The BMEP sensitivity for intake air temperature and pressure, waste gate presence, exhaust valve opening, air fuel ratio, compression ratio and injection timing is between the ranges of 0.2 to 0.6. But this value drops below 0.1 for variation in intake runner length and diameter, intercooler efficiency, exhaust runner diameter and muffler diameter. Therefore it is possible to reorganize these variables to three groups with primary variables having the most effect Table 1.

**TABLE 1**. different group of variables

| Primary | Secondary | Tertiary |
|---------|-----------|----------|
| IVO | P-IN | LRI |
| | T-IN | DRE |
| | ADVANCE | DM |
| | CR | ICE-EFF |
| | AFR | DRI |
| | EVO | |
| | NO-WG | |

## 4. Sensitivity Analysis Of BSFC

Sensitivity analysis of BSFC for certain variables at different engine speed is shown in figure 7, within the engine operating speed of 1000 to 5500 rpm, the BSFC of the SI engine varies with the changes of every variables. At high speeds BSFC is highly affected by the presence of waste gate. The change of intake runner length and diameter, intercooler efficiency, exhaust runner diameter, intake air temperature and muffler diameter have negligible effect on BSFC. Inlet valve opening, air fuel ratio and compression ratio at all speed has major and even effect. Intake air pressure has relatively big effect on BSFC especially at extremely low and high speeds. Injection timing and exhaust valve opening has little or no effect on BSFC. Sensitivity of BSFC to air fuel ratio is more than other about (0.95%), to Inlet valve opening and compression ratio is between 0.2 to 0.3. Also to Intake air temperature and Pressure, waste gate presence, exhaust valve opening and injection timing is between 0.05 to 0.15. This value for intake runner length and diameter, Intercooler efficiency, exhaust runner diameter and muffler diameter is below 0.05.
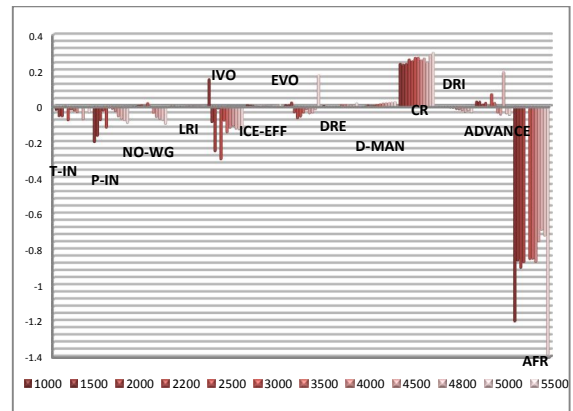


**Figure 7.** Sensitivity percentage of BSFC to various variable

Table 3 showes the moste effective parameters.

**Table 3-** different group of variables

| Primary | Secondary | Tertiary |
|---------|-----------|----------|
| AFR | CR | LRI |
| | IVO | DRE |
| | P-IN | DM |
| | | ICE-EFF |
| | | DRI |
| | | NO-WG |
| | | ADVANCE |
| | | EVO |
| | | NO-WG |

## 5. Sensitivity Analysis of Volumetric Efficiency

Sensitivity analysis of volumetric efficiency for certain variables at different engine speed is shown in figure 8, within the engine operating speed of 1000 to 5500 rpm, the volumetric efficiency of the engine varies with every single variable. In this case valve opening has the most effect among variables. Intake air temperature variation in speed domain has significant but almost equal effect. Intake air pressure has most effect on volumetric efficiency within 3000 to 5500 rpm bracket. Waste gate presence has most effect at intermediate speed range. While variation of intake runner length and diameter, intercooler efficiency, exhaust runner diameter, injection timing, compression ratio and muffler diameter has negligible effect. Air fuel ratio at all speed has relatively even and minor effect. Exhaust valve opening has significant effect on volumetric efficiency at low and high speed domain.

Mean value of absolute sensitivity percent within the speed range for all variables showes that sensitivity of volumetric efficiency for inlet valve opening and intake air temperature is more than others and about 0.95 while for intake air pressure is 0.75 and for exhaust valve opening is 0.45. But for waste gate presence, Injection timing, air fuel ratio and exhaust runner diameter is within the range of 0.1 to 0.2 and this variation for intake runner length, Intercooler efficiency, compression ratio, muffler diameter and intake runner diameter is below 0.05.
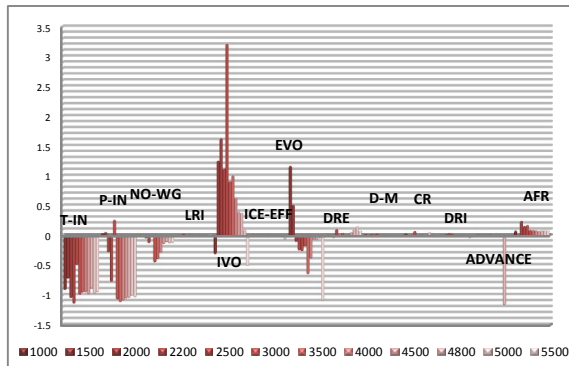


**Figure 8**. sensitivity percentage of volumetric efficiency to defined variable

Again it is possible to reorganize these variables to three groups in table 4.

Table 4- different group of variables

| Primary | Secondary | Tertiary |
|---------|-----------|----------|
| EVO | AFR | DM |
| T-IN | ADVANCE | CR |
| P-IN | NO-WG | ICE-EFF |
| IVO | | DRE |
| | | DRI |
| | | LRI |

## 6. Sensitivity Analysis of Turbocharger Speed

Sensitivity analysis of volumetric efficiency for certain variables at different engine speed is shown in figure 9, within the engine operating speed of 1000 to 5500 rpm. It is shown that turbocharger speed is sensitive to variation of all variable. Waste gate presence and intake air pressure are most influential variable on turbocharger speed especially at high engine speed. Intake air temperature has major effect at all speeds. Intake runner length, intercooler efficiency, exhaust runner diameter, injection timing, compression ratio, muffler diameter, air fuel ratio and intake runner diameter have negligible effect on turbocharger speed. Exhaust valve opening has relatively large effect on turbocharger speed at low engine speed from 1000 to1500 rpm also intake valve opening at speeds lower than 3000 rpm has major effect.

The most effective parameter on turbocharger speed is the presence of waste gate. The other important variable is intake air pressure which has sensitivity of around 0.65 on turbocharger speed. Inlet valve opening, intake air temperature and exhaust valve opening have almost similar effect which is about 0.4. Injection timing, air fuel ratio and exhaust runner diameter is nearly 0.1 and the value for compression ratio and muffler diameter around 0.05. Intake runner length, intercooler efficiency and intake runner diameter have negligible effect on turbocharger speed.
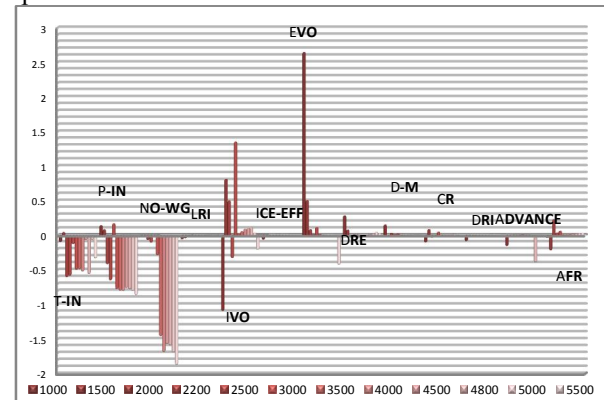


**Figure 9**. sensitivity percentage of turbocharger speed to defined variable

Table 5 shoes these variables to three groups.

Table 5- different group of variables

| Primary | Secondary | Tertiary |
|---------|-----------|----------|
| EVO | AFR | DM |
| T-IN | ADVANCE | CR |
| P-IN | DRE | ICE-EFF |
| IVO | | LRI |
| NO-WG | | DRI |

## 6. Sensitivity Analysis of compressor efficiency

Sensitivity analysis of compressor efficiency for certain variables at different engine speed is shown in figure 10, within the engine operating speed of 1000 to 5500 rpm. The compressor efficiency varies with changes of every single variable for different engine speed, where Inlet and exhaust valves opening have great effect for speeds below 4800 rpm. Intake runner length, intercooler efficiency, compression ratio, injection timing, intake and exhaust runner diameters, air fuel ratio, waste gate presence and muffler diameter have negligible effect on compressor efficiency. Also intake air temperature at all speeds has almost the same effect. Intake air pressure contributes a bigger share on compressor efficiency at high speeds. To sort out the degree of importance of different variables on compressor efficiency, the absolute values of these variations should be investigated.

Inlet and exhaust valves opening is The most effective parameter on compressor efficiency. The sensitivity effect on compressor efficiency due to intake air temperature and pressure is about 0.1. Waste gate presence, intake runner length and diameter, muffler diameter, intercooler efficiency and compression ratio has negligible effect. Also changes in exhaust runner diameter, injection timing and air fuel ratio has minor effect which is below 0.05.
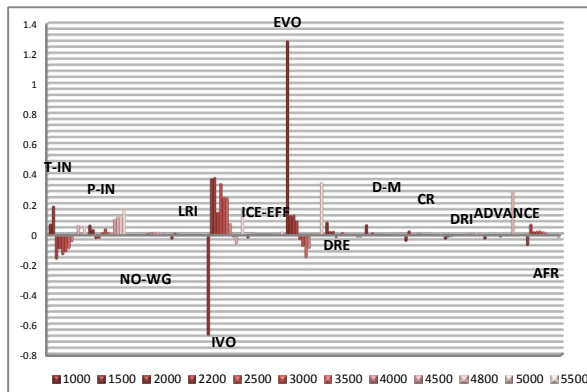


**Figure 10**. sensitivity percentage of compressor efficiency to defined variable

In table 6 variables are sorted in to three groups.

**Table 6.** different group of variables

| Primary | Secondary | Tertiary |
|---------|-----------|----------|
| EVO | AFR | DM |
| T-IN | ADVANCE | CR |
| IVO | DRE | ICE-EFF |
| P-IN | | NO-WG |
| | | DRI |
| | | LRI |

## Conclusion

During turbocharger matching in an SI engine many parameters of engine has to be changed. The chain effect of changes on these parameters has to be examined in detail for proper and suitable selection of these setting to optimize the performance of an engine regarding minimum fuel consumption and maximum torque and efficiency.

Through extended simulation, the characteristic parameters affecting the turbocharger performance together with engine performance has been identified and the degree of their influence is clarified. Parameters such as different intake, exhaust to and from turbocharging system, also air inlet and engine specification such as valve timings, injection timing and compression ratio, their effect on performance of SI engine has been investigated in detail. The computed and simulation results indicated that the effect of inlet valve open, intake air temperature, exhaust valve opening and intake air pressure on the BMEP, BSFC, volumetric efficiency, turbocharger speed and compressor efficiency is greatest among all variables within the engine speed. Intake runner Length, intercooler efficiency, muffler diameter, intake runner diameter and exhaust runner diameter have negligible effect on the wide range of parameters studied.

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