Optimization of waste gate in the diesel engines with turbocharger

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Abstract

The usage of turbochargers in diesel engines has led to the downsizing of the motors as well as usage of the waste gates in turbochargers. Any dimensional reduction in turbochargers and appurtenant leads to an enhancement on the performance of internal combustion engines and in environmental problems in terms of aerodynamic, thermodynamic and mechanical specifications for both engines and turbochargers. For this reason, the efforts need to be focused on the design of turbochargers and their waste gates accurately, in order to maintain its benefits as much as possible. The extent of waste gate opening, from full opened to closed valve, is demonstrated by the limiting compressor boost pressure ratio. Ultimately, an optimum point of limiting compressor boost pressure ratio is obtained then an increase in the values of BMEP and engine power for the same fuel consumption in range of waste gate opening is achieved

***Keywords**: Diesel Engines; Optimization; Turbocharger; Turbo match Software; Waste gate.*

Introduction

Nowadays internal combustion engines, with diesel and gasoline, have the benefits of utilizing turbochargers. Most of the automotive engines are categorized as gasoline kind, in which exploiting a turbochargers does not have remarkable advantages due to the lack of high efficiency when exhaust gas pressure is in the highest level. However available condition in diesel engine with a conventional radial turbine varies inversely and the best value of efficiency can be achieved in this situation [1].

Moreover based on new progresses in design, many accessories have been innovated to adjust the turbocharger in order to operate in a safe and efficient range without any defect. Components of the turbocharger such as the compressor and the turbine have been designed to have high efficiency. However, overall turbocharger operation and interaction with the engine through the off-design operation condition and stress limitations are significant. Thus, it must be considered that turbocharger performance is investigated as integrated unit which has close coherence with the engine operation [2].

After obtaining the turbocharger optimum point of performance, consideration of engine characteristics are essential, because, the final goal of applying turbochargers is the improvement of engine specifications. BMEP and output power per same fuel consumption must be enhanced. On the other hand, emission levels and overall engine downsizing have to be noticed.

Moreover environment problems are other criteria which must be considered in the designing process. This parameter pushes compressor operability to obtain higher pressure ratios and draws stability boundaries into low-efficiency areas in the performance map [3]. In order to obtain higher BMEP and reduce emissions levels, increasing boost pressure is required. Consequently, the required power supplied by the turbine for driving such compressor with high boost pressure will be increased [4]. Required high power and pressure ratios will accompany higher shaft speed and impeller speeds. It results in increasing the stresses in the rotating components and an inappropriate service life [5-7].

Generally, turbine, compressor, and the relevant bearings are identical in all kinds of turbochargers, whereas a controller device (waste gate) could be different. The waste gate is a simple device that must match with a turbocharger and hence with the diesel engine. To have a diesel engine operated under commutable conditions, the waste gate application is essentially important. The setting point of waste gate actuator is significant as far as the existence of a turbocharger itself.

2. Main Components

2.1 The Compressor, Turbine and Engines

The aim of applying the turbocharger is to compromise the turbine, compressor, performance and the engine operation, so that range limitations, durable life and maintaining costs must be considered [8-9]. Critical parameters that are significant for the compressor, turbine and engine include the choking, surging, turbocharger efficiency, BMEP, emission levels and power density, respectively.

As the speed of the turbocharger shaft increases, the amount of mass flow rate in turbine and compressor rises. Turbine inlet mass flow rate depends on exhaust gas mass flow of engine, the existence of EGR (Exhaust Gas Recirculation), and waste gate systems on the engine circuit. Therefore, according to Fig. 1 net turbine inlet mass flow rate can be calculated as:

$$\dot{m}_T = \dot{m}_{ENG} - (\dot{m}_{EGR} + \dot{m}_{Bypass}) \quad (1)$$

The exhaust gas mass flow rate is evaluated as:

$$\dot{m}_{ENG} = \dot{m}_{air} + \dot{m}_{fuel}) \quad (2)$$

Where $\dot{m}_{air}$ which is either engine inlet mass flow rate, or the compressor mass flow rate, is expressed as:

$$\dot{m}_{air} = \dot{m}_{C,e} = \eta_{vol} \cdot \rho_{C,e} \cdot V_{SW} \frac{N}{2} \quad (3)$$

Exit density of the compressor can be written as follow:

$$\rho_{C,e} \cong \frac{P_{C,e}}{R \cdot T_{C,e}} \quad (4)$$

The engine power is expanded as:

$$P_E = m_a \cdot \eta_f \cdot Q_f \frac{1}{AFR} \quad (5)$$

As AFR (air fuel ratio), the energy available in the fuel per unit mass Q_f and a fuel conversion efficiency η_f are defined.

2.2 Waste gates

Waste gate is simply a device, which bypasses some of the exhaust around the turbine, whenever it opens. Fig. 1 illustrates the schematic diagram of exhaust waste gate. Every turbocharger manufacturer organizes waste gate unit in their productions. The benefit that this brings to the turbocharger system stems from the different characteristics of the engine and the turbine [10].

Waste gate is composed of a valve, spring back of the valve, diaphragm and a tube relating high pressure fluid space with the valve diaphragm. Fig. 2 shows the internal components of the waste gate. Location of the installed waste gate can be different depending on the type of valve. It can be installed on the compressor or turbine housing, which has their own advantages.

2.3 Mean line Turbomatch Program and Settings

In this study, for matching the turbocharger with diesel engines and investigate the effect of a waste gate on the engine performance, package and design tools, and modules in concept NREC® which contain TURBOMATCH® linked dynamically to COMPAL® and RITAL®, are applied. It allows the preliminary design of a new compressor and turbine and performance maps, and interactive studies on the matching of the components. The most effective turbocharger design is tightly linked with the overall engine system. The complex interaction among the compressor, turbine, internal combustion engine, and other components in the overall system requires an integrated approach to design, like TURBOMATCH® [11]. Fig. 3 demonstrates the general schematic of turbocharger with associated components in the mentioned program. A detailed description of the theory behind this program can be found in Centrifugal Compressor Design and Performance by Japikse [10].

One of the most important options in TURBOMATCH® program is MODE option which consists of two main parts: 'design' and 'analysis' modes. In the 'design' mode of the system, the compressor and turbine can be sized to the required pressure ratios and automatically match the power and rotational speed of the two. The second mode of operation, the 'analysis' mode, allows manipulating the overall geometric characteristics of the compressor or turbine and examining the performance of the overall system as it interacts with the compressor and turbine maps. In this paper, the analysis mode for compressor and turbine models and also a conventional radial compressor and turbine with waste gate are selected. Crank shaft speed, swept volume of cylinder, boost pressure and volume efficiency for a 4-cylider, four stroke engine are 1500 rpm, 2 bar, 3.1 litre and 0.83, respectively, and by setting the point of waste gate, the actuation waste gate range is determined in every stage and performance parameters are controlled.

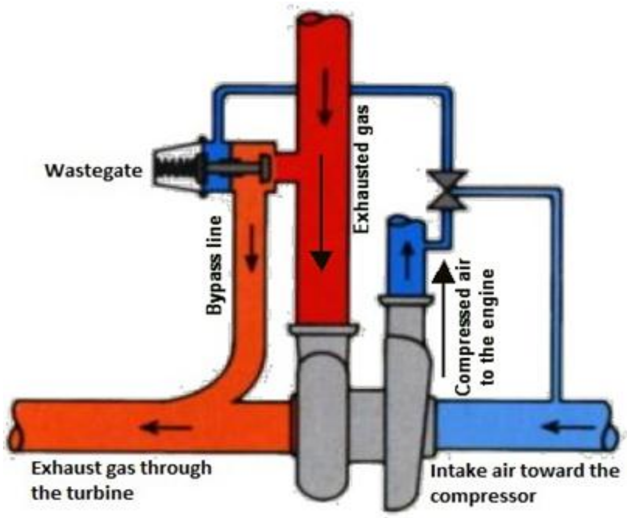

Fig1. Schematic diagram of exhaust WASTE GATE

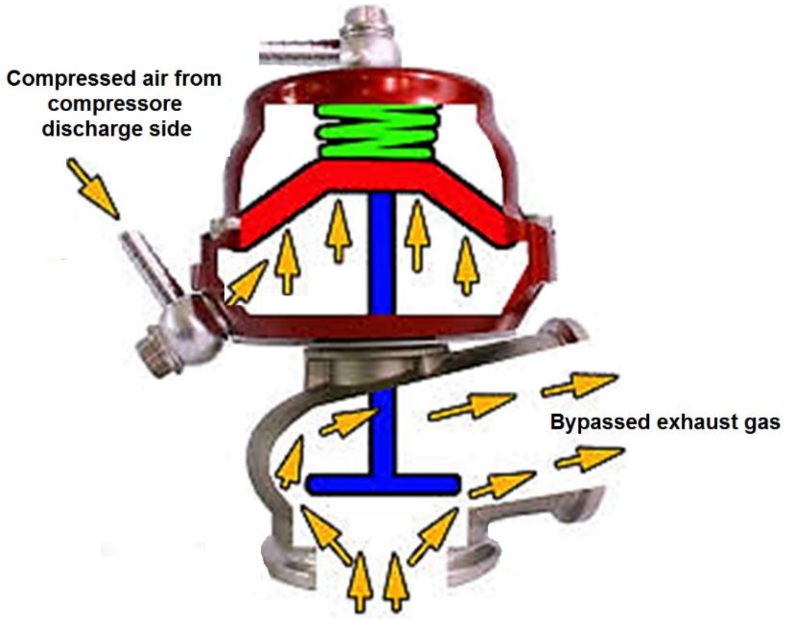

Fig2. General schema of a valve and the waste gate operation.

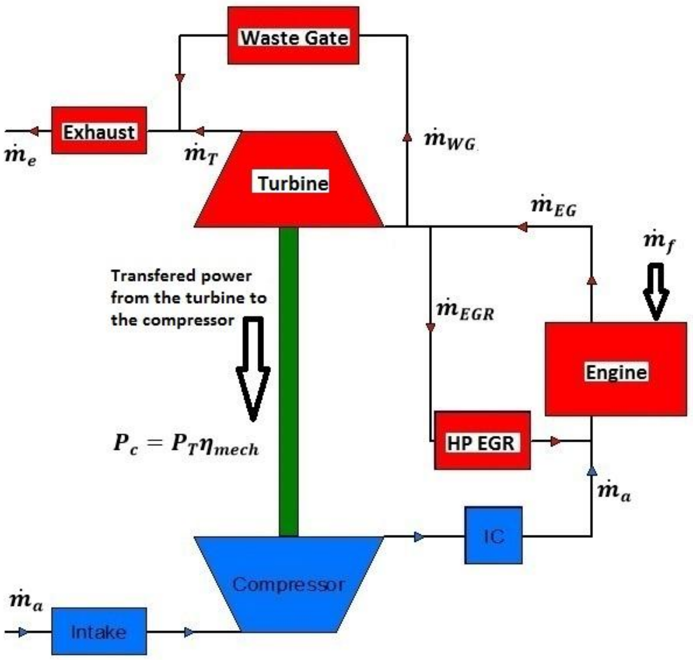

Fig3. Flow diagram of the turbocharger in TURBOMATCH program

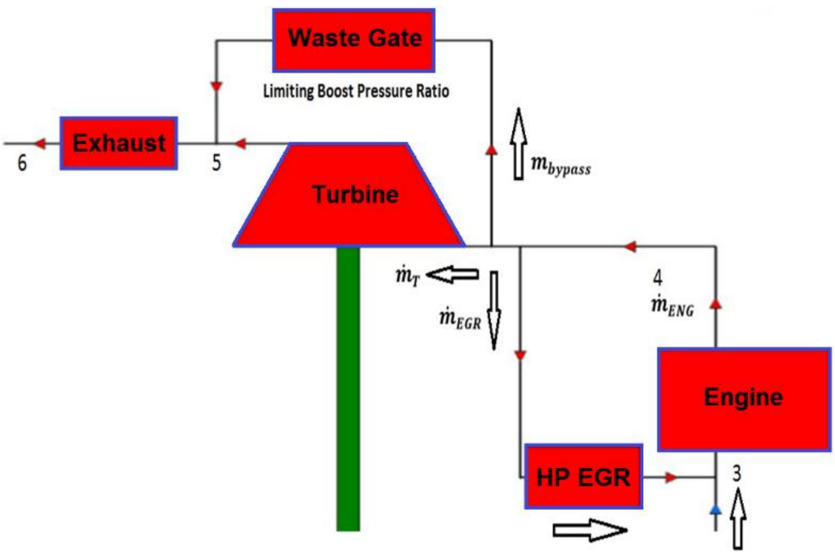

Fig4. Schema of the turbine flow diagram.

3. Methodology of the Analysis Process

The main aim of using turbochargers is to efficiently utilize the energy released through the exhaust gases. The waste gate is a crud device that bypasses the amount of gases without catching the energy of exhaust gases. It means that the earlier the valve opens, the more energy dissipates extensively. In general, designing of turbochargers are accomplished in both idle and high speeds of engines. However, the turbochargers equipped with a waste gate have a favourable condition at low speed in spite of undesirable high speed condition. Thus, actuating waste gate range overlays the minimum and maximum pressure ratios. The former is limited by pressure drop across the engine in order to restrain scavenging, while the latter is restricted by nominal design pressure ratio of turbocharger without waste gate and constraints cylinder pressure.

For the determination of an optimized point in limiting boost pressure ratio, the actuation waste gate range (Xpr) should be necessarily estimated. Initially maximum and minimum values of pressure ratio (Prmax, Prmin) are calculated according to bypass mass flow rate through the turbine (m bypass) and engine pressure drop (ΔPENG), respectively. It is also noteworthy that, the maximum extent (Prmax) is more likely to depend on constraints cylinder pressure, exhaust temperature and choking problem, so that it is limited by these parameters. This value can be obtained by design engine data. Each compressor has its nominal pressure ratio that has been considered through designing process. If designer's target is using waste gate in turbocharger system, the essential clauses in (6-8) have to be satisfied accurately to provide performances as well as constraints. Fig. 4 illustrates the flow diagram and interaction between the turbine, engine, and waste gate schematically. Mass conservation for this system can be written as follow:

$$\dot{m}_{bypass} = f(X_{pr}) \tag{6}$$

$$\dot{m}_{bypass} = \dot{m}_{ENG} - \dot{m}_{T} - \dot{m}_{EGR} \tag{7}$$

When the pressure of engine drop is negative, it is assumed that the pressure ratio is the minimum value. Either pressure drop is positive or differences of waste gate bypass mass flow against pressure ratio differences is equal to zero, it is considered as the maximum extent value. It can be also expressed mathematically as below:

If $\Delta P_{ENG} \le 0 \rightarrow \Pr = \Pr_{\min}$

If $\Delta P_{ENG} \ge 0, \frac{\Delta m_{bypass}}{\Delta \Pr} = 0 \rightarrow \Pr = \Pr_{\max}$

$$\Pr_{\min} \le X_{pr} \le \Pr_{\max} \tag{8}$$

$$X_{pr} = \left\{\Pr_{\min} + 0.1, \Pr_{\min} + 0.2, \ldots, \Pr_{\max} - 0.1\right\} \tag{9}$$

Where X_{pr} is the specifier of the waste gate range. Fig. 5 and Fig. 6 apparently demonstrate the related valve in closed and opened positions. When this valve starts to operate, a certain amount of mass flow bypasses through the turbine. It means, the earlier valve opens, the more exhaust energy dispatches to ambient without utilization. The available energy within the engine exhaust gas is 30-40% of the total energy; this is because that the compressor and the turbine with conventional designs do not have any flexibility against engine operation conditions. Therefore, optimum design of waste gate and its accurate setting can be significant in saving this energy. For instance, in a unit having turbocharger with the efficiency of 50%, if the exhaust waste gate opens and closes at optimum point, approximately 20% fractional energy release out of total energy would be recovered. It can be found in Fundamentals of Turbocharging by N. Baines [12].

In the current study, waste gate range was analysed according to idle and high engine speeds. Firstly, minimum and maximum pressure ratios were determined as correlation (8) to (11) and in Table 1 and Table 2. An optimum common range for both conditions was obtained subsequently. The engine operation with the pressure ratio of 1.4 and less led to scavenging (Fig. 9), compared to the engine having the pressure ratio of 1.6 which was followed by choking (Fig. 10). Thus the value of 1.5 was selected as the best point for the engine under high speed condition, while the engine and turbocharger performances at idle speed in Fig. 9 and Fig. 10 slightly degraded.

Table 1. Pressure Ratio Variation at High Speed of Engine with 2000 rpm

n	1	2	3
X_{pr}	1.4	1.5	1.6

Table 2. Pressure Ratio Variation at Idle Speed of Engine with 1000 rpm

n	1	2	3	4	5	6	7	8	9
X_{pr}	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9

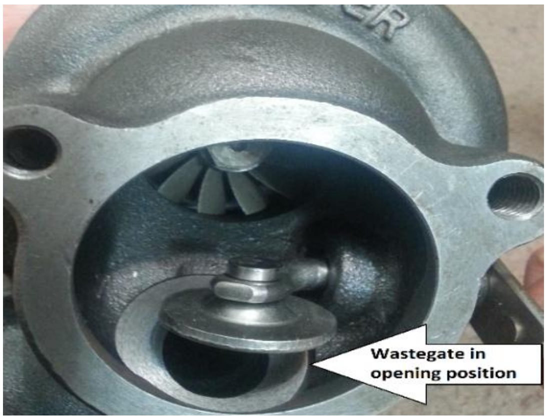

Fig5. Position of waste gate valve in the opening state.

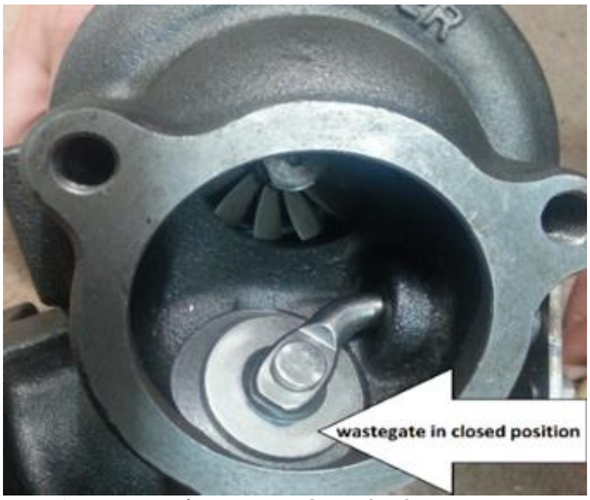

Fig6. Position of waste gate valve in the closing state.

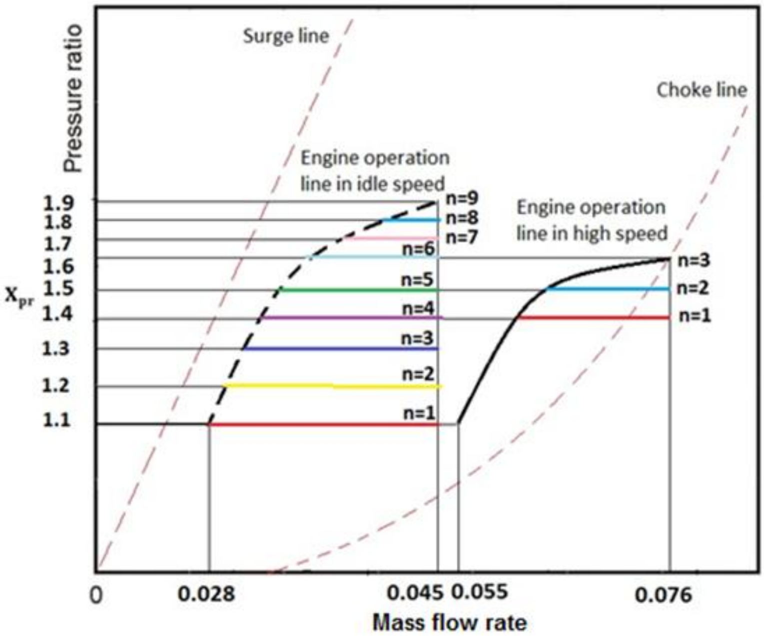

Fig7. Engine operating lines with different limiting pressure ratios.

Fig. 7 illustrates different engine operation lines for the variation of Xpr which each line follows the colour directions in the performance map.

Designing based on high speed of engine by N= 2000 rpm:

$$\Delta \mathrm{Pr}_{ENG} = 0 \rightarrow \mathrm{Pr}_{\min} = 1.4$$
$$\frac{\Delta m_{bypass}}{\Delta \mathrm{Pr}} = 0 \rightarrow \mathrm{Pr}_{N} = 1.6 \quad (10)$$
$$1.4 \leq X_{\mathrm{Pr}} \leq 1.6$$

Designing based on idle speed of engine by N= 1000 rpm:

$$\Delta \mathrm{Pr}_{ENG} = 0 \rightarrow \mathrm{Pr}_{\min} = 1.1$$
$$\frac{\Delta m_{bypass}}{\Delta \mathrm{Pr}} = 0 \rightarrow \mathrm{Pr}_{N} = 1.9$$
$$1.1 \leq X_{\mathrm{Pr}} \leq 1.9 \quad (11)$$

Whenever the turbocharger designing is based on maximum engine speed condition, applying the waste gate in turbochargers not only misses some exhaust gases, but also acts as back pressure imposed to the system, resulting in overall reduction in the performance. However using a turbocharger equipped with waste gate according to idle speed condition designing can be useful significantly. In this case, it does manage the exhaust energy utilization as well as possible. Furthermore by controlling the waste gate opening at high engine speed, it is possible to limit the compressor boost to prevent over-boosting and give a roughly constant engine torque characteristic. At low engine speed, the waste gate is closed and the turbocharger operates in its nominal design point efficiently. Due to the fact that the engine must work within the constraints of the cylinder pressure, exhaust gas temperature, and turbocharger speed, limiting boost pressure ratio cannot be increased to achieve high output power and also the best engine performance in high load and maximum engine speed.

4. Results and Discussion

TURBOMATCH® handles and runs a mentioned engine operating line in five different speeds (1000, 1300, 1500, 1750, 2000rpm) and limiting boost pressure ratios of 1 to 2 with the specific turbocharger. Fig. 8 shows how to the turbine, compressor and engine operation converge and interact together. It links dynamically to COMPAL® and RITAL® and do the analyses of a compressor and turbine for turbocharger with waste gate. waste gate is a simplex valve opening and closing to change the mass flow rate around the turbine, and speed of turbocharger shaft and to limit the compressor boost pressure ratio according to required engine pressure ratio. Mass flow rate of the turbine against limiting boost pressure ratio of the waste gate is shown in Fig. 12. Running the program for turbocharger and the engine along different limiting boost pressure ratio values are accomplished. Limiting boost pressure ratio is changed from 1 to 2 with 0.1 intervals by variation of the waste gate setting frequently.

Two points of the waste gate indicating scavenging and choke margin are more significant and should be prevented during engine operation. Fig. 10 and Fig. 11 demonstrate efficiency and shaft speed of the turbocharger which changes during the variation of the limiting boost pressure ratios. For waste gate range more than 1.4, turbocharger operates by consistent efficiency approximately; while the turbocharger has maximum efficiency in the range of 1.4 and 1.5 under high speed of engine condition. The range value of 1.6 for turbocharger has lower efficiency due to choking in this condition.

The highest increasing crank shaft speed, the highest turbocharger speed and turbocharger efficiency decreased because of higher mechanical losses. The compressor and turbine mass flow rate will be fixed and continue with the same value at the choking point. In this study with 2000 rpm, it is evident that choking point is 1.6 and its relevant value is 0.0393514kg/s according to Fig. 12. Fig. 13 shows power density per constant fuel consumption, for the turbocharged engine in different crank shaft speeds and waste gate boost pressure ratios. All futures shown against waste gate pressure ratio have been plotted in all Figures. A summary of the explanation related to below Figures and their comparison along variation of waste gate range have been gathered in Table 3 and Table 4.

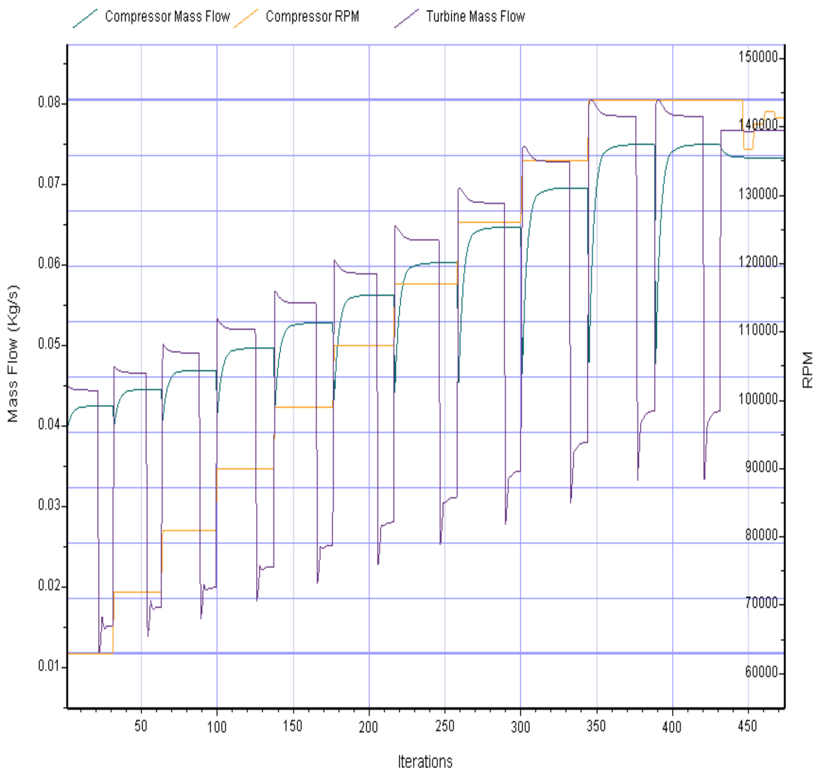

Fig8. TURBOMATCH® running and showing interaction between a compressor and a turbine PR

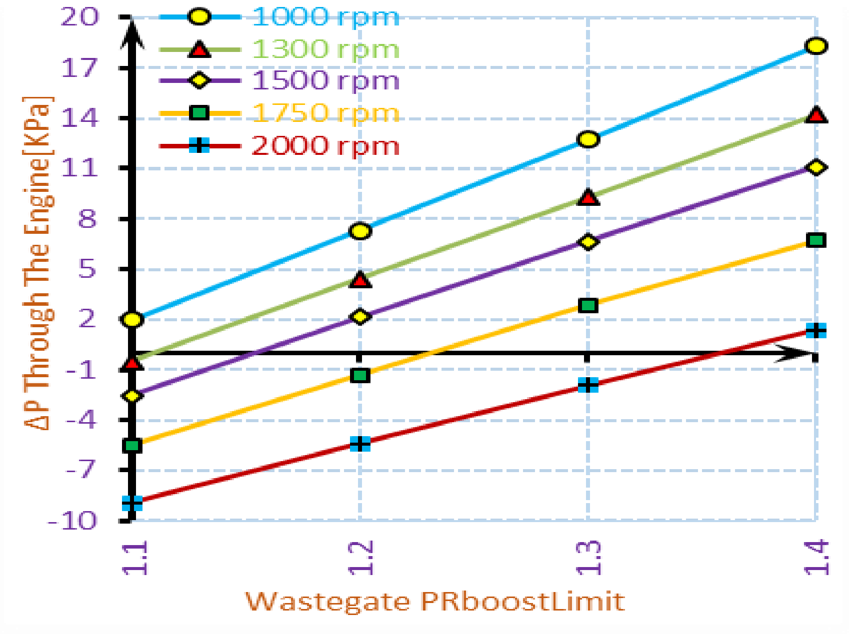

Fig9. Engine DELTA pressure.

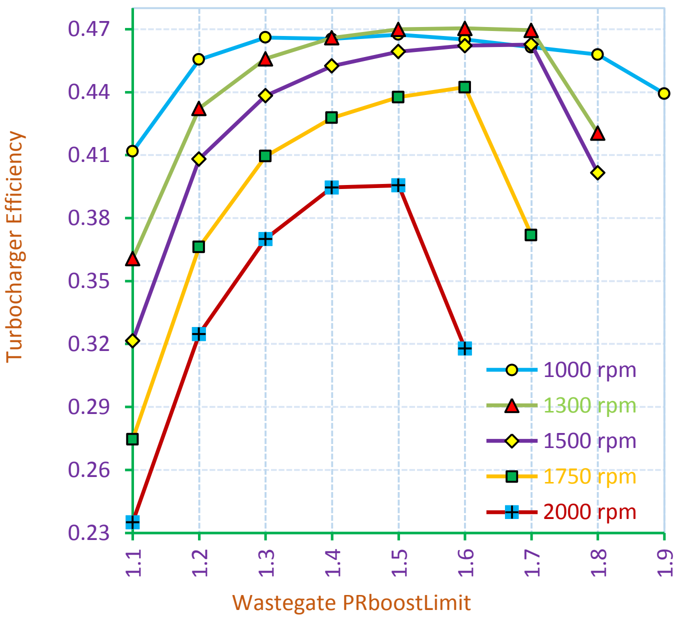

Fig10. Total Turbocharger Efficiency comparison at different speeds.

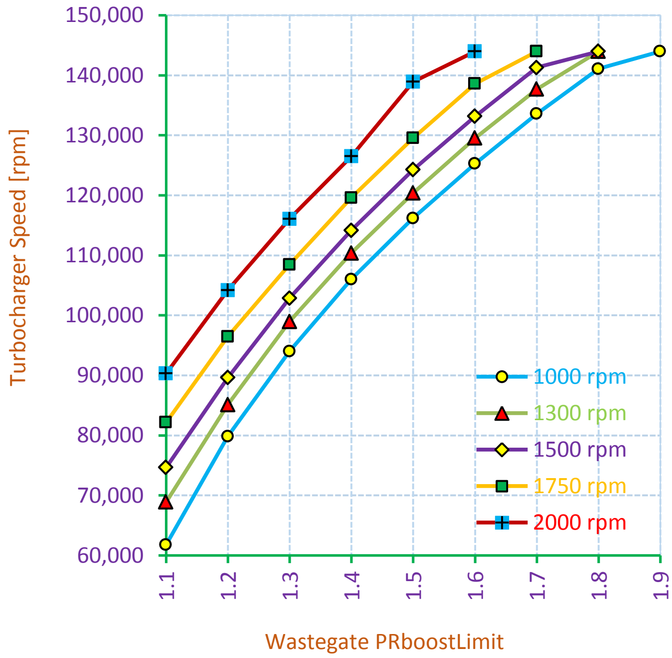

Fig11. Turbocharger speed VS. Limiting boost pressure ratio.

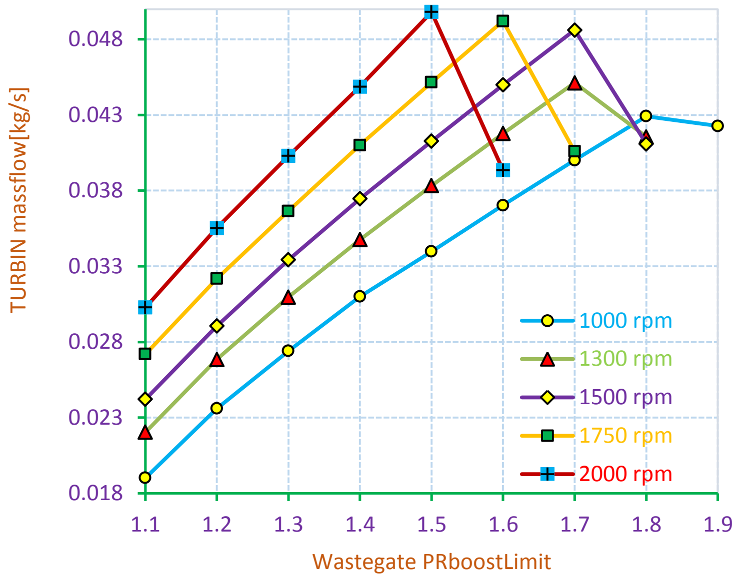

Fig12. Turbine mass flow comparison at different speeds.

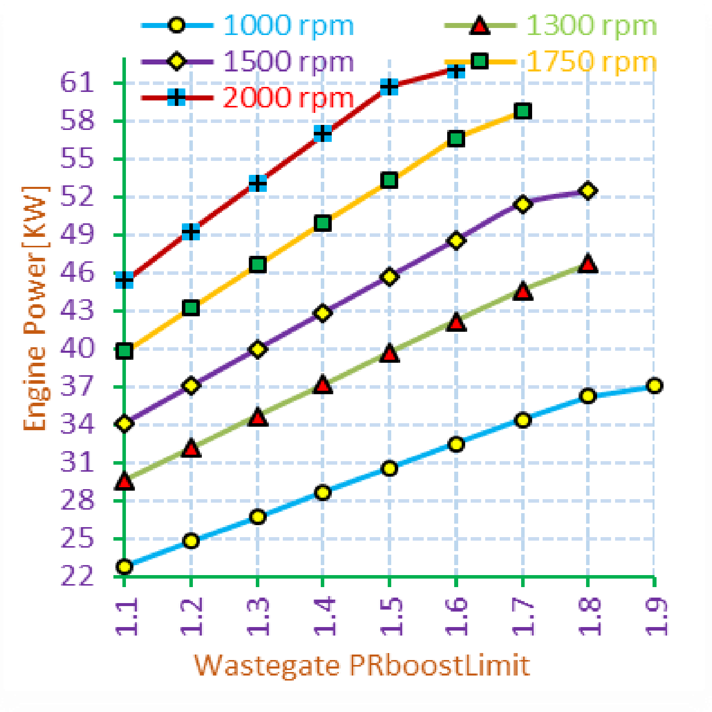

Fig13. Engine power VS. Pressure ratio.

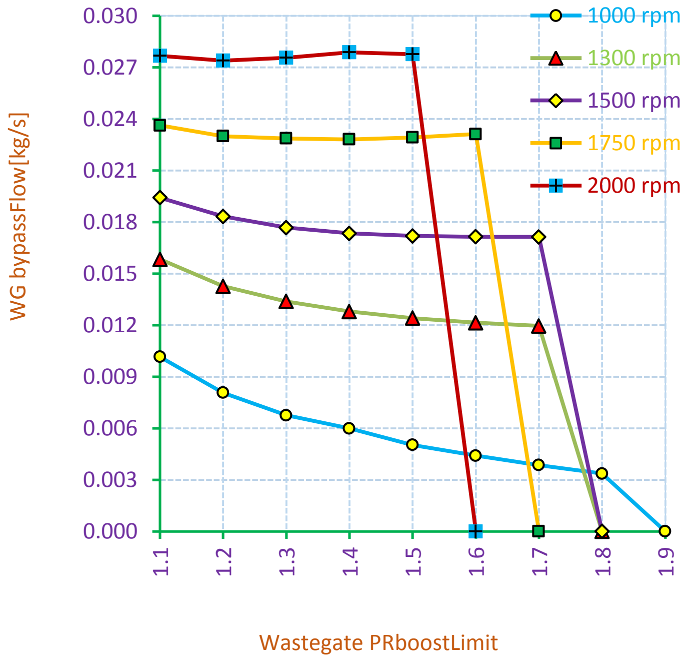

Fig14. WASTE GATE Bypass flow VS. Limiting boost pressure ratio.

Table 3. Comparison of Engine Features at 2000 rpm with Turbocharger Specifications.

Limiting boost pressure	Status	Turbine mass flow(kg/s)	Compressor mass flow(kg/s)	Turbocharger RPM	Turbocharger efficiency (%)	Engine Power out(kw)
1.1	Unaccepted	0.0302759	0.055414	90330.5	0.235084	45.362
1.2	Unaccepted	0.0355307	0.060158	104199	0.324799	49.2473
1.3	Unaccepted	0.040293	0.064875	116098	0.37007	53.1083
1.4	Normal	0.0448714	0.069555	126508	0.394602	56.9401
1.5	Normal	0.0498052	0.074159	138938	0.395629	60.7076
1.6	Choking	0.0393514	0.075859	144000	0.317931	62.11

Table 4. Comparison of Engine Features at 1000 rpm with Turbocharger Specifications.

Limiting boost pressure	Status	Turbine mass flow(kg/s)	Compressor mass flow(kg/s)	TC^2 RPM	TC efficiency (%)	Engine Power out(kw)
1.1	Unaccepted	0.019022	0.027885	61793.8	0.411741	22.8275
1.2	Normal	0.023603	0.030274	79859.5	0.455502	24.7833
1.3	Normal	0.027401	0.032648	94039.8	0.466028	26.7263
1.4	Normal	0.031002	0.035007	106027	0.465381	28.6573
1.5	Normal	0.03398	0.037352	116189	0.467408	30.5767
1.6	Normal	0.037031	0.039684	125290	0.465076	32.4856
1.7	Normal	0.040006	0.042003	133594	0.46138	34.3841
1.8	Normal	0.042913	0.04431	141075	0.457876	36.2726
1.9	Normal	0.042277	0.045225	144000	0.439262	37.0532

5. Conclusion

Adjusting the boost pressure ratio in all waste gates must be accomplished in terms of both idle and high speed engine conditions. The optimum range must satisfy both of the above mentioned conditions necessarily. Therefore, the waste gate operation under high speed condition will be limited by the engine and turbocharger requirements. Consequently using a waste gate in the turbocharger will improve the engine performance just under idle speed condition and promote drivability in that range. Thus, at the designing stage, it is important to collect adequate information about the kind of application and operation of engine.

Generally under idle speed condition, turbochargers with desirable design operate in low and high ranges of waste gate without any problems. However, turbocharge performance under high speed engine condition must be considered more accurately. In the current study, high speed condition was imposed to waste gate to have 1.4 through 1.6. The waste gate range less than 1.4 is unacceptable because of scavenging problem. Thus, the actuator cannot open the waste gate valve earlier than 1.4. On the other hand, with ranges more than 1.6, choking operation will follow and the amount of bypass flow rate will be equal to zero (Fig. 14). As a result, in this case by nominal pressure ratio of 2, the best point for limiting boost pressure ratio of the waste gate is 1.5, and the engine operates efficiently in all speed conditions. The mentioned procedure in this paper is suggested and should be accomplished and followed at the end of turbocharger detail designs. Therefore, the spring settings on the back of the waste gate can be done carefully by this optimum quantity of limiting boost pressure ratio.

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