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Optimizing the Responsiveness of a Turbocharged Ice Through a New Design of the Exhaust Line

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Abstract. The main goal of the research was to redesign the exhaust line of a Y61 code motored Nissan Patrol in a way that would result in a better throttle response of the engine without replacing the existing turbocharger with a newer design. To achieve this target, enthalpy of exhaust gases entering the turbine had to be increased while cylinder backpressure had to be reduced. To increase exhaust gas enthalpy, exchanged energy between hot gases and the surrounding of the exhaust manifold had to be reduced, while cylinder backpressure was reduced using a 4 in 2 in 1 design of the exhaust manifold. This arrangement takes advantage of greater distance between two consecutive firing, connecting first cylinders one with four, two with three, and then the two resulting gas flows, thus instead of 180 °CA the distance between two consecutive firing being 360 °CA.

Both designs (standard and optimized) were modeled in AVL BOOST software and simulations were run to show the benefit of the optimized version.

With the optimized design the torque curve of the engine was optimized, having a greater slope of the torque gradient over the 1500–2000 rpm bandwidth, thus improving the time to torque characteristics of the engine.

The novelty of the paper consists of the combination of the two design approaches applied to the exhaust line of the engine to achieve the proposed performance gains.

1 Introduction

Since the beginning of the 21st century, many spark ignited engines are turbocharged and aftercooled. This allows an increase in engine power density for the turbocharged engines related to their normally aspirated (N.A) counterparts.

Turbocharging the engine can be advantageous because it not only increases its (specific) brake power, but also because it provides better fuel economy and reduced CO_2 emissions – increased mechanical efficiency (downsized engines) and positive pumping work – and, in some circumstances, reduced exhaust gas emissions [1].

This trend led to the spreading of undersized, high specific brake power, low emission level engines, which on the other hand have poor responsiveness [2, 3]. The torque gradient of the engine is not steep enough while developed torque at low engine speeds is low. Along with the improvement in fuel consumption and reduction of pollutant emissions of engines, in the last few years many studies were carried out to conceive more advanced turbocharging units that would banish the inherent turbo-lag. As a result,

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for IC engines today we have twin scroll and variable geometry turbochargers, as well as many sequential charging units with up to four turbochargers [4, 5]. Analysts introduced a new quantity to assess the responsiveness of turbocharged engines. Time to torque (TTT) is referred as the time duration from an idle-to-full step torque command to the time when 95% of maximum torque is achieved [6]. When speaking of steady state torque, TTT is referred to the torque curve gradient, or the amount of torque developed per unit of displacement per 1000 rpm.

While naturally aspirated engines exhibit torque gradients in excess of 150 Nm/s/dm^3 at low engine speeds [7], turbocharged engines develop slower torque buildup, as seen in Fig. 1.

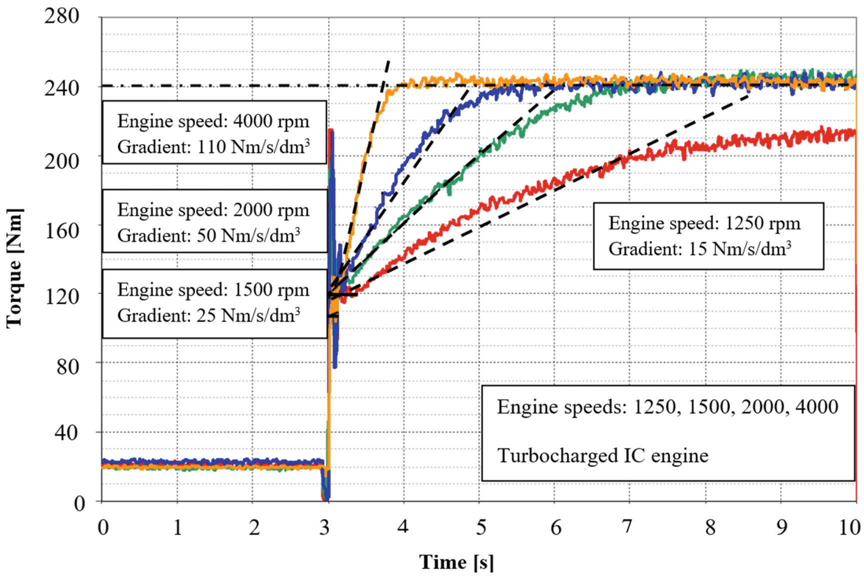

Fig. 1. Torque build-up of a turbocharged engine at different engine speeds [1]

There are many ways to reduce turbo-lag, some being costlier, some more on the simple side. One simple and less expensive way to enhance throttle response of the IC engine is to redesign the exhaust so that backpressure wouldn't influence the turbocharger operation to such a great extent and more energy can be transferred from gases to the turbine wheel.

This is the method used by Mazda for their new Skyactiv engines [8]. With conventional exhaust piping, the pressure wave that occurs during the exhaust stroke of one cylinder reaches the other cylinder, which is in overlap. Because the exhaust valve of the cylinder is open while in overlap, exhaust gas at high-temperature from the manifold is pushed back into the cylinder. With the 4-2-1 piping, because the angular distance between two consecutive firing is longer, it takes more time for the pressure wave to reach the cylinder, therefore the amount of exhaust gas pushed back in the cylinder is reduced (Fig. 2).

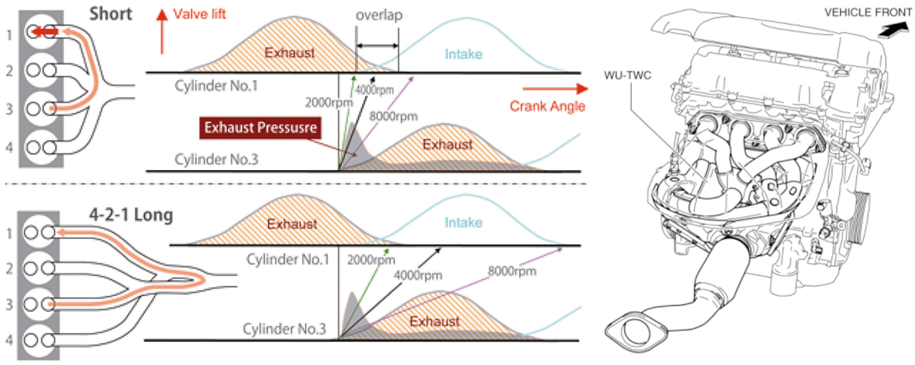

Fig. 2. Mazda's 4-2-1 exhaust [8]

Though this approach says that the amount of residual gas trapped in cylinders decreases along with increased piping length, when applied to turbocharged engines, the amount of internal energy of gases is crucial too. This is the reason why some engine manufacturers employed integrated exhaust manifolds (Fig. 3), some even made use of sheet steel turbine system, to further reduce energy transfer with ambient [10].

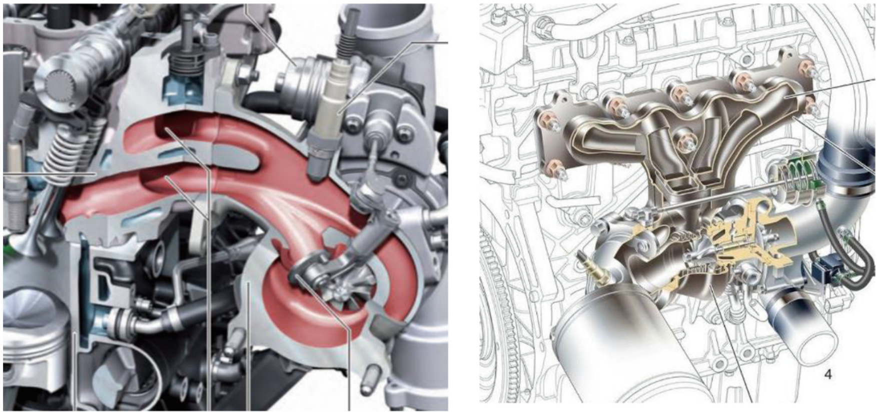

Fig. 3. Ways to reduce enthalpy loss of exhaust gases [9, 10]

For this reason, the 4-2-1 exhaust system was modeled with shortest possible piping, to achieve best responsiveness of the engine.

2 Simulation Model

Both simulation models as for the base engine, as well as for the optimized engine were developed in AVL BOOST. The engine is a turbocharged compression ignition engine and has a bore of 96 mm, a stroke of 102 mm, with a compression ratio of 17.9:1, having an in-line four lineup.

The base engine model includes the four cylinders, air filter (CL1), intercooler (CO1), intake plenum (PL1) and connections, exhaust plenum (PL2), turbocharger (TC1), muffler (PL3), boundary conditions (SB1, SB2) and measurement points (MP) (Fig. 4).

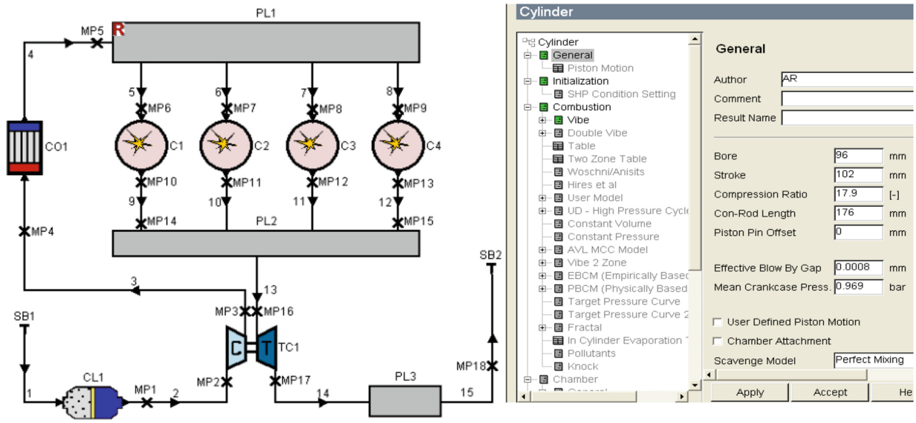

Fig. 4. Simulation model for the base engine

First, the accuracy of the simulation model was proved, given the torque curve of the base engine, most relevant being the torque gradient up to 2000 rpm, after that engine speed the amount of developed torque begins to decrease. For this reason, the simulation cases were defined for engine speeds up to 2000 rpm and one more case for 2500 rpm to show the regression of the curve (Fig. 5).

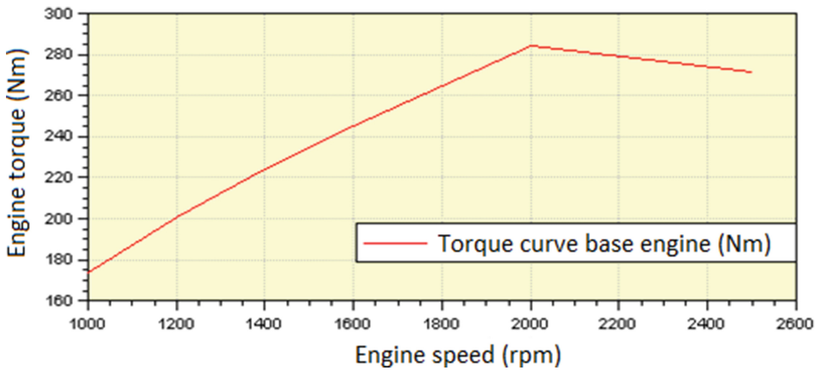

Fig. 5. Torque curve of the base engine

In the case of turbochargers, a key parameter for quick spool up is the specific enthalpy of the exhaust gases which expresses the internal energy of the system plus the product of pressure and volume of exhaust gases. This was measured at MP16, right before the gases entered the turbine (Fig. 6).

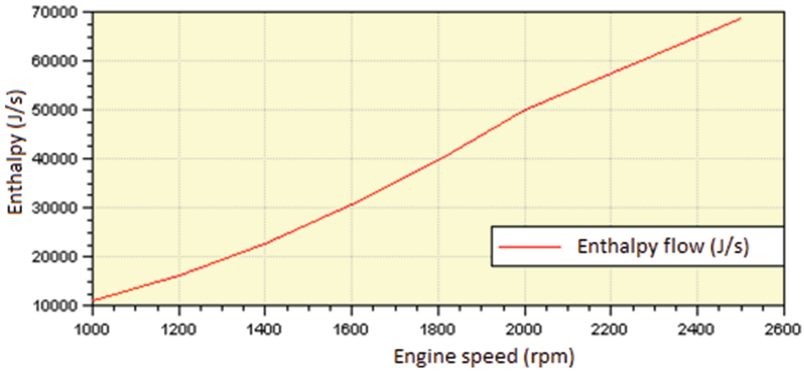

Fig. 6. Enthalpy of exhaust gases for the base engine

To optimize engine responsiveness, exhaust lines from cylinder 1 and 4, respectively from cylinder 2 and 3 were first linked together, and then the two resulting lines, which entered the turbine (Fig. 7). This construction ensures the lowest possible energy loss along with the least backpressure in the exhaust lines.

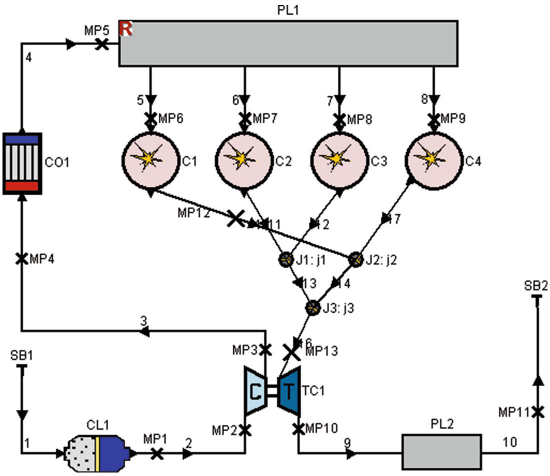

Fig. 7. Optimized simulation model

In the optimized simulation model, we do not have any longer the exhaust plenum before the turbocharger, the connections for the exhaust lines are managed with junctions; measurement point 16 (MP16) becomes MP13.

3 Results and Discussions

The optimizations resulted in lower temperature loss through the exhaust lines (Fig. 8), meaning that the energy which can rotate the turbine is greater. The main reason for this is the reduction of surface areas that permit heat transfer from hot gases to the environment.

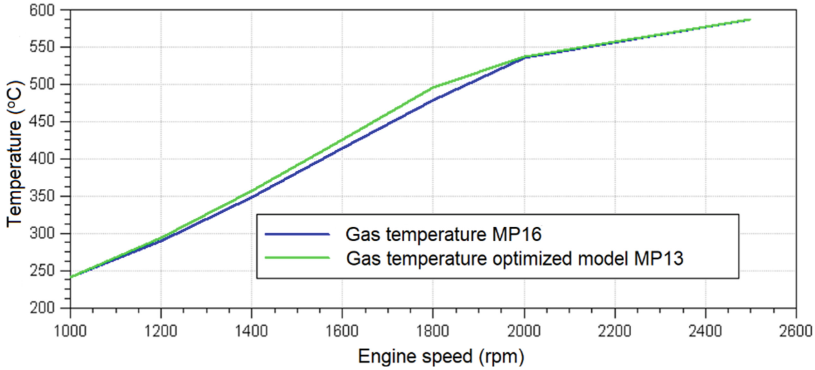

Fig. 8. Exhaust gas temperatures measured before turbine inlet for the two simulation models

Given the fact that with a 4-2-1 piping, the angular distance between two consecutive firing is longer, the amount of exhaust gas pushed back in the cylinder is reduced, thus the pressure in the exhaust, measured before turbine inlet (MP13) is greater (Fig. 9).

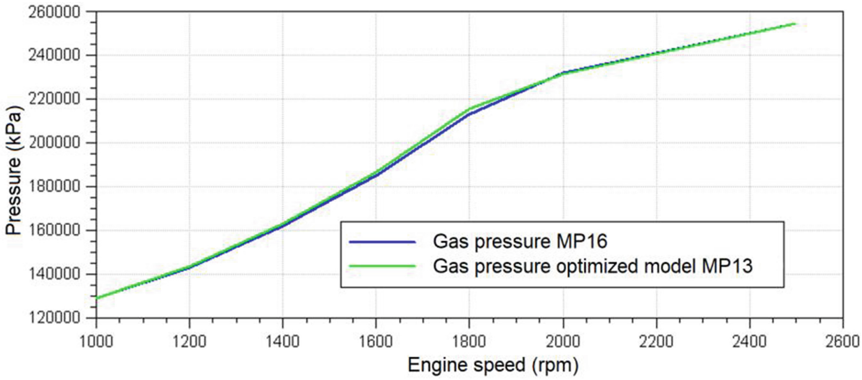

Fig. 9. Exhaust gas pressures measured before turbine inlet for the two simulation models

With higher gas pressure and temperature, the enthalpy of gases which act upon the turbine wheel of the turbocharger will be greater. Figure 10 shows a slight increase in enthalpy especially in the 1400–1900 rpm region, which is the most significant engine speed domain when accelerating in urban traffic.

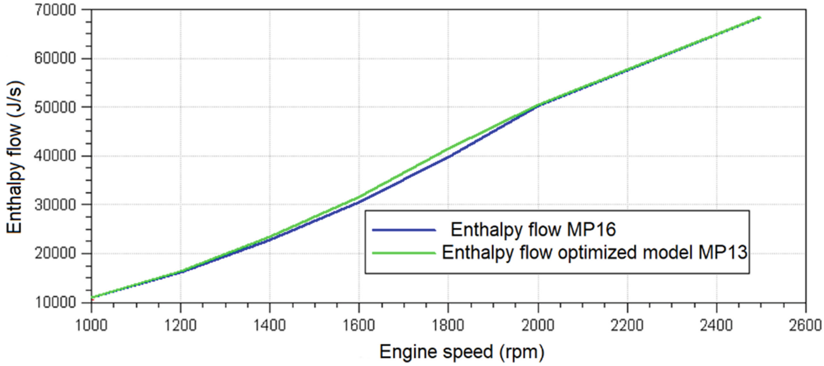

Fig. 10. Exhaust gas enthalpy measured before turbine inlet for the two simulation models

The increase of gas enthalpy has a positive result on the turbocharger rotor's angular acceleration, meaning that the boost pressure builds up quicker, and the torque gradient of the engine will be steeper, will exhibit larger amounts of torque in the low-region engine speeds (Fig. 11).

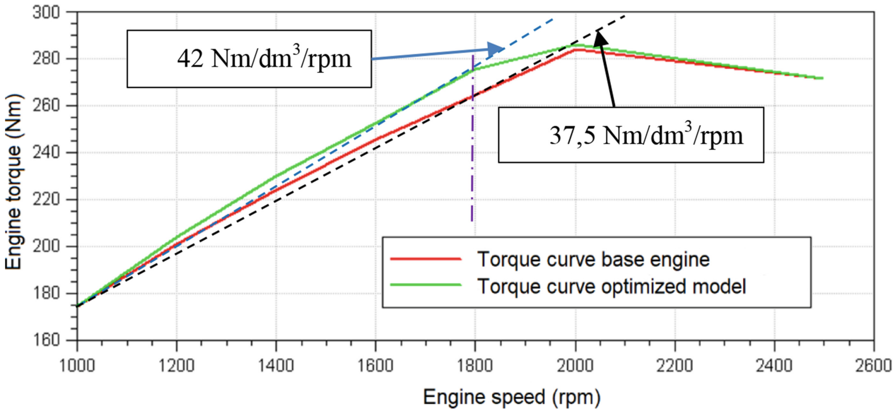

Fig. 11. Engine torque curve for the two simulation models

The increase in engine torque occurs at engine speeds as low as 1200 rpm, where the optimization is about 1%, while a more substantial (about 4,5%) increase is achieved at 1800 rpm. The maximum torque also increases, but it is achieved at the same engine speed, at 2000 rpm.

4 Conclusions

Throttle response is enhanced when torque gradient is optimized. Optimizing the exhaust line enhances torque gradient of the engine for the most critical engine speed domain.

This forecasts not only better engine responsiveness, but better fuel economy and lower pollutant emissions especially in urban traffic.

This is a simple method to enhance engine torque and responsiveness and it allows a modest optimization of around 5% for engine torque. In terms of engine responsiveness on the other hand this slight increase in torque measures in an increase of 12% in responsiveness.

It is yet to be measured the extent of fuel economy and pollutant emission reduction with this method.

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