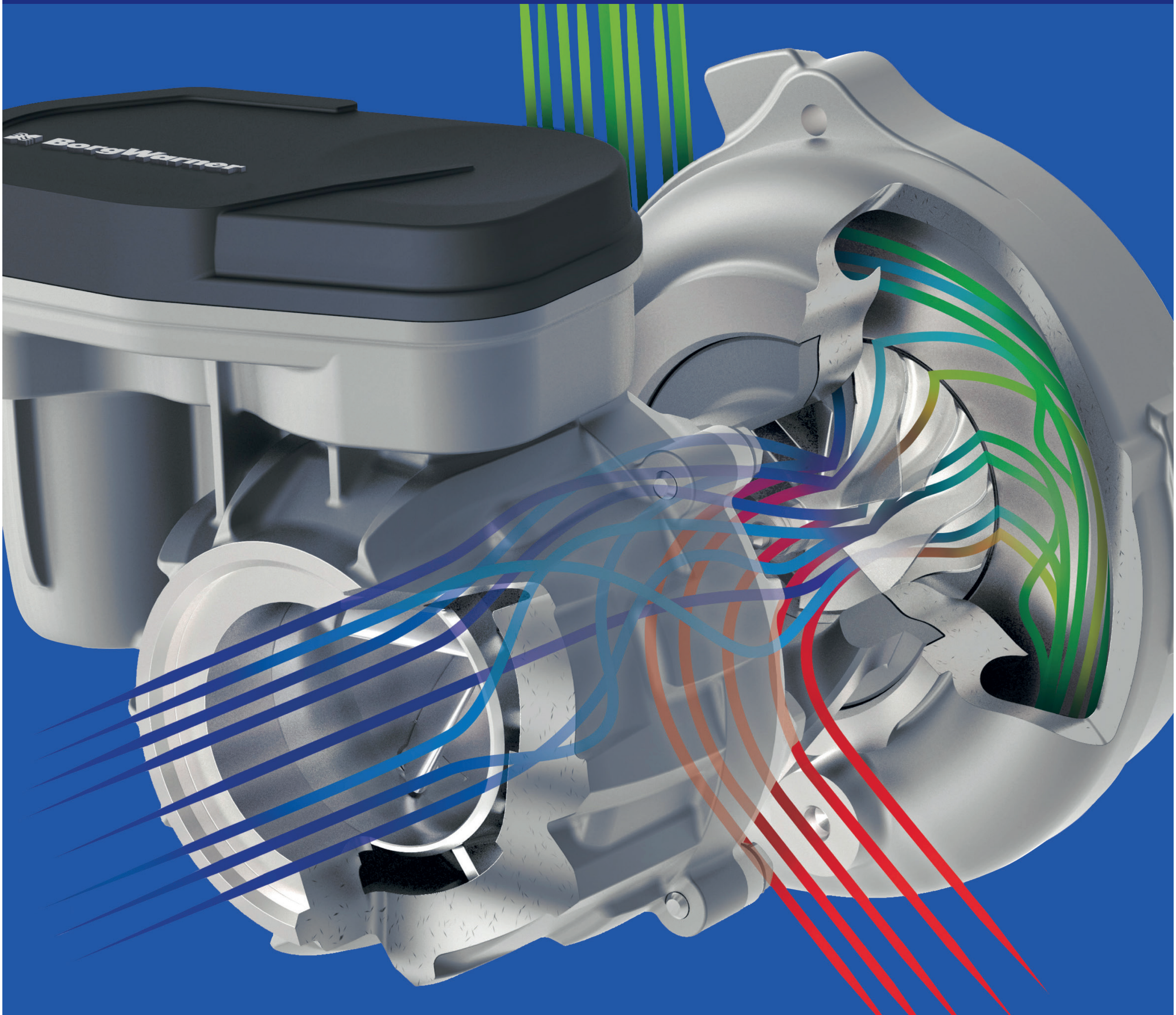
Intake Throttle and Pre-swirl Device for Low-pressure EGR Systems



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Intake Throttle and Pre-swirl Device for Low-pressure EGR Systems

Low-pressure EGR systems to reduce emissions are state of the art for diesel engines. They offer efficiency benefits compared to high-pressure EGR systems and will gain further importance. BorgWarner shows the potential of a so-called Inlet Swirl Throttle to make use of the losses and turn them into a pre-swirl motion of the intake air entering the turbocharger to improve the aerodynamics of the compressor.

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Technology to meet future Emission Standards

Low-pressure EGR systems (LP EGR systems), see Figure 1, for gasoline engines yield significant fuel consumption benefits, they are also an important technology to meet future emission standards (e.g. Real Driving Emissions) [1]. To achieve the targeted EGR rates in particular on diesel engines throttling the LP EGR path is necessary in some areas of the engine operating map. This can be done either on the exhaust or the intake side but to throttle the intake side is the more robust and by far the more cost efficient solution. In state of the art EGR systems, which means EGR systems with low pressure drop, the impact of intake and exhaust throttling on engine efficiency is comparable.

The IST (Inlet Swirl Throttle) replaces the conventional LP EGR throttle in the intake side before the compressor which is usually a simple butterfly valve. Throttling always means inducing losses. The approach of the IST is to make use of the losses and turn them into a pre-swirl motion of the intake air entering the turbocharger to improve the aerodynamics of the compressor. Obviously, pre-swirl will have a positive impact on the compressor also in areas where no throttling is required. So the IST can be used to improve engine efficiency and performance also in regions where no throttling or EGR is required.

Approach and Modes of Operation

With IST the throttling effect is achieved by adjustable inlet guide vanes in the fresh air duct. In other words, IST is an intake throttle designed as a compressor pre-swirl device. This approach is expected to have positive impact on the combustion engine, like:
- higher low-end torque
- reduced emissons
- lower fuel consumption.

To gain most out of the IST it needs to be operated in different modes depending on the engine operating point, see Figure 2. The angle of the inlet guide vanes is adjusted continuously with changing engine load and speed and the set point of the vanes is determined by a controls algorithm, also taking the position of the VTG (variable turbine geometry) and the EGR valves into account.

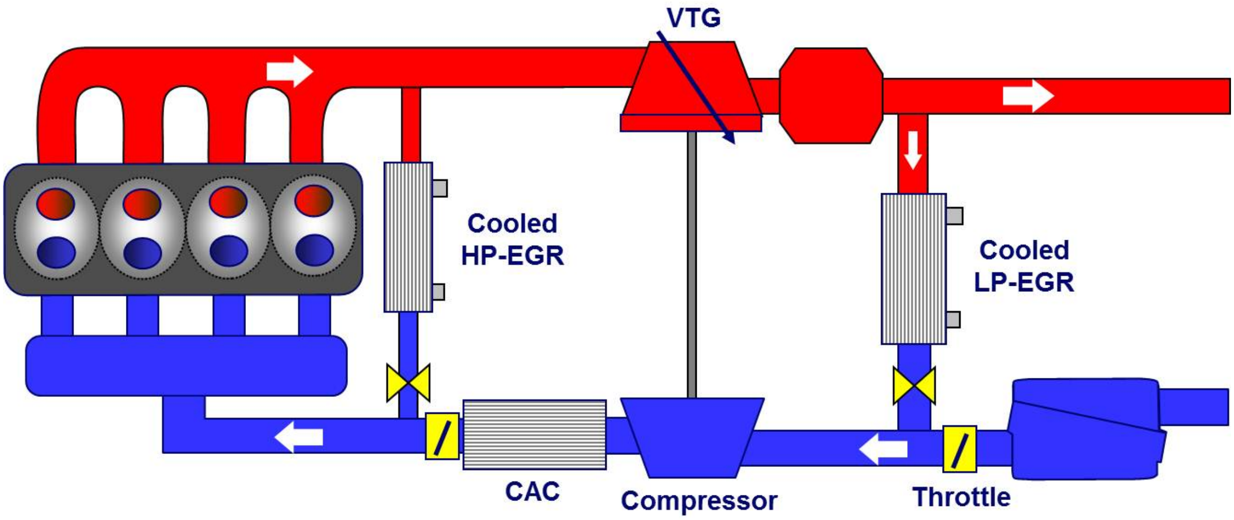

Figure 1. Engine with low-pressure and high-pressure EGR system

In mode 1 some areas of the engine operating map the target EGR rate can not be met even with the EGR valve fully open. In these areas IST is used to throttle the intake air to drive EGR so that the desired EGR rate can be reached. As a secondary effect of the throttling a pre-swirl with a rotational component with the same sense of direction as the compressor wheel (positive pre-swirl) is induced. Because the operating point in the compressor map is still away from the surge line, swirl has only minor effect on compressor aerodynamics. The swirl helps, however, to improve mixing of EGR gas and fresh air. This increases compressor efficiency significantly.

In mode 2, IST improves compressor efficiency. At higher engine loads EGR is faded out by closing the EGR valve. For high loads and low engine speeds (esp. relevant for downspeeding concepts) the operating point in the compressor map tends towards the surge line as it moves to higher pressure ratios and lower mass flows. Close to the surge line compressor efficiency drops steeply. Here positive pre-swirl improves compressor efficiency and thus reduces engine pumping losses and the IST angle is set to make full use of this effect. At maximum load and low engine speed (low-end torque area) the IST induced pre-swirl extends the compressor map towards lower mass flows. This provides extra air allowing for higher low-end torque.

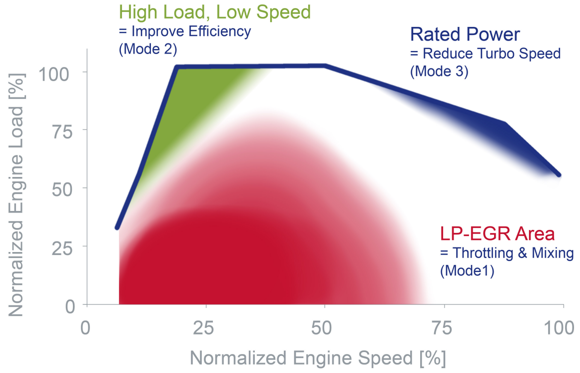

Figure 2. Operating modes of the IST

During mode 3, IST reduces turbo speed. According to the Euler equation negative pre-swirl reduces the speed of the turbocharger for a given operating point. This effect can be beneficial because a turbocharger matching is always a compromise between achievable low-end torque and allowed maximum turbo speed at rated power (including some margin for high altitude operation). IST can help to enhance the quality of the turbo matching by inducing a negative pre-swirl at rated power to reduce turbo speed. This gives an additional degree of freedom for turbo matching and can ultimately yield efficiency or performance benefits.

IST is set to fully open (or neutral) mode in the other areas of the engine operating map. In this mode the optimised aerodynamics of the inlet guide vanes reduces the pressure loss to approximately 6 mbar at maximum air flow, which was proven to have negligible impact on engine performance.

Design and Realisation

Most important development targets of the IST were cost efficiency, robustness and low weight, see Figure 3. This was achieved by a modular design, reduced number of parts, low number of seals, especially to the outside, and a careful choice of materials. In addition, the IST had to be compact and easy to integrate with only little necessary modifications to the interfacing components.

In its final design stage the IST has a size comparable to a conventional butterfly valve. It can either be a stand-alone solution or partially be integrated with the LP EGR system and the compressor housing. And importantly, the aerodynamics of IST can cope with a bend in the fresh air path upstream of the IST, like often found in real applications.

For further cost reduction the guide vanes are actuated by an off-the-shelve actuator from an EGR valve and a simple mechanism similar to a VTG actuation. The actuator is integrated in the IST housing. The vanes can completely close the fresh air duct; they can also be set into every intermediate position between completely open and closed. In order to induce negative pre-swirl the vanes can also be set to negative angles. A fail-safe mechanism opens the vanes completely in case of an actuator failure.

The aerodynamics of guide vanes and flow channel was optimised by comprehensive CFD simulations. Goal was to minimise the losses in the fully open, but also in the intermediate positions of the vanes. Of great importance was also to generate a stable swirl profile at the inlet plane of the compressor wheel with a dedicated radial velocity gradient. Finally, the vanes had to be designed in a way that high-cycle fatigue of the compressor wheel

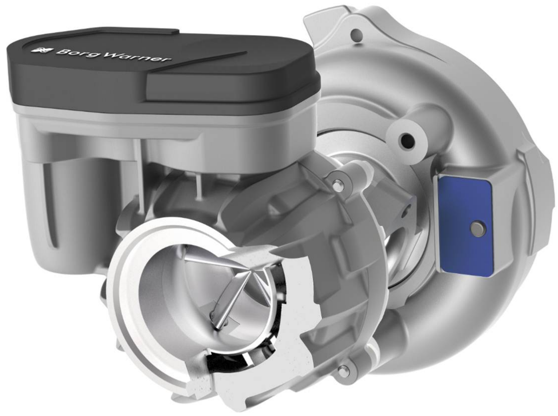

Figure 3. IST mounted upstream of the LP EGR junction and the compressor housing

caused by excitations through the intake flow is avoided.

Test Results

To confirm the expected performance of IST experimental investigations with prototypes were conducted on an engine dyno and a hot gas test stand. Some exemplary results are shown in Figure 4.

From literature it is known that pre-swirl does improve the efficiency of a turbo compressor operating close to the surge line [2, 3]. The cause for this improvement are reduced losses in the intake area of the compressor wheel: a positive pre-swirl changes the direction of the velocity vector of the intake flow relative to the compressor wheel making the interaction between flow and wheel more efficient. How IST works in that respect was investigated on the hot gas test stand to confirm the optimisation work done by CFD on both the IST guide vanes and the housing geometry. The measurements show that the pre-swirl induced by IST improved compressor efficiency by up to 2 % for constant flow and pressure ratio, see Figure 4 (top). Moreover, the shift of the surge line to a mass-flow reduced by 50 % was also confirmed (mode 2).

Throttling behaviour, linearity and controllability of the IST are key for a successful application on a real engine (mode 1). To investigate this a comprehensive controls approach was needed

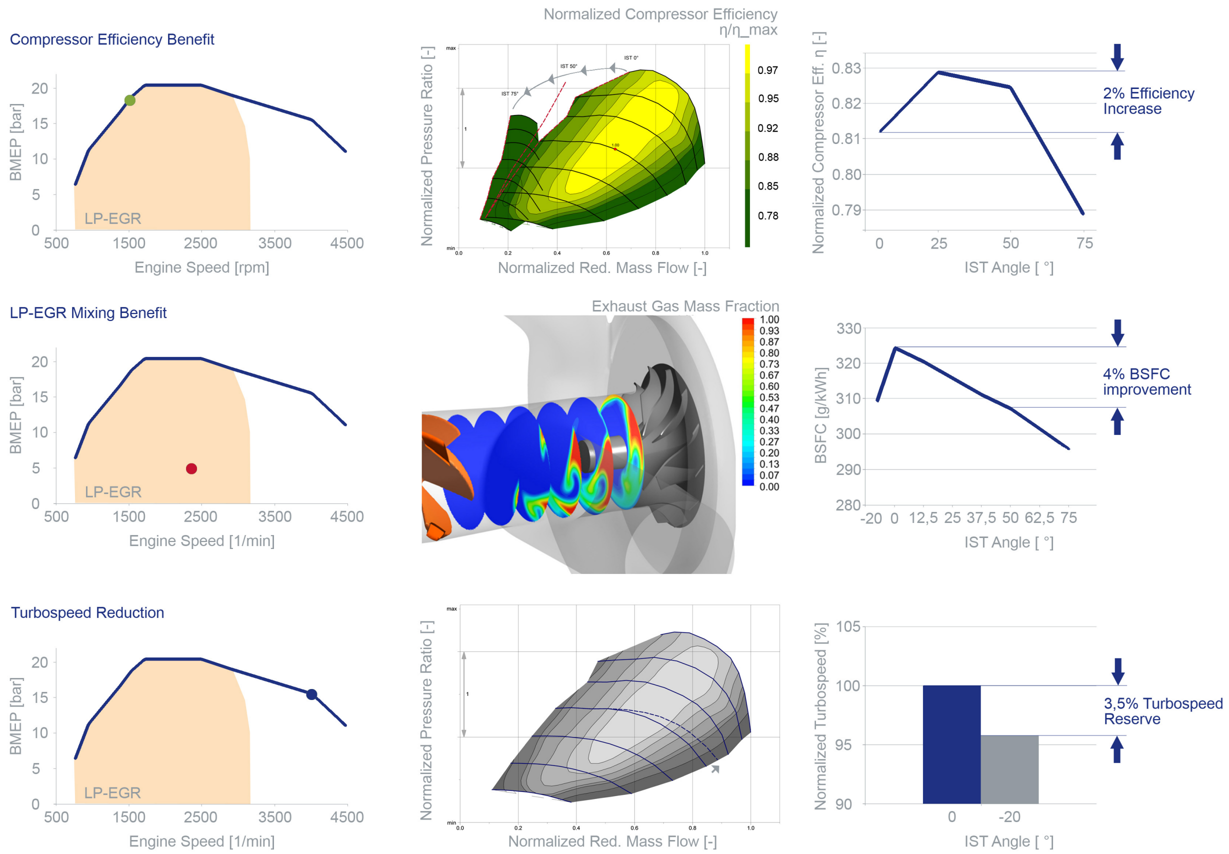

Figure 4. Results from engine dyno and hot gas test stand (modes in the image on the left as shown in Figure 2)

to determine optimal VTG and EGR valve positions taking the impact of IST position and IST operating mode on the air system into account. BorgWarner has a fully functional air system controller [4] available as a development tool to which the control of the IST was added.

The test engine was a state of the art 2.0-l diesel engine with a rated power of 100 kW meeting EPA US07 emission standards. The engine features both HP(high pressure)- and LP EGR systems. The IST was applied to that engine and a comprehensive test program was conducted covering the complete engine map. The results were encouraging: IST showed reproducible and well controllable behaviour. The reaction of the engine to the IST position was predictable and potentially critical operation modes like over speeding the turbocharger or oil leakage from the compressor through low pressure at the compressor inlet were safely prevented. And most important, the desired EGR rates were also met in steady state and transient operation.

This first set of investigations was conducted using the engine's series turbocharger. However, this turbo was not able to deliver the higher turbine power at low engine speeds which the compressor needed to provide more air with the shifted surge line. This made it impossible to significantly improve engine low-end torque. In the next project phase it is planned to continue the investigations with a re-matched turbocharger which will be able to make use of the extended compressor map with IST.

What the engine investigations did show was the mixing benefit of fresh air and recirculated exhaust gas from the intake swirl motion. The improvement of compressor efficiency from the mixing could be confirmed in the experiments as predicted in CFD: fuel consumption in steady state was improved by up to 4 % in cycle relevant load and speed points with EGR, see Figure 4 (middle).

Finally the effect of negative pre-swirl on turbo speed was quantified (mode 3). At constant rated power the turbocharger speed was reduced with IST by 3.5 % without compromising fuel consumption, see Figure 4 (bottom). This additional degree of freedom will be taken into account during the matching exercise for the new turbo in the next project phase.

Summary and Outlook

The IST is a new approach to replace the state-of-the-art butterfly-type intake throttle in a LP EGR system with an integrated pre-swirl and throttling device. IST offers remarkable benefits like reduced fuel consumption and improved engine performance for competitive cost in a component that is easy to integrate into current air systems. The ability of IST to widen the compressor map is of particular interest in gasoline engines, which makes IST an interesting option also as a stand-alone device.

The compact design and the possibility to integrate IST with other components make it a viable solution also in tight package environments. Concerns regarding controllability and oil leakage from the compressor could be overcome by comprehensive engine investigations.

Based on the results achieved so far further optimisation of the air path with IST is planned in the next project phase. Most important will be the new matching of a turbocharger taking the specific requirements and additional degrees of freedom IST offers into account. This, in conjunction with a more refined controls approach, will help to determine the full benefits of IST in the FTP test cycle.

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