Optimisation of Boosting Stage and LP EGR System through Pre-swirl Throttle

Knowledge Library

BorgWarner

Optimisation of Boosting Stage and LP EGR System through Pre-swirl Throttle

Driven by emissions legislation, need for CO_2 reduction, and customer demand for vehicle agility, passenger car diesel engines incorporate a combination of low pressure exhaust gas recirculation (LP EGR) and exhaust gas turbochargers (TC). BorgWarner has identified the combination of TC and a so-called inlet swirl throttle (IST) as a new way to optimise the engine for emissions, performance and cost.

By Urs Hanig, Program Manager for Pass Car Systems at BorgWarner,
Nicolai Halder, Design Engineer R&D at BorgWarner Emissions Systems,
Mihai Miclea-Bleiziffer, Development Engineer for Compressor Stage Aerodynamics at BorgWarner Turbo Systems, and
Jerry Song, Technical Specialist for Controls and Simulation at BorgWarner

System Layout to provide a new Solution

In [1] the IST (inlet swirl throttle) was introduced as a new component to provide multiple benefits. Through its location close upstream the TC compressor it has the ability to greatly impact the engine breathing system. The diesel engine used for system optimisation is the same as described in [1]. With 2.0-l displacement, a rated power of 100kW and dual loop EGR it represents a state-of-the-art architecture. In its delivery state it is equipped with a butterfly type exhaust throttle. Key element of the system optimisation is a switch from exhaust throttle to IST. When switching from exhaust throttle to inlet swirl type, three main modes of operation can be identified for IST:

- mode 1: part load LP EGR throttling and mixing
- mode 2: low speed, high load compressor stability improvement
- mode 3: rated power turbo speed reduction.

In [1] steady-state fuel economy improvements were shown when operating a first generation IST prototype along with the stock TC. In order to evaluate the full engine benefits, the boosting system was modified and a second generation IST prototype fit for improved geometrical coupling. The TC optimisation aimed at forming a new boosting stage with IST as an integral part and can be characterised by application of latest turbine technology to provide high turbine power at low engine speeds, adaption of the compressor housing to integrate IST and compressor surge specific instrumentation.

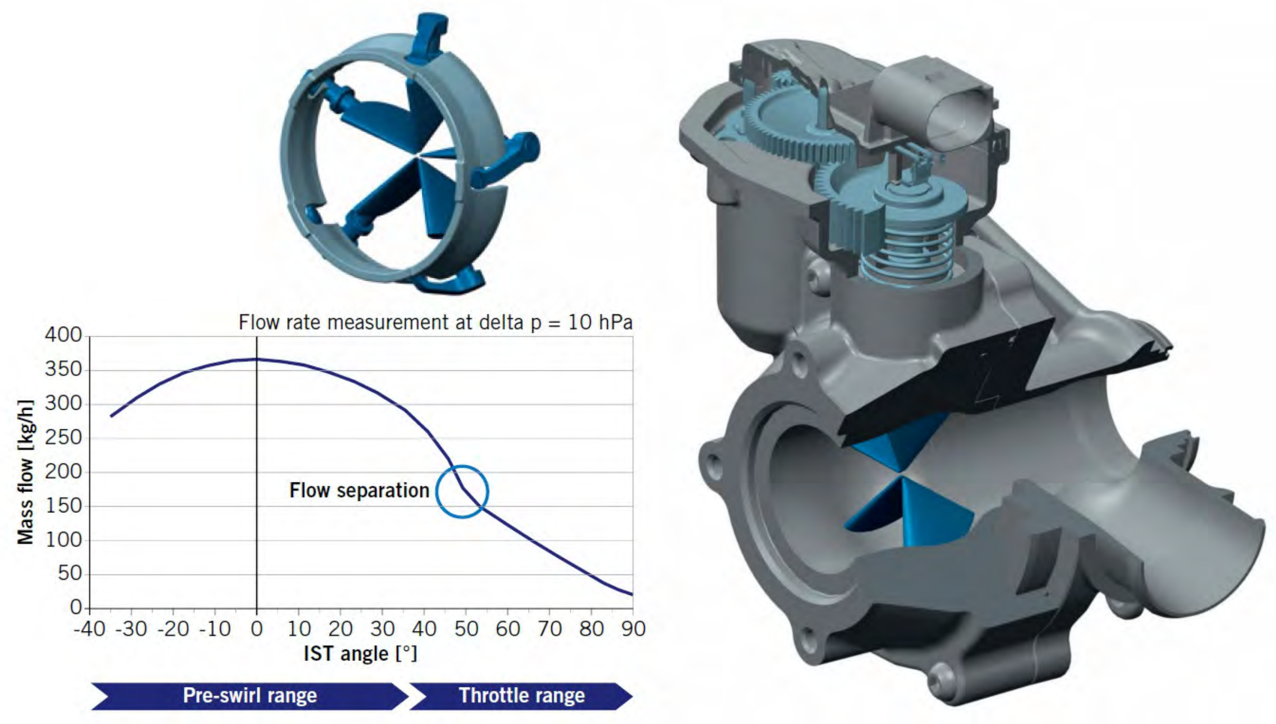

Figure 1. Component design and throttle characteristic

Component Design and Throttling Characteristics

IST represents a throttle valve and is installed at the compressor inlet, right in front of the LP EGR inlet position. It consists of several parts with housing functionalities and inner elements to drive the vanes which are exposed to fresh air flow, as to be seen in Figure 1. Inside the inlet housing a Direct Current (DC) motor with a two-stage spur gear transmission, a failsafe spring mechanism and a non-contacting position feedback sensor are located. This solution provides a compact and robust actuation system. A low friction, low play solution was chosen to synchronise the motion of all vanes. It relies on the known principle of an actuation ring and individual levers connected to the vane shaft ends.

Vanes with symmetrical profiles and a particular vane chamber contour lead to high aerodynamic reliability and low pressure losses in the wide open position. The throttle characteristic is shown in Figure 1. For small vane angles pressure loss is kept on a low level. Increasing pitch-angle leads to transition from pre-swirl generation to throttling. A change in slope characterises the point at which the flow starts to separate from the vanes. In fully closed position the gaps around the vanes determine the remaining air mass flow.

Compressor Impact

Previous attempts to apply inlet guide vanes to automotive TC compressors have shown that both map size and compressor efficiency are affected by pre-swirl. If positive pre-swirl is applied at the wheel's inlet the map is shifted to the left hand side. This behaviour is caused by the reduction of the incidence angle. By applying positive pre-swirl there are two other basic effects at the compressor's inlet: the inlet relative velocity is reduced and the total wheel work is reduced. The first effect can lead to an efficiency increase since the reduced velocity in the blade channel reduces friction losses [2]. Due to the reduced

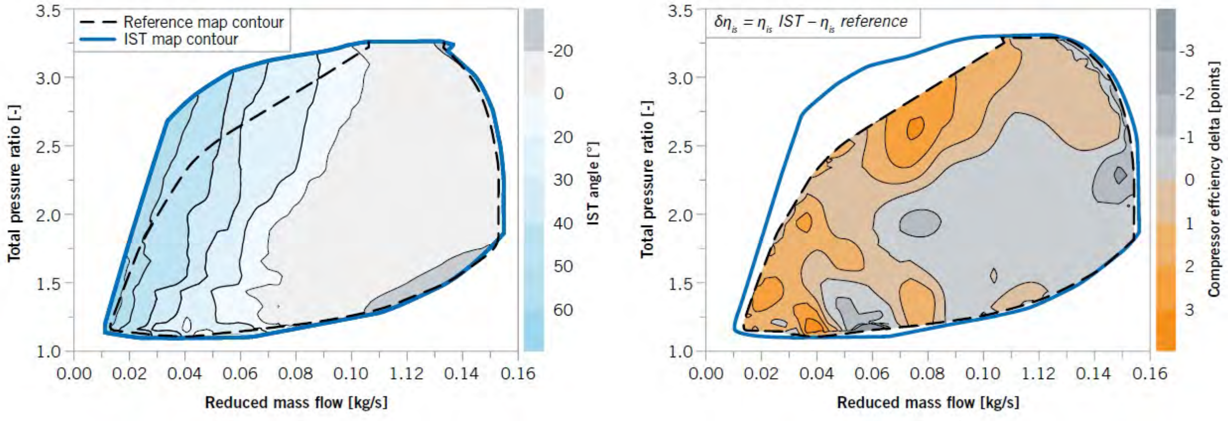

Figure 2. Compressor map comparison with IST vane angle positions and efficiency impact

wheel work, the compressor has to run at higher speeds in order to achieve the desired pressure ratio. In Figure 2 a comparison of compressor map envelopes is shown. To generate a reference the prototype compressor was measured with an ideal cone section instead of IST.

The measurements with IST were carried out with multiple vane angle positions. A combined map was deducted from the single individual maps. Gain in map width is visible for both low flow and high flow conditions. The vane angles which return best results are highlighted within the map. Efficiencies are compared within Figure 2 as well. The negative impact of added flow losses can be limited by using optimal vane angles. IST leads to benefits of up to three efficiency points.

Controls Approach

The BorgWarner air systems controller for a dual loop EGR diesel engine [3] was chosen to control IST during engine operation. It was modified to drive LP EGR using IST for intake throttling. The modification was achieved through 1-D controls-plant co-simulations. In combination with the low and high pressure EGR valves, IST can target and achieve the desired total amount of EGR flow and split. It also meets the boost pressure and air flow targets for the engine assisted by the Variable Turbine Geometry (VTG). In Figure 3 the controller layout is shown with outputs to all mentioned actuators. In addition to the basic EGR and boost functionalities the controller was expanded with features to provide additional IST benefits. In the low-end torque region, IST improves surge margin and also increases charging efficiencies, while delivering similar mass flow and boost pressure levels.

Furthermore it improves LP EGR mixing while throttling for LP EGR. A selection logic constantly monitors the engine state and sets IST into the appropriate mode of operation. Besides managing benefits, the selection logic also ensures safe engine operation. Compressor oiling can be avoided by restricting the rate and range of IST movements. After integration of IST into the controller layout, it was calibrated for high performance during a certification cycle. Figure 4 shows set points and measured values during Federal Test Procedure (FTP) 75. IST operates within its throttling range. Boost pressure and total EGR flow are continuously achieved.

Engine Evaluation

The potential of IST was evaluated through steady-state tests and FTP-75 cycles on an engine dyno. To deduct the impact of the adapted turbine individually from IST, three turbo-

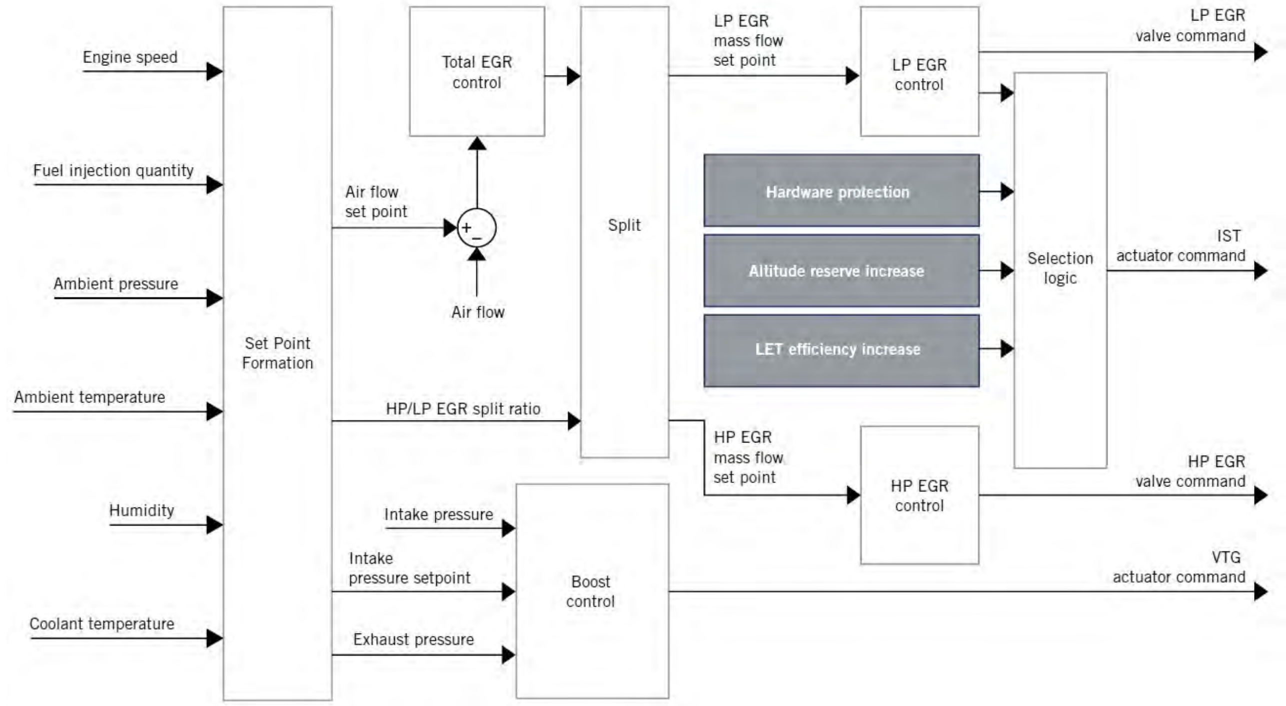

Figure 3. Air systems controller layout with IST functionalities

charger setups were tested. Setup 1 features a baseline stock TC. In setup 2 the new turbine technology and the base compressor are used. In setup 3 the new turbine technology, the base compressor and IST are used. As IST drives LP EGR, the exhaust throttle has been replaced with a pipe section.

Figure 5 shows the results for the full load investigations with all three setups. Differences between the setups become apparent in the low-end torque area. The reference full load curve was measured with setup 1. Maximum torque was reached at 1750 rpm. Resulting from the near closed state of the VTG at low

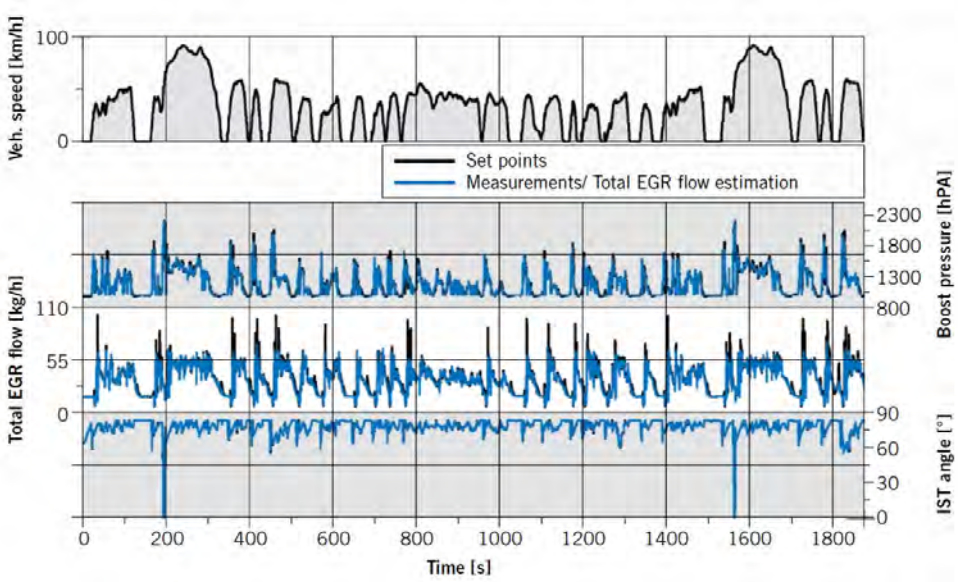

Figure 4. FTP-75 air systems controller performance

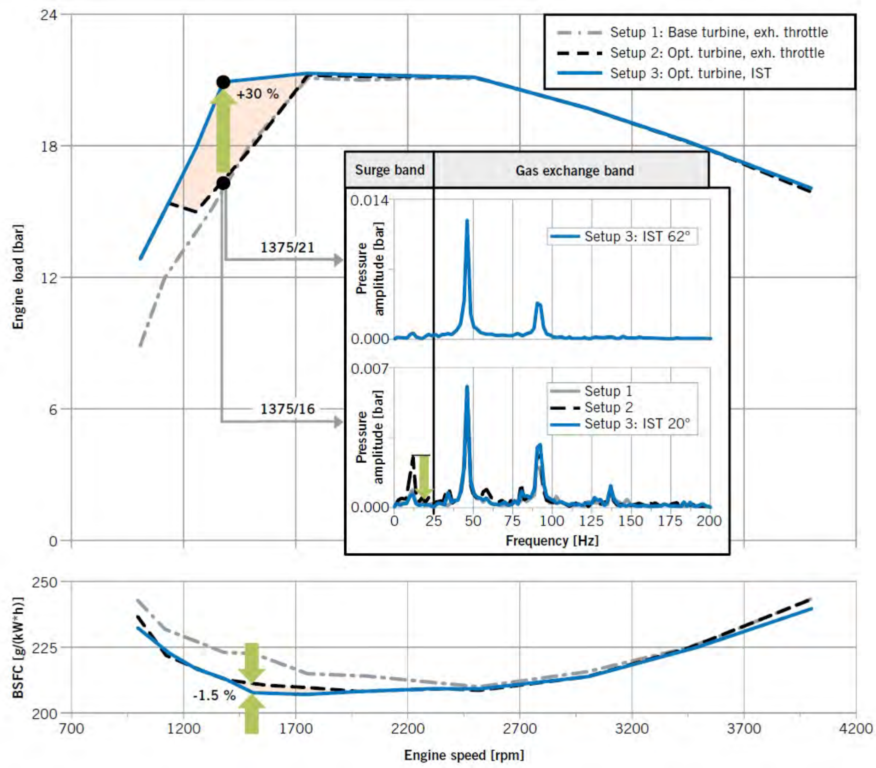

Figure 5. Steady state full load engine dyno results

speed full load, it was not possible to increase low end torque.

In setup 2 the optimised turbine provides substantially more turbine power. This power can be used to drive the compressor to higher pressure ratio and thus increased low-end torque (LET). A requirement for compressor operation at higher pressure ratio is stable operation with a margin to the surge line. As shown in [4] the dynamic pressure situation upstream the compressor indicates the state of stability. Analysis of the pressure pulsations in the range below 200 Hz at 1375 rpm and 16 bar shows a pressure amplitude peak at surge frequency. This trace of instability is a clear indicator of compressor operation close to the stability boundary. The remaining distance to the surge line was considered application reserve. The relative instability of the compressor prevented increased load despite the availability of turbine power.

When running setup 3 with IST, compressor stability is no longer an issue. Depending on the need for stabilisation, sufficient pre-swirl levels can be applied to prevent fluctuations. Application of 20° IST angle leads to stabilisation of the compressor at 1375 rpm and 16 bar. The same level of stability can be maintained up to 21 bar through 62° vane angle, leading to a low-end torque increase of 30 %. Full load Brake Specific Fuel Consumption (BSFC) is reduced for setup 2 and 3 compared to setup 1 while exhaust lambda never drops below 1.25. IST can provide additional 1.5 % BSFC benefit through improved compressor efficiency in the low-end torque area. VTG application reserve remains at stock level for setup 2 and 3. At 4000 rpm and full load all three setups reach rated power. The exhaust back pressure levels as well as exhaust temperatures stay below the specified limits.

The overall IST vane angle strategy for the examined system is illustrated in Figure 6. During

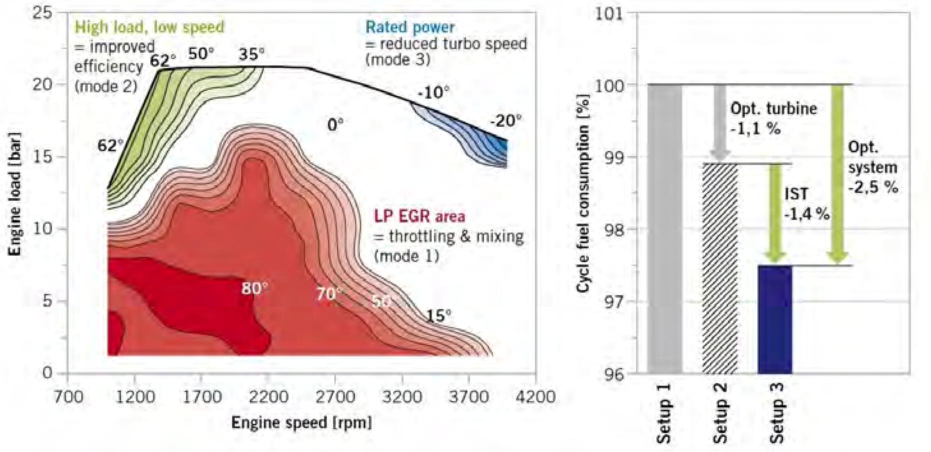

Figure 6. Engine dyno results for applied IST vane angles and FTP-75 fuel economy

part load operation IST acts as a throttle and operates at angles greater than 70°. During low speed, high load operation the compressor is stabilised by up to 62° positive pre-swirl. In the area of maximum turbo speed mild negative angles of -20° are applied to increase altitude reserve. Each operating mode can be applied on its own. The transition between modes can be achieved by seamlessly opening IST or blending angle areas into each other. Figure 6 compares FTP-75 fuel efficiency results for all three setups. Introducing latest turbine technology improved fuel efficiency by 1.1 % with IST providing 1.4% gain on top. The optimised system lowers cycle fuel consumption by 2.5 %.

Thermodynamic Advantage

Through extensive component and engine testing a new way to optimise the air path of a diesel engine was evaluated. Benefits were proven in terms of CO_2 emissions as well as engine performance. Through application of an IST and appropriate integration into the boosting stage, a multi benefit solution outside the frame of component optimisation is provided. Despite the presumed disadvantage of intake throttling on engine thermodynamics, the application of a swirl inducing throttle can lead to fuel efficiency benefits compared to exhaust throttling. Future analysis of IST in a gasoline engine is considered, where scavenging limitations for Real Driving Emissions (RDE) compliance make widened compressor maps even more attractive.

References

[1] Hanig, U.; Becker, M.: Intake Throttle and Pre-swirl Device for Low-Pressure EGR Systems. In: MTZ worldwide 76 (2015), No. 1, pp. 26-31

[2] Eckert, B.; Schnell, E.: Axial- und Radialkompressoren. Second Edition. p. 385, Berlin, Heidelberg, New York: Springer-Verlag, 1980

[3] Shutty, J.; Kienzle, D.; Wenzel, W.; Becker, M.: Air System Management to Improve a Diesel Engine. SAE Technical Paper 2011-01, Detroit, 2011

[4] Müller, D.; Grigoriadis, P.: Dynamische Pumpgrenze. Final report FVV project No. 845, Frankfurt, 2007

Contact
Email: technology@borgwarner.com
For more information please visit
borgwarner.com