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ABSTRACT

The new inline six cylinder Twin-Turbo gasoline engine forms the pinnacle of BMW's wide range of straight-six power units, developing maximum output of 300hp and a peak torque of 300 lb-ft with a displacement of 3.0 litre. Using two turbochargers in combination with the new BMW High Precision Fuel Injection leads to a responsive build-up of torque and to an impressive development of power over a wide engine speed range.

This paper gives a detailed overview of the turbocharger- and the injection system and describes the effect of both systems on power and torque, as well as on fuel consumption and emission. The big advantage of using two small turbochargers is their low moment of inertia, even the slightest movement of the accelerator pedal by the driver's foot serving to immediately build up superior pressure and power. This puts an end to the turbo "gap" previously typical of a turbocharged power unit. Therefore, the new Twin-Turbo power unit offers the same muscle as a much larger normal-aspiration engine, the 3.0-litre developing 300 lb-ft consistently throughout the engine speed range from 1,300 to 5,000 rpm, with the engine continuing to rev up to a speed range of 7,000 rpm.

To combine a thrilling driving experience with a standard of fuel economy appropriate in this day and age (e.g. 27,4 mpg for BMW 335i) , this Twin-Turbo is equipped with a direct gasoline injection and an all-aluminum crank-case. High Precision Fuel Injection performs the key function in this concept for maximum fuel efficiency: With even more exact dosage of fuel as well as a higher compression ratio (10,2:1) the new generation of BMW's direct gasoline injection power units meets all expectations also in practice in terms of fuel economy, without requiring any compromise in the engine's dynamic qualities. This is made possible by the central position of the piezo-injector between the valves. In this position the innovative injector opening up to the outside is able to distribute fuel in a conical, particularly consistent spread throughout the combustion chamber. Operating within a wide range of fuel pressure the system can perform up to three injection pulses per cycle to optimize the combustion process under its specific conditions. For a quick catalyst light-off for example a two pulse injection mode is used, leading to excellent combustion stability with very low hydrocarbon emission level.

Putting it all together this paper analyzes the properties of the turbocharger- and the injection system and shows their contribution to the dynamics, the fuel efficiency and the emission level of the new BMW Twin-Turbo engine.

INTRODUCTION

With the new model 335i BMW presented a totally new turbocharged six-cylinder engine. Developing maximum output of 300 hp and peak torque of 300 lb-ft, this new engine offers the highest standard of spontaneous and superior power and performance. The first straight-six with twin turbochargers, High Precision Fuel Injection and an all-aluminum crankcase offer a level of responsiveness never seen before on a turbocharged engine as well as supreme power and torque extending all the way to high engine speeds. A further benefit of this new turbocharged power unit is the running smoothness typical of a BMW straight-six. Particular efficiency in achieving this supreme power is ensured by the High Precision Fuel Injection, the second generation of direct gasoline injection making a significant contribution to the enhanced economy of the Twin-Turbo power unit. Fig. 1 gives an overview over the power and torque curves of the new Twin Turbo six-cylinder engine. [1]

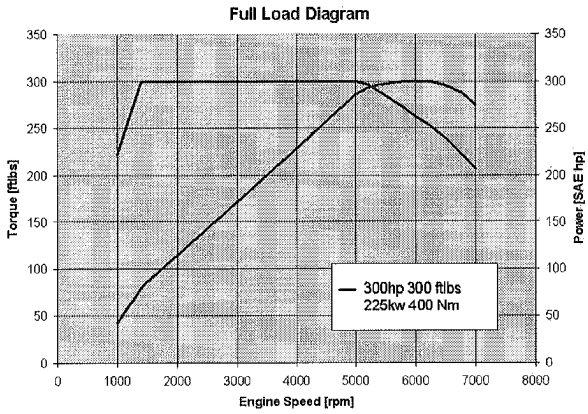

Fig.1: Engine data of the new Twin Turbo engine

HISTORY

For BMW there is a long and successful history producing engines with direct injection as well as turbo charging systems. In 1973 BMW presented the model "2002 turbo", which was the first turbo-charged production vehicle in Europe. Followed by the 745i in 1980 with its six-cylinder turbo-charged engine these two models demonstrated the great potential of innovative turbo-charging technologies for gasoline engines. BMW's history in direct injection engines goes back to the 1930s, when several airplane engines were equipped with direct injection fuel systems. Today the twelve-cylinder engine of the BMW 760i/iL is using a direct injection in combination with the Valvetronic to produce even more power and torque. However, for the improvement in fuel efficiency BMW developed the Valvetronic system, which is implemented worldwide throughout the whole engine family from 4- to 12-cylinder. With the new spray-guided system of the High Precision Injection BMW opens a new chapter of gasoline engine development. In combination with an innovative turbo charging concept it can realize even more dynamic and efficient engines like the new turbo-charged six-cylinder of the BMW 335i.

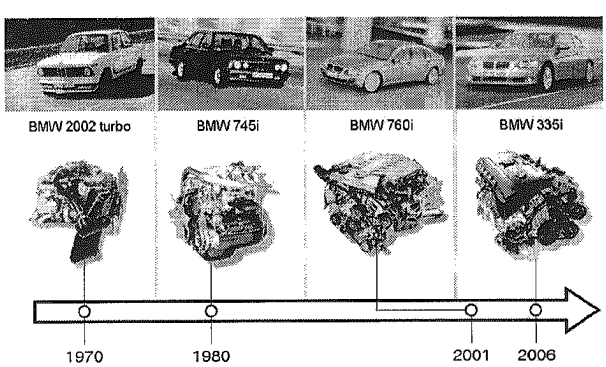

Fig.2: History of turbo-charged and direct injection engines at BMW

SYSTEM CONCEPT

The new six-cylinder Twin Turbo combines high torque at low engine speed with the excellent performance characteristic which BMW's inline six-cylinder engines stand for. This is achieved by the combination of High Precision Injection and Twin-Turbo charging system. Together with the Bi-VANOS system, which controls the valve timing at the intake- and exhaust side, it creates a great efficiency of the charge cycle and the combustion process. First of all the direct injection principle allows to increase the compression ratio significantly. Due to the evaporation enthalpy of the injected fuel the engine's knocking behavior is improved. Compared to the engines of the 1970s and 1980s the compression ratio was increased from about 7.0:1 to 10.2:1, which is comparable to naturally-aspirated engines. The compression ratio improves the performance as well as the thermal efficiency of the engine. Summed up the new Twin Turbo engine achieves a better fuel efficiency of 10% compared to turbocharged multipoint port-injection engines. The combination of turbo charging with direct injection is furthermore used to optimize the diameter of the compressor of the charging system. The direct injection enables a specific operation mode in order to realize high torque values at low engine speed: In combination with the Bi-Vanos at the intake and exhaust side the exhaust gas is completely removed from the cylinder. This leads to a high mass flow at the turbine and a high boost pressure, still keeping up a stoichiometrical A/F-ratio, which is important for the catalytic conversion of the exhaust gas. Thanks to this favorable effect at low engine speed the size of the compressor could be enlarged and is still producing the desired boost pressure which is needed for excellent low end torque. At the other end of the engine speed range – at high rpm - a bigger turbine increases the efficiency of the charging system, which helps to realize the power characteristic of a typical BMW gasoline engine. [2]

TURBO CHARGING SYSTEM

The development of the charging system was focused on an excellent power characteristic over a wide engine speed range and a brilliant response to the driver without the previously known "turbo gap." These demands led to a system design which bases on two small turbo charging units, each powered by the exhaust gas of a group of three cylinders. An intercooler reduces the temperature of the compressed gas which leads to an even higher charge mass and a further reduced knocking problem. Fig. 3 gives an overview over the system showing sensors and actors.

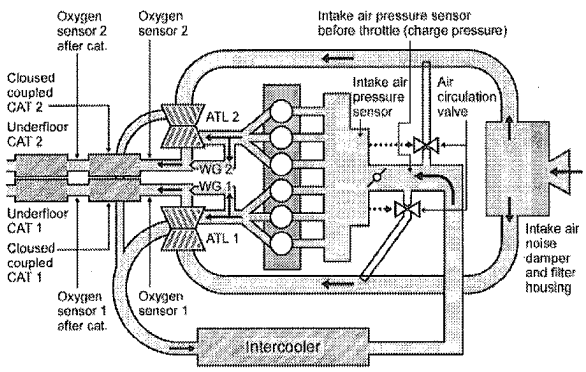

Fig.3: System overview of the charging system

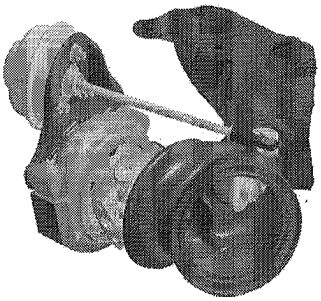

Fig.5: Vacuum activated wastegates

RESPONSE

The most important effect of using two small chargers instead of one larger one is the reduced moment of inertia of the smaller units. With the exhaust manifold being optimized regarding flow efficiency into the turbine the whole exhaust concept leads to a very high response. Fig. 4 shows a comparison of the new Twin Turbo with Mono Turbo concepts. It is obvious that only the Twin Turbo is able to combine high specific power output with the response comparable to a naturally aspirated engine.

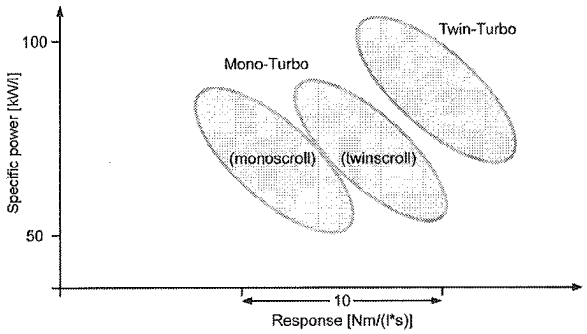

Fig.4: Comparison of different turbo charging concepts

WASTEGATE CONCEPT

To control the boost pressure in any operating condition the new Twin Turbo engine uses two wastegate valves actuated by vacuum (fig. 5). This is an important difference to other wastegate systems. Using vacuum it is possible to open and close the wastegate valves independently from the current boost pressure.

This feature is consequently used to improve the response and the fuel efficiency. At low engine speed and load the wastegates are predominantly closed to maintain a certain rotation of the turbine. This strategy ensures a spontaneous speedup of the turbine when higher torque is requested. Fig. 6 shows the effect of the wastegate position on the response. With closed wastegates the boost pressure is established significantly quicker when the throttle valve is opened. Therefore the engine is able to produce the requested torque more quickly.

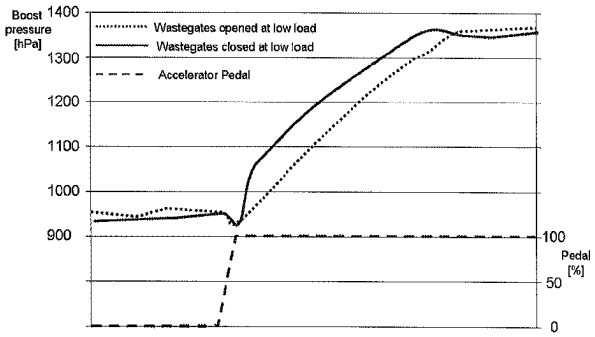

Fig.6: Effect of the wastegate position on response

At mid-range engine load a different wastegate position is adjusted: In order to reduce the fuel consumption the wastegates are partly opened to avoid undesired power loss by the turbine. Closing the wastegates at part load leads to a higher boost pressure, which has to be reduced by the throttle valve. Therefore the efficiency of the gas exchange process is reduced, when the wastegates are closed. The benefit of opening the wastegates partly is shown in fig. 7 for an engine running at 3000 rpm. At low engine load closed wastegates lead to only slightly higher fuel consumption of about one percent. This is accepted to improve the response. At higher load the losses lead to higher fuel consumption up to 3.5 percent, which is avoided by opening the

wastegates partly. Of course in turbocharged engine operating points the wastegates are used to control the boost pressure. This makes sure that the engine torque is limited to the allowed maximum to prevent mechanical damage. This flexibility is achieved by the vacuum activation on the one hand and by a specific software on the other hand which controls the boost pressure.

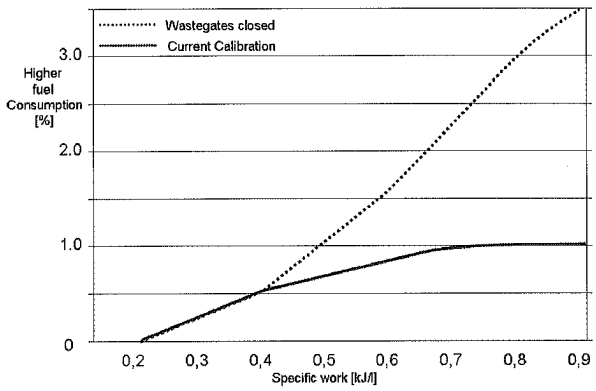

Fig.7: Effect of wastegate strategy on fuel consumption

SOFTWARE FUNCTIONS

Several software functions for the turbo charging system have been developed for the new six cylinder engine. The architecture of the software is shown in fig. 8. The specific software components for the turbo charging system are integrated into the existing software architecture containing the torque based functions and the load control. The torque based functions calculate the torque demand by the driver or assistance systems. The load control functions coordinate the several actuators which adjust the charge mass flow into the cylinder. Beside the position of the throttle valve and the valve timing actuators of the Bi-VANOS system the position of the wastegate valves is important for the mass flow. For a precise control of the boost pressure an adaptive feedback control is implemented. The control unit sets the position of the wastegate valves by a duty cycle signal.

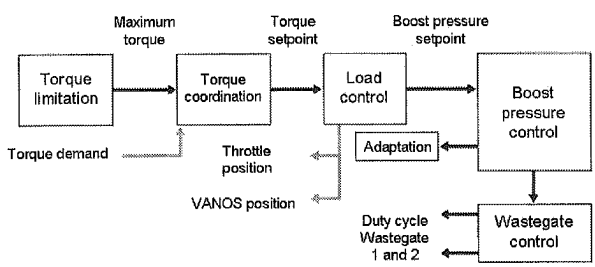

Fig.8: Software of the boost control

BOOST PRESSURE AFTER GEAR SHIFT

The potential of software functions to optimize the response of the car can be shown with the following example: After a gear shift with a manual transmission the boost pressure is normally low. In order to realize a high torque as soon as possible after the gear shift it is necessary to increase the boost pressure quickly. The decrease of boost pressure however is caused by the driver, who has no torque demand during gear shift. So a software function has been developed which is not closing the throttle valve during a short gear shift but decreases the torque of the engine by shifting the ignition time. So the mass flow through the engine and therefore the speed of the turbine is still high even if the driver is changing the gear. This leads to a much better torque right after the gear shift, because the turbines are only loosing a small part of their energy. The effect of this software function is shown in fig. 9.

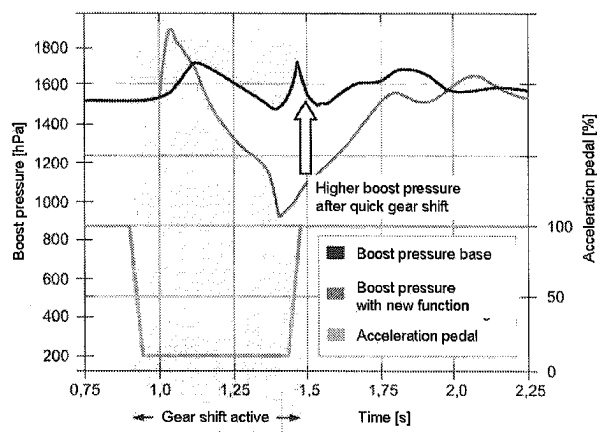

Fig.9: Control strategy at quick gear shift

HIGH PRECISION INJECTION

INJECTION SYSTEM

The most important innovation of the Twin Turbo engine's combustion system is the direct injection system. It's core component is a Piezo-activated fuel injector, which has a significantly higher potential to improve the combustion process than other direct injection systems. The most characteristic design attribute of the injection system is the central position of the injector right beside the spark plug. In combination with the symmetrical spray pattern of the injector this position leads to favourable spray propagation with a minimum impingement on the cylinder liner or the piston. Further more this configuration enables a spray-guided operation mode for lean burn combustion systems. Fig. 10 shows the concept of the centrally located injector and spark plug.

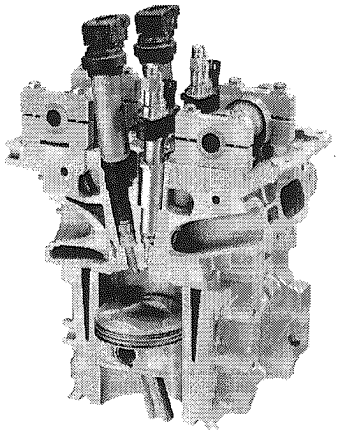

Fig.10: System concept of centrally located fuel injector

FUNCTIONAL POTENTIALS OF HIGH PRECISION INJECTION

Multiple injections for homogeneous combustion mode

Due to the lambda = 1 – concept of the new Twin Turbo engine the most frequent operation mode is the homogeneous combustion. The High Precision Injection can improve also this combustion mode. The fuel system is able to vary the fuel pressure (up to 200 bar) and the number of injection pulses (up to three per cycle) in order to reduce the wall wetting. This is particularly important to avoid smoke emission and oil dilution. Fig.11 shows the calibration of the fuel pressure setpoint and the number of injection pulses which are used depending on the engine operating point. Starting with a single injection pulse per cylinder and cycle a double pulse strategy is used at mid load points. At even higher engine load a triple injection pattern is applied to reduce the penetration of the fuel spray. In combination with the variable fuel pressure the High Precision Injection is providing maximum flexibility to adapt the fuel injection to the specific operating conditions.

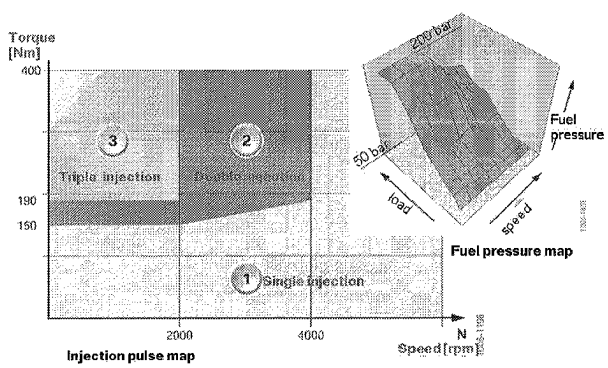

Fig.11: Fuel pressure calibration and number of injection pulses

Catalyst heating with twin injection

Regarding emissions it is most important to reach the light-off temperature of the catalysts as soon as possible. Engines with turbochargers make great demand on the emission system because of the thermal inertia of the turbo charger units. So these engines need much more exhaust enthalpy to heat up the catalyst than engines without turbochargers. To realize the required enthalpy the new Twin Turbo engine is using a special operation mode: During catalyst heating the engine is running at a very high load in order to increase the exhaust mass flow. For high exhaust temperatures the ignition time is retarded which is furthermore compensating the excessive torque of the high mass flow. The High Precision Injection is able to stabilize the combustion process even with very late ignition times. This is achieved using a double injection pattern with one early injection and a very small second injection right before ignition. Fig. 12 shows that this combustion produces the desired high exhaust enthalpy and very low hydrocarbon emission at the same time.

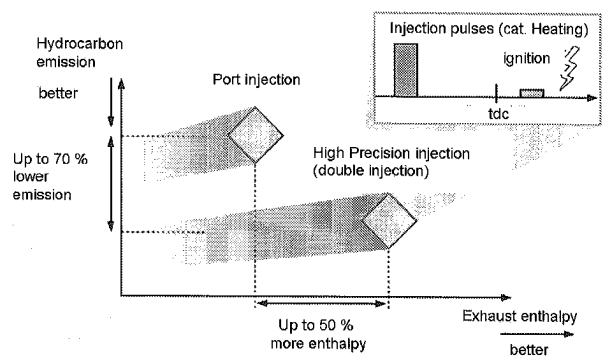

Fig.12: Effect of double injection during catalyst heating

PIEZO INJECTOR

Injector design

The new piezo injector is the core unit of the innovative High Precision Injection system. It is operated by a piezo actuator unit, which expands when electrical charge is applied. The charge is divided into packages. The number and size of the packages specify the lift of the injector needle. The needle lift and the injection time set the fuel mass which is injected during the injection pulse. In order to make sure that the injector is running with the same needle lift at different temperature conditions a thermal compensator is used which compensates the different elongations of the injector components.

Functional properties of the Piezo injector

One basic task of the injector is the precise metering of fuel in a wide range of mass and under various ambient

conditions. In addition the spray quality regarding atomization and spray pattern is important for the combustion. The characteristic spray pattern of the High Precision Injection is shown in fig. 13. The injector forms a cone spray with small vortices of fine droplets, which lead to an ignitable air/fuel concentration at the spark plug. Fig. 13 shows the spray at different times, recorded with a laser sheet visualization.

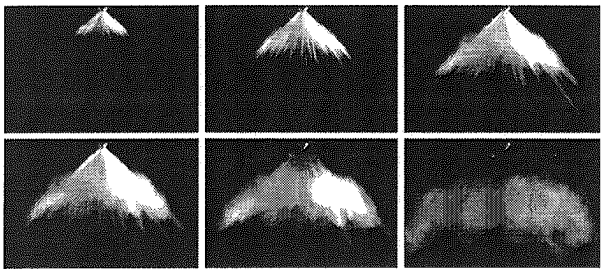

Fig.13: Fuel spray of High Precision injection

SOFTWARE FUNCTIONS OF HIGH PRECISION INJECTION

The new High Precision Injection is a mechatronical system. So for the performance of the system the software components are as important as the mechanical ones. Many software functions of the High Precision Injection have been especially developed for the new Twin Turbo engine. The architecture of the software is shown in fig. 14. The first part of the software contains the calculation of the energy and injection time, which is required for the specific operating point. Several corrections regarding fuel pressure and temperature are added. In order to consider the individual flow properties of the injectors specific flow data for each injector are measured and coded into the ECU. This first software part makes sure that any injector is running properly even under changing conditions like temperature or pressure.

Additionally several adaptive functions have been developed to maintain the correct air/fuel ratio for each cylinder over lifetime. First the lambda control is correcting and adapting the fuel mass for a group of three cylinders. The adaptive function, which has been developed for the new Twin Turbo engine, is based on an artificial neural network and stores the required correction factor continuously. The next function controls the air/fuel ratio of each single cylinder. The High Precision Injection is able to adjust the fuel mass of each cylinder independently from the other cylinders. Based on the signals of the existing lambda sensors an observer model calculates the cylinder specific air/fuel ratio. Finally the energy levels of the injectors are corrected until all cylinders are running at the same air/fuel ratio. To achieve an excellent engine stability at idle the engine speed is analyzed and used to modify the injection time in order to optimize the engine smoothness. Finally there is an adaptive function which is used especially for very short injection pulses.

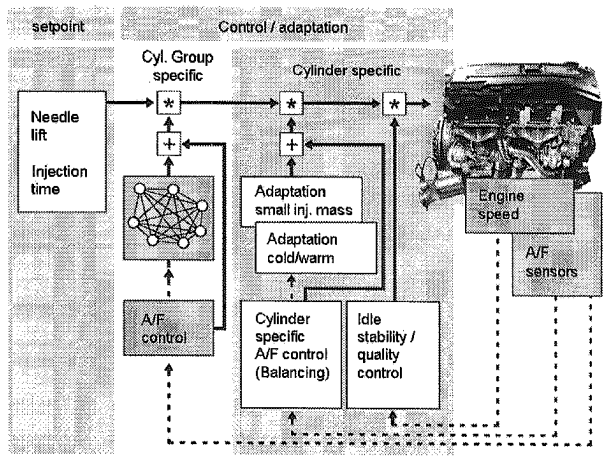

Fig.14: Control functions of the High Precision Injection

The numerous software functions of the High Precision Injection show the complexity of the system. It is furthermore obvious that such a system could not be realized without sophisticated software components.

CONCLUSION

The new BMW Twin Turbo engine with High Precision injection is able to combine excellent performance and good fuel efficiency. The combination of an innovative turbo charging systems and the new High Precision Injection leads to an impressive response and takes the "Efficient Dynamics" to a next step.

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