The Development of the Audi 3.6-litre V8 Twin Turbo FSI Engine for Le Mans

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Within a period of just 15 months, the race engine department of Audi Sport designed and developed a homogeneous direct-injection engine based on the successful engine of 1999 and 2000. Furthermore, all targets such as mixture homogeneity, power output and adaptation to the car's requirements were successfully achieved within six months The new engines went on to power the two Audi R8 race cars to an impressive victory in the Le Mans 24-hour race in June 2001.

Le Mans 24-Hour Race

The Le Mans 24-hour race has considerably changed its character in recent decades. The main reasons were the modifications to the rules and track profile as well as competition between the big manufacturers. The original idea – to prove the durability of cars and pit crews even through major repair work during the race – has been transformed into a 24-hour sprint race with very fierce competition. As in Formula 1, even the smallest details have to be regarded as decisive factors for a victory. But in this case, the race distance of a whole F1 season of more than 5000 km is completed in just 24 hours.

In order to create tight competition, the basic idea of the rules is to balance the chance of winning for all types of cars and engines. The mandatory type of fuel is provided by the organizer and corresponds to "Super plus" gasoline, but with closer tolerances. As a consequence, the

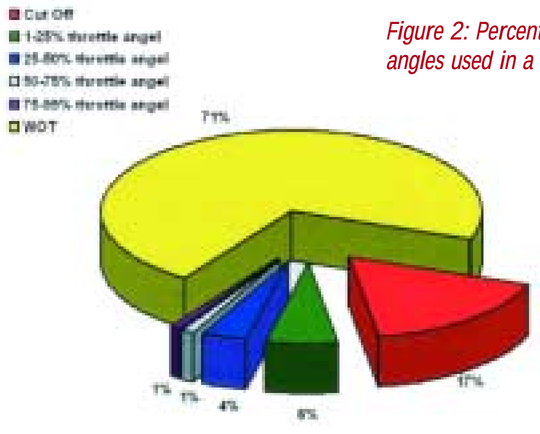


Figure 2: Percentage of the throttle angles used in a Le Mans race lap

engine performance is limited by air-restrictor(s) upstream of the air intake system(s) and by additional electronically controlled boost limits for turbocharged engines. The size of the restrictors depends on the engine capacity and technical complexity. For the Audi 3.6-litre twin turbo engine, the limits were defined by two air restrictors each with a diameter of 32.4 mm and by a maximum boost of 1.67 bar.

All design and development efforts were focused on the requirements to be met by a successful Le Mans engine. Besides competitive performance and high torque over all speed ranges, reliability and low consumption also play a greater role than in other races. A further important aspect is quick engine response and good driveability under all weather and race track conditions.

The basic engine, which was equipped with conventional technology, had already reached the limits of its possibilities stipulated by the rules. Only a completely new technical approach was able to achieve the necessary advantage in order to ensure future victories. Fuel straight injection (FSI) was regarded as the technological key. In January 2000, design work began on the new FSI engine planned for the race in 2001. The first run on the test bench was scheduled for November 2000 at the earliest, due to the lead time required. The development had to be completed by April at the latest.

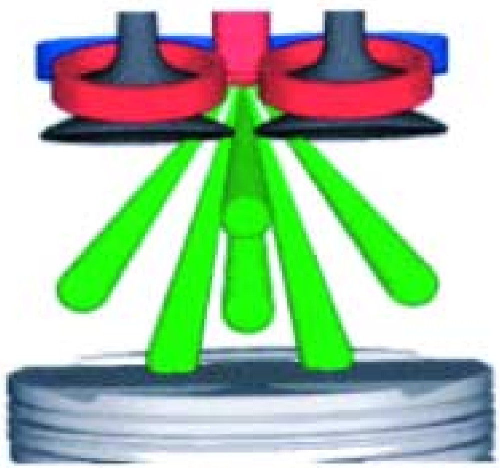
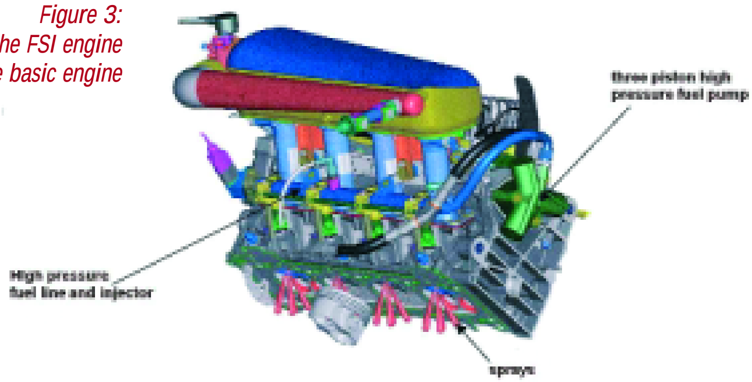


Figure 4: Geometrical array of the fuel sprays of a six-hole injector.

Figure 3: Visible changes to the FSI engine compared to the basic engine



The Basic Engine

The above-mentioned restrictions have been in force since 2000 on engines with a capacity of 3.6 litres, two turbochargers and 4 valves per cylinder installed in an open Le Mans prototype car.

The Audi engine was designed as a fully stressed 90 degree V8 DOHC unit with the following specifications:

- Bore: 85 mm
- Stroke: 79.2 mm
- Compression ratio, e: >11
- Cylinder head in aluminium with a pent roof combustion chamber
- Cylinder block in aluminium with a closed deck and nikasil"-coated cylinders without liners
- Bedplate in investment casting including a sophisticated scavenging system.
- Eight-stage gearwheel-driven oil scavenge and feed pumps
- Two independent water pumps in line with the oil pumps
- One combined water-cooled oil radiator for the engine and gearbox integrated into the V

The maximum performance of this basic Multipoint Injection (MPI) engine, which was restricted as described above, was 610 bhp at 6300 rpm. The maximum torque of more than 700 Nm was reached at 5500 rpm. The usable speed range was between 3500 rpm and 7800 rpm. The range with 90 litres of fuel (maximum permitted tank capacity) under race conditions at Le Mans was 12 – 13 laps (one lap : 13.85 km).

Engine Parameters

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The choice of the injection process was determined to a large extent by the character of a race lap at Le Mans. Race analyses, Figure 2, showed that the track requires more than 70 % of full load from an engine. A stratified mixture was not seen as an effective mixture process, considering the absence of part load sections. Therefore, a homogeneous mixture was seen as the best solution for increasing both performance and efficiency at the same time. Of the three possible direct injection processes (spray-guided, wall-guided and air-guided), the air-guided system offered the best possibilities and required the smallest modifications to the mechanical system of the engine, Figure 3.

The main target was to achieve the maximum performance possible with the available air. Therefore, the mixture of air and fuel was to be as homogeneous as possible with a ratio of between $\lambda = 0.85$ and $\lambda = 1.0$.

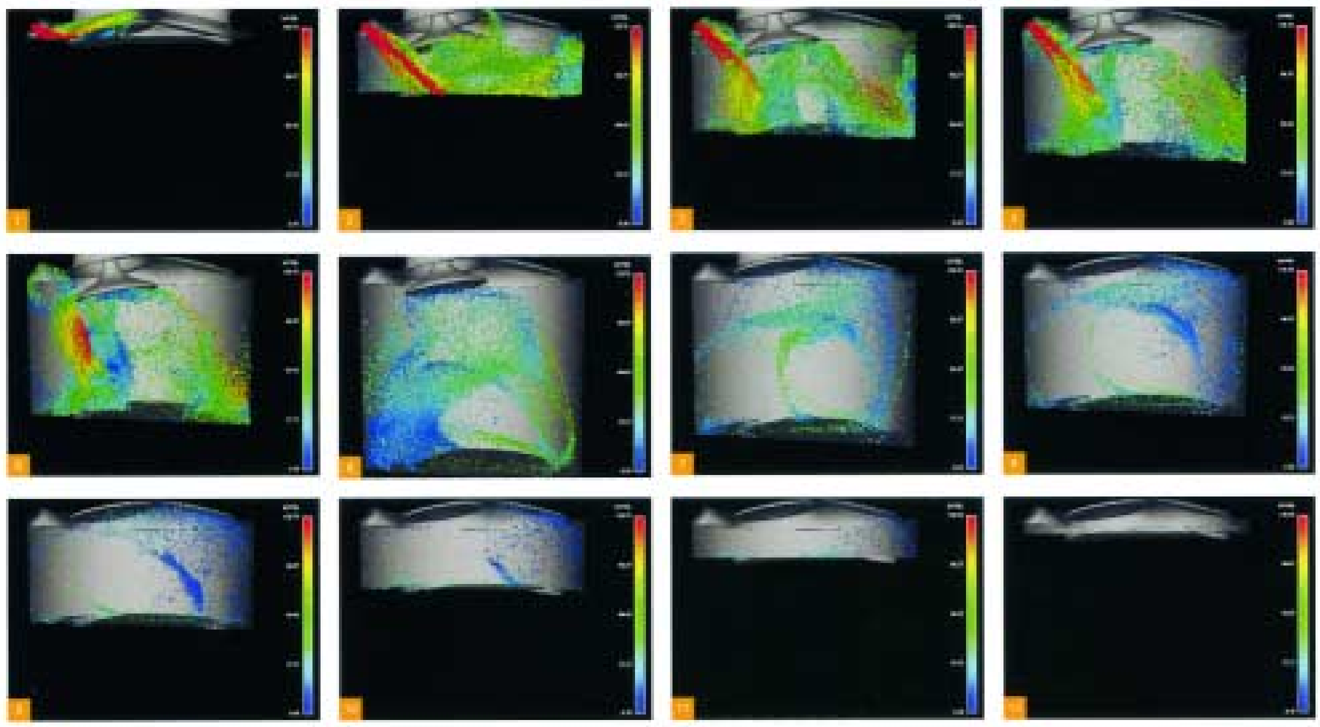

Figure 5: The CFD calculation was carried out in order to gain information about the mixing process between the injected fuel and the air forced into the tumble motion.

The extremely short test time required the development a sophisticated decision matrix in order to find the best combination of all the following parameters:

- the shape of the combustion chamber
- the number and position of the sprays/injectors
- the spray angles
- the cooling of the injectors and injector tips
- the fuel mass flow through the injectors
- the fuel mass flow and pressure generated by the fuel pumps in relation to the engine speed and load
- the compression ratio
- the inlet ports with different flow characteristics and different tumble ratios.

In addition, many assumptions had to be made due to a lack of knowledge and experience of this technology in such an engine.

The combustion chamber was to remain as similar as possible to the basic one. Therefore, all investigations were based on the existing 4-valve pent roof chamber combined with an almost flat piston crown. The determination of the injector position and orientation was guided by the design of the basic cylinder head. The intake port includes an angle of almost 45 degrees.

The central axis of the injector

The central axis of the injector had to be as close and as parallel as possible to the centreline of the port. This made it possible to minimise the bend angles of the different sprays and, as a result, the losses of the required mass fuel flow. Furthermore, fuel was to be prevented from making contact with the cylinder walls. The idea of using the exhaust side as a possible location for the injector had been dropped for safety reasons. Different spray angles were defined considering the shape of the combustion chamber, the position of the spark plug and the protruding intake valves, Figure 4.

In order to ensure sufficient cooling of the injector itself and of the injector tip, the water flow through the cylinder block and the cylinder head had to be modified. The modifications were based on CFD calculations. The new water jacket of the crankcase even allowed the adjustment of the main stream without any additional machining. In the cylinder head, water flow was directed more towards the area of the injector between the two intake valve seats.

The use of an already existing swirl injector was not possible, due to the limited mass flow rate of 15 cm^3/sec, as the performance of the engine required a mass flow high-

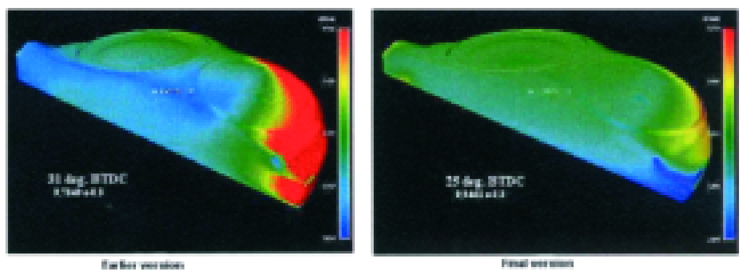

Figure 6: The optimum interaction between the spray geometry and the tumble is the keyto achieving optimum homogenisation. This figure shows two different examples.

er than 25 cm^3/sec. However, the variation of the injection phase at 6000 rpm and above required a shortening of the injection time and, as a consequence, an increase in that value even up to 50 cm^3/sec. In order to achieve such injection times in the range of a few milliseconds, a much higher electrical performance than that offered by the MPI low-pressure injectors had to be provided. Therefore, external amplifiers were added to the original Bosch MS 2.9 ECU.

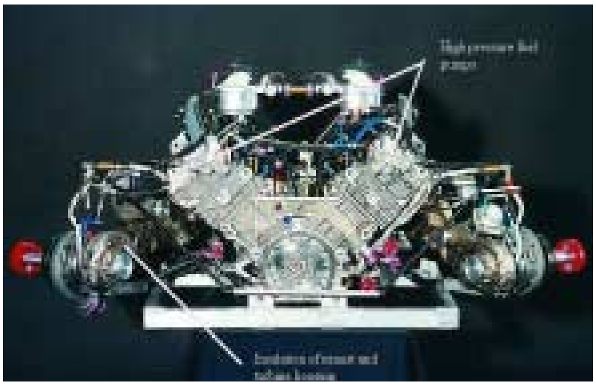

Figure 7: Audi R8 with V8 FSI twin turbo engine

The fuel pressure generated by two three-piston high-pressure pumps was limited to 110 bar and adjusted by an electronically controlled valve at each fuel rail. In order to avoid any possible bottlenecks, the first test runs were performed with an electric drive for the pumps. This step made it possible to determine the boundary conditions for the fuel system independently of the engine run. Furthermore, it was therefore possible to define the capacity of the pumps in accordance with the number of revolutions. However, the two pumps were later to be driven by the intake camshafts. As a result, the fuel mass flow of each pump had to be increased from 0.45 cm^3/rev to 0.65 cm^3/rev.

The optimum compression ratio could only be determined in test runs. For this purpose, a number of pistons with different piston crowns in combination with corresponding cylinder head gaskets were prepared. This made it possible to increase the compression ratio to an extremely high level without any restrictions of the camshaft timing.

In order to define an inlet port with optimum flow characteristics within a very short time, two parallel approaches were pursued. The first involved the preparation of a number of cylinder heads with different port designs in order to obtain results from running engines. The second approach was to carry out CFD calculations and simulations. This task was carried out by Cosworth Technology, a subsidiary of Audi AG. The calculations were based on port data from the flow bench, as well as on injector data provided by Bosch and on the results of a one-dimensional non-stationary calculation. An example of one of these CFD runs is shown in Figure 5.

The CFD calculation was carried out in order to gain information about the mixing process between the injected fuel and the air forced into the tumble motion. Figure 5 shows the velocity and distribution of the fuel droplets in relation to the crankshaft angle in steps of 30 degree starting and ending at BTDC. The results are

Figure 8: Detail image of the Bosch high-pressure injection pump on the cylinder head.

The optimum interaction between the spray geometry and the tumble is the key.

based on model calculations, taking into account such aspects as the wall effects between the droplets and the piston surface, as well as the vaporization speed and the required heat transfer. The influence of the tumble is clearly visible at 150 degrees. Evaporated droplets are no longer depicted.

The optimum interaction between the spray geometry and the tumble is the key to achieving optimum homogenisation. Two different examples are shown in Figure 6 . In the image on the left, a very lean mixture (blue region) around the spark plug inhibits safe ignition and good combustion. The image on the right, on the other hand, shows good homogenisation (green region) almost everywhere in the combustion chamber. This was achieved by using a six-hole injector in combination with an inlet port with a tumble value of almost 4. These calculations were subsequently verified in test runs.

The Test Programme

In November 2000, the first FSI engine was fired up on the test bench at the Audi Neckarsulm plant. To begin with, a hybrid injection system was used. A conventional MPI system was installed parallel to the FSI. This allowed the development steps to be compared with the actual type of engine which had powered the Audi R 8's to a one-two-three victory in June 2000.

After the optimisation of the fuel pump, the compression ratio was increased to a value above 12. Due to the increased efficiency, the exhaust temperature fell by 50 °C. Therefore, the insulation of the exhaust system and the turbine housing had to be improved in order to maintain a sufficient energy supply to the turbine at lower engine speeds, Figure 7.

The next development step was the adaptation of the engine to the car. The main requirements were autonomous starting, an instantaneous reaction to dynamic processes and the ability to shift gears up and down at full throttle. Fuel pressure during the runs varied between 40 and 100 bar. In contrast, when the engine was started, only a limited fuel pressure of 8 bar was available, and was provided by an electrical in-tank pump. Nevertheless, it was possible to start the engine without any delay under cold conditions and, even more important for the race, under hot conditions.

The mapping of the engine on the test bench convincingly proved the expected benefits of the FSI technology. No additional fuel was required during acceleration to avoid knocking. The real time reaction of power requirements during gear changes reduced the gear shifting time. Furthermore, the FSI technology also made it possible to control highly dynamic transition functions. The possibility of a cycle-to-cycle adjustment of the injection resulted in an additional considerable reduction in fuel consumption.

1000 km Without Any Problems

In February 2001, the first test in a car was performed for more than 1000 km without any major problems. This meant that it was already possible to start adapting the part load maps. The development programme on the test bench continued parallel to the road tests, with the focus now on increasing the power and torque. λ was raised to 0.93 and above and the ignition angles were optimised under qualifying conditions. For the first test bench runs, λ had been fixed at around 0.90 to avoid any possible knocking damage. Lean maps with λ values above 1.0 were created for race periods with lower power requirements (pace car, yellow periods) and were successfully tested. The durability of the new engine was checked under race conditions in the car and on the test bench in several test runs over periods of more than 30 hours.

Results

In the Le Mans Pretest in May 2001, all results previously achieved on the test benches in Ingolstadt and Neckarsulm were proved under real Le Mans conditions:

- an increase in performance by up to 9 % between 3000 rpm and 8000 rpm
- a reduction in fuel consumption by up to 8 – 10 % resulting in at least one additional lap at Le Mans between two pit stops for refuelling
- excellent driveability

The Le Mans 24-hour race in June 2001 finished with a convincing victory for the FSI technology. Under extremely difficult rainy conditions, Audi once again impressively confirmed its slogan of "Vorsprung durch Technik".

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