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The V 12 TDI® for the 24h of Le Mans - Victory of an Idea

Abstract

Fore more than 50 years there were several attempts to win the hardest endurance race of the world with a Diesel engine. AUDI who has pioneered the introduction of the first direct injection passenger engine TDI has developed an innovative powerplant for his purpose. With the first run at last years 24h race a historical victory was achieved. The new engine shows a very low weight, a very compact design and a new type of particulate filter system. In combination with a sophisticated combustion process and an extreme high injection pressure a remarkable power output along with low consumption and very low emissions are guaranteed in the race.
AUDI shows again its philosophy of customer orientated motorsport by developing and testing new technologies convincingly on the racetrack, before they will introduced in road cars.

1. 24 hours of Le Mans: the race and its background

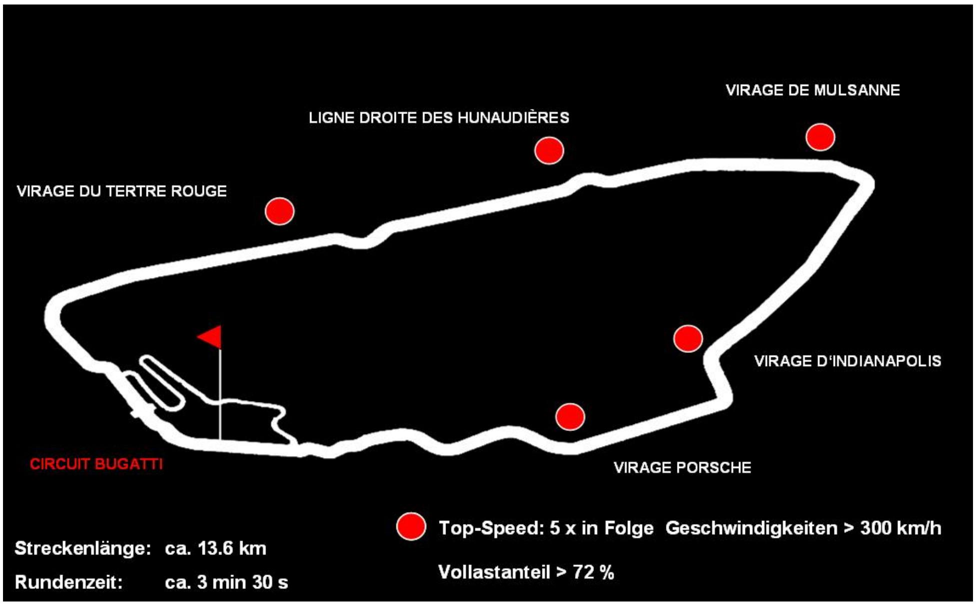
The 24 hours of the Le Mans Race are truly unique. This has been already in 1923 when the race took place for the very first time and this hasn’t changed even up to the present day. However the character of the race has changed dramatically during the last 83 years.
Starting with the idea of holding an endurance race for driver, car and crew with occasional stops for repairs, the race has turned into a 24-hour sprint race.
During the 24 hours the winning R 10 TDI® stood for only 30 minutes in the pit, including 27 stops for refuelling, change of tyres, drivers and a gearbox cluster!

With 48 cars on the grid a hard competition is guaranteed.

Figure 1: Start of the 74th Edition of the 24-hour Le Mans Race in 2006

The very sophisticated rules of the A.C.O. (Automobile-Club de l'Ouest), as the sanctioning body, try to provide equal chances for every concept of car and engine. Therefore every solution has to be exploited to its absolute limit. Even the smallest deficit can result in defeat.

Most of the circuit consists of public roads which are blocked for short periods for practicing and, of course, for the race itself.



● Top-Speed: 5 x in Folge Geschwindigkeiten > 300 km/h

Vollastanteil > 72 %

Streckenlänge: ca. 13.6 km

Rundenzeit: ca. 3 min 30 s

Figure 2: The Le Mans Circuit [5]

Therefore it is not possible to run tests on the Le Mans circuit. In fact, no race track worldwide has approximately a similar character and this is the very special challenge of this race. These circumstances require the development of new test and development methods, independent of the race track.

Just 2 weeks prior to the race, which traditionally takes place at the end of the second week in June, there is a test day with two 4hour sessions.
60 cars are admitted for this event.

During the race very extreme weather conditions can occur.
In 2001 there was torrential rain lasting 22 hours and the temperature dropped down to 8 °C.
A difference in the temperature range between day and night of up to 25 °C is possible. This is extremely challenging for the engine's cooling system.

The engine has to be stopped in the pits, before anybody is allowed to touch the car, even, for example, to refuel. Restarting the motor has to work without any supply of external assistance or energy. To avoid any loss of time the restarting procedure of a hot engine must be considered therefore as a most important part of the development process.

A competitive engine for this race needs some specific properties:

Parallel to the performance a wide and high level of torque is required.
Low fuel consumption and absolute reliability have a much higher importance than in other races.
Very good response and driveability in all weather and race-track conditions are part of the „comfort package“ provided for the drivers as well as a low level of vibration and noise.

The gearbox must not have more than 6 gears. Automatic gear change is not permitted. Power shift that allows up and downshift without a clutch function is allowed and needs a very sophisticated algorithm to execute this gear change in an extremely short time.
The tank capacity is 90 litres. The mandatory fuel is supplied by the A.C.O. and corresponds to the European Norm. The Diesel specification includes approximately. 25 % GTL (gas to liquid), i.e. a promising synthetic fuel with the identical properties of BTL (biomass to liquid).

The winning R10 TDI® with the drivers Frank Biela, Emanuele Pirro and Marco Werner had to cover 380 laps or 5187 km. This is the new distance record. The average speed was 215, 4 km/h including all 27 pit stops. During the race they applied the breaks 5100 times and made 15800 gear changes. Including all tests and qualifying sessions the engine ran overall 6402 km or 469 laps.

	2002	2003	2004	2005	2006
Formular 1	***5174 km*** (17 Races)	***4867 km*** (16 Races)	***5364,8 km*** (18 Races)	***5329,4 km*** (19 Races)	***5336 km*** (18 Races)
Le Mans (24h)	***5174 km***	***5157 km***	***5185 km***	***5084 km***	***5187 km***

Figure 3: Comparison of race distances between Le Mans – F1 season

As a further comparison:
In 2005 the F1 champion Alonso clocked-up 5329 km in 19 races with more than 38 pit stops and he used 11 engines.
In 2006 the same driver covered 5336 km in 18 races with 10 engines.
In other words, in comparison, the R10 TDI® ran a complete F1 season within 24 hours!

The three R10 TDI® pilots could substitute each other periodically , whereas the engine had to complete the whole distance.

Taking these facts into consideration one can ask the question “where is the real „royal class“ in motor sport and where is the top end of technical development?”

We at AUDI-Sport have the following answer :

AUDI stood and stands out like no other brand for technical innovations especially in racing. Quattro, turbo technology in rallye and FSI® in Le Mans are just a few but outstanding examples. All of these features have found an impressive way into the AUDI cars and there is no end in sight.
The AUDI philosophy in motorsport is to develop and test for the benefit of our customers and not just for PR Events.
About 73% of all Audi cars are actually equipped with a turbocharged engine and nearly every second Audi is powered by a Diesel-Engine, even in our luxury class the A8. In some models even more than 60 % of the customers want to drive TDI®.

No engine concept has seen a similar increase in performance during the last 20 years than the direct injected, turbocharged Diesel-Engine. The average power/litre increased from less than 40 kW/l to 60 kW/l and even more (4).

AUDI started its worldwide development of the first TDI® in passenger cars in 1989 and has constantly improved this development up to the latest Q7 12 Cylinder Diesel-Engine with 500 hp and 1000 Nm torque.

Unfortunately the „sporty“ image of Diesel-Engines has not developed at all!
Sporty engines were always gasoline engines.

Therefore the time was right for AUDI to make a logical and consequential decision:

AUDI, the pioneer in TDI® road engines, decided to pioneer the very first TDI® racing engine with the aim to win the hardest race in the world, the 24 hours of Le Mans.

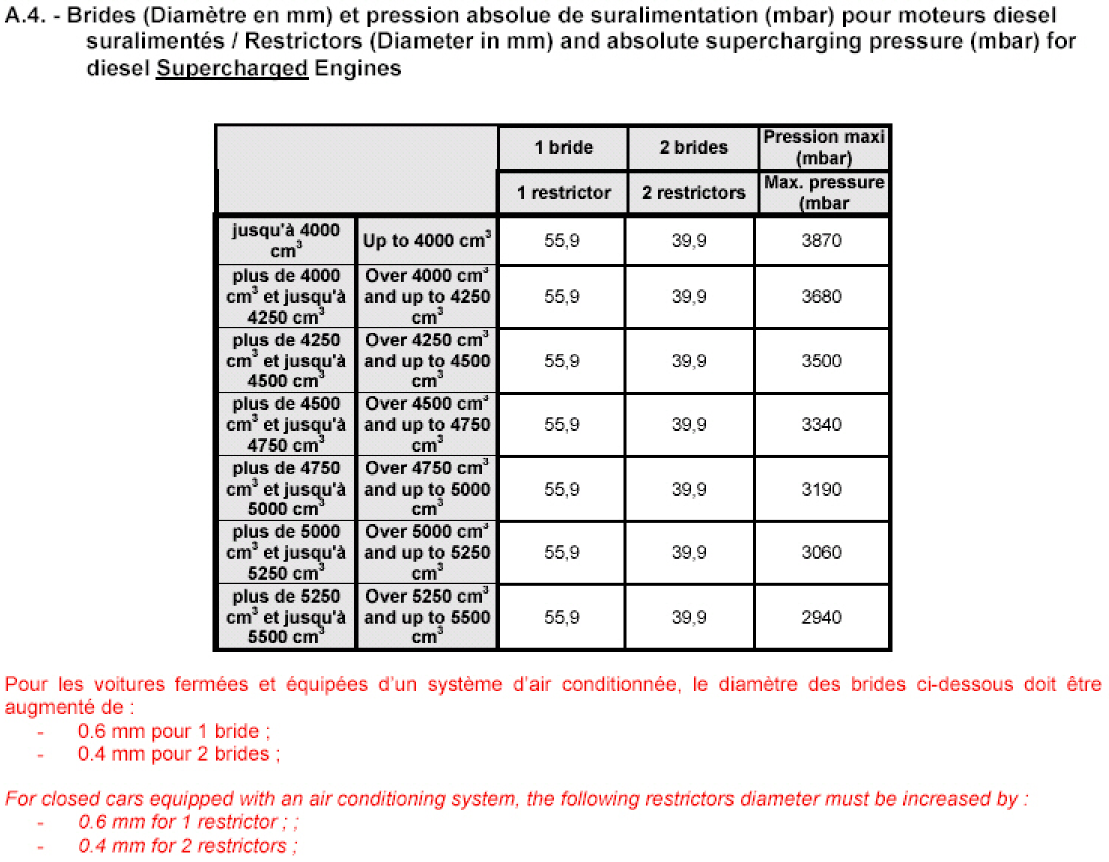
This also clearly follows the Le Mans rules and philosophy and the main principles of AUDI:

Reliability, sportiness and innovative technical competence at the highest level.

2. Regulations, Concept Evaluation and Development History

Discussions about the creation of a new regulation were held by the ACO with many contributors. The current regulation is valid since 1st January 2004.

In this regulation a new class of engines was created. Besides a 4-stroke Gasoline engine it is now also possible to use a 4-stroke Diesel engine with a capacity of between 4 litres and 5.5 litres. The number of cylinders is not stipulated neither is the overall layout of the engine. The ACO Standards foresee that all engines are fitted with an air restrictor, to limit the maximum available air and to limit the power. When 2 restrictors are used, the diameter is limited to 39,9 mm independent of the engine swept volume.



A.4. - Brides (Diamètre en mm) et pression absolue de suralimentation (mbar) pour moteurs diesel suralimentés / Restrictors (Diameter in mm) and absolute supercharging pressure (mbar) for diesel Supercharged Engines

		1 bride	2 brides	Pression maxi (mbar)
		1 restrictor	2 restrictors	Max. pressure (mbar
jusqu'à 4000 cm^3	Up to 4000 cm^3	55,9	39,9	3870
plus de 4000 cm^3 et jusqu'à 4250 cm^3	Over 4000 cm^3 and up to 4250 cm^3	55,9	39,9	3680
plus de 4250 cm^3 et jusqu'à 4500 cm^3	Over 4250 cm^3 and up to 4500 cm^3	55,9	39,9	3500
plus de 4500 cm^3 et jusqu'à 4750 cm^3	Over 4500 cm^3 and up to 4750 cm^3	55,9	39,9	3340
plus de 4750 cm^3 et jusqu'à 5000 cm^3	Over 4750 cm^3 and up to 5000 cm^3	55,9	39,9	3190
plus de 5000 cm^3 et jusqu'à 5250 cm^3	Over 5000 cm^3 and up to 5250 cm^3	55,9	39,9	3060
plus de 5250 cm^3 et jusqu'à 5500 cm^3	Over 5250 cm^3 and up to 5500 cm^3	55,9	39,9	2940

Pour les voitures fermées et équipées d'un système d'air conditionnée, le diamètre des brides ci-dessous doit être augmenté de :

- 0.6 mm pour 1 bride ;
- 0.4 mm pour 2 brides ;

For closed cars equipped with an air conditioning system, the following restrictors diameter must be increased by :

- *0.6 mm for 1 restrictor ; ;*
- *0.4 mm for 2 restrictors ;*

Figure 4: Restrictor Diameter (mm) and Boost pressure for Engine Swept Volumes

Compared with a gasoline engine the diameter has been enlarged. This should be adequate for the air requirement of the Diesel-Engine. The maximum boost pressure depends on the swept volume. It is 2,94 bar absolute for 5,5 litres. Finally it is not allowed to operate the engine with visible smoke at any time.

Together with the ACO data Standards and the valuable experience gained by the Audi-Team in 6 Le Mans victories, the concept of R10 TDI® was born.

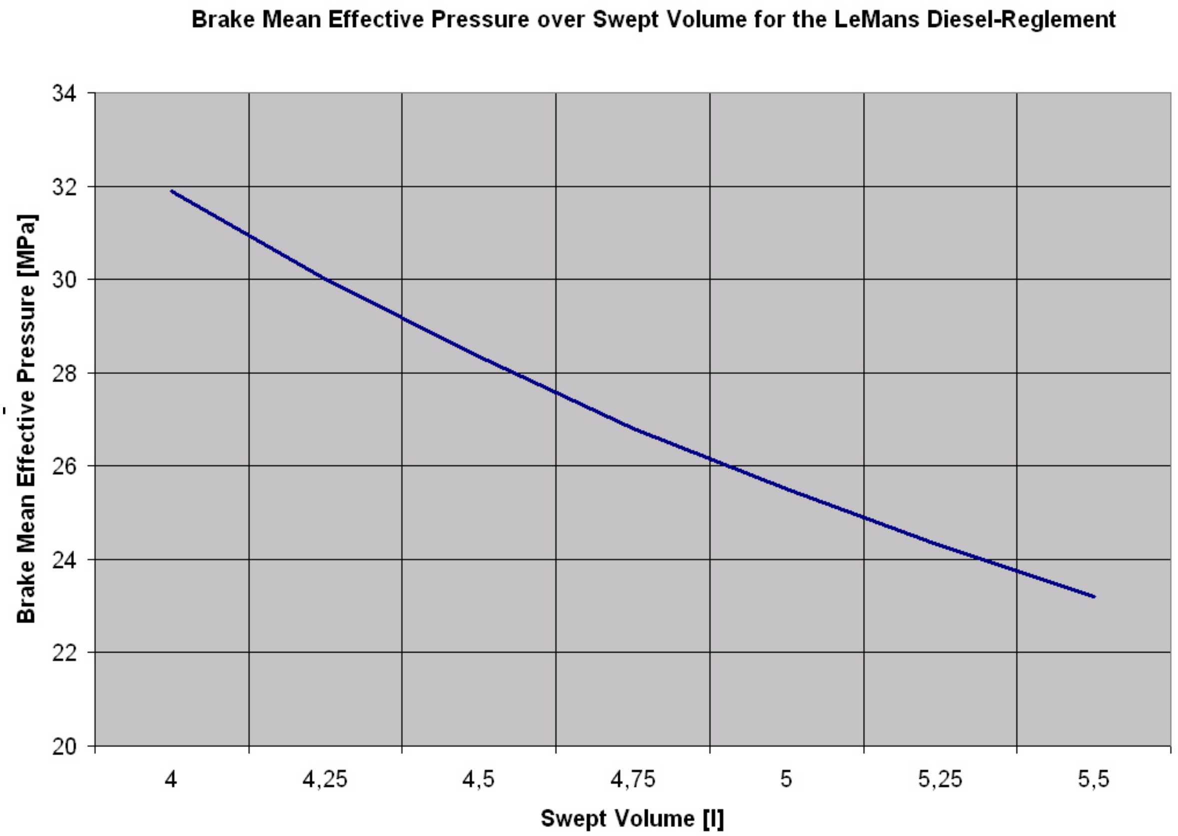


Figure 5: Brake Mean Effective Pressure over Swept Volume @4500 rpm and 478 kW

During initial stages engine concept studies were made, 8, 10- and 12- cylinder layouts were sketched and the main outcome was compared. The following parameters were evaluated:

- Package of engine and car
- Swept volume
- Engine weight
- Centre of gravity
- Engine length
- Piston load
- Vibration behaviour
- Development potential
- Technology transfer to/from production engines

The simulation calculations of the entire car on the Le Mans circuit produced the following results for a winning car concept:

- Power more than 650hp (470 kW)
- Torque more than 1100 Nm over a broad rev range to use a 5 speed gearbox

- Engine weight less than 260 kg
- Similar stiffness of engine and car
- Fully stressed engine (like R8)

The decision to use the chosen engine capacity was based on the actual state of the art of Diesel-Engine technology at the time of the concept study. The maximum power output for Diesel-Engines already produced at that time was significantly less than 100 kW/litre. A 4-litre engine had to achieve a power of more than 120 kW/litre which seemed unrealistic in the very limited development time available. Based on these facts, the decision to go for the largest possible capacity was made. In terms of power output and development the 5, 5 litre engine was potentially the best choice, but the package was much worse than a 4-litre concept.

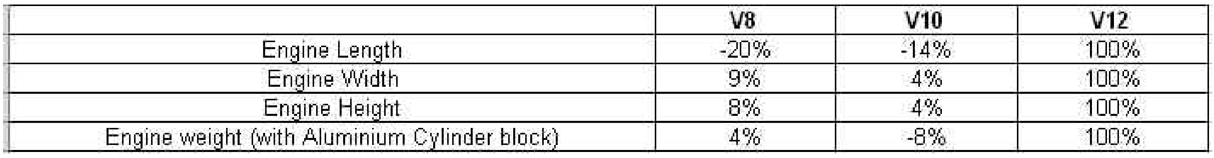
The second step was the selection of the package of the 5, 5 litres in terms of either a V8, V10, or V12 engine layout.

The V12 has disadvantages in terms of length and engine weight, but the V12 engine can be assembled very low in the car and has a smaller width and height.

The engine weight of the 10 cylinder engine is lower than the V12. The V8 engine, on the other hand, has a higher engine weight due to the structural reinforcement requirements. These come from the very high specific combustion forces per cylinder which result from the large bore size.

As a result the development of the V12 concept began.

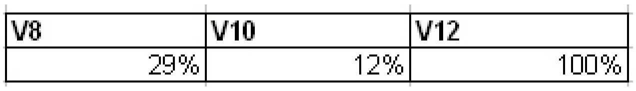
In order to reach the weight and power output targets of 260 kg and 650 hp the engine had to be manufactured completely from aluminium and had to resist more than 200 bar cylinder pressure during a period of more than 24 hours racing.



	V8	V10	V12
Engine Length	-20%	-14%	100%
Engine Width	9%	4%	100%
Engine Height	8%	4%	100%
Engine weight (with Aluminium Cylinder block)	4%	-8%	100%

Figure 6: Dimension difference comparisons of the V8, V10 and V12

Due to the larger bore diameter the piston load was enlarged by nearly 30 % compared to a V12 concept (same Bore /stroke ratio)



V8	V10	V12
29%	12%	100%

Figure 7: Piston Load Difference in Comparison

The Audi R8 with its legendary R8 FSI® engine was always a reference for all simulation calculations of the entire car. Of course there was no experience data available for the engine in a sport prototype car.

The aerodynamic performance and the balance of the car are the most important features and should not be influenced negatively by the engine.

From the concept decision to the first race, the development phase was limited to only 30 months.

3. Development Schedule and Development Method

The V12 TDI® engine did not have a basic engine, neither in the area of production engines nor in race engines.
Consequently all CAD and a calculation database had to be set-up from zero.
Together with the concept phase two other development lines were kicked off:

- Simulation calculation of the engine
- Design of a preliminary test engine

The V8 4 litre production engine of the Audi A8 was mainly modified to achieve the same bore stroke dimensions of V12 concept. Crankshaft, con rods and pistons were designed and manufactured, cam contours were laid out and the hydraulic injection system renewed. The turbocharger and boost control system was already renewed as well. The production of the ECU system EDC 16 was used for this first engine operation. The boost pressure and the restrictor diameter were used to establish first experience data.
The preliminary test engine was tested until the V12 engine was available. After the V12 engine was on the test benches, the V8 remained in use for turbocharger development.

The results of the preliminary test engine clearly confirmed that the defined V12 concept in terms of performance and reliability was good.

Different shapes and positions of the inlet ports were laid out together with the inlet and outlet valves position. These were verified in flow boxes on a “Tippelmann” flow test bench.
Essential knowledge flowed into the design of the V12 cylinder head.

The cylinder head concept was turned into metal in a 1-cylinder engine. This engine, which was used for the development of the R8 FSI® combustion process, was rebuilt with the new Diesel-Engine components.
The parts were produced in a short time with the help of Rapid Prototyping Technology.
The single cylinder engine then took over the core of the development of the combustion process, but some endurance features were also part of the engine’s programme.

Parallel to the single cylinder design, the cylinder head and the entire V12 engine were designed and calculated in a combined process.

At last the new V12 engine was on the test bench for the very first time and the new ECU MS14.1 ran for the first time too.
It was also the first time that all components for the development of the V12 engine had performed together.

The first step was the mechanical development of the engine, afterwards the engine was test-driven in a steady state and then in an environment dynamically similar to conditions on race tracks.
Finally endurance runs under Le Mans racing conditions together with the original gearbox and power shift system were performed.
As a result of this specific test bench work, the roll-out of the car and the following track test could be carried out without problems.

The remaining short period of time prior to the first race in Sebring was filled with several conventional car tests. Some dynamic specifications of the engine were tested and optimised to accommodate the best driver's responses.

Summary of the time frame of the development:

- Start of concept studies in summer 2003
- Project decided in Le Mans 2004
- Pre-development tests with V8 TDI® production engines in 2004 and 2005
- Single cylinder in 2005 for combustion process development
- First start of the V12 engine on a test bench in May 2005
- First R10 race car test in Misano/Italy, November 2005
- Presentation of the R10 race car in Paris, 12th December 2005
- First Race and 1st place at the 12 hour race in Sebring, March 2006
- Race in Le Mans, 1st and 3rd place, June 2006
- ALMS championship and 6 first places in the ALMS series

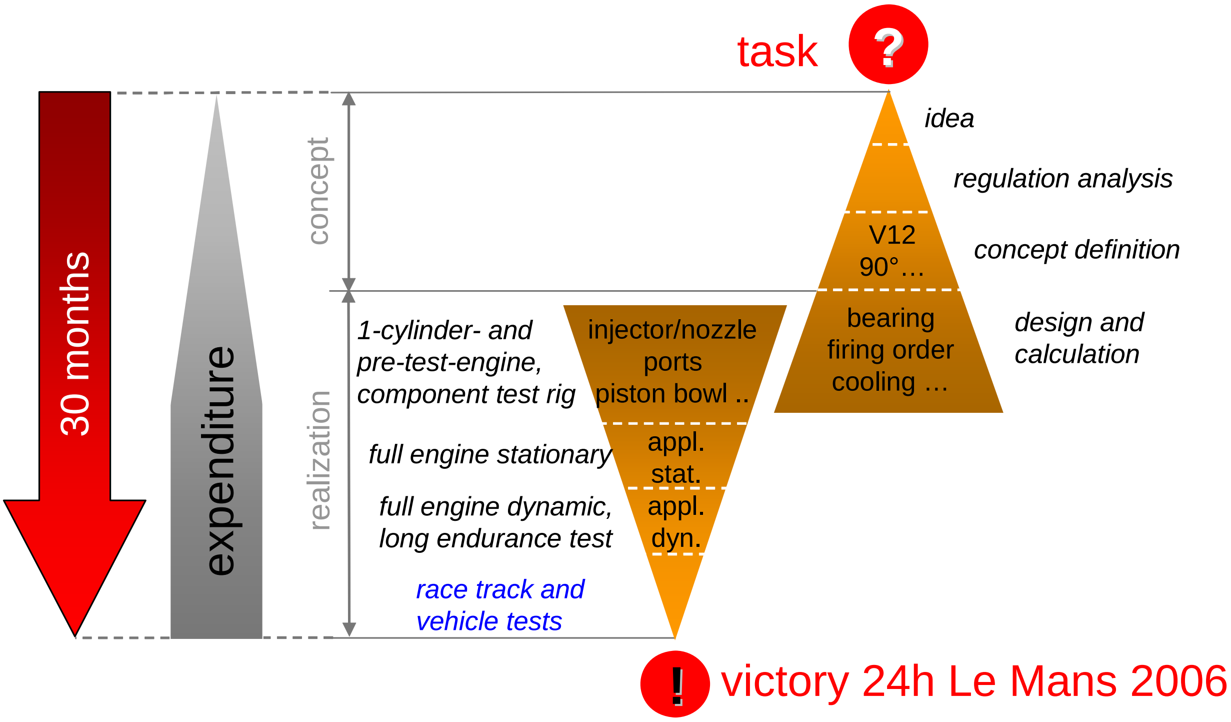


Figure 8: Engine Development Schedule

4. The Engine Concept of the R10 TDI®

The engine was designed with the following main targets:

- Compact dimensions
- High engine stiffness at low weight
- Very high mechanical stress resistance

The following specifications should guarantee the mechanical reliability based on the positive experience gained from the R8 FSI® race engine.

- High level of component integration
- Few external interfaces

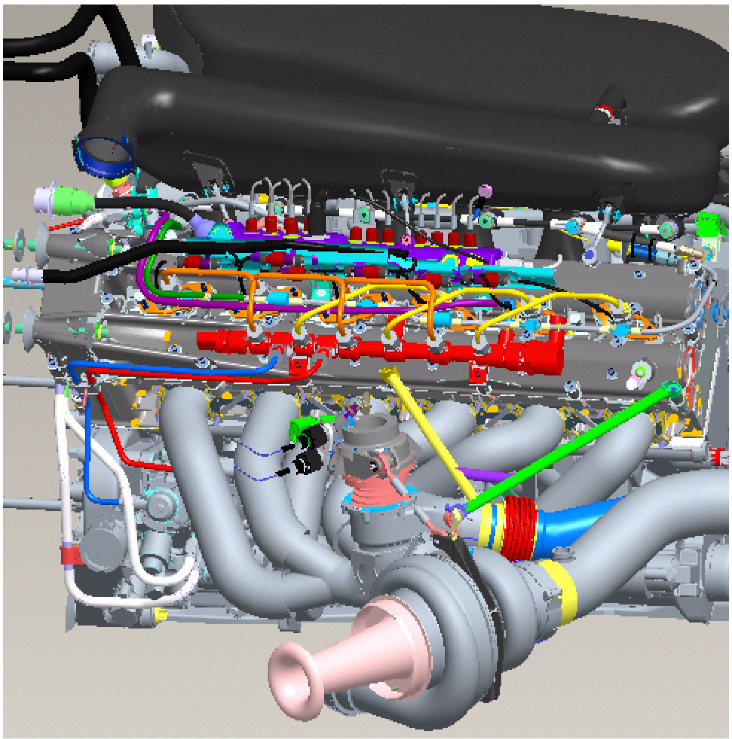


Figure 9: General View of the Engine

A 90° cylinder bank angle was chosen as the best compromise between torsion stiffness, overall engine height and the centre of gravity for this prototype LM sports car. For a race engine the resulting non-even ignition-intervals for a non-split-pin crankshaft do not have an influence.

The vertical position of the crankshaft is mainly influenced by the engine stroke. With about 100 mm between the crankshaft centre and the bottom plate of the car the R10 TDI® engine has a low position in the car and therefore a low centre of gravity can be achieved.
All components of the exhaust and induct were designed in modules to make sure that they could be replaced in the race within a very short time.

4.1 Cylinder block and Bedplate

The cylinder block (closed-deck-concept) is cast in an alloy pressure sand-casting process. The material is an under-eutectic aluminium alloy. The cylinders are coated with Nikasil.

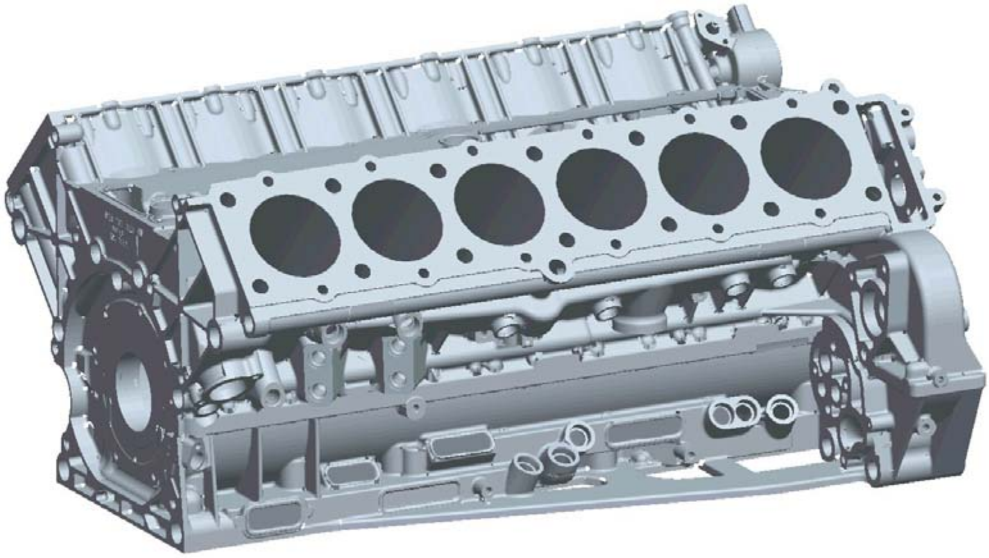


Figure 10: Cylinder Block of the R10 TDI®

Oil channels and pressure valves are integrated in the block for the piston cooling. The cast water ports are connected to the oil-water heat exchanger and only have an interface to the car's radiators and a water swirl-pot. This separates air from water and bleeds the engine and radiators.
The cylinder block is split in the main bearing area. The lower part of the cylinder block is a complex bedplate design. It integrates many functions and can be loaded (positioned) high.
The investment casting rough part has very high yield strength of 35 MPa and a high elongation by using the Sophia casting process. The minimum wall thickness is less than 2 mm.
The bedplate has oil chests on the side. These and additional ribs connect the main bearings to a stiff unit. Together with the cylinder block a very stiff unit is achieved. Engine and monocoque have nearly the same stiffness.
The main bearings are bolted with 2 bolts on each side.
Four bolts of the lower engine fixation to the monocoque are connected to the cam drive timing chest. Further ribs reinforce and connect to the main bearings.

4.2 Crank Drive

Due to the V12 engine characteristics the engine is externally completely free of forces or momentums. The layout of the crankshaft incorporates several aspects:

- Bearing forces resulting from maximum ignition pressure and mass forces
- Torsion and bending stiffness
- Minimum weight

With the help of main bearing calculations together with fluid dynamics in combination with FEA, the crankshaft was laid out in its main dimensions. Diameter and width of the main bearings and crank pins, together with the width of the pin and counterweight resulted from these calculations. High torsion stiffness was necessary for this long highly loaded crank shaft.
The counterweights were optimised in terms of the loads and the rev range.
A torsion damper was not necessary with this layout.
On the rear side of the crankshaft a lightweight steel flywheel submits the torque on the clutch.

An integrated flywheel increment supplies impulses for the rev sensor of the Bosch ECU. Another increment wheel is positioned in front of the cam-drive gear on the crankshaft and therefore the rev sensor is redundant.
The con rod is separated under an angle in the large bore. It has an H-profile and is optimised with the help of FEA with regard to strength, reliability and weight.

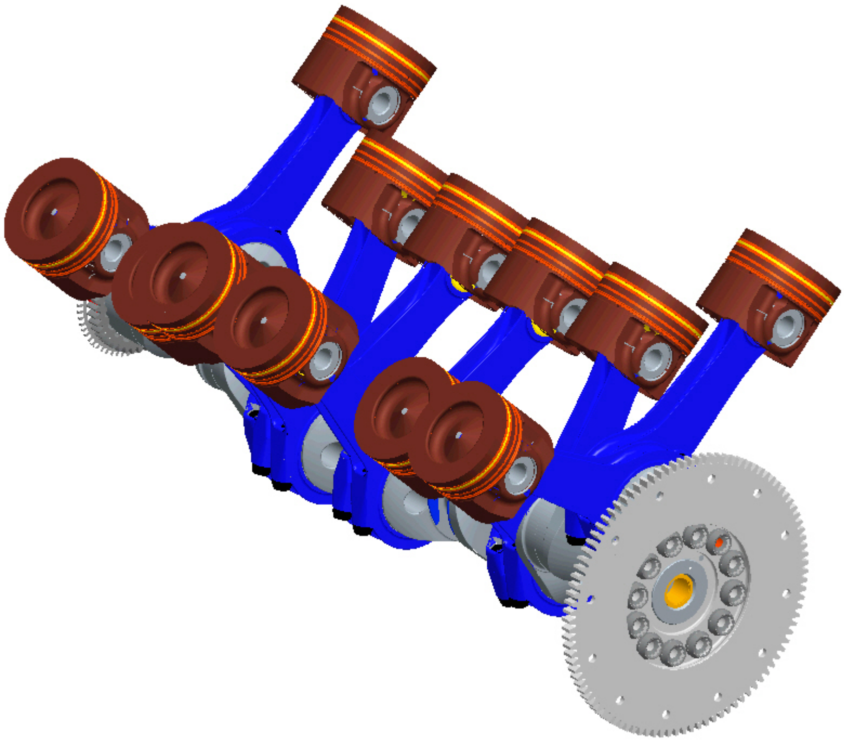


Figure 11: Crankshaft with pistons and con rods

The pistons with integrated oil chamber were specially developed for the R10 TDI®. The combustion bowl shape resulted from the single cylinder development and is special for this engine. The very high load on the piston combined with the heat which is generated made it necessary to use 2 oil jets per cylinder. One is used for the oil cooling channel and one is directed on lower bowl face.

4.3 Cam Drive and Drive of Ancillaries

The position of a cam drive gear train on the front side of the engine provides an advantage in terms of overall stiffness of both the engine and race car. In main aspects of this concept was transferred from the R8 FSI® engine.
Beside the camshafts, both the oil and water pumps are gear-driven. The steel gears are equipped with needle bearings. These run on axes which are held in the cylinder block and cylinder head.
One of the axes of each bank takes over the function of balancing the tolerances between the cylinder head, the block and the gasket thickness.

4.4 Oil and water pumps

As a part of the dry-sump oil drainage system, the suction position with cutter plates is situated on the right side of the engine’s bedplate. The oil and water pumps are located on both sides of the engine, whereas the gear-type oil pressure pump is on the left side. The oil-filter is positioned upright in the V. All scavenge pumps for cylinder block, head and turbocharger are positioned on the right side of the engine. The high pressure fuel pumps, Bosch CP4, are positioned above the right/left oil pumps. Their gears are part of the whole cam drive.

A separate gear train, as a part of the oil pump drive, provides the water pump shafts and can be positioned close to the cylinder block which makes it possible to vary the revs of the water pump impeller.

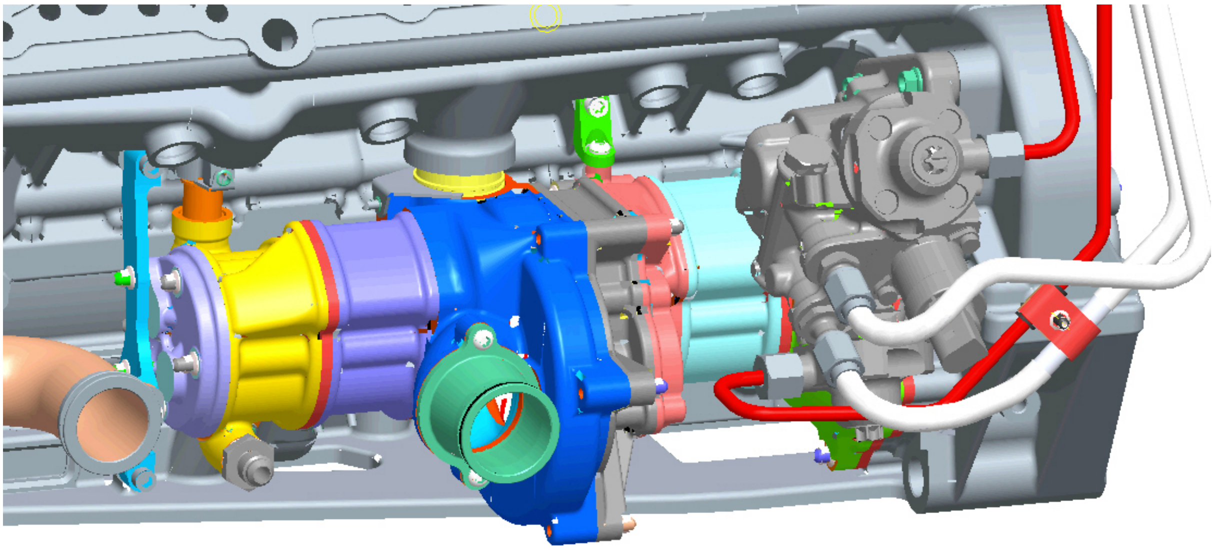


Figure 12: Right hand side of the engine with Oil and Water Pump

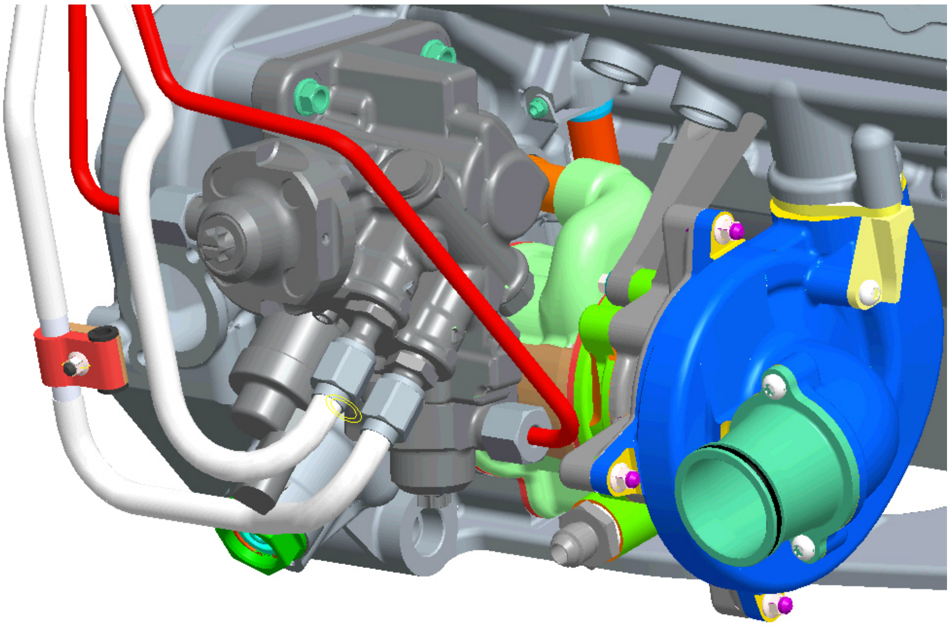


Figure13: Left hand side of the engine with high pressure fuel pump, oil pressure pump and water pump.

4.5 Alternator and starter motor

The alternator is placed on the front side of the engine in the V directly behind the oil tank. The alternator drive pulley is fixed on an alternator gear which is part of the cam drive. The alternator is driven by a short Poly-V belt. The belt eliminates the vibrations from the crankshaft. The starter motor is placed on the left side, its position is very low and it can be interchanged easily.

4.6 Cylinder head

The cylinder head is cast in a low-pressure sand process in an Aluminium alloy. The injector chest with the in-line Piezo high-pressure injector from Bosch is positioned in the centre of the cylinder. The whole structure of the head was designed to achieve a very high stiffness from the fire face to the top end of the head. A very good cooling through the water jacket was also necessary.

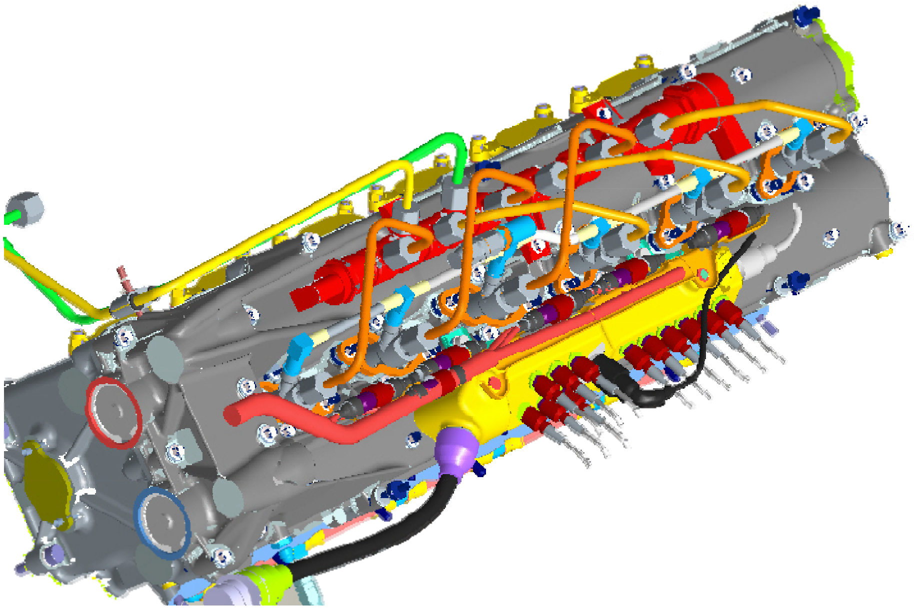


Figure 14: General Arrangement of the Cylinder Head R10 TDI®

Two inlet and outlet valves are parallel to the cylinder axis. The valve seats are made from special sintered material. The valve guides are made from copper Beryllium alloy. The sodium filled steel valves are part of the valve train with springs and roller cam followers.
The cam shafts are made from steel. For weight reasons they are bored hollow.
The cam cove with the integrated engine fixations are made from solid aluminium bar for reasons of high tensile stress resistance. The cam bearings are integrated in the cover and are connected by ribs so that a very stiff structure is created. Using this method, high forces from the car can be conducted.
A loom chest is mounted on the cam cover. This has the function of connecting the car loom to the engine sensors. The injectors are connected to the ECU with a separate loom (figure 14).

4.7 Hydraulic system

The hydraulic combustion system of the R10 TDI® was developed in collaboration with Bosch.

The components basically come from the Bosch product programme, but they were further developed for race application in many essential points. High pressure fuel pumps CP4 are driven with a gear ratio of 0,75 relative to the crank speed. The pump capacity was adapted to the fuel demand in the used engine rev range and very lightweight fuel rails were designed for this engine. The Piezo injectors are specified to the cylinder head and modified in several items. The injector nozzles were laid out for the fuel rate and defined by the number of holes and size. Also the position and direction of the holes had to be taken into consideration. The projection of the injector finally defined the combustion parameters.

The fuel lines of the low and the high pressure hydraulic system were adapted to the engine bay. Interfaces to the car's fuel system are made by quick-release couplings. The car's fuel system, with its race-type tank pumps and catch-tank system, was newly designed for the R10 TDI®.

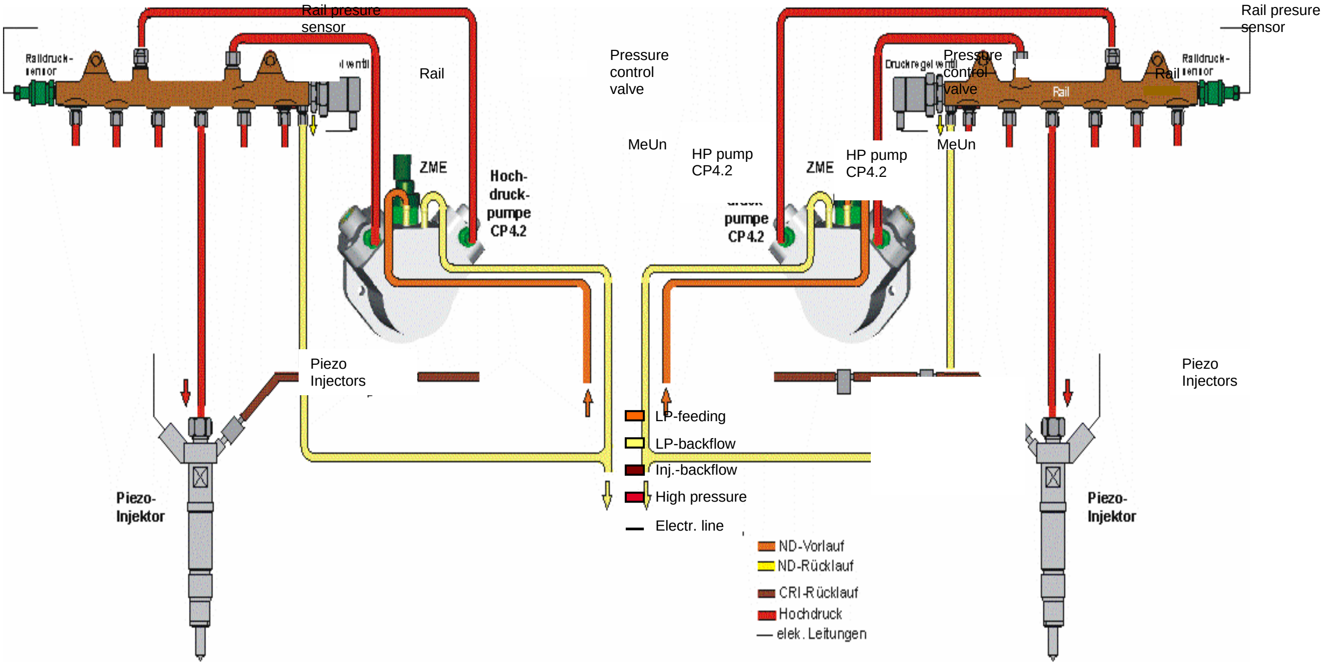


Figure 15: Hydraulic System [7]

5. Engine in Car

The development of a Diesel-Engine as a pure race engine is already a very demanding challenge. Additionally the engine must fit in the very tight space of the car package of a Le Mans prototype.

Similar to the Le Mans sport-prototype R8, engine and car were designed as a harmonic unit.

To achieve optimum chassis performance, the stressed components of the car have to have the same stiffness.

The fully stressed engine is bolted rigidly between the rear face of the monocoque and the gearbox.

The package of a turbo-charged engine is much more complex than that of a naturally aspirated engine, due to the air ducts.

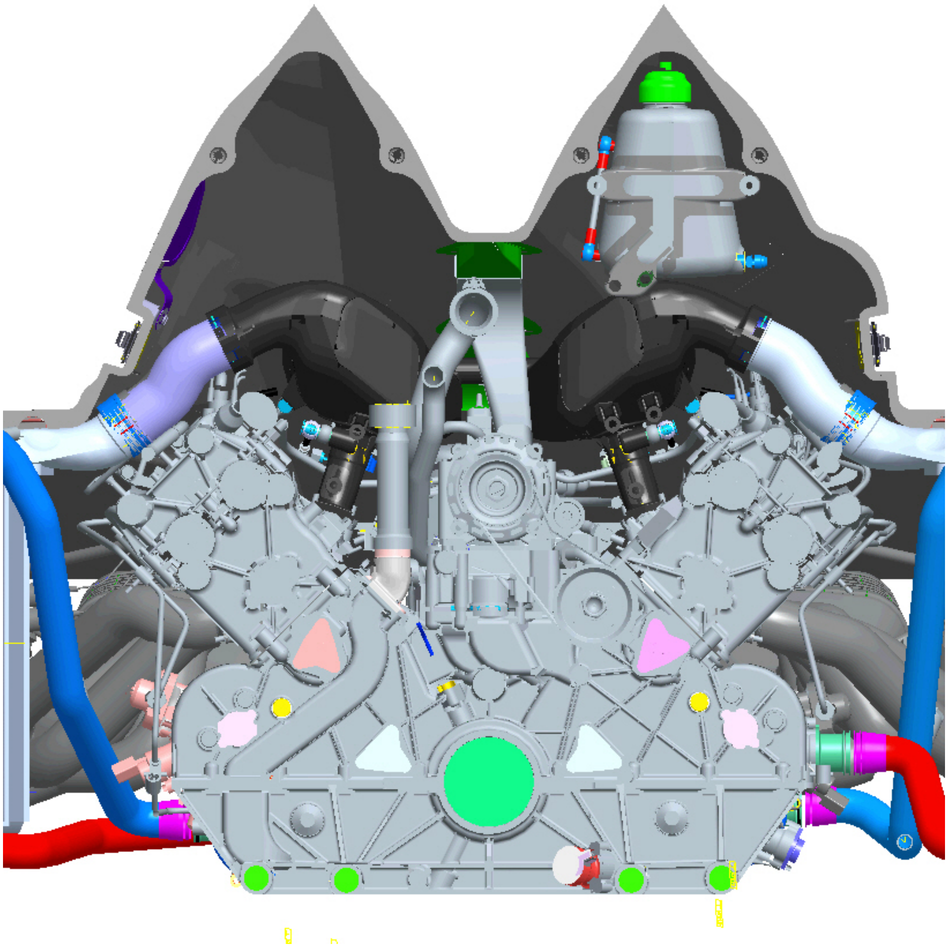


Figure 16: Cross-section through engine bay

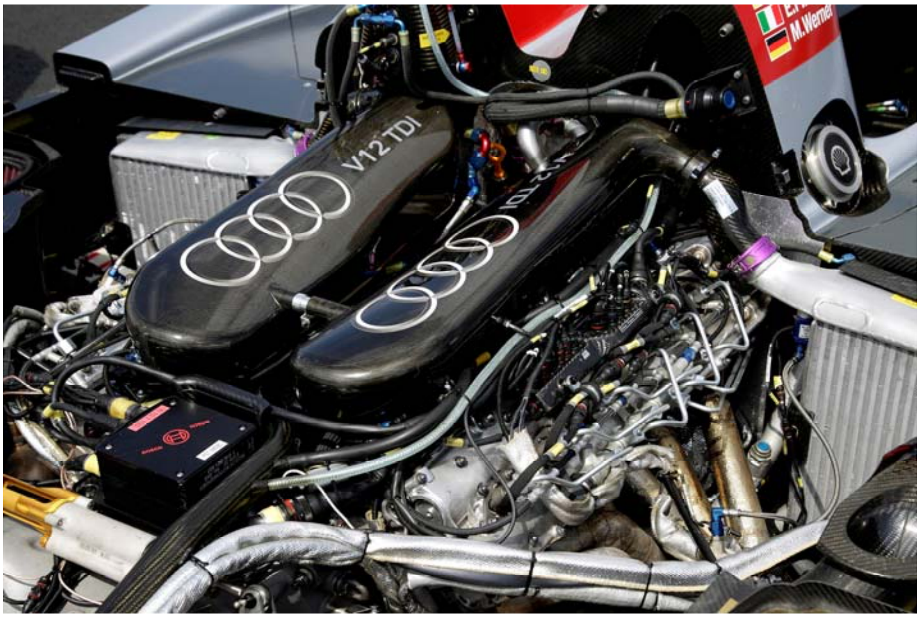


Figure 17: R10 TDI® in the race car

The radiator concept of the R8 was basically transferred to the R10 TDI® but modified to accommodate the special demands of a Diesel engine. The charge air intercoolers and water radiators are positioned on either side of the monocoque near the engine, so only small pressure losses result in the tubes.

The cooling concept of the car was optimised in wind-tunnel tests. The cooling system is so efficient that both oil and water temperatures are considered acceptable even under extensive racing conditions.

The fresh-air induction system is also similar to that found in the R8. The outstanding air scoops “Schnorchels” with integrated air filters provide the restrictors with a very good and wide air flow. The use of the dynamic pressure at high speed brings a slightly higher air flow through the restrictor. In the compressor the air is compressed to 2.94 bar (abs.) and enters the intercoolers with more than 200°C. Cooled down the air enters the plenum by a short carbon connection pipe.

The plenum and air distribution parts are made from carbon fibre material for weight reasons.

5.1 Turbocharger, Waste gate, Particulate Filter

The turbocharger was developed with Garrett only for this engine and the centre housing is made from Titanium.

The compressor has a new layout; both compressor wheel and wheel ration are adapted for the R10 TDI® flow and pressure rates. The turbine was adapted to the compressor demands and especially the dynamic behaviour and counter pressure was focused upon during the development.

The turbocharger is fed with oil and is suctioned by a pump.

All elements are fixed by quick-release couplers and clamps so that the components can be changed quickly.

The regulation of the turbocharger is carried out by the waste-gate control system, which controls the valve position by pneumatic/electronic devices.

The turbocharger rev is controlled.

Behind the waste-gate and turbine outlet the exhaust pipes are united in a Y-junction and the particulate filter is positioned behind this at the end of the car.

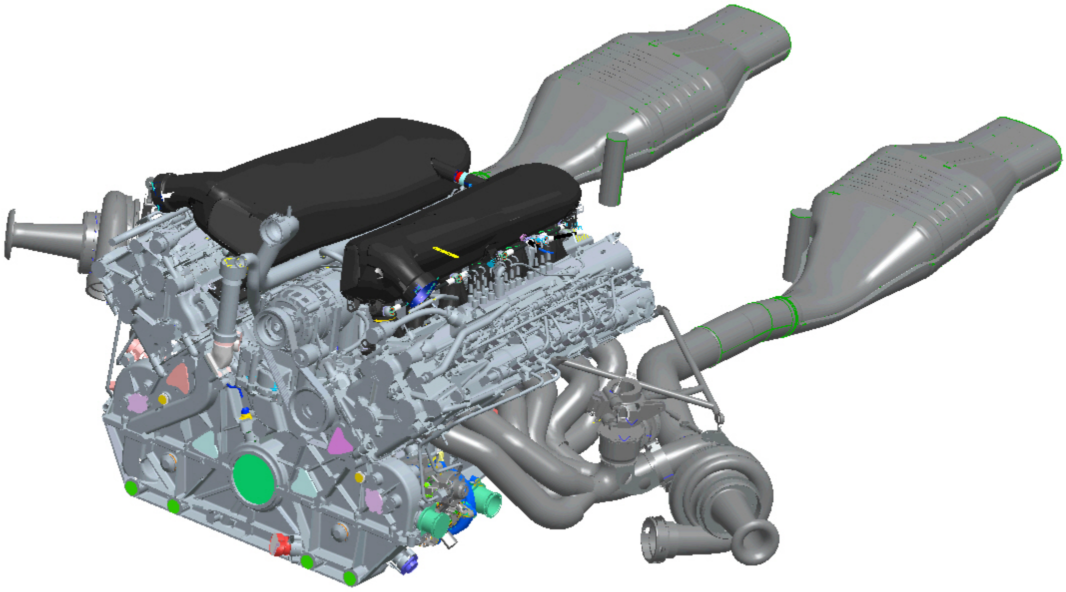


Figure 18: Virtual Mock-up of the R10 TDI®

5.3. Oil Tank System

Contrary to the R8, the oil tank is positioned in front of the engine in a recess of the monocoque. Its volume is only 10 litres. Near the top, the tank is combined with an oil-swirl-system which reliably separates oil from blow-by-air so that the pressure pump can suck only the oil with little or no air content. A driven centrifuge is not necessary.

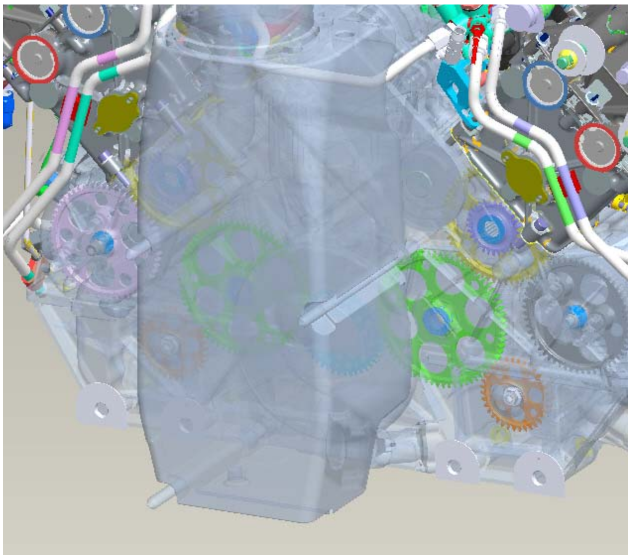


Figure 19: Front view with oil tank

5.4 Engine ECU

The engine ECU MS 14 was developed with Bosch for the R10 TDI®.

- ➔ Dual processor technology
- ➔ 70 universal analogue-inputs
- ➔ 4 wheelspeed inputs for traction control
- ➔ 2 Rev. inputs for turbocharger
- ➔ 2 linear Lambda inputs
- ➔ 2 FireWire interfaces for high speed data logging
- ➔ 5 CAN communication busses
- ➔ 12 Injection power stages for piezo injectors
- ➔ 4 H-bridges and 20 PWM outputs
- ➔ Dust and waterproof magnesium housing with military connectors

Figure 20: ECU MS 14 [7]

6. Engine Development

The extensive computer simulations on the combustion process and the charge cycle had shown the expected conflicts of aims concerning the development of the V12 TDI®-Engine. For the configuration of the race engine it was necessary to find out the best compromise between the following fields of activity:

- High effective power output and ideal torque characteristics in a wide usable rev range.
- Low fuel consumption and smoke degree/numbers (SN) in operating fields with low excess air (limited air flow at full load through restrictor–handicap).
- Design of the radiators for water, oil and turbocharged air under taking the higher heat output of the V12 TDI®-Engine into consideration. Sufficient cooling air for the radiators and the engine compartment without deteriorating the air drag coefficient of the car.
- Special attention to the engine friction losses.
- Secure control of the component stress limits imposed by temperature, cylinder pressure and torque.
- Minimizing the charge cycle losses by the diesel particulate filter (DPF).

These tasks lead to an early start of the test bench investigations. Parallel to the design and computer simulations of the R10 V12 engine, a production Diesel-Engine (Audi V8 4.0 TDI®) was used to build up a V8 derivate with 3.67 litres as a preliminary test engine (PT-Engine). This engine ran as 2/3-model of the R10 race engine (Figure 8). This way, particularly in the development areas of the combustion process and the mechanical tests on the piston unit, it was possible to define important expertises to integrate them very early in the V12 design. Also the PT-Engine provided helpful information about the calibration of the turbocharging and dimensioning of the intercoolers.

Additionally the preliminary R10 test bench development was assisted by investigations on a single-cylinder engine with the main requirement to vary the thermodynamics and Common-Rail-Injection parameters. Due to the fact that there were no experienced values for the development of a Le Mans Diesel race engine until this time, the single cylinder test station also supplied essential support on the mechanical side for continuative calculations and design aspects for the complete engine.

6.1 Thermodynamics

There are a huge number of influencing variables on combustion which form a large matrix of versions. The following list includes the most important parameters which particularly had to be considered and optimized during the development work.

- Inlet and outlet port with swirl and flow rate
- CR-Injector/nozzle
- Injection spray geometry (number of holes, hole geometry, angle, projection)
- Rail pressure
- ECU data for the CR-System
- Compression
- Piston bowl geometry

- Piston cooling
- Restrictor position, turbine and compressor (TC) incoming flow
- Turbocharger choice
- Turbocharged airline and intercooler

The influence of increasing the rail pressure is shown exemplary as one of these development areas. Currently the maximum rail pressure for production cars with CR-Technique is 1600 bar. Through modifications on the CR-System it was permitted to increase the maximum rail pressure up to 2000 bar, which led to a distinct gain in power output (figure 21).

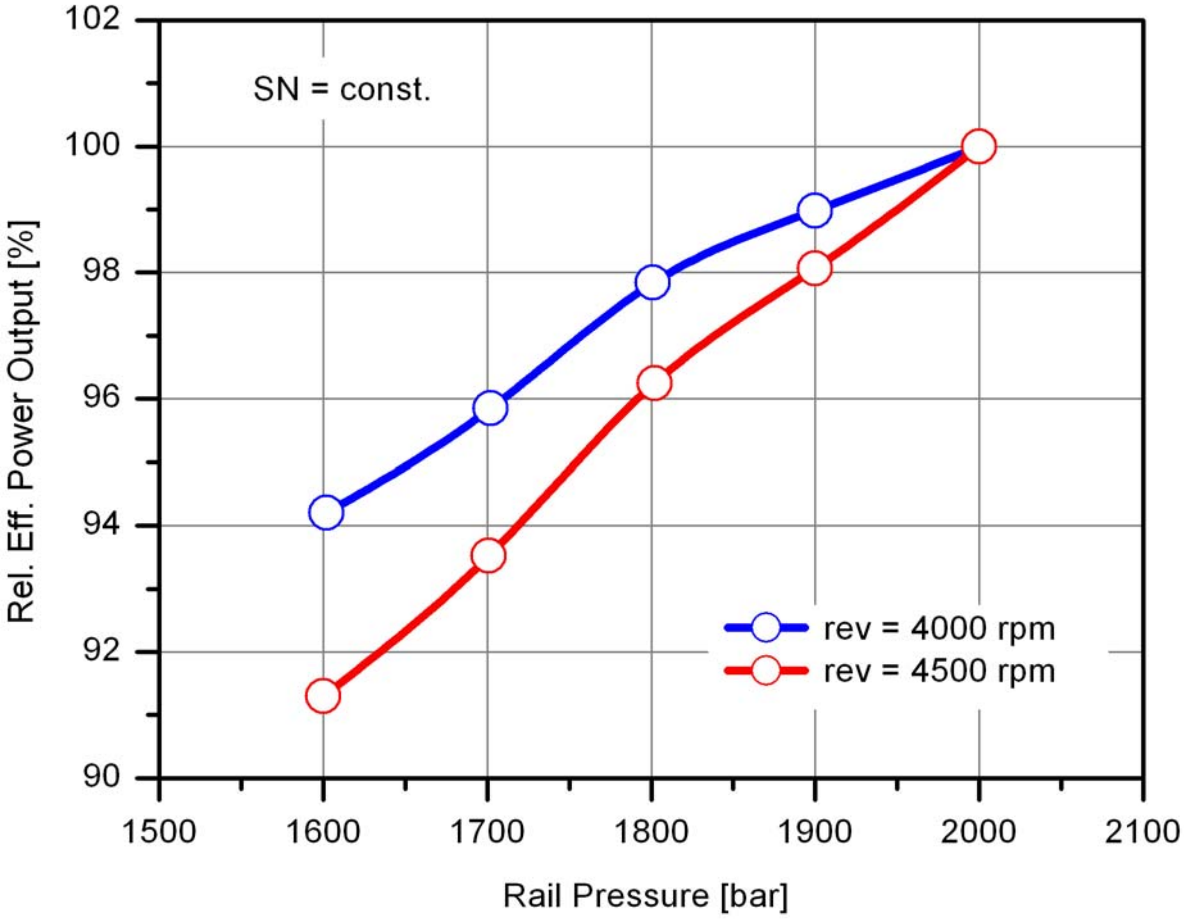


Figure 21: Influence of rail pressure on the power output

The illustration with two characteristic revs (below and inside the restrictor working range) indicates a power output advantage for the R10 TDI®-Combustion of up to 9% by the rail pressure increment. Due to a better fuel spray and fuel mixture preparation, it was possible to gain this improvement with constant smoke numbers and without a significant deterioration of the fuel consumption.

At the same time, the curves show that the benefit of increasing the rail pressure with higher pressures flattens, because of a decreasing air/fuel ratio. For this reason it is necessary to find a compromise between the durability of the whole injection system (injector, rails, high pressure pump, etc.) and the possibility of achieving perhaps an even better performance under racing conditions.

6.2 Power Output Development

The PT-Engine already provided in early stages the power output potential of the R10 race engine. A comparison of the specific power output of the V8 TDI®-PT-Engine and the R10 race engine displays a clear correlation (figure 22). Both engines, PT-Engine and R10 race engine, deliver nearly the same specific power output and smoke emissions.

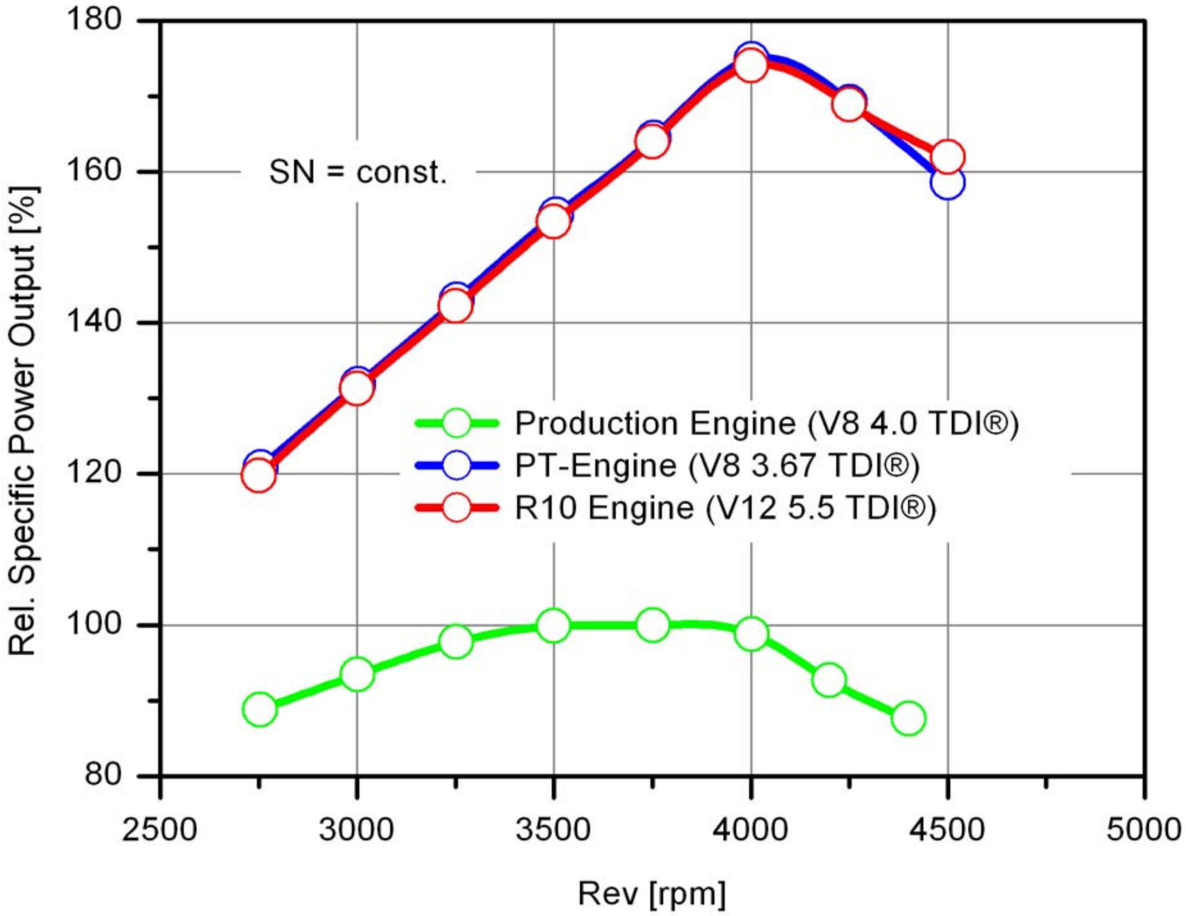


Figure 22: Comparison of specific power output between the preliminary test engine and the R10 race engine

Starting with a production Diesel engine with a maximum power output in the rev range between 3500 and 3750 rpm, it was possible to increase the specific power output on the PT-Engine and the R10 race engine by about more than 70% in spite of the restrictor disadvantage.

Thereby, the emphasis was to ensure not only no visible smoke at the end of the exhaust behind the DPF (according to the ACO-Regulations), but also that the engine itself delivers a smoke-free combustion. As a benchmark the smoke number limits of the production engines were used to support the exchange of experience between Motorsport and serial development.

The developed combustion process from the singe cylinder station was fully integrated into both the PT-Engine and the R10 race engine.

The performance characteristic of the R10 shows moderate operating speeds up to 4500 rpm. For naturally-aspirated race engines an increase in engine speed would be the usual way to increase power output. For competitions with regulations specifying restrictors, this is the wrong way. The limitation of the combustion air flow at higher revs (restrictor working range) causes a drop in power. The increase of friction losses and decrease in efficiency result only in a worse fuel consumption.

6.3 Fuel Consumption

To be competitive at the 24 hours Le Mans Race, a power output development at the cost of a worse fuel consumption is not appropriate. The fuel consumption plays a major role in the Le Mans race, because the number of laps a race car can do in one stint (race period between two pit stops with refuelling) define the number of fuel pit stops necessary through the entire race.

To demonstrate the typical advantage in fuel consumption of a Diesel engine under racing conditions, it is essential to compare its behaviour with other outstanding long-distance race engines. The winning Audi R8 engines in the years 2000-2005 (as MPI-Engine in 2000, afterwards as FSI®, 2003 used in a modified version for Bentley) therefore represent a very good basis for this comparison.

For a better comparability of the Audi R8 MPI, R8 FSI® and R10 TDI® engines the relative specific fuel consumption is plotted against a normalised speed range (Figure 23). Indeed, for all three engines the used speed range is different, but the gap between minimum and maximum engine rev is nearly the same. For this reason a relative presentation of the speed range is chosen.

The MPI as well as the FSI® race engine both show their minimum fuel consumption in the rev area of the rated power output. The fuel consumption of the Audi MPI engine rises in the lower and higher rev ranges, while for the FSI®-Engine the fuel consumption stays constant over a wide rev range. Only when the FSI® engine is used in higher rev ranges of the restrictor working area, a loss of efficiency is noticeable. As a result, changing from a MPI to a FSI® combustion process already led to a reduction in fuel consumption of 3-4% under steady-state operating conditions. Under transient operating conditions the improvement of the lap fuel consumption is even 8-10% [1].

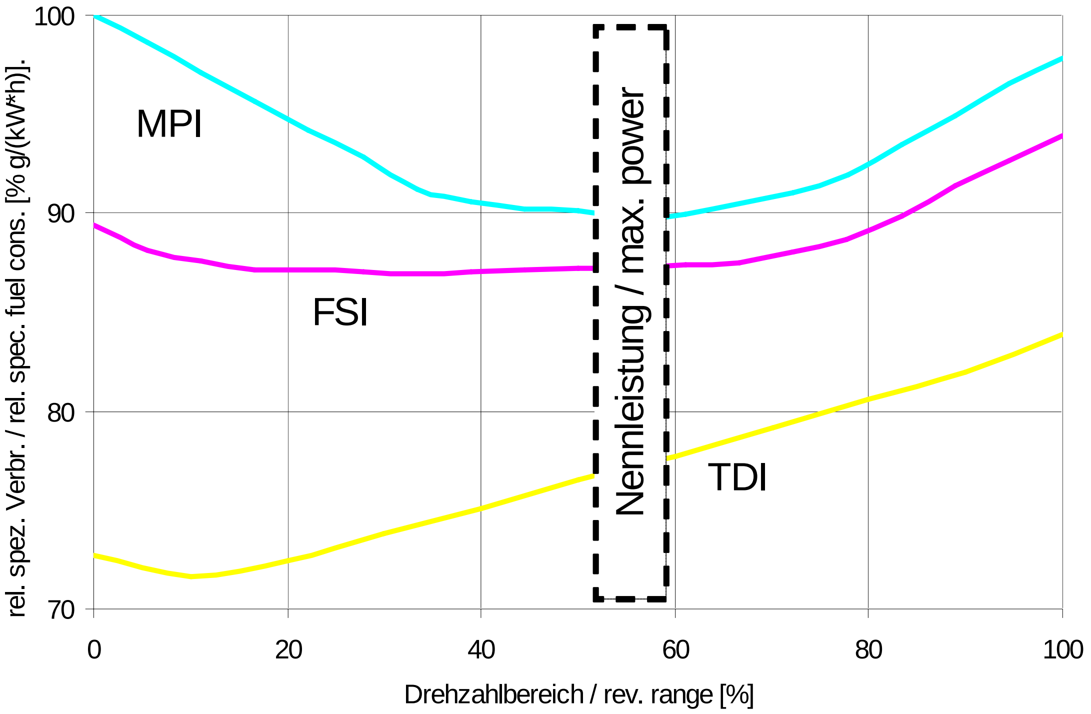


Figure 23: Audi Le Mans race engines with restrictor and boost-control

Under full load, the TDI® race engine has, in principle, its minimum fuel consumption in the lower rev range, this increases with increasing revs. In the relevant rev range during the race, the advantage of efficiency compared to the FSI®-Engine improves by another 10%. This ensures 1-2 more laps in a stint with a 90 litre fuel tank capacity.

Another positive effect for the environment arises is the overall relative low engine speed level in combination with high a degree of turbocharging and an exhaust-gas line with TC and DPF. A very low noise level and an acceptable frequency spectrum are also major steps towards an earplug-free race amusement for the spectators.

6.4 Exhaust Gas Aftertreatment

Compliance with current emission regulations is the primary development target in the field of combustion engine research today. This is true, and without exception, for all commercial road vehicles, but less so for race cars. However, Audi has used exhaust-gas control systems in motorsport since 1990. It goes without saying that this fact also contributed to the decision, derived from the Audi brand’s innovative claim, to equip the R10 TDI with fully functioning particulate filter technology. The following basic requirements had to be fulfilled for this purpose:

- closed system
- regeneration without using additives
- low back pressure level
- low weight
- compact
- excellent durability

Analysis of conventional filter materials available on the market showed that Dow's advanced ceramic material (ACM) met the previously mentioned requirements in a very specific way. The unique open microstructure of ACM provides low weight and a significant advantage in back-pressure compared to other materials (figure 24 [8]). Also of note, is the low sensitivity of the back-pressure level to the amount of catalyst washcoat applied to the honeycomb. The sum of the features mentioned, irrespective of the high gas-flow, enables a back pressure level of less than 200 mbar to be achieved with a filter size of 9" width, 4" height and 5" length.

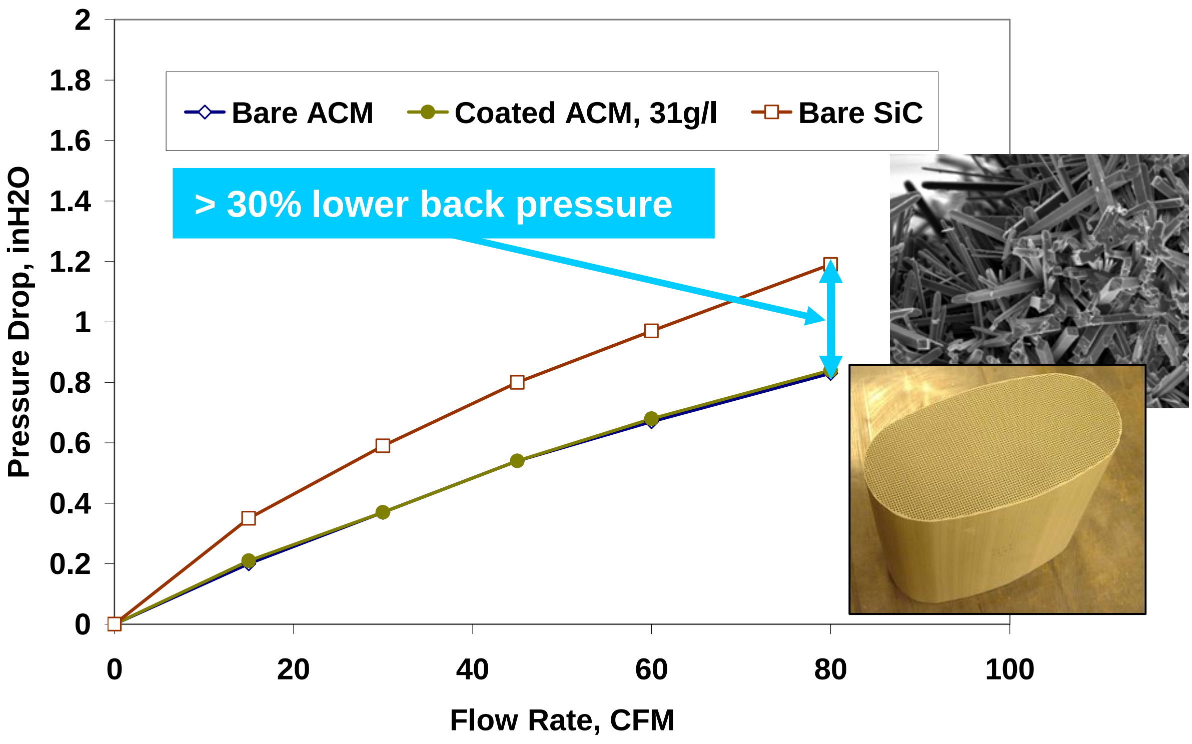


Figure 24: Pressure drop performance of Dow DPF

The behaviour of the DPF in a race car is entirely different to that in a commercial road vehicle. Basically, the sequence between loading and regeneration cycles also takes place, but at a significantly reduced scale. During the period of full-load, which usually lies between 50 and 75% subject to a race track's characteristics, soot is deposited in the DPF at high exhaust-gas temperature due to lack of oxygen, which is then burnt off during the braking phase owing to the excess of oxygen. In spite of the comparatively low gas temperature during braking, the combustion occurs as a result of the heat energy stored in the honeycomb. The temperature level increases in relation to the full-load percentage. Figure 25 shows the exhaust-gas temperature behaviour during the Le Mans race. The regeneration process also works reliably on race tracks with lower full-load percentages. Catalyst coating supports the regeneration performance.

In this manner, AUDI even succeeded in making a valuable contribution to environmental protection in motor racing by using fully functioning particulate filter technology, and without being forced to accept a loss of competitiveness. For this reason, the R10 is released from discussions concerning particulate matter, and there is no threat of prohibiting driving demonstrations in highly contaminated urban areas. This can be demonstrated very easily: The exhaust pipe after a 24-hour race is free of soot.

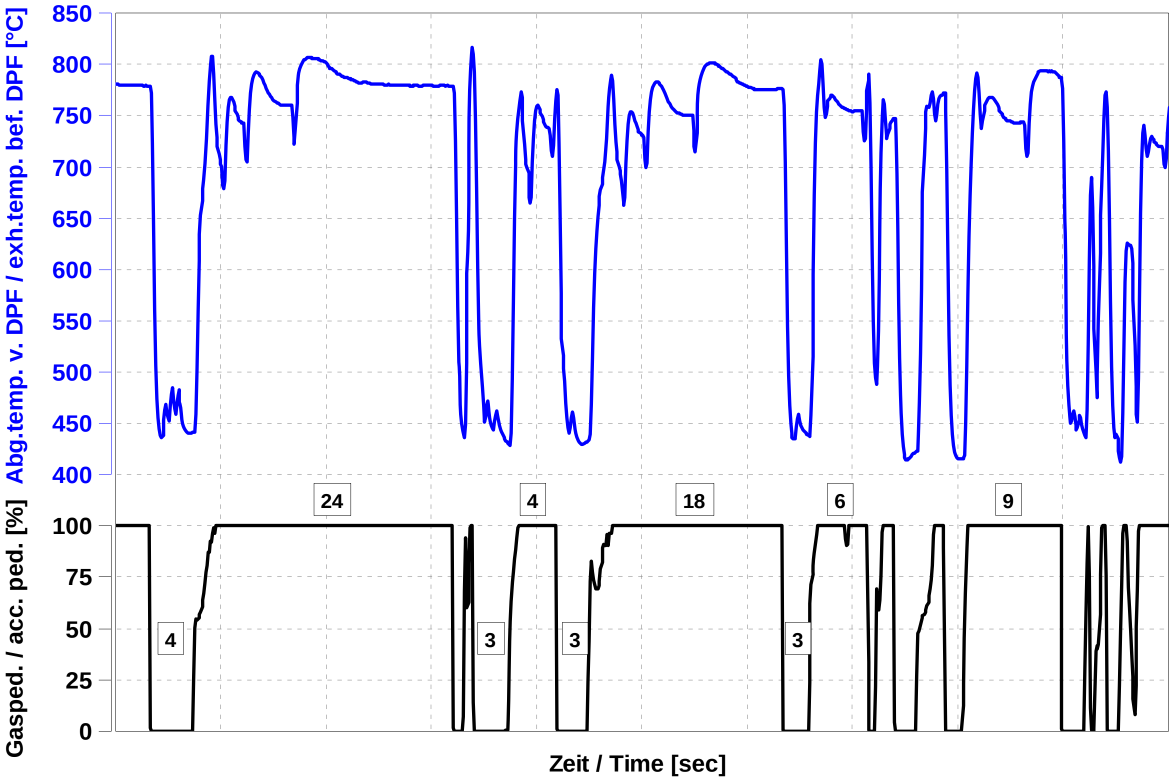


Figure 25: Loading and regeneration cycle (part of Le Mans racetrack)

7. Conclusion and prospects

Figure 26: Finish after 24 h on Sunday 18th of June 2006 at 17.00h

The first victory of a Diesel-powered race car at Le Mans and in the American Le Mans Series, AUDI has written history in Motor sport.

The company has continued its long tradition with innovation in motor racing. Furthermore AUDI succeeded in cooperation with the A.C.O and Shell to use GTL on a mayor scale as race fuel. This is a huge step towards the acceptance of Bio Fuels in their second generation and to regenerative and CO2 neutral fuels. Combined with a state-of-the-art cleaning technology AUDI could once again cross the boundary between fascinating technology in racing and environmental-friendly and promising technology for the cars of tomorrow.

It was not and is not AUDI’s target just to make PR-events at Le Mans.AUDI’s target is to push the development in Diesel technology by finding new solutions for our next generation of engines and for our customers, and to secure our long-term mobility.

Our drivers today are already testing for you the technology of tomorrow.

Figure 27: the winner

According to the slogan of AUDI

Vorsprung durch Technik

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