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Realizing Future Trends in Diesel Engine Development

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ABSTRACT

Volkswagen is the first automobile manufacturer to supply a passenger car with a direct fuel injection diesel engine to the US market, starting 1996. To meet the stringent US exhaust gas legislation the very successful European 1.9 liter TDI engine has been further developed for the 1996 and 1997 Passat. This TDI incorporates a number of innovations in advanced diesel technology. Emissions-reducing innovations include:

- reduced crevice volume
- higher injection pressures
- upgraded injection management
- integrated EGR manifold system
- EGR cooling
- diesel catalytic converter

This TDI engine configuration is also to be offered in the 1997 Golf and Jetta class and the new Passat in model year 1998. Over the coming years the TDI engine concept will be further optimized by utilizing variations of the above innovations.

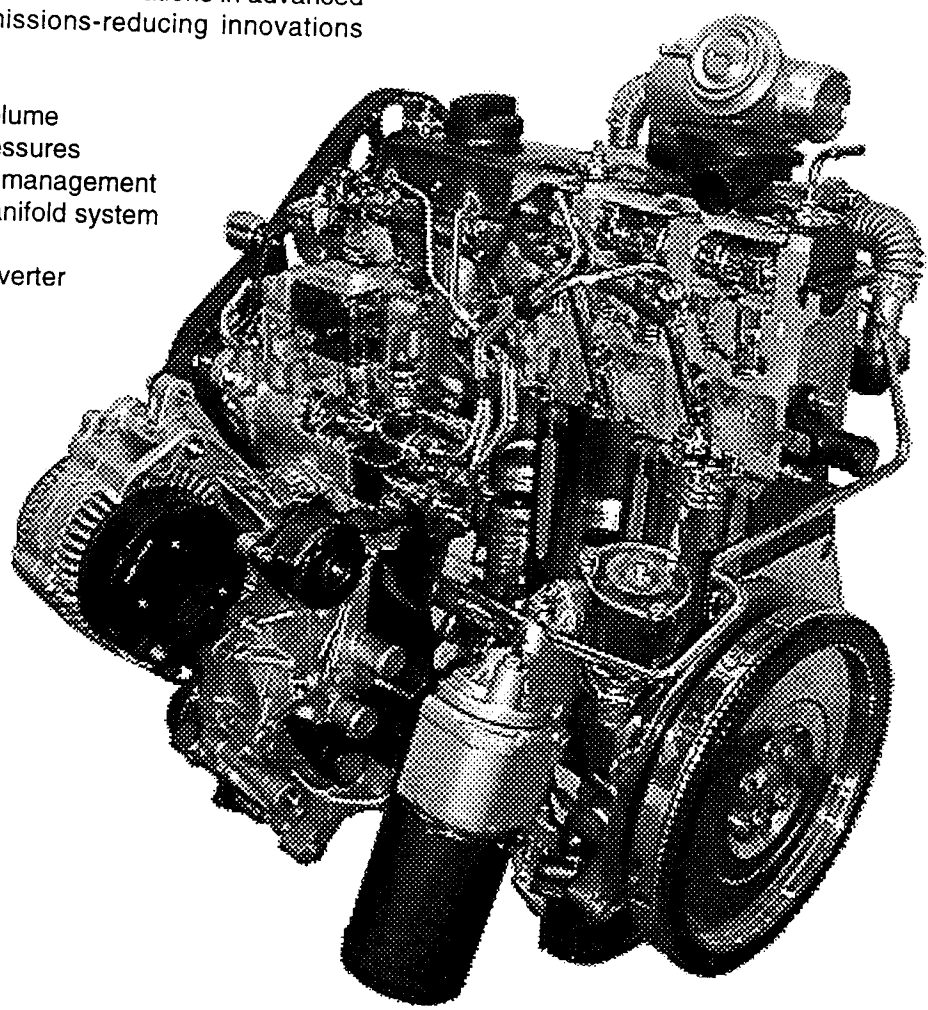


Fig. 1: 1.9l TDI - Diesel Engine

INTRODUCTION

The TDI engines of the Volkswagen Group have been setting standards for passenger car diesel engines since 1989. Today the abbreviation "TDI" (Turbo-Diesel-Direct-Injection) stands not only for a combination of driving enjoyment and fuel economy, but also for mobility combined with environment-friendliness. (2)

Worldwide more than 1.5 million passenger cars and light trucks with 4 and 5 cylinder TDI engines have been sold. The TDI engine replaces the swirl chamber diesel engines in the VW model lines due to the 15-20% reduction of fuel consumption. Ten years of development were necessary to meet the high standards Volkswagen sets before launching a new product on the market. Through giving special attention to power output, torque, fuel consumption, exhaust composition, noise production and economic feasibility, a commonly known heavy truck combustion concept was optimized for use in a passenger car engine.

BASIC ENGINE DESIGN

In October of 1991 the first 1.9l TDI diesel engine equipped with exhaust turbo charging, scavenging air cooler, exhaust gas recirculation, electronic injection control and oxidation catalytic converter was introduced. (1)

Table 1: Technical Data of the 1.9l TDI Basic Engine

Type:	4-Cycle Diesel
No. of Cylinders:	4 In-Line
Displacement (cc):	1896
Bore / Stroke (mm):	79.5 / 95.5
Compression Ratio:	19.5
Cylinder Distance (mm):	88
Crankshaft Main Bearing Diameter (mm):	54
Crankshaft-end Bearing Diameter (mm):	47.8
Connecting Rod Length (mm):	144
Intake Valve Diameter (mm):	36
Outlet Valve Diameter (mm):	31.5
Induction:	Turbocharged
Turbocharger:	T 15 (Garret)
Combustion System:	Direct Injection
Valve Configuration:	OHC
Injection Pump:	Bosch VE VP 37
Injector Nozzle:	5-Hole-Nozzle
Performance-Data:	
Max Output (kW/rpm):	66/4000
Max Torque (Nm/rpm):	210/1900
Volumetric Eficciency (kW/l):	34.8
Maximum Mean Effective Pressure (bar):	14
Piston Speed at Rated Engine Speed (m/s):	12.7

This engine has been on the market since 1992. A naturally aspirated version with a power output of 47 kW and a power optimized version with 81 kW have followed. (3)

SHORT BLOCK

High maximum pressure values are characteristic of the combustion process in direct injection diesel engines. The engine therefore requires special reinforcements. The crankcase made of gray cast iron was optimized with the help of FEM-Analysis in the area of the bearing. The crankshaft with 5 main bearings and 8 counterweights is forged out of carbon steel. The high strength needed to carry the torque in the flutes of the crank pin, withstanding bending and torsion stress, prompted special measures in the manufacturing process. The familiar technique of roll-compacting the flutes causes deformation which has to be removed by straightening. Unfortunately, the straightening reduces the built-in tension. A 100% gain in reinforcement can only be reached when the roll- straightening method is used incorporating optimized parameters for roll force, roll angle, number of repetitions and size of flute radius. To further minimize the critical torsion amplitudes, a torsion damper is installed on the front end of the crankshaft. (1) The development was supported by intensive FEM (Finite Element Method) calculations (Figure 2).

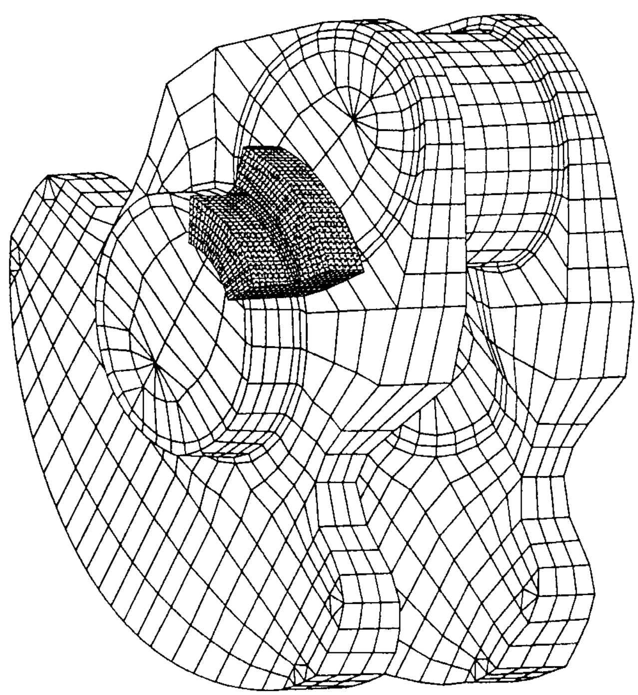


Fig. 2: FEM-Model of a Crankshaft Section

The thermally and mechanically highly-stressed full shaft pistons are made of hardened and tempered aluminum. A piston recess (bowl) forms the combustion chamber (Figure 3).

Critical tensions are found at the bowl edge, in the piston pin boss and in the boss support. With carefully directed rounding of the bowl edge, placement of a bronze bushing in the pin drilling, reinforcement and rounding of the support areas and sprayed oil cooling to the inner bottom, durability was achieved. To minimize wear, the first piston ring is installed in an embedded Niresist carrier.

While the first engines were delivered with soft material cylinder head gaskets, later ones received multi-layered steel gaskets which are very resistant to thermal shocks.(Figure 4).

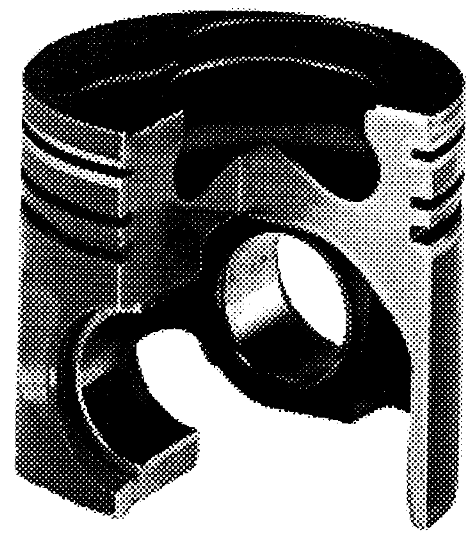


Fig. 3: Piston

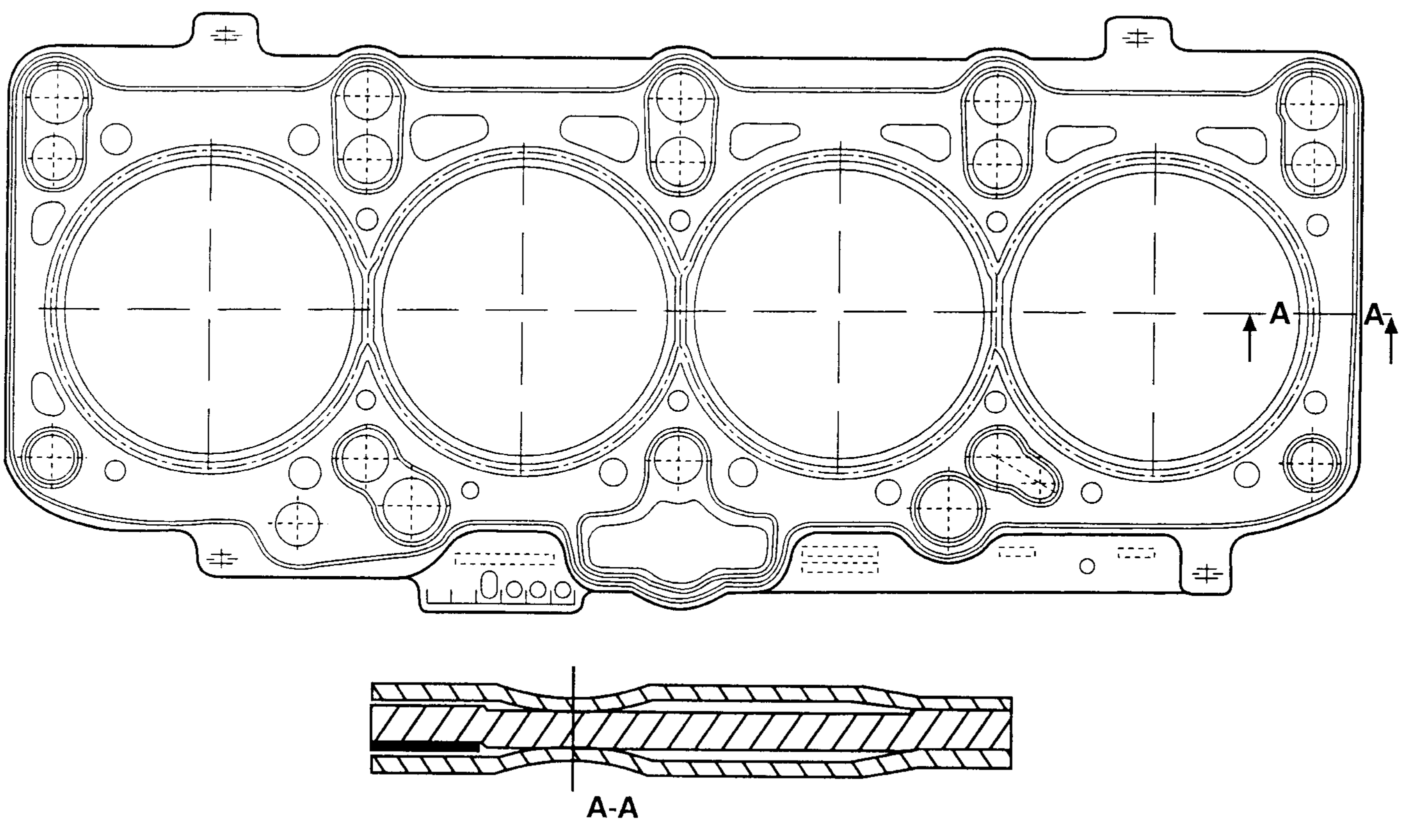


Fig. 4: Cylinder Head Gasket

A longitudinal and cross-section of the basic 1.9l 66 kW engine is shown in Figures 5 a and b, which is the basis for further technical development.

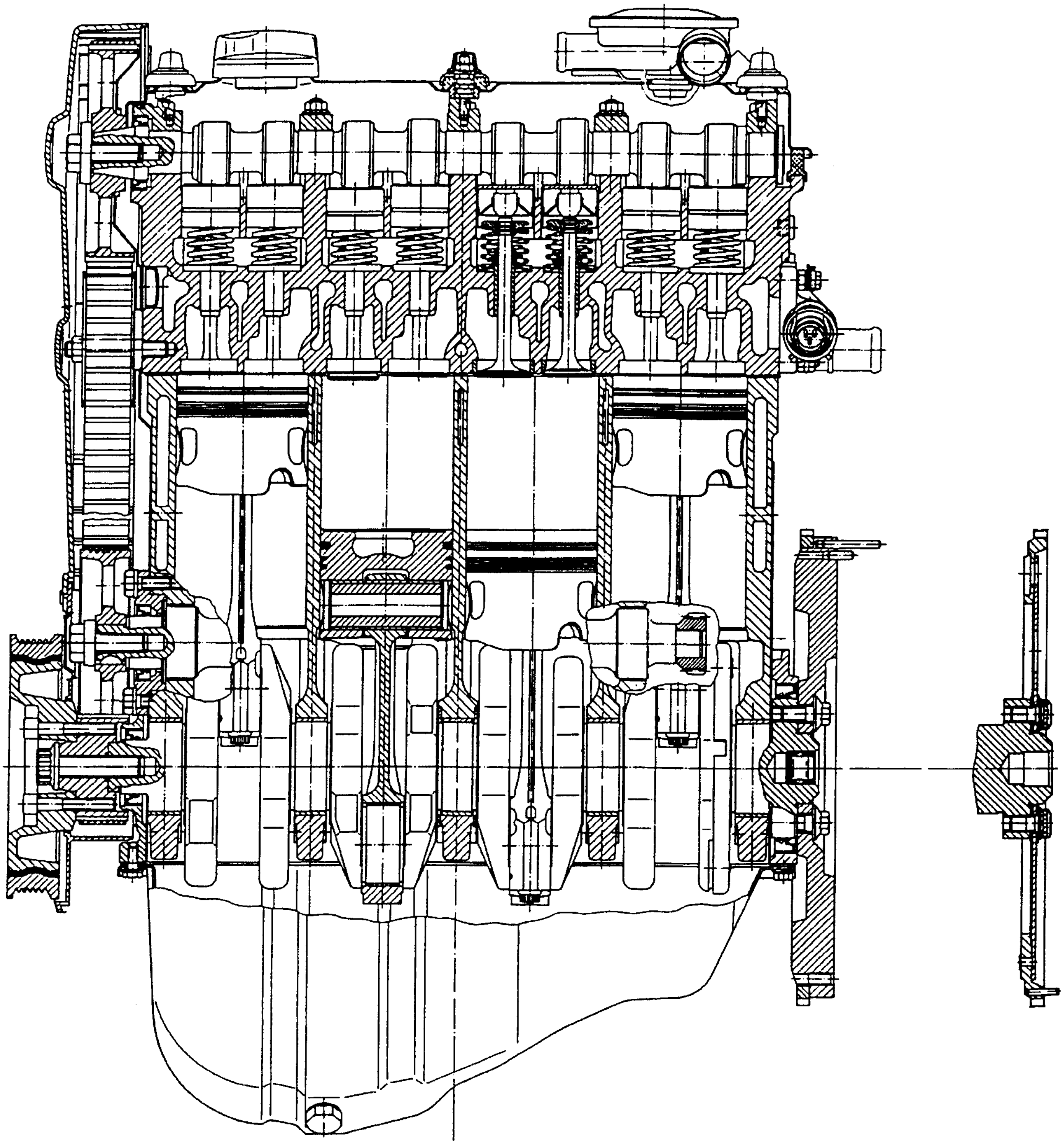


Fig. 5a: Longitudinal Section of a 1.9l TDI

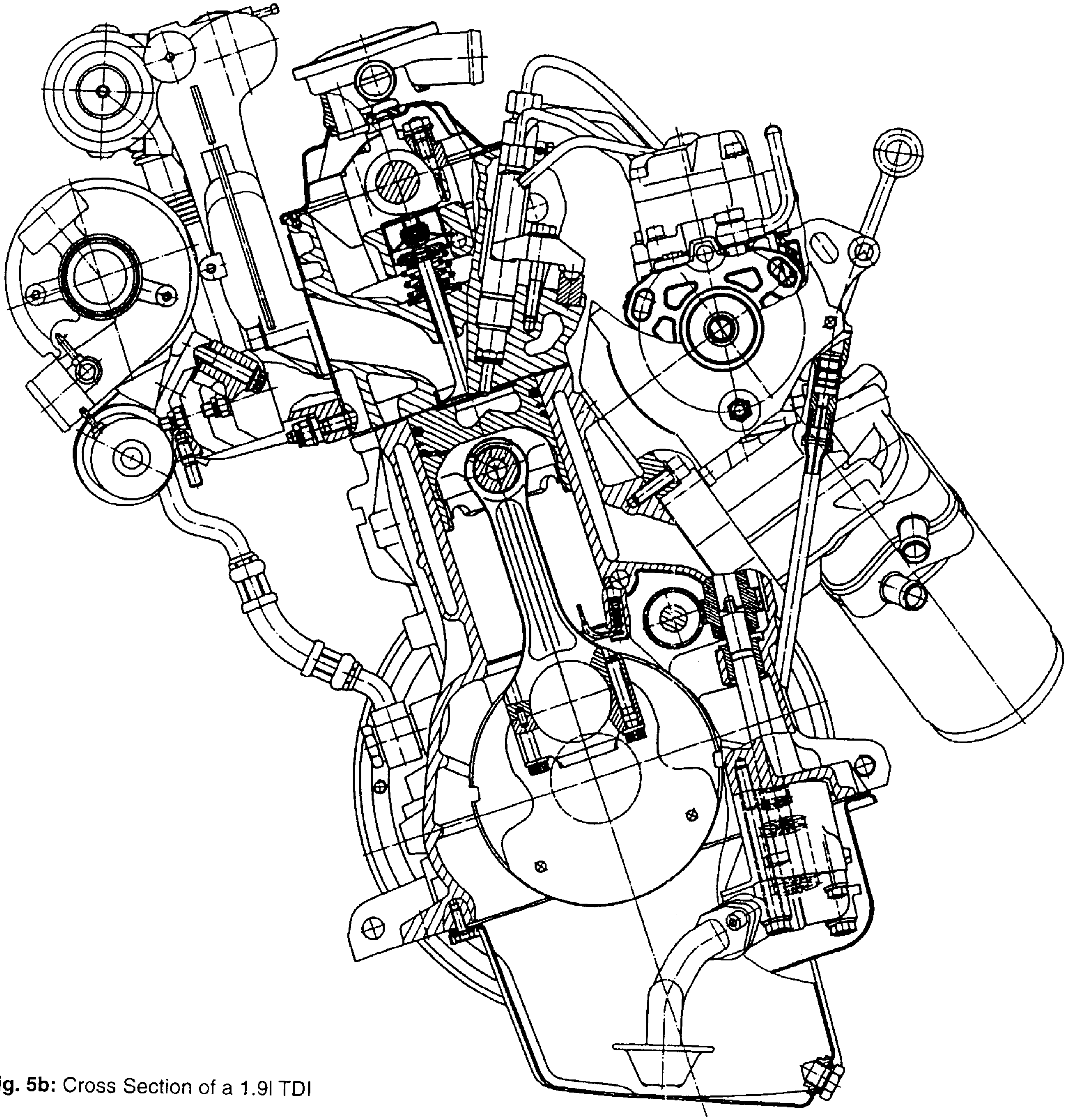


Fig. 5b: Cross Section of a 1.9l TDI

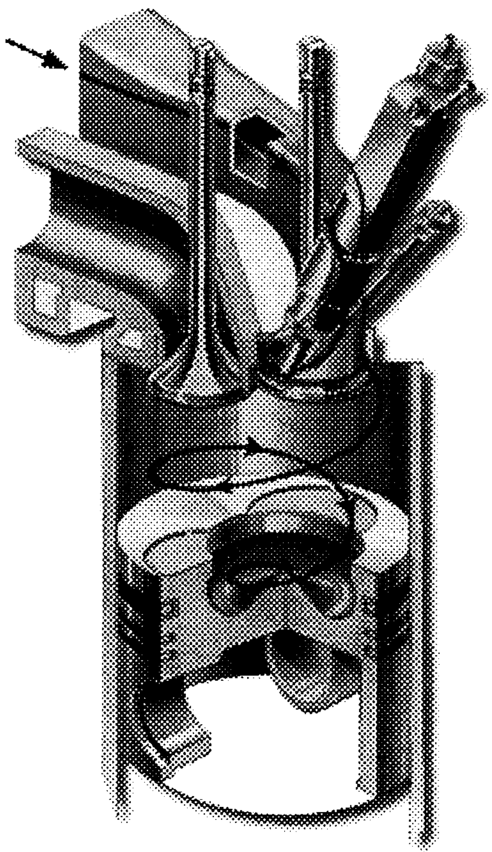
COMBUSTION SYSTEM

The essential parameters of the combustion system to be optimized for application in passenger cars are shown in the following (Figure 6):

- Intake Swirl Channel
- Piston Bowl
- Injection System

The fundamental measures for optimizing the piston bowl are shown in Figure 7. The combustion bowl 2a in the piston is the result of a long-term investigation. The aim was to achieve high mean pressure with a low BOSCH number at full load. At the same time low emissions, low fuel consumption and low noise emissions had been required. Another important factor was the resistance of the piston bowl edge to fractures. (1) When the engines went into series production in October 1991, the TDI engine fulfilled the European Exhaust Emission Regulation XXIII and was classified "low pollutant". By further development on the injection system, the turbocharging system and the design of the combustion chamber the TDI engine achieved as early as 1993 the stringent European 96 (EG II) standards. The new target then was to meet the US '96 (Tier 1) standards.

Swirl Port



Piston Bowl

5-Hole Injector

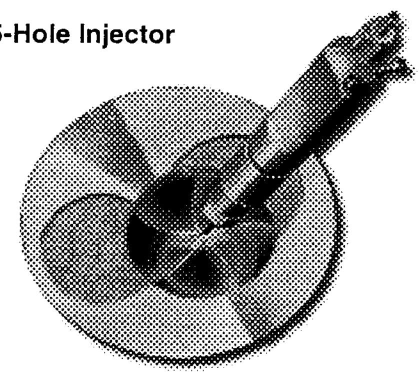
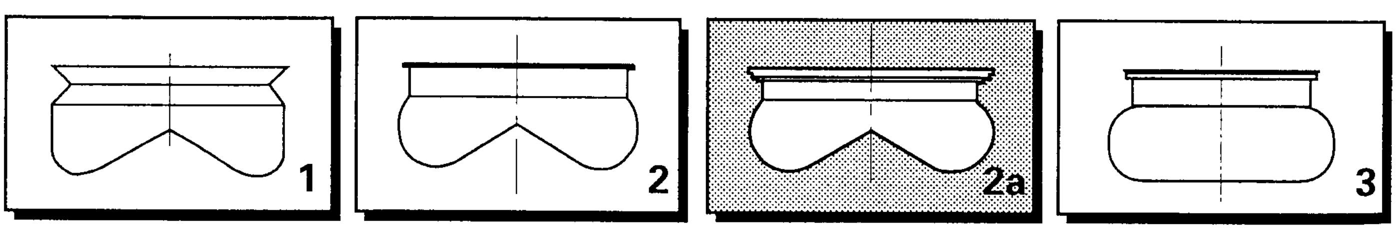


Fig. 6: Volkswagen-TDI-Combustion-System



The illustrated piston bowls were tested.
Bowl 2a represents the optimum under the given limiting conditions.

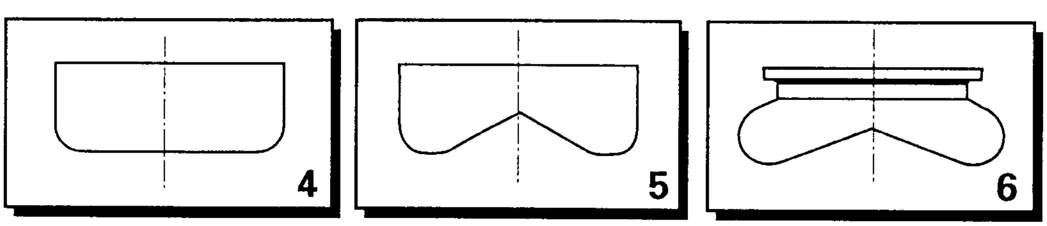


Fig. 7: Different Combustion Bowl Shapes

POWER AND HIGH TORQUE

The small, high-revving Diesel engine cannot be regarded as a low-power option for passenger cars. In Europe the TDI engine now also powers convertibles and "GTI's" and it even shows its potential in motor sports. For the latter application the VW engineers increased the maximum power of the 1.9 liter TDI to 125 kW (170 bhp). Combined with an even torque at all engine speeds, this leads to a masterful driving experience which has made the TDI one of the most popular engines of the VW Group in Europe. Today more than 33% of all Passats are powered by a TDI engine.

The latest 66 kW TDI version is characterized by very low smoke emissions and an improved "drivability". The maximum torque, achieved as low as 1900 rpm, has been increased from 202 Nm to 210 Nm. This allows the customer to shift gears earlier and therefore leads to a further improved fuel economy. Torque of the TDI vs. a gasoline engine of the same power output of 66 kW and in comparison with the 55 kW IDI with the same displacement is shown in Fig. 8.

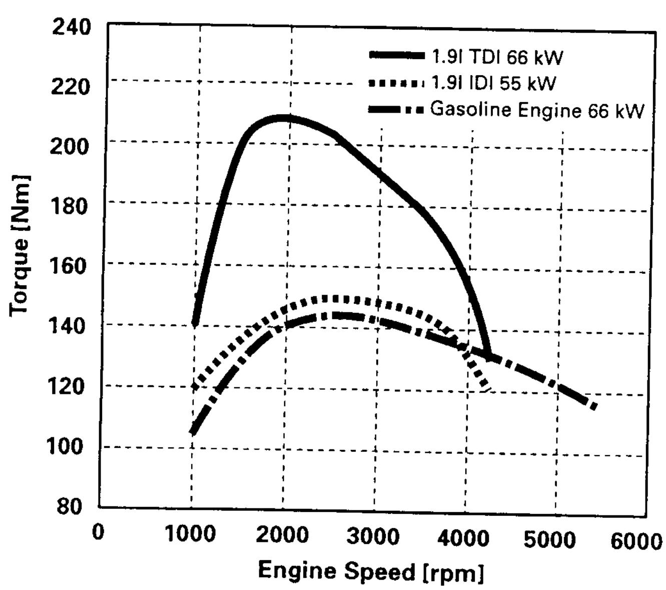


Fig. 8: Comparison of Torque Curves for TDI, IDI, Gasoline

FUEL ECONOMY

Diesel vs. Gasoline - Because of its overall energy efficiency of up to 43 % the TDI Diesel engine is the passenger car engine with the best fuel economy in its class. Compared with a spark ignition gasoline engine the TDI Diesel has an advantage of up to 40 % in fuel economy. The emission of greenhouse gases can be decreased by about 45% (5).

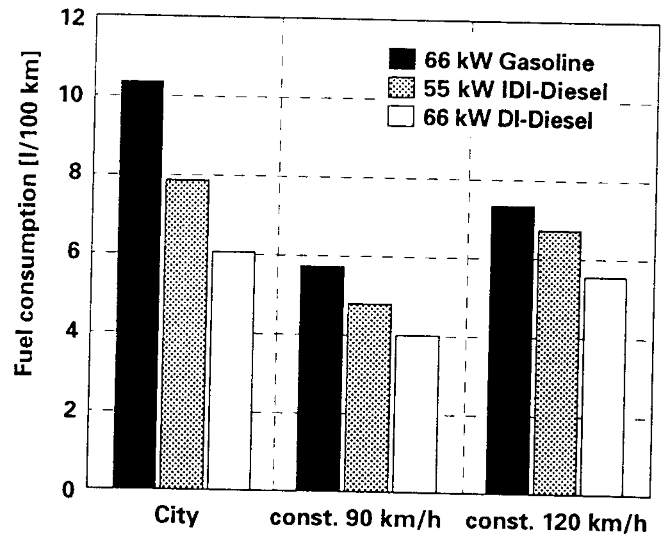


Fig. 9: Fuel Consumption Gasoline, IDI- and TDI-Diesel (European Mode) in a Passat

The DI engine has a thermodynamic advantage compared to the IDI engine of about 20% due to:

- fast one-stage burning process
- no pressure losses between swirl chamber and main combustion chamber
- favorable surface to volume ratio

So – one of the major arguments in favor of the DI engine is fuel economy (Figure 9).

CONCEPT AND INNOVATION FOR THE NORTH AMERICAN MARKET

Table 2: Concepts and innovations at the Passat 1.9l TDI

	MY '96	MY '97	MY '98
Injection Pump	VP 37, 700 bar	VP 37, 700 bar	VP 37, 950 bar
Nozzle	5-hole	5-hole, optimized	5-hole, optimized, adjusted
Turbocharger	T 15 (Garret)	T 15 (Garret)	VNT (Garret), Variable Turbine Geometrie
EGR-System	close loop	close loop, cooling	close loop, cooling
Engine Control Module	MSA 12	MSA 15	EDC 15

FUEL INJECTION SYSTEM

Throughout all model years an axial-piston distributor injection pump by Bosch, type VP 37, is installed. As a result of intensive development for the upcoming model year 98, the pressure within the piston of the pump has been increased from 700 bar to 950 bar (Fig.10). The application within the system with a specially adjusted injection nozzle with a hole diameter of 0.158 mm instead of 0.184 mm now allows a pressure of 1350 bar prior to the nozzle orifice. Fig. 11 shows the plunger lift and the plunger velocity of the North American-version compared with the European version. Thus it has become possible to achieve a pressure level which can usually only be produced by radial piston pumps, inline systems or by high pressure injection systems. Due to the high injection pressure the spray formation in the combustion chamber has been further improved and lower smoke emissions have been achieved.

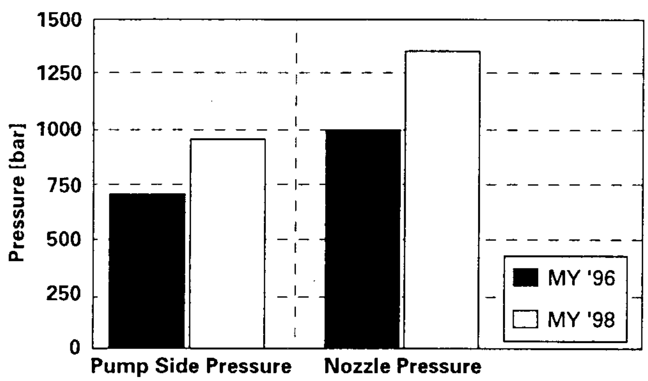


Fig. 10: Pressure Development of Injection Pump at Rated Power

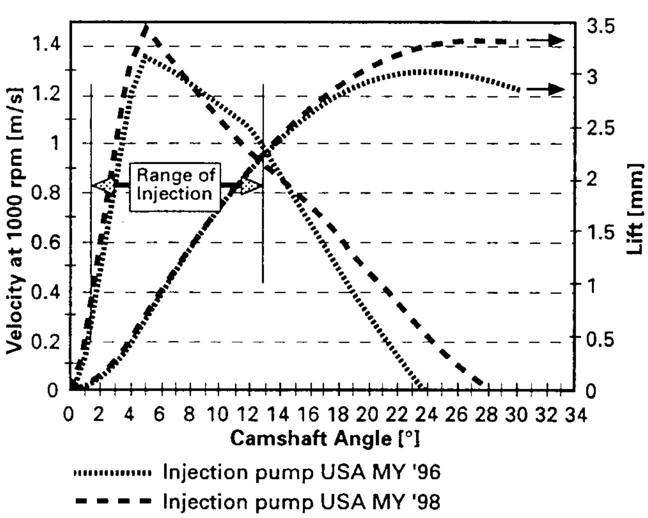


Fig. 11: Plunger Lift and Plunger Velocity

REDUCED CREVICE VOLUME

Further reductions in emissions of both unburned hydrocarbons and particulates are achieved by reducing crevice volume. This is the result of a newly developed piston which is characterized by a reduced distance between the piston crown and the first compression ring (from 9 to 6 mm). Therefore the volume that does not take part in the combustion is further decreased (Figure 12).

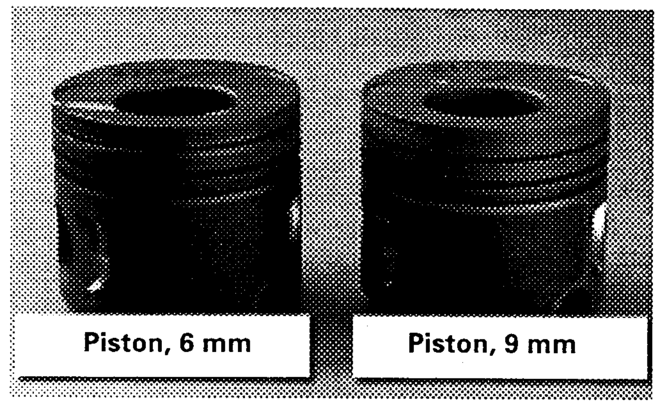


Fig. 12: Reduced Crevice Volume

TURBOCHARGER

The new MY 98 Passat is equipped with a special VNT turbocharger (Variable Nozzle Turbine - Figure 13). On the compressor side, the structure of the VNT is the same as that of the previous T 15. Turbine design of the VNT 15, however, is more open than the T 15, which is designed with its fixed turbine to provide high boost pressures even at low RPMs. This determines the low exhaust back pressure in the midddle and upper ranges. At low RPMs, higher boost pressures can nevertheless be created by the variable geometry of the VNT. The variable blades are drawn together, small jets are created, which in turn create high flow speeds in the turbine inlet with the increasing exhaust pressure. As a result, the turbine of the VNT, which is more open, can deliver more at the compressor than the narrower turbine of the T15, since higher boost pressure is created (6). A classic wastegate is not necessary. The boost is controlled by the ECM, which actuates a vacuum sytem which moves the blades of the turbine guide system.

For the customer this means improved fuel economy and more motoring enjoyment due to a greater torque in all areas of the engine map.

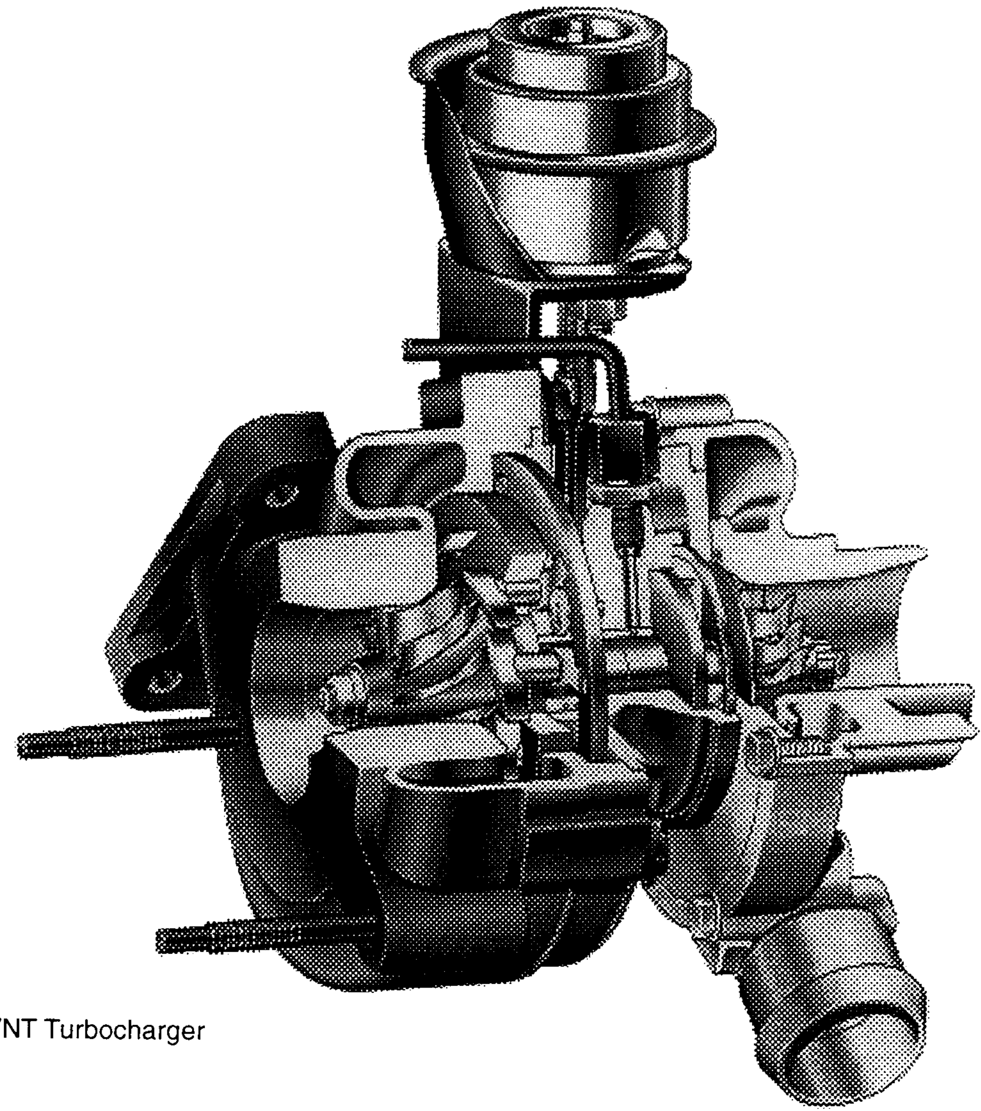


Fig. 13: VNT Turbocharger

EGR WITH EGR COOLING

The pneumatics in a closed-loop-method controlled EGR-system have been further improved by the application of EGR cooling. The result is an additional NO_x-reduction due to a lowering of the peak combustion temperature (Figure 14).

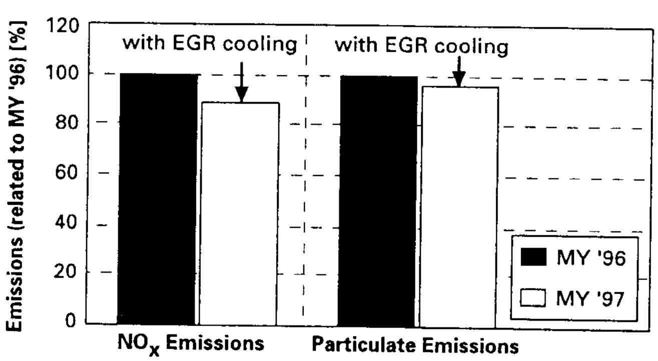


Fig. 14: Improvement of EGR System, Comparison of Emissions in Relation to Model Year 1996

ECM – ELECTRONIC CONTROL MODULE

Since the introduction of the 4-cylinder TDI engines in October 1991 in Europe with the MSA 6, now control units of the fourth generation, EDC 15, are installed in the new VW Passat. Increasing demands in terms of emissions, fuel consumption and comfort are leading to a strongly increasing number of characteristic lines and maps to control the connection of incoming and outgoing parameters. The hardware of the control unit has been changed form 8-bit to 16-bit, the amount of data increased from 64 Kbytes to almost 256 Kbytes, software included.

A general overview of all the relevant incoming and output signals is lined up in the "OBD Diesel System Block Diagram" (Figure 15). Control data essential for the engine performance such as injection start and EGR rate are permanently updated with changing environmental conditions. Thus up to 10 correction parameters are used to hold exhaust pollutants and fuel consumption within a defined range. Closed control circuits guarantee that these values are stable throughout the service life of the engine.

Every driver will notify that it was made possible to get constant maximum torque and nominal power output up to elevations of 2600 metres above sea level without any black smoke emissions. An electronic accelerator pedal (drive-by-wire) and active shock absorbers will lead to a driving refinement which will satisfy even hard-to- please customers.

An internal fault detection system and the integrated OBD II functions make sure that every VW-service station is capable of detecting any malfunctions in the system within the shortest period of time. In specially designed memory addresses additional data is placed enabling the service personnel to find out at what running conditions the malfunction first appeared.

This is a useful tool for sporadic faults which now can be solved without detailed customer interrogation. Another advantage is the location of malfunctions which cannot be detected by the driver because of other security devices which take over the work of the defective part.

The CAN-bus used in the EDC15 unit offers the possibility of data exchange between engine, transmission and brake control units.

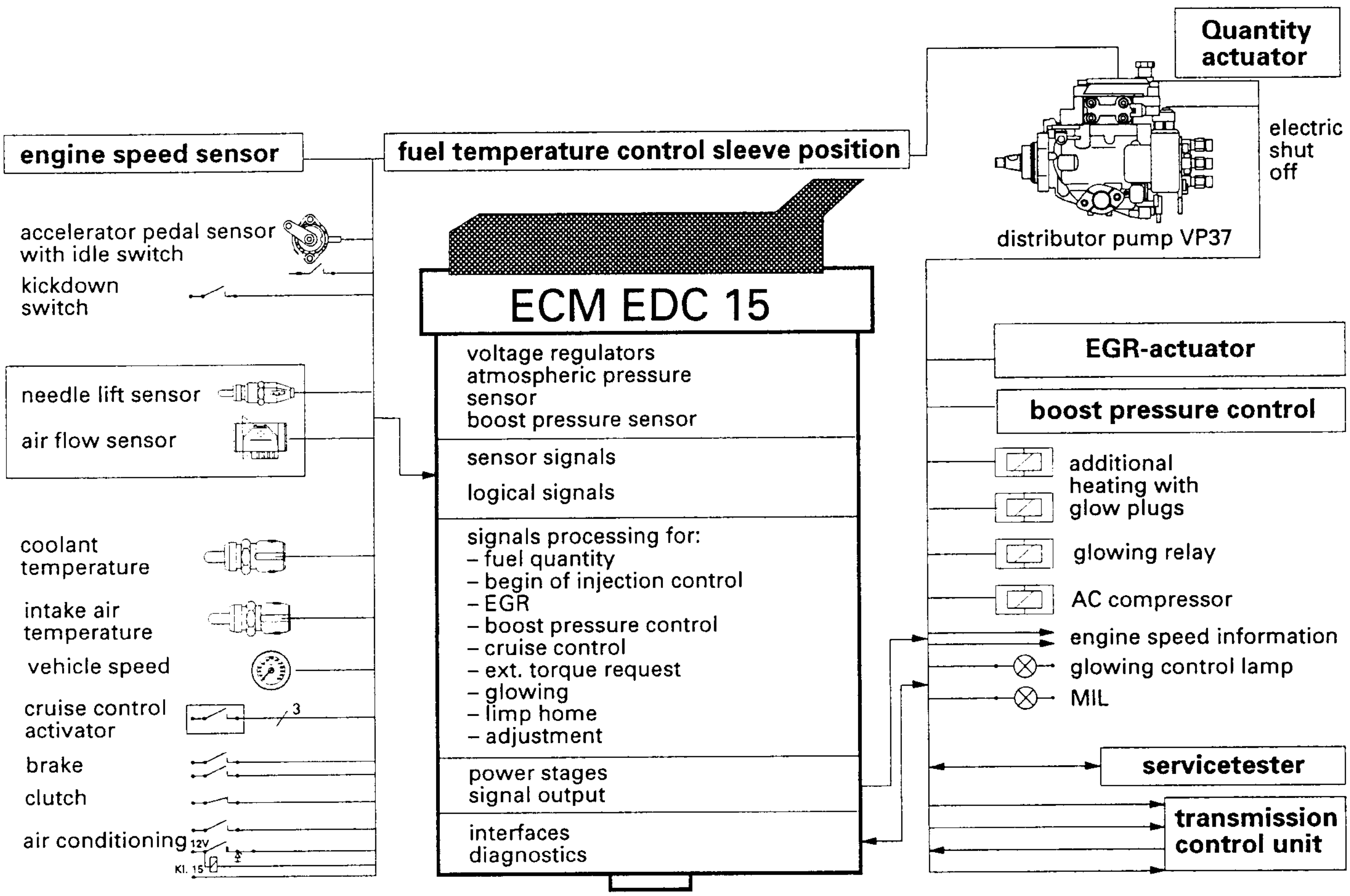


Fig. 15: OBD Diesel System Block Diagramm

PERFORMANCE DATA

The measured full load values of the US version of the 1.9l TDI engine are seen in Fig. 16. For good performance characteristics the shape of the torque curve is more important than the maximum power output. The TDI engine delivers a torque of 140 Nm at 1000 rpm and reaches its maximum of 210 Nm at 1900 rpm (see Figure 16).

The application of technical improvements on the TDI made it possible to achieve US and California emissions requirements without any loss of performance to the European version.

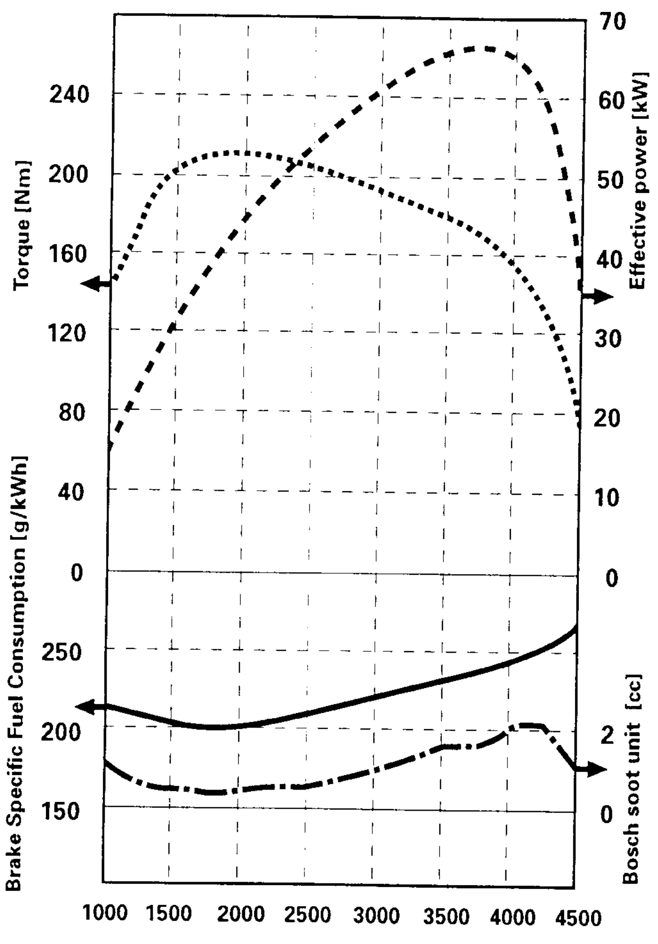


Fig. 16: Performance Data Passat 1,9l TDI MY '98

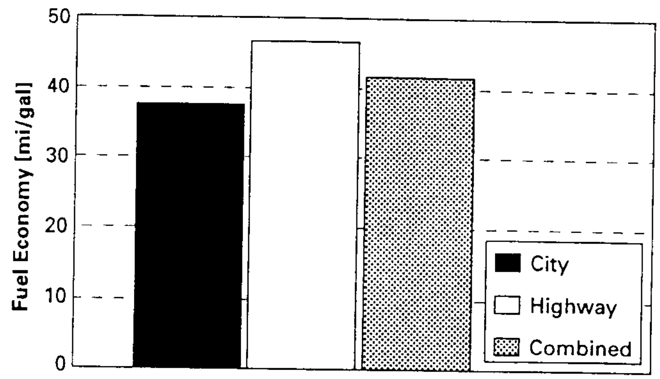


Fig. 17: Fuel Economy (Passat 1.9l TDI)

In addition a remarkable fuel economy has been achieved in the midsize class Passat (Figure 17). The very low fuel consumption has been realized over the wide range of engine performance (Figure 18).

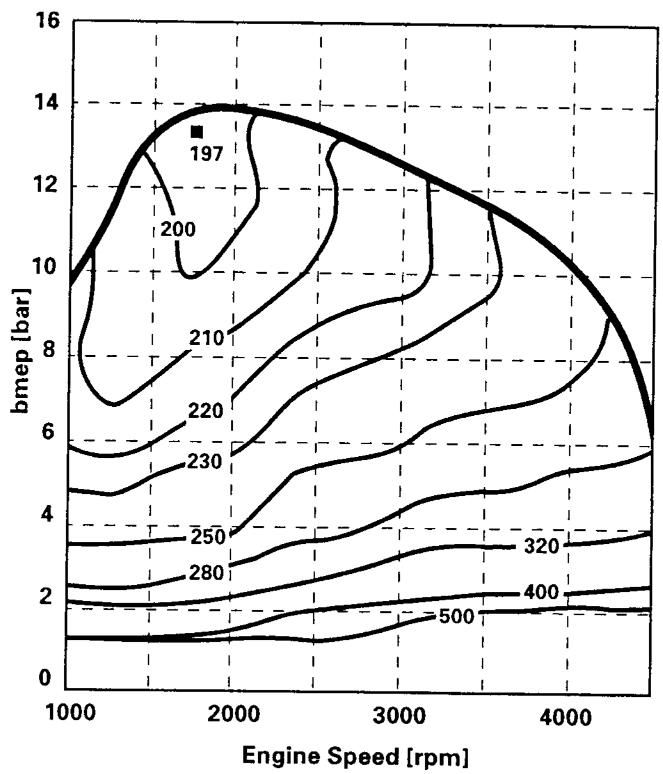


Fig. 18: Engine Fuel Consumption Map

FUTURE DEVELOPEMENT

In addition to complying with all statutory provisions, a future car has to arouse the customer's enthusiasm. This includes the engine's delivering even more than what is expected from it. (4)

Main emphases of development are:

Fuel consumption:

With small-volume engines in light vehicles the objective to be achieved is a consumption of 3 litres of fuel per 100 km (78,4 mpg). In the foreseeable future this can only be achieved with TDI technology in conjunction with drive-train management.

Exhaust quality:

In order to underbid the future TLEV figures for TDI, new methods must be developed in respect of the combustion process and exhaust gas treatment. Fuel and oil quality must also be markedly improved.

Performance:

The potential of power and torque output of the TDI engine is presented in Figure 20. The lower pollutant limits of the EG II directive allow the 1.9l engine to achieve a nominal power output of 81 kW (110 hp). Given no emissions restrictions, a racing version has been developed that achieves 125 kW output from the 1.9l TDI.

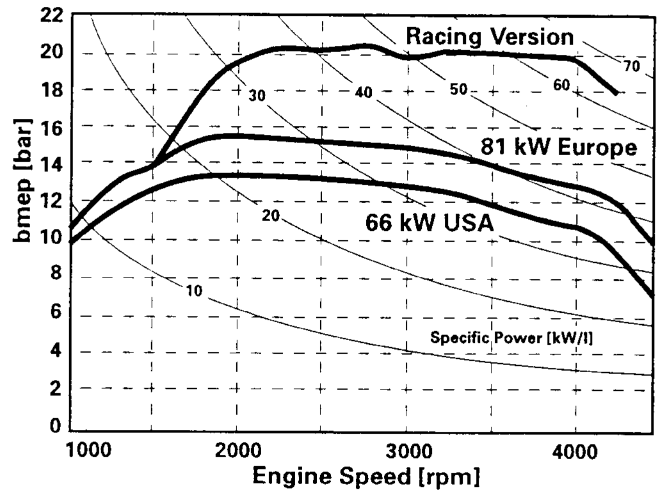


Fig. 20: Potential of Power and Torque Output of the TDI Engine

Further increases in power output are possible by using

- High pressure injection systems (2000 bar),
- Injection shape rating,
- 4 V-Technology,

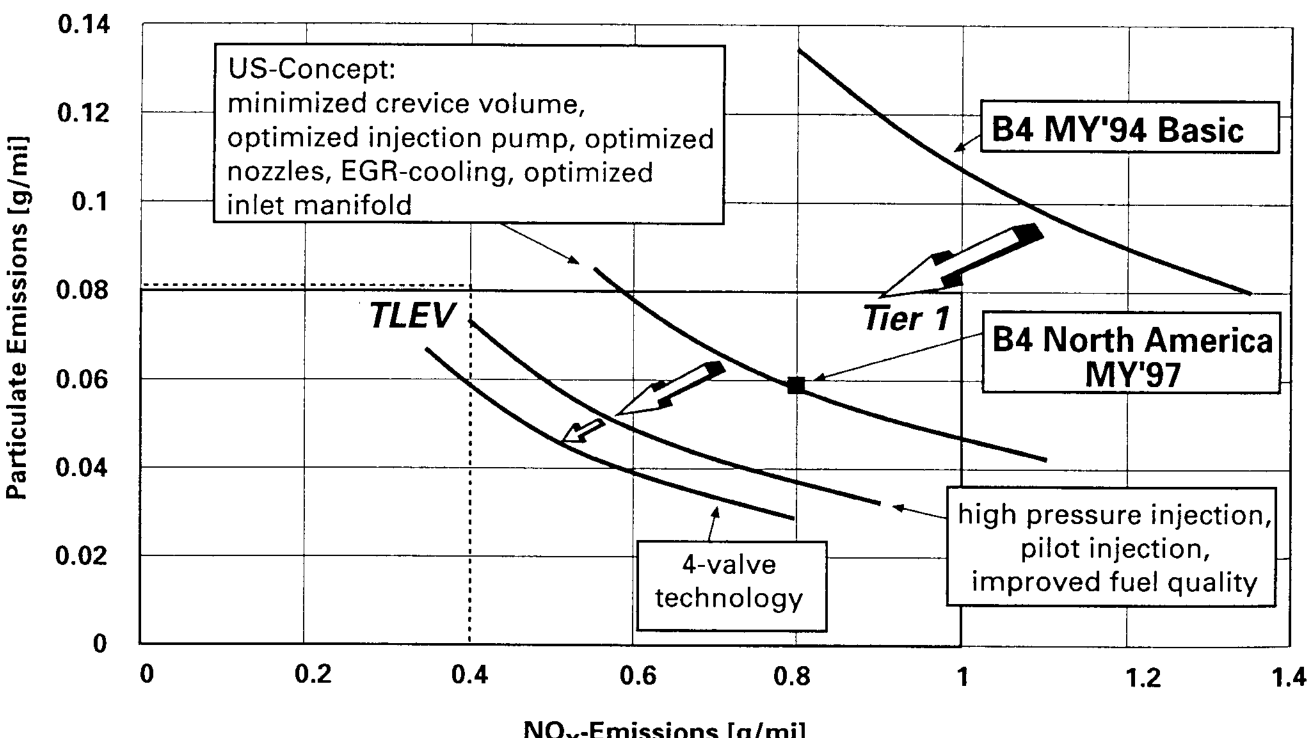


Fig. 19: Realization Emission Strategy TDI in North America

The trade off between power output and exhaust pollutants shown in Figure 21 and limits our options.

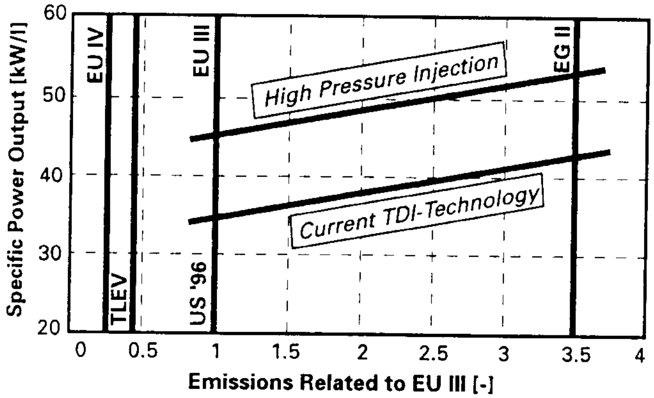


Fig. 21: Trade Off Between Specific Power Output and Exhaust Emissions

Comfort:

Further noise reductions are possible through:

- Combustion process with pre-injection
- Structural measures on noise-conducting and noise-radiating components
- Further extension of encapsulation measures

Vibrations can be reduced through:

- Optimized engine-gearbox mounting,
- Possible use of balancing shafts

CONCLUSION

After a very successful market launch, the 1.9l TDI engine has found widespread acceptance. It has set up the following records in its class:

- Fuel consumption
  First 47 mpg in the Golf and Passat class
- Maintenance:
  First car diesel engine with an oil change interval of 15,000 km
- Exhaust emissions :
  First direct injection diesel engine to fulfill the EG II exhaust limits and meet US and CARB standards

In contrast to spark-ignition engines, the TDI engine delivers exhaust values which will remain stable throughout its service life.

The special torque characteristics of the 1.9l TDI engine makes this engine highly suitable for combination with an automatic transmission. The characteristics are very much like those of a spark-ignition engine with a swept volume of 2.5 l.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

MSA: Menge, Spritzbeginn, Abgasrückführung (injection quantity, timing, EGR)

EDC: Electronic Diesel Control

TDI: Turbo Diesel with Direct Injection

VNT: Variable Nozzle Turbine

FEM: Finite Element Method

ECM: Electronic Control Module

OHC: Overhead Camshaft

NO_x: Nitrogen Oxides

OBD: On-Board-Diagnostic

EGR: Exhaust Gas Recirculation

CAN: Control Area Network