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Volkswagen High Performance TDI-Engines for Passenger Cars

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VOLKSWAGEN

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Volkswagen High Performance TDI®-Engines for Passenger Cars[1)]

1. Introduction
2. State of the Art
    - 81 kW TDI® Engine
3. Power Tuning
    - R* TDI® Engine
4. Prospects
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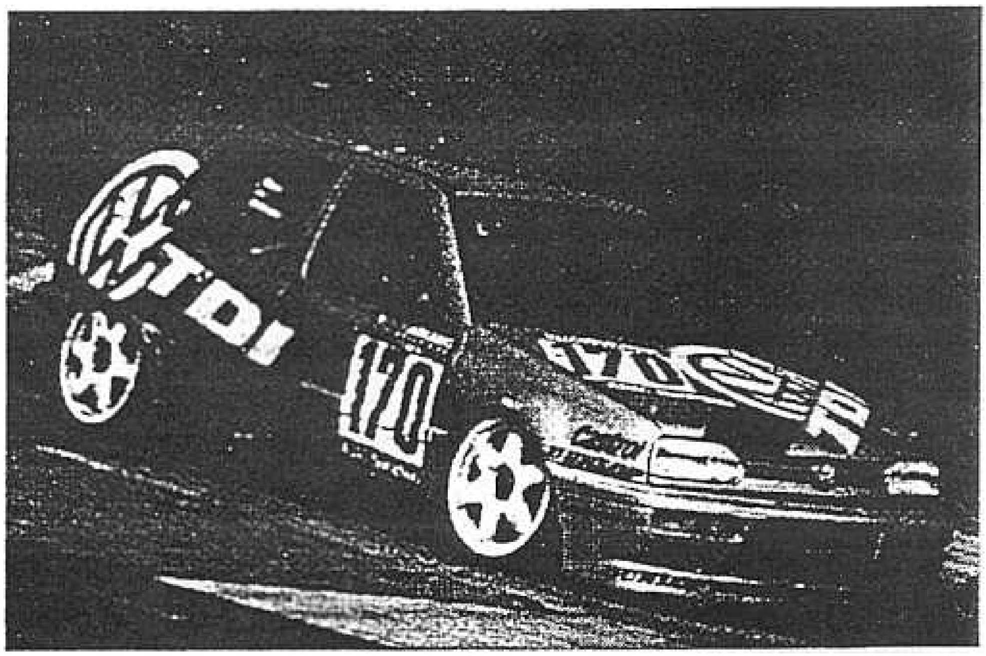

1) TDI® ist eine eingetragene Marke von VW und Audi. TDI® is a trademark registered by VW and Audi.

Chart 1 shows the output power range of direct injection diesel engines from the VW Group. All engines are based on the series with an 88 mm cylinder gap.

Passenger cars

Four-cylinder engines

SDI

- 1.7 l - 44 kW-D3
- 1.9 l - 47 kW
- 1.9 l - 50 kW

TDI®

- 1.9 l - 55 kW
- 1.9 l - 66 kW-D3
- 1.9 l - 81 kW

TDI® V6 six-cylinder engine

- 2.5 l - 110 kW

Light duty trucks

Five-cylinder engines

SDI

- 2.5 l - 55 kW

TDI®

- 2.5 l - 75 kW

Chart 1
Gradated output power levels of DI engines for passenger cars and light trucks from the VW Group

All direct injection diesel engines from the Group comply with the Euro 2 emissions limits. Since 1996, the 66 kW TDI® engine has also been sold in the U.S.A. with an extra emissions package /6/. Recently, a variant has been derived from this which falls within the D3 emissions limits and thereby qualifies for a DM 500 tax exemption.

Furthermore, the Polo with a 1.7 l SDI D3 engine emits in the MVEG-A test less than 120 g CO_2/km and consequently qualifies for a double tax exemption.

The 81 kW TDI® Engine

The market success of the four and five-cylinder TDI® engines facilitated the decision to expand the range of direct injection diesel engines by broadening the power output spectrum. Fig. 1 shows a cross-section through the 81 kW TDI® engine /5/.

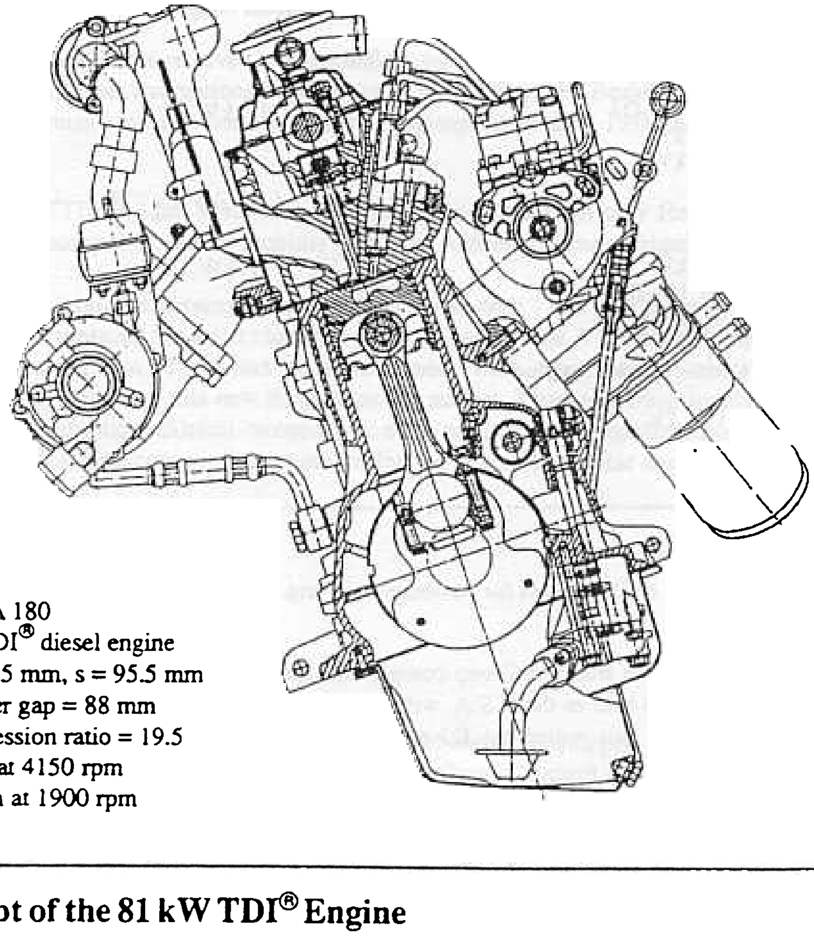

Fig. 1
VW EA 180
1.9 l TDI® diesel engine
D = 79.5 mm, s = 95.5 mm
Cylinder gap = 88 mm
Compression ratio = 19.5
81 kW at 4150 rpm
235 Nm at 1900 rpm

The Concept of the 81 kW TDI® Engine

Operating Method

*Swirl-assisted, air-distributing multi-jet direct diesel injection process
*Two-stage five-hole seat-hole injector nozzle
*Bosch VP 37 electronically controlled axial piston distributor-type injection pump
*Garrett VNT 15 turbocharger with variable turbine intake geometry and electronic boost pressure governing system
*Intercooling
*Electronically controlled exhaust gas recirculation system
*Diesel oxidation catalytic converter

Engine

*Reinforced four-cylinder engine with cast aluminium full-skirt pistons and spray-jet oil cooling
*Sputtered connecting rod bearing shells on the rod end
*Crankshaft with roller-straightened fillets
*Tandem-weight flywheel
*Alternator freewheel

Engine Management

*Bosch EDC 15 control unit with 16-bit microprocessor

Injection System

In order to increase the power output, a larger volume of fuel should be injected within a constant injection period. There are basically two possibilities for doing this:
* Increasing the flow rate through the nozzles by widening the injection orifices.
Limits are imposed in this case by the atomization quality in the part-load range and, consequently, the particulate emissions.
* Increasing the injection pressure

The hydraulic performance of the axial piston distributor-type injection pump is restricted by the mechanical characteristics of the pump drive train. The Hertzian compression on the cam of the eccentric disk is at its greatest in the area where the radius is the smallest at the tip of the cam. The level of Hertzian compression and the tribological conditions on the cam determine the service life of the pump drive train. Accelerating the plunger speed in the area of the large radius and decelerating it where the Hertzian compression is high makes it possible to obtain a greater injection pressure at the same time as lengthening the service life, provided an optimized cam is used. Trials to demonstrate the principle conducted using different fuel injection pumps have shown that the DI engine rewards increasing injection pressures with higher BMEPs whilst the amount of black smoke remains constant.
Broadening the 5 injection orifices from 0.184 to 0.205 mm in conjunction with a "sharper" cam contour caused injection pressures to be increased to 800 bar in the pump element and 1200 bar prior to the nozzle at rated power. The increased injection pressure combined with broader nozzle apertures permits a greater volume to be injected within the same injection period, which is the requirement for raising the power output.

Turbocharger

The 81 kW TDI[3] engine is equipped with a special VNT turbocharger (Variable Nozzle Turbine (Fig. 2). 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 middle 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 T 15, since higher boost pressure is created /7/. A classic wastegate is not necessary. The boost is controlled by the ECM, which actuates a vacuum system 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.

Exhaust Backpressure and Exhaust Temperature

The guide blades of the VNT 15 turbocharger are almost closed up to 1300 rpm. This produces a higher exhaust backpressure in the lower engine speed range than with the T15 turbocharger. The turbocharger runs faster and the engine responds more rapidly when accelerating from lower speeds. The blade setting is used for controlling the boost pressure in the middle and top engine speed range. The lower exhaust backpressure in this range reduces the negative pressure differentialgradient p2 - p3. In the 81 kW engine, there is a positive scavenging gradient in the speed range from 1750 to 2700 rpm at full-load; this is not the case in the 66 kW engine. Thus, the efficiency is increased.

Due to the improved efficiency, the injection volume of the VTG turbocharger is lower
for the same BMEP - except in the slow engine speed range. In turn, this means the injection period is curtailed. Both these factors reduce the exhaust temperature and consequently also the thermal stress placed on components, in particular pistons, the cylinder head gasket, exhaust manifold and turbine. The use of expensive materials can thus be avoided.

Turbocharger with Variable Turbine Intake Geometry

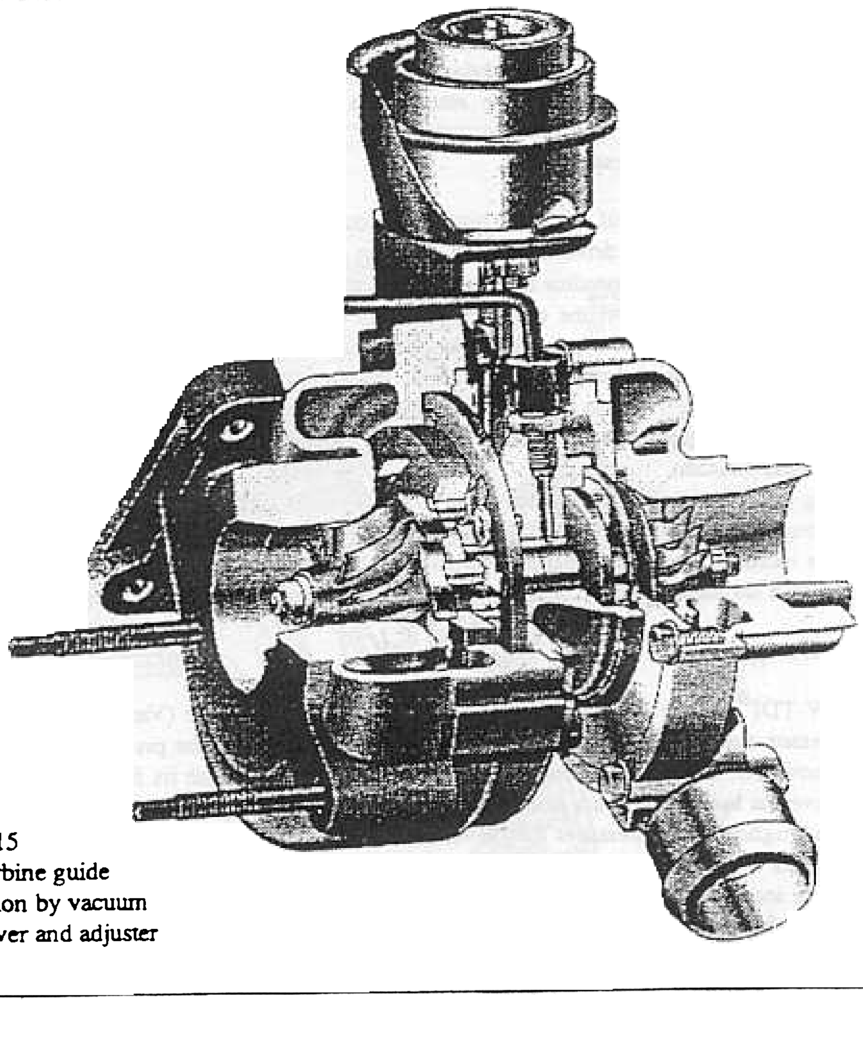

Fig. 2
Garrett VNT 15
Adjustable turbine guide blades, actuation by vacuum capsule via lever and adjuster

Boost Pressure

The boost pressure of the 81 kW TDI® engine at full-load is higher than that of the 66 kW engine throughout the entire engine speed range. The resulting higher charging efficiency makes it possible to convert a larger injection volume with the same opacity value.

The improved efficiency of the engine when using a variable turbine geometry turbocharger can be harnessed in conjunction with the better performance of the fuel injection system to inject the volume of fuel within a window from 15° BTDC to 21° ATDC. This reduces the strain on the engine.

If one were to attempt to obtain the same power output from 81 kW with the T15 turbocharger, as practiced by chip tuners, it would be necessary to have a larger injection volume than in the VNT 15 as a result of the lower efficiency. Thus, the injection period is longer with the same injection equipment. It is only through combining an injection system offering better performance with the variable turbine geometry turbocharger that one obtains the improved efficiency required for injecting the volume of fuel within a 36° CA window at rated speed. This reduces the strain on the pump drive train.

Full-load Values

Fig. 3 shows the full-load values of the 81 kW TDI® engine. Both the specific power output of 42.7 kW/l and the maximum BMEP of 15.6 bar are amongst the highest for all passenger car diesel engines. The medium pressure gradient already reaches 10.3 bar at just 1000 rpm. During mixed cycle driving, this permits the vehicle to be driven with few gear changes and predominantly at low engine speeds, thereby reducing fuel consumption. The turbocharger with its variable turbine guidance apparatus improves the response characteristics. The moderate increase in rated speed to 4150 rpm expands the useful speed range.

At minimum, the fuel consumption characteristic map displays a specific consumption of 196 g/kWh, corresponding to an efficiency of 43.8 %. The effective efficiency is still 37 % even at the rated power point. This success is thanks to the reduced exhaust backpressure when the guide blades are open. This has made the 5 l car possible in the B class. The exhaust emission values fall within the Euro 2 limits. All in all, the increase in power has been possible at the same time as reducing fuel consumption, maintaining a high level of driving comfort and cutting environmental impact.

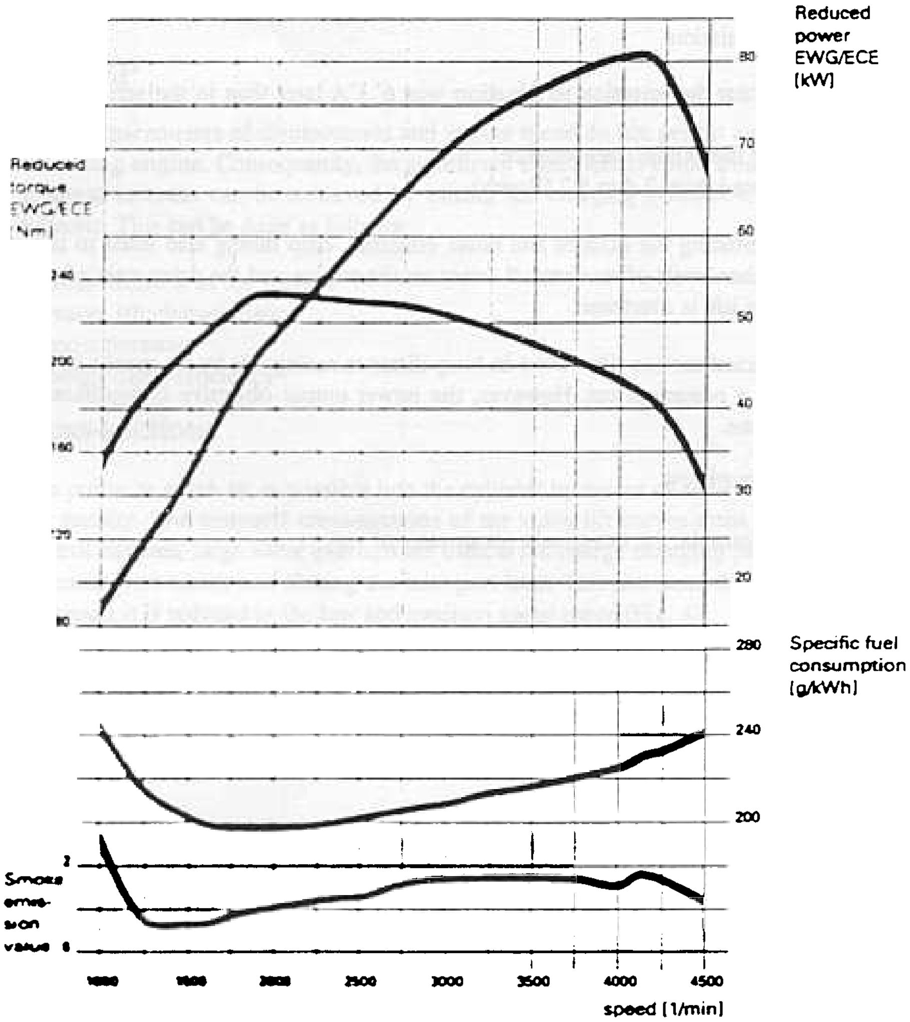

Fig. 3
Full-load values of the 81 kW TDI® engine

3. Increasing power output

The simpliest way to boost the engine power is to go to one of the many chip tuners. They promise an increase of approx. 20 % in power output for about DM 1000. We have investigated a data record of this type on the engine test bed.

Chip Tuning

The tuned chip in the control unit increases the injection volume by 23 % and the boost pressure by approx. 11 %. A maximum power output of 92 kW was measured at 3750 to 4150 rpm.

Due to the poorer efficiency in comparison to the series production engine, the injection volume at 4150 rpm was increased disproportionately to 47.5 mg/stroke. When the injection hydraulics are unchanged, the result of this is an injection period extended to 44° crankshaft angle.

The injection start was moved forward by 2° CA. The consequences are:
* A 15 bar rise in the peak cylinder pressure
* An increase of approx. 50 % in the pressure gradient dp / dα
* Increased nitrogen oxide emission

Furthermore, it was found that the injection termination was 6° CA later than in the series production engine. The consequences are:
* A rise of approx. 150 K in the exhaust temperature
* The smoke number increased from 2.4 to 5.2 (Bosch)

Summary: As well as exacerbating the exhaust and noise emission, chip tuning also leads to increased thermal stress on the engine and higher levels of mechanical stress on the engine and the drive train of the fuel injection pump. Consequently, service life is shortened.

In a racing engine, the expected service life - even in long-distance racing - is by no means as high as that of a series production engine in a passenger car. However, the power output objective is significantly higher than permitted by chip tuning alone.

Power Output Parameters

Based on the power output formula, the three main parameters of
* displacement,
* engine speed,
* BMEP

offer possible approaches for raising the power output. However, in motor racing, **the displacement** is a fixed parameter for the various categories. In the diesel racing engine, we did not utilize the full displacement of 2 l since this permitted us to use many series production parts.

Increase in Engine Speed

DI engines for trucks have rated speeds of 1900 to 2600 rpm. Those of DI engines for passenger cars are about 4000 to 4300 rpm. The 81 kW TDI® engine with a twin-valve cylinder head develops its maximum power at 4150 rpm.

Since the smoke limit is almost reached again at rated speed, the engine requires more air in order to produce more power. To do this, a larger turbocharger is required in conjunction with a more efficient intercooling system. Both of these are used in the racing engine.

Four-valve technology offers good prospects for increasing the charging efficiency in the top engine speed range. Even in a series production four-valve engine, the rated speed is increased to 4300 rpm.

At 4000 rpm, the 36 ° CA window for injecting the fuel represents just 1.5 ms. This time period is shortened as the engine speed rises; consequently, a **higher-performance injection system** is required.

For the purposes of comparison, a Formula 1 engine running at 16 800 rpm has approx. 3.6 ms for intaking and compressing the fuel/air mixture, and thus also for mixture formation and fuel induction.

Increase in BMEP

We have seen that the parameters of displacement and engine speed do not permit any major increase in power output in a diesel racing engine. Consequently, the significant effect has to come from increasing the BMEP. In this case, the greatest increase can be achieved by raising the charging efficiency, i.e. by increasing the air density in the cylinder. This can be done as follows:

* Increasing the cross-sections of the valves
* Optimizing the valve lift characteristics
* Increasing the boost pressure
* Increasing the intercooling efficiency

Temporal cross-sections

The objective is to pump as much air as possible into the cylinder by means of
increasing the air density. The temporal cross-sections of the valve lift curves must be formed accordingly to achieve this. In petrol engines, large valve overlaps are used at the charge changing process TDC in conjunction with opening the outlet port earlier and closing the inlet port later. This increases the charging efficiency at fast engine speeds, although it is reduced in the low and medium speed range (Fig. 4).

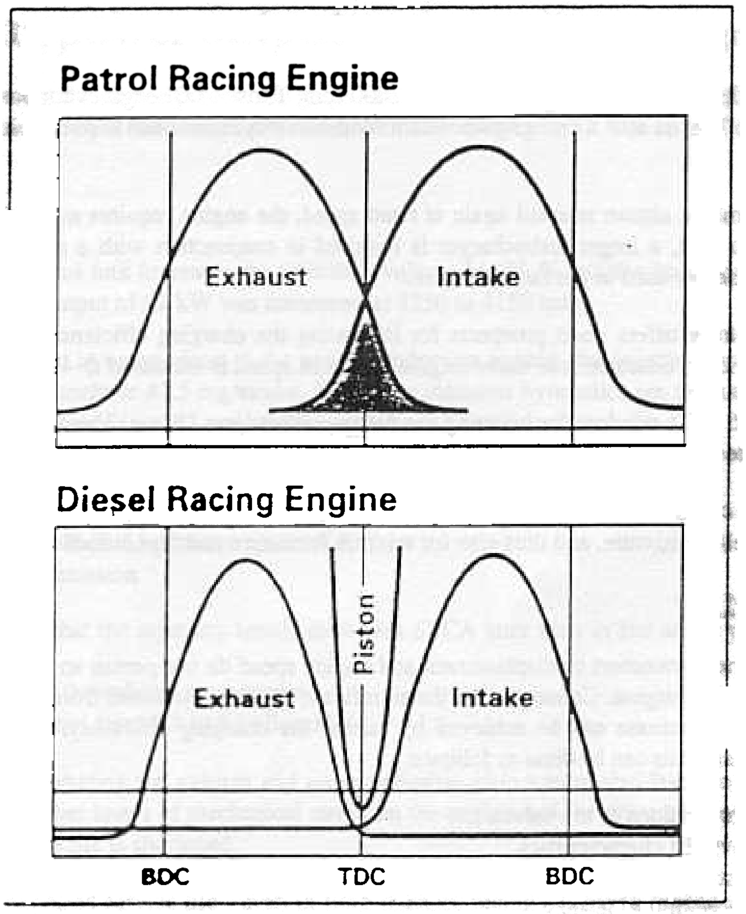

Fig. 4
Valve lift and piston stroke curves of the 1.9 l TDI® engine in comparison to a high-performance petrol engine

In diesel engines, the dead space of the combustion chamber is kept as small as possible in order to achieve low soot emissions. To do this, it is necessary to match the piston lift curve to the valve lift curve as far as possible, whilst allowing for tolerances, heat expansion and dynamic deformation. Consequently, having valves in overlap can only be achieved in a diesel engine through deeper valve pockets. However, this increases the dead space.

In the diesel engine, a moderate expansion in the temporal cross-sections can be obtained by steeper cam flanks at the expense of more rapid valve accelerations. The influence of the "outlet port opens" and "inlet port closes" valve timings on the BMEP was investigated. Fig. 5 shows the BMEP and fuel consumption for camshafts with varying inlet port closure. Retarding it by 10° CA causes the BMEP to increase by up to 0.3 bar above 4250 rpm and leads to losses in other engine speed ranges. As already mentioned, the diesel engine speeds are significantly slower than those of the petrol racing engine. Consequently, gas-dynamic effects are not so strong and changing the valve timing only permits minor successes to be achieved.

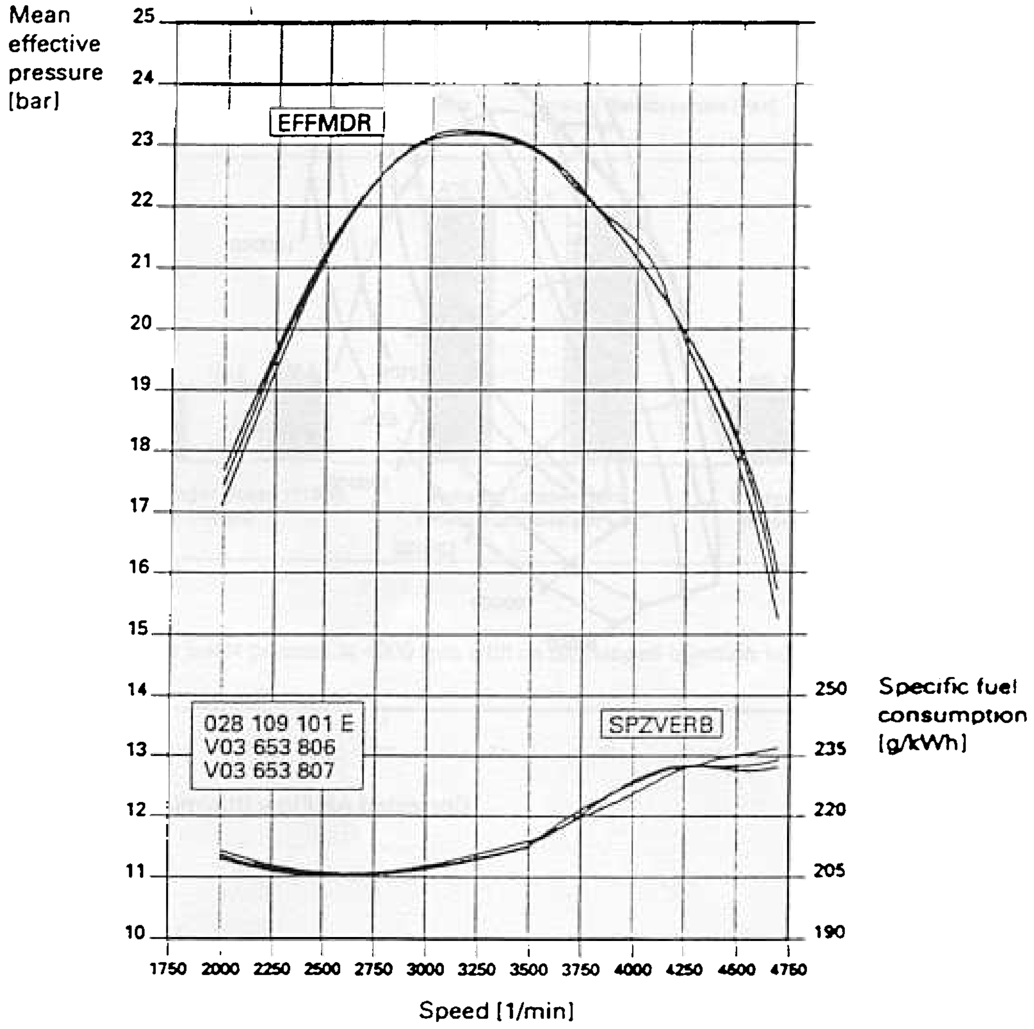

Fig. 5
Influence of the inlet port closure on BMEP and specific fuel consumption in the 1.9 l R•TDI® engine

Supercharging

It is possible to achieve a significant increase in BMEP in a diesel engine by higher boost pressures in conjunction with an efficient intercooling system and a high-pressure injection system. A large turbocharger with variable turbine geometry, the Garrett VNT 20, is used in the R*TDI® engine. Fig. 6 shows the compressor characteristic map with the engine charging curve.

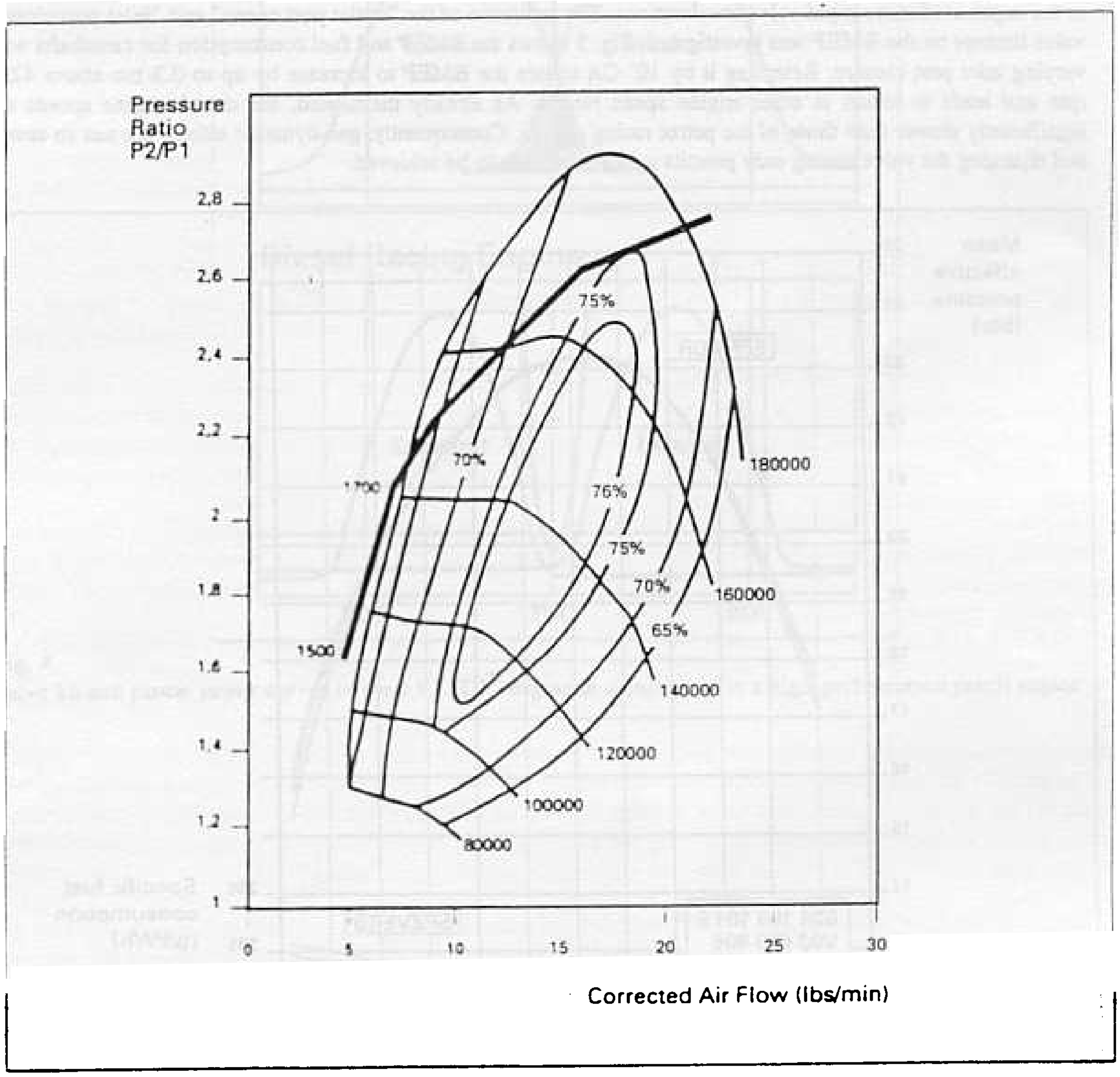

Fig. 6
Compressor characteristic map of the Garrett VNT 20 turbocharger with the engine charging swallowing curve of the 1.9 l R*TDI® engine

Fig. 7 shows what effect increasing the boost pressure by changing the angle of attack of the turbine guide blades has on the opacity emissions value, exhaust backpressure, exhaust temperature, charging efficiency, turbocharger speed and charge air temperature before entering the intercooler.

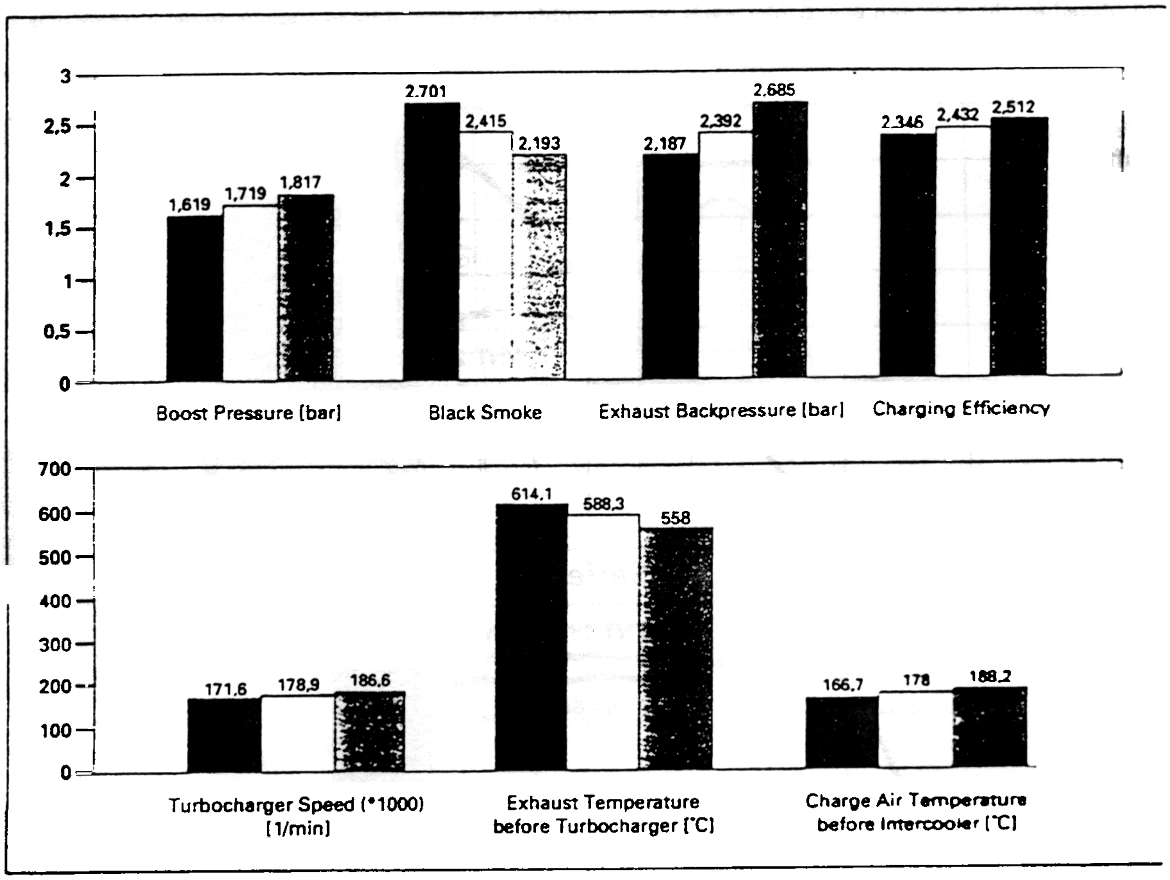

Fig. 7
Effects of increasing the boost pressure at 4000 rpm with an unchanged injection volume in the R*TDI® engine

Boost Pressures and Injection Volumes

With the VNT 20 turbocharger, the current build of the R*TDI® engine in its current construction stage (Bst. 3) achieves a maximum boost pressure of 2.87 bar absolute (Fig. 8). Under transient conditions, overshoots occur in the control range just as in the series production engines. In addition, the injection volumes at full-load are displayed for the various power output levels.

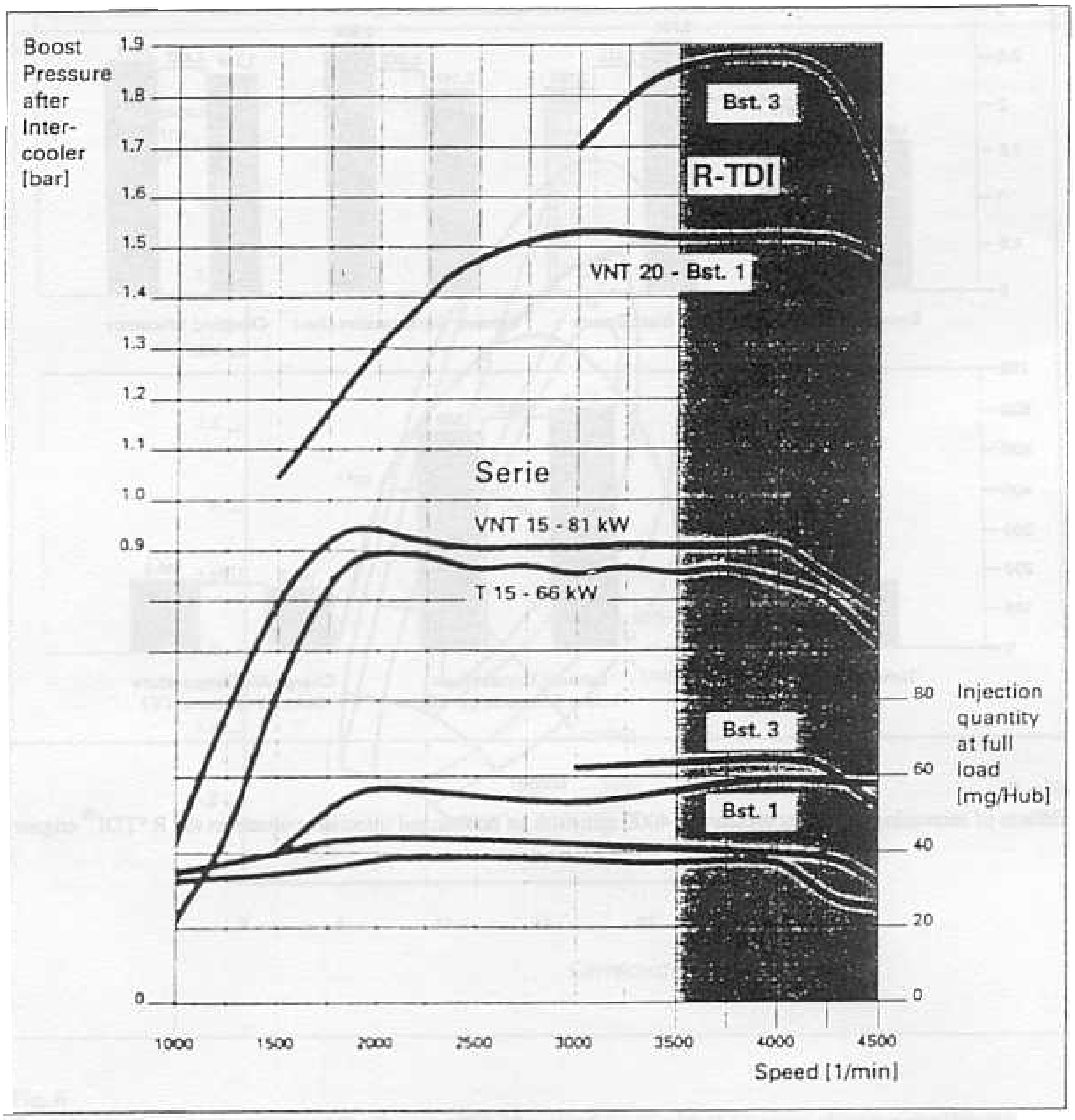

Fig. 8
Boost pressures and injection volumes at full-load for various power output levels of the 1.9 l TDI® engine

Recordings made with the Data Logger indicate that the engine is almost exclusively run between 3500 and 4500 rpm when racing in conjunction with a six-speed gearbox. The full-load values should therefore be optimized in this case.

The charge changing ducts in the cylinder head were reworked to increase throughflow. The suction pipe from the SDI engine produced a greater charging efficiency.

Intercooling

A significantly larger intercooler with better throughflow is used in the R*TDI® engine. With this, it is possible to lower the charge air temperature by 143 degrees at approx. 4000 rpm (Fig. 9).

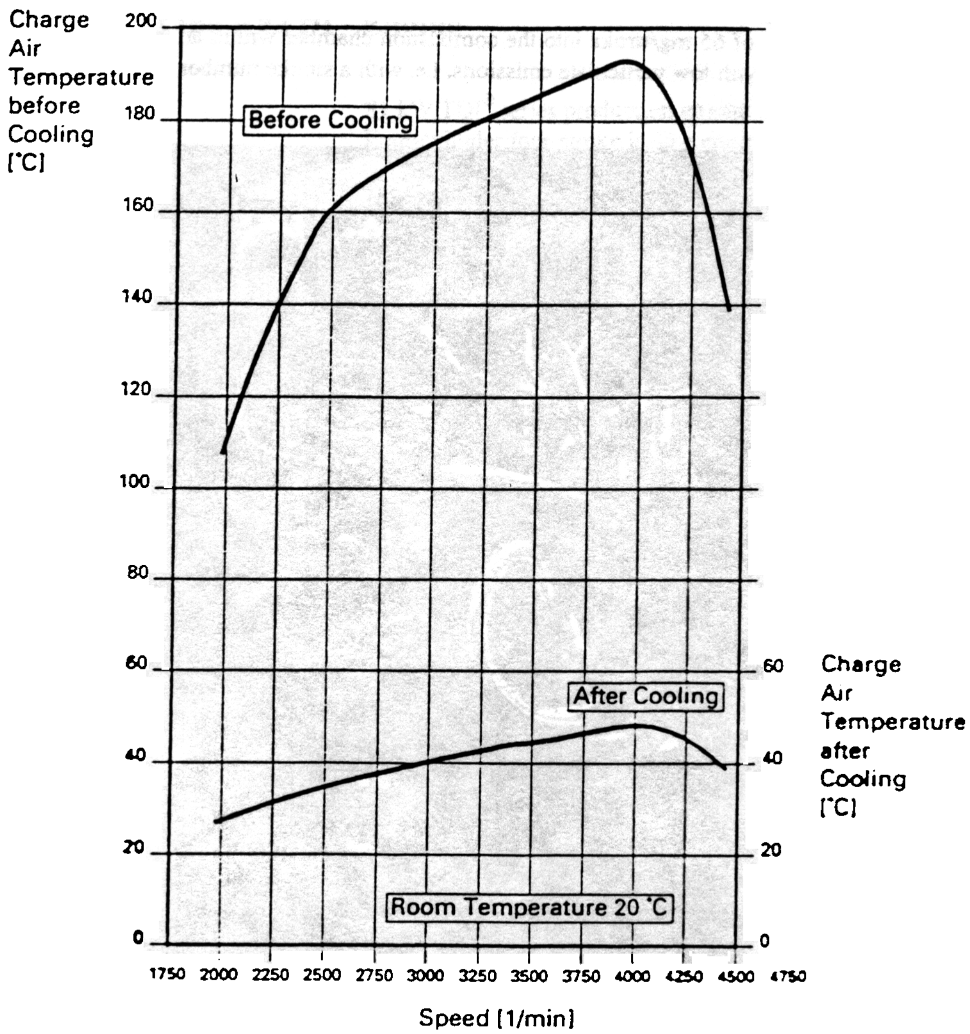

Fig. 9
Charge air temperature upstream and downstream of the intercooler at full-load

The R*TDI® Engine

The R*TDI® engine (Fig. 10) has undergone continuous further development. The current construction stagebuild 3 version is described below. The piston recess was increased to 17.5 in order to reduce the compression ratio. This means the peak cylinder pressure, of approx. 185 bar, was kept within acceptable limits despite the increased boost pressure and the larger injection volume and delivery rate. To increase stability, the edge of the piston recess was fibre-reinforced and a trapezoidal connecting rod was fitted.

The orifice diameter of the injector nozzles was increased to 0.26 mm. The required fuel injection pump with an 11 mm plunger was already on our "test component shelf". With this equipment, it proved possible to inject the maximum injection volume of 65 mg/stroke into the combustion chamber within an injection period of approx. 36° CA and to burn it there with low particulate emissions, i.e. with a smoke number of max. 2.5 Bosch units.

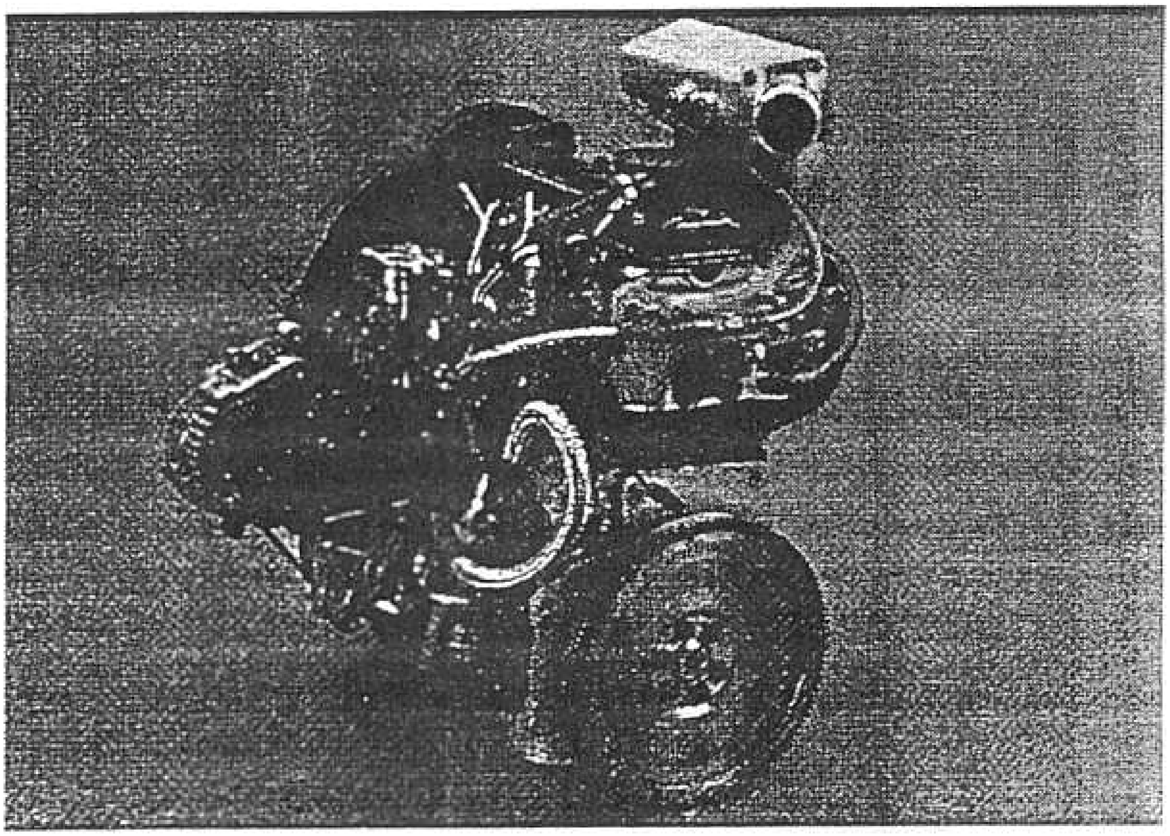

Fig. 10
The 1.9 l R*TDI® engine

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Dry Sump Lubrication

The vehicle was lowered for the '97 season. For this purpose, it was necessary to fit a shallow oil sump with a dry sump lubrication system. The series production hydraulic pressure pump was re-engineered into a bilge pump and a hydraulic pressure pump was installed instead of the vacuum pump. The connection to the oil tank in the front end is by means of adapter pieces and hoses.

Technical Data of the R*TDI® Engine

Basic engine	81 kW TDI® series production engine Four-cylinder four-stroke in-line engine
Displacement	1896 l
Cylinder gap	88 mm
Cylinder bore	79.5 mm
Piston Stroke	95.5 mm
Connecting rod length	144 mm
Crankshaft main bearing diameter	54 mm
Conrod bearing diameter	47.8 mm
Compression ratio	17.5
Valve train	OHC
Fuel injection pump	Bosch VP 37
Injector nozzles	Bosch DSLA five-orifice nozzles
Supercharging	Garrett VNT 20 turbocharger with variable turbine geometry and intercooling
Engine control system	Bosch EDC 15 with 16-bit microprocessor control of injection system and boost pressure
Rated power	140 kW (190 h.p.) at 4000 rpm
Maximum torque	350 Nm at 3500 rpm
Maximum BMEP	23.2 bar
Maximum boost pressure	2.87 bar
Maximum cylinder pressure	185 bar

Full-load Values of the R*TDI® Engine

Optimizing the operating method permitted a specific power output of 73.7 kW/l to be achieved with a smoke number of 2.5 Bosch (Fig. 11).

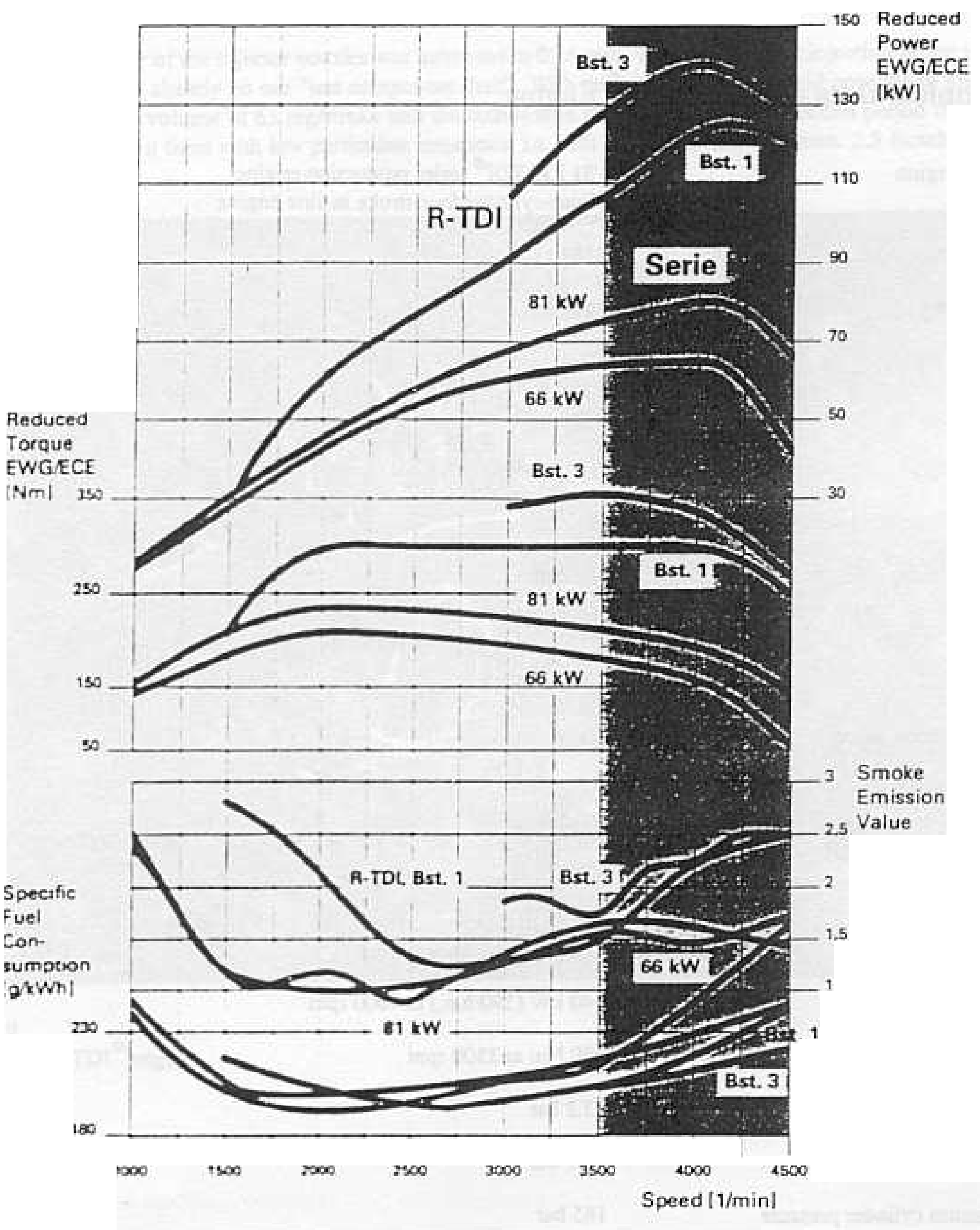

Fig. 11
Full-load values at different power output levels of the 1.9 l TDI® engine

At rated power and 4000 rpm, the fuel consumption of build 3 of the R*TDI® engine in its construction stage 3 version is 222 g/kWh. It has been possible to increase the torque to 350 Nm at 3500 rpm. The minimum measured fuel consumption of 194.6 g/kWh corresponds to an efficiency of 44.2 % in comparison to 43.8 % as in the series production engine.

Summary

In 1996 and 1997, our R*TDI® Golfs raced in the 24-hour events at the Nürburgring/Germany and at Spa-Franchorchamps/Belgium, as well as in some of the Veedol Cup races over about 3.5 hours at the Nürburgring.

Out of 12 races in all, our cars failed to finish on just three occasions, once due to a damaged engine and twice as a result of crashes. The R*TDI® engines thus amply demonstrated their performance and endurance capabilities.

Our best result was the second place in this year's 24-hour race at the Nürburgring. At Spa, the Golf R*TDI® came fourth behind two petrol-engined super saloon cars and one diesel-engined super saloon. A continuous improvement in the engine and the vehicle is apparent. We also intend to take part in saloon car challenge races next year. We're looking forward to some exciting racing.

4. Prospects

Is There a Future in Diesel-engined Motor Racing?

The diesel engine has long since put to rest its old image of being loud, dull and sluggish. Powerful engines and reduced environmental impact are not mutually exclusive. At the same time, the self-imposed smoke number of 2.5 Bosch should be maintained, because smoky diesel engines will soon find themselves banned from racing tracks once again. With its effective efficiency of 44.2 %, the racing diesel has set new standards for engines of this size. With an accordingly structured racing formula, naturally aspirated petrol engines and supercharged diesel engines could compete with one another in endurance motor racing and possibly also in rallies. The broad range of technologies would quicken the spectators' interest.

As long as the racing diesel engines are derived from series production engines, there remains a fruitful level of feedback for series production development. Motor racing allows new techniques to be tested and preliminary development work to proceed without worrying about series production restrictions. Competition is a locomotive of progress in this instance.

Conflict of Interests between Power Output and Exhaust Emissions

All notable manufacturers of diesel engines for passenger cars are currently developing TDI® engines using different concepts. The objective is to solve conflicts of interest, such as that between power output and exhaust emissions. A high engine power output demands large injection orifices to give a short injection period, whereas low particulate emissions require small orifices for good atomization at low engine speeds and low load levels. The limited hydraulic performance of injection systems currently on the market limits the maximum power if specific exhaust emissions limits have to be maintained (Fig. 13).

With the current technology, the Euro 3 exhaust emissions limits can only be achieved by reducing engine power output. New diesel technologies will in future restore the freedom of action for further increases in power output, even in motor racing.

More powerful TDI® engines with larger displacements will in future offer the power-conscious customer an alternative to the corresponding petrol engines.

New TDI® Technology

The Euro 4 exhaust emissions values represent a further significant intensification of the limits. Additional work will have to be done on the DI combustion process, the injection system (e.g. higher injection pressures) and supercharging (e.g. boost pressure governing system) as well as exhaust post-treatment (e.g. NO_x catalytic converter) in order to bring heavier passenger cars and cars with automatic gearboxes into compliance with these limits as well. The emissions potential in improved diesel fuels has already been demonstrated. Comprehensive supplies will have to be assured.

Furthermore, monitoring of components relevant to exhaust emissions is prescribed (on-board diagnosis).

As far as fuel consumption is concerned, the small-capacity, direct injection diesel engine in conjunction with an intelligent engine management system in lightweight vehicles will be able to achieve the extreme consumption target of more than 90 mpg within the foreseeable future, thereby setting new standards.

Further improvements can be expected in engine noise and vibrations.

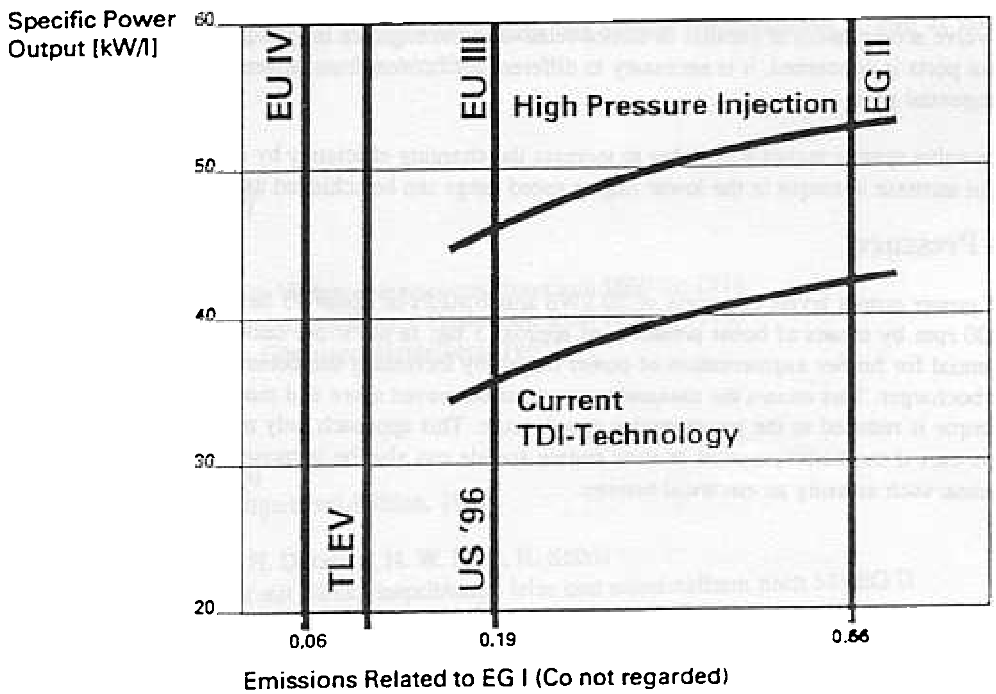

Fig. 13
Correlation between achievable specific power output and the exhaust emission laws which have to be observed with the 1.9 l TDI® engine

High Pressure Injection

The conflict of interests between power output and exhaust emissions can be better solved by a further increase in injection pressure up to 2000 bar and more. High pressure injection displaces more of the mixture formation energy to the injection side, thereby opening up new freedom of action for increasing the BMEP throughout the entire speed range. The following maximum injection pressures can be achieved nowadays with the injection systems of the future:

* Common rail	1350 bar
* Hydraulic pump nozzle	1800 bar
* Pump nozzle	2000 bar

Further potential is afforded by injection rate structuring involving injecting some of the volume in advance and perhaps also by employing injector nozzles with a variable cross-section.

Four-valve Cylinder Head

The major advantage of the four-valve concept in the direct injection diesel engine is that the injector nozzles are positioned centrally and in parallel to the axis of the cylinder. This means the fuel is distributed more evenly throughout the air and improves air utilization.

The four-valve head demands very carefully designed and configured charge changing ducts. If development starts from a very good twin-valve base, the four-valve engine must also be significantly optimized with regard to swirl and throughflow in order to produce any notable benefit. A decision needs to be taken about whether to put the valve arrangement in parallel or turned relative to the engine's longitudinal axis. As far as the design of the intake ports is concerned, it is necessary to differentiate between two tangential ports and combining a swirl and a tangential port.

The four-valve system makes it possible to increase the charging efficiency by approx. 10 % in the rated power range. An increase in torque in the lower engine speed range can be achieved using a ram intake system.

Boost Pressure

Specific power output levels in excess of 70 kW/l and BMEPs of about 45 bar are achieved in truck racing at only 2200 rpm by means of boost pressures of approx. 5 bar. In the super saloon racing diesel engine, there is also potential for further augmentation of power output by increasing the boost pressure using an appropriately sized turbocharger. This causes the maximum torque to be moved more and more towards higher engine speeds whilst torque is reduced in the lower engine speed range. This approach only makes sense in series production passenger cars if the boost pressure at low engine speeds can also be increased under transient conditions by other means, such as using an electrical booster.

Summary

Volkswagen four-cylinder TDI® engines with twin-valve cylinder heads have established milestones in the development of series production vehicles:

* First "five litre car" of the Golf class

  First direct injection engine to comply with Euro 2 exhaust emissions limits

* Specific power output 42.7 kW/l

* Maximum BMEP 15.5 bar

* First direct injection engine in the U.S. market including California

* First direct injection engine for passenger cars to comply with D3 exhaust emissions limits

Even after the appearance of the first four-valve direct injection engines, twin-valve TDI® engines remain amongst the leaders when it comes to specific engine ratings.

Racing diesel engines in the super saloon car sector are just at the outset of their development. Competition will accelerate the race for increased power output. With a specific power output in excess of 70 kW/l, they have already closed the gap to the racing truck engines. By employing all the future technologies in the diesel sector, it looks as if it will be possible to reach the 100 kW/l limit in motor racing within the not too far distant future.

In future, fiercer competitive pressure will mean there will be more to selling cars than simply satisfying all statutory regulations - a motor car will also have to generate enthusiasm amongst its buyers. Consequently, an engine will have to do more than satisfy the customer's expectations. All notable manufacturers of diesel engines for passenger cars are currently developing TDI® engines using different concepts. New diesel technologies in the engine, engine management system and exhaust post-treatment as well as improved diesel fuel will make it possible to achieve the objectives.

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