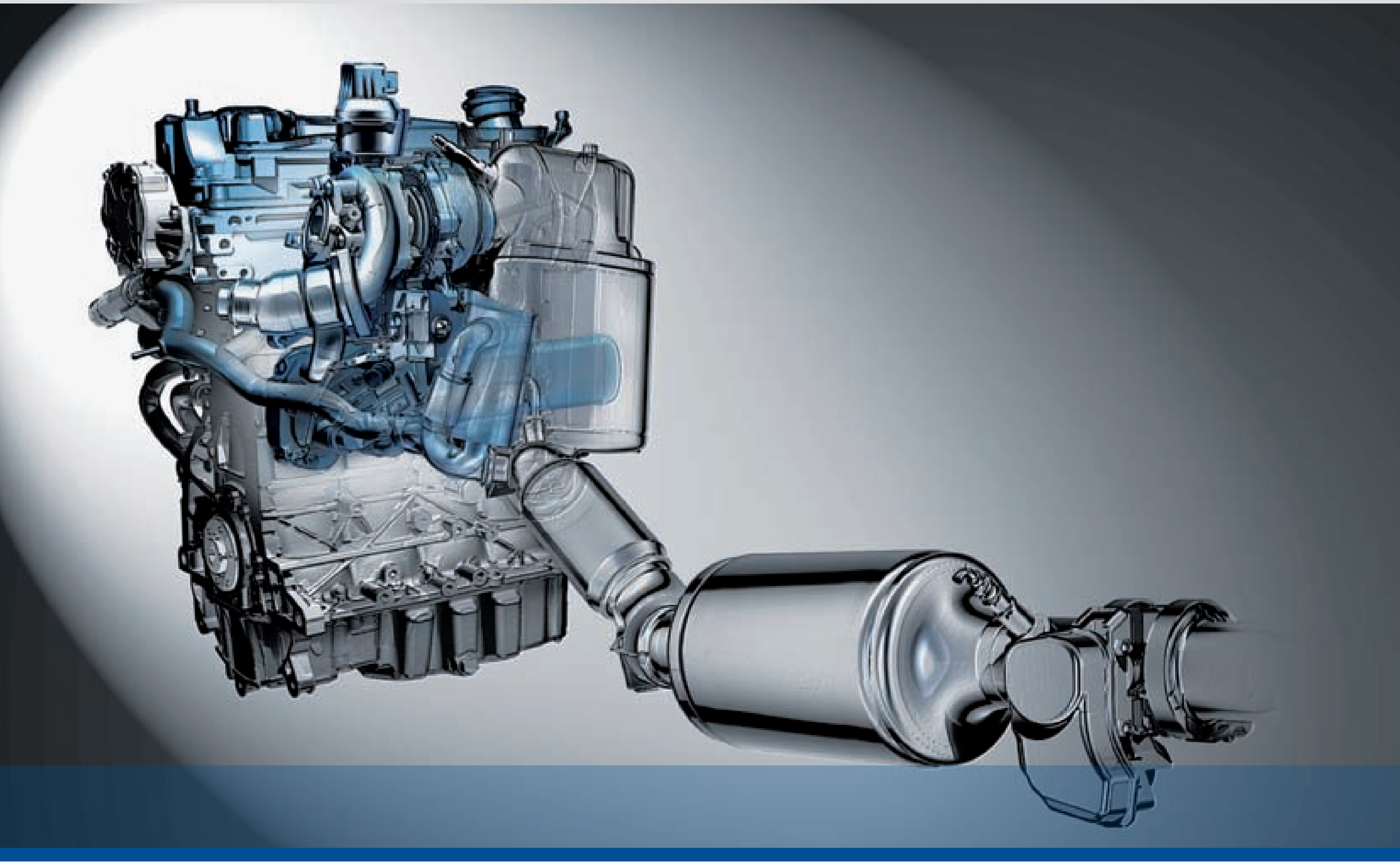


# Volkswagen's New 2.0 l TDI Engine for the Most Stringent Emission Standards – Part 1

Having already being launched in Europe in the VW Tiguan and Audi A4, Common Rail engines have been redeveloped to comply with the strictest exhaust fume limits in the world, namely the Tier 2 Bin5 emission legislation in the USA, and will consequently be launched in the VW Jetta there mid-2008. As well as internal engine features like an optimised injection system, a low-pressure exhaust gas recirculation system and a new method of cylinder pressure control, a technical highlight is the implementation of an $NO_x$ exhaust gas aftertreatment system. These new engine components require the development of new control algorithms and intensive coordination of parameters for this entirely new combustion process.

## 1 Introduction

As a result of the low emission limits stipulated by Californian law, the market for diesel cars in the USA has remained stagnant at a low level. In contrast to the European automobile market, passenger cars with diesel engines are much less common in North America, in particular in the US, largely due to the fact that diesel engines have suffered from a poor image in the past. Nowadays, due to both a drastic rise in environmental awareness and the explosion in petrol prices, diesel engines are increasingly becoming a genuine alternative for American customers. It is primarily their significantly lower consumption and accordingly higher range that makes diesel engines attractive for American customers. Price differences between petrol and diesel are not significant however since there are no taxation benefits in place for diesel. Regardless of this upsurge in interest in diesel engines among American customers, certain challenges still need to be overcome from a technical point of view to enable a sustainable breakthrough to be achieved.

## 2 Development Objectives

The challenge for the new TDI engine with Common Rail is to restrict emissions to the lowest Bin5 limit values while ensuring a stable combustion and taking into account differences in fuel qualities. The introduction of the regulated $NO_x$ reservoir catalytic converter places additional requirements on engine control and application, such as the need for a cyclical regeneration phase to function properly. The introduction of low emission vehicles in model year 2009 also places new requirements on the OBD system resulting from the strict standards of the Californian legislation. The law primarily affects emissionsrelated threshold value diagnoses.

The technical challenge with regard to the reduction of particulate and $NO_x$ emissions when compared to the previous Bin10 limit is illustrated in **Figure 1**. Based on the 2.0 liter TDI Common Rail engine with four valves, redevelopments to meet the Tier 2 Bin5 norm produce the technical data shown in the **Table**.

## 3 Engine Related Changes

Meeting the low limit values for particulate matters and $NO_x$ requires comprehensive improvements in engine combustion in order to achieve significant reductions in raw emissions. Component changes and additional engine components for improving raw emissions are primarily concentrated in the areas of injector design, optimisation of the high pressure injection pump, regulation of the injection moulding sequence supported by a cylinder pressure-based engine control system and in the introduction of the high and low pressure exhaust gas recirculation system (dual circuit EGR system) [1].

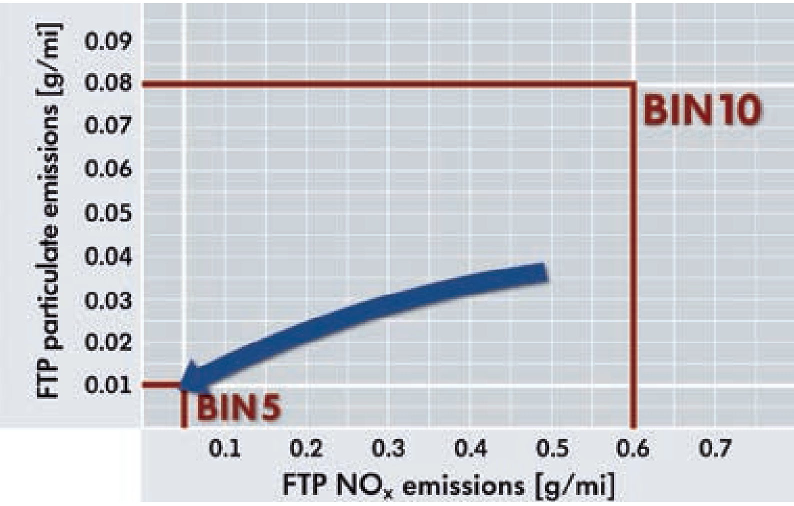


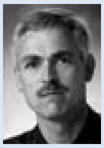

**Figure 1:** Emissions targets for the fulfilment of Tier 2 Bin5 limits

## The Authors


**Dr.-Ing. Jens Hadler** is Executive Director Powertrain Development at Volkswagen AG in Wolfsburg (Germany).

**Dipl.-Ing. Falko Rudolph** is Head of Diesel Engineering at Volkswa-gen AG in Wolfsburg (Germany).

**Dipl.-Ing. Richard Dorenkamp** is Head of Department Lowest Emission Engines and Exhaust Aftertreatments at Volkswagen AG in Wolfsburg (Germany).



**Dipl.-Ing. H. Stehr** is Group Leader Diesel Engine Combustion at Volkswagen AG in Wolfsburg (Germany).

**Dipl.-Ing. J. Hilzendeger** is Group Leader Diesel Engine Durability and Design at Volkswagen AG in Wolfsburg (Germany).

**Dr. rer. nat. Sebastian Kranzusch** is Group Leader Power Electronics and Ignition, Drivetrain Electronics at Volkswagen AG in Wolfsburg (Germany).

### 3.1 Emission-optimised Design of the Injector

The injector of the EU5 basis engine, with its 1800 bar Piezo technology and the mini blind hole nozzle with eight conical flow-optimised spray orifices, was used for the 2.0 liter CR Tier 2 Bin5 engine [2]. The spray cone angle, at 162°, was adapted to the emission-optimised piston bowl. While the EU5-type engines have a nozzle flow of 785 $cm^3$/min with an orifice diameter of 0.123 mm, the Bin5 engine implements the emissions-reducing potential of smaller spray orifices together with higher rail pressures.

Across nearly the entire engine map, significantly higher rail pressures have been achieved without increasing the combustion noise. This enables a reduction of particle and raw emissions at nearly-constant consumption and nitrogen oxide emission levels. A nozzle flow of 705 $cm^3$/min with a spray orifice diameter of 0.117 mm have emerged as the optimal specifications for a Bin5 engine with 103 kW output.

**Table:** Parameters of the 2.0 l TDI Tier 2 Bin5 engine

| | |
|---|---|
| **Numbers of cylinders / valves per cylinder** | 4 / 4 |
| **Displacement** | 1968 $cm^3$ |
| **Bore** | 81 mm |
| **Stroke** | 95,5 mm |
| **Cylinder spacing** | 88 mm |
| **Compression ratio** | 16,5 |
| **Weight (DIN 70020-7) / manual gearbox** | 165 kg |
| **Power / at engine speed** | 103 kW / 4000 rpm |
| **Torque / at engine speed** | 320 Nm / 1750 ... 2500 rpm |
| **Emission level** | Tier 2 Bin5 |

Another important feature of the optimised nozzle is the new manufacturing method for rounding the injector orifice inlets, called „Advanced EDM" (Electrical Discharge Machining), which significantly increases the efficiency of the nozzle and thus enables realisation of the tiniest injector orifices with high specific performance. In conjunction with a reduced injector orifice length of 0.85 mm, the new EDM method also enables a reduction of the surface sensitivity.

It also utilises the newly developed needle valve seat from Bosch with inverse seat angle difference and undercut (ZHI-DR), which drastically improves fuel quantity drift behaviour.

Compared to the EU5, the tolerances for elevation angle and the diameter of the injector orifices are reduced by half, significantly narrowing the range of emissions. **Figure 2** shows a comparison of the characteristic values of the nozzles.

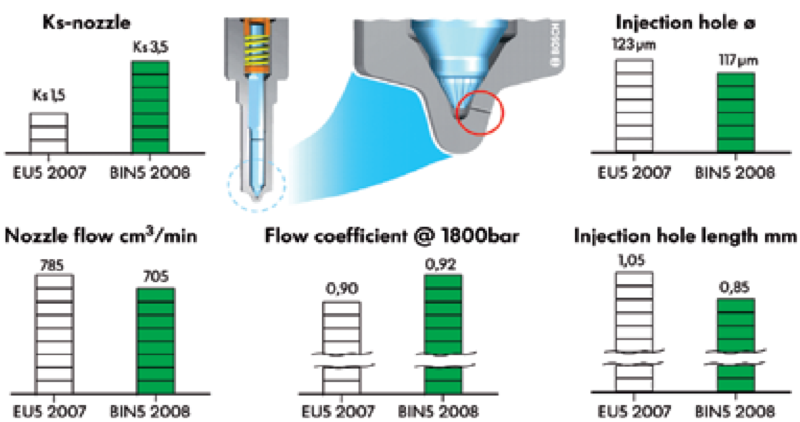



**Figure 2:** Characteristics values of the Bin5 nozzle design compared to the EU5 basis

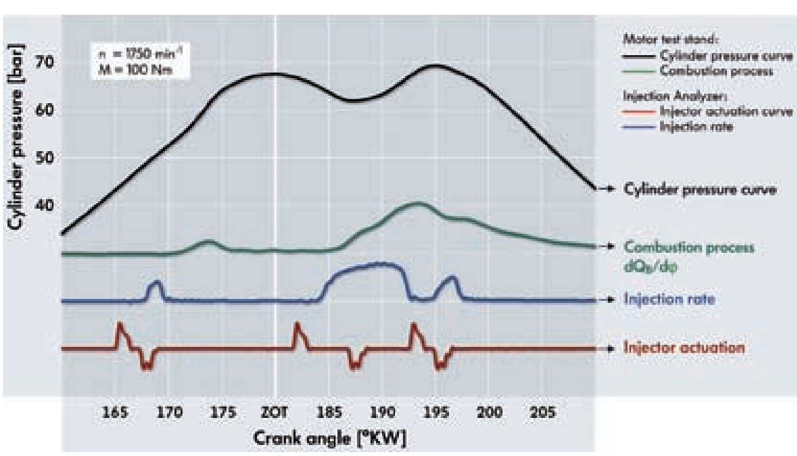



**Figure 3:** "Split Main Injection" – injection sequences

### 3.2 Potential of New Injection Strategies

High potential for improvement of the particulate/$NO_x$ trade-off is offered by the piezo Common Rail system due to its high dosage precision, especially at low injection quantities. This makes it possible to apply very small pre- and post injection quantities at extremely small intervals for stable combustion.

Of note in the engine application is the use of post injection or split main injection for particulate post oxidation in a broad load and speed range, **Figure 3**.

In the engine map, an optimal value for post injection quantity and the offset from the main injection was determined, which enabled an over 20 % reduction of the particulate filter load at constant $NO_x$ values compared to the basis application.

As a coupled post injection causes the torque to vary according to position and quantity, engine management without closed-loop control, and in particular a torque-neutral post injection variation, would be difficult to achieve.

A cylinder pressure-based engine control, by contrast, which sees its introduction into standard production in this engine, enables even non-stationary engine operation with post injection without any affects on performance or acoustics.

### 3.3 High Pressure Injection Pump

The Bin5 variant of the 2.0l 4V TDI engine utilises the CP4.1 high pressure pump from Bosch. The design of this pump corresponds to the EU5 variant. The single piston pump is characterised by a very high pressure potential even at low pump speeds, good hydraulic efficiency and injection-synchronous conveyance. This positively affects emission quality, fuel consumption and engine smoothness. Further development of the high pressure pump became necessary as a result of the higher requirements engendered by the fuel quality in the U.S.

To counteract greater wear due to higher water content and contamination, as well as reduced lubricity, the Bin5 high pressure pump was equipped with an anti-wear package. This includes diamond like carbon (DLC) coating of the high pressure piston on the top and shell surfaces as well as optimised heat treatment of the aluminium cast housing, **Figure 4**.

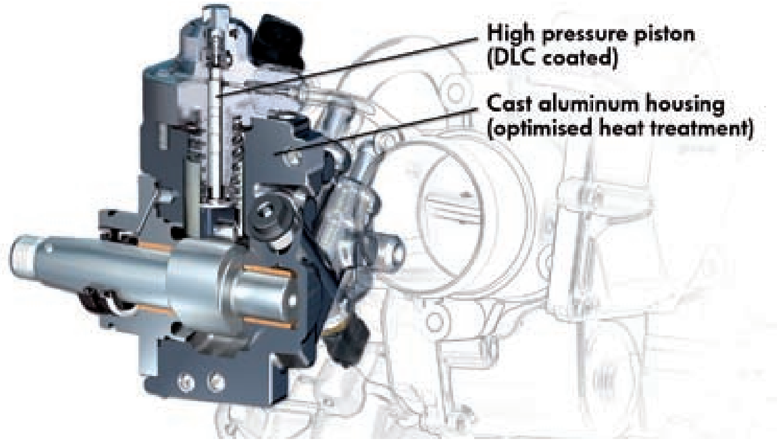



**Figure 4:** Bosch CP4.1 injection pump

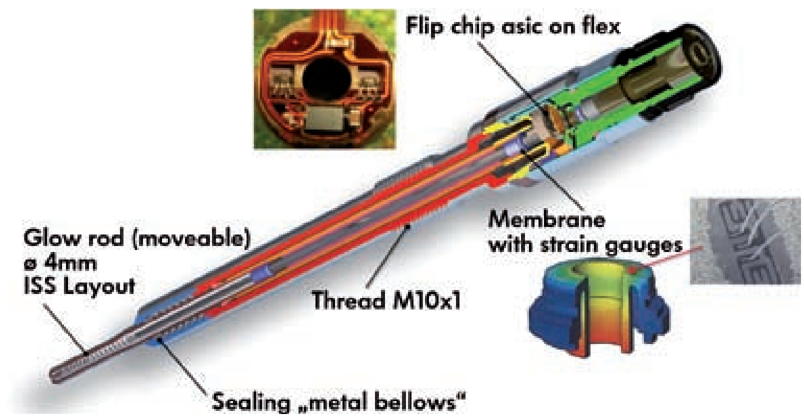



**Figure 5:** Structure of the cylinder pressure sensor

### 3.4 Cylinder Pressure Regulation

To achieve the lowest emission limits, it is necessary to reduce system tolerances to a minimum. The combustion pressure-regulated engine management developed by Volkswagen and launched in this engine makes a significant contribution to reaching this goal. The new system is a pressure-based combustion regulation system which enables fast, cylinder-specific regulation of the indexed torque and the centre of combustion.

#### 3.4.1 Structure and Function of the Cylinder Pressure Sensors

An important part of the combustion regulator is the cylinder pressure sensor, which was developed for production in conjunction with Beru [3]. The cylinder pressure sensor measures the combustion pressure per cylinder and returns the signal to the engine control unit, which calculates the required cylinder pressure characteristics from the measured signal. The cylinder pressure signal is determined directly by measuring the pressure via a connection to the combustion chamber in order to ensure the required precision of the sensor. Due to the compact design in the glow plug, in the pressure sensor, **Figure 5**, it was possible to maintain the dimensions of a serial glow plug (ISS rapid start plug) in the plug shaft as well as in the combustion chamber, and thus utilise the cylinder head thread dimension (M10) of the EU5 engine.

The function is based on the effect of the combustion chamber pressure exerted on the heating rod. The heating rod, in contrast to the serial glow plug, is positioned so as to be movable and transfers the pressure via an extension to a steel membrane, thereby deforming it. On the membrane there are resistance strain gauges, whose resistance changes as a result of their deformation. Based on the change in resistance, the integrated electronics with Flip chip ASIC calculate a tension which is proportional to the combustion chamber pressure. The temperature dependency of the resistance strain gauges is corrected by a subsequent shift.

The characteristics of the cylinder pressure sensors were tested with regard to long term stability, vibration behaviour and electromagnetic disturbance coupling in multiple engine and vehicle tests. Compared to water-cooled quartz sensors (reference sensors), the tests showed a good correlation between the measurement results.

#### 3.4.2 Control

The basis for this combustion control is a precise, real-time calculation of the regulation variables. This also involves calculating the two combustion characteristics centre of combustion $AQ_{50}$ and indexed torque $M_i$, for each of the cylinders based on the respective cylinder pressure signal.

Both variables are recorded and regulated for each cylinder, whereby each cylinder is regarded as a separate controlled system. For the calculation of the two cylinder pressure characteristics $AQ_{50}$ and $M_i$, the cylinder pressure curves are scanned, digitised and saved from -180° to 180° from the upper DC in 1° crank angle steps. The indexed mean pressure of high pressure phase $p_{mi\_HP}$ can be determined from the circular integral above the cylinder volume from a -180° to 180° crank angle, **Figure 6**.

In order to determine the centre of combustion, it is necessary to determine the differential heat curve $\Delta_{QHR}$ (derived from [4]) in accordance with the φ crank angle. The integral heat curve is determined by means of numerical integration of the smoothed differential heat curve $\Delta_{QHR,f}$. The crank angle position, the integral heat curve $AQ_{50}$, is determined using the maximum and minimum of the integral heat curve.

The simplified illustration of the structure of the combustion regulator is primarily comprised of a cylinder-specific two variable control for the indexed torque and the combustion centre as well as the previously described calculation of the cylinder pressure characteristics. The structure of the injection control („lower“ path) is equivalent to the conventional engine control and functions in the new regulated system as a pilot control for the combustion control. Furthermore, the controlled structure is influenced by the cylinder pressure control: Firstly, the position control of the centre of combustion generates a parameter that corrects the start duration of the main injection. Secondly, the engine‘s target torque is achieved by means of an additional correction of the main injection’s fuel quantity.

Differences in emissions primarily arise due to component tolerances for the engine and for key engine components as well as external disturbances not accounted for by the conventional diesel engine control. In this context, correct admeasurement of fuel mass and measurement of fresh air and exhaust gas recirculation mass in the cylinder becomes a key factor. Through a series of rigorous tests, it was demonstrated that control of the indexed torque in each cylinder through the combustion control significantly reduced dispersions of the injected overall fuel mass in the observed mapping areas and that utilising cylinder pressure-based combustion control significantly reduces the range of emissions as compared to conventional diesel engine control units, concerning particulate and $NO_x$ emissions. The cylinder pressure-based combustion control developed by Volkswagen opens completely new possibilities. These controls make it possible to correct inaccuracies in the fuel injection system due to ageing effects, component tolerances, fuel quality or varying operating conditions which lead to deviations in the indexed torque or the centre of combustion individually for each cylinder. In this way, transitions between different engine modes or injection strategies can be realised without being noticed by the driver.

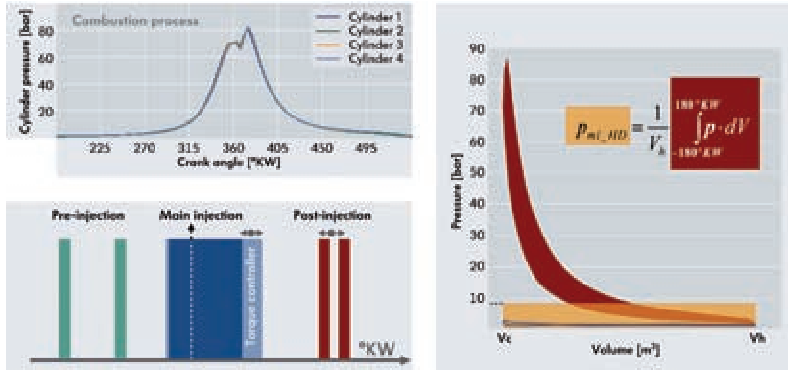



**Figure 6:** Determining the indexed mean pressure

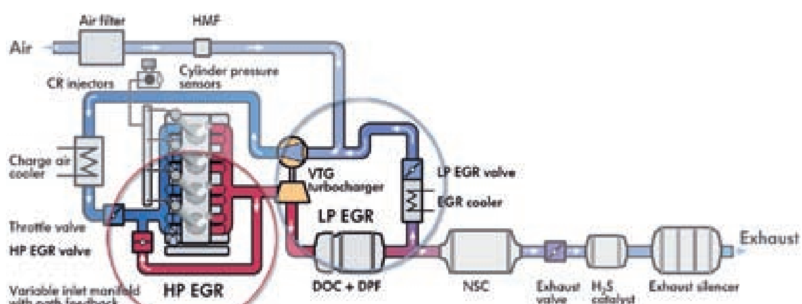



**Figure 7:** System illustration of the LP-EGR system

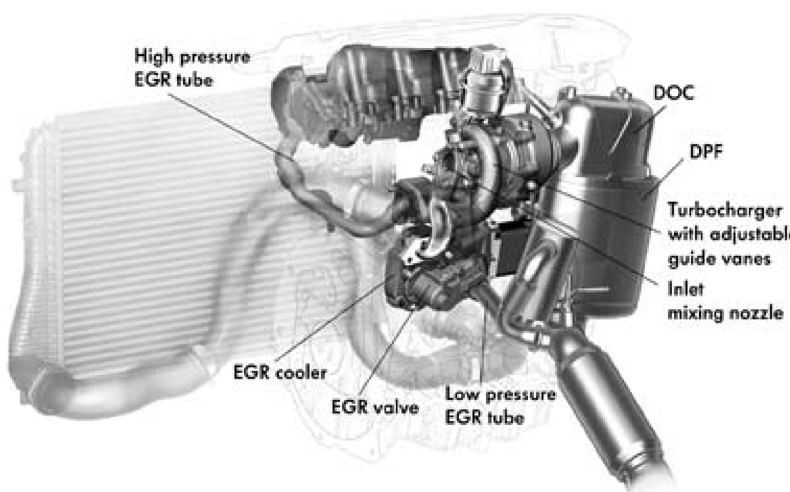



**Figure 8:** Components of the low pressure EGR system

This is a requirement for the application of a partially homogeneous combustion process in certain areas of the map.

### 3.5 High and Low Pressure EGR System

The most effective method of achieving engine-based reductions of $NO_x$ emissions is to maintain the highest possible exhaust gas recirculation rates with simultaneously high cylinder fill rates. Ideally, this is done across the entire engine map at the lowest possible gas mixture temperatures in the intake manifold. To achieve this, it was necessary to technically enhance, in part with a coolant, the high pressure EGR system which is so widely used in many applications today. A coherent technical solution is presented by the low pressure exhaust gas recirculation system (LP-EGR system) described below, which in combination with a high pressure EGR system in the 2.0l 4V TDI Bin5 engine is being introduced into standard production in a passenger vehicle for the first time worldwide, **Figure 7**.

In the LP-EGR system, the exhaust gas is first extracted behind the diesel particulate filter (DPF) near the engine. The catalytically cleaned and particulate-free exhaust gas is first circulated to a powerful stainless steel EGR cooler with more than 8 kW of cooling performance. When the electrically-controlled EGR valve is activated, the exhaust gas is channelled via a short connecting pipe in a newly designed mixing unit directly upstream of the compressor of the exhaust gas turbo charger into the intake air stream. The pressure gradient can be raised when using an electrically-controlled exhaust valve. This valve is positioned in the exhaust stream behind the $NO_x$ storage catalytic converter (NSC) and is operated together with the LP-EGR valve in an integrated control loop.

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**MTZ** WORLDWIDE

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05|2008 · May 2008 · Volume 69
**Vieweg+Teubner Verlag | GWV Fachverlage GmbH**
P.O. Box 15 46 · 65173 Wiesbaden · Germany
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Johannes Winterhagen (win)
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E-Mail: johannes.winterhagen@vieweg.de

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Engine
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E-Mail: richard.backhaus@rb-communications.de

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Ruben Danisch (rd)
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E-Mail: martina.schraad@vieweg.de

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Dipl.-Ing. Michael Reichenbach (rei)
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E-Mail: michael.reichenbach@vieweg.de

**English Language Consultant**
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**Permanent Contributors**
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Heiko Köllner
Phone +49 611 7878-177 · Fax +49 611 7878-464
E-Mail: heiko.koellner@gwv-fachverlage.de

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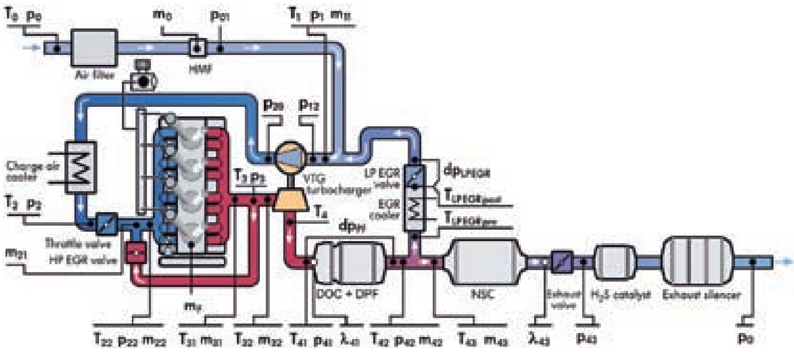


**Figure 9:** Model-based EGR control (ASmod)

(NSC) and is operated together with the LP-EGR valve in an integrated control loop.

The turbocharger of the 2.0l 4V TDI EU5 basis engine was optimised for use with the LP-EGR.

It features a pneumatically operated guide vane adjustment at the turbine; the respective current position of the guide vanes is detected by a position sensor. The compressor housing and the compressor wheel are coated to protect against acidic exhaust components. The pulsation damper flanged on to the compressor housing is made of stainless steel. After compression, the exhaust and airmass flow is again cooled in a high performance charge air cooler and channelled to the engine inlet manifold. **Figure 8** shows the central components of the EGR system and highlights their compact arrangement.

The fundamental advantages of the LP-EGR system are:

- nearly engine map-wide possibility of $NO_x$ emission reductions through exhaust gas recirculation
- EGR rates can be regulated independently of drops in charge air pressure
- low, homogeneously distributed $NO_x$ concentrations across the engine map
- low loss of exhaust gas enthalpy through extraction of exhaust gas energy after the turbocharger or particulate filter with simultaneous high air ratios
- nearly ideal equal distribution during exhaust gas recirculation through mixing in the diffuser in the compressor and in the charge air cooler
- improved boost pressure build-up with partial load and high EGR rates
- no sooting of the EGR cooler as exhaust gas is cleaned of particulates.

In addition to the LP-EGR system, the 2.0 l 4V TDI Bin5 engine also features a traditional high pressure EGR system. This dual circuit EGR system makes it possible to set almost any exhaust gas recirculation rate and selectable quantity ratio of high and low pressure EGR in any engine operating state, which also makes it possible to manipulate the intake manifold temperature at will. Thus it is possible, for example, to increase the proportion of high pressure EGR when external temperatures are very low in order to improve combustion stability. In case of fast changes to the load state, exhaust intake must be adjusted as nearly simultaneously as possible. In this case, the high pressure EGR control loop can compensate for delays in the low pressure system resulting from the increased gas circulation time through the charge air cooler.

## 3.6 Air Model and Control

The complex air management, with two exhaust gas recirculation systems and the increased requirements for exhaust gas after-treatment, necessitated a new type of model-based control and regulation structure, **Figure 9**. This new feature required extensive information about important status specifications in the air path. Thus an engine model was developed to map the physical behaviour of the air system and the exhaust train with a minimal number of sensors. In addition to all pressure values, temperature, mass flow rates in the air flow, the model also supplies information about raw emissions and the oxygen content in the intake manifold. To ensure the precision of the modelled signals about service life as well as series scattering, a new parameter adaptation was developed. This compares modelled and measured, as well as independently modelled signals with each other and corrects the affected parameters of the model according to the relevant operating point.

In addition to modelbased dew point activation of lambda probes, various diagnosis functions as well as load data collection for the particulate filter and the $NO_x$ storage catalytic converter, EGR rate control profits especially from the high precision of the modelled signals in dynamic operation. This enables individual or parallel control of the leading variables fresh air mass, HP-EGR rate and LP-EGR rate, for example. To decouple the various control loops, calculation of the control values for the individual actuators is model-based. While engine map control units have heretofore only assigned a particular position to the actuators according to the operating point, in this case the triggering effect is predefined and the algorithms determine the required positions independently.

Typical interference in air system regulation, such as dynamic pressure and temperature fluctuations or the load-dependent flow resistance of the particulate filter do not impair the performance of this new system. Furthermore, the newly developed system ensures that the various actuators do not interfere with each other with a coordinated control system. The new air flow regulation system therefore combines excellent performance with simple parameterisation and low use of resources.

*Read the second part of this article in MTZ 6/2008.*

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