OBJECTIVES

The modular transverse matrix (MQB) of the Volkswagen Group enables uniform processes within vehicle platforms to be carried out both during development and at production sites. The new modular diesel engine system (MDB) of Volkswagen is likewise based on a modular strategy [1]. It must be possible to implement both the performance and the emission versions for Euro 4 through Euro 6 on the same base module, ❶ [2, 3].

In order to implement the Euro 6 versions economically and, in regard to emissions, in the modular diesel engine system, the following goals were defined in the engine specifications:

- to take a modular approach without changes to the basic engine
- to use internal engine measures to reduce untreated emissions
- to exploit the advantages of close-coupled exhaust gas treatment
- to minimise pressure loss for exhaust gas recirculation and treatment
- to develop software in house
- to render in the gas model all functions relevant to the application for all emission standards.

MOST IMPORTANT COMPONENTS OF THE EURO 6 ENGINES

To meet Euro 6 standards, a variable valve train, high-pressure exhaust recirculation (HP EGR), a new cylinder-pressure regulation system and a 2000-bar injection system were added to the familiar 2.0-l and the 1.6-l TDI engines.

Depending on the conditions imposed by the vehicle, the close-coupled exhaust gas treatment module will have two Euro 6 versions, one with a NO_x storage catalytic converter (NSC) and the other with selective catalytic reduction (SCR) technology, ❷.

VARIABLE VALVE TRAIN

The variable valve train (VVT) with a camshaft adjuster used in the Euro 6 engines is the most important component for reducing emissions inside the engine. The implemented design enables

- high effective compression during cold starting and warming up
- low-emission combustion with very good soot/NO_x trade-off in the partial-load range

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THE EURO 6 ENGINES IN THE MODULAR DIESEL ENGINE SYSTEM OF VOLKSWAGEN

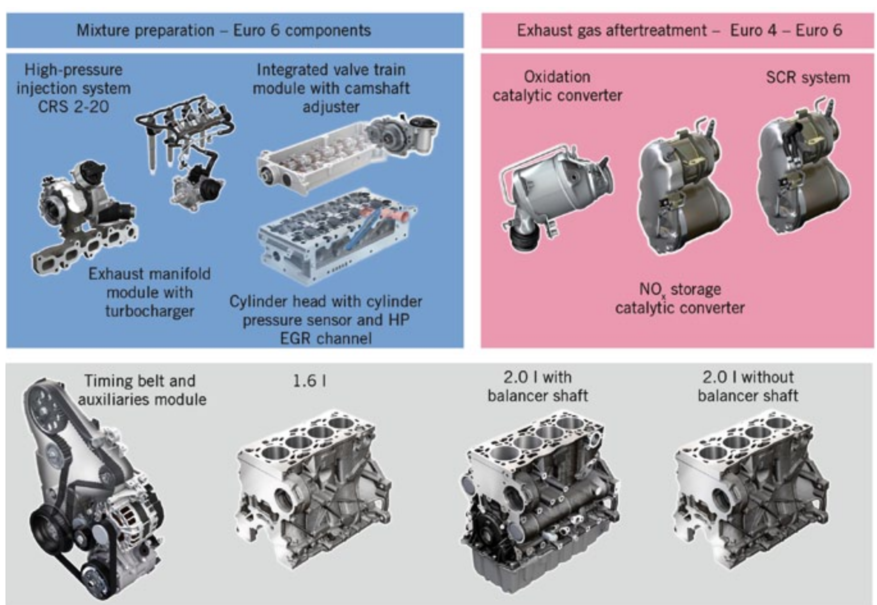
Following the introduction of the Euro 5 engines in the Volkswagen modular diesel engine system, the next step will be to implement additional internal engine measures and to integrate the deNO_x exhaust emissions aftertreatment for Euro 6 engines. The modular basis was already designed with the additional engine measures in mind and also permits the choice of using the NO_x storage catalytic converter or SCR technology.

: retention of good filling in the full-load range.

The basis of the VVT design is the familiar cylinder head with a rotated valve layout used in the Euro 5 engine, ❸. This enables the intake and exhaust valves to be situated one behind the other, respectively, from the perspective of the intake manifold flange. The camshaft adjuster can continually adjust the intake-side camshaft along with one intake and one exhaust valve per cylinder up to 50 °CA relative to the crankshaft. The camshaft adjuster is designed as a hydraulic rotary actuator, ❹.

The volume-flow regulated oil pump supplies oil pressure to the adjuster by means of a bore in the cylinder head. In addition, a pressure accumulator supports the adjustment process by providing the necessary quantity of oil quickly. In this way, it enables fast adjustment speeds even at low oil pressures. A non-return valve is fitted upstream to prevent the oil supply from running out through the engine's oil supply channels when the pressure is low.

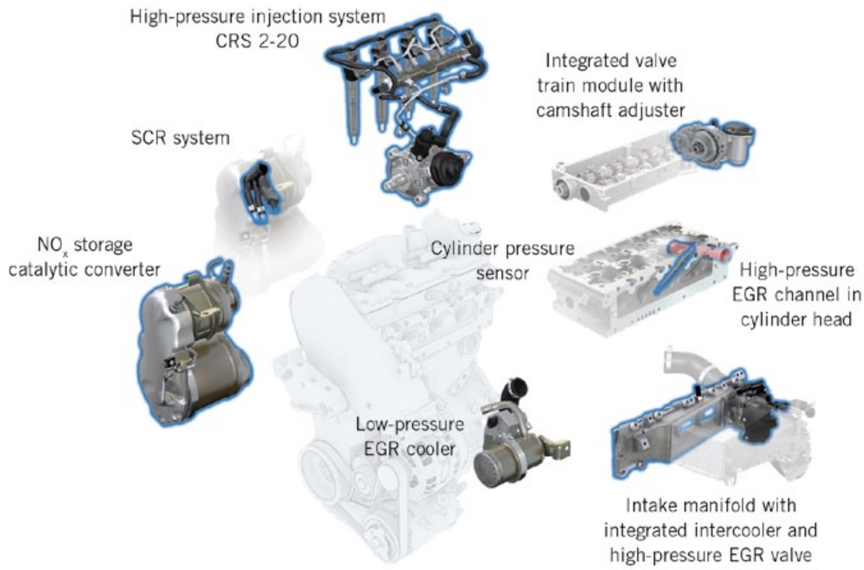
The adjustment of the camshaft, which is initiated by the engine control unit, is carried out by means of a 4/2-way proportional valve actuated by pulse-width modulation and integrated in the central valve bolt. The adjusting motion of the camshaft occurs when the valve applies oil pressure to the working chambers between the rotor and the stator of the rotary actuator. Together, the rotated valve layout and the camshaft adjuster enable greater variability in



		MDB 1.6 l	MDB 2.0 l	
Nominal output	kW at rpm	81 at 3500 – 4000	110 at 3500 – 4000	135 at 3500 – 4000
Nominal torque	Nm at rpm	250 at 1500 – 2750	320 at 1750 – 3000	380 at 1750 – 3000
Euro 4 standard	–	–	X	–
Euro 5 standard	–	X	X	X
Euro 6 standard	–	X	X	X

❶ Modular diesel engine system

valve timing, ❺. This variability generates, for example, a significant reduction in NO_x and soot emissions through the combination of increased swirl and reduced compression.



❷ Most important components of the Euro 6 TDI engines

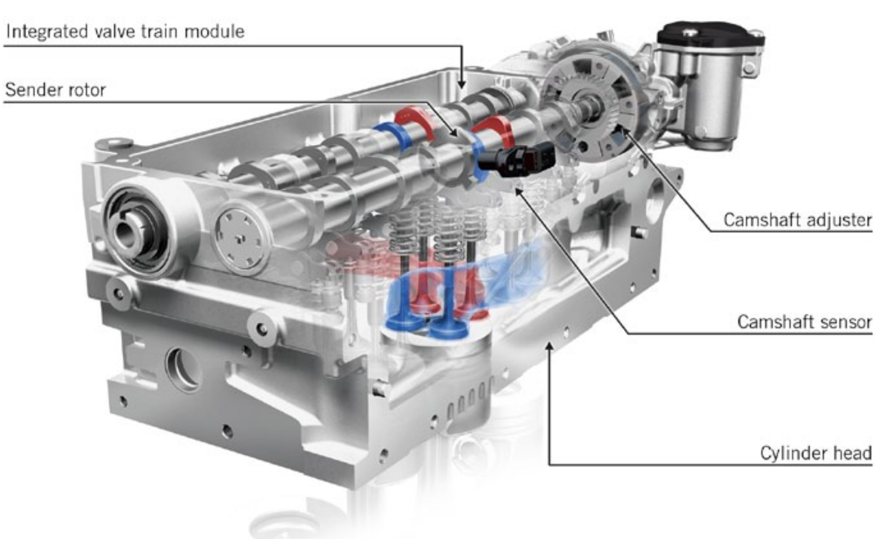
DUAL-CIRCUIT EGR SYSTEM: LINKED LOW- AND HIGH-PRESSURE EGR

The dual-circuit exhaust gas recirculation system comprises a cooled low-pressure EGR system (LP EGR) and the Euro 6-specific uncooled high-pressure EGR system (HP EGR). The uncooled exhaust gas is conducted through the cylinder head on the intake side of the engine and regulated by an HP EGR valve, ❻.

The increased demands on emissions behaviour in the Euro 6 emission standard require a reduction in emissions immediately following a cold start in the NEDC. In this situation, the uncooled high-pressure EGR is primarily employed. Furthermore, the addition of HP EGR also prevents the cooling of exhaust gas aftertreatment in the lower low-load range for engines at operating temperature.

CYLINDER PRESSURE REGULATION

In the Euro 6 engine, the combustion characteristics 50 % combusted, indexed average pressure, peak pressure and maximum pressure increase are calculated in real time on the basis of combustion pressure measurements in one cylinder. A model based on the highly resolved crankshaft speed is used to determine the characteristics of the other three cylinders. The actuation angle of the main injection is the regulating variable for the conversion rate regulation, and the duration of the main injection is the regulating variable for cylinder pressure equalisation. In conjunction with zero fuel-mass calibration, an equalisation of the pilot injection reaction with the main combustion with significantly better fuel sensitivity is possible. Quantity tolerances and injector drift which may occur can be compensated throughout the service life.



❸ Cylinder head with integrated valve train module and camshaft adjuster

INJECTION SYSTEM

The common rail system CRS 2-20 by Bosch with 2000-bar system pressure is used in the Euro 6 MDB engine. The system pressure, which has been increased in comparison to the Euro 5 engines, increases flexibility in shaping the course of combustion through the reduction of injection time and the nozzle flow volume. The CRI 2-20 model injector with solenoid valve is a further development of the CRI 2-18 injector used in the Euro 5 engines and is characterised by significantly faster start and end-of-actuation behaviour. The main areas of optimisation are an additional quantity of fuel in the form of a mini-rail in the injector body, the use of an innovative guide located near the seat and a nozzle in the form of a nano blind-hole nozzle.

CLOSE-COUPLED EXHAUST EMISSIONS TREATMENT

To achieve the Euro 6 exhaust emissions limits, a NO_x aftertreatment was added to the coated particulate filter and the oxidation catalytic converter in a manner similar to the close-coupled exhaust gas aftertreatment module of the Euro 5 engine. A NO_x storage catalytic converter (NSC) is used for small (light) vehicles. To fulfil Euro 6 emission standards in vehicles with greater mass as well, an SRC (selective catalytic reduction) system must be used.

EXHAUST SYSTEM WITH NO_x STORAGE CATALYTIC CONVERTER

The exhaust system has two oxygen sensors. The oxygen sensor upstream to the NO_x storage catalytic converter is responsible for the regulation of reduced-air operating modes. In addition, it provides the input value for the control unit's model for determining the engine's NO_x and soot emissions. With the help of the second oxygen sensor, an excess of reducing agent during the regeneration phase can be detected, from which the loading and ageing conditions of the NSC can be determined. The three temperature sensors integrated in the exhaust system provide the input values for the regulation of the regenerative operating modes and the exhaust gas temperature models, ❼.

REGENERATIVE OPERATING MODES

The extension of the exhaust gas aftertreatment system to include an NSC enabled the introduction of additional regenerative operating modes to ensure the conversion of NO_x. NO_x operation places high demands on the engine application. In spite of the significantly reduced fresh-air mass and the simultaneous increase in the injection quantity by means of multiple post-injections, the engine's torque and noise levels must not be affected in any driving situation. The oxygen concentration and the exhaust gas components necessary for the reduction of the stored NO_x mass are regulated by an oxygen sensor during the deNO_x phase. A model for determining the surface temperature of the NO_x storage catalytic converter is used to ensure that the converter works in the optimal range during the deNO_x phase, ❽.

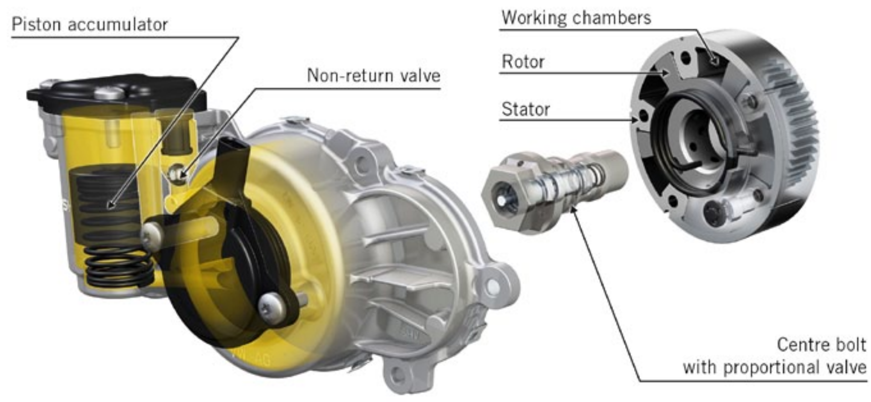
DeNO_x regeneration is triggered by a loading and unloading model calculated in the engine control unit. The loading of the NSC is simulated on the basis of saved NO_x storage curves, the calculated temperatures of the catalytic converter bed and the NO_x mass flows. A correction depending on thermal ageing guarantees the efficient operation of the NSC throughout the vehicle's service life. To determine the end of regeneration, the unloading of the NSC is modelled using the flow of reducing agent mass.

The formation of sulphates from the sulphur contained in diesel fuel steadily leads to the deactivation of the NSC. The engine control unit calculates the reduced storage capacity, taking the deNO_x requirement into consideration. As the NO_x conversion decreases and the sulphur loading limit is exceeded, desulphurisation (deSO_x operation) begins to reactivate the NSC. Due to the high thermal stability of the sulphate, significant desulphurisation in a reducing atmosphere will take place only at temperatures above approximately 620 °C. The engine control unit calculates the sulphur loading on the basis of a model and determines the time for desulphurisation. The sulphur content of maximum 10 ppm as prescribed in Europe results in a deSO_x interval of about 1000 km. To reduce the time required to heat the exhaust system, this process is always carried out in conjunction with particulate filter regeneration.

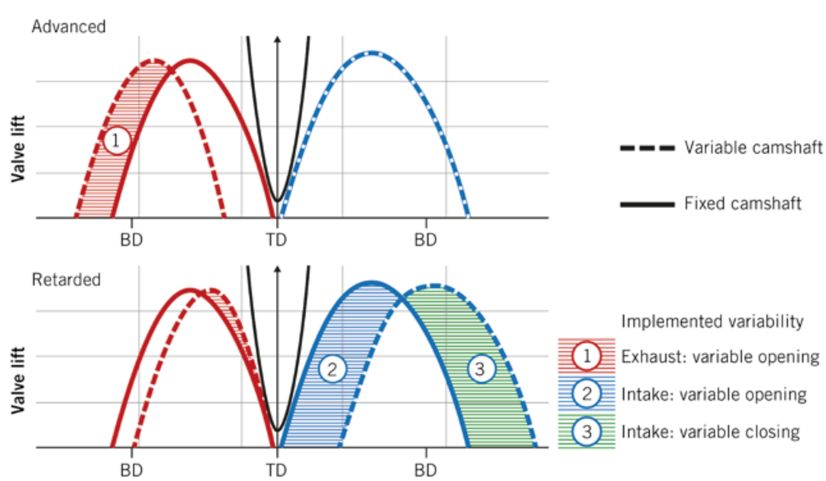
The introduction of new regenerative operating modes for nitrogen aftertreatment and desulphurisation results in more frequent alternation among combustion processes. These are called operating mode transitions. Sub-stoichiometric operating modes require special attention. For this purpose, special sets of functions were integrated into the gas system, and the requirements were taken into consideration during the creation of the operating mode coordinates and the planning of the operating modes. These measures make the transitions between modes imperceptible for the customer.

DESIGN OF THE SCR EXHAUST SYSTEM

❾ shows the design of the Euro 6 exhaust system, which is constructed in the same way as in vehicles for the US



❹ Camshaft adjuster



❺ Variability of valve timing

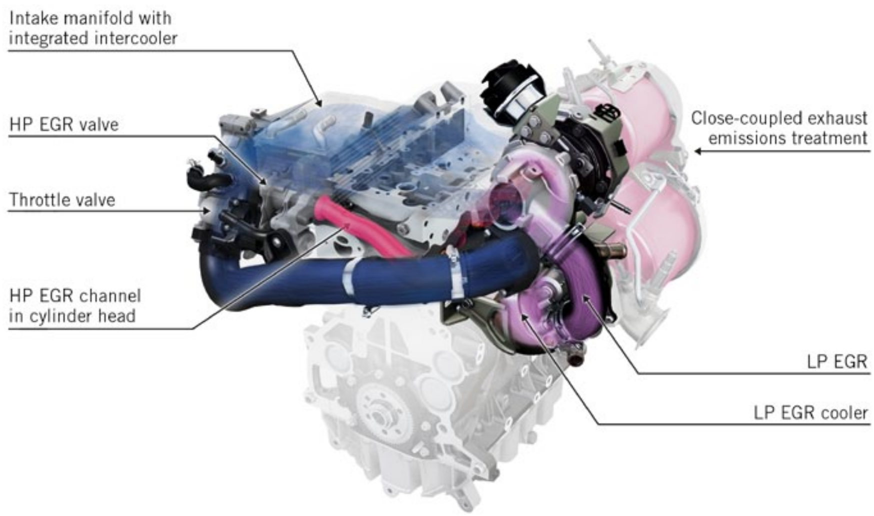
market to satisfy the strict Tier 2 BIN5 emission standard. The modular design of the Euro 5 exhaust system was modified in only the following points:

- diesel particulate filter with SCR coating
- adaptation of the connecting duct and the integration of a mixer for optimal ammonia distribution
- provision of water cooling for the SCR metering module
- high-temperature version of the SCR metering line.

The integration of the SCR coating in the particulate filter enables close-coupling of the system. Compared to the previous location of the SCR catalytic converter in the vehicle's underbody, this innovation results in a temperature advantage of about 30 K. Following the cold start of the engine, the working temperature of the SCR catalytic converter is attained faster and maintained longer at low-load operating modes. No further modifications to the engine for heating the catalytic converter are needed.

The application of the voluminous SCR coating to a close-coupled particulate filter requires that the coating be further developed just as the particulate filter substrate is. In this process, the following goals must be attained:

- increased thermal stability of the SCR coating
- homogeneity of the SCR coating on the particulate filter
- optimal properties in NO_x conversion and NH_3 storage behaviour
- low exhaust back pressure of component
- assurance of filtration efficiency (maintaining particulate limits for mass and number).

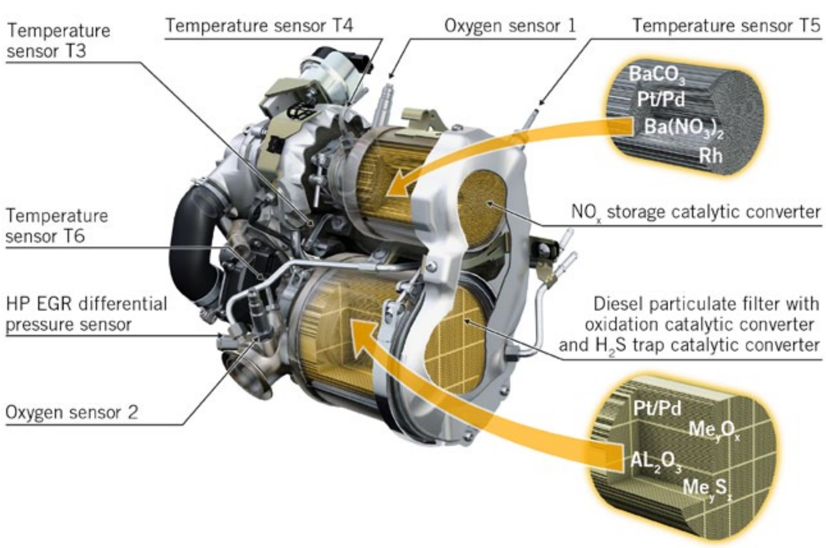


❻ Components of the dual-circuit exhaust gas recirculation system

Copper-zeolite is used as the catalytic converter, as it was in the former SCR system in the underbody. Its thermal stability was further developed for its integration in the particulate filter to ensure the SCR's performance even at high thermal loads during the particulate filter's regeneration throughout its service life.

To attain high coating quantity on the particulate filter without disadvantages in back-pressure behaviour, optimisation of the porosity, the pore size distribution and the thickness of the substrate's walls was necessary. Although the porosity of the filter was significantly increased, it was possible to maintain the particulate limits.

The SCR-coated DPF is followed by a trap catalytic converter which, with a combination coating of SCR and oxidation catalyst, is responsible for two tasks. The CO produced during soot regeneration is oxidised to CO_2 by means of a precious-metal coating. In addition, the trap catalytic converter eliminates the small quantities of NH_3 which escape the DPF at high temperature gradients.

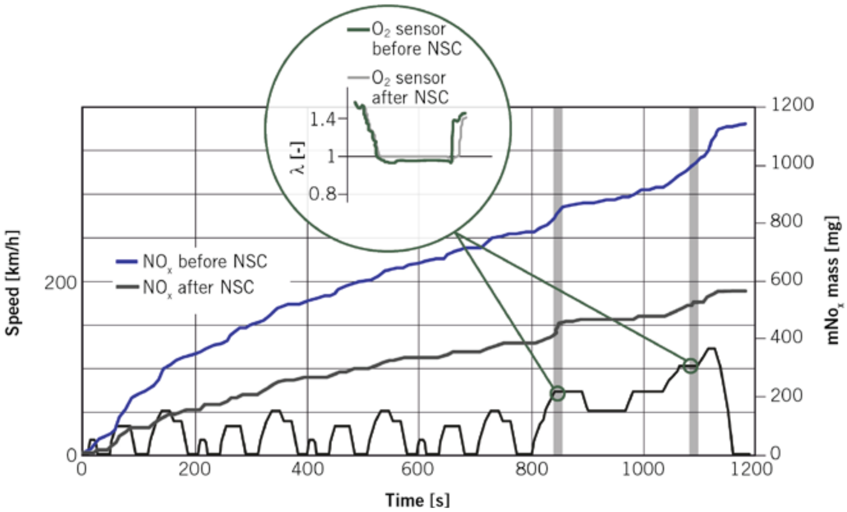


❼ Design of the exhaust system with NO_x storage catalytic converter

METERING MODULE, REDUCING AGENT PREPARATION AND INTRODUCTION

The aqueous urea solution AdBlue, which is required for the SCR process, is conducted through a metering line from the tank to the metering module. The position near the engine posed new challenges due to both the thermal and dynamic conditions and the maintenance of the reducing agent's temperature limit.

The SCR metering module is integrated behind the oxidation catalytic converter above the connecting duct so that the total volume in the duct is available for mixture preparation. Due to the high thermal load, air cooling is no longer sufficient, so the module is equipped with a water-cooling jacket which protects the electrical connection and the valve from overheating. The metering module is included in the engine's low-



❽ DeNO$_x$ strategy

temperature cooling circuit. The metering line is composed entirely of high-temperature resistant materials, so that no further insulation is required. In addition, the line is routed far enough from local heat sources that the heat transfer to the reducing agent is sufficiently low.

The limited installation space poses a major challenge for mixture preparation and requires an exact design of the spray pattern and mixer. The typical radially symmetrical spray does not fit the geometry of the modular exhaust system, so the spray pattern had to be modified. The mixer is located at a position in the connecting duct where it can attain the best compromise of equal distribution, exhaust back pressure and robustness in regard to component tolerances. This mixing design with baffles and swirl function enables good ammonia distribution in spite of the short distance for mixing.

SCR METERING SOFTWARE

During the development of the metering software, one goal was to fundamentally revise the model which had, until now, been designed for a separate SCR catalytic converter. First, the functional structures consisting of determining the specifications, calculating the loading and modelling the catalytic converter were extended. Second, precise consideration of NH_3 transport in the model is necessary for determining both the NH_3 loading and the conversion on the downstream catalytic converter substrate. For these reasons, an NH_3 adsorption/desorption model was developed and implemented, taking NH_3 oxidation into account. This model is responsible for determining the rate of transfer between the DPF and the trap catalytic converter on the basis of the state of equilibrium, the current loading and the metered quantity.

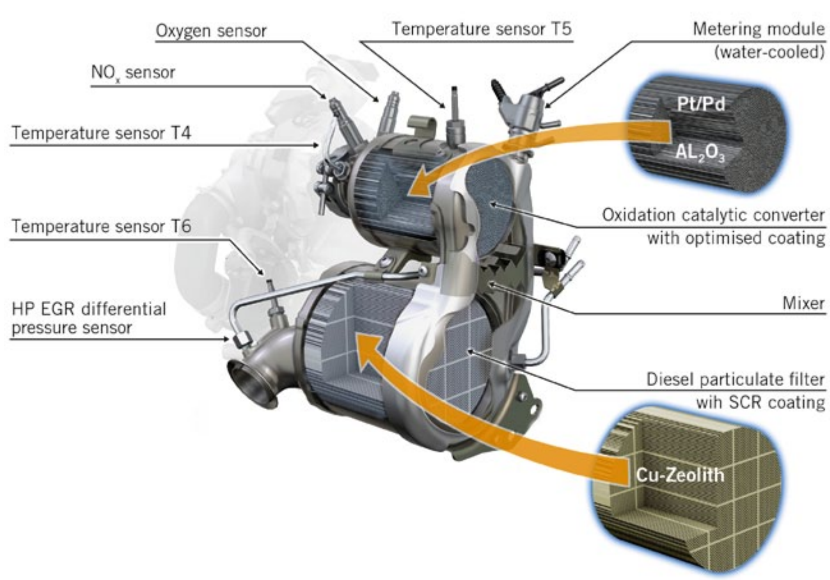
ENGINE-CONTROL SOFTWARE

The selected software structure is designed to be highly configurable so that the gas-system model is suitable for engines which meet various emission standards (Euro 4, Euro 5, Euro 6 and BIN5) and have various hardware versions. Precise control and regulation structures are required especially for maintaining the Euro 6 standard while simultaneously reducing CO_2.

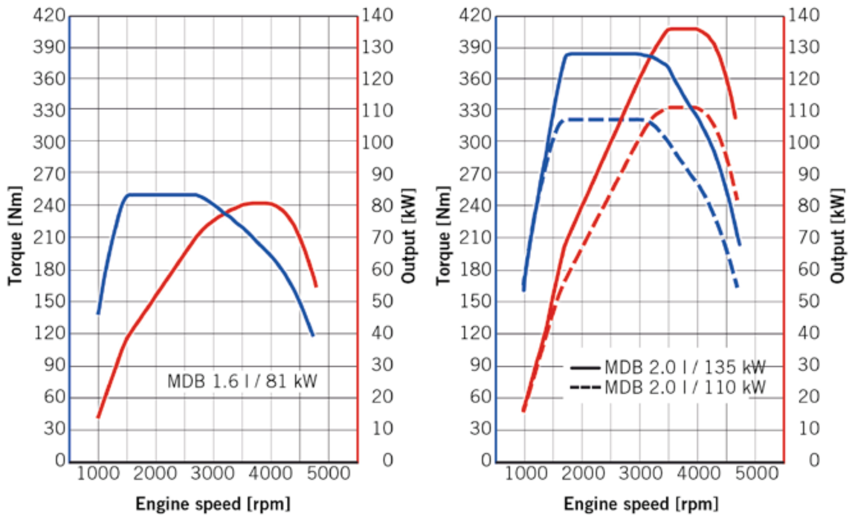
The scope of the model includes the modelling of values for the fresh-air and exhaust-gas paths of the diesel engine.

To attain a unique system state, a nominal value is assigned to each of the up to six gas-system actuators in the gas-system regulation. The structures of the nominal values are grouped into static and dynamic specifications. This permits the optimisation of emissions in dynamic operation as well. Because active exhaust gas aftertreatment is gaining importance, the structures of the nominal values are specially adapted to the operating mode systems. The regulating system is selected so that there is no switching between structures when the operating mode system changes. The physical values of the adjuster are converted to pressures and volume flows in the control unit, and then the required actuator positions are determined by the model-based control systems and regulators.

A further advantage of the gas system is that all control units from the various system manufacturers have the same functionality. Therefore, this scope was created as object code and can be integrated into the control unit software at the various system suppliers. Another scope in object code is the operating-



❾ Design of exhaust system with SCR system



		1.6 L / 81 KW	2.0 L / 110 KW	2.0 L / 135 KW
Top speed	km/h	195	216	230
Acceleration 0 – 100 km/h	s	10.5	8.6	7.1
Elasticity 80 – 120 km/h (4th gear)	s	9.5	7.0	5.7
Elasticity 80 – 120 km/h (5th gear)	s	13.0	9.5	7.5
Fuel consumption	l/100 km	3.8	4.1	4.2
CO_2 emissions/km NEDC	g/km	99	106	109

⑩ Full-load diagram (above) and vehicle results (below) of the Euro 6 TDI engines in the new Golf VII (Euro 6, manual transmission with front-wheel drive)

mode coordination, which controls the selection of the specified values.

The various combustion processes, such as particulate filter regeneration or $DeNO_x$ mode, are designated as operating modes. Development focused on the reciprocal effects of the normal combustion process and the exhaust gas aftertreatment strategies. To manage these complex interactions, a hierarchical structure was created in the operating-mode coordination. The operating-mode requests of the subordinate coordinators were prioritised by the superordinate positions in the hierarchy. They simultaneously control and monitor the interaction of various subordinate coordinators during complex regeneration processes, such as those which occur during the desulphurisation of the NO_x storage catalytic converter. The switching of the process data between the various operating modes is centrally controlled in the system coordinator. For this purpose, in addition to the next and the subsequent operating modes, the ramp factor for mode transitions is created and provided to user components which perform the changes.

PERFORMANCE, FUEL CONSUMPTION AND EMISSIONS

Overall, the new Euro 6 engine demonstrates the great potential of the modular diesel engine system in regard to performance, fuel consumption and emissions, ⑩. A substantial improvement in the soot/NO_x trade-off across the entire map range has been attained through the new level of flexibility provided by the VVT, the improved injection system and the cylinder-pressure regulation. In spite of stricter emissions requirements, fuel consumption could be maintained at the same level as the already optimised Euro 5 TDI engine. Moreover, particulate-mass emission remains unchanged in spite of stricter demands on untreated NO_x emissions.

SUMMARY

Thanks to state-of-the-art engineering, the engines of the modular diesel engine system have been developed to meet the future challenges of increasingly strict emissions legislation and increasingly demanding customer requirements. In combination with the so-called BlueMotion Technologies, the modular structure of this new design simultaneously provides the opportunity for further reductions in fuel consumption and potential for improved performance.

REFERENCES

[1] Neußer, H.-J.; Kahrstedt, J.; Jelden, H.; Engler, H.-J.; Dorenkamp, R.; Jauns-Seyfried, S.; Krause, S.: Die neue modulare TDI-Generation von Volkswagen. 33. International Vienna Motor Symposium, 2012

[2] Schmidt, A.; Wietholt, B.; Hilzendeger, J.; Müller, C.; Woelke, D.: Das Aufladekonzept der neuen modularen TDI-Generation von Volkswagen. 17th Supercharging Conference, Dresden, 2012

[3] Neußer, H.-J.; Thielecke, R.: Die neuen Motoren: ökonomisch, sauber, dynamisch. In: ATZextra Der neue VW Golf, 2012