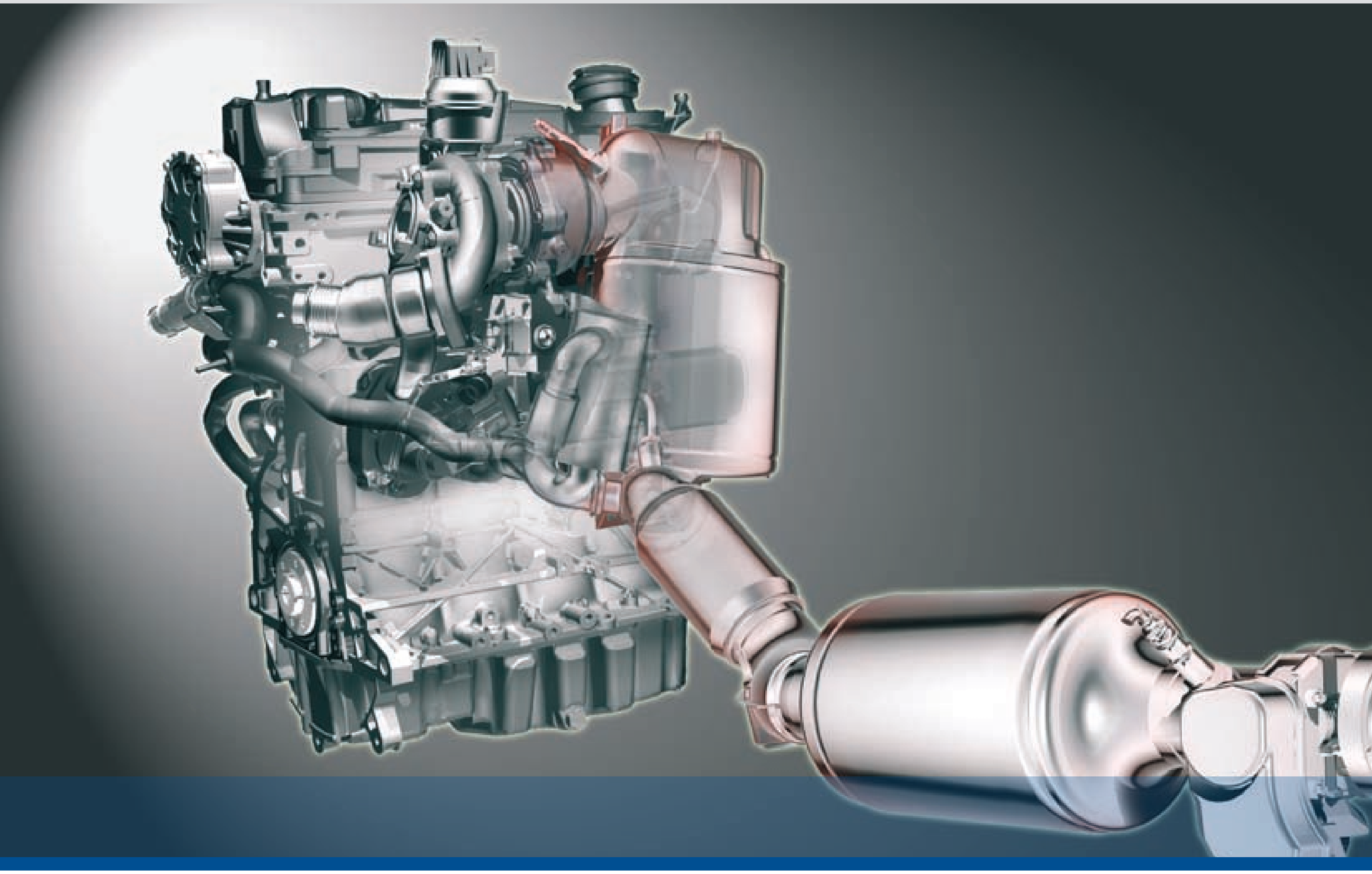

Volkswagen's New 2.0 l TDI Engine for the Most Stringent Emission Standards – Part 2

Beginning mid-2008, a vehicle will be sold on the US market that complies with the exhaust emission standards Tier 2 Bin5: the VW Jetta. This objective was achieved by applying modifications to the Euro 5 Common-Rail engine already available in Europe for the VW Tiguan and the Audi A4 and by introducing the NO_x exhaust gas aftertreatment system. The previous article provided information on the optimisation of the injection system and on the implementation of low-pressure exhaust gas recirculation and cylinder pressure control. These measures have a decisive impact on the improvement of the raw emissions, on the reduction of the emission range and on the reliability of the engine's operating procedure. The following article discusses the development of the NO_x exhaust gas aftertreatment system and the new operating-mode control for overall system management and also describes the OBD functions.

4 Exhaust Gas Aftertreatment

4.1 Exhaust System Structure

To attain the Tier 2 Bin5 threshold value for emissions, in addition to the comprehensive engine optimisations and the new developments for reducing raw emissions and for narrowing the distribution range of particle and NO_x emissions described in this document, an efficient system for exhaust gas aftertreatment is also required. A NO_x storage catalytic converter is to be used to supplement the established particulate filter system.

The modular system mounted close to the engine which consists of an oxidation catalytic converter and a coated particulate filter and which is already in use in the new 2.0 l TDI engines with four valves for Euro 5 in Europe [2], is distinguished by its extremely compact design **Figure 10**. The catalytic coating of these components has been adjusted to the special emission requirements, so that in addition to the high soot extraction rate, a high level of oxidation of CO and HC is ensured during its service life.

By placing the NO_x storage catalytic converter away from the engine in the vehicle underbody, thermal ageing is considerable reduced. This also has the advantage that CO and HC have already been oxidised by the oxidation catalytic converter and particulate filter for optimum NO_x conversion by the NO_x storage catalytic converter. The exhaust system has two lambda sensors. The lambda sensor upstream of the oxidation catalytic converter regulates the air-reduced operating modes for the NO_x s catalytic converter [3]. It is also used as the initial value for the air model stored in the engine control unit which, among other functions, serves to determine the model-based NO_x and soot emissions of the engine. The second lambda sensor, which is placed downstream of the NO_x storage catalytic converter, detects an excess of reduction medium in the regeneration phase; this is used to determine the load and ageing condition of the NO_x storage catalytic converter.

The three temperature sensors integrated in the exhaust system enable the OBD functions for the catalytic components and are used as initial values in the regulation of the regeneration operating modes and the exhaust temperature model.

4.2 Additional Engine Operating Modes for Exhaust Aftertreatment

4.2.1 DPF Regeneration

The process is already successfully established for the 2.0 l TDI Euro 5 engine for the regeneration of the particle filter to ensure its function over the entire characteristic range. The particulate filter is regenerated starting from a certain soot load threshold by an intervention in engine management. The regeneration time is determined in this process by the burning rate of the soot on the filter.

The regeneration temperatures and the oxygen surplus ($\lambda>1$) are regulated as a function of the soot load and driving condition in such a way that in addition to filter regeneration that is as complete as possible, the thermal load threshold of the filter is not exceeded.

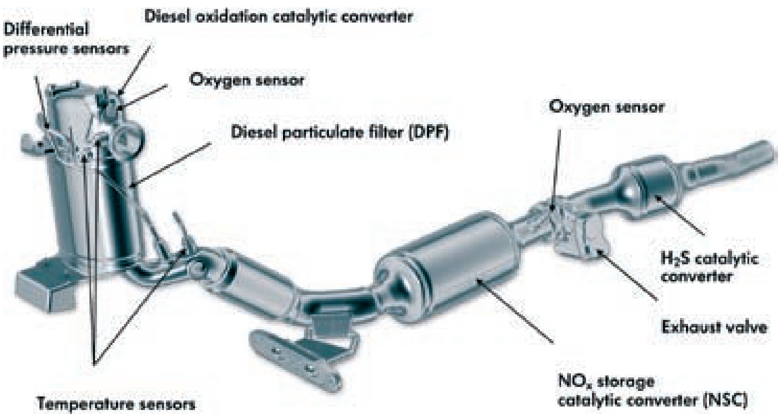

Figure 10: Structure of the exhaust system

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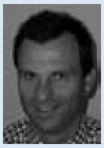

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4.2.2 DeNO$_x$ Mode

The enhancement of the exhaust aftertreatment system with a NO$_x$ storage catalytic converter necessitates the introduction of further, new regeneration modes to ensure the NO$_x$ conversion throughout the unit's service life.

Unlike particulate filter regeneration, a sub-stochiometric exhaust gas composition is necessary for the regeneration of the NO$_x$ storage catalytic converter (DeNO$_x$ mode). In λ<1 operation the nitrous oxides stored during lean operation are reduced by the exhaust enriched reduction media consisting of HC, CO and H_2.

In DeNO$_x$ mode, the temperature is set to between 250 °C and 450 °C.

4.2.3 DeSO$_x$ Mode

A further regeneration mode is provided by the sulphur removal of the NO$_x$ storage catalytic converter (DeSO$_x$ mode). This is necessary as the sulphur contained in fuel causes sulphate formation with slowly deactivates the NO$_x$ storage catalytic converter. Due to the high thermal stability of the sulphates, significant levels of sulphur reduction in a reducing atmosphere are only possible at temperatures above approximately 620 °C. The sulphur reduction procedure has been designed so that the storage capacity of the catalytic converter can largely be restored without irreversible damage to the storage material. The sub-stochiometric engine mode is very demanding in terms of engine management. **Figure 11** shows the most important interventions in the air and injection system.

To be able to set air mass and exhaust gas recirculation independently of each other, two separate control circuits are used. The air mass is set using the inlet manifold throttle valve and the exhaust recirculation rate is set using a new, model-based regulation concept. By comparison to conventional high pressure EGR, the characteristic range in which sub-stochiometric engine operation is possible could be significantly expanded by using low pressure exhaust gas recirculation. A suitable combination of high pressure and low pressure EGR with corresponding compression temperatures enables stable λ<1 engine operation even in the low load range with the fuel qualities that are typical for the USA. In addition, the injection concept for rich mode has been changed. Up to six injections are used depending on characteristic values to attain a stable combustion low in soot [4].

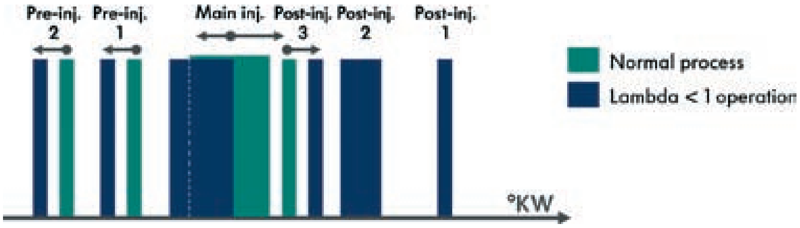

Figure 11: Injection scheme for sub-stochiometric combustion (λ<1)

To attain the necessary exhaust gas temperatures in DeSO$_x$ operation, the conflict of interests between component protection of the turbocharger and higher sulphur reduction performance was resolved by using very late, non-combusting post-injection. This fuel partially reacts at the oxidation catalytic converter with the residual oxygen contained in the exhaust gas and hereby generates residual heat for the sulphur reduction of the NO$_x$ storage catalytic converter.

These interventions in engine management are regulated to a neutral torque meaning that the process has no noticeable effect on driving characteristics. As shown in **Figure 12**, the regeneration intervals depend on the corresponding load conditions of the NO$_x$ storage catalytic converter with sulphur, nitrous oxide or the particulate filter's load in terms of soot. The maximum load conditions were adjusted to the permissible operating thresholds of the components.

4.3 Regeneration Concepts of NO$_x$ Aftertreatment

4.3.1 DeNO$_x$ Concept

Taking the necessary engine operation and regeneration conditions as well as the catalytic converter properties into consideration, the corresponding regeneration mode is prioritised by a co-ordination program in the engine control unit [1].

To shorten the required heating cycle of the exhaust system, sulphur reduction in the NO$_x$ storage catalytic converter is only conducted at the end of a particulate filter regeneration cycle. DeNO$_x$ regeneration is given higher priority than other regenerations to prevent thermal NO$_x$ desorption.

A loading and discharging model is stored in the engine control unit for DeNO$_x$ regeneration. This maps the charac-

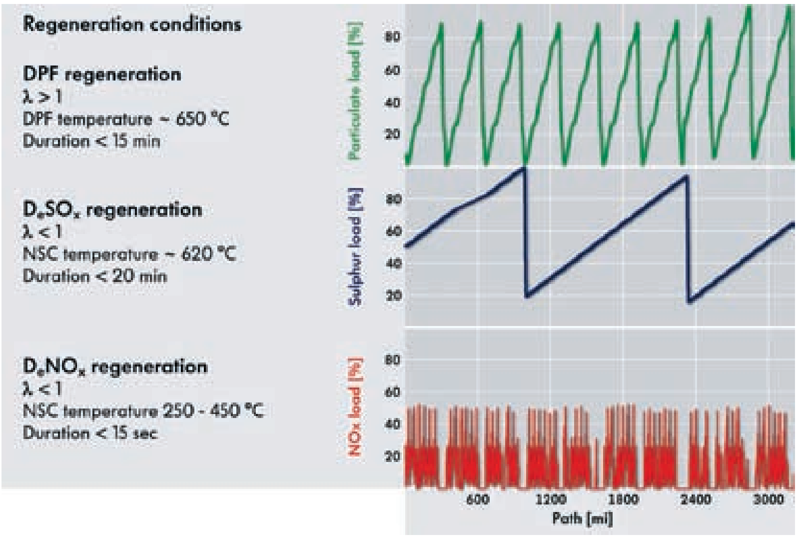

Figure 12: Graph of regeneration modes in the dynamic driving cycle (standard road cycle)

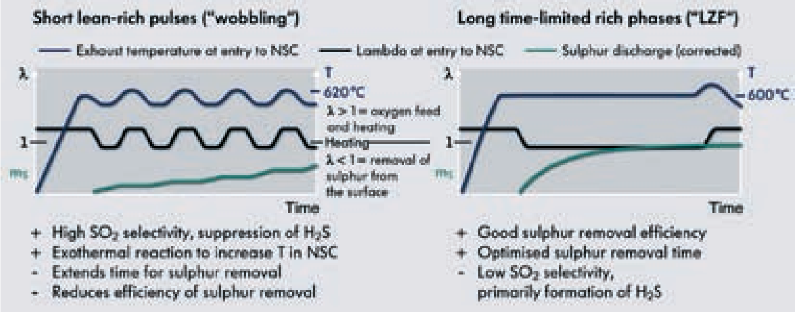

Figure 13: Possible strategies for sulphur reduction of the NO_x reservoir catalytic converter

teristics of the NO_x storage catalytic converter. The load condition of the catalytic converter is modelled during engine operation using the NO_x storage curves which are stored as a function of temperature and capacity speed as well as the calculated NO_x raw emissions. If the NO_x load value exceeds a threshold value which represents the optimum conversion rate for the catalytic converter, the regeneration is conducted when the operating condition of the engine permits regeneration mode to be activated.

Two criteria, which relate to the lambda signal or a NO_x discharge model, are used to determine the end of regeneration. As soon as the lambda sensor detects a rise in reduction medium after the NO_x storage catalytic converter, it is free of nitrous oxide and regeneration is ended. Due to the susceptibility to interference of the lambda probe, this criterion is not permissible under a certain threshold temperature. For this reason, the discharge of the NO_x storage catalytic converter is also modelled on the basis of the requirement and provision of reduction medium to reduce the stored NO_x.

4.3.2 Sulphur Reduction Concept

There are various strategies for the sulphur reduction of the NO_x storage catalytic converter. These differ according to the duration of the rich mode. The characteristics of these strategies can be seen in **Figure 13**. Operating with short lean-rich pulses („wobbling") will prevent H_2S formation by switching from rich to lean mode in good time. The sulphur reduction performance is however restricted as the reduction of sulphur by the catalytic converter is conducted in less than optimum conditions. The long time required by lean operation means that the sulphur reduction time rises correspondingly.

The „long time-restricted rich phase" used in this concept accepts the disadvantageous H_2S formation in order to attain an efficient sulphur reduction within the short regeneration time. The H_2S catalytic converter, which was specially developed for this application, is placed downstream of the NO_x storage catalytic converter and converts the H_2S which is created during the $DeSO_x$ regeneration mode, completely into SO_2. The requirement for a $DeSO_x$ mode is necessitated by the sulphur load of the NO_x storage catalytic converter and is calculated from fuel consumption and the sulphur content of the fuel. The duration of the sulphur reduction process depends on the speed of sulphur reduction that is calculated for the NO_x storage catalytic converter which in turn depends on the λ ratio and the temperature as calculated by the engine control unit.

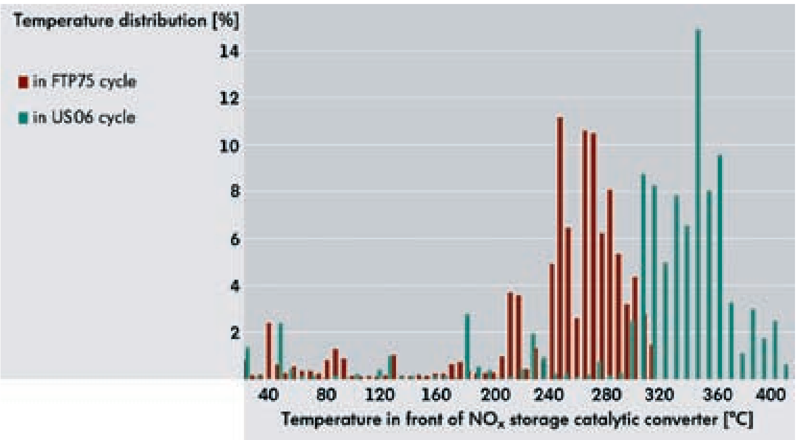

Figure 14: Temperature distribution in front of the NO_x storage catalytic converter in FTP75 and US06 cycle

4.4 Catalytic Converter Development for the NO_x Aftertreatment System

The decisive factor for the development of the coating of the NO_x storage catalytic converter is the prevailing temperature where it is installed in the vehicle underbody. **Figure 14** below shows the temperature distribution in front of the NO_x storage catalytic converter in the FTP75 and US06 cycle. This resulted in the necessity to reduce the temperature range for catalytic converter activity to below 300 °C and to improve the activity's consistency over the catalytic converter's service life. Attaining the necessary temperature for the sulphur removal of the NO_x storage catalytic converter is a great additional challenge, especially if it is placed away from the engine, as the temperature loss that results over the length of the exhaust system must be taken into account and compensated.

For this a further mode of operation ($DeSO_x$ heating) was necessary. This precludes the possibility of the particulate filter module overheating using corresponding exhaust gas volume flows and oxygen content. A further development of the catalytic converter coating was also necessary.

With the help of Umicore, the NO_x storage catalytic converter was optimised so that impaired activity over its service life caused by sulphur and thermal ageing was minimised, and thermal stability – especially at low system temperatures – was improved. Another special development step was the simultaneous reduction of the temperature for

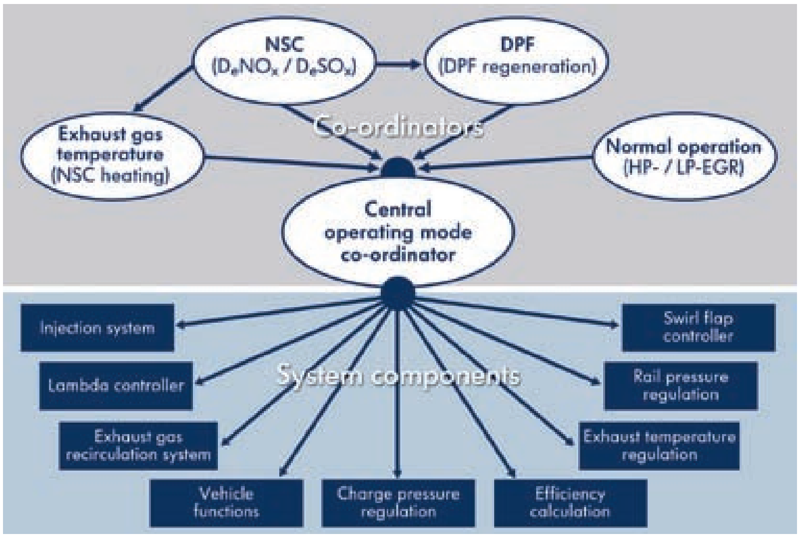

Figure 15: Operating mode co-ordination

complete sulphur removal. The reduction of the sulphur removal temperature from 650 °C to 620 °C means increased process security and is especially useful for ensuring the functions of components close to the engine and also serves to expand the range of suitable engine operation points.

5 The Regulation Concept – Operating Mode Co-ordination

The use of the particulate filter and the NO_x storage catalytic converter requires a large number of different combustion procedures and engine operation modes **Figure 15** [1]. To be able to co-ordinate these operating modes and their requirements, a new, complex operating mode management system with a hierarchically encapsulated and resource-protecting structure was developed. In total ten different operating modes were implemented. These are divided within the co-ordinators into two normal operation modes and eight exhaust aftertreatment operating modes.

The following operating modes are used:

- Normal mode with LP and HP-EGR
- normal mode with only HP-EGR
- DPF regeneration (3 different levels, depending on temperature and DPF load)
- $DeNO_x$ heating mode
- $DeNO_x$ preparation level
- $DeNO_x$ rich mode
- $DeSO_x$ lean mode
- $DeSO_x$ rich mode.

The function co-ordinators (NSC, DPF, normal operating mode co-ordinator and exhaust gas temperature management) determine the necessary requirements for the operating modes using system values such as NO_x load (NSC), SO_x load (NSC), particulate load (DPF), cooling water and exhaust gas temperature (T3-T6) and driving situation, as well as the environmental conditions ambient temperature and atmospheric pressure.

Interference between the co-ordinators is largely avoided. The four function co-ordinators communicate directly with a central operating mode co-ordinator. This prioritises the individual requirements and triggers a mode change if necessary. The central co-ordinator addresses the necessary characteristics and characteristic curves in the system components. During development, great value was set in attaining operating mode synergies. Thus, for example, $DeSO_x$ lean and $DeSO_x$ rich have the same preinjection configuration but different post-injection configurations. To save control unit resources and also development time, different direct and indirect operating mode transitions were introduced.

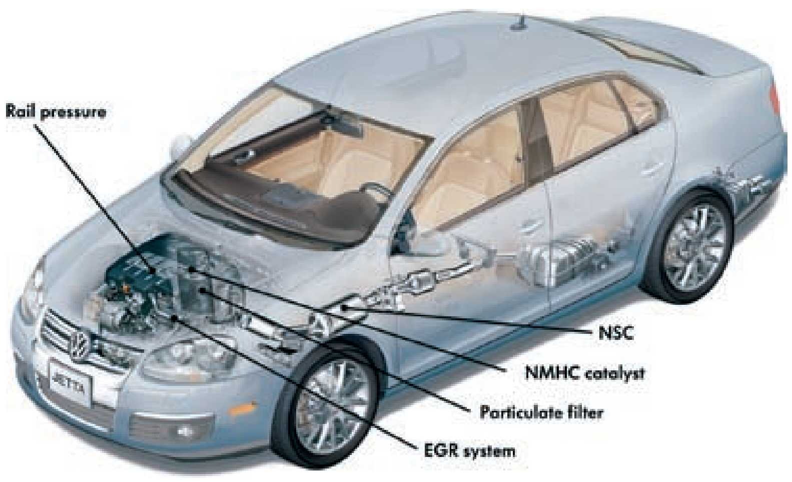

Figure 16: OBD diagnosis

6 OBD System

The requirements of the OBD system are characterised by the current strict Californian legislature for model years 2007-2009. The regulations on correlating threshold diagnosis for exhaust gases in particular have been made more stringent. The diagnosis functions required by the engine are shown in **Figure 16** with the corresponding requirements for exhaust emission functions. Many new functions were developed in order to adhere to these diagnosis requirements. Particularly noteworthy are the monitoring of the NMHC catalytic converter, the NO_x storage catalytic converter and the efficiency diagnosis of the diesel particulate filter. In order to monitor the NMHC catalytic converter the exothermic properties are evaluated during DPF regeneration. The NO_x storage catalytic converter monitoring is based on the difference between the lambda sensor signals (before and after the converter) during the NO_x regeneration phase.

For the first time, the particulate filter efficiency diagnosis function using an evaluation of the load gradients, has made it possible to detect a partial defective system. Another challenge is the legally prescribed monitoring of diagnosis frequency (rate-based monitoring) which has been implemented for the 2.0 l 4V TDI Bin5 engine and which is output via the generic scan tool interface.

7 Summary

Taking the Bin10 engines available to-date in the USA as a basis, further development of the common rail engine and the use of NO_x aftertreatment have enabled the particulate matter and NO_x emissions to be reduced by over 90 %. Adherence to the emission values under customer conditions has been proven in the USA with a large fleet of vehicles and taking the climatic and geographic conditions into account. A key factor in the endurance tests was the effects on the function of the overall system of the fuel quality which deviates from the European standard.

One aim of the development was therefore to keep fuel consumption constant when compared with previous models, in spite of the high requirements in terms of assuring the function of emissions-relevant components.

With a specific consumption of 204 g/kWh as its best value, the new 2.0 l TDI engine with four valves for Bin5 continues the tradition of Volkswagen diesel engines of attaining better consumption figures while at the same time attaining the lowest emission values and considerably improved driving performance.

It should be noted that due to the co-ordination of HP and LP exhaust gas recirculation, constant specific consumption values could be attained in a wide range of engine speeds. The typical torque characteristics for a charged diesel engine support a start without delays.

The multiple injection concept of the comon rail injection system has enabled a significant improvement of noise characteristics, setting new standards in this area. However, the acoustic optimisations are completely contrary to the consumption and emissions requirements. Therefore the best possible compromise between acoustics, emissions and consumption was chosen for the application, **Table 2**.

Table 2: Vehicle results

Power	103 kW (140 HP) at 4000 rpm
Torque	320 Nm at 1750 – 2500 rpm
Max. speed	> 200 km/h
Acceleration 0 – 100 km/h	9.8 s
Elasticity 80 – 120 km/h	12.0 s
Consumption	~ 34 mpg
Emissions standard	Tier 2 Bin5

The new engine has a perceptibly improved acoustic performance when compared with unit injection engines and it is also one of the best in its class in this regard when compared to the acoustics of competitor vehicles.

The cylinder-based combustion regulation developed by Volkswagen has created new possibilities in terms of engine application. This means that diesel engines can be operated closer to the stability limits of combustion even with differing fuel qualities. It has also made it possible to compensate for interference factors such as component tolerance, ageing and changing operating conditions.

In addition to the engine, a completely new, complex exhaust gas aftertreatment system has been developed. Levels of efficiency and long-term stability that were regarded as impossible until very recently have been attained in collaboration with the Emitec, Corning and Umicore companies, in particular in the area of the NO_x aftertreatment system.

Alongside the stationary test bench optimisations, the driving dynamics regulation concepts are also key to success. Therefore, in addition to the new individual components, particular emphasis was placed on ingenious regulation technology and the interaction of components in the system.

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