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The New EA211 1.5 l TSI evo2

With the EA211 1.5 l TSI evo, Volkswagen began series production of the highly efficient TSI evo combustion process – derived from the Miller cycle – combined with VNT forced induction for the first time in 2016. The basic development remains a ground-breaking achievement even today, combining low consumption characteristics for customers with the agile driving dynamics typical of TSIs. Thanks to further technical developments, the second generation, which is being launched soon, enables a substantial, customer-effective reduction in consumption, lower emissions and an increase in performance.

WRITTEN BY




Dr.-Ing. Pierre Scheller
is Head of the
Calibration subdepartment
at Volkswagen AG
in Wolfsburg (Germany).

David Sudschajew, M. Sc.
is Head of the Thermodynamics/
Calibration subdepartment
at Volkswagen AG
in Wolfsburg (Germany).

Dipl.-Ing. (FH), Dirk Warnke, MBA
is drive train project manager
for the EA211 1.5l TSI evo2
at Volkswagen AG
in Wolfsburg (Germany).

Dipl.-Ing. Tim Thaler
is calibration specialist
for gas systems and ACT$^+$
at Volkswagen AG
in Wolfsburg (Germany).

The second generation of the 1.5 l TSI evo successfully implements the familiar combination of the TSI evo combustion process and forced induction in a higher performance class through the use of a Variable Nozzle Turbine (VNT) [1, 2]. In addition to the numerous changes, **FIGURE 1**, which define a revised engine generation, the following aspects characterize the 1.5 l TSI evo2 and will be described in detail.

Based on optimizing the combustion chamber cooling, the enhanced combustion process and forced induction achieve an exceptionally dynamic interaction. Furthermore, the cylinder management ACT (Active Cylinder Termination) has been fundamentally reworked and enables greater efficiency when running on two cylinders together with reduced losses when switching between two- and four-cylinder operation. In addition, the exhaust gas aftertreatment will be discussed. This system now consists of a close-coupled catalytic converter to reduce gaseous emissions and a subsequent gasoline particulate filter. The corresponding software functions play an essential role in the interaction of all of the component-specific characteristics.

COMBUSTION PROCESS AND VNT FORCED INDUCTION

The TSI evo combustion process is already familiar from the 1.5 l TSI evo with $P_e = 96$ kW. This process is derived from the Miller cycle and enables a comparatively high compression ratio of $\varepsilon = 12.0$. This is possible because the Miller cycle expands and cools the fresh air charge by closing the inlet valves early and counteracting the increased knocking tendency as a result. When combined with a highly efficient charge air cooling, high levels of forced induction with good mean fraction burn can also be maintained with regard to the knocking tendency even in the sensitive low-end torque range.

These fundamental principles have been modified for the second generation and the $P_e > 110$ kW performance class can be derived as a result. The measures include improved combustion chamber

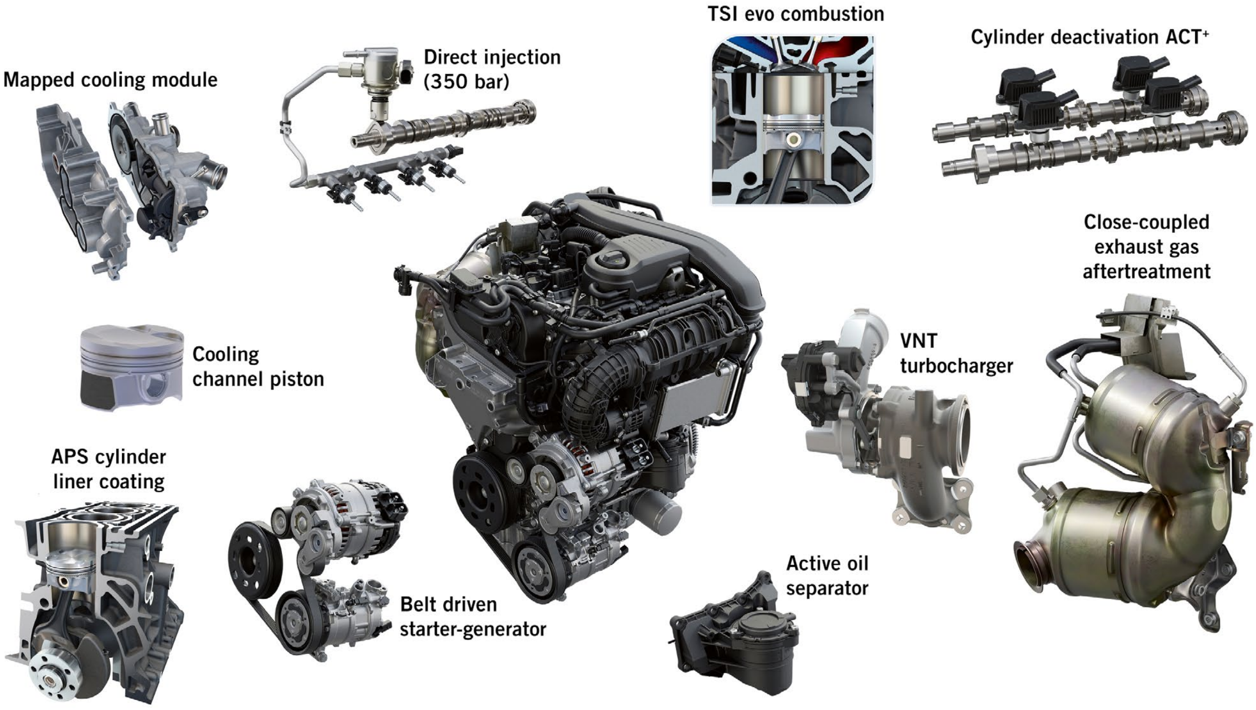

FIGURE 1 The new and enhanced technology modules of the 1.5 l TSI evo2 [3] (© VW)

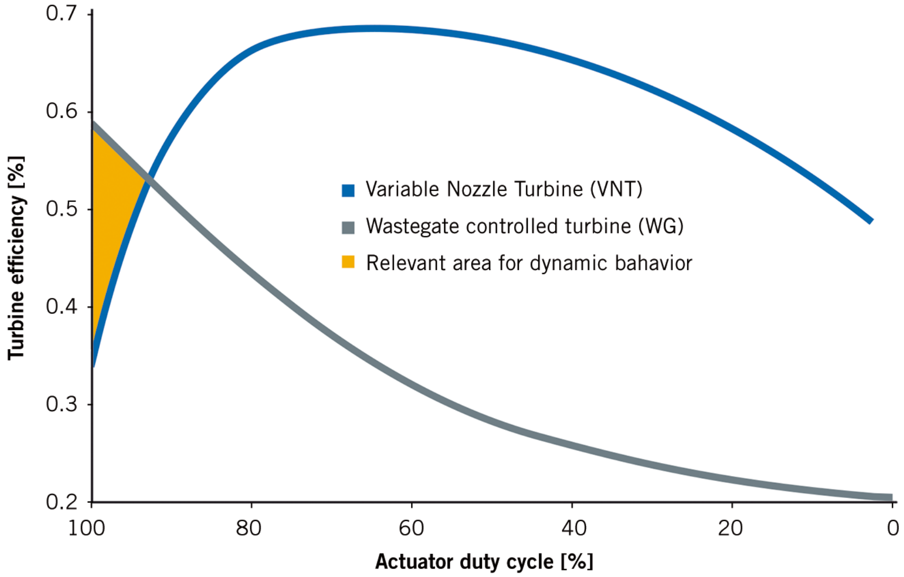

FIGURE 2 Comparison of turbine efficiency between wastegate and VNT control (© VW)

cooling achieved by diverse modifications to the cylinder head together with the use of a cooling channel piston, as well as an enhanced turbocharger design. As the basic engine is also designed for high peak pressures, the combined characteristics enable mean fraction burn positions with optimum efficiency throughout a wide operating range. This forms the basis for a comparatively low exhaust gas temperature enabling a combustion air-fuel ratio of $\lambda = 1.0$ throughout the entire engine map. Moreover, it enables the use of a VNT turbocharger which fulfils the necessary conditions for the TSI evo combustion process. This technology demonstrates high efficiency advantages over a traditional wastegate-controlled turbine as throughout the exceptionally wide control range of the VNT vanes, the entire exhaust mass flow always passes through the turbine, **FIGURE 2**. In turn, this forms the foundation for a positive flushing gradient in the combustion chamber together with reduced gas exchange work. The adjustable phasing of the inlet camshaft enables the TSI evo combustion process to be configured to achieve full-load engine operation at very high compressor efficiencies by adjusting the charge pressure requirement.

In summary, the unique advantages of the TSI evo combustion process arise from its combination with the VNT turbocharger. This turbocharger efficiently provides the charge pressure required to compensate for the filling disadvantage resulting from the early closing of the inlet valves. This leads to significantly reduced losses in both compression and gas exchange work when compared to a conventional combustion process, resulting in a corresponding reduction in consumption for customers.

CHALLENGES WITH TRANSIENT OPERATION

Despite the substantial advantages in the steady-state engine operating mode, system-related disadvantages can arise in relation to the dynamic response behaviour. When a spontaneous load request occurs, the VNT vanes are almost completely closed. This results in a noticeable efficiency disadvantage compared to a wastegate design, **FIGURE 2** (100 % activation). This disadvantage is due to the high incidence angle of the turbine wheel resulting from the closed vanes. To ensure that the transient torque generation fulfils the requirements of a TSI engine, especially at low engine speeds, various software functions are utilized in the engine management system, which have been precisely adapted to the combustion process characteristics.

FIGURE 3 shows a step load example demonstrating the various control variables and dynamic interventions. If the driver has a correspondingly high load requirement, the fast phase controller briefly shifts the inlet camshaft to an optimum filling position. This reduces the filling disadvantage compared with steady-state operation to decisively support the filling through the spontaneously increasing volumetric efficiency.

The exhaust and turbine conditions are more complex. The decreased efficiency of the VNT turbine when the vanes are in the closed position has to be compensated for so that the maximum possible turbine performance is available in the event of a dynamic requirement. This is achieved by a controlled increase in turbine intake pressure, which simultaneously does not exceed the thermodynamic limits of the combustion process. Exhaust backpressure limiting is utilized for this purpose. This function maintains a previously defined negative scavenging difference. During the process, a maximum possible VNT position is calculated, which is related to the current intake manifold pressure and defines a corresponding exhaust backpressure that can still be maintained by the combustion process.

The complex transient interaction arising from the TSI evo combustion process and the VNT forced induction technology is achieved through the patented camshaft and VNT control functions which are implemented in Volkswagens internal engine management software. Therefore, the dynamic requirements are also fulfilled in addition to the outstanding steady-state characteristics, enabling an appealing customer driving experience.

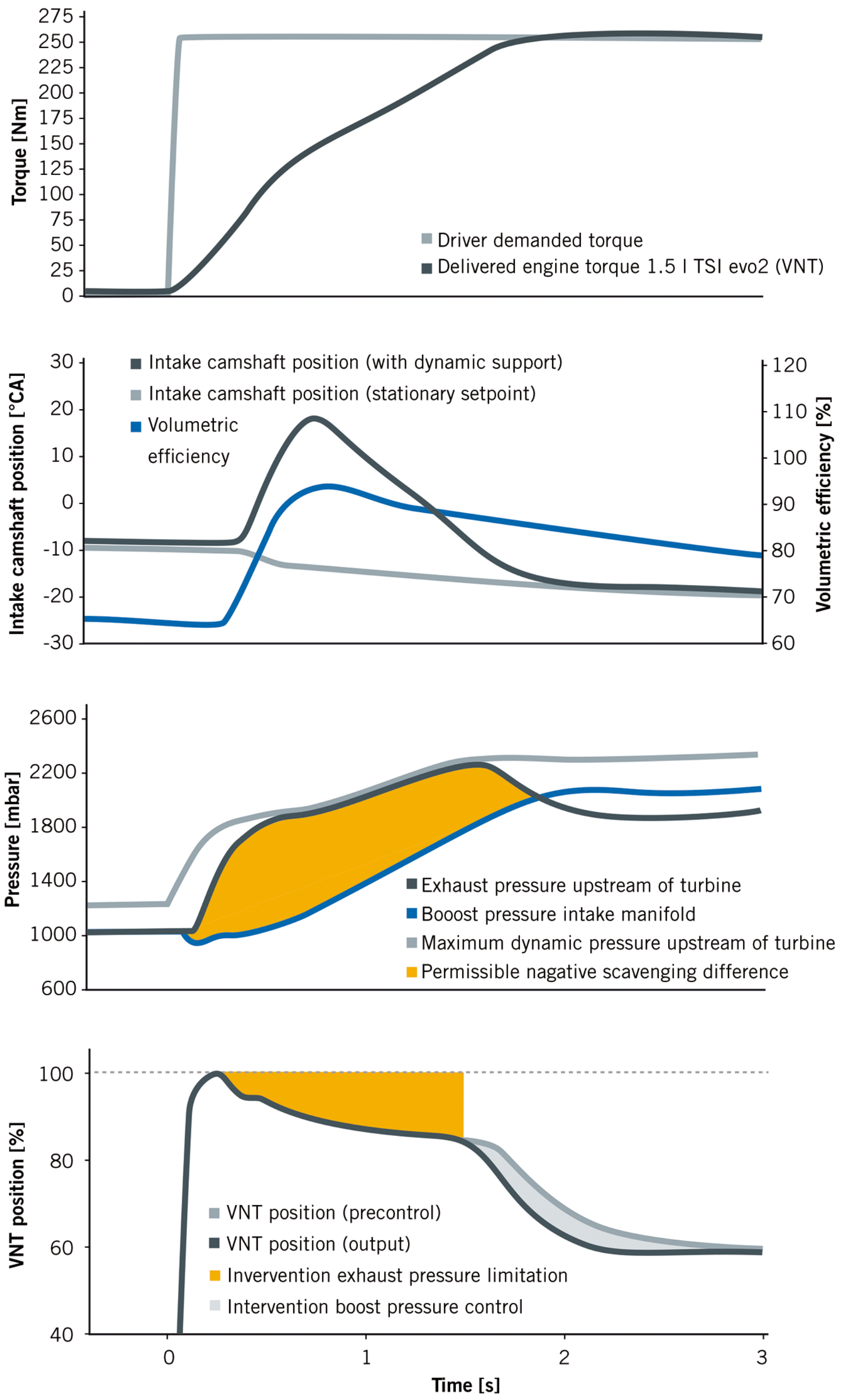

FIGURE 3 Transient torque generation process, example at n_{Mot} = 1500 rpm (© VW)

CYLINDER DEACTIVATION TO REDUCE CO$_2$ EMISSIONS

The cylinder management system ACT is an integral part of the operating strategy for reducing the CO$_2$ emissions for the 4-cylinder gasoline engines, particularly in customer relevant operation.

The inlet and exhaust valve strokes of the inner cylinders are deactivated by shifting axially movable cam sleeves located on the respective camshaft. Next to the classic valve lift curve, there is a second contour, the so called zero cam. Thus, the valves are not lifted and remain permanently closed. Gas exchange then does not take place and injection and ignition are switched off. In this Half-engine operating Mode (HEM), the deactivated cylinders no longer provide a positive torque contribution. The outer cylinders, which remain active, are then operated at a higher load point to maintain the constant total torque output of the combustion engine.

The consumption advantage compared to the Full-engine operating Mode (FEM) primarily results from a reduction in gas exchange losses due to the lack of gas exchange by the deactivated cylinders. As well as reduced throttling of the intake side to achieve a higher specific load on the active cylinders, shifting the operating point towards more favorable efficiencies.

FUNDAMENTAL DEVELOPMENT ENHANCEMENT

The 1.5 l TSI evo2 implements the optimized ACT$^+$ system, which provides improvements in two-cylinder operation and in the dynamic changeover phases between FEM and HEM. This is made possible by introducing sliding combined cam sleeves which carry both cams of the deactivated inner cylinders and those of the adjacent outer cylinders which remain active, **FIGURE 4**. Compared to the previous use of individual cam sleeves on cylinders 2 and 3 and rigid cam contours on cylinders 1 and 4, this enables the option of designing the gas exchange separately for the cylinders which remain active, as this enables optimized valve lifts – particularly for this ACT operating range. As a consequence, switching the engine operating mode now always changes the cam contour of the active cylinders.

STEADY-STATE CONSUMPTION ADVANTAGE

The speed range in the HEM goes up to n_{Mot} = 3500 rpm. This makes it possible to implement a fuller and wider cam profile on the intake side together with a wider cam profile on the exhaust side for the two active cylinders. This is implemented while remaining within the limits of the maximum valve accelerations and landing speeds. This combination reduces throttle and gas exchange losses while retaining the same high

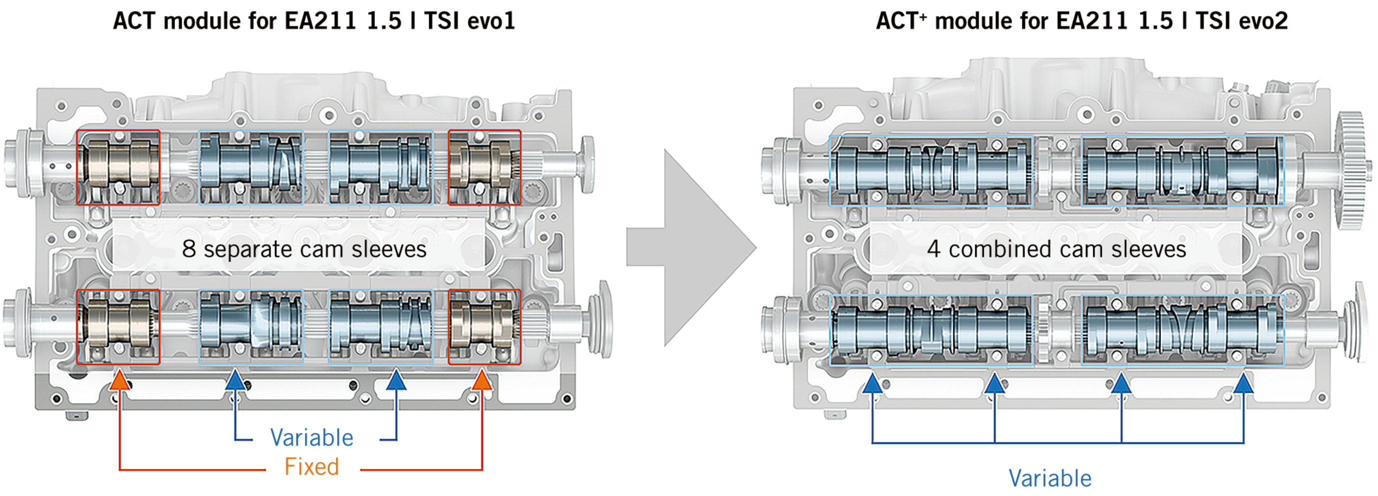

FIGURE 4 Differences between ACT (1.5 l TSI evo1) and ACT⁺ (1.5 l TSI evo2) modules (© VW)

utilization of the expansion work in two-cylinder mode compared to the configuration of the TSI evo combustion process in four-cylinder mode.

FIGURE 5 illustrates the operating range of the cylinder deactivation including the consumption difference compared to the full-engine operating mode. The wide torque range available with a consumption advantage enables the HEM to be used for urban and interurban driving. When the load requirements lie outside the consumption advantage of the HEM, the system switches to the FEM. The high maximum achievable HEM torque aids in creating a seamless acceleration until the inner cylinders are activated.

REDUCTION OF CHANGEOVER LOSSES

The changeover phases between the two engine operating modes generally involve consumption disadvantages. To prepare for the HEM, a pressure reserve is generated in the intake manifold so that, during the subsequent cylinder deactivation, sufficient fresh air volume is available in the cylinders that remain active to produce the required torque. The theoretically possible additional torque generated in all four cylinders as a result is offset against a deterioration of the ignition angle efficiency until the changeover has taken place. The resulting higher fuel consumption increases proportionally to the pressure reserve while the combustion air ratio remains the same.

FIGURE 6 displays the progression of the relevant engine variables when switching from the FEM to the HEM. In the classic ACT system, the cylinder filling increases to the value required in the HEM prior to the changeover. The inlet camshaft is moved to a later position to increase the filling dynamics and to reduce the residual gas content in the combustion chamber, which destabilizes the combustion.

With the ACT⁺ system, the intake cam of the cylinders which remain active is rotated to later timing compared to the FEM configuration. This results in a jump in the volumetric efficiency at the time of changeover as more fresh air flows into the combustion chamber at the same intake manifold pressure. Taking the jump in volumetric efficiency into consideration, the intake manifold pressure is only increased to the extent that is required for the subsequent combustion processes in the HEM. As a consequence, the new ACT⁺ system is able to significantly reduce the additional consumption during the changeover phase in comparison to the previous ACT system.

EMISSION CONTROL MODULE CONCEPT

Meeting ambitious emissions targets is a key challenge in engine development. In particular, rapid heating of the exhaust gas system to achieve complete operational readiness plays a critical role and is supported by both hardware and software measures. To fulfil the increasingly strict legal requirements in the future

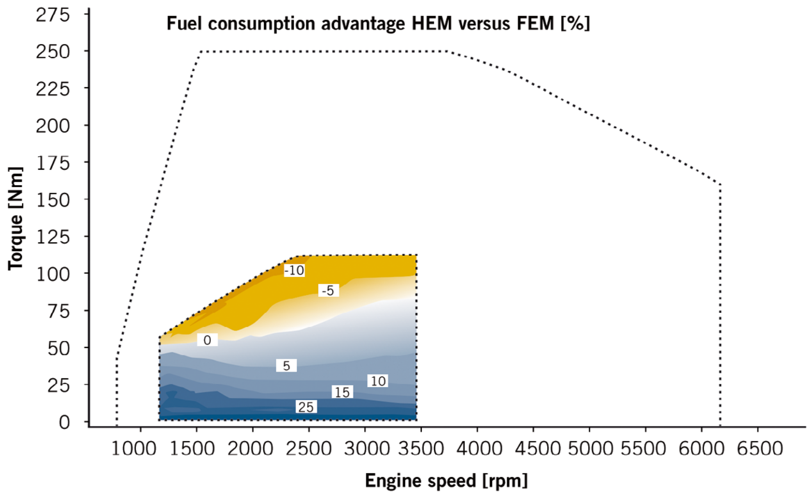

FIGURE 5 Percentage consumption advantage of HEM compared to FEM (© VW)

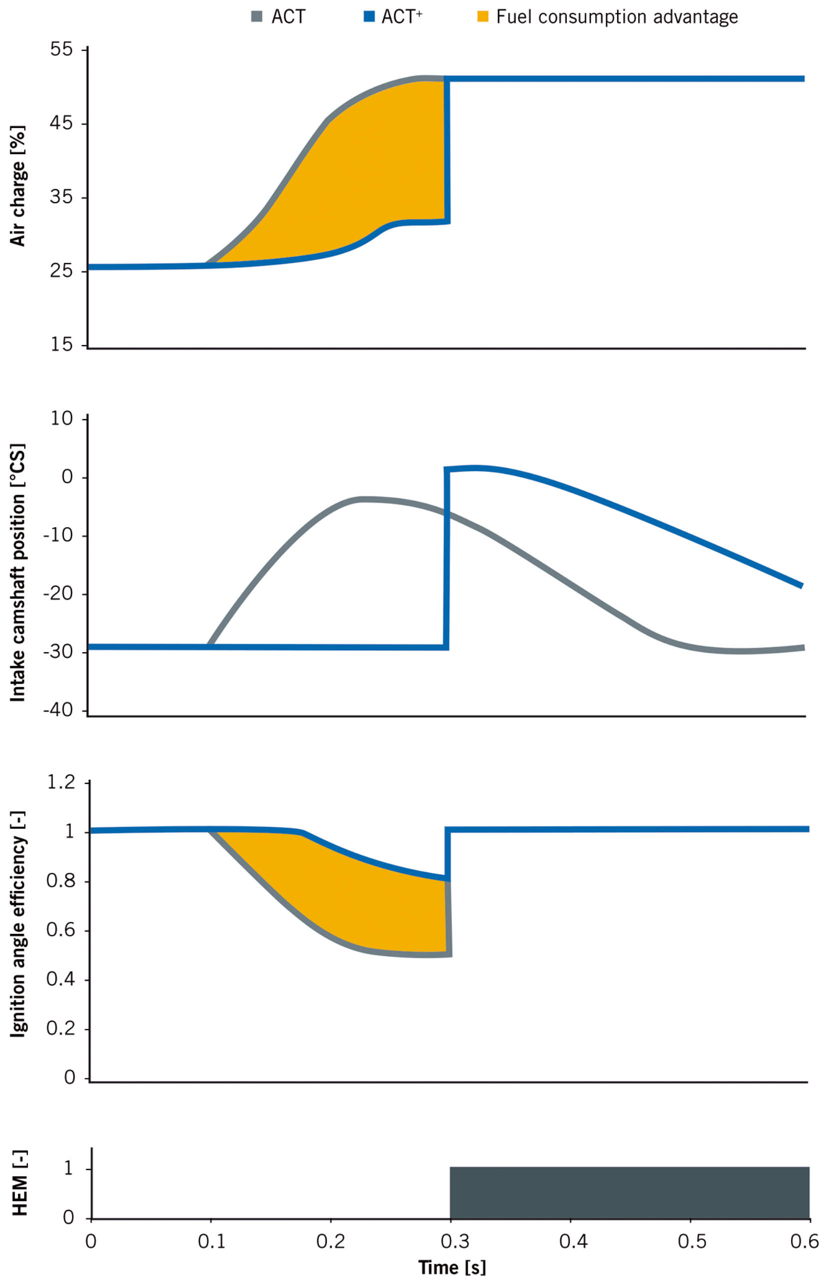

FIGURE 6 Changeover strategy between FEM and HEM (© VW)

and beyond this to achieve a significant reduction in emissions under all driving conditions. The emission control concept has been transformed and the heating process evolved. The exhaust system in the 1.5 l TSI evo2 is also referred to as closed-coupled emission control module (Motornahe Abgasreinigung, MAR), **FIGURE 7**. This system separates the gaseous emissions reduction and oxidation tasks from the particulate separation. A three-way catalytic converter is located in the first position, directly on the turbine outlet of the turbocharger, to ensure that it reaches it is operating temperature as quickly as possible. The Gasoline Particulate Filter (GPF) is located after the catalytic converter. Pressure differential and temperature sensors integrated into the MAR serve to record the load level of the GPF, as well as the exhaust gas temperature. The new arrangement enables reduced use of precious metals in comparison to the first generation and contributes to sustainability as a result. At the same time, it also forms the foundation for future emission standards.

FIGURE 7 Emission control module (© VW)

ENHANCEMENT OF THE CATALYTIC CONVERTER HEATING STRATEGY

The oxidation and reduction processes in the catalytic converter require an exhaust gas temperature of at least T = 300 °C. This is also known as the light-off temperature. Ignition angle retardation is used to heat up the system as quickly as possible. The correspondingly delayed mean fraction burn positions create a significantly higher exhaust gas temperature in the exhaust tract than that achieved by consumption-optimized ignition. As a result, the light-off temperature is reached as quickly as possible under all required conditions.

Following this initial ignition angle retardation phase, the lambda split process or chemical catalytic converter heating is utilized. This mode of operation is familiar from CNG engines [4] and is now being optimized and adapted for gasoline operation. This strategy focuses the heating far more on the required location in the catalyst monolith through a post-reaction of non-combusted air and fuel components rather than heating the entire exhaust system.

Specifically, this is achieved by operating two cylinders over-stoichiometrically and two cylinders sub-stoichiometrically. The non-combusted reac-

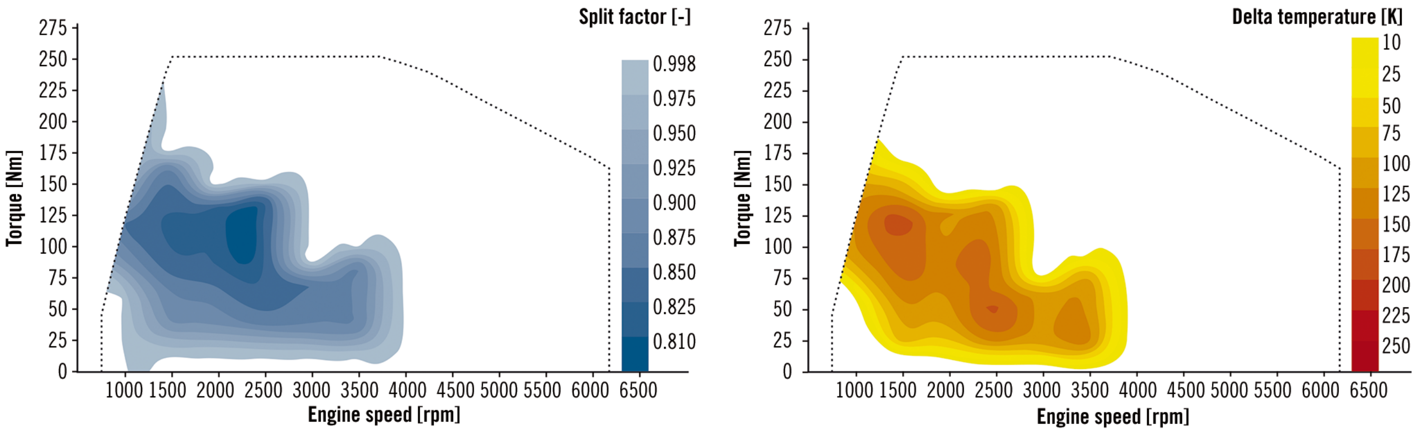

FIGURE 8 Split factor and the resulting temperature difference compared to normal operation (© VW)

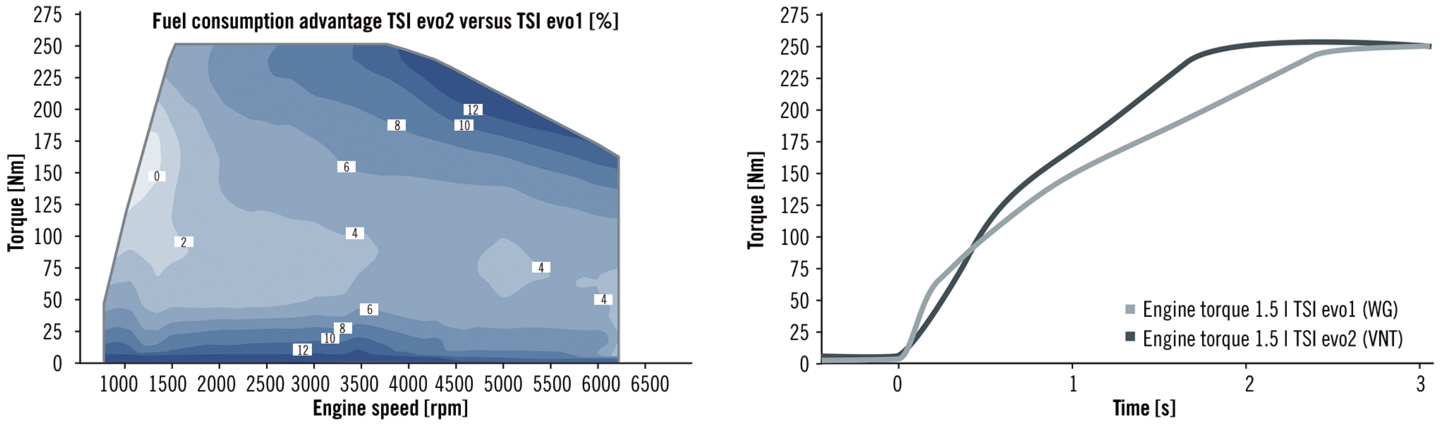

FIGURE 9 Consumption advantage in engine map and load step comparison at n_{Mot} = 1500 rpm (TSI evo2 compared to TSI evo1) (© VW)

tion partners then homogenize in the exhaust tract and the exothermic post-reaction takes place directly in the catalyst, resulting in controlled heating of the substrate. Using this method, the heating gradient depends on the division and calibration of the split factor, which determines the extent of the sub-stoichiometric operation. The ratio to the over-stoichiometrically operated cylinders results automatically with the aim of achieving a combustion air ratio of λ = 1.0 in the catalytic converter. **FIGURE 8** shows an example of the temperature increase achieved through split operation compared to base combustion process.

The combined heating method consisting of initial ignition angle heating and subsequent split operation enables significant CO_2 savings during the catalytic converter heating phase.

SUMMARY

The key factors for success in the second TSI evo generation consist of the combination of the TSI evo combustion process with VNT forced induction technology, together with advances in the ACT system and emission control. The high complexity demands perfectly tailored software solutions which are developed inhouse. These features are integrated into the Volkswagen protected part of the engine management system. This enables the capabilities of the individual components to be fully utilized within the system as a whole.

FIGURE 9 illustrates the results of the enhancements which customers experience. The 1.5 l TSI evo2 achieves a reduction in fuel consumption throughout the entire operating range while simultaneously delivering excellent dynamic characteristics. The load step time has been significantly reduced, particularly at low engine speeds. In conjunction with the highly effective exhaust gas after-treatment system, the engine is ready for future emissions targets and to be used worldwide.

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