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First ULEV Turbo Gasoline Engine

- The Audi 1.8 l 125 kW 5-Valve Turbo

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ABSTRACT

In an age when there is growing tension between customer expectations of high engine performance, low fuel consumption and compliance with the legal requirements on the emission of airborne pollution, the ability of a vehicle to meet the most stringent emission standards is becoming an increasingly important aspect of its market appeal.

The 1.8 l, 5-valve turbo engine which Audi launched in 1994 represented an emissions concept which, thanks to its innovative close-coupled catalytic converter, provided an ideal basis for further development to an engine meeting the US ULEV emission standard, as the current engine does [1].

Its configuration as a ULEV concept necessitated the blanket optimisation of all components which influence the exhaust emissions. The pistons and injectors were improved in order to reduce untreated emissions. The main potential was tapped by incorporating intake camshaft adjustment and a cascade catalytic converter for emissions aftertreatment, together with extensive measures for the engine management system.

The overall concept has enabled Audi to become the first car manufacturer to offer an exhaust-gas turbocharged gasoline engine that meets the US ULEV emission standard.

1. Introduction

Since the mid-1980s, US legislation has required vehicles with gasoline engines to meet exhaust emission limits. The State of California in particular has specified a gradual reduction in HC and NO_x emissions. The legislation requirements for unburned hydrocarbons specified as the average for all vehicles sold in a given model year have fallen from an initial 0.41 g/mile (THC) for the "tier 0" which applied before 1995, to a current 0.07 g/mile (NMOG) for the 2001 model year.

To attain these fleet averages, vehicle manufacturers are encouraged to offer vehicles with emissions conforming to the stringent limit for Ultra Low Emission Vehicles (ULEV) over a distance of 50,000 miles.

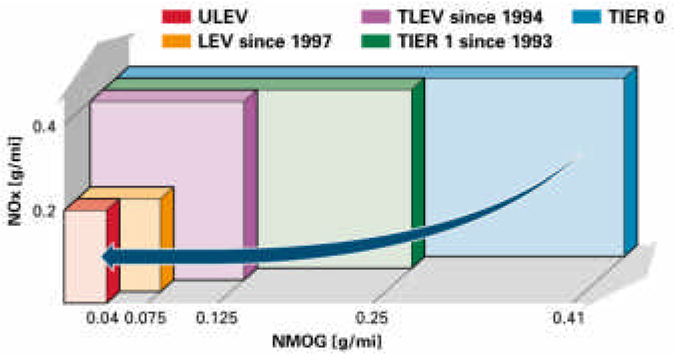

Figure 1: Development of the USA exhaust emission limits

Since mid-2000, the first vehicle with a turbocharged gasoline engine that satisfies this ULEV standard has been available on the US market, in the guise of the Audi A4 1.8 T. Both the manual and automatic versions of this car, whether with front-wheel or quattro drive, conform to the standard. On the basis of the 1.8 l 5-valve turbo engine with one main close-coupled catalytic converter, as first developed in 1994, this engine impressively extends the downsizing strategy – the power and torque of a larger engine with fuel consumption that is in practice close to that of a 1.8 l naturally-aspirated engine – to the field of advanced emissions technology. The space requirements for improved emissions control that were inherent to the Audi A4's vehicle package and engine design from the very outset facilitated the implementation of this concept. Growing popularity, with over 300,000 1.8 l turbo engines built for the VW Group in 1999 and the receipt of the Top 10 awards "Best Engines of 1997" from the trade periodical Wards Auto World for the Audi A4 1.8 T and "Best Engines of 1998" for the VW Passat 1.8 T serve to endorse this concept.

To satisfy the ULEV standard, the engine was further developed on the basis of the LEV engine that has been available since 1998 and uses the same fundamental concept. The secondary air system already incorporated into this earlier version, together with engine management with electronic throttle control, were adopted in modified form.

At no change to the fuel consumption values, the maximum power output was raised by 15 kW to 125 kW and the peak torque increased by 15 Nm to 225 Nm (between 1950 rpm and 5000 rpm).

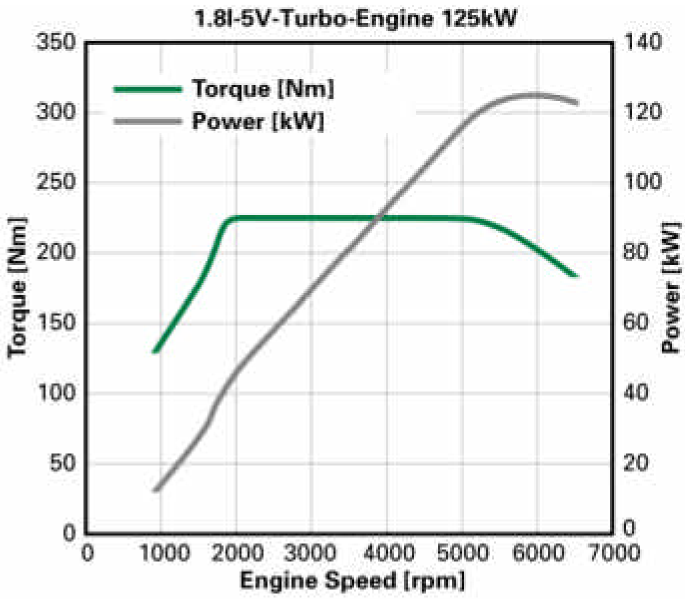

Figure 2: Performance and torque curve

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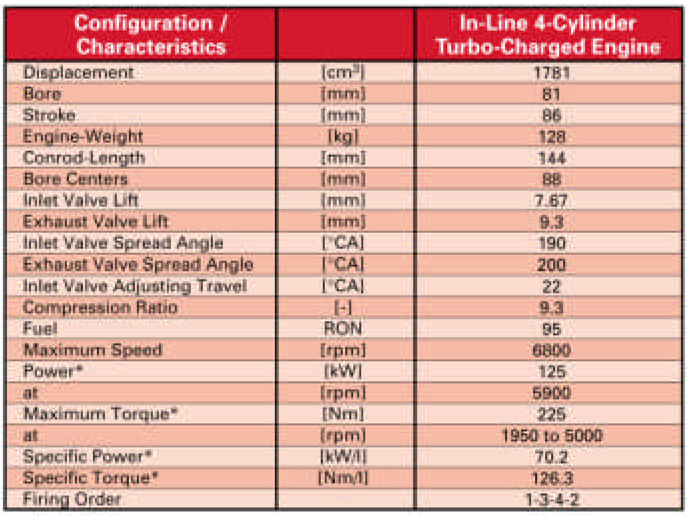

Configuration / Characteristics		In-Line 4-Cylinder Turbo-Charged Engine
Displacement	[cm³]	1781
Bore	[mm]	81
Stroke	[mm]	86
Engine-Weight	[kg]	128
Conrod-Length	[mm]	144
Bore Centers	[mm]	88
Inlet Valve Lift	[mm]	7.67
Exhaust Valve Lift	[mm]	9.3
Inlet Valve Spread Angle	[°CA]	190
Exhaust Valve Spread Angle	[°CA]	200
Inlet Valve Adjusting Travel	[°CA]	22
Compression Ratio	[-]	9.3
Fuel	RON	95
Maximum Speed	[rpm]	6800
Power*	[kW]	125
at	[rpm]	5900
Maximum Torque*	[Nm]	225
at	[rpm]	1950 to 5000
Specific Power*	[kW/l]	70.2
Specific Torque*	[Nm/l]	126.3
Firing Order		1-3-4-2

* Results measured using super unleaded fuel (RON)

Figure 3: Technical data

2. Engine-based measures to attain the ULEV standard

The key challenge in developing a ULEV engine is to reduce hydrocarbon emissions, which need to be virtually halved compared with the LEV standard.

Components and the engine management are optimised with the result that exhaust-gas heat brings the catalytic converter to light-off as rapidly as possible.

A close-coupled catalytic converter position is essential in order to minimise the heat storage capacities between the engine and the catalytic converter. The heat sink created by the interposed turbine is a particular challenge to the engine developers in the case of this engine concept.

2.1 Reducing untreated emissions

Independently of this, the untreated emissions need to be optimised, as they significantly influence the test result in the first phase of the American FTP-75 emissions test until an adequate degree of conversion is attained by the catalytic converter.

The main portion of the overall emissions in the FTP-75 test are emitted in the very first idling phase. It is also necessary to exploit this potential for cutting emissions in order to meet the exhaust gas legislation over life-time, as these measures are not subject to service-life related changes.

2.1.1 Pistons

One of the sources of hydrocarbons in the exhaust gas are the gas recesses in the cylinder, into which the mixture but not the combustion flame reaches (wall quenching effect). The top land recess between the upper edge of the piston, the first piston ring and the cylinder wall is particularly affected by this. The dead volumes could be significantly cut by reducing the height of the fire land on the ULEV engine's new piston by 2.3 mm to 6 mm.

This measure brings noticeable benefits, especially in phase 1 (bag 1) of the FTP test, the cold-running stage.

A comparison of HC emissions between the previous production piston and the new piston with a 6 mm fire land reveals how it was possible to cut the crude emissions in phase 1 by 6 %.

Related to the overall test procedure, the improvement is 4 %, which is tantamount to a 4 % reduction in overall emissions after passing through the catalytic converter.

In addition to the emission-relevant reduction in the fire land's height, this engine is the first to have cast pistons instead of the forged pistons that have conventionally been used in turbo charged engines. Thanks to the greater design freedom compared with the forged version, it was possible to reduce the weight of the cast version by 5 %. In conjunction with a trapezoidal connecting rod and a weight-reduced piston pin, the oscillating masses of the crankshaft drive were cut by 10 % [2].

The new piston therefore brings significant benefits in terms of emissions, costs and convenience.

2.1.2 Injectors

The emissions in the starting and post-starting phase are determined by a complex interplay of the injected amount of fuel, the point of injection and the mixture formation during cold-starting. This offers a great deal of scope for further optimising the injection spray. The new injection geometry and strategy for the ULEV engine was developed in conjunction with the designated system supplier of the injectors for this engine, Robert Bosch GmbH.

The configuration process involved several stages: with the aid of 3D CAD data for the intake ports, the intake manifold and the injectors' position, the parameters jet bend, jet cone and spread angle (split) between the two jets were geometrically optimised.

The assessment criteria were:

- Wall impact
- Wetted area
- Secondary droplets resulting from wall rebound
- Wetting of the port's base, roof and sides
- Evenness of distribution of the fuel in front of the 3 intake valves

This initial configuration indicated that the Bosch-EV6 with a split angle of 15°, bend angle of 10° and cone angle of 7° was the best variant and thus the best basis for further investigations

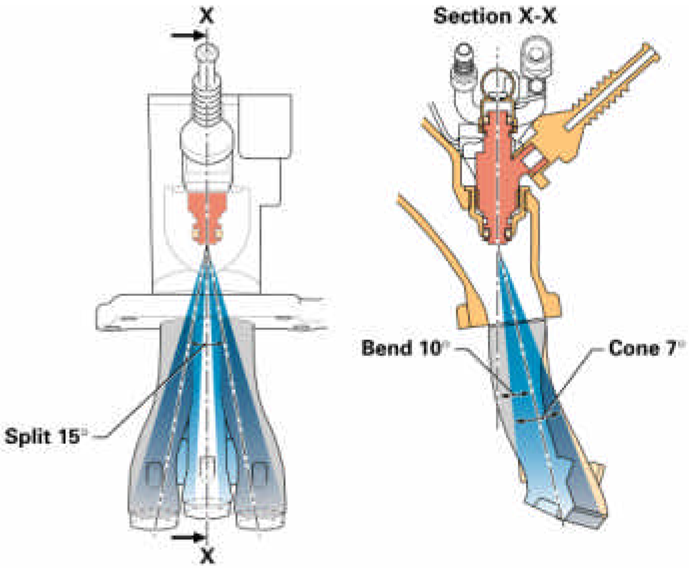

Figure 4: Layout of the fuel-injection geometry

With the aid of endoscopy, the actual mixture preparation process was visualised on a test rig in near-real engine conditions. Here, a transient gas flow was passed through the cylinder head of the turbo engine through operation of the intake and exhaust valves, by applying a partial vacuum to the combustion chamber.

The flow in the vicinity of the intake valves is critical when analysing the movement of the mixture. The conditions in the intake manifold and combustion chamber are adapted such that the intake stream is simulated realistically. It is not necessary for the mixture to be burned. For all the injector variants selected, the fuel carried into the intake port and combustion chamber was visualised by means of an endoscopic system.

Specific assessment criteria here were:

- The quality of the delivered droplets when the intake valve opens
- The uniformity of the delivered droplets in the combustion chamber
- Wetting of the spark plugs and roof of the combustion chamber.

In the next step, the configuration of the spray and measurements for influencing the correction angle were examined on the stationary engine test rig. The emissions behaviour for a ULEV concept must be considered in "cold-running conditions" with coolant temperatures of 20°C and at the significant operating points of the post-starting phase. The comparison of HC emissions at various ends of injection with the LEV and the optimised ULEV injector clearly reveals the influence of the spray's geometry on the level of emissions.

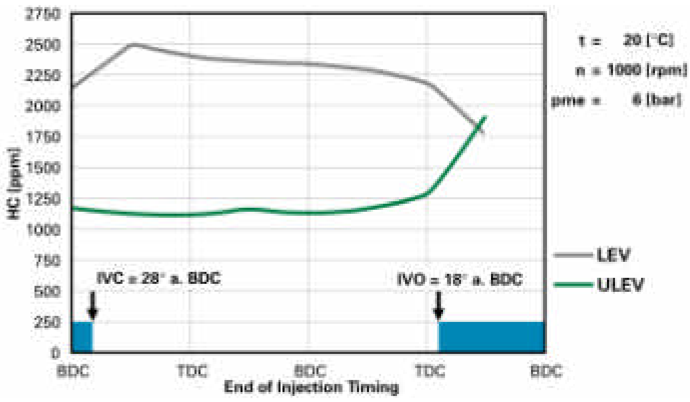

Figure 5: HC emissions over varied injection timing with LEV and ULEV fuel-injectors

In zones where the fuel was genuinely pre-injected, HC emissions could be virtually halved. The behaviour during the transition to injection into the open intake valve differs considerably, and the emissions are approximately the same. The LEV configuration consequently necessitated an end of delivery closer to when the intake valve is open, whereas the optimum for the ULEV is genuine pre-injection. For the newly developed injector, in steady-state conditions the HC values are almost halved compared with fuel injection into the open intake valve on the LEV engine.

The parameters in the engine management system must be adapted individually for transfer to the vehicle and for purposes of evaluation in the exhaust gas test:

- Optimisation of initial injected amounts
- Adjustment of the fuel amount during starting-up, and of injection timing, taking account of the fuel's flight time
- Adjustment of the transient functions (wall film model).

Only when these parameters have been optimised on the new version and on the original injector, using the same criteria in each case, different spray configurations can be plausibly compared in the exhaust gas test.

In phase 1 of the FTP-75 test, the emissions can thus be reduced by approx. 20 %, confirming the results obtained on the steady-state engine test rig. The improvement for the overall test is around 9 %.

2.1.3 Variable camshaft adjustment

In particular immediately after the engine has been started from cold, the untreated emissions can be reduced considerably by warming up the intake ports and the cylinder fill. The intensified evaporation of the fuel results in improved mixture preparation. This can be achieved without additional input by specifically diverting hot exhaust gas back into the intake port (internal exhaust gas re-circulation). This is done by advancing intake-valve opening (IO) when the engine is cold. The control times of the unadjusted valve gear, with ramp, produce an effective valve opening overlap of 40° crankshaft (CS). For steady-state measurement of the untreated emissions, the intake camshaft was adjusted in six stages between zero and 28° towards advanced closing of the intake valve. The investigation was conducted at operating points which are reached in the exhaust-gas test cycle FTP-75 in the starting and post-starting phase. The engine temperature was held at a constant 20°C.

With increasing advance of the intake control times, the HC emissions decrease noticeably. At the same time, the engine's smoothness deteriorates due to the higher residual gas in the cylinder caused by the greater valve opening overlap. The standard deviation of the indicated mean pressure σ_{pmi}, which consequently rises, serves as a measure of this.

The development objective is to achieve an optimum balance between maximum introduction of heat and acceptable smoothness. A deterioration in smoothness can be counteracted by advancing the ignition point.

The optimum balance between reducing untreated emissions and smoothness was found to be at a camshaft timing angle of 22° and an ignition point advanced by 6° CS. The overall flow of heat available to the catalytic converter remains unchanged.

A reduction in HC emissions of 50% can thus be achieved.

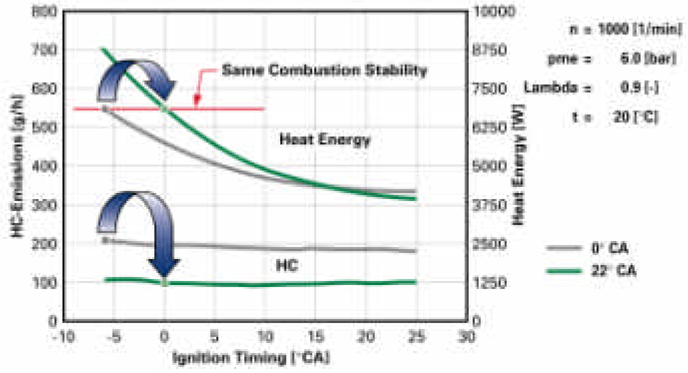

Figure 6: HC emissions in relation of camshaft position and ignition timing

A hydraulic two-point camshaft adjuster with integral chain tensioning device, as already found on the Audi 1.8 l and 2.8 l naturally aspirated engines, is used as the adjusting element.

A hydraulically pressurised piston, energised by a solenoid valve, alters the position of the chain sliding blocks and thus the length of the chain's centre between the exhaust camshaft driven by the timing belt and the intake camshaft. IO (basic position 18° CS after TDC) is adjusted by 22° CS after IO, to 4° CS before TDC (in each case with a valve stroke of 1 mm).

In the "advanced" position, the effective valve opening overlap is thus 62° CS.

The valve overlap area is greater than the basic position by a factor of 5.

The theoretical 50 % reduction in HC deduced from the test-rig results cannot be transferred in full to the starting and post-starting conditions in the FTP test. In the first 125 seconds of the FTP-75 test, untreated emissions are nevertheless reduced by 30 percent.

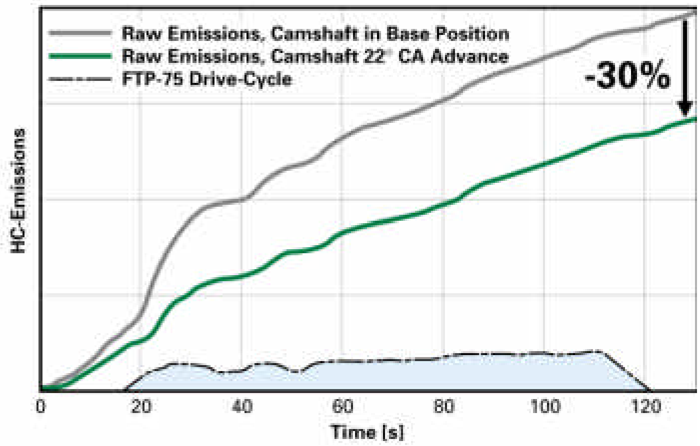

Figure 7: Comparison of cumulative engine-out-emissions in the FTP-75 test, with and without camshaft adjustment

After the catalytic converter, the value for this period is likewise of the same magnitude. The reduction for the overall test reaches a notable 21 %.

On the basis of the LEV engine, the following reductions can be assumed to apply for the individual measures discussed.

4%	Reduction in height of piston top land
9%	Optimisation of injection spray:
21%	Variable camshaft adjustment:

The results given here show only the influence of each measure individually; it is of course not permissible to add them together.

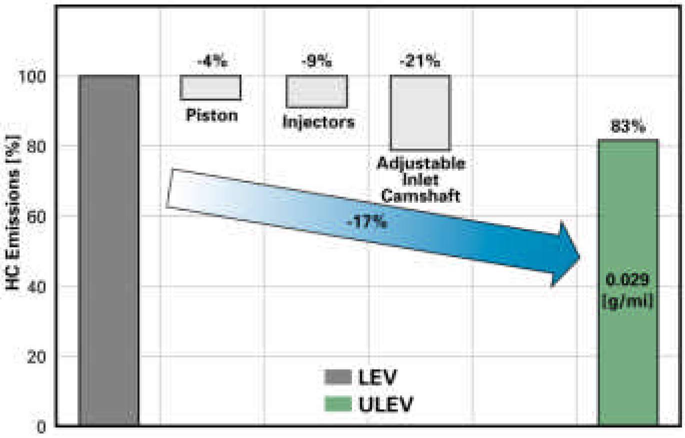

Figure 8: Contribution of individual measures to the ULEV concept

3. Emissions aftertreatment measures

The existing LEV concept, with close-coupled main catalytic converter, already constituted a very good starting point for optimisation with a view to meeting low emissions limits.
In addition to a conversion rate of almost 100 % at normal operating temperature, the advantages include above all a very short light-off time after the engine has been started. To this end, the exhaust gas temperature is raised after a cold start by means of suitable ignition and mixture preparation measures, in conjunction with secondary-air injection.
This process is hindered by the thermal masses, located in front of the catalytic converter, which draw heat from the exhaust gas particularly during the cold-starting and post-starting phase. In this instance a turbocharged engine, with the additional mass of the exhaust turbocharger, places very high demands on the exhaust-gas aftertreatment system.

The profile of the cumulative HC engine-out-emissions from the 1.8 l 5-valve turbo engine reveals that the ULEV limit is exceeded only 24 seconds after a cold start (figure 9).

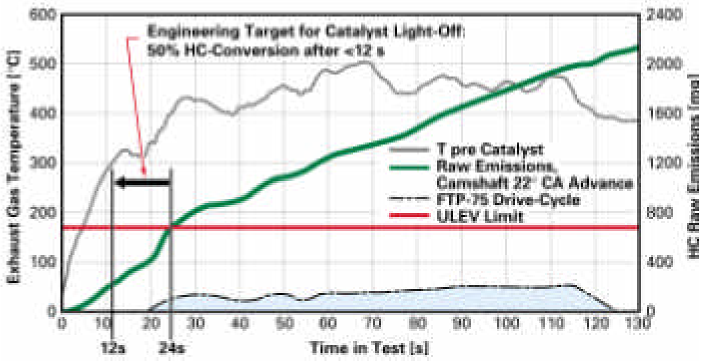

Figure 9: Engine-out-emissions and temperature behaviour as criteria for catalyst light-off

The derivative development target is thus to achieve an HC conversion rate of 50 % (light-off) within less than 12 seconds after cold-start. This target is based on the assumption of a linear increase of the conversion rate and a 100 % conversion rate from 12 seconds after cold start on. Together with the existing profile of engine-out emissions a HC-emission result of approx. 40 % of the ULEV emission standard can be achieved.

This ensures that the emissions in new condition are significantly below half the permitted emission standard.

3.1 Configuration of the catalytic converter

3.1.1. Cold start

The basic idea behind the configuration of the new catalytic converter concept was to develop a modular system that will also serve to meet European emission standards. The previous outer package dimensions as well as the flange position of the LEV concept were to be strictly adhered to.

Manifold and exhaust turbo-charger were to be integrated into the ULEV concept without any changes. The improvement of the light-off behaviour was to be achieved primarily by the optimisation of the catalytic system.

The most important configuration criteria were:

- Cold-start (light-off)
- Overall effectiveness
- Pressure-loss
- Long-term stability

To derive optimum benefit from the energy present in the exhaust gas and therefore to heat up the catalytic converter as rapidly as possible, the support must combine minimum thermal capacity (c_p) with maximum catalytic surface area (GSA). In order to evaluate the various different systems, the

cold-start factor = GSA / c_p

was used [3]. The cold-start factor depends on the cell density and wall thickness of the material, which the support is made of.

On the basis of calculations with the finite-element tool KATPROG a number of different catalytic converters with metal substrate were examined. Figure 10 shows cumulated HC emissions in the cold start phase of the FTP-test with various 1-brick and 2-brick systems. Modally measured exhaust-gas components, the exhaust-gas mass flow rate and the temperature in front of the catalytic converter served as the input data.

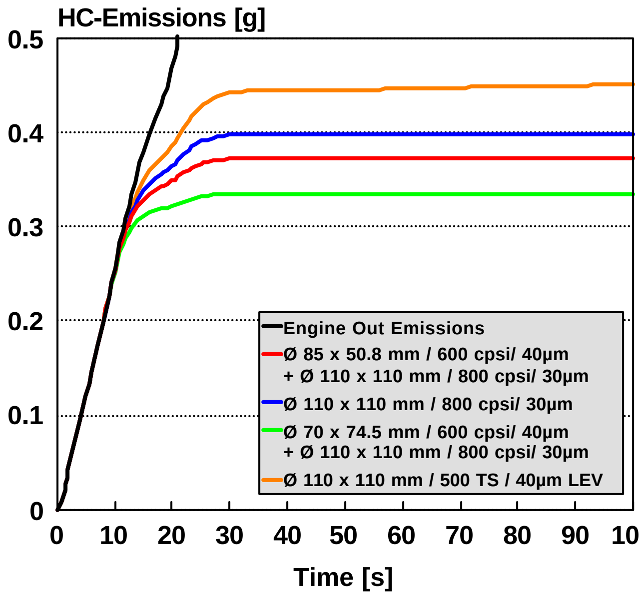

Figure 10: Accumulated HC-emissions of various 1- and 2-brick systems during the FTP-cold start

It came up very early that a cascade-type arrangement of two different sizes of catalysts (a smaller catalyst diameter followed by a larger one) produces very good results with respect to the flow distribution and cold-starting effectiveness [4].

The specific dimensions of the primary catalytic converter were determined using additional simulation calculations of the heat-up behaviour.

A catalyst with a diameter of 85 mm, length of 50.8 mm (volume 0.29 l) and a cell density of 600 cpsi was selected as a practicable version.

3.1.2 Warm operating condition

In a warm operating condition, the catalytic effectiveness is limited only by the transport of mass, assuming optimum lambda control in the simulation. This is influenced primarily by the hydraulic diameter (d_h) of the channels.

The evaluation number is the

effectiveness factor = GSA / d_h

Higher cell densities mean improved effectiveness in respect of all pollutants. The improved mass transfer from the flow of exhaust gas to the substrate wall and into the pores of the wash coat is responsible for this.

However, the catalytic advantage is achieved at the expense of a higher pressure loss. This has a direct effect on the engine's power output and fuel consumption, with the result that a suitable compromise once again had to be found.

The second stage of the cascade was defined taking into account the above-mentioned requirements. A metal catalytic converter with a diameter of 110 mm, a length of 110 mm (volume 1.05 l) and a cell density of 800 cpsi was chosen.

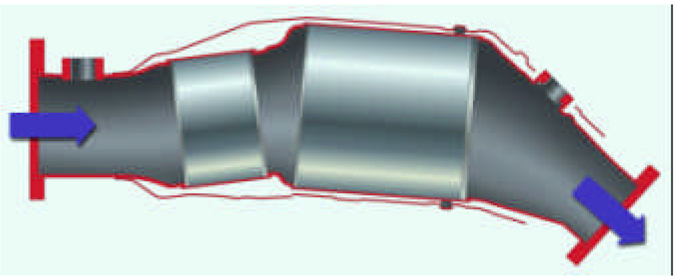

Figure 11: The cascade of catalytic converters for ULEV

To achieve optimum catalytic efficiency throughout the operating period, the thermal and mechanical durability as well as flow distribution were also critical in choosing the most suitable version.

Flow distribution was measured in using a static flow test bench with a Reynolds number of 60.000 and open as well as closed wastegate. Figure 12 shows the flow distribution behind the first brick of the cascade catalyst with closed turbocharger wastegate.

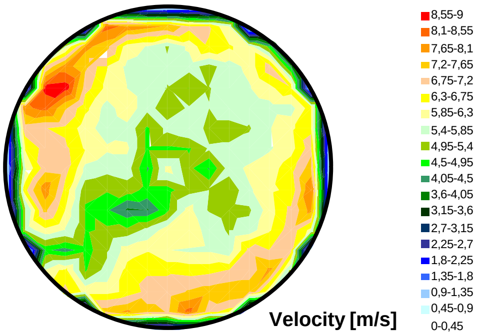

Figure 12: Flow distribution downstream of the first brick, measured with closed turbocharger wastegate

The Uniformity Index [5] as a number equivalent to the quality of the flow distribution amounted to 0,937. The used portion of the inlet surface area amounts to 91,3 % and is therefore quite satisfactory.

The decisive factors in respect of mechanical durability are the stability of the catalysts and the bond they form with the mantle and the canning. The high level of material expansion as a result of the high component temperatures, as well as the oscillation of the engine and the pulsation of the exhaust gas, place extreme demands on the catalytic converter in the case of close-coupled concepts. Engines with an exhaust turbocharger are at an advantage thanks to their lower peak-pressure and temperature loads.

Vibration analyses were carried out for different foil winding concepts and complete catalytic systems.

A distinction needs to be made between the absolute forces of acceleration and the frequency spectrum in which the acceleration occurs. The natural resonance frequencies of the complete catalytic converter system must be greater than the highest excitation frequencies occurring during vehicle operation.

The acceleration frequencies were recorded by means of an three-dimensional acceleration transducer up to a maximum frequency of 6 kHz during full-load engine start-up from 1000 to 6000 rpm. Figure 13 shows the acceleration load as a function of frequency. The maximum excitation frequency of 4000 Hz is still below the critical resonance frequency of the selected catalyst beds and does not lead to any problems. The total acceleration load amounts to 90 g.

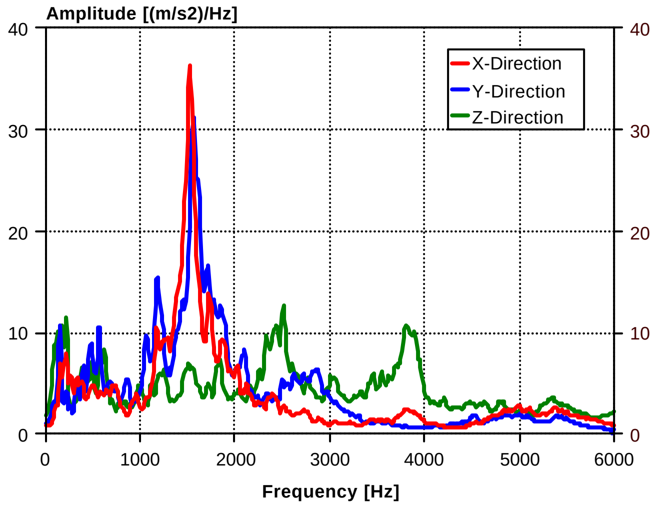

Figure 13: Acceleration load of the 1,8l Turbo catalyst as a function of frequency

In the case of close-coupled concept, particular attention needs to be paid to the thermal loads in dynamic processes, in order to prevent the premature ageing of the catalytic coating. Driving manoeuvres in high load/speed ranges, such as gear-changing at full load in the case of an automatic transmission or fuel cut-off, can, if improperly tuned, cause a sharp rise in the amount of unburned hydrocarbons reacting with oxygen in the catalytic converter. These reactions result in extreme local and temporal temperature gradients for the catalytic coating and catalytic converter, potentially impairing the effect of its catalytically active coating. Sufficiently swift catalytic light-off characteristics in the emission test can then no longer be guaranteed. In view of their transient occurrence, these phenomena can scarcely be resolved with conventional temperature-sensing technology. The use of rapid HC exhaust-gas sensing techniques in the vehicle, in conjunction with highly responsive temperature sensing technology, made it possible to identify the causes of temperature peaks. In this concept, a constant lambda control which is capable of establishing specified lambda values rapidly and accurately means that non-critical exhaust gas temperatures are assured in all engine operating states.

A metal support with SM-shaped winding technology, manufactured by Emitec, has been chosen as the most suitable catalytic converter support for both the first and the second brick. A comparison of coatings revealed that coating JM 405 by Johnson Matthey is the best version in terms of long-term stability and light-off behaviour.

4. Results of the exhaust-gas test (FTP-75)

In addition to the bag emission results for measurements in the vehicle, exhaust-gas emissions of comprehensive tests were recorded second-by-second on a dynamic dynamometer were, in order to obtain a better picture of the cold-start behaviour in particular. Additional thermocouples were installed ahead of the catalytic converter, behind the first monolith and behind the catalytic converter, to determine the temperature of the gas.

The recorded temperatures show that light-off temperature is achieved about 12 seconds after the engine is started, as intended.

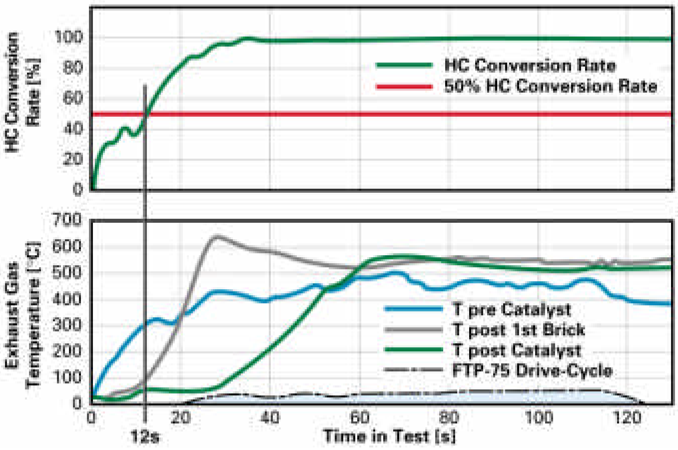

Figure 15: Temperature behaviour of the ULEV-catalyst in the FTP-75 test

At this point, the catalytic converter inlet temperature is over 300°C. The first metalit, approximately 20 % of the entire catalytic converter's volume, is heated up entirely after 25 seconds; at this moment, the temperature at the

outlet of the front metalit is 650°C. After 60 seconds, the entire catalytically active surface of the two cascades has reached operating temperature.
The use of the cascade converter reduces the HC-emissions in bag 1 of the FTP-75 test by 37 % compared to 1-brick solution.

4.1 Compliance with the ULEV standard – in new condition

As part of the US Low Emission Vehicle Program, various emission standards have been specified by law for a mileage of up to 50,000 miles and up to 100,000 miles. From a mileage of 50,000 miles, the vehicle may emit 0.055 g/mile NMOG (compared with 0.04 g/mile when new). Compliance with this long-term standard is checked on a regular basis by the CARB governmental body, with customer vehicles chosen at random.

By combining the individual engine-related measures described and carefully co-ordinating the emission-relevant parameters in the engine management system in conjunction with the cascade catalyst, emissions being less than 50 % of the ULEV standard achieved with new vehicles. Using the 2-brick cascade solution, the reduction in overall HC emissions after the cascade catalytic converter is 51 percent compared with the LEV concept (see figure 16).

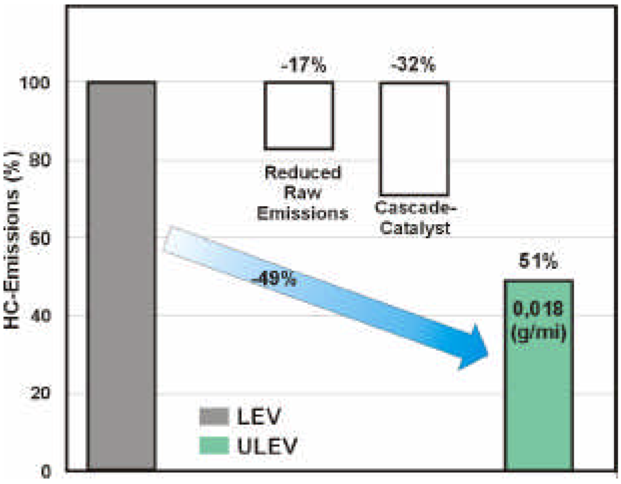

Figure 16: Contribution of individual measures to the ULEV concept

4.2 Compliance with the ULEV standard - after a distance of 200,000 miles

To assure the emissions required by law over 100,000 miles, a fleet of vehicles was driven on US roads according to customer driving profiles. Exhaust gas emissions tests were conducted at regular intervals, to determine the pattern of deterioration in the exhaust emission concept. Over the legally required 100,000 miles, some vehicles from the fleet were driven further, to a total distance of more than 200,000 miles. Using the measurements for these vehicles, the long-term stability of and compliance with the ULEV standard can be impressively substantiated, even after a high mileage (see figure 17).

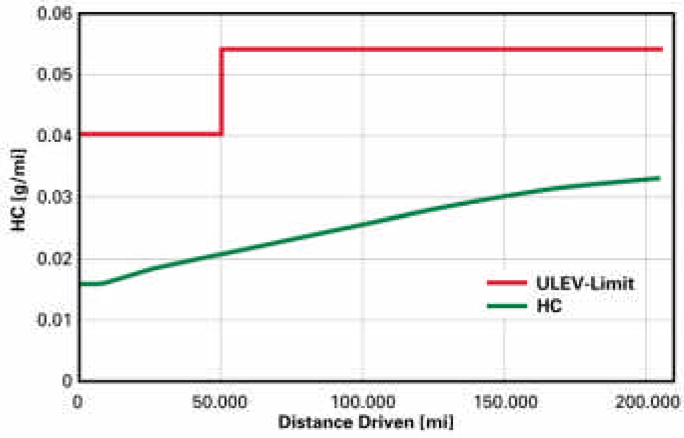

Figure 17: Exhaust emission results in endurance road test over 200.000 miles

5.Summary

By systematically refining key components of the basic concept of the 1.8 l turbo engine with close-coupled catalytic converter, complying with the LEV emission standard, the world's first series-production turbo gasoline engine to comply with the stringent ULEV standard was created for the Audi A4 1.8 T. This consequently once again demonstrates that there is no inherent contradiction between a downsizing concept with exhaust-driven turbocharger and the realisation of pioneering exhaust emissions technology. As the measurements indicate, this exhaust emissions concept is notable for its stable emissions and durability.

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