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The Audi TDI – Tech Workshop 2014

25 years of TDI

Audi is celebrating a very special anniversary in 2014 – 25 years of TDI. At the IAA in Frankfurt am Main in fall 1989, the company presented the Audi 100 equipped with a 2.5 TDI, a fully electronically-controlled diesel engine with direct injection. The brand with the four rings has since then continuously increased its lead in this field of technology and established new milestones.

“25 years of TDI mean a quarter-century of progress, efficiency, dynamics and power,” says Prof. Dr. Ulrich Hackenberg, Member of the Board of Management of AUDI AG, Technical Development. “We look back on this time with pride. For the TDI, which Audi brought to the market before any other carmaker, is today the world's most successful efficiency technology. It thus made a big contribution to our brand’s upward positioning in the premium segment of the market.”

Since 1989, TDI technology has helped to make the diesel engine an overwhelming success. Development has been in multiple steps, with forced induction, fuel injection and emissions controls being the major drivers. Over the course of these 25 years, the TDI has seen its power and torque relative to displacement increase by over 100 percent, while pollutant emissions have come down by 98 percent over the same period.

To date Audi has produced roughly 7.5 million cars with TDI engines – nearly 600,000 in 2013 alone. TDI models are a major reason why the brand with the four rings has been able to reduce the average CO_2 emissions of its EU new vehicle fleet by three percent per year in recent years. Of the 156 TDI models currently in the Audi lineup, 58 have CO_2 emissions between 85 and 120 grams *(136.8 and 193.1 g/mi)*. With its 1.6-liter TDI, the Audi A3 ultra consumes on average just 3.2 liters of fuel per 100 km (*73.5 US mpg*). The term “ultra” represents sustainability throughout the company. Audi is rapidly expanding its range of highly efficient ultra models at the moment.

All of the TDI engines available from Audi today are highly efficient, clean, cultivated, comfortable and powerful. With the exception of the Audi R8, TDI engines can be found in every model series, with displacements from 1.6 to 4.2 liters and outputs between 66 kW (90 hp) for the 1.6 TDI and 283 kW (385 hp) for the 4.2 TDI. The unchallenged leader in terms of sales is the 2.0 TDI. Nearly three million units have been sold so far, nearly 370,000 of them in the past year alone.

TDI technology from Audi has an impressive history of success and a bright future. The completely redesigned, low-emissions 3.0 TDI clean diesel represents a new milestone, and the new 1.4 TDI clean diesel with three cylinders will soon debut in the compact models. In the V6 TDI engines, a supplemental electric compressor will provide for the immediate development of power even at low rpm in the future, making the driving experience even more visceral and sporty.

The electric biturbo also represents the first step in Audi's electrification of the TDI. The new hybridization components will soon be launched on the market. In the future there will be a tailored solution for every customer and requirement, up to and including a TDI with plug-in hybrid technology. When it comes to fuels, the brand is committed to sustainably produced Audi e-diesel, which enables CO_2-neutral driving.

Audi is striving to reduce the fleet consumption of its models to an average of 95 grams CO_2 per kilometer *(152.9 g/mi)* by 2020. The developers are therefore working intensely on not just hybridization, but also the classic technology fields. These include friction reduction, thermal management and the combustion process with the aspects fuel injection and forced induction. Audi is focusing on rightsizing, i.e. the right engine size for the respective size of the car, rather than downsizing. The six and eight-cylinder TDI engines, for example, have proven in practice to be highly efficient because they run smoothly at extremely low rpm.

Racing is part of Audi's DNA. The racetrack is the toughest testing laboratory for new developments destined for use in production vehicles. The TDI engine made its debut at the 24 Hours of Le Mans in 2006. Since then, the brand with the four rings has taken the checkered flag as the overall winner eight times in nine starts. In principle, the same requirements apply on the racetrack and in production:

The goal is to always get more and more out of every drop of fuel. The racing successes powerfully document the potential of TDI technology from Audi. Most recently with a 1-2 finish at Le Mans in the world's most prestigious endurance race.

TDI development

Turbocharging, fuel injection and emissions control are the three main drivers for the development of TDI engines. The engineers are working continuously to further reduce fuel consumption, increase power and torque, and improve running smoothness.

Additional requirements have their roots in legislation and business, such as emissions standards, quality requirements and the composition of diesel fuel in the various markets throughout the world. In Europe, the focus is on biodiesel admixtures and the future RDE (real driving emissions) test cycles. The new 3.0 TDI is already equipped with a two-stage, cooled exhaust gas recirculation system for the ULEV-II standard in some states in the U.S.A. If China, a country in which fuel quality still varies widely today, becomes a diesel market, the criteria altitude and thin air will become more important.

Turbocharging

The numbers used today to describe the Audi turbochargers are impressive. The turbocharger in the new 3.0 TDI develops up to 2.0 bar of relative boost pressure, and at full load can theoretically compress 1,200 cubic meters (1.2 metric tons) of air per hour. Its drive power is in the range of 35 kW with over 200,000 revolutions per minute.

Audi is continuously working to advance the development of turbocharger technology, and its engineers place great emphasis on efficiency, torque development, transition behavior, acoustics and lightweight construction. Progress is made in the form of countless individual steps and in the thousandths of a millimeter range. One example of this are the future compressor wheels. They are machined from a solid block and are even more precise than the castings used today.

The turbocharger in the new 3.0 TDI uses an electric VTG actuator that adjusts the position of the turbine wheel vanes in less than 200 milliseconds. It is installed in a newly developed cartridge, whose halves are riveted together. The narrow rivets disrupt the flow less than the cast connecting points of the previous-generation component. The exhaust gas temperatures, which can reach 830 degrees Celsius, place extreme demands on the moving parts in particular. Any further increase in temperature would require new materials.

Fuel injection

With most engines, Audi uses peak pressures of 2,000 bar in the common rail injection system. The next target is 2,500 bar, and the engineers are already thinking beyond this mark. The TDI engine in the Audi R18 e-tron quattro race car shows what is possible. The four-liter V6 uses an injection pressure of over 2,800 bar to produce roughly 100 kW per liter of displacement. Steel pistons, another option for production models, absorb the ignition pressure, which at for more than 200 bar exceed the level of street TDI engines.

The piezo injectors that Audi uses in its V-engines have nozzle holes only 0.1 millimeter *(0.004 in)* in diameter so that the fuel can be finely atomized even at low load. The higher the pressure, the more precise the mixture, and that benefits not just power and torque, but also smoothness and emissions.

The common rail system in the new 3.0 TDI can make nine individual injections per work cycle. Pre-injection helps to ensure that the engine runs smoothly at low speeds; post-injection serves regeneration of the particulate filter and desulfatizing of the future NOx storage catalytic converter. Audi injection systems must retain their precision, which is measured in the milligram range, over many tens of thousands of kilometers. Even tiny deviations could adversely impact emissions testing results.

Emissions control

In the past, the developers had to design emissions-control components for early response. As the efficiency of the TDI engines increases, exhaust gas temperatures are steadily falling. In the ECE cycle, temperatures measured downstream of the oxidation catalytic converter take 2.5 minutes to reach 150 degrees Celsius. Conversion does not take place below this threshold.

With the new 3.0 TDI, both catalytic converters – the enlarged oxi-cat and the diesel particulate filter with SCR coating – have been moved extremely close to the engine. The water-cooled SCR pump injects the AdBlue solution into the short, bent connecting pipe between the two. With the 160 kW (218 hp) version of the new V6 diesel, the new V6 biturbo and the 4.2 TDI, the oxi-cats are also electrically heated.

Audi's next step will come in 2015 with the 3.0 TDI. Instead of an oxidation catalytic converter, a new NO_x storage catalytic converter will be used. The NOC (NO_x Oxidation Catalyst) stores the oxides of nitrogen until it is completely full. Cleaning is by means of mixture enrichment in the engine. To keep fuel consumption as low as possible, the NOC is only active at low exhaust gas temperatures, i.e. following engine start and at low load. In all other situations, NO_x conversion is handled by the diesel particulate filter with SCR coating. With the great potential harbored by these technologies, Audi is extremely well positioned to meet future emissions regulations.

The new 1.4 TDI

The new 1.4 TDI follows the two-liter four-cylinder engine as the second engine in the Volkswagen Group's modular diesel engine platform (MDB). The three-cylinder unit is designed as a transverse engine and will enter volume production shortly. It has a displacement of 1,422 cc. The stroke of 95.5 millimeters *(3.8 in)* is taken from the 2.0 TDI; the bore has been reduced from 81.0 to 79.5 millimeters *(3.2 to 3.1 in)*. Cylinder spacing is 88.0 millimeters *(3.5 in)*.

Unlike the predecessor engine used through 2005 in the Audi A2, the new 1.4 TDI has a lightweight crankcase made of an aluminum-silicon alloy – a rare exception in its competitive environment. The crankcase is produced via gravity chill casting, which enables particularly high strength, density and homogeneity. Targeted ribbing and detailed measures affecting the engine periphery minimize noise emissions.

The crankcase weighs just 17 kilograms *(37.5 lb)* – 12 kilograms *(26.5 lb)* less than the cast iron block used previously. The engine has a total weight of 132 kilograms *(291.0 lb)*. The thin-walled piston sleeves made of cast iron are thermally joined; the weight of the pistons and connecting rod has been reduced. Piston clearance, ring contour and ring pretensioning have been optimized for low friction losses.

A balance shaft rotates in the opposite direction of the crankshaft. Its drive unit has been integrated into the “duopump”: the oil pump and vacuum pump share a common case. The oil pump switches between three pressure levels as necessary. Another efficiency measure is the separation of the coolant loops for the cylinder block and the cylinder head. The block loop can be deactivated during the warm-up phase. Only the head loop, which also supplies the heat exchanger for the cabin heater, is active here. This thermal management concept quickly brings the 1.4 TDI up to operating temperature following a cold start.

Elaborate needle bearings are used in the drive system for the camshafts. The shafts are mounted in a separate frame and joined to it during engine production. The new valve drive module combines high stiffness with low weight.

The common rail injection system produces 2,000 bar of system pressure. Solenoid valves open and close the nozzle needles in the seven-hole injectors. The high pressure enables an even finer atomization of the fuel in the combustion chambers, and thus more efficient, lower-emissions combustion.

The turbocharger in the 1.4 TDI features pneumatic adjustment of the turbine wheel vanes. The intercooler, which is water-cooled via a separate loop, is mounted on the cylinder head. The low-pressure exhaust gas recirculation system (AGR) is also water-cooled and discharges directly upstream of the turbocharger. It reduces NOx emissions when the engine is hot and at intermediate and high loads, while the uncooled high-pressure AGR is primarily responsible for the phase following a cold start. The new engine complies with the limits of the Euro 6 standard. The entire emissions control system is compact and designed for minimal flow losses.

The new 1.4 TDI produces 66 kW (90 hp) and delivers 230 Nm *(169.6 lb-ft)* of torque between 1,500 and 2,500 rpm.

The new longitudinally-mounted 2.0 TDI

The 2.0 TDI is a true all-rounder in the Audi model lineup. From the Audi A1 to the Audi A6, the two-liter, four-cylinder engine powers a wide variety of models. In the Audi Q5 mid-size SUV, the 2.0 TDI is designed to be installed longitudinally and offers impressive emissions controls that satisfy the EU 6 standard.

Two versions with 110 kW (150 hp) and 140 kW (190 hp) are available. Maximum torque is 320 and 400 Nm *(236 and 295.0 lb-ft)*, respectively. With the 110 kW engine, the Audi Q5 accelerates from 0 to 100 km/h *(62.1 mph)* in 10.9 seconds. Top speed is 192 km/h *(119.3 mph)*, and average fuel consumption is 4.9 liters of fuel per 100 kilometers *(48.0 US mpg)*, a CO_2-equivalent of 129 grams per kilometer *(207.6 g/mi)*. These same figures for the top-of-the-line four-cylinder diesel are 8.4 seconds, 210 km/h *(130.5 mph)*, 5.7 liters of fuel per 100 kilometers *(41.3 US mpg)* and 149 grams CO_2 per kilometer *(239.8 g/mi)*.

The 2.0 TDI with its 1,968 cc of displacement (bore x stroke 81.0 x 95.5 mm *(3.2 x 3.8 in)*) was systematically designed for low efficiency losses. The toothed belts for the camshafts and ancillary components run smoothly and quietly. The two balance shafts, relocated upward from the oil pan to the crankcase, are mounted on roller bearings with oil mist lubrication. Needle bearings are used for the drive wheels of the camshafts as well.

The shafts are pressed into a separate bearing frame, and the new valve drive module exhibits high stiffness and low weight. The valve star in the cylinder head is rotated 90 degrees. Both camshafts actuate one intake and one exhaust valve per cylinder. The intake camshaft can be adjusted hydraulically by as up to 50 degrees. The variable timing improves filling of the combustion chambers, swirling, effective compression and expansion duration.

The common rail injection system produces up to 2,000 bar of system pressure. Solenoid injectors atomize the fuel via eight-hole nozzles. A mini-rail in the injector provides for an additional fuel volume. This minimizes the shock waves at the nozzle needle and ensures defined injection volumes. A sensor in one of the glow plugs analyzes pressure conditions during combustion. The measurements influence engine management.

At the pistons, reduced stress on the rings results in smooth running; in manufacturing the engine, a honing process in fine machining of the cylinder liners guarantees high precision. The two-stage oil pump saves drive energy. The thermal management system is flexible. The coolant loop in the cylinder block can be deactivated during the warm-up phase via a switchable pump in order to quickly heat up the motor oil. The cylinder head microloop is driven by an electric pump and supplies both the cabin heating system and the low-pressure exhaust gas recirculation system.

With its emissions control system, in which an oxidation catalytic converter and a diesel particulate filter with an SCR coating (SCR: selective catalytic reduction) are mounted close to the engine, the new 2.0 TDI in the Audi Q5 complies with the limits of the Euro 6 standard. The uncooled high-pressure exhaust gas recirculation (AGR) system, which is active following a cold start and at very low loads, runs horizontally through the cylinder head. The very compact low-pressure AGR is mounted directly on the engine and is cooled. It covers the majority of the operating range and is designed for low flow losses.

The turbocharger's variable turbine geometry (VTG) is actuated pneumatically. The water-cooled intercooler is integrated into the induction pipe. This type of construction leads to short gas paths, high control quality and very good efficiency.

The new 3.0 TDI

The 3.0 TDI represents the very latest technology. The Audi bestseller in the large model series is now even cleaner and satisfies the requirements of the Euro 6 emissions standard. Performance has also increased. Output is 200 kW (272 hp), the maximum torque of 580 Nm *(427.8 lb-ft)* is available between 1,250 and 3,250 rpm.

The updated Audi A7 Sportback, in which the new V6 diesel is being used for the first time, accelerates with quattro all-wheel drive from 0 to 100 km/h *(62.1 mph)* in 5.7 seconds on its way to an electronically limited top speed of 250 km/h *(155.3 mph)*. Fuel consumption is just 5.2 liters of fuel per 100 km (*45.2 US mpg*) on average, which corresponds to 136 grams of CO_2 per km (*218.9 g/mile*). The new 3.0 TDI is thus 13 percent more efficient than the previous model.

In the ultra model, the new V6 diesel is even more efficient and delivers new best marks. With 160 kW (218 hp) and 400 Nm *(295 lb-ft)* of torque, it accelerates in 7.3 seconds from zero to 100 km/h *(62.1 mph)* and reaches a top speed of 239 km/h *(148.5 mph)*. It consumes just 4.7 liters of fuel per 100 kilometers *(50.0 US mpg)*, a CO_2 equivalent of 122 grams per kilometer *(196.3 g/mi)*.

The new 3.0 TDI, which works with ignition pressures of up to 180 bar, has taken over the key dimensions of the two previous generations: the bore of 83.0 millimeters *(3.3 in)* and the stroke of 91.4 millimeters *(3.6 in)* for a displacement of 2,967 cc. The cylinder banks arranged at 90 degrees to one another; a balance shift spins in the cylinder crankcase. The cylinder crankcase is made of high-strength, yet lightweight vermicular graphite cast iron. Intensive detail work has shaved some weight from it. The entire engine weighs 192 kilograms *(423.3 lb)*.

The forged crankshaft, which has also been optimized for weight, uses the splint-pin principle for smooth running behavior. The connecting rods of the opposing pistons offset by 30 degrees, resulting in even firing intervals. Cast channels supply the aluminum pistons with cooling oil. To reduce friction, the piston pins received a diamond-like carbon coating. The first piston ring also has a high-end hard coating. The ring package has been completely redeveloped. Tangential tension has been reduced by more than 25 percent, so the rings now slide more easily in the piston sleeves. The compression ratio is 16.0:1.

Elaborate plate honing is used in the production of the 3.0 TDI. A plate, which is bolted to the crankcase prior to the mechanical honing of the piston sleeves, simulates the tension later exerted in operation by the cylinder head and which results in deviations from perfect roundness measured in thousandths of a millimeter.

The V6 diesel uses advanced thermal management. The cylinder crankcase and the cylinder heads each have their own coolant circuits connected to one another by a valve. During the warm-up phase, the coolant is not circulated in the block, so the motor oil heats up quickly. To save energy, the coolant often remains stationary at low load, too. The coolant in the head loop heats the cabin and is also supplied to the intercooler for the exhaust gas recirculation system. The cylinder heads' cooling jackets are divided into an upper section and a lower section to reduce pressure losses.

Pressures in the common rail system reach up to 2,000 bar. The extremely fast-switching piezo injectors with their eight-hole nozzles can perform up to eight injections per work cycle. The central swirler flap mounted at the entrance to the induction pump helps to minimize pressure losses. At low rpm, the closed intake channel results in greater swirl, which promotes the development of torque. At high rpm, however, the open channel ensures that the combustion chambers are well filled.

The water-cooled turbocharger is a next-generation design. The electrically actuated positioning mechanism on the turbine side (VTG) is now more aerodynamic and precise, so the engine reacts more quickly to the position of the accelerator. Maximum relative boost pressure has increased from 1.6 to 2.0 bar. The exhaust manifold has also been revised. The newly developed oil pump is now load and engine-speed-controlled over a large range of its characteristic, and the oil cooler has been integrated into the loop via a thermostatically controlled bypass.

Thanks to an emissions-control unit compliant with the Euro 6 emissions standard, all versions of the 3.0 TDI bear the “clean diesel” designation. In the new engine, the components have been moved as close as possible to the rear side to enable quick activation. With the 160 kW (218 hp) V6, the enlarged oxi-cat is mounted coaxially downstream of the turbocharger's turbine outlet. Immediately downstream is a diesel particulate filter. The inner lining of its filters has a coating that removes nitrogen oxides from exhaust emissions by means of selective catalytic reduction (SCR). A metering module injects the additive AdBlue.

The new packaging of the emissions-control components resulted in modifications to the chain drive. The oil/vacuum pump and the high-pressure pump of the common rail system each have their own drives. Intermediate wheels mounted on needle bearings and gear stages replace the large chain wheels in the camshaft drive. As assembled hollow shafts, the camshafts are particularly lightweight. They actuate the valves via extremely rigid roller cam followers. Camshaft bearings with reduced diameters reduce friction.

Audi A7 Sportback 3.0 TDI competition

The Audi A7 Sportback 3.0 TDI competition features the 3.0 TDI biturbo clean diesel with a capacity of 2,967 cc. Modifications in the charging and camshafts have boosted its power by an additional 5 kW (7 hp) compared with the standard model, to 240 kW (326 hp). When the driver accelerates in full, a boost function provides an additional 15 kW (20 hp) on top for a brief period. The maximum torque of 650 Nm (479.4 lb-ft) is available between 1,400 and 2,800 rpm. On average, the powerful and sporty-sounding V6 diesel makes do with 6.1 liters of fuel for every 100 kilometers (38.6 US mpg), which equates to CO_2 emissions of 162 grams per kilometer (260.7 g/mi). The emissions rating is Euro 6.

In keeping with its dynamic character, the Audi A7 Sportback 3.0 TDI competition comes with the S line sport package, which also includes lowering the body by 20 millimeters (0.8 in). The wheels, with their five-spoke W design, have black painted sides. At 20 inches in diameter, they look very impressive; the tire dimension is 265/35. Red brake calipers and discs in 17-inch format on the front and rear axles underscore this special edition model’s sporty character.

The S line exterior package and black gloss package lend the body a dynamic elegance; there are also V6 T emblems on the fenders, black exterior mirror housings and high-gloss black tailpipe trims. The special edition model is offered in Daytona Gray, Misano Red, Nardo Gray and Sepang Blue.

In the style of the S line sport package, the interior of the Audi A7 Sportback 3.0 TDI competition is designed in black. The sport seats are upholstered in fine Valcona leather in black or lunar silver and decorated with S line embossing. As an option, Audi offers the S sport seat with contrasting stitching in Misano Red or Agate Gray; in this case, the armrests are also upholstered in leather with contrast stitching. The inlays consist of aluminum and Beaufort wood in black – an especially high-grade metal/wood combination. The door sill trims feature “quattro” logos. The shift paddles behind the multifunction sport steering wheel can be used to control the eight-speed tiptronic manually.

This special edition model comes packed with all the features that have already gone into the revised A7* model series. They include LED headlights as standard as well as turn signals with dynamic display. As an option, Audi can supply the Matrix LED headlights, the even more powerful MMI Navigation plus and further developed driver assistance systems such as night vision assist.

Customers can order the Audi A7 Sportback 3.0 TDI competition starting in early August; the vehicles will begin shipping in the fall. The base price is 72,000 euros.

The 4.2 TDI

The 4.2 TDI has more torque than any other engine in the Audi lineup. The latest version in the Audi A8 delivers 850 Nm *(626.9 lb-ft)* between 2,000 and 2,750 revolutions per minute. Its peak output of 283 kW (385 hp) is available at just 3,750 rpm.

The tremendous power provides for a sporty and composed driving experience. Mated with an eight-speed tiptronic and quattro drivetrain, the V8 diesel accelerates the luxury sedan from 0 to 100 km/h *(62.1 mph)* in 4.7 seconds on its way to a governed top speed of 250 km/h *(155.3 mph)*.

The top-of-the-line TDI from Audi displaces 4,134 cc (bore x stroke 83.0 mm x 95.5 mm *(3.3 in x 3.8 in)*. Its vermicular cast iron crankcase is a major reason for the engine's comparatively low total weight of approximately 250 kilograms *(551.2 lb)*. Four chain-driven camshafts actuate a total of 32 valves via roller cam followers.

The developers updated the 4.2 TDI for use in the Audi A8. The aluminum pistons got reinforced bowl edges, which, like the new exhaust valves, further improve temperature stability. The common rail system develops up to 2,000 bar of pressure, and piezo inline injectors with newly developed, eight-hole nozzles spray the diesel fuel into the combustion chambers.

Improvements were also made to the two VTG turbochargers, primarily with respect to the mounting of the compressor wheels. Each of the two turbochargers, which produce up to 1.7 bar of relative boost pressure, feeds air to one cylinder bank via a downstream intercooler. With the variable turbine geometry, power begins to develop just slightly above idle speed.

Thanks to this and the highly refined running behavior, the diesel engine can be operated at engine speeds of just 800 rpm if the Audi drive select system is set to efficiency mode. The low engine speed significantly reduces actual fuel consumption. In the ECE cycle, the Audi A8 4.2 TDI clean diesel consumes just 7.4 liters of fuel per 100 kilometers *(31.8 US mpg)*, corresponding to 194 grams CO_2/km *(312.2 g/mi)*.

The 4.2 TDI clean diesel in the Audi A8 meets the requirements of the Euro 6 emissions standard. Two heated oxidation catalysts are located close to the engine; the two particulate filters with an SCR coating are located in the rear. A metering pump injects the AdBlue additive that breaks down the nitrogen oxides. The solution is supplied from two tanks having a combined volume of 27 liters *(7.1 US gal*).

The Audi ultra models

The term “Audi ultra” is reserved for the most fuel-efficient model of each model series. It represents not just full everyday practicality, but also sustainable mobility. Audi currently offers a total of 23 ultra models in the A3, A4, A5, A6 and A7 model series, 15 of which are equipped with TDI engines. With an average fuel consumption of 3.2 to 4.9 liters per 100 kilometers *(48.0 to 73.5 US mpg)* and CO_2 emissions of 85 to 122 grams per kilometer *(136.8 to 196.3 g/mi)*, the ultra models from Audi are among the most efficient cars of their respective classes – without compromising driving dynamics or comfort.

3.2 liters of fuel per 100 kilometers *(73.5 US mpg)*, a CO_2 equivalent of 85 grams per kilometer *(136.8 g/mi)* – the Audi A3 ultra is the most efficient model in the entire Audi lineup. It is powered by the 1.6 TDI, which is designed for minimal friction and produces 81 kW (110 hp) and 250 Nm *(184.4 lb-ft)* of torque. The five-door Audi A3 Sportback ultra and the A3 Sedan ultra consume 3.3. liters per 100 kilometers *(71.3 US mpg)*, corresponding to 88 grams CO_2 per kilometer *(141.6 g/mi)*. The Audi A3 Cabriolet ultra requires just 4.9 liters of fuel per 100 kilometers *(48.0 US mpg)*, corresponding to 114 grams CO_2 per kilometer *(183.5 g/mi)*.

The intensively revised 2.0 TDI is used in the new A4 and A5 ultra models. Depending on the version, it produces either 100 kW (136 hp) or 120 kW (163 hp) and 320 or 400 Nm *(236.0 or 295.0 lb-ft)* of torque. The A4 Sedan with 100 kW (136 hp) consumes just 4.0 liters of fuel per 100 kilometers *(58.8 US mpg)*, a CO_2 equivalent of 104 grams per kilometer *(167.4 g/mi)*. These same figures for the A4 Avant and A5 Sportback, both of which are equipped with the 100 kW (136 hp) engine, are 4.2 liters per 100 kilometers *(56.0 US mpg)* and 109 grams CO_2 per kilometer *(175.4 g/mi)*. The A4 Sedan and the A5 Coupé have 120 kW (163 hp). Efficiency figures for the equally powerful A5 Sportback are 4.3 liters *(54.7 US mpg)* and 111 grams CO_2 per kilometer *(178.6 g/mi)*, and for the 120 kW (163 hp) A4 Avant 4.4 liters per 100 kilometers *(53.5 US mpg)* and 114 grams CO_2 per kilometer *(183.5 g/mi).*

The ultra models in the A6 lineup use the top-of-the-line version of the 2.0 TDI, which produces 140 kW (190 hp) and 400 Nm *(295.0 lb-ft)*. The exact values: A6 Sedan with S tronic – 4.4 liters per 100 kilometer *(53.5 US mpg)* and 114 grams CO_2 per kilometer *(183.5 g/mi)*; A6 Sedan with manual transmission – 4.5 liters per 100 kilometers *(52.3 US mpg)* and 117 grams CO_2 per kilometer *(188.3 g/mi)*; A6 Avant with S tronic or manual transmission – 4.6 liters per 100 kilometers *(51.1 US mpg)* and 119 grams CO_2 per kilometer *(191.5 g/mi)*.

The Audi ultra models come standard with a manual transmission with a somewhat taller gear ratio in the upper gears. The optional S tronic in the A6 model is a completely new design. The driver information system with efficiency program and the start-stop system also contribute to efficiency. Rounding out the package in models from the A3 and A4 families are aerodynamic modifications and a lower ride height. All ultra models are visually identifiable by the discreet lettering at the rear.

The racing engines

Audi considers racing to be the ideal test bench for production, and the toughest testing lab of all is the 24 Hours of Le Mans. 2006 was the first time that Audi entered a car powered by a TDI engine. Audi has celebrated 13 overall victories in 15 starts, eight of them with TDI engines. This includes a 1-2 finish on June 15. The same requirements apply to the sport prototypes at Le Mans and in the FIA World Endurance Championship (WEC) as to production cars: to always get more and more out of every drop of fuel, to increase efficiency and at the same time continuously reduce consumption even further.

Over the years the rules at Le Mans have placed increasingly restrictive limits on TDI engines. For example, the diameter of the air restrictor has decreased by 34 percent since 2006, displacement by nearly 33 percent. Absolute output declined as a result by approximately 25 percent from more than 478 kW (650 hp) in 2006 to around 360 kW (490 hp) in 2013.

At the same time, Audi rigorously downsized and vastly improved the specific output. This increased from 87 kW (118 hp) per liter of displacement in 2006 to 107 kW (146 hp) in 2011 – an increase of nearly 24 percent. The piston area output – the output delivered by each individual cylinder – grew during this period of time from 40 kW (54 hp) to 66 kW (90 hp), in other words by 65 percent. While the driven speed has increased further, Audi dramatically reduced fuel consumption during race operations at Le Mans.

2006 – 2008: The V12 TDI in the Audi R10 TDI

With the R10 TDI and its twelve-cylinder TDI engine, Audi opened a new chapter in racing. Following its debut, the diesel race car has completed an overwhelming series of victories. With 1,100 Nm *(811.3 lb-ft)*, the 5.5-liter TDI engine vastly exceeded that of the gasoline engines. At rated speed, the very quiet-running twin-turbo produced roughly 480 kW (more than 650 hp). Drivers shifted into second gear at just 5,000 rpm. Two particulate filters cleaned the exhaust gas, and a sequential five-speed transmission transferred the power to the rear axle.

The comparatively low fuel consumption and the long range of the R10 TDI were the key to success at the 24-Hours of Le Mans in 2006. Frank Biela, Emanuele Pirro and Marco Werner brought their car into the pits just 27 times. The same team won again with the Audi R10 TDI in 2007, despite difficult weather conditions and the fact that the race organizers reduced the permissible fuel tank volume by ten percent. In 2008, Rinaldo Capello, Allan McNish and Tom Kristensen completed the hat trick for the Audi R10 TDI.

2009/2010: The V10 TDI in the Audi R15 TDI

With the R15 TDI, Audi spread the 5.5 liters of displacement across two fewer cylinders. The V10 TDI had roughly 440 kW (approximately 600 hp) and more than 1,050 Nm *(774.4 lb-ft)* of torque. It was shorter and lighter than the twelve-cylinder, which benefited the agility of the new sport prototype significantly.

Audi celebrated a dominating 1-2-3 finish with the open sport prototype in 2010. Timo Bernhard, Romain Dumas and Mike Rockenfeller improved the distance record, which Porsche had established 39 years before, by five laps or 75.4 kilometers *(46.9 mi)* to 5,410.713 kilometers *(3,362.1 mi)*.

Although the Le Mans rules had once again reduced boost pressure and air flow, the performance of the ten-cylinder TDI remained virtually unchanged. Audi used turbochargers with variable turbine geometry (VTG) for the first time in the V10 TDI, which improved throttle response substantially. Exhaust gas temperatures of up to 1,050 degrees Celsius were extremely demanding on the material. Steel pistons, which had previously been tested in the V12, were also used for the first time in the V10 TDI. This enable even higher pressures to be used, thus providing for even greater efficiency.

2011 – 2013: The V6 TDI in the Audi R18 TDI, R18 ultra and R18 e-tron quattro

In 2011, Audi took to the track at the 24-hour race in the R18 TDI – the brand's first closed sport prototype since the R8C in 1999. The new rules required drastic downsizing of the engine to a displacement of 3.7 liters. Newly designed from the ground up, the lightweight and compact V6 TDI with a cylinder bank angle of 120 degrees produced over 397 kW (540 hp) and more than 900 Nm *(663.8 lb-ft)* of torque, which was transferred to the wheels via the likewise new six-speed transmission. The common-rail system generated up to 2,600 bar of pressure.

Audi also broke new ground with respect to the layout and cooling of the cylinder heads. From now on the intake side was on the outside, the hot exhaust side on the inside. The mono-turbocharger was located inside the V and drew its fresh air from the scoop on the roof. The large VTG turbocharger, which developed up to 2.0 bar of relative boost pressure (2011: 2,960 mbar absolute; 2012 – 2013: 2,800 mbar absolute), featured an innovative double-flow design and opposing intakes for the exhaust flows, plus two outlets on the compressor side. The compressed air flowed via separate intercoolers into two exhaust manifolds. The race at Le Mans was very dramatic. Marcel Fässler, André Lotterer and Benoît Tréluyer took the checkered flag in the remaining Audi R18 TDI just 13.854 seconds ahead of four Peugeots.

With the motor-generator unit (MGU) on the front axle, which depending on the amount of energy can temporarily produce up to 170 kW of power, the Audi R18 e-tron quattro had temporary all-wheel drive. Fässler, Lotterer and Tréluyer celebrated the first victory of a hybrid race car at Le Mans with an Audi 1-2-3 finish in 2012. Tom Kristensen, Loïc Duval and Allan McNish won the following year.

2014: The new V6 TDI in the Audi R18 e-tron quattro

The new R18 e-tron quattro that Audi entered at Le Mans in June 2014 is powered by a completely redesigned V6 TDI with a displacement of 4.0 liters. Its performance data: a good 395 kW (537 hp) and more than 800 Nm *(590.0 lb-ft)* of torque. Injection pressure is more than 2,800 bar. Thanks to very intensive detail work, the engine is easily the lightest and at the same time most efficient racing diesel engine from Audi. Fuel consumption decreased by more than 25 percent compared with the 3.7-liter engine. The hybrid system – the motor-generator unit at the front of the car and the flywheel storage system next to the driver – delivers more than 170 kW. Equipped with this technology package, Audi entered the 24-hour race in the energy class up to two megajoules of recuperative energy. The new rules limited the amount of available energy per lap, but left many other parameters freely configurable. In a dramatic race marked by numerous lead changes, the No. 2 Audi R18 e-tron quattro claimed the overall victory. Marcel Fässler/André Lotterer/Benoît Tréluyer completed 379 laps. Tom Kristensen/ Luca di Grassi/Marc Gené took second place in the No. 1 car to complete the Audi triumph. The winning car consumed 22 percent less fuel than its predecessor from 2013. Since the start of the TDI era (2006), Audi has reduced fuel consumption at the 24 Hours of Le Mans by 38 percent.

Electric biturbo and hybridization

The TDI engine gets its power from the boost pressure developed by the turbocharger, which is dependent on the energy of the exhaust. The electric biturbo breaks this dependency. Its supplemental electric compressor enables a rapid buildup of boost pressure and high torque even at low engine speeds. 25 years after the invention of the TDI, Audi is now taking the next big step and making the diesel engine even more emotional and sporty.

In addition to the classic exhaust gas turbocharger, the electric biturbo has a second charger arranged in series. Instead of a turbine wheel, it contains a small electric motor that applies a maximum drive power of seven kW to accelerate the compressor wheel to maximum speed within 250 milliseconds.

The electric compressor is downstream of the intercooler. At very low engine speeds and thus correspondingly low exhaust gas energy at the turbocharger, the bypass valve closes and the air is routed to the electric compressor. This can be flexibly and compactly integrated into a variety of forced induction concepts.

Audi has built two technology studies with the electric biturbo: The Audi A6 TDI concept is equipped with the new 3.0 TDI monoturbo; the Audi RS 5 TDI concept with the 3.0 TDI biturbo. In steady-state – no additional impetus – the monoturbo produces a constant 240 kW (326 hp) and 650 Nm *(479.4 lb-ft)* of torque, the latter between 1,500 and 3,500 rpm. The electric compressor fills the gap in the torque curve below this range and provides for fast response and excellent elasticity. Acceleration from 60 to 120 km/h *(37.3 to 74.6 mph)* in sixth gear is reduced from 13.7 to 8.3 seconds.

The modified V6 biturbo in the Audi RS 5 TDI concept is even more impressive. It produces 283 kW (385 hp), and peak torque of 750 Nm *(553.2 lb-ft)* is available between 1,250 and 2,000 rpm. The electric compressor provides for tremendous power when starting off. If the driver stays on the accelerator, 100 km/h *(62.1 mph)* is reached in roughly four seconds. Boost pressure is available immediately after each change of gears thanks to the intelligent interplay between the two turbochargers.

The most impressive aspect of both technology studies, however, is the rapid, nearly seamless development of power even at low engine speeds. The strengths of the electric biturbo lie exactly where they make the most sense in everyday driving. It eliminates the need for constant downshifting, keeping engine speeds low. Sporty drivers will really appreciate the passing power and immediate delivery of power when exiting a curve. The electric biturbo is suitable for use in many Audi model series as well as with gasoline engines, in principle. It will soon enter series production in the TDI sector.

The energy required to drive the electric compressor is largely generated by recuperation during coasting phases, so that the end effect is essentially neutral with regard to energy consumption. It is supplied with power via a separate 48-volt electrical system, complete with its own compact lithium-ion battery in the trunk and power electronics. A DC/DC converter provides the connection to the 12-volt electrical system.

The new 48-volt subsystem offers major advantages. It can supply the high-performance electrical consumers of the future – thermoelectric heating elements, electromechanical rear brakes or engine auxiliaries such as oil and water pumps – with more energy than the 12-volt electrical system. Higher voltage means lower currents, allowing for smaller cable cross-sections and thus reduced weight. Audi plans to introduce the 48-volt electrical subsystem to multiple model series shortly.

In parallel to this, the Audi engineers are also working to electrify the drivetrain. There will be a tailored solution for each customer. The hybrid platform offers numerous solutions, from the electric biturbo to the TDI with plug-in technology. The combination with the electric motor opens up new possibilities. It enables targeted shifting of the load points to the benefit of both fuel consumption and emissions behavior. In urban traffic, the electric motor provides for zero-emissions power.

Another interesting electrification option is the electric quattro drive, the e-quattro. Audi has shown this in many of its show cars. The TDI and an electric motor drive the front wheels, while a second electric motor in the rear drives the rear wheels. The battery can be installed in part in the floor tunnel.

Audi e-diesel

In collaboration with the U.S. firm Joule, Audi is taking a fundamentally new approach to the diesel fuel of the future. The biotech company, founded in 2007 and based in Bedford, Massachusetts, is working on producing synthetic fuels – Audi e-diesel and Audi e-ethanol – with the help of special microorganisms. They are virtually climate-neutral, as they only release as much CO_2 during combustion as was bound during production. According to current projections, a car operated on Audi e-diesel will achieve a good carbon footprint similar to that of a battery-electric car using electricity produced from renewable sources.

Audi e-diesel and Audi e-ethanol require water, CO_2, solar energy and special microorganisms – single-cell organisms measuring roughly three-thousandths of a millimeter. Just as plants do, these organisms operate with what is known as oxygenic photosynthesis – they utilize sunlight and CO_2, e.g. from waste gases, to form carbohydrates and grow. They do not need an environment of clean drinking water; saltwater or wastewater is sufficient. One of the byproducts of oxygenic photosynthesis is oxygen.

The experts at Joule have modified this photosynthesis process such that these microorganisms produce alkanes – important components of diesel fuel – and ethanol directly from the carbon dioxide. The fuels are separated from the water and cleaned.

Audi e-diesel offers the advantage of high purity – it is free of sulfur and aromatics. This is in stark contrast to petroleum-derived diesel, which is a mixture of a wide variety of hydrocarbon compounds. The new fuel will also offer excellent ignition performance thanks to its high cetane number. And its chemical composition will permit unlimited blending with fossil fuel diesel. No major modifications are required in order to operate Audi's clean diesel engines on Audi e-diesel.

In 2012, Audi and Joule jointly built a demonstration facility in Hobbs, New Mexico (USA) – a barren, non-arable region with lots of sunshine. The two companies have been partnering since 2011. The American company has patented its technology; Audi is Joule's exclusive automotive partner. Audi engineers are contributing their expertise in the area of fuel and engine testing and the preparation of LCAs (life cycle assessments) to the development of marketable fuels, the production of which could begin within the next few years.

Audi's activities in the development of CO_2-neutral fuels extend beyond the partnership with Joule, however. The Audi e-gas plant in Werlte, Lower Saxony, is the world's first industrial power-to-gas plant. It produces synthetic methane, thus making it possible to store large amounts of wind and solar energy. Besides the green electricity, the process requires nothing other than water and CO_2. Audi is also conducting joint research into the synthesis of Audi e-gasoline with Global Bioenergies of France.

The Audi show cars with TDI engines

The concept studies date from 2005 to the present. TDI engines with four, six, eight, ten and even twelve cylinders were used.

2007: Audi Q7 coastline

368 kW (500 hp), 1,000 Nm *(737.6 lb-ft)* of torque: The Q7 V12 TDI show car that Audi presented at the Detroit Auto Show in January 2007 was the herald of the production model launched in 2008. Its performance catapulted the concept SUV into the sports car league. The standard sprint took just 5.5 seconds, and acceleration did not stop until reaching an electronically-governed top speed of 250 km/h *(155.3 mph)*.

The technology of the six-liter TDI corresponded to that of the production model. The common rail system with piezo injectors produced injection pressures of up to 2,000 bar. Both VGT turbochargers generated up to 1.6 bar of relative boost pressure. The crankcase was cast from vermicular graphite, and the cylinder banks were arranged at an angle of 60 degrees from one another. The V12 diesel from Audi also impressed with its incredible smoothness.

2008: Audi R8 V12 concept and the R8 TDI Le Mans

In early 2008, Audi presented the Audi R8 V12 TDI concept in Detroit. A few weeks later, the structurally identical R8 TDI Le Mans was at the Geneva Motor Show. Both studies referenced the victories that Audi scored at the 24-hour race with the R10 TDI in 2006 and 2007.

The show car features a six-liter V12 TDI similar to that in the race car. The mid-mounted engine sat directly behind the driver and passenger. The storage space for a golf bag normally found in the Audi R8 was eliminated. 368 kW (500 hp), 1,000 Nm *(737.6 lb-ft)* of torque – the latter at 1,750 rpm – accelerated the two-seater from 0 to 100 km/h *(62.1 mph)* in 4.2 seconds and beyond to a top speed of more than 300 km/h *(186.4 mph)*. Fuel consumption was computed at less than ten liters per 100 kilometers *(23.5 US mpg)*.

2008: Audi A3 TDI clubsport quattro

The Audi A3 TDI clubsport quattro was first presented in May 2008. It put out 165 kW (224 hp) and produced 450 Nm *(331.9 lb-ft)* of torque at 1,750 rpm. The show car sprinted from zero to 100 km/h *(62.1 mph)* in 6.6 seconds and reached a top speed of 240 km/h *(149.1 mph)*.

The specific values for the two-liter diesel were 83.8 kW (113.8 hp) and 228.7 Nm *(168.7 lb-ft)* of torque per liter of displacement. An enlarged VTG turbocharger pressed the air into the combustion chambers; the common rail system injected the fuel under a pressure of 1,800 bar. Switchable resonance chambers in the tailpipes of the exhaust system gave the 2.0 TDI a full sound.

2010: Audi e-tron Spyder

The Audi e-tron Spyder, one of the stars of the 2010 Paris Motor Show, was an open two-seater measuring a good four meters *(14.1 ft)* in length. It had an aluminum structure in an Audi Space Frame design, an outer skin of carbon fiber-reinforced polymer (CFRP) and a plug-in hybrid drive.

A three-liter TDI with twin turbochargers drove the rear wheels with 221 kW (300 hp) and 650 Nm *(479.4 lb-ft)*. Two electric motors with 64 kW and 352 Nm *(259.6 lb-ft)* powered the front wheels. They could be individually controlled, thus enabling intelligent torque vectoring. Power was supplied by a lithium-ion battery with a capacity of 9.1 kWh. The electric range was 50 kilometers *(31.1 mi)*. The Audi e-tron Spyder consumed 2.2 liters of fuel per 100 kilometers *(106.9 US mpg)*, corresponding to 59 grams CO_2 per km *(95.0 g/mi)*. The dynamic performance figures: from 0 to 100 km/h in 4.4 seconds. Top speed was capped at 250 km/h *(155.3 mph)*.

2013: Audi nanuk quattro concept

Audi showed the Audi nanuk quattro concept technology study at the 2013 IAA in Frankfurt am Main. The two-door coupe crossover concept combined the dynamics of a high-performance sports car with Audi's quattro expertise – on the road, on the race track and off-road.

It was powered by a V10 TDI mounted longitudinally in front of the rear axle. The powerful 5.0-liter diesel produced more than 400 kW (544 hp) and developed 1,000 Nm *(737.6 lb-ft)* of torque starting at 1,500 rpm. It used a twin-turbo register charging unit and the Audi valvelift system (AVS) – technologies which have since undergone intensive further development by Audi. Its common rail system developed up to 2,500 bar of pressure. The Audi nanuk quattro concept sprinted from zero to 100 km/h in 3.8 seconds and reached a top speed of 305 km/h *(189.5 mph)*. It consumed on average just 7.8 liters of fuel per 100 kilometers *(30.2 US mpg)*.

2005 to 2009: Additional show cars with TDI engines

Audi presented additional studies with TDI engines to the public besides the show cars described above. The Audi allroad quattro concept at the 2005 Detroit Auto Show presented the at that time new V8 diesel, which entered production shortly thereafter. In 2008, Audi showed the Cross Coupé quattro in Shanghai and the Cross Cabriolet quattro in Los Angeles. The closed two-door used the 2.0 TDI; the Cabriolet the three-liter diesel. The Sportback concept was on the Audi stand in Detroit in early 2009. The precursor of the Audi A7 Sportback had the 3.0 TDI clean diesel with SCR (selective catalytic reduction) catalytic converter under the hood.

Technology milestones

Audi has further developed the TDI engine continuously since its premiere in 1989. In 25 years, the brand with the four rings has since then continuously increased its lead and established numerous milestones.

1970s: Pressure from the oil crisis

Development of the TDI began at Audi in the mid-1970s. The oil crisis gave rise to the task of creating a fuel-efficient new engine. During predevelopment, the developer team of ten Audi engineers decided on the multi-jet process. Systems supplier Bosch developed an electronically controlled, axial piston injection pump that developed up to 900 bar of pressure. Two-spring holders opened the nozzle needles in two stages with different amounts of lift. They enabled the pre-injection of smaller amounts of fuel, which made combustion softer and the acoustics more pleasant.

1989: 2.5 TDI

Audi presented a milestone of technology at the 1989 IAA in Frankfurt am Main: the 2.5 TDI, installed in an Audi 100. The inline five-cylinder engine displacing 2,461 cc was a direct-injection turbo diesel with fully electronic management – the first TDI. No one suspected at that time that it would help the diesel engine to break through to volume automobile production in Europe and would mark the start of a new era.

With 88 kW (120 hp) and 265 Nm *(195.5 lb-ft)* of torque, the latter at 2,250 rpm, the power set completely new standards in its competitive environment. The Audi 100 2.5 TDI reached a top speed of nearly 200 km/h *(124.3 mph)*, yet according to the standard valid at that time consumed just 5.7 liters of fuel per 100 kilometers *(41.3 US mpg)*. Beginning in 1994, the five-cylinder engine, equipped with a new radial piston pump, oxi-cat and exhaust gas recirculation, produced 103 kW (140 hp) in the Audi A6. An 85 kW (115 hp) version was available as an alternative.

1991: 1.9 TDI with VTG turbocharger

TDI engines from Audi also embarked on the road to success in the mid-size class. The four-cylinder 1.9 TDI made its way to the Audi 80 in 1991, producing 66 kW (90 hp) and 182 Nm *(134.2 lb-ft)*. An updated version with 81 kW (110 hp) followed four years later in the Audi A4. This increase was due primarily to a new turbocharger with adjustable vanes on the exhaust side. The VTG turbocharger enabled smooth and early development of torque beginning at 1,700 rpm.

1997: World's first V6 TDI

Audi did pioneering work again in 1997. A further innovation in the automotive diesel segment was the combination of a V6 TDI with a four-valve cylinder head. The 2.5-liter engine produced 110 kW (150 hp) and 310 Nm *(228.6 lb-ft)* of torque. The engine presented solutions such as swirl and tangential channels in the intake as well as a radial piston injection pump developing up to 1,850 bars of pressure. The 2.5 TDI was used in the A4, the A6 and the A8, with the last generation producing 132 kW (180 hp).

1999: V8 TDI

3,328 cc of displacement, four overhead camshafts, 32 valves, two VGT turbochargers – the V8 TDI, since October 1999 standard in the Audi A8, was a high-tech statement. Its crankcase was made of high-strength, yet lightweight vermicular graphite cast iron; the charge air and the recirculated exhaust gas were cooled with water. A common rail system – then new at Audi – injected the fuel at a pressure of 1,350 bar. With 165 kW (225 hp) and 480 Nm *(354.0 lb-ft)* of torque, the V8 TDI was a composed and cultivated engine. It took top speed to a whole new dimension with a figure of 242 km/h *(150.4 mph)*.

2001: 1.2 TDI

Audi set a lasting accent in 2001: The Audi A2 1.2 TDI achieved an average fuel consumption of 2.99 liters per 100 kilometers *(78.7 US mpg)*, a CO_2-equivalent of 81 grams per kilometer *(130.4 g/mi)*. The compact five-door with the strictly aerodynamically shaped aluminum body was powered by a three-cylinder engine with a displacement of 1.2 liters that produced 45 kW (61 hp) and 140 Nm *(103.3 lb-ft)*. The engine featured two valves per cylinder, a VTG turbocharger and pump-injector fuel injection with 2,050 bar of pressure, a technology from the Volkswagen Group that Audi introduced the year before. The A2 1.2 TDI remains today the world's only five-door, three-liter car.

2004: 3.0 TDI

The 3.0 TDI introduced in 2004 was the first member of the new family of Audi V-engines with a uniform cylinder angle of 90 degrees, cylinder spacing of 90 millimeters *(3.5 in)* and timing chains on the rear side. Like all the large Audi diesel engines, it had a lightweight but extremely strong vermicular graphite cast-iron engine block. A diesel particulate filter – new at Audi – cleaned the exhaust gas.

Another first were the piezo inline injectors. They could inject tiny amounts of fuel and open and close extremely quickly to perform multiple, staggered injections. This enabled a finely modulated rise in pressure to a maximum of 1,600 bar and a combustion process that provided for quiet engine acoustics. The V6 TDI was launched in three versions with 150 kW (204 hp), 165 kW (224 hp) and 171 kW (233 hp). It was widely used throughout the model lineup. Audi introduced a second generation in 2009.

2008: V12 TDI

The twelve-cylinder, deployed in the Q7 in late 2008, crowned Audi's TDI technology as the world's most powerful production diesel engine for an automobile. Features included the common rail system with 2,000 bar of pressure, and the two VTG turbochargers. The cylinder bank angle of 60 degrees provided for excellent mass balance and thus supremely smooth running.

Displacing 6.0 liters, the V12 TDI produced 368 kW (500 hp) and 1,000 Nm *(737.6 lb-ft)* of torque, the latter between 1,750 and 3,250 rpm. With it, the big SUV accelerated like a sports car from zero to 100 km/h *(62.1 mph)* in 5.5 seconds and reached an electronically governed top speed of 250 km/h *(155.3 mph)*.

2009: 3.0 TDI clean diesel

In response to increasingly stringent emissions standards, particularly in the U.S.A., Audi introduced clean diesel technology in 2009. The 3.0 TDI clean diesel had a common rail system with 2,000 bar of pressure and innovative combustion chamber sensors on board. The fine atomization and precise combustion of the fuel provided for low untreated emissions. An SCR catalytic converter (selective catalytic reduction) reduced oxides of nitrogen in the exhaust system. The aqueous additive AdBlue injected into the system decomposed in the hot exhaust flow to ammonia, which reacted with the oxides of nitrogen to form water and nitrogen.

This was followed in 2013 by a new component that consolidated two previous ones: the diesel particulate filter with an SCR coating. Ceramic substrates – aluminum titanate or silicon carbide – on the filter walls take over conversion of the NO_x. A downstream ammonia slip catalyst (ASC) converts the remaining ammonia molecules that can be emitted at high loads.

TDI lexicon

From A for the Audi 100 TDI to V for Vermicular graphite cast iron, Audi has perfectly mastered the alphabet of diesel technology.

Audi 100 TDI (1989)

At the 1989 IAA Frankfurt Motor Show, Audi exhibited a milestone in automotive technology: The five-cylinder in the Audi 100, which displaced 2,461 cc, was the first direct-injection turbo diesel with fully electronic management – the first TDI. With 88 kW (120 hp) and 265 Nm *(195.5 lb-ft)* of torque, the latter at 2,250 rpm, the two-valve-per-cylinder engine produced ample power with groundbreakingly low fuel consumption.

Swirler channels in the inlet ports produced turbulence in the air. The distributor-type injection pump developed up to 900 bar of pressure, and the five-hole nozzles in the injectors ensured a precise spray pattern. The two-spring nozzle holders – one of the major breakthroughs in the development of the TDI – made possible a pre-injection that took the harshness out of the combustion process and reduced the noise level. The charge air cooler reduced the temperature of the compressed induction air.

Ancillaries

Audi is also continuously improving the efficiency of the ancillaries. The latest oil pumps, for example, are hydraulically regulated by the volumetric flow and only consume the amount of energy they actually need. Audi is working on electrified units in the medium term.

Audi e-diesel

Audi e-diesel is a synthetic, CO_2-neutral fuel of the future. To make it, special microorganism that live in water produce long-chain alkanes – important components of diesel fuel, by photosynthesis. All they require for this is sunlight and CO_2. The new fuel offer stands out for its chemical purity and high cetane number.

Audi has partnered with the American biotechnology company Joule to build a demonstration plant in New Mexico, which in addition to Audi e-diesel also produces Audi e-ethanol. Cars that use these fuels are similarly eco-friendly as pureLY electric cars operated on green electricity.

Biturbo

The 3.0 TDI biturbo is Audi's most powerful V6 diesel. A changeover valve connects its two in-series turbochargers. At low revs it is closed. The small charger with its variable turbine geometry does most of the work, and the large charger is responsible for the pre-compression. From about 2,500 rpm, the valve starts to open and the small charger increasingly transfers the major share of work to its counterpart. In the range between 3,500 and 4,000 rpm, the valve opens completely, and only the large charger still operates.

Given its high-performance concept, Audi has refined numerous details of the engine and its periphery. A sound actuator in the exhaust system gives this diesel engine a rich, resonant sound reminiscent of an eight-cylinder unit. The 3.0 TDI biturbo is used in such models as the Audi SQ5 TDI, the first Audi S model with a diesel engine.

clean diesel

To drastically reduce oxides of nitrogen emissions and thus meet the limits of the new Euro 6 emissions standard, Audi is converting its TDI engines to clean diesel technology. In most cases, this requires changes to the engine and the exhaust system. A $DeNO_x$ catalytic converter suffices for the more compact engines and models.

The technology is a bit more complex for the large models and engines. The new 3.0 TDI has a larger oxidation catalytic converter, which in the version with 160 kW (218 hp) is electrically heated. A larger catalytic converter with oxygen sensor is arranged coaxially downstream of the turbocharger’s turbine outlet. Audi is the first carmaker to combine a NOx storage catalytic converter with a diesel particulate filter and SCR injection (selective catalytic reduction) in one assembly. A metering module injects the additive AdBlue.

Common rail

A common rail injection system is a pipe-like high-pressure accumulator that maintains the fuel at a constant high pressure, which in Audi production engines is up to 2,000 bar. It is filled by a pump powered by the engine. The injectors are connected to the common rail by short steel pipes, and opened and closed by electrical impulses.

Common rail technology separates pressure generation from injection, which enables the developers to freely configure all injections in the characteristic. This gives them great freedom; up to nine individual injections are possible per work cycle. The pre-injection stages allow fuel pressure to be built up gradually, so that combustion is quieter; post-injection reduces pollutant emissions and is also used to regenerate the particulate filter.

Electric biturbo

The electric biturbo is a brand new technology from Audi. The exhaust turbocharger works together here with a supplemental, electric-powered compressor. Instead of a turbine wheel, it uses a small electric motor that accelerates the compressor wheel to very high speeds in an extremely short time.

The electric turbocharger is downstream of the intercooler. In most operating states, it is bypassed. When the energy of the exhaust gas is low at very low engine speeds, the bypass valve closes and the new component is activated. The new technology enables a spontaneous development of power never before seen when starting off and at low rpm.

Exhaust gas recirculation (EGR)

At high combustion chamber temperatures, oxides of nitrogen are produced in combustion engines. These can be largely avoided through the use of exhaust gas recirculation. With the TDI engines, EGR returns a large portion of the exhaust gas to the combustion chamber. This reduces the fraction of fresh, oxygen-rich air and combustion chamber temperatures decrease.

Audi introduced EGR with its very first TDI engine: The first generation of the 2.5-liter five-cylinder was equipped with it in 1994. To increase efficiency, a water-cooled system is used on nearly all engines today. On its way back to the engine, the exhaust gas flows through a water cooler. The new 2.0 TDI and the future 1.4 TDI combine a cooled and an uncooled EGR.

Four-valve technology
Engines with four valves operate more efficiently than two-valve engines, because internal gas flow is sped up and the cylinders filled more effectively. Since they burn their fuel with greater efficiency, they generate more power and torque, with reduced consumption and exhaust emissions.

Audi introduced the four-valve technology with dual overhead camshafts for the 2.5-liter V6 TDI diesel in 1997. The injector nozzle could then be in the ideal position at the precise center of the combustion chamber. Another major advantage was obtained by giving the two inlet ports different patterns: In the swirl duct, the inflowing air is turbulent at low load and rpm, which increases torque. The tangential channel enables high dynamics by reducing resistances at higher rpm.

Hybridization
Audi already has a variety of hybrid models on the market, and the compact Audi A3 Sportback e-tron with its plug-in hybrid technology is coming to dealerships this year. The next step will follow shortly: the new models with longitudinal engines.

The second-generation modular longitudinal platform is designed for combining electric motors with combustion engines, including TDI units. This will be done specifically for each model. Audi has developed a technology matrix with electrification stages up to the plug-in hybrid drive.

Intercooler
When a turbocharger compresses the intake air, it heats it to as much as 200 degrees Celsius. Hot air has a lower density, however, and thus contains less oxygen for combustion. An intercooler is therefore placed downstream of the turbocharger to greatly cool the compressed air before it enters the combustion chamber.

Intercoolers are standard equipment at Audi. Depending on their design, they use air and/or water from the coolant circuit as a cooling medium. The Audi engineers have also taken measures to maximize efficiency in the intercooler – in terms of weight, efficacy and lower flow resistance.

Internal friction

Audi has drastically reduced internal friction in many of its TDI engines. Among the means used to do this are high-end processing technologies in manufacturing, such as laser exposure and plate honing of the cylinder sleeves. The more durable and precise cylinder sleeves make it possible to minimize the tension of the piston rings so that they slide more easily. Smaller bearings at the crankshaft, the connecting rods and the camshafts also contribute greatly to the reduction in friction.

Another field of innovation are the materials in the engines. In the new 3.0 TDI, for example, the first piston ring has a coating produced using an innovative method. The piston pins have a diamond-like carbon (DLC) coating.

Multi-hole nozzles

The common rail systems from Audi are extremely high-precision components. They inject tiny amounts of fuel into the combustion chambers at pressures of up to 2,000 bar. The fuel exits the nozzles at several times the speed of sound.

In some engines, Audi uses piezo injectors with eight-hole nozzles, with each hole only around 0.1 millimeters (0.0039 in) in diameter. The extremely fine atomization produces a spray pattern in the combustion chamber that provides for ignition and combustion that is fast, homogenous, acoustically comfortable and above all efficient.

Particulate filter

When diesel oil is burned in an engine, soot particles are formed in the combustion chamber in certain operating ranges. To eliminate these particles, Audi uses diesel particulate filters with an efficiency of more than 95 percent.

As the particles flow into the filter, they adhere to its porous wall. They are burned off at intervals that depend on the way the vehicle has been driven. This burn-off process is initiated by deliberately retarding the post-injection of fuel, which causes the exhaust temperature to rise sharply for a brief time.

Piezo principle
The piezo principle is an ideal complement for common rail fuel injection. Piezo crystals change their structure in a few thousandths of a second by expanding slightly when an electrical voltage is applied to them. Several hundred piezo wafers are stacked one above the other in the injector. As this stack expands, linear movement takes place and is transmitted directly to the injector needle, with no mechanical linkage in between.

The injectors close again after mere thousandths of a second. In this way, very small amounts of fuel weighing as little as 0.8 of a milligram can be injected.

SCR catalytic converter
SCR stands for selective catalytic reduction for the conversion of oxides of nitrogen in the exhaust gas. A solution known as AdBlue is injected into the SCR catalytic converter from a storage tank. In the hot exhaust gas flow, this waterborne additive breaks down and forms ammonia, with the help of which the oxides of nitrogen are converted into harmless nitrogen and water. Audi has combined the SCR catalytic converter and the diesel particulate filter in the new 3.0 TDI.

Thermal management
The thermal management system reduces the fuel consumption of TDI engines by several percent. The details vary depending on the engine. In the new 3.0 TDI, for example, the cylinder crankcase housing and the cylinder heads have separate cooling circuits. To reduce the pressure losses, the water jackets for the heads are divided into two sections.

During the warmup phase, the coolant is not circulated and the oil cooler is bypassed. The motor oil quickly comes up its operating temperature and the phase of elevated friction losses due to cold, viscous oil in the crank and valve train are greatly reduced. The head circuit supplies the cabin heating and exhaust gas recirculation system. The coolant in the crankcase is often not circulated, even at low load when the engine is warm. This saves drive energy for the water pump.

Turbocharger

A turbocharger comprises a turbine driven by the exhaust gas flow and a compressor for the intake air. The two components are opposite one another on a common shaft, and their maximum speed can be more than 200,000 rpm. The Audi turbochargers develop up to 2.2 bar of relative boost pressure. The 3.0 TDI biturbo theoretically compresses 1,200 cubic meters of air per hour at full load.

The monoturbos and the biturbo in the Audi lineup will be joined in the future by the electric biturbo. Audi is working very hard to further advance all aspects of turbo technology to make throttle response, efficiency, weight and acoustic even better.

Variable Turbine Geometry

Variable Turbine Geometry (VTG) is standard with the TDI engines from Audi. It provides for a spontaneous and smooth buildup of torque at low rpm. If the driver presses the gas pedal down firmly, the turbine vanes move to a shallow angle. This reduces the inlet cross-section into the turbine casing and forces the exhaust gas to flow in at a higher speed. The turbine wheel rotates faster, the volume of fresh air delivered by the turbocharger increases and boost pressure builds up instantly.

As the volume of exhaust gas increases or at low load, the turbine vanes return to a steeper angle. The inlet cross-section increases, and the exhaust gas flows more slowly. The turbine wheel also spins slower, while boost pressure and turbine output remain virtually constant. Audi uses electric VTG actuators in the large TDI engines, pneumatic ones in the four-cylinder diesel engines.

Vermicular graphite cast iron

The crankcase of the Audi V6 TDI engines and the eight-cylinder engine are made of vermicular graphite cast iron (GJV-450). The material with the wormlike distribution of graphite produced in a high-tech casting process is characterized by extreme strength, even at high temperatures. Compared to gray cast iron (GJL), it permits lower wall thicknesses, which reduce the weight.