ELECTRONICALLY CONTROLLED DIESEL INJECTION SYSTEMS
FOR CARS

DIESEL KNOW-HOW

HISTORY OF THE DIESEL ENGINE

Diesel engines have long been established in passenger cars. Nearly every other new vehicle has a compression-ignition engine under the hood. These engines feature high torque and running smoothness, low consumption and low emissions. Their history is more than 100 years old.

Milestones of the diesel engine

1897
First diesel engine is introduced

1927
Diesel injection pump is ready for series production

1936
First series passenger car with diesel engine

1975
Distributor-type injection pump used in mass-produced models

In 1892, Rudolf Diesel began researching his idea for a completely new internal combustion engine with self-ignition. Not until five years later was he able to present the first diesel engine to the world.

It was 20 up at 175 RPM. Compared to the popular engine concepts of the time, such as steam-engines and gasoline engines, Diesel's design had crucial advantages: Its engine burned less fuel and was able to be set up for higher outputs. Diesel's invention was first implemented in stationary and ship engines. High-speed diesel engines could not be implemented in the beginning because, in the early days, the fuel was injected into the combustion chamber using compressed air. This injection procedure did not permit any noteworthy engine speed increase.

First injection pump

In 1922, Robert Bosch decided to develop an injection system for diesel engines. Here, he benefited from his own experiences in developing lubricating pumps. This product knowledge accelerated the development progress. The Stuttgart-based experimenter also combined his own expertise with the knowledge of other diesel pioneers. As early as 1924, the new product was tested in Germany on the first series diesel trucks. In 1926, Bosch supplied the first prototypes to interested customers from the automotive industry. The pump was ready for production at the end of 1927. The first customer, MAN, was delivered the pump in 1928. Other customers quickly followed. In the 1930s, numerous European manufacturers equipped their trucks and agricultural vehicles with the new diesel injection system.

Increasing application variety

The diesel engine found more and more areas of application. Along with trucks and tractors, diesel locomotives, ships, airships and even airplanes (1929 Junkers, 1930 Fiat) were equipped with compression-ignition engines.

Injection systems for passenger cars, the most lucrative product field in terms of numbers, initially remained unattempted. The injection pumps were too large for this application and smaller engines with smaller pumps would not yet have been powerful enough. Not until 1936 did the first manufacturers take a chance on the market with a diesel passenger car: Mercedes-Benz introduced the 260 D. Hanomag introduced a 1.9 liter diesel engine passenger car, but it did not find use until 1938 in the “Rekord” model. However, before World War II, diesel engines could not yet be implemented in passenger cars.

After 1945, diesel engines have found increased currency. They were equipped with traditional in-line pumps, which were expensive from a constructional point of view and very oversized. However, the first distributor-type injection pumps were not developed until 1960. Yet, the large diesel passenger car manufacturers at the time, Peugeot and Mercedes-Benz, continued to favor the in-line pump.

1986
Injection pumps receive electronic control system

1996
First high-pressure injection system with radial piston distributor pump

1997
First series passenger car with common rail

1998
Unit injector system enters the market

Only once Volkswagen focused on the small, energy-saving diesel passenger car with the development of the Golf Diesel did the distributor-type injection pump become appealing due to its smaller dimensions and lower costs. The sales launch of the Golf Diesel in 1975 nearly marked a boom in compact-class diesel models. Starting in 1986, the distributor pumps were equipped with electronic control systems, followed by in-line pumps in 1987. This was done to optimize emissions, noise development, output and fuel consumption.

Diesel high-pressure systems

In the mid-1990s, there were crucial advancements in high-pressure diesel injection technology, which made the diesel engine increasingly popular. Several variants of the high-pressure systems hit the market soon after: the radial piston distributor pump (1996), the common-rail system (1997) and the unit injector (1998). At the beginning, they were designed for injection pressures up to 1,500 Bar.

But, in the end, common rail was implemented. Compared to other diesel injection systems, it offers numerous advantages. One of the most important advantages is that the pressure generation and fuel injection system are decoupled. This makes the injection pressure freely selectable for any operating range, regardless of the engine speed. As a result of this, high pressures can be generated at low speeds and in the partial load range. The high flexibility also applies to the selection of the injection period, which is bound to mechanical limits in cam-operated injection systems.

The amount to be injected can also be divided into multiple portions. Thus, for a smooth combustion, a multi-level pre-injection can be implemented, followed by the main injection and post-injection. The latter is an important option for the function of exhaust gas treatment systems, such as the regeneration of particle filters. In the early times of high-pressure injection systems, common rail also had the advantage of adapting easily to existing engine concepts.

THE DIESEL PRINCIPLE

The diesel engine has a high degree of efficiency. This makes it economical and cost-efficient. No other internal combustion engine is as versatile as the compression-ignition engine.

The function of the diesel engine is based on the principle of self-ignition. During this process, air is taken in and highly compressed. This procedure is used to develop high temperatures that are sufficient for igniting the injected fuel. The energy contained in the diesel fuel is converted into heat and mechanical work. The compression-ignition engine is the most efficient internal-combustion engine. For large, slow-running engines, an efficiency of up to 50 percent or more can be achieved. Diesel engines can be either two-stroke or four-stroke. The latter is used for personal vehicle and commercial vehicle applications.

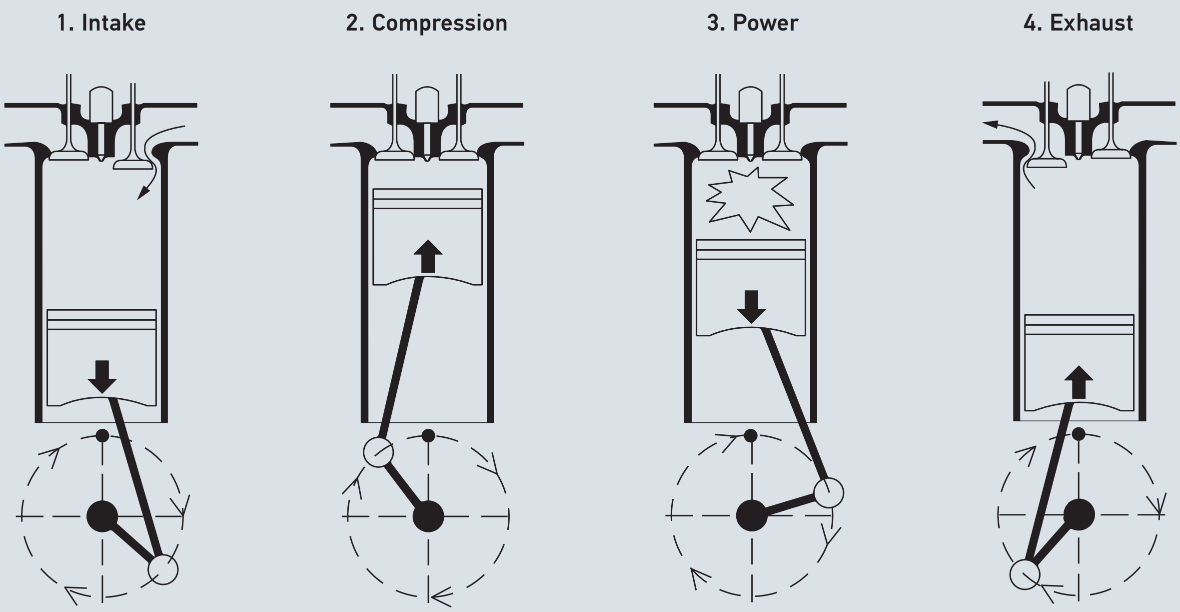
Diesel four-stroke cycle
The gas exchange of the four-stroke diesel engine is controlled by the inlet and exhaust valves.

1st cycle: Intake
During the intake cycle, the engine‘s piston moves downward. The volume above the piston increases. This allows the engine to take in air through the opened inlet valve. The inlet valve is closed at the end of the intake cycle.

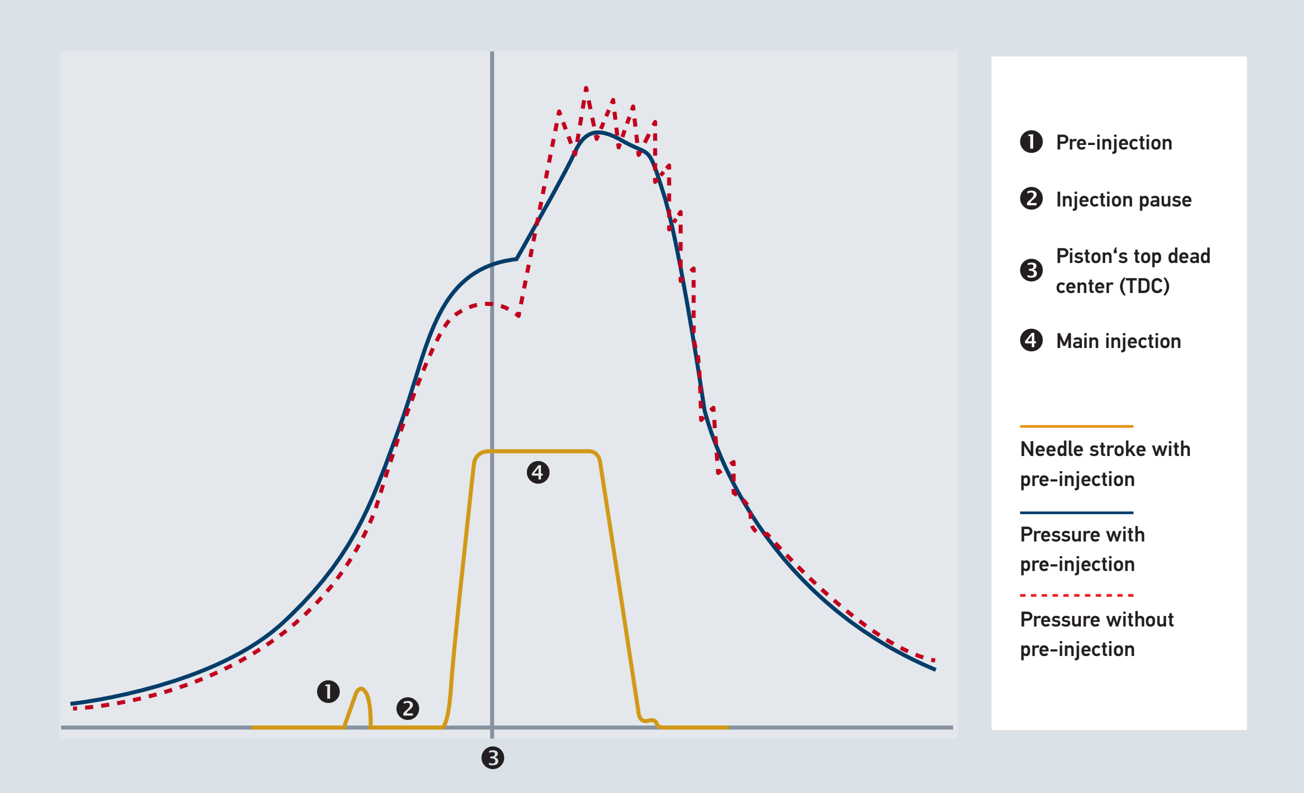
2nd cycle: Compression
During the compression cycle, the piston moves back up. During this process, the drawn in air is compressed and heated to a temperature of up to 900 °C . Toward the end of the compression cycle, fuel is injected into the combustion chamber under high pressure. The amount of fuel injected determines the power output of the diesel engine.

3rd cycle: Power
The finely atomized fuel ignites when it makes contact with the highly compressed and heated air and initiates the work cycle. Through the combustion of the fuel, the pressure in the cylinder increases and drives the pistons down. This is how the chemical energy contained in the fuel is converted into movement energy for the piston.

4th cycle: Exhaust
The exhaust valve opens shortly before the piston‘s bottom dead center. The hot gases can escape into the exhaust manifold. The upward-moving piston supports this process. A new working cycle begins then.



The four cycles of the diesel engine | Graphic: HELLA



Pressure in the diesel engine with and without pre-injection | Graphic: HELLA

Carburetion and combustion
The carburetion in the diesel engine occurs directly in the combustion chamber. Depending on the design, diesel engines have divided (combustion chamber engine) or undivided (direct-injection engine) combustion chambers. Combustion chamber engines have lower noise development because the fuel does not combust suddenly. However, direct injectors are more efficient. Therefore, the direct injection process has also found use in passenger car diesel engines.

Adequate carburetion is necessary for a complete and efficient combustion of the fuel in the diesel engine. To achieve this, the fuel must be injected in the correct amount, at the correct time and, if possible, at a high pressure. Existing slight deviations lead to increased pollutant emissions, loud combustion noises and high fuel consumption.

Diesel engines have an ignition lag inherent to their functional principle. This is defined as the time between the beginning of the injection and the beginning of the increase in pressure in the combustion chamber. The lowest ignition lag possible is desired for the optimal combustion sequence within the diesel engine. However, too much fuel being injected during this time leads a sudden increase in pressure in the cylinder and, therefore, loud combustion noises. For this reason, the injection process is divided into multiple phases in modern diesel engines.

Pre-injection
The pre-injection, also called pilot injection, occurs before the main injection and has the task of implementing the smoothest combustion sequence possible. By combusting an initially small amount of fuel, the pressure and temperature in the combustion chamber increase gradually. This allows the ignition lag to be reduced and creates the best requirements for a fast ignition of the main injection amount. Positive impacts of the pre-injection also include the decrease in combustion noise and nitrogen oxide emissions.

Main injection
During the main injection, adequate carburetion is very important for combusting the fuel as completely as possible. The highest injection pressure possible is necessary so that the fuel and air can mix with each other well. A complete combustion results in low pollutant emissions and high power output.

Post-injection
Post-injection immediately after the main injection causes the soot emissions to decrease. A late post-injection can be used to increase the exhaust gas temperature for the regeneration of a particle filter.

ELECTRONICALLY CONTROLLED DISTRIBUTOR-TYPE INJECTION PUMPS

Distributor-type injection pumps have helped passenger car diesel engines achieve unforeseen success. But the mechanical regulation of the injection amount using timing edges, bores and slides hit its limits during the rapid development of automotive technology.

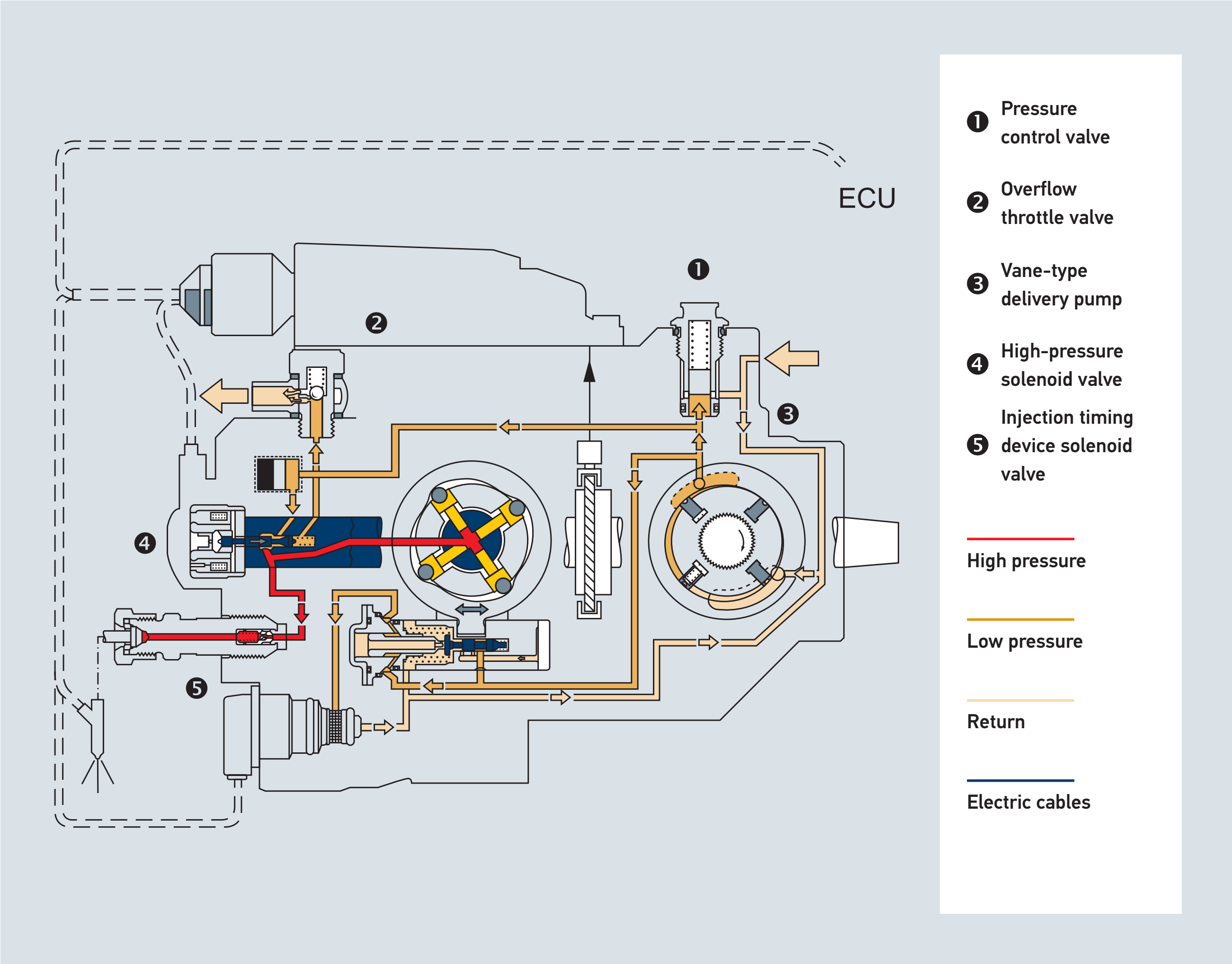
The increasingly stringent emission limit values for diesel engines, the demand for increased output and comfort while reducing consumption at the same time has led to the introduction of electronic control in the distributor-type injection pump area. At the same time, high-pressure control has moved from mechanical edge control to solenoid valves. This allows higher flexibility in terms of starting and finishing pumping and greater measuring accuracy. Furthermore, controlling the high pressure using solenoid valves enables pre-injection and cylinder-specific quantity correction.

The most common distributor-type injection pumps controlled by solenoid valves include radial-piston pumps and axial-piston pumps. The third solution is known under the name “EPIC”. This is also a radial-piston pump, but sets itself part in its unique type of function and quantity control.

The radial-piston pump
By uncoupling the pressure generation from the pressure distribution, you can use the radial-piston pump through skillful pressure wave layering to reach pressures of over 2,000 Bar on the injector nozzle, which nearly corresponded to the level of the unit injector system.

The radial-piston pump consists of multiple assemblies that are all located in one housing:

- **Vane-type delivery pump** with pressure control valve and overflow throttle valve
- **High-pressure radial-piston pump** pump with distributor shaft and orifice check valve
- **High-pressure solenoid valve**
- **Injection timing device** with injection timing device solenoid valve
- **Turning angle sensor**
- **Pump control unit**



Fuel flow in the radial piston distributor pump | Graphic: HELLA

In regard to fuel, the radial-piston pump is subdivided into the low-pressure and high-pressure circuit. The fuel pumped from the vane pump is routed through internal bore holes, a storage volume and the opened solenoid valve into the high-pressure chamber. At the same time, the injection timing device is also supplied with the required fuel pressure. As soon as the solenoid valve closes, the compression phase begins. Here, pressures up to 1,100 Bar on the pump side are achieved. Targeted pressure wave layering is used to achieve peak pressures of over 2,000 Bar on the injection nozzle. The end of injection is initiated by opening the high-pressure solenoid valve. During the pressure build-up phase, this also enables a pre-injection for a soft combustion sequence.

The injection start is adjusted in the radial-piston pump by turning the cam ring either opposite (ignition advance) or in the drive shaft‘s direction of rotation (ignition retard). The cam ring is adjusted electro-hydraulically using a pulse-width-modulated injection timing device solenoid valve that is activated by the pump control unit and injection timing device.

The turning angle sensor also has an important function. It detects the angular position of the pumps and engine camshaft, the pump speed and the position of the injection timing device. The latter is necessary for injection start control. Additionally, the angular position of the cam ring is necessary for calculating the time for triggering the high-pressure solenoid valve. If the crankshaft speed sensor fails, the signal of the turning angle sensor is used as a replacement for the engine speed.

The radial-piston pump is controlled via an EDC system (Electronic Diesel Control). In the first radial-piston pump generation, two control units are used: the engine control unit (ECU) and the pump control unit (PCU). Both can be connected to each other via CAN bus. In the second radial-piston pump generation, the pump and engine control unit are combined in one electronic control unit and mounted directly on the pump.

The axial-piston pump

The axial-piston pump has a similar structure to the radial-piston pump. Only the pressure generation and distribution correspond to the traditional distributor pump, where an axial-piston carries out a lifting and rotary movement at the same time. Besides this, the quantity regulation and injection start control is identical to that of the radial-piston pump. This pump type has been installed in Ford diesel models, for example. Due to the pressure level, the axial-piston pump, at up to 1,500 Bar on the injector nozzle, can keep up well with the first-generation common rail.

EPIC

The EPIC system is also included among solenoid-valve-controlled distributor-type injection pumps.

Its assemblies include:

- → Injection pump with actuators and solenoid valves
- → Electronic control unit
- → sensors for detecting the operating and ambient conditions

The injection pump itself consists of a compact housing, in which the drive shaft, the transfer pump (vane-type delivery pump), the hydraulic head and the injection timing device housing are located. Injection amount and start are calculated by the control unit based on the sensor data and stored characteristic maps. The activation signals are converted to the desired mechanical dimensions by internal pump actuators and solenoid valves.

The EPIC injection pump also consists of a low-pressure and high-pressure circuit. The transfer pump takes in the fuel from the fuel tank via the fuel filter and ensures a defined transfer pressure within the pump. Lastly, the desired level is regulated by the transfer pressure control valve depending on the speed. The fuel reaches the hydraulic head using an internal filter – in principle, a radial-piston pump. Its special feature is a plunger piston with variable stroke. The plunger piston's stroke determines the amount of fuel pumped. The compressed fuel is allocated via a distributor rotor to the respective cylinder.

The injection quantity regulation of the EPIC pump is carried out using two types of solenoid valves, the "injection quantity -" solenoid valve and the "injection quantity +" solenoid valve. By opening and closing the two solenoid valves, the axial position of the rotor can be moved to the calculated position at any time. This movement changes the stroke of the plunger via the bevels in the rotor.

The injection timing also occurs by rotating the cam shaft by a defined angle with or opposite the drive shaft's direction of rotation. The most important components of injection timing are the injection timing device housing and the solenoid valve. The shut-off solenoid valve is charged to stop the engine. Consequently, it opens and releases the transfer pressure. In this way, the fuel supply to the rotor is disconnected.

Solenoid-valve-controlled distributor-type injection pumps in real-world application

In the case of complaints in terms of engines with solenoid-valve-controlled distributor-type injection pumps, the customer should be asked first, exactly under which operating and load conditions the fault occurred. In addition, the mechanical state of the engine should be checked.

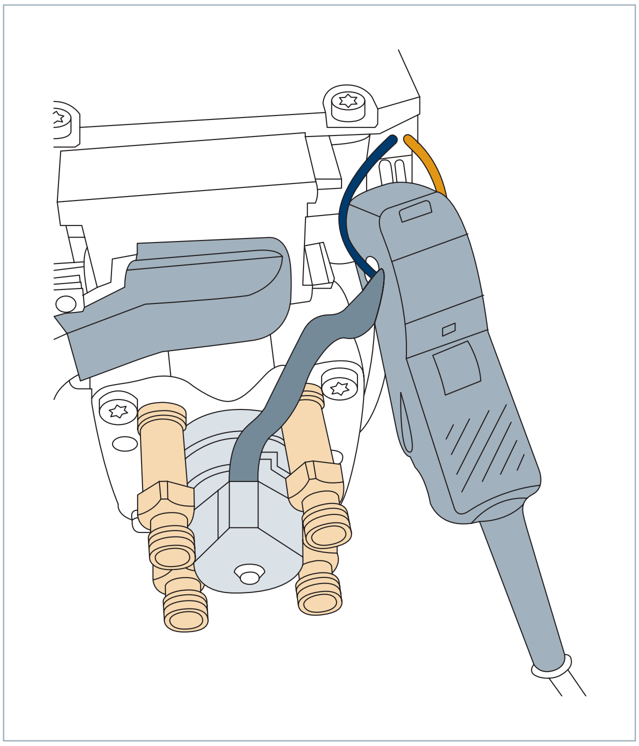
This includes compression, signs of wear (e.g. on camshafts), lubrication (including correct oil specification), valve timing and correct assignment of the injection pump to the engine. It is also important to fully utilize all the control unit diagnostics options. Here, there is a need to clarify whether faults are saved, the parameters appear to be plausible and whether actuators convert electrical signals to mechanical values properly during the actuator test. Additional specific test steps can be initiated if there are no faults in this area.

First, this includes checking the fuel supply. The following checkpoints are useful in this area:

- → Amount of fuel in the tank
- → Tank ventilation system
- → Fuel quality (impermissible mixing of gasoline or biodiesel, for example, can lead to disruptions in the pump functions)
- → Fuel filter and collecting chamber of the water trap. In case of doubt, replace fuel filter
- → Check fuel system with transparent fuel line for bubbles or foaming
- → Bleed the fuel system
- → Check whether leakage oil lines have leaks and are functioning properly
- → Check that the overcurrent throttle valve is running smoothly. If chips or deposits (e.g. due to biodiesel) are detected, mechanical damage to the injection pump cannot be ruled out.

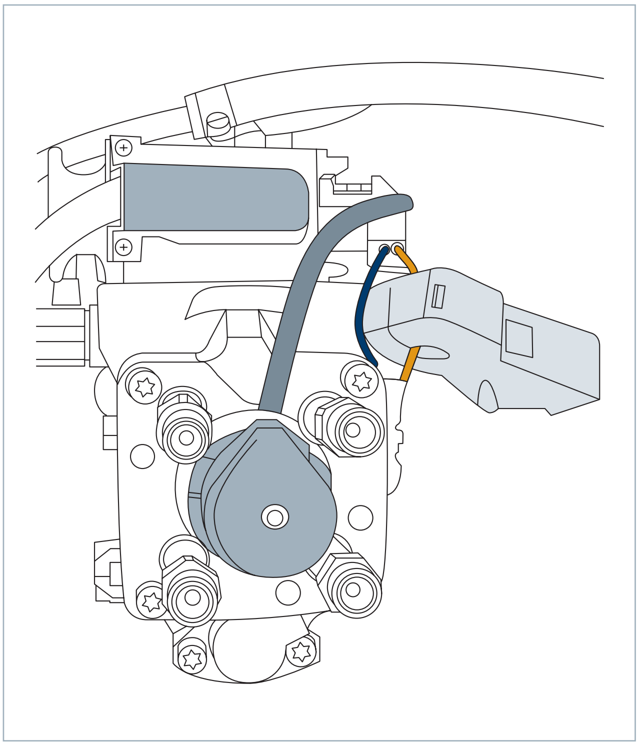
Bubbles or foaming may not be detected in the distributor-type injection pumps controlled by solenoid valves in the fuel system.
A transparent hose is looped into the fuel supply for the test.

Photo: Linzing



The activation signal for the high-pressure solenoid valve is recorded with a clamp-on current probe.

Graphic: HELLA



The injection timing signal is also checked using a clamp-on current probe. This is a pulse-width-modulated signal.

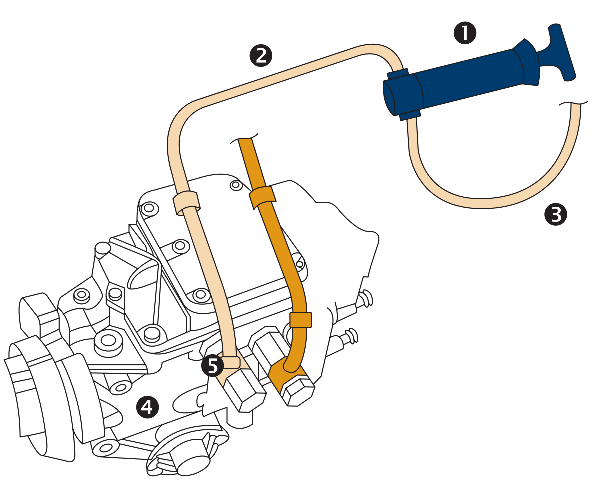
Graphic: HELLA

After checking the fuel supply, the quantity solenoid valve and injection timing device solenoid valve signals must be tested with an oscilloscope. However, the two valves cannot be replaced in general garages. This should be left to specialized diesel support centers.

When removing and installing solenoid-valve controlled distributor-type injection pumps, observe the respective specifications of the relevant vehicle manufacturer. In general, a thorough engine wash should be carried out before opening fuel lines to prevent particles of dirt from entering into the fuel system. During the entire work process, also ensure that work clothing, tools and workstations are as clean as possible.

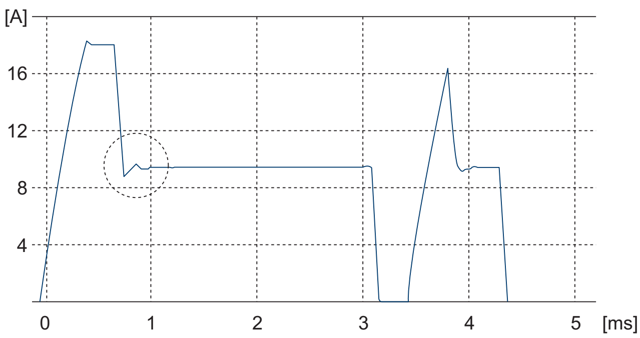
When installing the injection pump, the following must be ensured:

- → Assignment of the injection pump to the crank and camshaft. To do so, you must use the special tools for locking the camshaft, crankshaft and pump drive of the respective vehicle manufacturer
- → De-energized routing of the high-pressure lines. Warping in conjunction with high pressures can lead to crack formation along the lines
- → Maintaining precise tightening torque of union nuts on the injection nozzles



The radial-piston distributor-type injection pump is bled using a double-action hand pump or an electric fuel pump.

Graphic: HELLA



The oscillation process after the first signal peak indicates that the solenoid valve is also actually closing.

Graphic: HELLA

The radial-piston pump **is not** bled automatically, as opposed to the helix- und solenoid-valve-controlled distributor-type injection pump. To prevent damages that can arise due to dry running the injection pump, it must be filled with diesel fuel after installing or idling the injection pump. This can be accomplished using an electric fuel pump or double-action hand pump. Before doing this, however, you must make sure that the tank contains at least five liters of diesel fuel, all leakage oil and fuel lines are installed properly and the battery charge state is OK.

After bleeding the radial-piston pump, the start of injection must be checked dynamically. This also applies after replacing the toothed belt. The basic setting is also checked using a control unit diagnostics device when the engine is at operating temperature. If the measured start of injection is outside of the tolerance range, the position of the injection pump must be corrected by the respective value. The procedure for this is different depending on the manufacturer and must be taken from the relevant repair documents.

The following work steps are required to bleed the radial-piston pump:

→ Remove overcurrent throttle valve on the return connection of the injection pump

→ Fasten a transparent fuel line using a ring connection piece and hollow screw to the injection pump output

→ Connect an electric or manual suction pump to the other end of the transparent fuel line

→ Operate the pump until fuel escapes the distributor-type injection pump without bubbles

→ Remove ventilation equipment and reinstall the overcurrent throttle valve

HELLA KGaA Hueck & Co.
Rixbecker Straße 75
59552 Lippstadt, Germany
Tel.: +49 2941 38-0
Fax: +49 2941 38-7133
Internet: www.hella.com