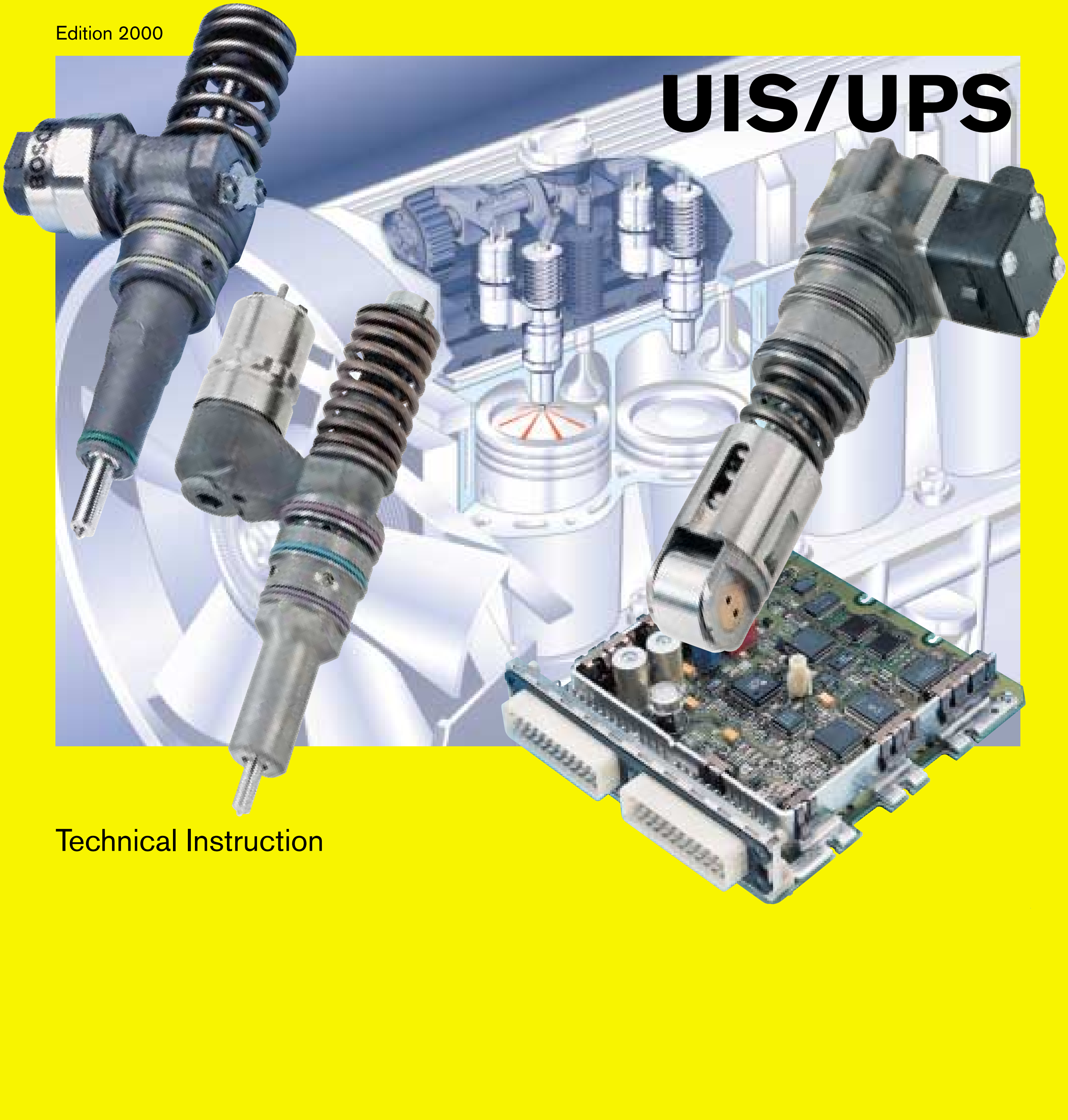
Electronic engine management for diesel engines

Diesel Fuel-Injection Systems Unit Injector System/Unit Pump System

Edition 2000



Technical Instruction

BOSCH

Published by:
© Robert Bosch GmbH, 2000
Postfach 30 02 20,
D-70442 Stuttgart,
Automotive Equipment Business Sector,
Department KH/PDI2
Product-Marketing software products,
technical documentation.

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Technical graphics:
Bauer & Partner, Stuttgart.

Printed in Germany.
Imprimé en Allemagne.

1st Edition, March 2000.

English translation of the German edition dated: September 1999.

Diesel Fuel-Injection Systems Unit Injector System (UIS)/ Unit Pump System (UPS)

More and more demands are being made on modern internal-combustion engines. On the one hand they must become more powerful and quieter, while on the other they must at the same time be cleaner and use less fuel. Particularly in the diesel-engine sector, tremendous advances have been made in the past few years thanks to the ongoing developments in fuel-injection technology.
The Unit Injector System (UIS) and the Unit Pump System (UPS) are among the most significant innovations in this field. They inject precisely the right amount of fuel individually into each cylinder, at very high pressure, and at exactly the right moment in time. This results in considerably more efficient combustion than is the case with conventional injection systems. This, in turn, equates to higher output, less fuel consumption, and lower levels of noise and exhaust-gas emissions.
In this "Technical Instruction" manual you will learn about the Unit Injector System (UIS) for passenger cars and commercial vehicles, and about the Unit Pump System (UPS) for passenger cars.
The manual also contains information on how the individual components function, and on the interaction between them. The operating concept and the design of the high-pressure injection, the electronic control (EDC), and the sensor technology are dealt with in detail.

Combustion in the diesel engine

The diesel engine is a compression-ignition (CI) engine which draws in the air needed for combustion and compresses it to a very high level in the combustion chamber. During compression, the air heats up to temperatures which are high enough for the injected diesel fuel to ignite of its own accord (auto ignition).

With its overall efficiency figure (in the case of very large, slow-revving diesel engines this is more than 50 %), the diesel engine rates as the most efficient combustion engine (CE). The diesel engine's significance is underlined by its high fuel-economy figures, together with the low levels of pollutants in the exhaust gas, and the reductions that have taken place in noise emissions, for instance due to the use of pilot injection.
Diesel engines can operate according to either the 4-stroke or 2-stroke principle. In automotive applications though, diesels are practically always of the 4-stroke type (Figs. 1 and 2).

Working cycle (4-stroke)

Stroke 1: Induction stroke
During the first stroke, the induction stroke, the downward movement of the piston draws unthrottled air through the open intake valve and into the combustion chamber.

Stroke 2: Compression stroke
During the second (compression) stroke, the air trapped in the cylinder is compressed by the piston which is now moving upwards. Compression ratios ε are between 14:1 and 24:1. In the process, the air heats up to temperatures around 900 °C. Shortly before the end of the compression stroke, the injection system injects fuel into the heated air in the cylinder at pressures of up to 2050 bar.

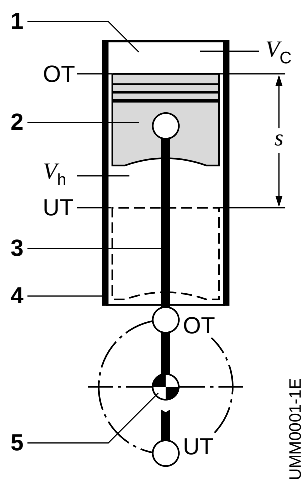
Stroke 3: Power stroke
Following the ignition delay (several degrees crankshaft), at the beginning of the third (power) stroke the finely atomized fuel ignites due to auto-ignition and burns almost completely. The cylinder charge heats up even further and the cylinder pressure increases again. The energy released due to ignition is applied to the piston which is forced downwards and transforms the combustion energy into power output (torque) by means of a crank mechanism.

Stroke 4: Exhaust stroke
The piston moves up again during the fourth (exhaust) stroke and drives the burnt gases out through the open exhaust valve. A fresh charge of air is then drawn in (induction stroke) and the 4-stroke cycle begins again.

Fig. 1

Principle of the reciprocating engine

1 Combustion chamber,
2 Piston,
3 Crank mechanism,
4 Cylinder,
5 Crankshaft.
OT TDC,
UT BDC,
V_h Piston displacement,
V_C Compression losses,
s Piston stroke.



Combustion chambers, turbocharging and supercharging

Both divided and non-divided combustion chambers are used in diesel engines (prechamber and direct-injection engines respectively).

Direct-injection (DI) engines are more efficient than their prechamber (indirect injection/IDI) counterparts, and are thus more economical. They are therefore used in all commercial vehicles and trucks and the majority of newer diesel-engine passenger cars. By applying the pilot injection of small amounts of fuel, the hard combustion noise which is typical for the DI diesel engine can be reduced to the level of the prechamber and whirl-chamber diesel engines. Due to their higher fuel-consumption figures, the percentage of IDI engines is dropping steadily.

In addition to pilot injection (for the reduction of NO_X and noise emissions), secondary injection is also being successfully applied in order to reduce soot emissions.

The diesel engine is particularly suitable for use with an exhaust-gas turbocharger or with a mechanical supercharger. Using an exhaust-gas turbocharger with the diesel engine not only increases its power yield and efficiency, but also reduces the combustion noise and the toxic content of the exhaust gas.

Diesel-engine exhaust emissions

The combustion products from the diesel engine are dependent upon the design of the engine, its output power, its speed, and the load applied to it.

At part load for instance, the share of toxic emissions in the exhaust-gas mass is approx. 1%. The design of the combustion process (piston-head recess, air movement, excess air, air temperature from charge-air cooling, compression, and EGR), and the application engineering carried out on the fuel-injection system, all affect the formation of toxic emissions. In the first place, water and CO_2 are generated as the products of complete combustion. The following toxic substances are also produced (limited by legislation):

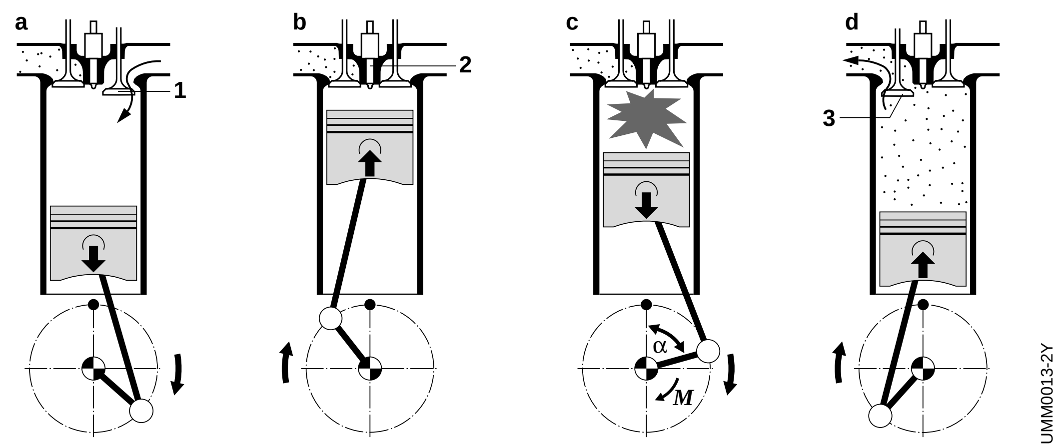
- Carbon monoxide (CO),
- Unburnt hydrocarbons (HC),
- Nitrogen oxides (NO_X),
- Particulate matter (soot, HC, sulphates, abraded matter, dirt and water), and
- Sulphur dioxide (SO_2).

Sulphur dioxide and sulphates originate from the sulphur content of the fuel. Particularly when the engine is cold, the exhaust-gas contents which are immediately noticeable are the non-oxidized or only partly oxidized hydrocarbons in droplet form which are directly visible in the form of white or blue smoke, black smoke (soot), and the pungent aromatics and aldehydes.

Fig. 2

4-stroke diesel engine

a Induction stroke, **b** Compression stroke, **c** Power stroke, **d** Exhaust stroke.
1 Intake valve, **2** Injection nozzle, **3** Exhaust valve. M Torque, α Crankshaft angle.



Fuel-injection characteristics

For an internal-combustion engine, exhaust-emissions behaviour is of decisive importance and makes the following demands on the injection system:

- Timing of the moment of injection must must be extremely precise. Even the smallest deviations lead to considerable increases in fuel consumption, toxic emissions, and combustion noise.
- The injection pressure should be adaptable to the engine's operating point (e.g. load, engine speed). As far as possible, adaptation should be independent of other factors.
- Since uncontrolled secondary injection or dribble leads to increased emissions, injection should terminate reliably and cleanly.

Depending upon the particular engine application, the following injection functions are also required (Fig. 1):

- Pilot injection (1) for the reduction of combustion noise and NO_X emissions,
- A pressure curve which rises during the main injection period (3) and serves to reduce NO_X emissions,
- "Boot-shaped" pressure curve (4) during the main-injection period in order to reduce the NO_X and soot emissions,
- High pressure during the main-injection period (3, 7) in order to reduce soot emissions during EGR,
- Secondary injection immediately following the main-injection period (8) for the reduction of soot emissions, or
- Delayed secondary injection (9) to act as a reduction agent for NO_X catalytic converters.

Conventional fuel-injection characteristics

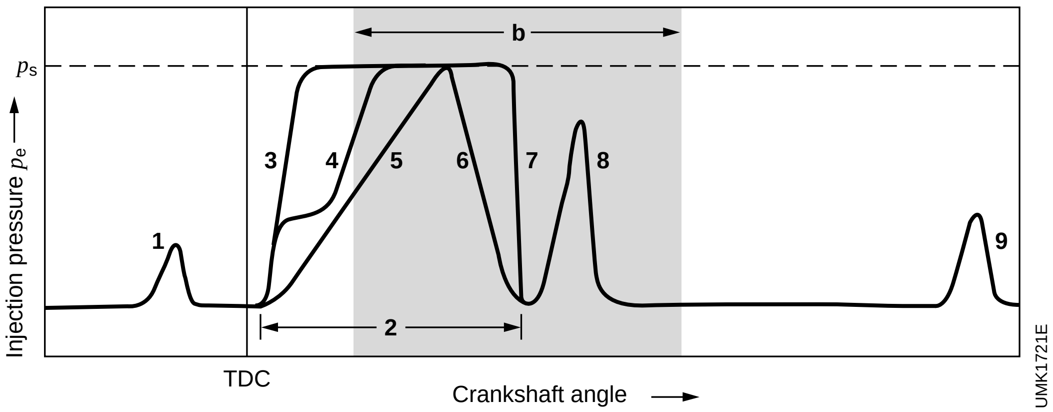
On conventional injection systems, injection pressure during the main-injection period is continually increased by the injection-pump plunger. In the case of port-controlled distributor pumps and in-line injection pumps, injection only takes place during the main-injection period (Fig. 1, Pos. 5 + 6), and there is no pilot and secondary injection. Developments on the solenoid-valve-actuated distributor injection pumps will in future provide for pilot injection (1). On the passenger-car unit injector systems (UIS), mechanical-hydraulic pilot injection has already been implemented.

On conventional systems, pressure generation and the provision of the injected fuel quantity are directly coupled to each other by cams and delivery plunger. This has the following consequences for the injection characteristic:

Fig. 1

Rate-of-discharge curves

1 Pilot injection, **2** Main injection, **3** Steep pressure rise (CR), **4** "Boot-shaped" pressure rise, **5** Pressure rise (conventional injection), **6** Flat pressure drop (in-line and distributor pumps), **7** Steep pressure drop (UIS, UPS, CR), **8** Advanced secondary injection, **9** Retarded secondary injection. p_s Peak pressure, b Combustion duration.



– Injection pressure climbs along with increasing speed and injected fuel quantity (Fig. 2),
– Injection pressure increases at the beginning of injection, but then drops again to the nozzle closing pressure before injection terminates.

The results are as follows:
– Small quantities of fuel are injected at lower pressures, and
– The rate-of-discharge curve is practically triangular. This is the shape demanded for efficient combustion without EGR ("soft" pressure increase).

The peak injection pressure is decisive for the loading of the injection pump and its drive components. For the injection system as a whole, it is decisive for the quality of the A/F mixture formation in the combustion chamber.

Pilot injection

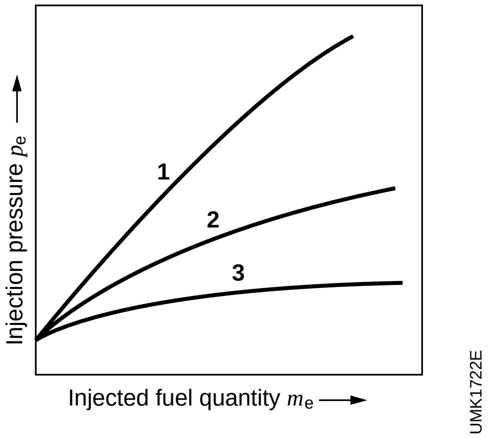
Pilot injection leads to a "softer", less abrupt combustion-pressure increase. The combustion process is influenced to such an extent that combustion noise and, depending upon the particular combustion principle, NO_X and HC emissions are reduced.
In the case of the rate-of-discharge curve without EGR (Fig. 3), the injection pressure increases slightly along with the compression, only to jump abruptly as soon as combustion starts. It is this abrupt rise in injection pressure which is mainly responsible for the diesel engine's combustion noise.
With pilot injection, the combustion chamber is "preconditioned" by injecting a small amount of fuel (1...4 mm^3) into the cylinder. Specifically, this has the following effects:
– The lag in ignition of the main injection is reduced, and
– The curve representing the combustion-pressure increase is flatter (Fig. 4).

Specific fuel consumption can vary according to the start of the main injection, and the interval between pilot injection and main injection.

Fig. 2

Rate-of-discharge curve: Conventional injection

1 High engine speeds,
2 Medium engine speeds,
3 Low engine speeds.



Needle lift at the injection nozzle and pressure curve in a cylinder without pilot injection

h_{HE} Needle lift for main injection.

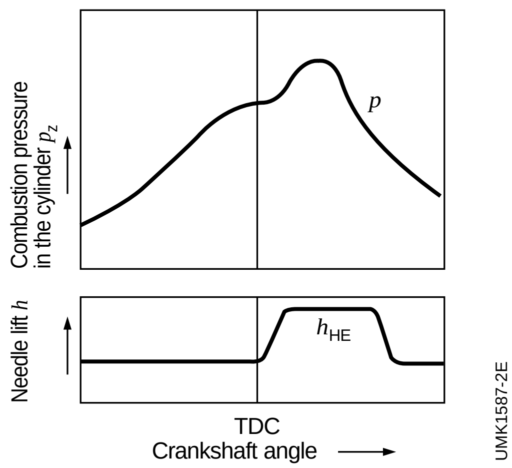
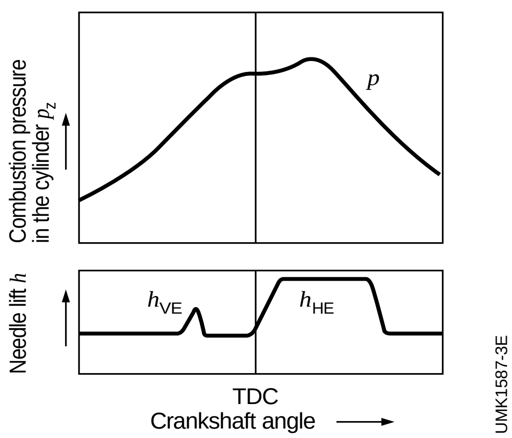


Fig. 3

Fig. 4

Needle lift at the injection nozzle, and pressure curve in a cylinder with pilot injection

h_{VE} Needle lift for pilot injection,
h_{HE} Needle lift for main injection.



The reduction of pollutant emissions

Mixture formation and combustion

Compared to gasoline engines, diesel engines use fuel with a higher boiling point (approx. 160...360 °C), which is more easily ignitable (cetane number approx. 50). In the diesel engine, the A/F mixture formation can be subdivided into two phases:
– The “premixing” phase which takes place during the ignition lag, and
– The diffusion phase which takes place during combustion.

The diesel-engine A/F mixture is heterogeneous. In order to keep emissions of soot, CO and HC down, and to avoid high fuel-consumption figures, the engine must always run with excess air (λ >1.0). A/F mixture formation is a function of the following quantities:
– Number of nozzle fuel jets appropriate for the air swirl,
– Direction of spray appropriate for the combustion-chamber shape, start of injection, and duration of injection,
– Injection pressure (fuel-droplet size and distribution),
– Rate-of-discharge curve (fuel injection as a function of time).

Engine speed, injected fuel mass, pressures, and temperatures, together with the excess-air factor λ, are the parameters which vary during operation of a given engine.

The engine's output quantities are:
- Specific fuel consumption,
- NO_X emissions (NO and NO_2),
- Particulate emissions,
- HC emissions,
- CO emissions, and
- Combustion noise.

The power and torque characteristics as a function of engine speed are adapted in line with the engine manufacturer's requirements.

All parameters involved in the A/F mixture formation have an effect upon the engine output quantities. NO_X formation is promoted by high combustion temperatures, by excess air and by air movement at the start of combustion. Soot develops due to (local) lack of air or air deficiency, together with inefficient A/F mixture formation.

Measures taken at the engine

In addition to the above-named mixture-formation parameters, combustion-chamber design, choice of compression ratio, and movement of air in the cylinder, all have an effect on the engine's emissions and fuel-consumption figures. With today's 4-valve techniques, intake and exhaust-valve configuration permits the injector to be situated in the center of the cylinder head referred to the particular cylinder. This provides the optimal basis for uniform spray distribution in the combustion chamber. Using an exhaust-gas turbocharger with variable turbine geometry (VTG), provides more air in wider ranges of the load-speed map. It also shortens the transient buildup of charge-air pressure and reduces exhaust-gas back pressure. Charge-air cooling reduces NO_X emissions and fuel consumption.

Exhaust-gas recirculation (EGR)

EGR is an effective measure for reducing NO_X. For years now, EGR has been state-of-the-art in passenger-car diesel engines, and is also used for NO_X reduction in commercial vehicles. Whereas, in accordance with the legally stipulated certification cycles, the EGR on diesel-engine passenger cars only comes into effect in the low load and low engine-speed ranges, it is needed across practically the complete load/speed map in the heavy-duty truck sector.

The NO_X-reducing effects of EGR are based on three mechanisms:
– Reduction of the oxygen concentration in the combustion chamber,
– Reduction of the exhaust-gas flow leaving the tailpipe,
– Temperature reduction due to the higher specific heat of the inert gases H_2O and CO_2 (gases which do not take part in the combustion process).

Recirculation of cooled exhaust gases is particularly effective. With passenger cars, recirculation can total as much as 50 %, and on commercial vehicles it is between 5 and 25 %.
To recirculate the exhaust gas at low load, on passenger cars there is always a drop in exhaust-gas pressure from downstream of the turbine to upstream of the compressor (exhaust-gas turbocharger with wastegate, or variable turbine geometry (VTG)). On commercial vehicles though, at higher loads the exhaust-gas pressure downstream of the turbine is normally lower than the charge-air pressure upstream of compressor or intercooler. To provide the pressure drop required for efficient EGR, therefore, the exhaust-gas turbocharger must be appropriately configured, or a VTG turbocharger used. A venturi tube (low pressure at the constriction point) can also be used in the bypass to the fresh-air passage. EGR can be regulated by air-differential mass control using an air-mass meter.

Effects of fuel injection

The most important parameters for influencing the engine output quantities are start of injection, injection pressure, rate-of-discharge curve, and pilot and secondary injection.

Passenger cars
In the vicinity of the exhaust test cycle, retarding the start of injection serves to lower NO_X emissions. At high loads and high speeds, advanced start of injection results in reduced fuel consumption and higher output powers. With the engine cold, start of injection is advanced (HC).

Commercial vehicles
At medium and heavy loading, low NO_X emissions result from retarding the start of injection, although this increases fuel consumption. With the engine cold and at low loads, start-of-injection advance is necessary (HC).
In the case of modern injection systems equipped with EDC (Electronic Diesel Control), start of injection is a freely selectable adaptation quantity. Start-of-injection control or BIP control (BIP = “Beginning of the Injection Period”, (also known as the “Begin-of-injection period”)) controls the start of injection, or the start of delivery, with an accuracy of approx. ±1° cks (crankshaft). Using the starting point of solenoid-valve triggering, the Common Rail System (CRS) controls the start of injection with similar accuracy.

Injection pressure
A a rule, soot emissions drop along with increases in injection pressure. Fuel consumption is lower with an advanced start of injection than when it is retarded. With the start of injection retarded, fuel consumption can be reduced slightly by increasing injection pressure, although NO_X emissions increase. Together with start-of-injection and EGR rate, injection pressure (that is, peak pressure or rail pressure) is one of the quantities which must be carefully optimized. In the test range, the weighting values are fuel consumption and soot emissions on the one side, and NO_X emissions on the other. A worthwhile compromise must be made between these quantities. On diesel-engine passenger cars, in the higher load/speed range very high injection pressures are necessary for high output powers and low specific fuel consumption.

Rate-of-discharge curve
The rate-of-discharge curve is defined as the curve of fuel mass flow as a function of time during the injection period.
The injection of only a small quantity of fuel during the ignition lag is of advantage for low NO_X emissions and low combustion noise. The combustion noise can also be considerably reduced by precisely metered pilot-injection. In a similar manner, pilot injection leads to NO_X reduction and a drop in fuel consumption at higher loads. Here though, black smoke usually increases slightly.
Soot emissions can be reduced by secondary injection of finely atomized fuel immediately after main injection. This has hardly any negative effect on the other engine characteristics. Development is proceeding on systems with secondary injection.

Diesel injection systems: Overview

Diesel engines are characterized by their high levels of economic efficiency. Since the first series-production injection pumps were introduced by Bosch in 1922, injection-system developments have continued unceasingly.

Diesel engines are employed in a wide range of different versions (Fig. 1 and Table 1), for example as:

- The drive for mobile electric generators (up to approx. 10 kW/cylinder),
- High-speed engines for passenger cars and light commercial vehicles (up to approx. 50 kW/cylinder),
- Engines for construction, agricultural, and forestry machinery (up to approx. 50 kW/cylinder),
- Engines for heavy trucks, buses, and tractors (up to approx. 80 kW/cylinder),
- Stationary engines, for instance as used in emergency generating sets (up to approx. 160 kW/cylinder),
- Engines for locomotives and ships (up to approx. 1,000 kW/cylinder).

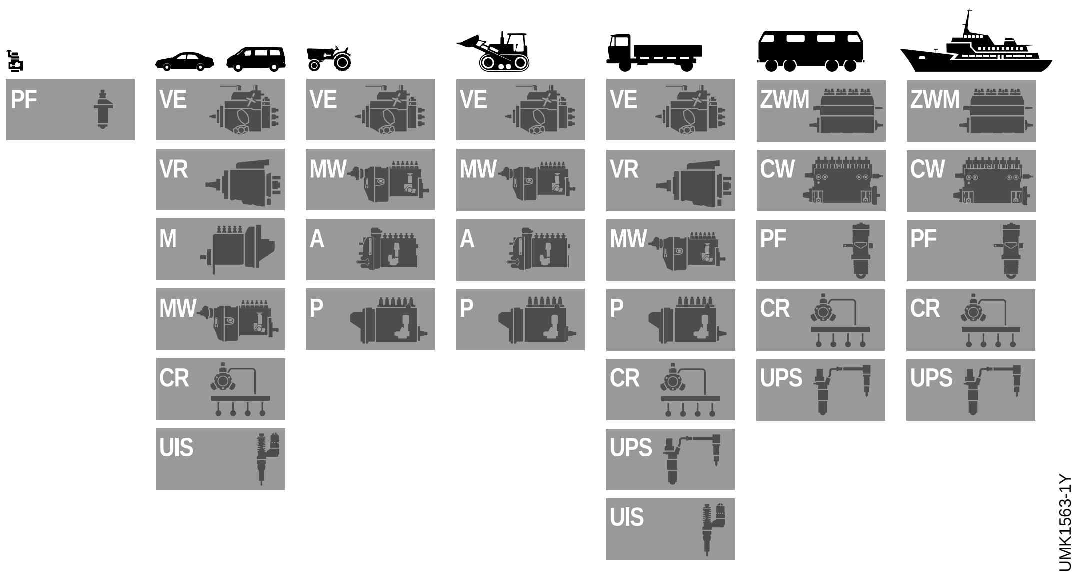
Technical requirements

In line with the severe regulations coming into force to govern exhaust and noise emissions, and the demand for lower fuel consumption, increasingly stringent demands are being made on the diesel engine's injection system. Basically speaking, depending on the particular diesel combustion process (direct or indirect injection), in order to ensure efficient A/F mixture formation the injection system must inject the fuel into the combustion chamber at a pressure between 350 and 2,050 bar, and the injected fuel quantity

Fig. 1

Applications overview of the Bosch diesel fuel-injection systems

M, MW, A, P, ZWM, CW in-line injection pumps in order of increasing size, **PF** single-plunger injection pumps, **VE** axial-piston distributor injection pumps, **VR** radial-piston distributor injection pumps, **UPS** Unit Pump System, **UIS** Unit Injector System, **CR** Common Rail System.



must be metered with extreme accuracy. With the diesel engine, load and speed control must take place using the injected fuel quantity without intake-air throttling.
For diesel injection systems, the mechanical governor is increasingly being superseded by the Electronic Diesel Control (EDC). In passenger cars and commercial vehicles, the new diesel injection systems are all EDC-controlled.
According to present technical developments, it is mainly the high-pressure injection systems below which are used for vehicle diesel engines.

Table 1
Diesel fuel-injection systems: Properties and characteristic data

Fuel-injection system Type	Injection				Engine-related data			
	Injected fuel quantity per stroke mm³	Max. nozzle pressure bar	Mechanical / Electronic / Electromechanical / Solenoid valve m / e / em / MV	Direct injection / Indirect injection DI / IDI	Pilot injection / Post injection VE / NE	No. of cylinders	Max. speed min⁻¹	Max. power per cylinder kW
In-line injection pumps								
M	60	550	m, e	IDI	–	4…6	5,000	20
A	120	750	m	DI / IDI	–	2…12	2,800	27
MW	150	1,100	m	DI	–	4…8	2,600	36
P 3000	250	950	m, e	DI	–	4…12	2,600	45
P 7100	250	1,200	m, e	DI	–	4…12	2,500	55
P 8000	250	1,300	m, e	DI	–	6…12	2,500	55
P 8500	250	1,300	m, e	DI	–	4…12	2,500	55
H 1	240	1,300	e	DI	–	6…8	2,400	55
H 1000	250	1,350	e	DI	–	5…8	2,200	70
Axial-piston distributor injection pumps								
VE	120	1,200/350	m	DI / IDI	–	4…6	4,500	25
VE…EDC [1]	70	1,200/350	e, em	DI / IDI	–	3…6	4,200	25
VE…MV	70	1,400/350	e, MV	DI / IDI	–	3…6	4,500	25
Radial-piston distributor injection pump								
VR…MV	135	1,700	e, MV	DI	–	4.6	4,500	50
Single-plunger injection pumps								
PF(R)…	150… 18,000	800… 1,500	m, em	DI / IDI	–	arbitrary	300… 2,000	75… 1,000
UIS 30 [2]	160	1,600	e, MV	DI	VE	8 [3a]	3,000	45
UIS 31 [2]	300	1,600	e, MV	DI	VE	8 [3a]	3,000	75
UIS 32 [2]	400	1,800	e, MV	DI	VE	8 [3a]	3,000	80
UIS-P1 [3]	62	2,050	e, MV	DI	VE	6 [3a]	5,000	25
UPS 12 [4]	150	1,600	e, MV	DI	VE	8 [3a]	2,600	35
UPS 20 [4]	400	1,800	e, MV	DI	VE	8 [3a]	2,600	80
UPS (PF[R])	3,000	1,400	e, MV	DI	–	6…20	1,500	500
Common Rail accumulator injection system								
CR [5]	100	1,350	e, MV	DI	VE [5a]/NE	3…8	5,000 [5b]	30
CR [6]	400	1,400	e, MV	DI	VE [6a]/NE	6…16	2,800	200

[1] EDC Electronic Diesel Control; [2] UIS unit injector system for comm. vehs. [3] UIS unit injector system for pass. cars; [3a] With two ECU's large numbers of cylinders are possible; [4] UPS unit pump system for comm. vehs. and buses; [5] CR 1st generation for pass. cars and light comm. vehs.; [5a] Up to 90° crankshaft BTDC, freely selectable; [5b] Up to 5,500 min^{-1} during overrun; [6] CR for comm. vehs., buses, and diesel-powered locomotives; [6a] Up to 30° crankshaft BTDC.

Injection-pump designs

In-line fuel-injection pumps

All in-line fuel-injection pumps have a plunger-and-barrel assembly for each engine cylinder. As the name implies, this comprises the pump barrel and the corresponding plunger. The pump camshaft is integrated in the pump and driven by the engine, and forces the pump plunger in the delivery direction. The plunger is returned by its spring.

The plunger-and-barrel assemblies are normally arranged in-line, and plunger lift cannot be varied. In order to permit changes in the delivery quantity, slots have been machined into the plunger, the diagonal edges of which are known as helixes. When the plunger is rotated by the movable control rack, the helixes permit the selection of the required effective stroke. Depending upon the fuel-injection conditions, delivery valves are installed between the pump's pressure chamber and the fuel-injection lines. These not only precisely terminate the injection process and prevent secondary injection (dribble) at the nozzle, but also ensure a family of uniform pump characteristic curves.

PE standard in-line fuel-injection pump

Start of fuel delivery is defined by an inlet port which is closed by the plunger's top edge. The delivery quantity is determined by the second inlet port being opened by the helix which is diagonally machined into the plunger. The control rack's setting is determined by a mechanical (flyweight) governor or by an electric actuator (EDC).

Control-sleeve in-line fuel-injection pump

The control-sleeve in-line fuel-injection pump differs from a conventional in-line injection pump by having a “control sleeve” which slides up and down the pump plunger. By way of an actuator shaft, this varies the plunger lift to port closing, and with it the start of delivery and the start of injection. The control sleeve's position is varied as a function of a variety of different influencing variables. Compared to the standard PE in-line injection pump therefore, the control-sleeve version features an additional degree of freedom.

Distributor fuel-injection pumps

Distributor pumps have a mechanical (flyweight) governor, or an electronic control with integrated timing device. The distributor pump has only <u>one</u> plunger-and-barrel assembly for all the engine's cylinders.

Axial-piston distributor pump

In the case of the axial-piston distributor pump, fuel is supplied by a vane-type pump. Pressure generation, and distribution to the individual engine cylinders, is the job of a central piston which runs on a cam plate. For one revolution of the driveshaft, the piston performs as many strokes as there are engine cylinders. The rotating-reciprocating movement is imparted to the plunger by the cams on the underside of the cam plate which ride on the rollers of the roller ring.

On the conventional VE axial-piston distributor pump with mechanical (flyweight) governor, or electronically controlled actuator, a control collar defines the effective stroke and with it the injected fuel quantity. The pump's start of delivery can be adjusted by the roller ring (timing device). On the conventional solenoid-valve-controlled axial-piston distributor pump, instead of a control collar an electronically controlled high-pressure solenoid valve controls the injected fuel quantity. The open and closed-loop control signals are processed in two ECU's (engine ECU and pump ECU). Speed is controlled by appropriate triggering of the actuator.

Radial-piston distributor pump

In the case of the radial-piston distributor pump, fuel is supplied by a vane-type pump. A radial-piston pump with cam ring and two to four radial pistons is responsible for high-pressure generation and fuel distribution. The injected fuel quantity is metered by a high-pressure solenoid valve. The timing device rotates the cam to adjust the start of delivery. As is the case with the solenoid-valve-controlled axial-piston pump, all open and closed-loop control signals are processed in two ECUs. Speed is controlled by appropriate triggering of the actuator.

Single-plunger fuel-injection pumps

PF single-plunger pumps

PF single-plunger injection pumps are used for small engines, diesel locomotives, marine engines, and construction machinery. Although these pumps have no camshaft of their own, their operating concept corresponds to that of the PE in-line pumps. When used with large engines, the mechanical-hydraulic governor, or the electronic controller, is attached directly to the engine block. The fuel-quantity adjustment as defined by the governor (or controller) is transferred by a rack integrated in the engine. The cams for actuating the individual PF single-plunger injection pumps are on the engine camshaft, and this means that injection timing cannot be implemented by rotating the camshaft. Instead, injection timing takes place by adjusting an intermediate element (for instance, a rocker between camshaft and roller tappet), whereby an advance angle of several angular degrees can be obtained.

Single-plunger injection pumps are also suitable for operation with viscous heavy oils.

Unit Injector System UIS

In the unit injector system, the injection pump and the injection nozzle form a unit. One of these units is installed in the engine's cylinder head for each engine cylinder and driven directly by a tappet or indirectly from the engine's camshaft through a valve lifter.

Compared with the in-line and distributor injection pumps, considerably higher injection pressures (up to 2050 bar) have become possible due to the omission of the high-pressure lines. Such high injection pressures coupled with the electronic map-based control of the duration of injection (or injected fuel quantity), mean that a considerable reduction of the diesel engine's toxic emissions has become possible.

Electronic control concepts permit a variety of auxiliary functions.

Unit Pump System UPS

The UPS uses the same operating concept as the UIS system. It is a modular high-pressure injection system. In contrast to the UIS though, the pump and the nozzle are joined by a short, precisely matched delivery line leading from the pump to the nozzle-and-holder assembly. The UPS features an injection unit for each cylinder comprised of the actual pump, the delivery line, and the nozzle-and-holder assembly. The pump is driven from the engine's camshaft.

On the UPS too, start of delivery and start of injection are controlled electronically. In coordination with the high-speed solenoid-controlled injector it is possible to precisely define the characteristic of each individual fuel-injection process .

Accumulator injection system

Common Rail System CR

In contrast to conventional injection systems, in the Common Rail accumulator injection system the processes of pressure generation and fuel injection are decoupled from each other. The injection pressure is generated independently of engine speed and injected fuel quantity and is permanently available in the “rail” (fuel accumulator) as needed for the injection process. The instant of injection and the injected fuel quantity are calculated in the ECU and implemented by the injector (injection unit) at each cylinder by means of a triggered solenoid valve.

UIS/UPS: System overview

UIS/UPS: System overview

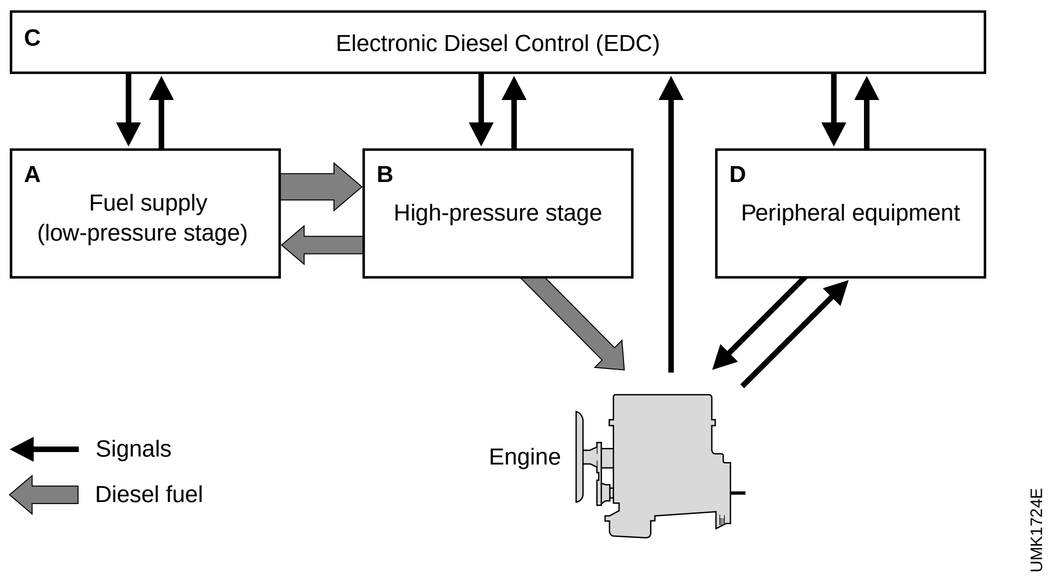
Increasingly severe requirements have led to the development of a variety of different diesel fuel-injection systems which are precisely aligned to specific demands. Requirements dictate that modern-day diesel engines not only run quietly, are low on emissions, and are economically efficient, but at the same time they must provide high power outputs and high torques.
At present, the highest injection pressures are achieved by the Unit Injector System (UIS), and the Unit Pump System (UPS). The fact that these systems permit injection to be precisely matched to the the engine's momentary operating conditions, means that the above dictates can be complied with. These modern injection systems demand that a wide variety of different system components coordinate closely with each other.

Fields of application

The UIS and UPS systems incorporate time-controlled, single-cylinder injection pumps, and are used on direct-injection diesel engines. Compared to conventional port-controlled systems, they provide far higher flexibility in the adaptation of the injection system to the particular engine. Their advantages are:
– Wide range of applications: For passenger cars and light commercial vehicles with power outputs of up to 30 kW/cylinder, for heavy trucks with up to 80 kW/cylinder. Single-plunger injection pumps are used for engines with up to 500 kW/cylinder in locomotives and ships. These are not dealt with though in this manual,
– High injection pressures up to 2,050 bar,
– Variable start of injection,
– Possibility of applying pilot injection.

Fig. 1

System stages of the Unit Injector System (UIS) and the Unit Pump System (UPS)



Design and construction

UIS and UPS contain:
– Fuel supply stage (low-pressure stage),
– High-pressure stage,
– Electronic diesel control (EDC), with the following system blocks: Sensors, ECU, and actuators,
– Peripheral equipment (exhaust-gas turbocharger and exhaust gas recirculation (EGR)).

Fig. 1 shows the principal interaction between system stages. Figures 2 and 3 on the following pages present an overview of passenger-car and commercial-vehicle systems with full equipment. Individual components are omitted depending upon type of operation and vehicle.

For commercial vehicles, the design and construction of the UIS and UPS are similar, and only differ in the high-pressure stage. The fuel-supply and EDC stages of UIS and UPS are very similar and will be dealt with together in a special chapter. The high-pressure stages of the UIS and UPS are each allocated a chapter of their own.

Operating concept

UIS and UPS are diesel fuel-injection systems which utilise time-control via integrated solenoid injectors. The instant at which the solenoid valve is triggered – that is, the moment it closes – defines start of delivery. The length of time that it is triggered is a measure of injected fuel quantity. Taking the momentary engine operating mode and environmental data into consideration, triggering point and triggering period are determined by the ECU in accordance with programmed maps. Among other things, the following data are registered:
– Crankshaft speed,
– Camshaft speed,
– Accelerator-pedal position,
– Charge-air pressure,
– Temperature of the intake air, coolant, and fuel,
– Road speed, etc.

Data is registered by sensors and conditioned in the ECU. Using this information, the ECU applies the open and closed-loop control to the vehicle, and in particular to the engine, as needed in order to obtain optimum vehicle operation.

Basic functions

The basic functions serve to control the injection of the correct quantity of diesel fuel at the right instant in time and at maximum pressure. This ensures that the diesel engine is fuel-efficient, runs quietly, and generates low emissions.

Auxiliary functions

An wide range of auxiliary closed and open-loop control functions can be incorporated. These serve to reduce emissions and fuel consumption, or to increase safety, comfort and convenience.
Examples of such auxiliary functions are:
– Exhaust-gas recirculation,
– Boost-pressure control,
– Cylinder shut-off,
– Cruise control,
– Electronic immobilizer etc.

As a rule, with a commercial-vehicle diesel engine running at high load, there is no pressure drop between the exhaust manifold upstream of the turbine and the intake manifold downstream of the compressor. This means that the cooled, controlled circulation of exhaust gas necessitates auxiliary equipment such as an exhaust-gas turbocharger with variable turbine geometry (VTG), or a venturi tube. Although a variety of different systems are presently under development, none of them has yet succeeded in coming to the forefront.

Data exchange with other electronic systems in the vehicle (for instance, ABS or electronic transmission-shift control) is implemented by the CAN serial bus system (CAN: Controller Area Network). During servicing, stored system data and fault store can be retrieved and evaluated via a diagnosis interface.

Fig. 2

Unit Injector System (UIS) for passenger cars: System overview

A Fuel supply (low-pressure stage)
1 Fuel tank,
2 Fuel filter,
3 Fuel pump with non-return valve,
4 Pressure limiter,
5 Fuel cooler.

B High-pressure stage
6 Unit injector.

C Electronic Diesel Control (EDC)
7 Fuel-temperature sensor,
8 ECU,
9 Accelerator-pedal sensor,
10 Vehicle-speed sensor,
11 Brake contacts,
12 Air-temperature sensor,
13 Camshaft speed sensor,
14 Intake-air temperature sensor,
15 Boost-pressure sensor,
16 Intake-manifold flap,
17 Hot-film air-mass meter,
18 Engine-temperature sensor (coolant),
19 Crankshaft-speed sensor (inductive).

D Peripheral equipment
20 Instrument cluster with signal display for fuel consumption, engine rpm etc.,
21 Glow control unit,
22 Sheathed-element glow plug,
23 Clutch switch,
24 Operator unit for cruise control (FGR),
25 A/C compressor,
26 Operator unit for A/C compressor,
27 Glow-plug and starter switch,
28 Diagnosis interface,
29 Battery,
30 Exhaust-gas supercharger, **31** EGR cooler,
32 EGR positioner, **33** Boost-pressure actuator,
34 Vacuum pump, **35** Engine,
CAN Controller Area Network (serial data bus in the vehicle).

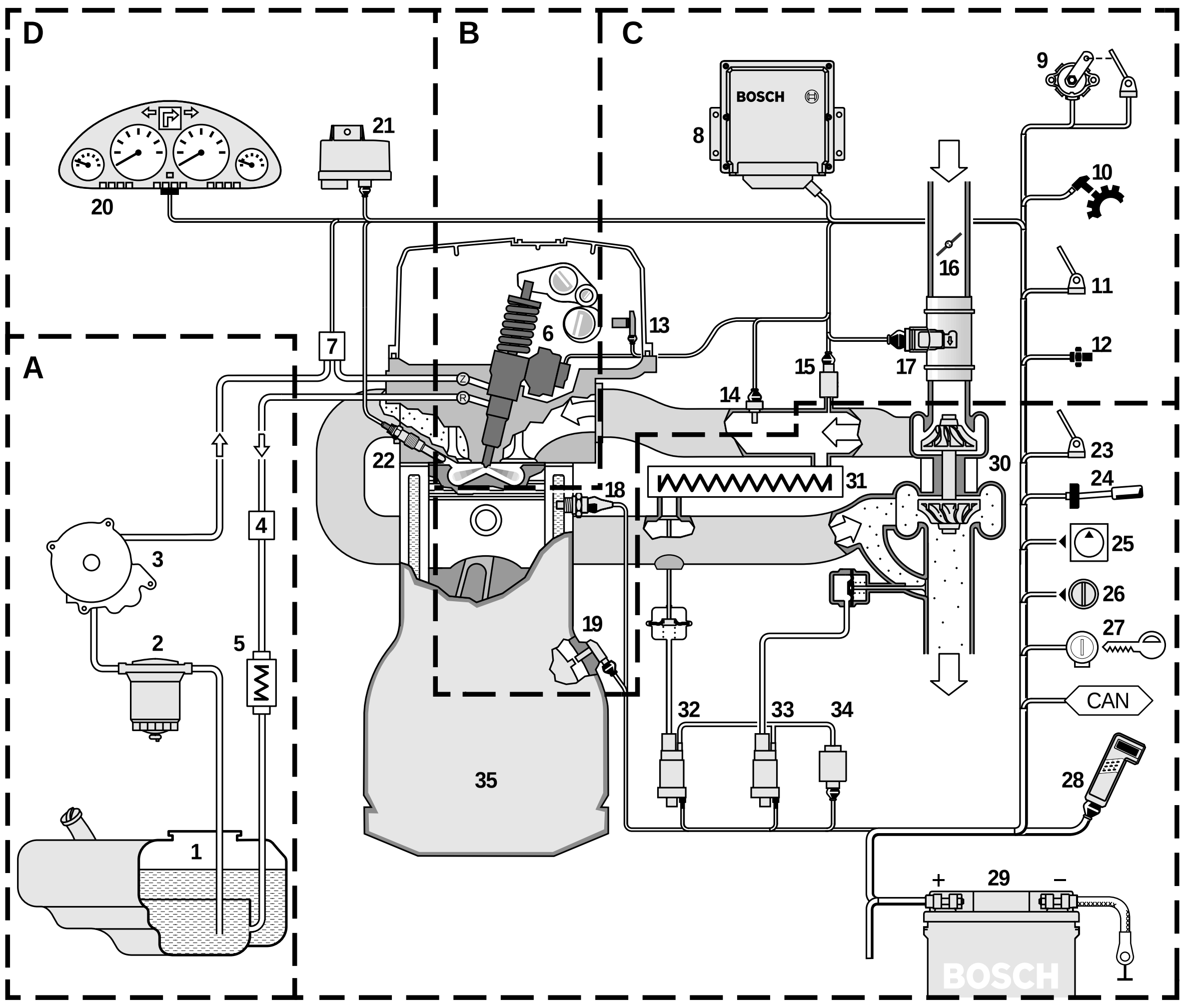


Fig. 3

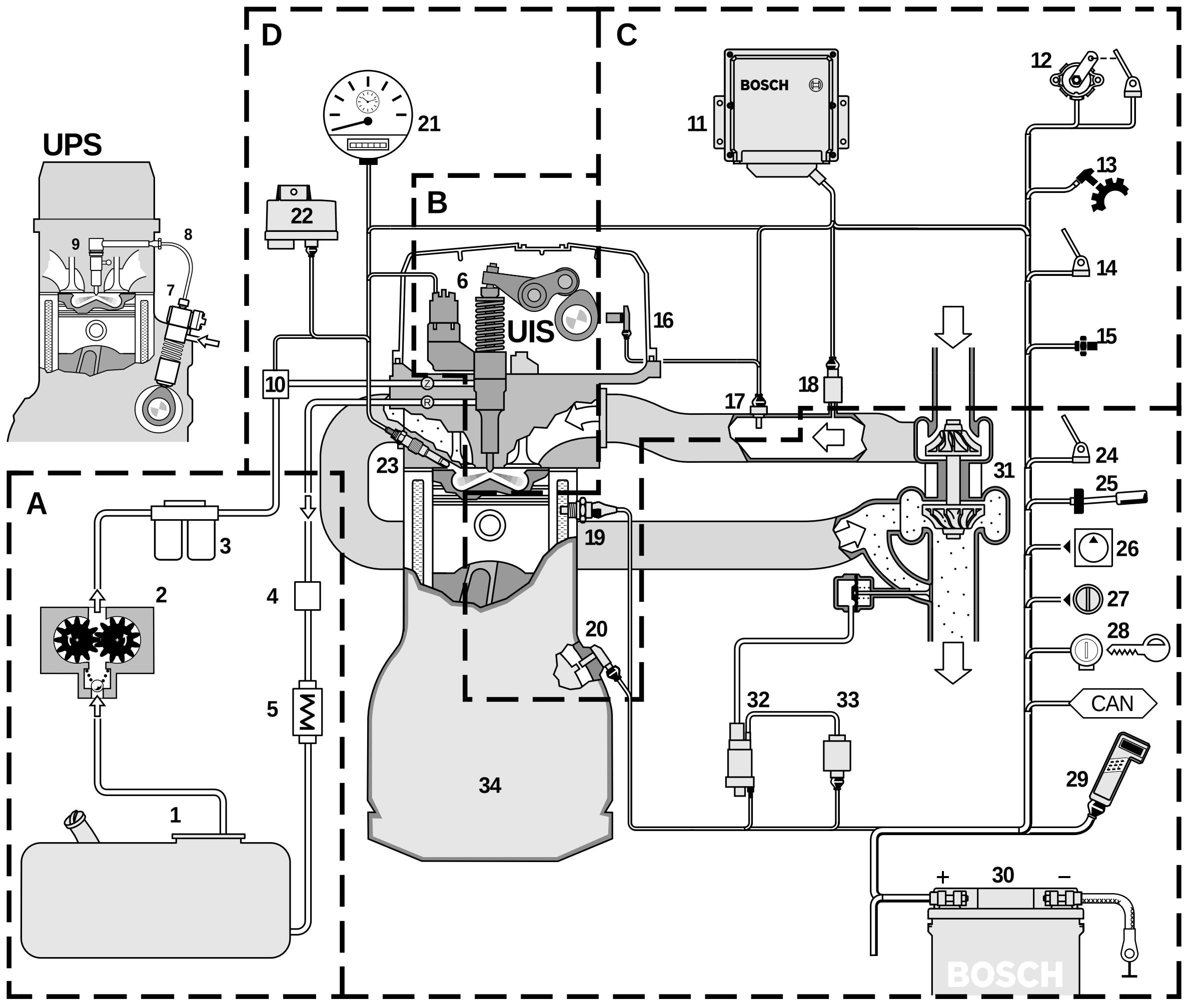
Unit Injector System (UIS) and Unit Pump System (UPS) for commercial vehicles: System overview

A Fuel supply (low-pressure stage)
1 Fuel tank with pre-filter,
2 Fuel pump with non-return valve and hand primer pump,
3 Fuel filter, **4** Pressure limiter,
5 Fuel cooler.

B High-pressure stage
UIS:
6 Unit injector.
UPS:
7 Unit pump,
8 High-pressure delivery line,
9 Nozzle-and-holder assembly.

C Electronic Diesel Control (EDC)
10 Fuel-temperature sensor,
11 ECU, **12** Accelerator-pedal sensor,
13 Vehicle-speed sensor (inductive),
14 Brake contact, **15** Air-temperature sensor,
16 Camshaft speed sensor (inductive),
17 Intake-air temperature sensor,
18 Boost-pressure sensor,
19 Engine-temperature sensor (coolant),
20 Crankshaft-speed sensor (inductive).

D Peripheral equipment
21 Instrument cluster with signal display for fuel consumption, engine rpm etc.,
22 Glow control unit,
23 Sheathed-element glow plug, **24** Clutch switch,
25 Operator unit for cruise control (FGR),
26 A/C compressor,
27 Operator unit for A/C compressor,
28 Glow-plug and starter switch,
29 Diagnosis interface,
30 Battery,
31 Exhaust-gas turbocharger,
32 Boost-pressure actuator,
33 Vacuum pump,
34 Engine.
CAN Controller Area Network (serial data bus in the vehicle).



Fuel supply (low-pressure stage)

It is the job of the fuel-supply stage to store the required fuel, filter it, and under all operating conditions supply it to the fuel-injection system at the stipulated pressure. For some applications the fuel is also cooled.

The fuel-supply stage comprises the following major components:

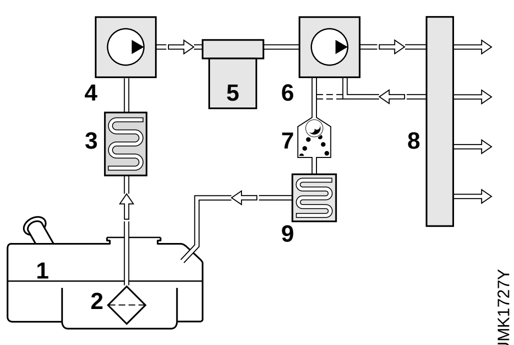
– Fuel tank (1),
– Preliminary filter (not on UIS for passenger cars) (2),
– ECU cooler (optional) (3),
– Presupply pump (optional, on passenger cars also in-tank pump) (4),
– Fuel filter (5),
– Fuel pump (low pressure) (6),
– Pressure-control valve (overflow valve) (7),
– Fuel cooler (optional) (9),
– Low-pressure fuel lines.

Individual components can be combined to form modules (for instance the fuel pump and the pressure limiter). On the axial and radial-piston distributor pumps, as well as on the Common Rail System, the fuel pump is integrated in the high-pressure pump.

Fig. 1

Fuel-supply components (low-pressure stage)

1 Fuel tank, **2** Preliminary filter, **3** ECU cooler, **4** Presupply pump with non-return valve, **5** Fuel filter, **6** Fuel pump, **7** Pressure-control valve (UIS, UPS), **8** Distributor tube (passenger-car UIS), **9** Fuel cooler (UIS, UPS, CR).



Fuel tank

As its name implies, the fuel tank stores the fuel. It must be corrosion-resistant and not leak even at a pressure defined as double the normal operating pressure, but at least at 0.3 bar overpressure. Suitable openings, safety valves etc. must be provided to permit excess pressure to escape. Fuel must not escape past the filler cap, nor through the pressure-equalisation devices. This also applies in the case of road shocks, in curves, or when the vehicle is tilted. The fuel tank must be remote from the engine so that ignition of the fuel is not to be expected even in the event of an accident.

Fuel lines

Fuel lines for the low-pressure stage can be manufactured from seamless metal tubing, or flame and fuel-resistant synthetic hose. They must be protected against mechanical damage, and must be positioned so that the possibility of dripping or evaporating fuel accumulating on hot components where it can ignite is ruled out. Fuel lines are not to be impaired in their correct operation by vehicle twist, engine movement or similar motions. All fuel-carrying components must be protected against heat which could otherwise impair correct operation.

Diesel fuel filters

The fuel filter removes the solid particles from the fuel in order to reduce its level of contamination. By doing so, it ensures that the injection components which are subject to wear are supplied with fuel which has a minimum level of contamination. In order to ensure long service intervals, the filter must feature adequate particle-storage capacity. A blocked filter results in a reduction of fuel delivery and engine output power drops accordingly.
Extremely high precision applies in the manufacture of the components of the diesel fuel-injection systems, and these react drastically to even the most minute contamination. This means that in order to guarantee that reliability, fuel-consumption figures, and compliance with the emission limits are maintained throughout the vehicle's service life (for commercial vehicles this is taken to be approx. 1 000 000 km), very high demands are made upon the measures taken to protect against wear. The fuel filter must be precisely matched to the fuel-injection system in question.
For extended maintenance intervals or particularly high levels of protection against wear, filter systems are installed which feature a preliminary filter and a fine filter.

Versions

A variety of combinations are available which incorporate the following functions:

Preliminary filters for presupply pumps
The preliminary filter (Fig. 1, Pos. 2) is usually a strainer with 300 µm mesh size, and is installed in addition to the main fuel filter (Fig. 1, Pos. 5).

Main filter
Main filters in the form of easy-change filters (Fig. 2) with pleated-star or wound filter elements (Fig. 2, Pos. 3) are in widespread use, and are screwed onto a filter bracket in the vehicle. Two filters can also be fitted in parallel (higher retention capacity), or in series (multistage filter for increased filtration efficiency or fine filter with precisely matched preliminary filter). Filters in which only the filter element is replaced are becoming increasingly popular again.

Water separator
The diesel fuel can contain water in emulsified or free form (for instance, condensate as a result of temperature change). Such water must be prevented from entering the injection system.
Water droplets form on the filter medium due to the different surface tensions of water and fuel, and accumulate in the water separator (Fig. 2, Pos. 8). For free (non-emulsified) water, an additional water separator can be used which removes water droplets by means of centrifugal force. Conductivity sensors are used to monitor water level.

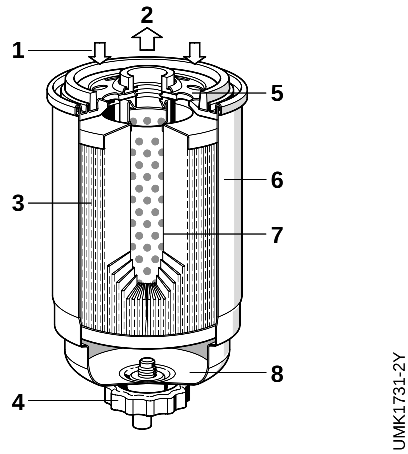
Fuel preheating
During low-temperature operation, this facility prevents the filter-element pores becoming blocked due to paraffin crystals in the fuel. The preheating components are usually incorporated in the filter and heat the fuel either electrically, by means of the engine coolant, or by using heat from the fuel-recirculation system.

Hand primer pump
Used to refill and vent the system following a filter change, and usually incorporated in the filter cover.

Fig. 2

Diesel fuel filter with water separator

1 Filter inlet, **2** Filter outlet, **3** Filter element, **4** Water drain screw, **5** Filter cover, **6** Filter case, **7** Support tube, **8** Water reservoir.



Diesel fuel filters

Fuel-supply pump

The fuel-supply pump in the low-pressure stage (the so-called presupply pump) is responsible for maintaining an adequate supply of fuel to the high-pressure components. This applies
– Irrespective of operating state,
– With a minimum of noise,
– At the necessary pressure, and
– Throughout the vehicle's complete service life.

In the axial-piston and radial-piston distributor pumps, a vane-type pump is used as the presupply pump and is integrated directly in the injection pump.
In the UIS/UPS injection systems, the presupply pump draws fuel out of the vehicle's fuel tank and continuously delivers the correct quantity (fuel for injection and fuel for purging) in the direction of the high-pressure injection system (60... 200 l/h, 300...700 kPa). Many pumps bleed themselves automatically so that starting is possible even when the tank has been run dry before filling again.

There are three designs:
– Electric fuel pump (as used in passenger cars),
– Mechanically driven gear-type fuel pumps, and
– Tandem fuel pumps (passenger-car UIS).

Electric fuel pump EKP

The electric fuel pump (Figs. 1 and 2) is only used in passenger cars and light commercial vehicles. Within the system-monitoring framework, in addition to fuel delivery it is also responsible for cutting off the supply of fuel if this is necessary in an emergency.
Electric fuel pumps are available as in-line or in-tank versions. In-line pumps are fitted to the vehicle's body platform outside the fuel tank in the fuel line between tank and fuel filter. In-tank pumps on the other hand are mounted in the fuel tank itself using a special mounting which usually also incorporates a suction-side strainer, a fuel-level indicator, a swirl pot which acts as a fuel reservoir, and electrical and hydraulic connections to the outside.
Starting with the engine cranking process, the electric fuel pump runs continuously independent of engine speed. This means that it permanently delivers fuel from the fuel tank and through a fuel filter to the fuel-injection system. Excess fuel flows back to the tank through an overflow valve.
A safety circuit is provided to prevent the delivery of fuel should the ignition be on with the engine stopped.
An electric fuel-supply pump is comprised of three function elements inside a common housing:

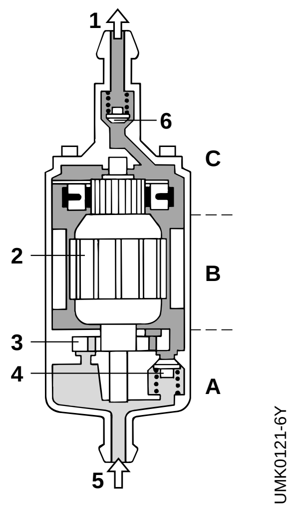
Pumping element (Fig. 1, Pos. A)
There are a variety of different pumping-element versions available depending upon the fuel pump's particular field of application. Roller-cell pumps (RZP) are normally used for diesel applications.
The roller-cell pump (Fig. 2) is a positive-displacement pump consisting of an eccentrically located base plate (4) in which a slotted rotor (2) is free to rotate. There is a movable roller in each slot (3) which, when the rotor rotates, is forced outwards against the outside roller path and against the driving flanks of the slots by centrifugal force and the pressure of the

Fig. 1

Single-stage electric fuel pump (schematic)

A Pumping element,
B Electric motor,
C End cover.

1 Pressure end,
2 Motor armature,
3 Pumping element,
4 Pressure limiter,
5 Suction end,
6 Non-return valve.



fuel. The result is that the rollers now act as rotating seals, whereby a chamber is formed between the rollers of adjacent slots and the roller path. The pumping effect is due to the fact that once the kidney-shaped intake opening (1) has closed, the chamber volume reduces continuously.

Electric motor (Fig. 1, Item B)
The electric motor comprises a permanent-magnet system and an armature (2). Design is determined by the required delivery quantity at the given system pressure. The electric motor is permanently flushed by fuel so that it remains cool. This design permits high motor performance without the necessity for complicated sealing elements between pumping element and electric motor.

End cover (Fig. 1, Item C)
The end cover contains the electrical connections as well as the pressure-side hydraulic connection. A non-return valve (6) is incorporated to prevent the fuel lines emptying once the fuel pump has been switched off. Interference-suppression units can also be fitted in the end cover.

Gear-type fuel pump

This gear-type fuel pump (Fig. 3) is used to supply the fuel-injection modules of the single-plunger injection systems (passenger cars) and of the Common Rail System (for passenger cars, commercial vehicles, and off-road vehicles). It is directly attached to the engine, and in the case of Common Rail is integrated in the high-pressure pump. Common forms of drive are via coupling, gearwheel, or toothed belt.

The main components are two counter-rotating gearwheels which mesh with each other when rotating, whereby fuel is trapped in the chambers formed between the gear teeth and transported from the intake (suction) side (1) to the outlet (pressure) side (3). The line of contact between the rotating gearwheels provides the seal between the suction and pressure ends of the pump, and prevents fuel flowing back again.
The delivery quantity is practically proportional to engine speed, so that it is necessary to reduce the delivery quantity by a suction throttle at the inlet (suction) end, or limit it by an overflow valve at the outlet (pressure) end.

The gear-type fuel pump is maintenance-free. In order to bleed the fuel system before the first start, or when the tank has been driven “dry”, a hand pump can be installed directly on the gear pump or in the low-pressure lines.

Fig. 2

Roller-cell pump (schematic)
1 Suction (intake) end, **2** Slotted rotor, **3** Roller, **4** Base plate, **5** Pressure (outlet) end.

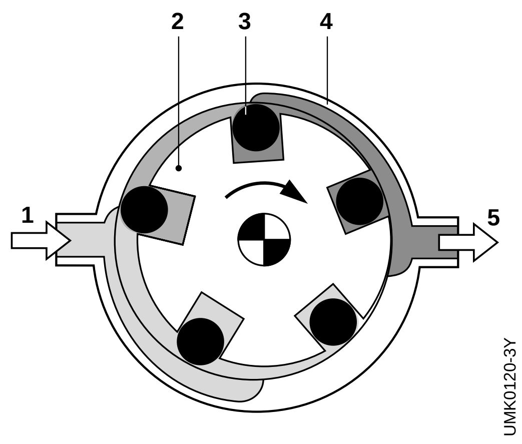
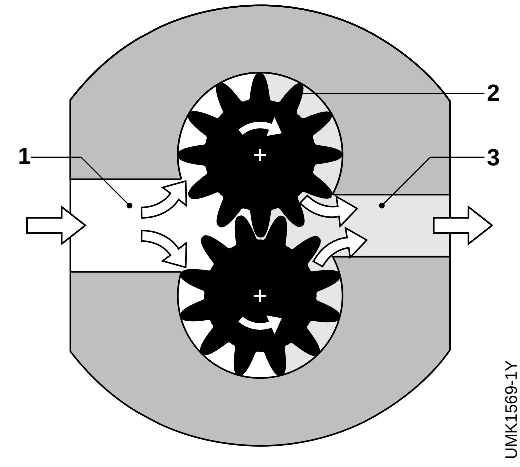


Fig. 3

Gear-type fuel pump (schematic)
1 Suction (intake) end, **2** Drive gear, **3** Pressure (outlet) end.



Vane-type pump with separating vanes

In the version of this pump used with the passenger-car UIS (Fig. 4), two separating vanes are pressed by springs (3) against a rotor (1). When the rotor rotates, volume increases at the intake (suction) end (2) and fuel is drawn into two chambers. With continued rotation, chamber volumes decrease, and fuel is forced out of the chambers at the outlet (pressure) end (5). This pump delivers fuel even at very low rotational speeds.

Tandem pump

The tandem pump used on the passenger-car UIS is a unit comprising the fuel pump (Fig. 5) and the vacuum pump for the brake booster. It is attached to the engine's cylinder head and driven by the engine's camshaft. The fuel pump itself is either a vane-type pump with separating vanes or a gear pump (3), and even at low speeds (cranking speeds) delivers enough fuel to ensure that the engine starts reliably. The pump contains a variety of valves and throttling orifices:

Suction throttling orifice (6): Essentially, the quantity of fuel delivered by the pump is proportional to the pump's speed. The pump's maximum delivery quantity is limited by the suction throttling orifice so that not too much fuel is delivered.

Overpressure valve (7): This is used to limit the maximum pressure in the high-pressure stage.

Throttling bore (4): Vapor bubbles in the fuel-pump outlet are eliminated in the fuel-return throttling bore (1).

Bypass (12): If there is air in the fuel system (for instance if the vehicle has been driven until the fuel tank is empty), the low-pressure pressure-control valve remains closed. The air is forced out of the fuel system through the bypass by the pressure of the pumped fuel.

Thanks to the ingenious routing of the pump passages, the pump's gearwheels never run dry even when the fuel tank is empty. When restarting after filling the tank, therefore, this means that the pump draws in fuel immediately. The fuel pump is provided with a connection (8) for measuring the fuel pressure in the pump outlet.

Distributor tube

The passenger-car UIS is provided with a distributor tube which, as its name implies, distributes the fuel to the unit injectors. This form of distribution ensures that the individual injectors all receive the same quantities of fuel at the same tem-

Fig. 4

Vane-type pump with separating vanes (schematic)

1 Rotor, **2** Inlet (suction) side, **3** Spring, **4** Separating vane, **5** Outlet (pressure) side.

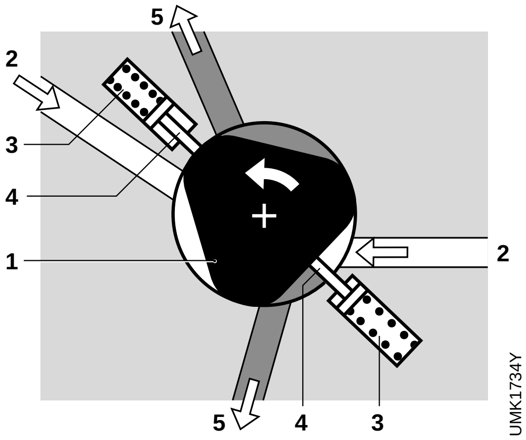
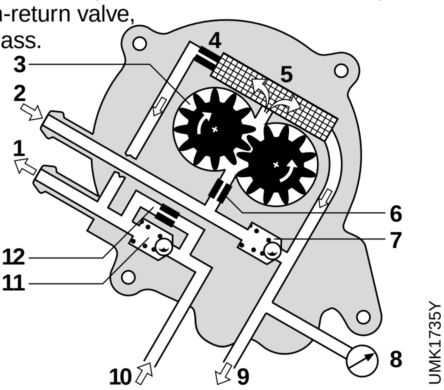


Fig. 5

Fuel pump in a tandem pump

1 Return to tank, **2** Entry from the fuel tank, **3** Pumping element (gearwheel), **4** Throttling bore, **5** Filter, **6** Suction throttling orifice, **7** Overpressure valve, **8** Connection for pressure measurement, **9** Outlet to the injector, **10** Return from the injector, **11** Non-return valve, **12** Bypass.



perature, and smooth engine running is the result. In the distributor tube, fuel flowing to the unit injectors mixes with fuel flowing back from them in order to even out the temperature.

Low-pressure pressure-control valve

The pressure-control valve (Fig. 1) is an overflow valve installed in the fuel return of the UIS and UPS systems. Independent of operating status, it provides for adequate operating pressure in the respective low-pressure stages so that the pumps are always well filled with a consistently even charge of fuel. The accumulator plunger (5) opens at a “snap-open pressure” of 3...3.5 bar, so that the conical seat (7) releases the accumulator volume (6). Only very little leakage fuel can escape through the gap seal (4). The spring (3) is compressed as a function of the fuel pressure, so that the accumulator volume changes and compensates for minor pressure fluctuations. When pressure has increased to 4...4.5 bar, the gap seal also opens and the flow quantity increases abruptly. The valve closes again when the pressure drops. Two threaded elements, each with a different spring seat, are available for preliminary adjustment of opening pressure.

ECU cooler

On commercial vehicles, ECU cooling must be provided if the ECU for the UIS or UPS systems is mounted directly on the engine. In such cases, fuel is used as the cooling medium. It flows past the ECU in special cooling channels and in the process absorbs heat from the electronics.

Fuel cooler

Due to the high pressures in the injectors for the passenger-car UIS, and some Common Rail systems (CRS), the fuel heats up to such an extent that in order to prevent damage to fuel tank and level sensor it must be cooled down before returning. Fuel flowing back from the injectors passes through the fuel cooler (heat exchanger, Fig. 2, Pos. 3) and transfers heat energy to the coolant in the fuel-cooling circuit. This is separated from the engine-cooling circuit (6) since at normal engine temperatures the engine coolant is too hot to absorb heat from the fuel. In order that the fuel-cooling circuit can be filled and temperature fluctuations compensated for, the fuel-cooling circuit is connected to the engine-cooling circuit near the equalizing reservoir. Connection is such that the fuel-cooling circuit is not adversely affected by the engine-cooling circuit which is at a higher temperature.

Low-pressure pressure-control valve

Fig. 1

Pressure-control valve for the UIS and UPS (steel-plunger accumulator valve)

1 Valve body,
2 Threaded element,
3 Spring,
4 Gap seal,
5 Accumulator plunger,
6 Accumulator volume,
7 Conical seat.

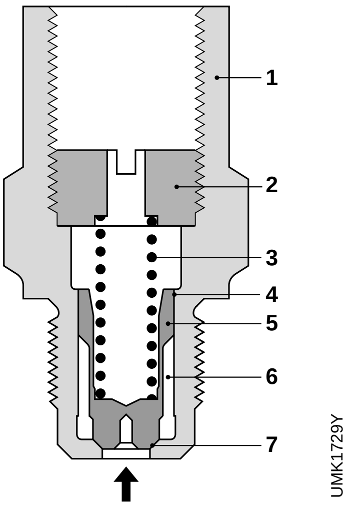
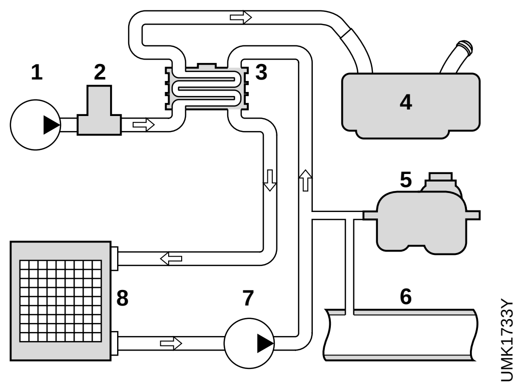


Fig. 2

Fuel-cooling circuit

1 Fuel pump, **2** Fuel-temperature sensor,
3 Fuel cooler, **4** Fuel tank,
5 Equalizing reservoir, **6** Engine-cooling circuit,
7 Coolant pump, **8** Auxiliary cooler.



Unit Injector (UI)

The Unit Injector (UI) injects into the engine cylinders the exact amount of fuel at the correct pressure and precise instant in time as calculated by the ECU. This accuracy must be maintained in all operating ranges and throughout the engine's useful life. The UIS supersedes the nozzle-and-holder assembly of the conventional fuel-injection system. With the UIS though, high-pressure delivery lines have become redundant, a fact which has a positive effect upon the fuel-injection characteristics.

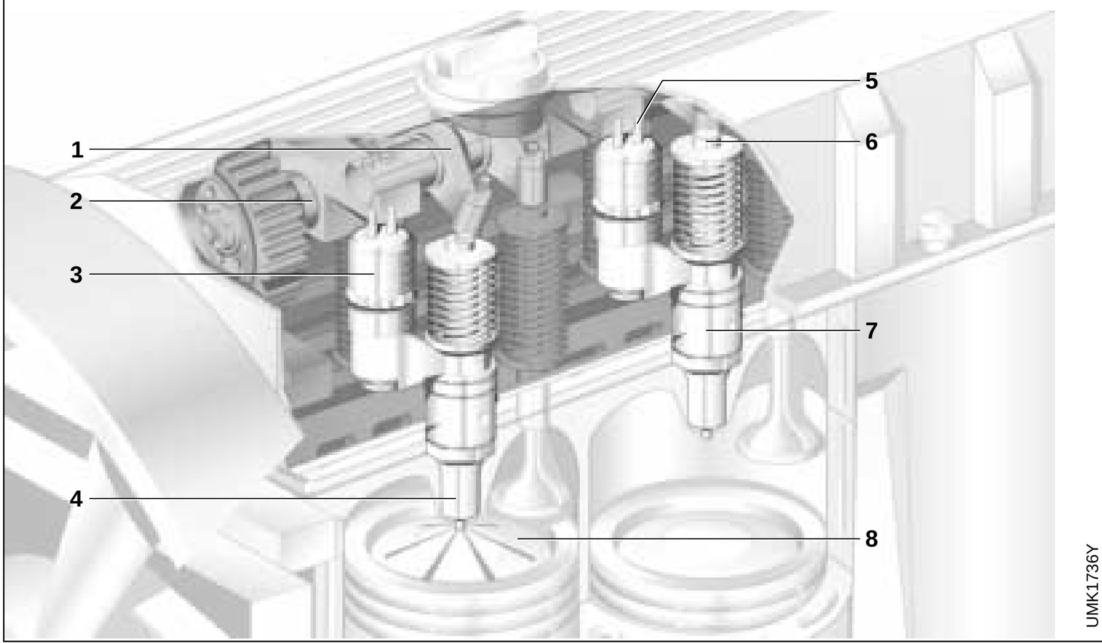
Installation and drive

Each cylinder has its own Unit Injector (UI) which is installed directly in the cylinder head (Fig. 1). The nozzle assembly (4) is integrated in the UI and projects into the combustion chamber (8). The engine camshaft (2) has an individual cam for each UI, the particular cam pitch being transferred to the pump plunger (6) by a rocker (1) so that the plunger moves up and down under the combined action of rocker and plunger follower spring.
In addition to the electrical triggering, start of injection and injected fuel quantity are a function of instantaneous plunger velocity which itself is defined by the cam shape. This is one of the reasons for such high precision being required in camshaft manufacture. Torsional vibration is induced in the camshaft by the forces applied to it during operation, and adversely affects injected-fuel-quantity tolerance and injection characteristics. It is therefore imperative that in order to reduce these vibrations the individual-pump drives are

Fig. 1

Installation of the Unit Injector (UI)

1 Rocker, **2** Engine camshaft, **3** Solenoid valve, **4** Nozzle assembly, **5** Electrical connection, **6** Pump plunger, **7** Unit injector (UI), **8** Engine combustion chamber.



designed to be as rigid as possible (this applies to the camshaft drive, the camshaft itself, the rocker, and the rocker bearings).

Design and construction

The UI body assembly (Fig. 2, Pos. 4) serves as the pump barrel. It has an extension arm in which the high-pressure solenoid valve (1) is integrated. Passages in the injector's body provide the connections between high-pressure chamber (5) and solenoid valve/low-pressure stage, and between high-pressure chamber and nozzle assembly (6). The unit injector's shape is such that the UI can be fastened in the engine's cylinder head (3) by means of a special clamp (9). The follower spring (2) forces the pump plunger against the rocker (7) and the rocker against the actuating cam (8). This ensures that plunger, rocker, and actuating cam are always in mechanical contact during actual operation. As soon as injection has finished, the follower spring forces the plunger back to its initial position. Figs. 3 and 4 on the following pages show details of the design and construction of unit injectors for passenger cars and commercial vehicles.
The unit injector is sub-divided into the following function units:

High-pressure generation
The major components involved in high-pressure generation are the pump body assembly, the pump plunger, and the follower spring (Figs. 3 and 4 on the next pages, Positions (4), (3), and (2)).

High-pressure solenoid valve
The high-pressure solenoid valve controls the start (instant) of injection and the duration of injection. Its major components are: Coil (10), solenoid-valve needle (8), armature (9), magnet core and solenoid-valve spring (26).

Nozzle assembly
The nozzle assembly (20) atomises the fuel and distributes it in the combustion chamber in precisely metered quantities. It shapes the rate-of-discharge curve. The nozzle assembly is attached to the unit-injector body assembly by the nozzle nut (19).

Fig. 2

Installation of the Unit Injector in the engine's cylinder head

1 High-pressure solenoid valve, **2** Follower spring, **3** Engine cylinder head, **4** Unit-injector body assembly, **5** High-pressure chamber, **6** Nozzle assembly, **7** Rocker, **8** Actuating cam, **9** Clamp, **10** Fuel return, **11** Fuel inlet, **12** Nozzle nut, **13** Engine valve.

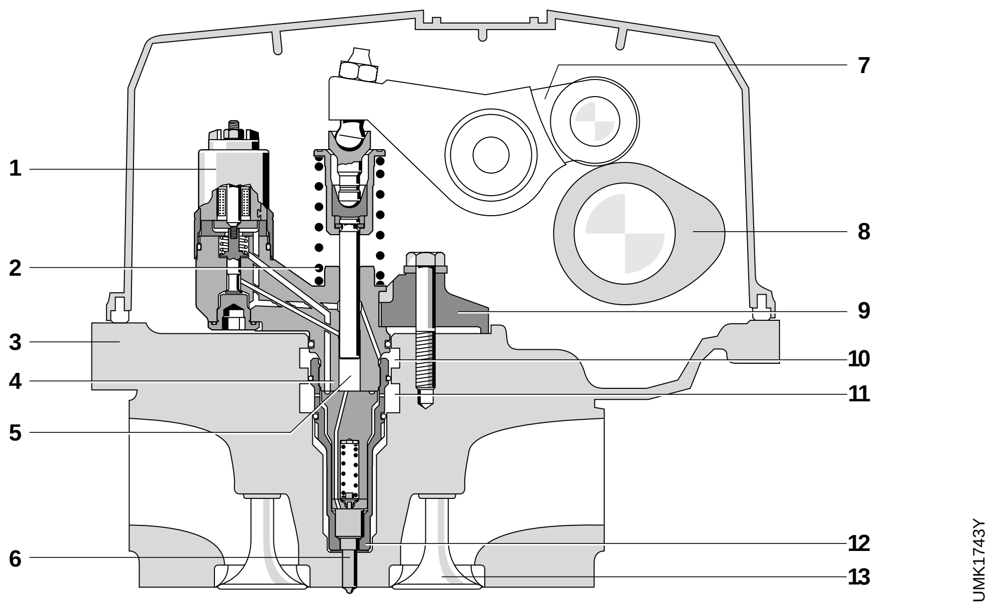


Fig. 3

Passenger-car Unit Injector: Design and construction

1 Ball pin, **2** Follower spring, **3** Pump plunger, **4** Pump-body assembly, **5** Plug-in connection, **6** Magnet core, **7** Compensating spring, **8** Solenoid-valve needle, **9** Armature, **10** Solenoid-valve coil, **11** Fuel return (low-pressure stage), **12** Seal, **13** Inlet passages (approx. 350 laser-drilled holes acting as a filter), **14** Hydraulic stop (damping unit), **15** Needle seat, **16** Sealing disc, **17** Engine combustion chamber, **18** Nozzle needle, **19** Retaining nut, **20** Integral nozzle assembly, **21** Engine cylinder head, **22** Needle-valve spring, **23** Accumulator plunger, **24** Accumulator chamber, **25** High-pressure chamber, **26** Solenoid-valve spring, **27** Drive camshaft, **28** Roller rocker.

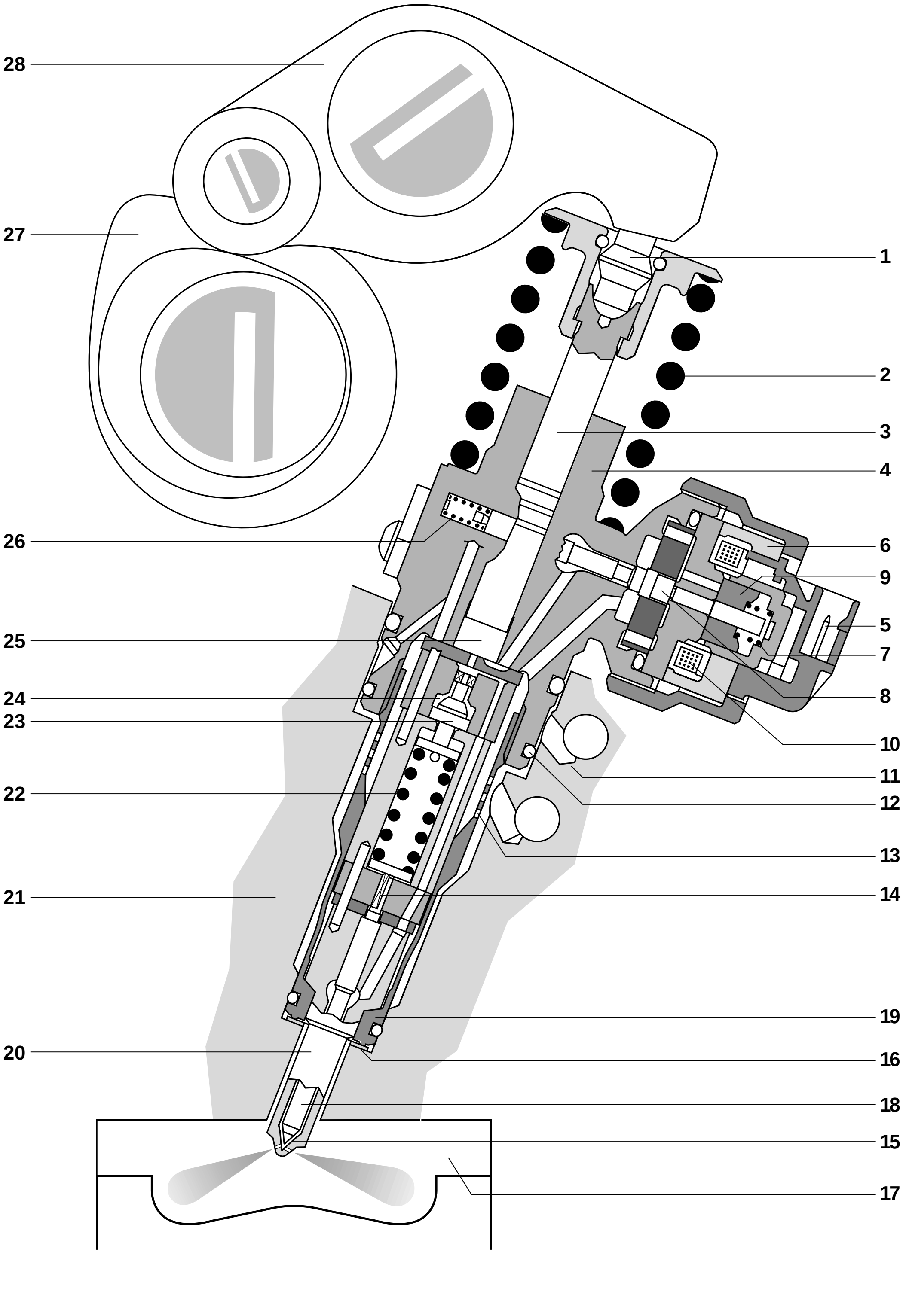
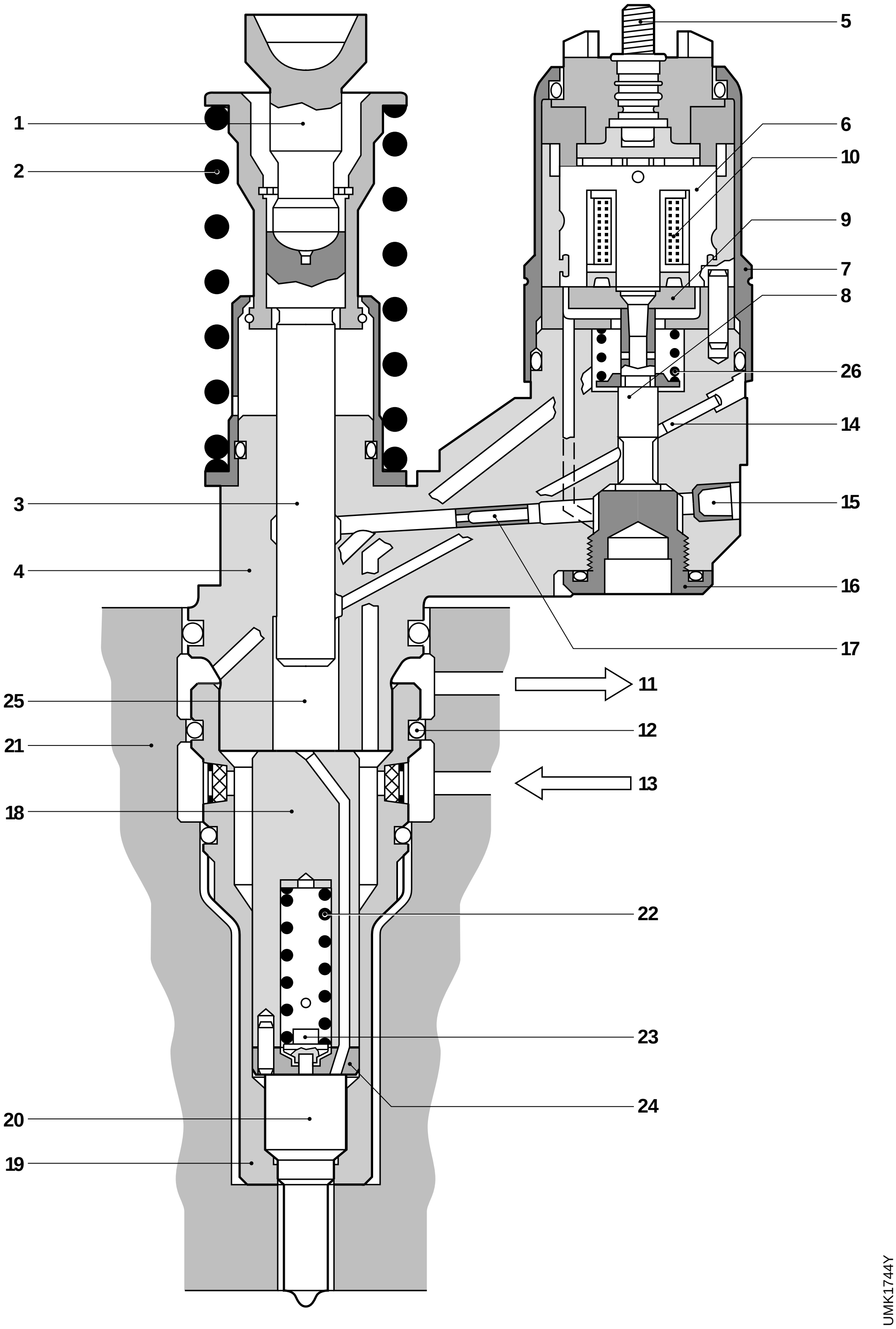


Fig. 4

Commercial-vehicle Unit Injector: Design and construction

1 Ball pin, **2** Return spring, **3** Pump plunger, **4** Pump-body assembly, **5** Plug-in connection, **6** Magnet core, **7** Solenoid-valve retaining nut, **8** Solenoid-valve needle, **9** Armature plate, **10** Solenoid-valve coil, **11** Fuel return (low-pressure stage), **12** Seal, **13** Fuel inlet, **14** High-pressure plugs, **15** Low-pressure plugs, **16** Solenoid-valve stroke stop, **17** Throttling orifice, **18** Spring retainer, **19** Retaining nut, **20** Integral nozzle assembly, **21** Engine cylinder head, **22** Needle-valve spring, **23** Pressure pin, **24** Shim, **25** High-pressure chamber, **26** Solenoid-valve spring.



Operating concept

Main injection

The function of these single-cylinder injection-pump systems can be subdivided into four operating states (Fig. 1):

Suction stroke (a)

The follower spring (3) forces the pump plunger (2) upwards. The fuel in the fuel supply's low-pressure stage is permanently under pressure and flows from the low-pressure stage into the solenoid-valve chamber (6) via the bores in the engine block and the inlet passage (7).

Initial stroke (b)

The actuating cam (1) continues to rotate and forces the pump plunger downwards. The solenoid valve is open so that the pump plunger can force the fuel through the fuel-return passage (8) into the fuel supply's low-pressure stage.

Delivery stroke and injection of fuel (c)

At a given instant in time, the ECU outputs the signal to energise the solenoid-valve coil (9) so that the solenoid-valve needle is pulled into the seat (10) and the connection between the high-pressure chamber and the low-pressure stage is closed. This instant in time is designated the “electrical start of injection” or “Beginning of the Injection Period”, BIP, (also known as the “Begin of injection period”). The closing of the solenoid-valve needle causes a change of coil current. This is recognized by the ECU (BIP detection) as the actual start of delivery and is taken into account for the next injection process. Further movement of the pump plunger causes the fuel pressure in the high-pressure chamber to increase, so that the fuel pressure in the injection nozzle also increases. Upon reaching the nozzle-needle opening pressure of approx. 300 bar, the nozzle needle (11) is lifted from its seat and fuel is sprayed into the engine's combustion chamber (this is the so-called “actual start of injection” or start of delivery). Due to the pump plunger's high delivery rate, the pressure continues to increase throughout the whole of the injection process.

Residual stroke (d)

As soon as the solenoid-valve coil is switched off, the solenoid valve opens after a brief delay and opens the connection between the high-pressure chamber and the low-pressure stage.
The peak injection pressure is reached during the transitional phase between delivery stroke and residual stroke. Depending upon pump type, it varies between max. 1800 and 2050 bar. As soon as the solenoid valve opens, the pressure collapses abruptly, and when the nozzle-closing pressure is dropped below, the nozzle closes and terminates the injection process.
The remaining fuel which is delivered by the pumping element until the cam's crown point is reached is forced into the low-pressure stage via the fuel-return passage.

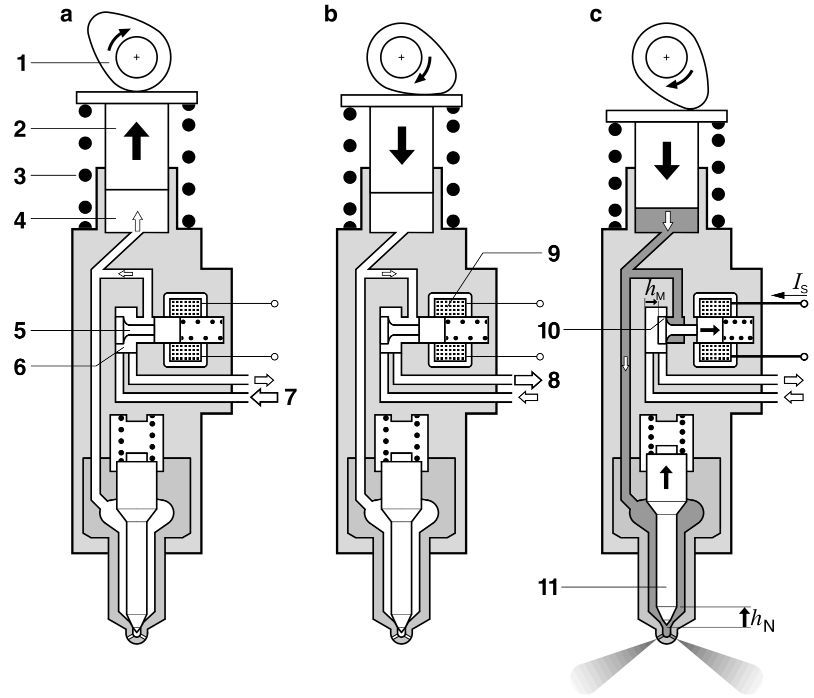
These single-cylinder injection systems are intrinsically safe. In other words, in the unlikely event of a malfunction, one uncontrolled injection of fuel is the most that can happen. For instance:
If the <u>solenoid valve remains open</u>, no injection can take place since the fuel flows back into the low-pressure stage and it is impossible for pressure to be built up. And since the high-pressure chamber can only be filled via the solenoid valve, when this <u>remains closed</u> no fuel can enter the high-pressure chamber. In this case, at the most only a single injection can take place.

The unit injector is installed in the engine's cylinder head and is therefore subject to very high temperatures. In order to keep its temperatures as low as possible, it is cooled by the fuel flowing back to the low-pressure stage.

Special measures applied in the fuel inlet to the unit injector ensure that differences in fuel temperature from cylinder to cylinder are kept to a minimum.

Fig. 1

Unit Injector (UI) and Unit Pump (UP): Functional principle

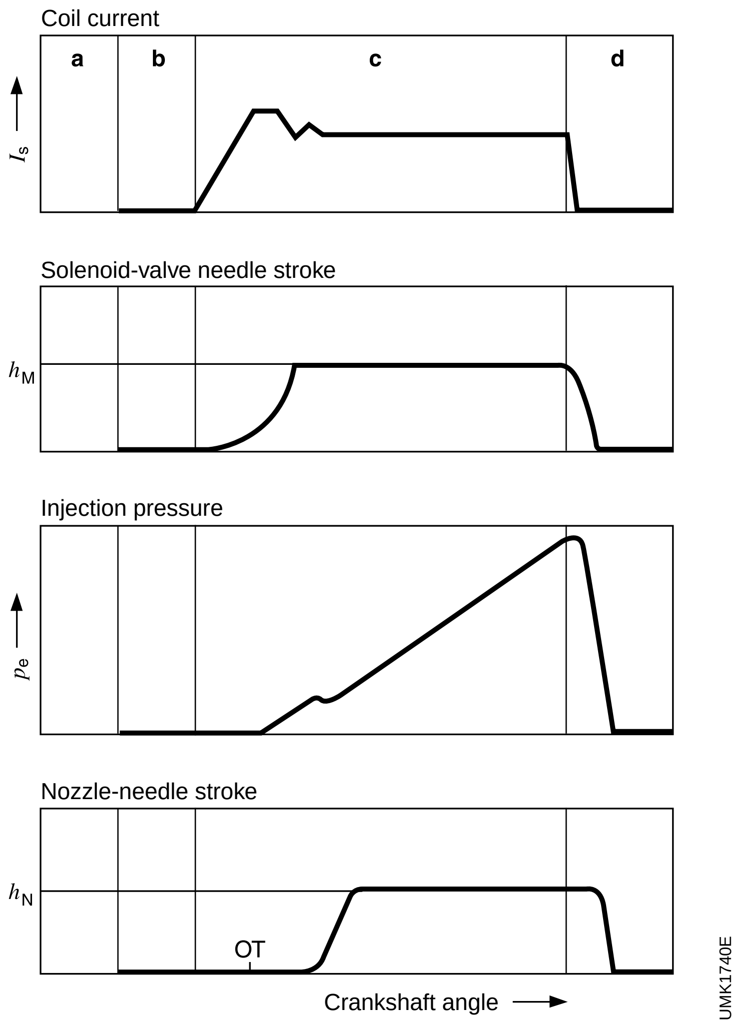


Operating states:

a Suction stroke,
b Initial stroke,
c Prestroke,
d Residual stroke.

1 Actuating cam,
2 Pump plunger,
3 Follower spring,
4 High-pressure chamber,
5 Solenoid-valve needle,
6 Solenoid-valve chamber,
7 Feed passage,
8 Fuel-return passage,
9 Coil,
10 Solenoid-valve seat,
11 Nozzle assembly.

I_S Coil current,
h_M Solenoid-valve needle stroke,
p_e Injection pressure,
h_N Nozzle-needle stroke.



OT = TDC

Pilot injection (passenger cars)

Pilot injection with mechanical-hydraulic control is incorporated in the passenger-car unit injector. This serves to reduce both noise and pollutant emissions (refer to the Chapter “Diesel combustion”). This facility can be subdivided into four operating states (Fig. 2):

Initial position
Nozzle needle (7) and accumulator plunger (3) are up against their seats. The solenoid valve is open which means that no pressure can build up.

Start of pilot injection
Pressure buildup starts as soon as the solenoid valve closes. When the nozzle opening pressure is reached, the needle lifts from its seat and pilot injection commences. During this phase, the nozzle needle's stroke is limited hydraulically by a damping unit.

End of pilot injection
Further pressure increase leads to the accumulator plunger lifting from its seat so that a connection is set up between the high-pressure (2) and the low-pressure chambers (4). The resulting pressure drop, and the accompanying increase in the spring's (5) initial tension, lead to the nozzle needle closing. This marks the end of pilot injection.
For the most part, the pilot-injection quantity of approx. 1.5 mm³ is defined by the accumulator-plunger opening pressure. The interval between the main and pilot injection phases is essentially a function of the accumulator-plunger stroke.

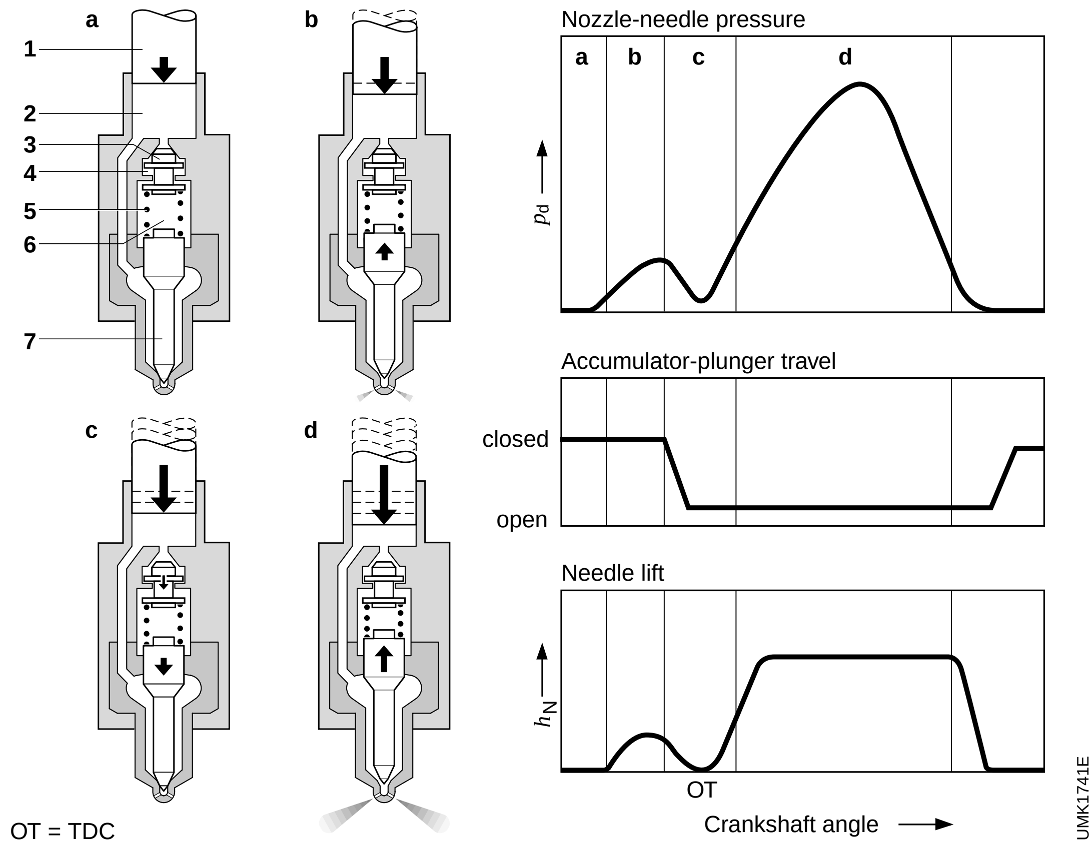
Start of main injection
The continuing movement of the pump plunger leads to the pressure in the high-

Fig. 2

UIS mechanical pilot injection: Functional principle

a Initial position, **b** Start of pilot injection, **c** End of pilot injection, **d** Main injection.

1 Pump plunger, **2** High-pressure chamber, **3** Accumulator plunger, **4** Accumulator chamber, **5** Spring, **6** Spring-retainer chamber, **7** Nozzle needle.



pressure chamber continuing to increase. The main injection phase starts once the now higher nozzle opening pressure is reached. During the actual main injection phase, the injection pressure increases to about 2050 bar.

The opening of the solenoid valve marks the termination of the main injection phase. Nozzle needle and accumulator plunger return to their initial positions.

Operating concept

The history and the future of the unit injector (UI)

1905
The idea behind the unit injector is practically as old as the diesel engine itself, and originated from Rudolf Diesel.

1999
It took the ideas, ingenuity, and hard work of countless engineers and technicians to turn Diesel's idea into a modern fuel-injection system.

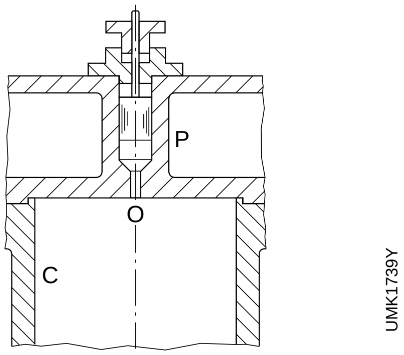
But first of all, numerous difficulties and problems in the areas of materials technology, production engineering, control engineering, electronics, and fluid mechanics had to be overcome.

The Electronic Diesel Control (EDC) today places the unit injector system (UIS) in the position of being able to optimally control the various diesel-engine functions in a wide variety of operating states.

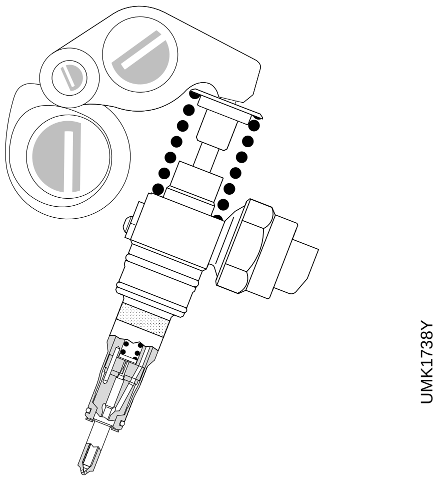
This system is capable of generating the highest injection pressures on today's market.

2000 onwards
Even considering today's high level of UIS development, there are still perspectives for the future. Further refinement of the electronic control, and even higher injection pressures, are only two of the possibilities on which the development departments are expending great effort.

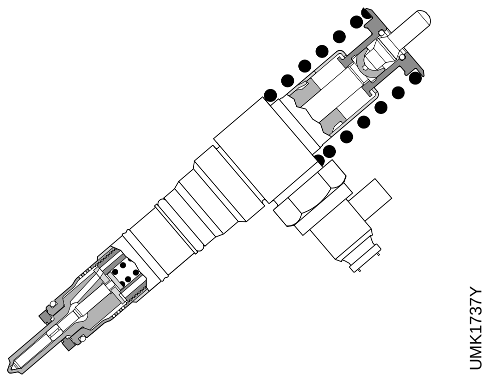
In other words, the unit injector systems (UIS) are well prepared for the future.



Sketch from Rudolf Diesel's patent document from 1905



Unit injector 1999



Unit injector of the future

High-pressure solenoid valve

It is the job of the high-pressure solenoid valve to initiate injection at the correct instant in time, and to ensure precision metering to the engine cylinder of the correct amount of fuel for a precisely measured length of time (injection duration).

Design and construction

The high-pressure solenoid valve is subdivided into two major subassemblies:

Valve
The valve itself is comprised of the valve needle, the valve body as an integral part of the pump body, and the valve spring (Figs. 1 and 2, Pos. 2, 12, and 1 respectively).
The valve body's sealing surface is conically ground (10), and the valve needle is also provided with a conical sealing surface (11). The angle of the needle's ground surface is slightly larger than that of the valve body. With the valve closed, when the needle is forced up against the valve body, valve body and needle are only in contact along a line (and not a surface) which represents the valve seat. As a result, sealing is very efficient (dual-conical sealing). High-precision processing must be applied to perfectly match the valve needle and valve body to each other.

Magnet
The magnet is comprised of the fixed stator and the movable armature (16).

The stator itself is composed of the magnet core (15), a coil (6), and the corresponding electrical contacting with plug (8).

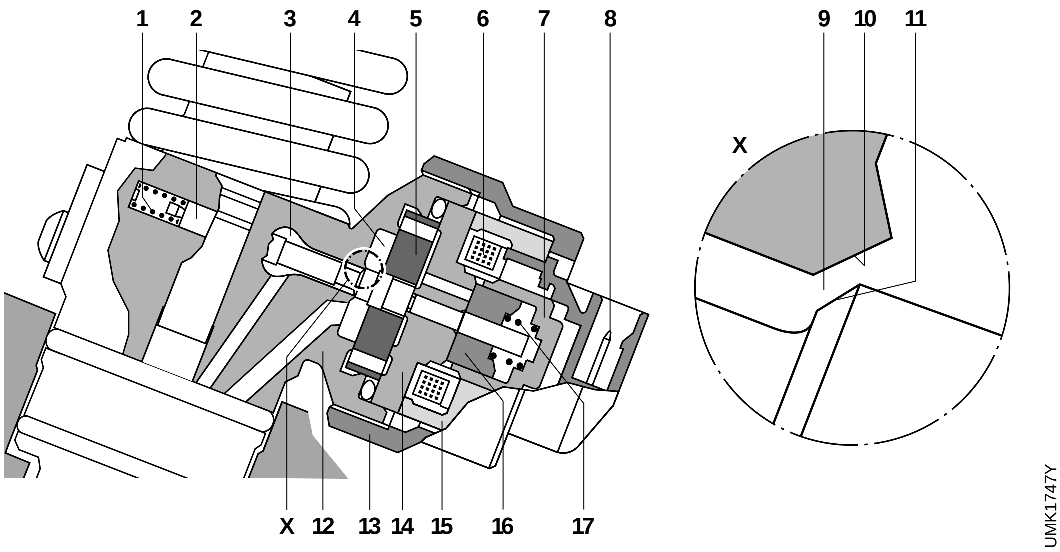
The armature is fastened to the valve needle.

In the non-energized position, there is an initial air gap between the stator and the armature.

Fig. 1

Passenger-car Unit Injector: High-pressure solenoid valve

1 Valve spring, **2** Valve needle, **3** High-pressure area, **4** Low-pressure area, **5** Shim, **6** Coil,
7 Retainer, **8** Plug, **9** Valve flow cross-section, **10** Valve-body sealing surface, **11** Valve-needle sealing surface, **12** Integral valve body, **13** Union nut, **14** Magnetic disc, **15** Magnet core,
16 Armature, **17** Compensating spring.



Operating concept

The solenoid valve has two switched positions: Open and closed. It is open when no voltage is applied across the coil (non-energized). It closes when energized by the ECU driver stage.

Valve open
The force exerted by the valve spring pushes the valve needle up against the stop so that the valve flow cross-section (9) between the valve needle and the valve body is opened in the vicinity of the valve seat. The pump's high-pressure (3) and low-pressure (4) areas are now connected with each other. In this initial position, it is possible for fuel to flow into and out of the high-pressure chamber.

Valve closed
When fuel injection is required, the coil is energized by the ECU driver stage (refer also to the “ECU” Chapter). The pickup current causes a magnetic flux in the magnetic-circuit components (magnet core and armature) which generates a magnetic force to shift the armature towards the stator. Armature movement is halted by the needle and the valve body coming into contact at the seal seat. A residual air gap remains between the armature and the stator. The valve is now closed, and injection takes place when the pump plunger is forced downwards.

The magnetic force is not only used to pull in the armature, but must at the same time overcome the force exerted by the valve spring and hold the armature against the spring force. Apart from this, the magnetic force must apply a certain force to keep the sealing surfaces in contact with each other. The force at the armature is maintained as long as the coil is energized.

The nearer the armature is to the magnet stator, the greater is the magnetic flux. When the valve is closed, therefore, it is thus possible to reduce the current to the holding-current level. The valve remains closed nevertheless, and the power loss (heat) due to current flow is kept to a minimum.

Commercial-vehicle Unit Injector: High-pressure solenoid valve

1 Valve spring, **2** Valve needle, **3** High-pressure area, **4** Low-pressure area, **5** Stop, **6** Coil, **7** Cover, **8** Plug, **9** Valve flow cross-section, **10** Valve-body sealing surface, **11** Valve-needle sealing surface, **12** Integral valve body, **13** Solenoid-valve clamping nut, **14** Adjusting element for residual air gap, **15** Magnet core, **16** Armature plate.

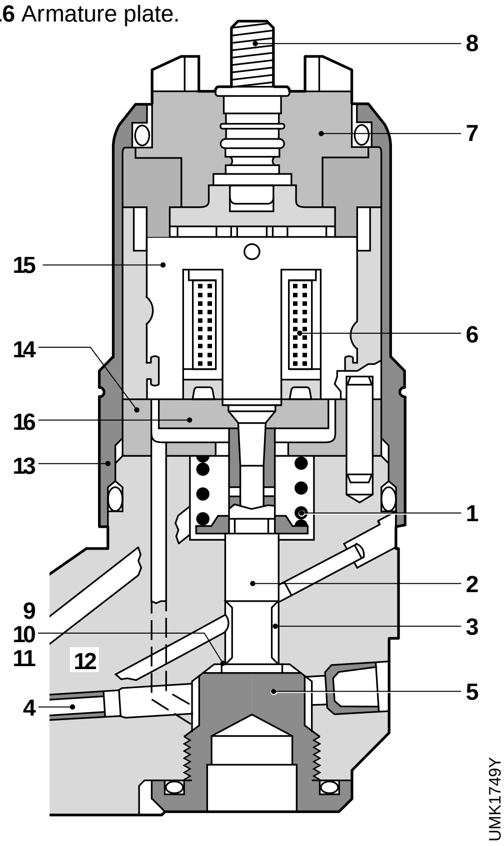


Fig. 2

To stop the fuel-injection process, the current through the solenoid coil is switched off. As a result, the magnetic flux and the magnetic force collapse, and the spring forces the valve needle to its normal position against the stop. The valve seat is open.

Solenoid-valve switching must be extremely rapid and very precise in order to comply with the tolerances demanded from the injection system regarding start of injection and injected fuel quantity. Irrespective of operating conditions, this high-level precision is maintained from stroke to stroke, and from pump to pump.

Unit pump (UP)

The assignment and operating concept of the unit pump (UP) correspond to those of the unit injector (UI). The fact that the UP separates the function units "High-pressure generation" and "High-pressure solenoid valve" from the "Injection nozzle" by a short high-pressure delivery line is the only difference between it and the UI system.

The unit pump is of modular design, and the fact that the pumps are integrated in the side of the engine block (Fig. 1) has the following advantages:
– New cylinder-head designs are unnecessary,
– Rigid drive, since no rockers needed,
– Simple handling for the workshop since the pumps are easy to remove.

The UPS nozzles are installed in nozzle holders (refer to the Chapter "Nozzles and nozzle holders").

Design and construction

High-pressure delivery lines
All pumps have a very short delivery line (6). These are all of the same length, and must be able to permanently withstand the maximum pump pressure and the to some extent high-frequency pressure fluctuations which occur during the injection pauses. High-tensile, seamless steel tubing is therefore used for these delivery lines which normally have an OD of 6 mm and an ID of 1.8 mm.

Unit pump
Each pump is driven directly by an injection cam on the engine camshaft (4). Connection to the pump plunger is through the return spring (8) and the roller tappet (9). A flange on the pump body is used to fasten the pump in the engine block.

Fig. 1

Unit Pump: Installation

1 Stepped nozzle holder, **2** Engine combustion chamber, **3** Unit pump, **4** Engine camshaft,
5 Pressure fittings, **6** High-pressure delivery line, **7** Solenoid valve, **8** Return spring, **9** Roller tappet.

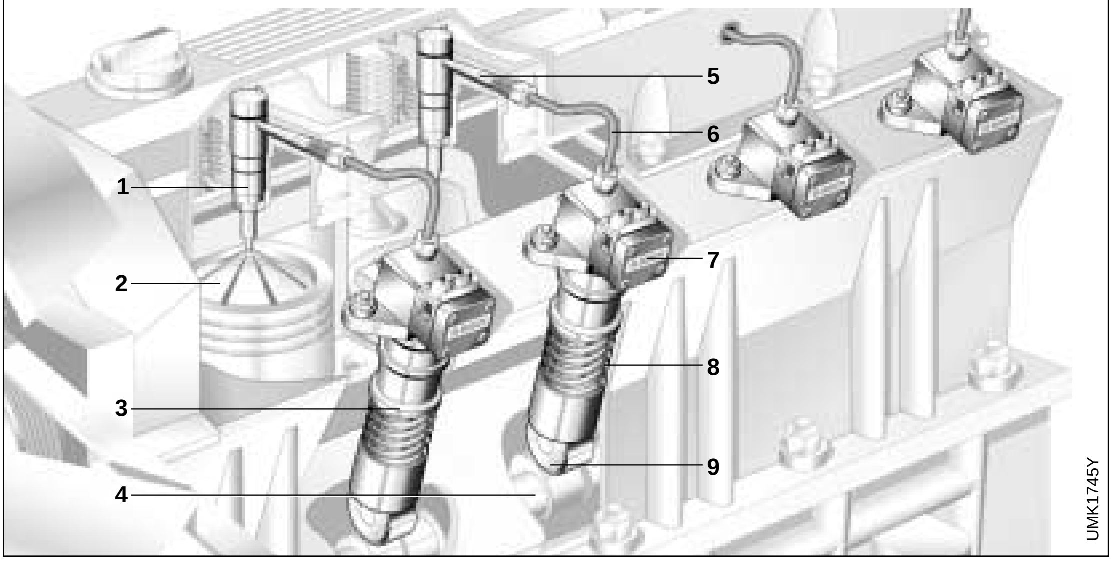
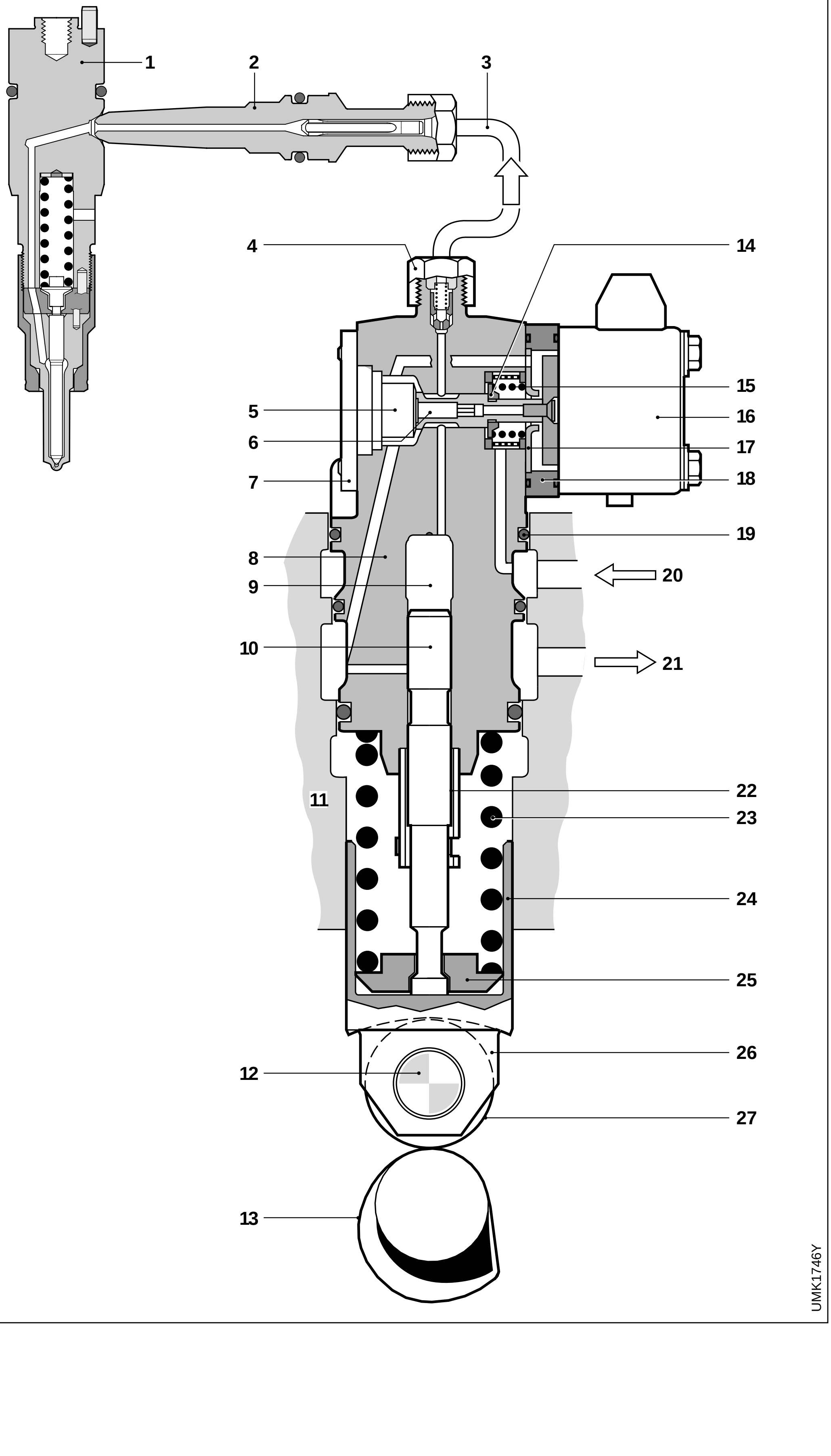


Fig. 2

Commercial-vehicle Unit Pump: Design and construction

1 Nozzle holder, **2** Pressure fitting, **3** High-pressure delivery line, **4** Connection, **5** Stroke stop, **6** Solenoid-valve needle, **7** Plate, **8** Pump housing, **9** High-pressure chamber, **10** Pump plunger, **11** Engine block, **12** Roller-tappet pin, **13** Cam, **14** Spring seat, **15** Solenoid-valve spring, **16** Valve housing with coil and magnet core, **17** Armature plate, **18** Intermediate plate, **19** Seal, **20** Fuel inlet (low pressure), **21** Fuel return, **22** Pump-plunger retention device, **23** Tappet spring, **24** Tappet body, **25** Spring seat, **26** Roller tappet, **27** Tappet roller.



Nozzles and nozzle holders

The nozzle holders and their associated nozzles are major fuel-injection-system components at the engine. They have a direct influence on combustion and therefore also on engine power, as well as on exhaust-gas and noise emissions. Optimal operation of the nozzles and nozzle holders demands not only a variety of different versions, but also that these be precisely adapted to the engine. Nozzle holders and nozzles are responsible for:

- **The shaping of the rate-of-discharge curve (exact distribution of pressure and injected fuel quantity per degree crankshaft),**
- **Atomization and distribution of fuel in the engine's combustion chamber,**
- **Sealing off the fuel system from the combustion chamber.**

The fuel is injected into the combustion chamber through nozzles which in the case of UPS are installed in the engine using nozzle holders. On CR and UIS high-pressure injection systems, the nozzle is integrated in the injector so that separate nozzle holders are unnecessary. The nozzle is opened by fuel pressure, and injected fuel quantity is defined for the most part by the nozzle ports and the duration of injection. The nozzle must be aligned to the different conditions prevailing at the engine:

- Combustion process (prechamber, whirl chamber, direct injection),
- Combustion-chamber geometry,
- Injection-spray shape and direction,
- “Penetrating power” and atomization of the fuel spray,
- Duration of injection, and
- Injected fuel quantity per degree crankshaft.

The required flexibility and a minimum of individual-part variation is ensured by standard sizes and assemblies.

Fig. 1

Principle of the nozzle and nozzle holder using a direct-injection (DI) engine as an example

1 Nozzle holder with spring, filter, and connections,
2 Nozzle,
3 Cylinder head,
4 Combustion chamber.

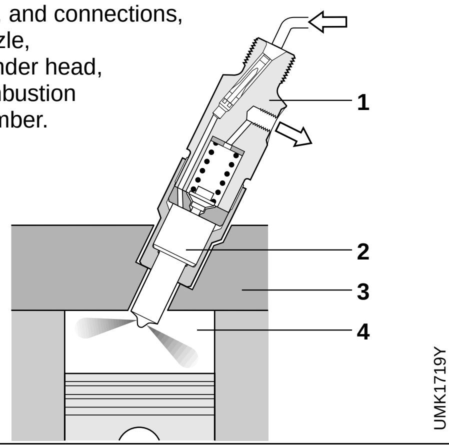


Table 1

Nozzles and nozzle holders: Applications.

Fuel-injection system	Pintle nozzles	Hole-type nozzles	Standard nozzle holders	Step-type nozzle holders	Two-spring nozzle holders
Single-plunger injection pumps	X	X	X	X	X
Standard in-line injection pumps	X	X	X	X	X
Control-sleeve injection pumps	–	X	X	X	X
Axial-piston distributor pumps (VE)	X	X	X	X	X
Radial-piston distributor pumps (VR)	–	X	X	X	X
Unit pump system (UPS)	–	X	X	X	–
Unit injector system (UIS)	–	X	–	–	–
Common rail system (CR)	–	X	–	–	–

Dimensions in fuel-injection engineering

The world of diesel fuel-injection is a world of superlatives.

During its useful life, the nozzle of a commercial-vehicle diesel engine opens and closes more than 1,000 million times. It not only reliably seals against pressures of up to 2050 bar, but must also withstand severe loading:
– It must absorb the shocks resulting from rapid opening and closing (including pilot and secondary injection, this happens up to 10,000 times per minute with a passenger-car engine),
– It must resist the high flow loading during the actual injection process,
– It must stand up to the high temperatures and pressures in the combustion chamber.

The following comparisons underline the amazing performance of modern-day injection nozzles:
– There is a pressure of up to 2050 bar in the nozzle injection chamber. This is equivalent to the pressure which would be exerted on a finger nail by the weight of a top-range automobile.
– The duration of injection is between 1 and 2 milliseconds (ms). The sound wave from a loudspeaker only travels about 33 cm in this time.
– On a passenger car, the injected fuel quantities vary between 1 mm^3 (pilot injection), and 50 mm^3 (full-load), whereas on a commercial vehicle, the quantities are between 3 mm^3 and 350 mm^3 respectively. 1 mm^3 corresponds to the volume of a pinhead. 350 mm^3 is equivalent to the volume contained in 12 large drops of rain (30 mm^3 per raindrop). Within 2 milliseconds, this quantity is forced at a velocity of 2000 km/h through an opening with a diameter of less than 0.25 mm^2.
– Nozzle-needle clearance in the nozzle is 0.002 mm (2 µm). A human hair is 30 times thicker (0.06 mm).

Compliance with this very demanding range of high-performance specifications is the result of extensive know-how in development, materials technology, production engineering, and measurement techniques.

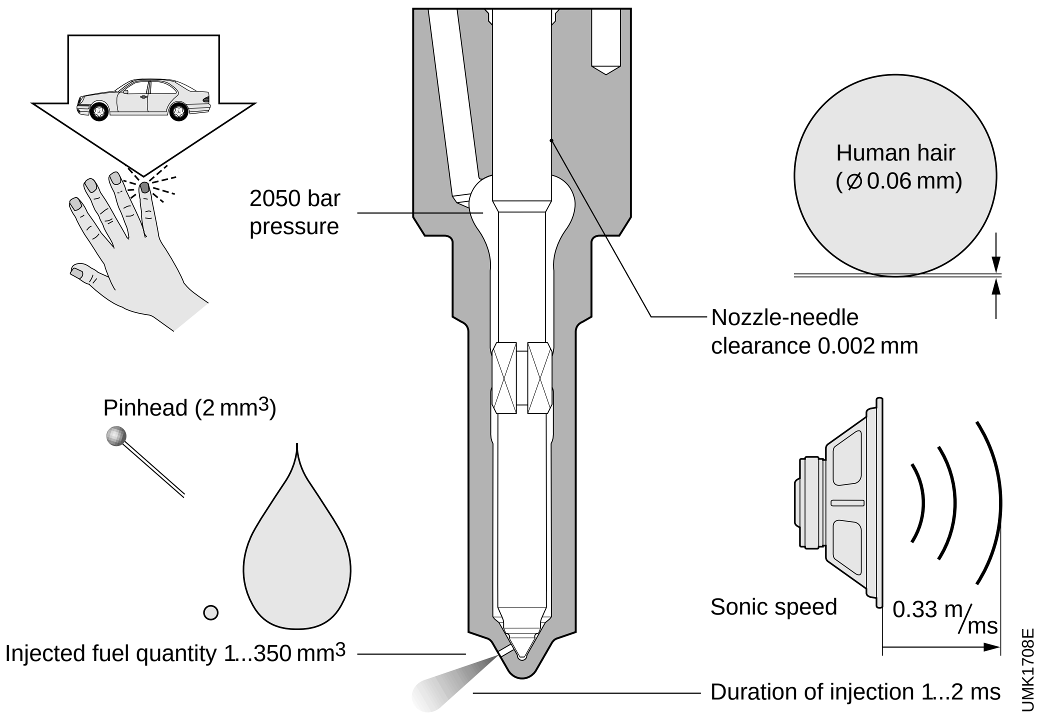
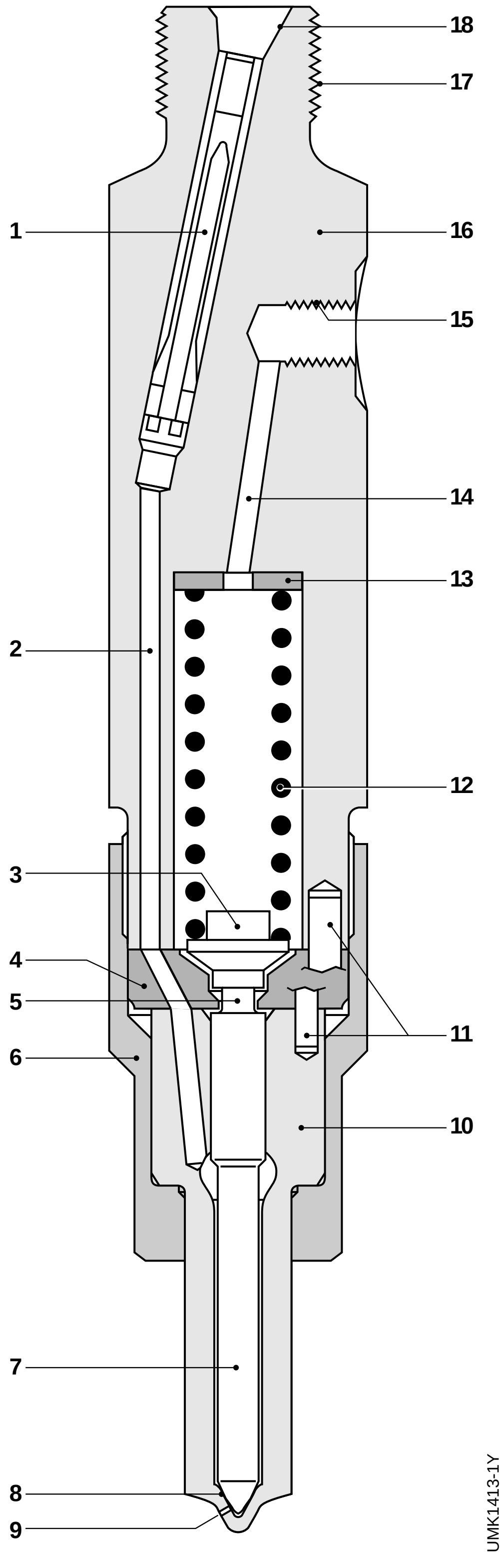


Fig. 1

Standard nozzle holder

1 Edge-type filter, **2** Inlet passage, **3** Pressure pin, **4** Intermediate element, **5** Pressure pintle, **6** Nozzle-retaining nut, **7** Nozzle needle, **8** Nozzle-body seat, **9** Injection orifice, **10** Nozzle body, **11** Locating pin, **12** Spring, **13** Shim, **14** Leak-fuel passage, **15** Leak-fuel connection thread, **16** Nozzle-holder body, **17** Connection thread for central pressure connection, **18** Sealing cone.



Nozzle holders

Nozzle holders can be combined with various nozzles. With regard to nozzle holders, one differentiates between

- Standard nozzle holders (single-spring nozzle holders), and
- Two-spring nozzle holders.

The stepped nozzle-holder version is particularly suitable for cramped installation conditions.

Nozzle holders are used both with and without needle-motion sensors.

The nozzle is an integral injector component in such injection systems as CR (Common Rail) and UIS (Unit Injector) and a nozzle holder is unnecessary.

Nozzle holders can be attached to the cylinder head by means of flanges, special clamps, male pipe fittings, and a screw-in thread in the cylinder head. The pressure connection is either in the center of the nozzle holder or at the side of it.

Standard nozzle holders

Application, design and construction

The standard nozzle holders described here have the following characteristics:

- Cylindrical shape with diameters of 17, 21, and 26 mm,
- Bottom-mounted springs (lead to low moving masses),
- Locked to prevent misalignment (for DI engines),
- Possibility of a variety of combinations due to standardized components (springs, pressure pins, nozzle-retaining nuts).

The nozzle-and-holder assembly is comprised of the nozzle itself and the nozzle holder (Fig. 1). The nozzle holder is assembled from the following components:

- Nozzle-holder body (16),
- Intermediate element (4),
- Nozzle-retaining nut (6),
- Pressure pin (3),

– Spring (12),
– Shim (13), and
– Locating pins (11).

The nozzle is centered in the nozzle body and fastened using the nozzle-retaining nut. When nozzle body and retaining nut are screwed together, the intermediate element is forced up against the sealing surfaces of the nozzle body and the retaining nut. The intermediate element serves as the needle-lift stop, and with its locating pins centers the nozzle in the nozzle-holder body.
The pressure pin centers the spring, whereby the pressure pin is guided by the nozzle needle's pressure pintle (5).
The nozzle is connected to the injection pump's high-pressure line via the nozzle-holder feed passage, the intermediate element, and the nozzle-body feed passage. If required, an edge-type filter can be installed in the nozzle holder to remove course contamination from the fuel.

Operating concept

The spring in the nozzle-holder body applies pressure to the nozzle needle through the pressure pin. The spring's initial tension defines the nozzle's opening pressure. This can be adjusted by a shim (changes the initial tension).
On its way to the nozzle seat (8), the fuel passes through the edge-type filter (1), the nozzle-holder inlet passage (2), the intermediate element (4), and the nozzle body (10). When injection takes place, the nozzle needle (7) is lifted by the injection pressure (approx. 110...140 bar for throttling pintle nozzles, and approx. 150...300 bar for hole-type nozzles), and fuel is injected through the injection orifices (9) into the combustion chamber. Injection terminates as soon as the injection pressure drops far enough for the nozzle spring (12) to force the nozzle needle back onto its seat. Start of injection is therefore controlled by the pressure, and the injected fuel quantity is essentially a function of the duration of injection.

Step-type nozzle holders

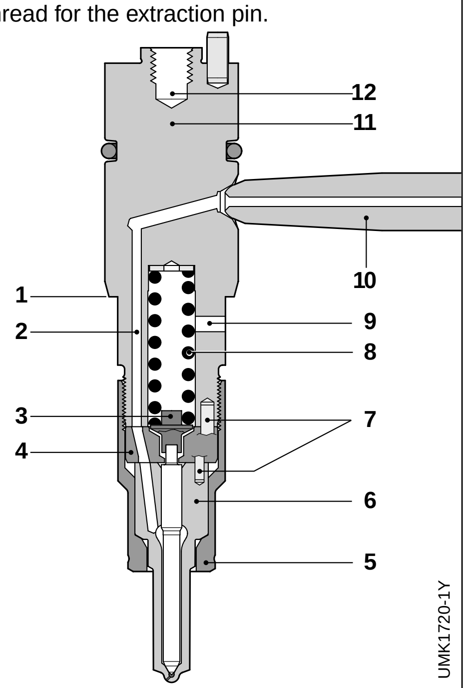
Application, design and construction

These nozzle holders are used particularly in 4-valves-per-cylinder commercial-vehicle diesel engines where lack of space means that the nozzle-holder combination must be installed vertically. The “step” designation comes from the nozzle holder's shape.
Design, construction, and operating concept correspond to the standard nozzle holder, the major difference being in the fuel-line connection: Whereas with the standard nozzle holder this is screwed in at the end opposite to the nozzle, on the step-type version, connection is through a pressure fitting. This usually permits very short lengths of fuel-injection tubing, a fact which due to reduced dead volume has a positive effect upon the injection pressure. Step-type nozzle holders are available with and without leak-fuel connection.

Fig. 2

Step-type nozzle holder

1 Step, **2** Inlet passage, **3** Pressure pin, **4** Shim, **5** Nozzle-retaining nut, **6** Nozzle body, **7** Locating pin, **8** Spring, **9** Leak-fuel passage, **10** Pressure fitting, **11** Nozzle-holder body, **12** Thread for the extraction pin.



Hole-type nozzles

Applications

Hole-type nozzles are used on direct-injection (DI) engines. The engine design is usually decisive for their installation position. The nozzle's spray holes are at various angles and must be correctly aligned to the combustion chamber (Fig. 1).
Hole-type nozzles are subdivided into
– Sac-hole, and
– Sac-less (vco) nozzles.

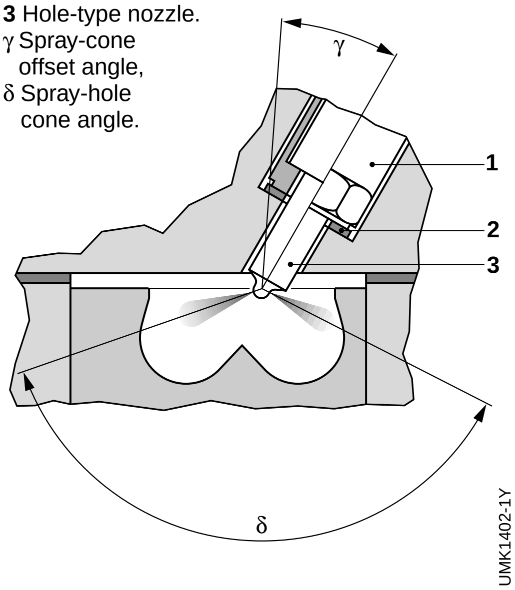
In addition, the nozzles also vary according to their size:
– Type P with 4 mm needle diameter (sac-hole and sac-less (vco) nozzles), or
– Type S with 5 and 6 mm needle diameters (sac-hole nozzles for large engines).

In the Unit Injector and Common Rail systems (UIS and CR respectively), the hole-type nozzles are integrated in the injectors so that these also assume the role of a nozzle-holder assembly.

Fig. 1

Position of the spray holes in the combustion chamber

1 Nozzle holder,
2 Gasket,
3 Hole-type nozzle.
γ Spray-cone offset angle,
δ Spray-hole cone angle.



Design and construction

The spray holes are located on the envelope of the nozzle cone (Fig. 3, Pos. 5). The number of spray holes and their diameter depend upon:
– The required injected fuel quantity,
– The combustion-chamber shape, and
– The air swirl in the combustion chamber.

The input edges of the spray holes can be rounded by hydro-erosive (HE) machining.
At those points where high flow rates occur (spray-hole entrance), the abrasive particles in the hydro-erosive medium cause material loss. This so-called HE-rounding process can be applied to both sac-hole and sac-less nozzles, whereby the target is:
– Prevent in advance the edge wear caused by abrasive particles in the fuel and/or
– Reduce the flow tolerance.

The nozzles must be carefully aligned to the conditions encountered in the particular engine.
Nozzle design also has a decisive effect upon:
– Precise metering of injected fuel (duration of injection and injected fuel quantity per degree crankshaft),
– Preparation of the fuel (number of spray jets, spray shape, atomization of the fuel jet),
– Distribution of the fuel in the combustion chamber,
– Sealing-off the combustion chamber to the outside.

Following combustion, the residual fuel trapped below the edge of the nozzle-needle seat (residual volume) vaporises and makes a considerable contribution to hydrocarbon emissions (HC). In order to reduce HC emissions, therefore, it is imperative that this residual volume is kept to a minimum. Sac-less (vco) nozzles are therefore best used here.

Versions

Sac-hole nozzles

The spray holes of the sac-hole nozzle (Figs. 2 and 3) are located around the sac hole.
In the case of a round nozzle tip, the spray holes are drilled mechanically or by means of electrical-discharge machining (EDM electrical particle removal).
Sac-hole nozzles with conical tip are always drilled using EDM.
Sac-hole nozzles are available with either a cylindrical or a conical sac hole in a variety of different dimensions.

Sac-hole nozzle with cylindrical sac hole and round tip (Fig. 3a): The tip comprises a cylindrical and a hemispherical section, and permits a high level of design freedom with repect to the number of spray holes, spray-hole length, and spray-hole cone angle. The nozzle tip is hemispherical, and together with the shape of the sac hole, ensures that the spray holes are of identical length.

Sac-hole nozzle with cylindrical sac hole and conical tip (Fig. 3b): This form of nozzle is used exclusively with spray-hole lengths of 0.6 mm. The tip's conical

Fig. 2

Sac-hole nozzle

1 Pressure pin, **2** Needle-lift stop face, **3** Inlet passage, **4** Pressure shoulder, **5** Needle shaft, **6** Nozzle cone, **7** Nozzle-body shaft, **8** Nozzle-body shoulder, **9** Pressure chamber, **10** Needle guide, **11** Nozzle-body collar, **12** Locating hole, **13** Sealing surface, **14** Pressure-pin contact surface.

δ Spray-hole cone angle, F_F Spring force, F_D The pressure on the pressure shoulder resulting from the fuel pressure.

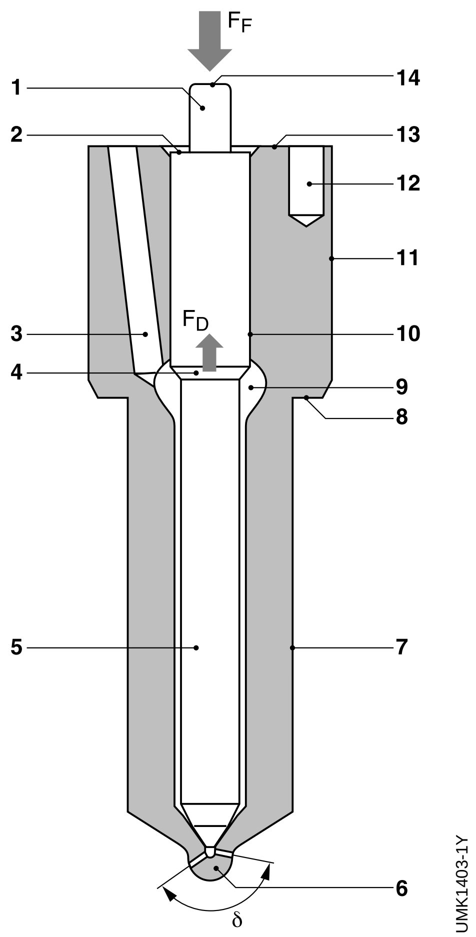
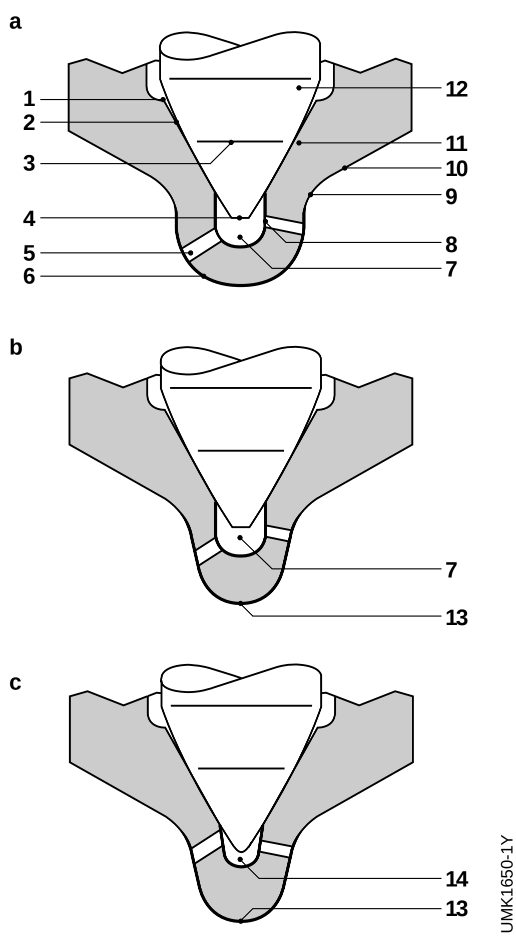


Fig. 3

Nozzle cones and sac-hole shapes

a Cylindrical sac hole and round tip,
b Cylindrical sac hole and conical tip,
c Conical sac hole and conical tip.

1 Shoulder, **2** Seat entrance, **3** Needle seat, **4** Needle tip, **5** Spray hole, **6** Round tip, **7** Cylindrical sac hole (residual volume), **8** Injection-orifice entrance, **9** Throat radius, **10** Nozzle-tip cone, **11** Nozzle-body seat, **12** Damping cone, **13** Conical tip, **14** Conical sac hole.



Tip shape of a sac-less vco nozzle

1 Tip shape, **2** Injection orifice, **3** Sac hole.

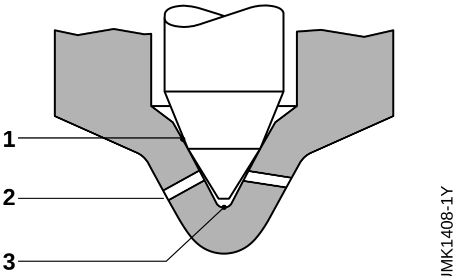
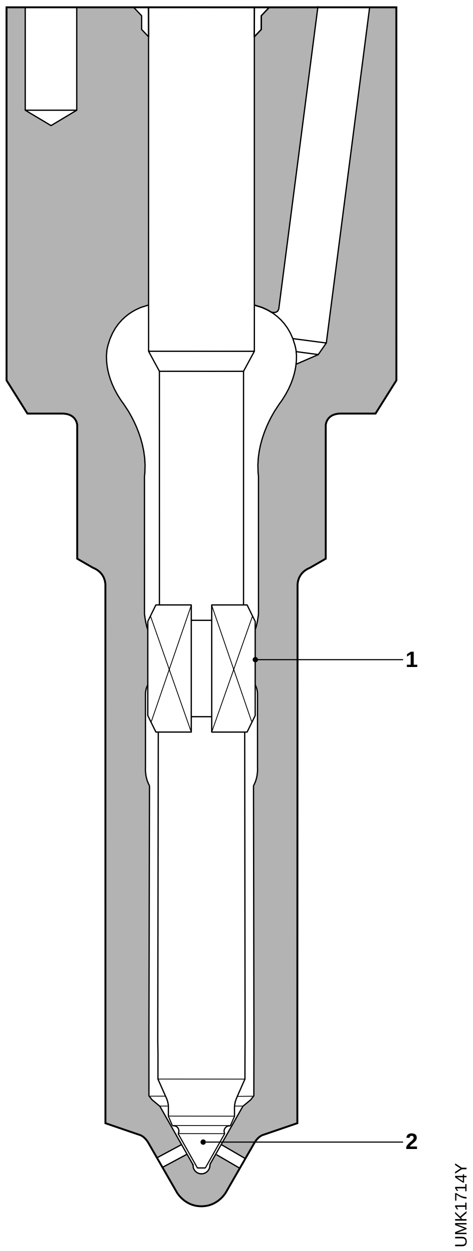


Fig. 4

Fig. 5

Example of a sac-less vco nozzle

1 Dual needle guide,
2 Complex needle-tip geometry.



shape enables the wall thickness to be increased between the throat radius (9) and the nozzle-body seat (11), thus resulting in higher nozzle-tip strength.

<u>Sac-hole nozzle with conical sac hole and conical tip</u> (Fig. 3c).This has a lower residual volume than the nozzle with cylindrical sac hole. The volume is between that for a sac-less (vco) nozzle and a sac-hole nozzle with cylindrical sac hole. In order to achieve uniform tip-wall thickness, the tip's conical design corresponds to that of the sac hole.

Sac-less (vco) nozzle

In order to minimise the residual volume – and therefore the HC emissions – the start of the spray hole is located in the seat taper, and with the nozzle closed it is covered almost completely by the nozzle needle. This means that there is no direct connection between the sac hole and the combustion chamber (Fig. 4). The residual volume here is much lower than in the sac-hole nozzle. Since sac-less vco nozzles have a much lower loading limit than sac-hole nozzles, they are only manufactured with a spray-hole length of 1 mm. For reasons of strength, the nozzle tip is conical, and the spray holes are always formed using electrical discharge machining (EDM) methods.

Special injection-orifice geometries are used together with a dual needle guide (Fig. 5, Pos. 1), or complex needle-tip geometry (Fig. 5, Pos. 2), to further improve spray dispersion and with it the mixture formation.

The maximum temperature limit for hole-type nozzles is in the region of 300 °C (thermostability of the material). For especially difficult applications, Bosch has thermal-protection sleeves available, and cooled injector sleeves for large engines.

Diesel fuel injection: High-precision technology

Ask average drivers about the diesel engine, and the majority of them will think you are talking about rough mechanical engineering and not about a piece of high-precision technology. High precision, because modern-day diesel-engine components are precision parts which are subjected to extreme loading.

The nozzle represents the interface between fuel-injection system and engine. Throughout the engine's complete service life, it must open and close with utmost precision. When closed, it must not permit leaks since these would increase the fuel-consumption figures as well as negatively affecting the exhaust-gas emissions. Leaks could even lead to engine damage.
Since the nozzles on such modern injection systems as the VR (VP 44), CR, UPS, and UIS must seal-off reliably at injection pressures up to 2050 bar, they must be specially designed and constructed with extreme precision. Here are a number of examples:
– In order that the nozzle body's sealing surface (1) seals reliably, a maximum form tolerance of 0.001 mm (1 µm) is stipulated. In other words, a manufacturing accuracy of approx. 4000 metal atoms.
– The play (2) between nozzle needle and nozzle body is 0.002...0.004 mm (2...4 µm). Thanks to microfinishing, form tolerances are better than 0.001 mm (1 µm).

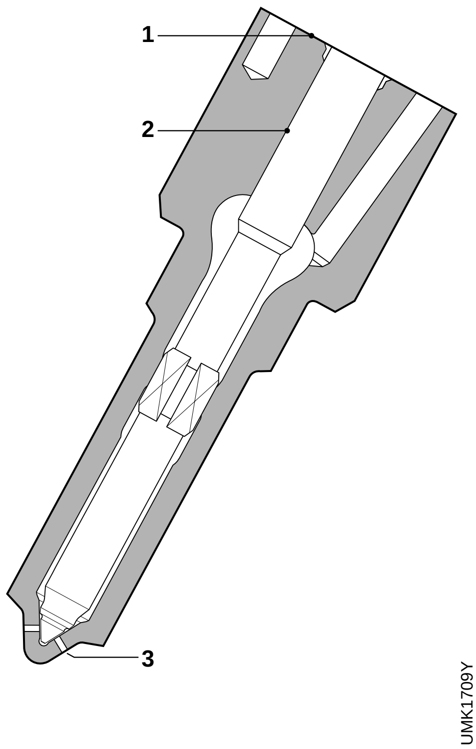
Electrical discharge machining (EDM) is used for producing the nozzle's very fine injection orifices (3). With this process, metal vaporises due to the high temperature resulting from spark discharge between electrode and workpiece. High-precision electrodes coupled with exactly adjusted parameters produce very fine 0.12 mm dia. orifices. The smallest diameter of the injection orifices is therefore only double that of a human hair (0.06 mm). The injection characteristic is improved by using flow grinding to round-off the inlet edges of the orifices with a special liquid (hydro-erosive machining).

Such extremely tight tolerances necessitate the use of special, high-precision measuring techniques, such as:
– Optical 3D coordinate gauging machine for measuring the injection orifices,
– Laser interferometry for measuring the nozzle sealing-surface evenness.

In other words, component manufacture for diesel fuel injection equates to “high-tech” in mass production.

Here's where precision is of decisive importance:

1 Nozzle-body sealing surface,
2 Play between nozzle needle and nozzle body,
3 Injection orifice.



Electronic diesel control (EDC)

Modern electronic diesel-engine control permits the precise and highly flexible definition of the fuel-injection parameters. This is the only way to comply with the wide range of technical demands made on a modern diesel engine. The Electronic Diesel Control (EDC) is subdivided into the three system blocks "Sensors and desired-value generators", "ECU", and "Actuators".

Technical requirements

The calls for reduced fuel consumption and emissions, together with increased power output and torque, are the decisive factors behind present-day developments in the diesel fuel-injection field. In the past years this has led to an increase in the use of direct-injection (DI) diesel engines. Compared to prechamber or whirl-chamber engines, the so-called indirect-injection (IDI) engines, the DI engine operates with far higher injection pressures. This leads to improved A/F mixture formation, combustion of the more finely atomized fuel droplets is more complete, and there are less unburnt hydrocarbons (HC) in the exhaust gas. In the DI engine, the improved mixture formation and the fact that there are no overflow losses between pre-chamber/whirl chamber and the main combustion chamber results in fuel-consumption savings of between 10...15 % compared to the IDI engine.
In addition, the increasing requirements regarding vehicle driveability have a marked effect on the demands made on modern engines, and these are subject to increasingly more severe requirements with regard to exhaust-gas and noise emissions (NO_X, CO, HC, particulates). This has led to higher demands being made on the injection system and its control with respect to:

- High injection pressures,
- Structured rate-of-discharge curve,
- Variable start of injection,
- Pilot injection and possibly secondary injection,
- Adaptation of injected fuel quantity, boost pressure, and start of injection to the given operating state,
- Temperature-dependent start quantity,
- Load-independent idle-speed control,
- Cruise control,
- Closed-loop-controlled exhaust-gas recirculation (EGR), and
- Tighter tolerances for injected fuel quantity and injection point, together with high accuracy to be maintained throughout the vehicle's useful life.

Conventional mechanical (flyweight) governors use a number of add-on devices to register the various operating conditions, and ensure that mixture formation is of high standard. Such governors, though, are restricted to simple open-loop control operations at the engine, and there are many important actuating variables which they cannot register at all or not quickly enough.
The increasingly severe demands it was subjected to, meant that the EDC developed from a simple system with electrically triggered actuator shaft to become a complex engine management unit capable of carrying out real-time processing of a wide variety of data.

System overview

In the past years, the marked increase in the computing power of the microcontrollers available on the market has made it possible for the EDC (Electronic Diesel Control) to comply with the above-named stipulations.
In contrast to diesel-engine vehicles with conventional in-line or distributor injection pumps, the driver of an EDC-controlled vehicle has no direct influence, for instance through the accelerator pedal and Bowden cable, upon the injected fuel quantity. On the contrary, the injected fuel quantity is defined by a variety of actuating variables, for instance:
- Driver input (accelerator-pedal setting),
- Operating state,
- Engine temperature,
- Effects on toxic emissions etc.

Using these influencing variables, the ECU not only calculates the injected fuel quantity, but can also vary the instant of injection. This of course means that an extensive safety concept must be implemented that detects deviations and, depending upon their severity, initiates appropriate countermeasures (e.g. limitation of torque, or emergency (limp-home) running in the idle-speed range). EDC therefore incorporates a number of closed control loops.
EDC also permits the exchange of data with other electronic systems in the vehicle, e.g. with the traction control system (TCS), the electronic transmission-shift control, or with the electronic stability program (ESP). This means that engine management can be integrated in the overall vehicle system (e.g. for engine-torque reduction when shifting gear with an automatic gearbox, adaptation of engine torque to wheel slip, release signal for fuel injection from the vehicle immobilizer, etc.).
The EDC system is fully integrated in the vehicle's diagnostics system. It complies with all OBD (On-Board Diagnostics) and EOBD (European On-Board Diagnostics) stipulations.

System blocks

The EDC system comprises three system blocks:

1. Sensors and desired-value generators for the detection of operating conditions and the generation of desired values. These convert the various physical quantities into electrical signals.

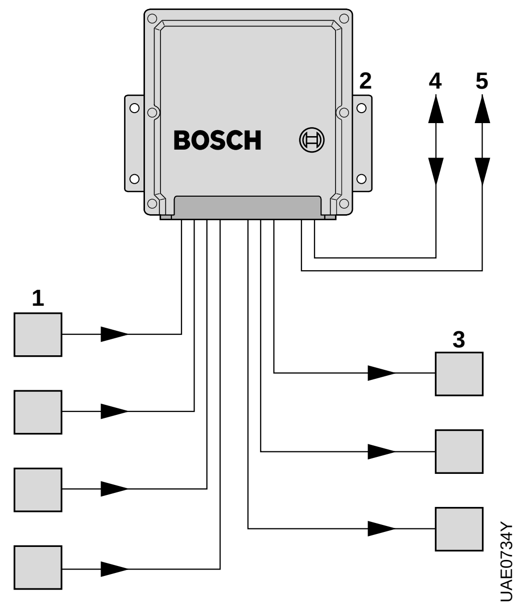
2. Electronic control unit (ECU) processes the information from the sensors and the desired-value generators in accordance with given computational processes (control algorithms). The ECU triggers the actuators with its electrical output signals and also sets up the interfaces to other systems in the vehicle and to the vehicle diagnosis facility.

3. Solenoid actuators convert the ECU's electrical output signals into mechanical quantities (e.g. for the solenoid valve which controls the injection, or for the solenoid of the actuator mechanism).

Fig. 1

Major EDC components

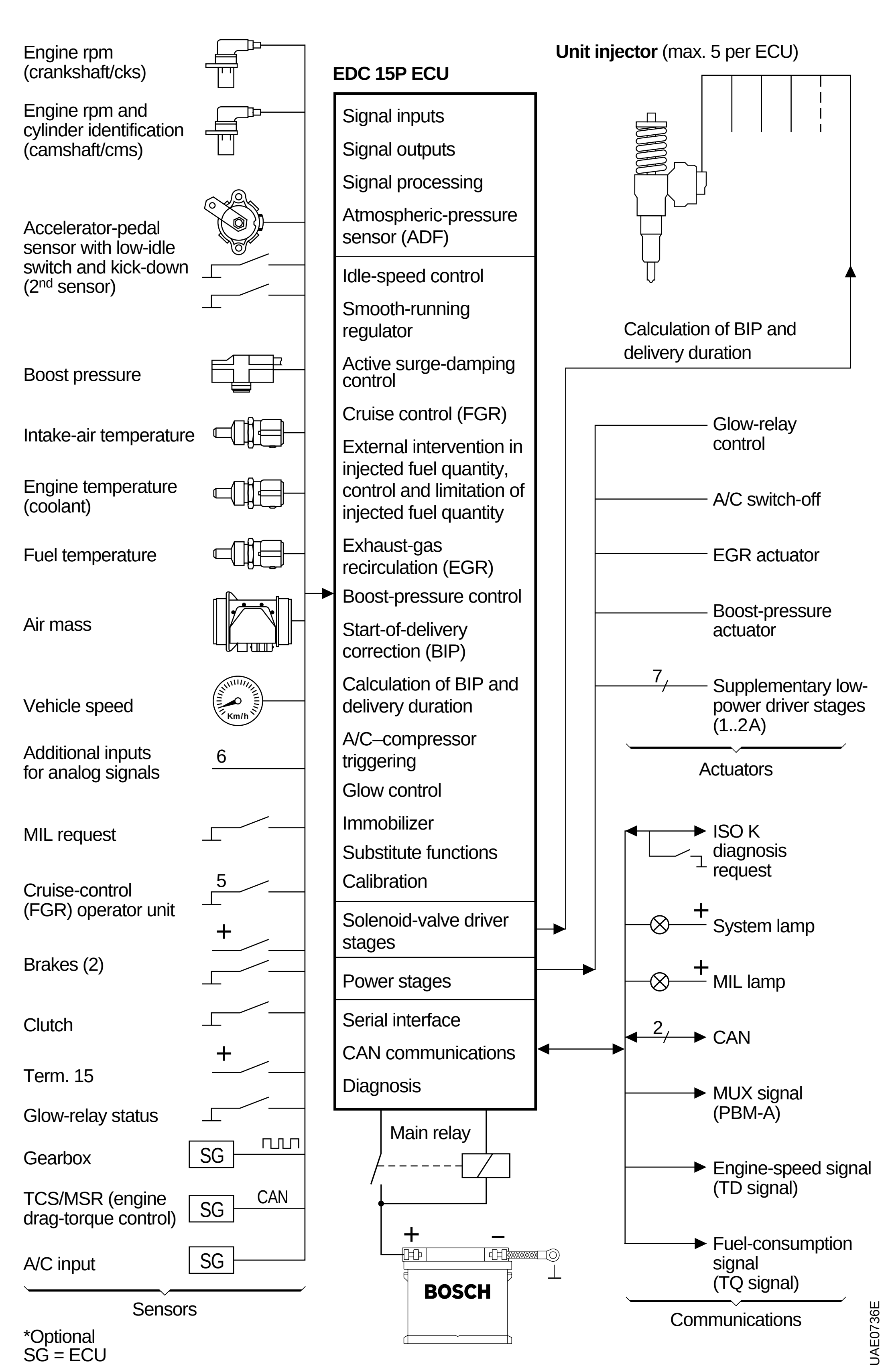
1 Sensors and desired-value generators, **2** ECU, **3** Actuators, **4** Interface to other systems, **5** Diagnosis interface.



UIS for passenger cars

Fig. 1

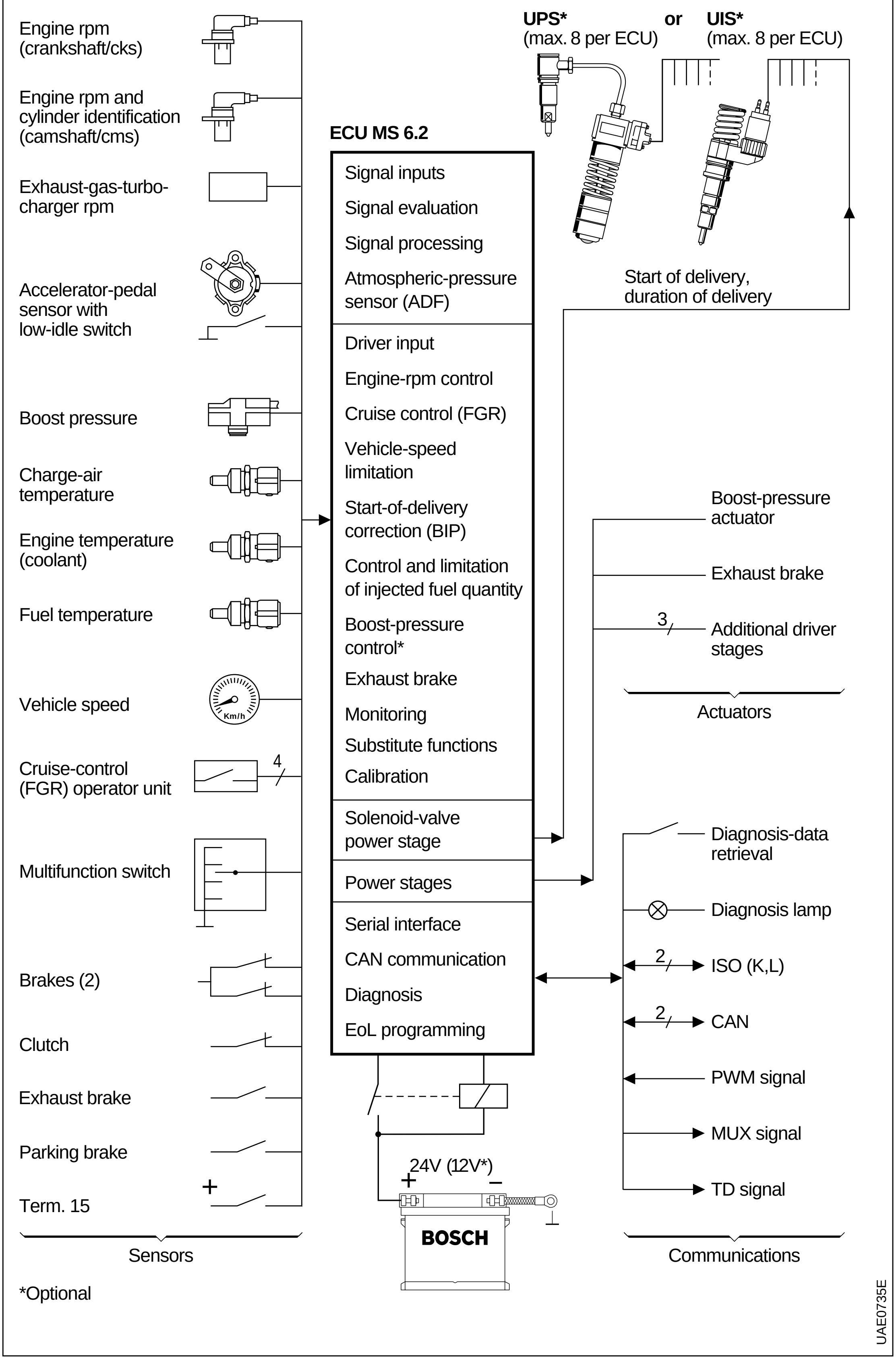
EDC overview for passenger-car unit injector systems (UIS)



UIS and UPS for commercial vehicles

Fig. 2

EDC overview for commercial-vehicle unit injector systems (UIS) and unit pump systems (UPS)



*Optional

Sensors

Sensors and desired-value generators register the operating states (e.g. engine speed) and setpoint values (e.g. accelerator-pedal position). They convert physical quantities into electric signals. Without high-precision, fast-acting sensors, the multitude of closed and open-loop controls in a modern vehicle would be unthinkable.

Automotive applications

Sensors and actuators represent the interfaces between the ECU's, as the processing units, and the vehicle with its complex drive, braking, chassis, and bodywork functions (the Electronic Stability Program ESP, and the air conditioner for example). As a rule, a matching or interface circuit in the sensor converts the signals so that they can be processed by the ECU.

Since they are hidden away in the depths of the engine compartment or somewhere else in the vehicle, sensors for the most part lead a somewhat secluded life. Apart from this, the fact that they are continually getting smaller means that they are becoming even less conspicuous. Furthermore, the trend today is to “hide” such sensors in modules so that the module's technical value is increased, and the overall costs reduced as a result. Good examples of such modules are the accelerator-pedal module with integral pedal-travel sensor, crankshaft CSWS (Composite Seal with Sensor) module complete with rotational-speed sensor, and the intake-air module with hot-film air-mass meter.

On the other hand, sensors must comply with increasing demands regarding costs and function. Being as sensor output signals directly influence the engine's power output and torque, together with its emissions, driveability, and safety and security, the call is that they become increasingly more precise.

Compliance with these tight tolerances demands that future sensors be “intelligent”. That is, the sensor electronics will incorporate evaluation algorithms (computational processes), sophisticated alignment functions, and self-calibration functions where possible.

EDC sensors

The following paragraphs deal with the sensors applied today for diesel-engine management.

The future though will see the integration of new sensors in the system. These will assist in

- Complying with the continuously more severe emissions-control legislation, and
- Providing the continuously operating diagnosis system (OBD = On-Board Diagnostics) with information.

These sensors will be exhaust-gas sensors and will include not only the already familiar Lambda oxygen sensor as used with the gasoline engine, but also exhaust-gas-pressure and exhaust-gas-temperature sensors.

PTC and NTC temperature sensors

Applications

Such temperature sensors are installed at a variety of different positions on the vehicle:

Engine-temperature sensor
This is incorporated in the coolant circuit and measures the coolant temperature as a measure of engine temperature (Fig. 1). This information enables the engine management to adapt itself precisely to the engine's operating temperature. The measurable temperature range is –40 ... +130 °C.

Air-temperature sensor
This is installed in the engine's intake tract and measures the temperature of the intake air. In coordination with a boost-pressure sensor, this intake-air temperature can be used to precisely measure the mass of the air drawn into the engine. Apart from this, the setpoint values for closed control loops (e.g. EGR, boost-pressure control) can be adapted as a function of the air temperature. The measurable temperature range is –40 ... +120 °C.

Engine-oil temperature sensor
The signal from the engine-oil temperature sensor is used when determining the service interval. The measurable temperature range is –40 ... +170 °C.

Fuel-temperature sensor
This sensor is in the low-pressure stage. Fuel temperature is an important factor in precisely defining the injected fuel quantity. Measurable temperature range: –40 ... +120 °C.

Design and operating concept

Depending upon the application, temperature sensors are available in a variety of different shapes and versions. There is a temperature-dependent measuring resistor inside the sensor housing. It is either of the NTC (Negative Temperature Coefficient) or PTC (Positive Temperature Coefficient) type. With increasing temperature, its electrical resistance decreases (NTC) or increases (PTC). The measuring resistor is in a voltage-distributor circuit across which 5 V is applied, and the voltage measured across it is therefore temperature-dependent. This is inputted to the ECU through an A/D converter and is a measure for the temperature at the sensor. The engine ECU has a characteristic which allocates a specific temperature to each voltage value (Fig. 2).

Fig. 1

Engine-temperature sensor

1 Seal ring, **2** Sensor thread,
3 Electrical connections, **4** Housing,
5 Measuring resistor, **6** Coolant.

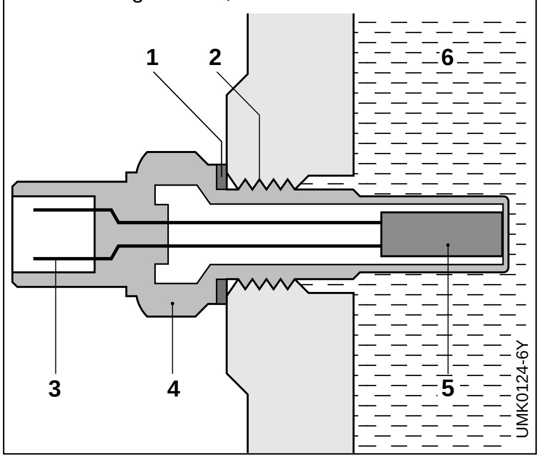
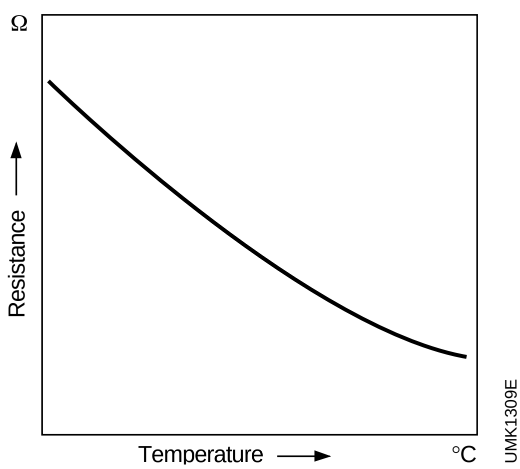


Fig. 2

Characteristic curve of an NTC resistor



Micromechanical pressure sensors

Applications

Intake-manifold sensor and/or boost-pressure sensor

Usually, the boost-pressure sensor is mounted directly on the manifold between the supercharger and the engine. It measures the absolute pressure in the intake manifold (2...400 kPa or 0.02...4.0 bar). Actual measurement is referred to a reference vacuum and not to the surrounding pressure. This permits precise measurement of the air mass so that the supercharger can be controlled in accordance with engine requirements.
When the sensor is not mounted directly on the intake manifold, it is connected to it by a hose.

Atmospheric-pressure sensor

The atmospheric-pressure sensor can be installed in the ECU or at another location in the engine compartment. Its signal is used for altitude-dependent correction of the setpoint values for the closed control loops (for instance for the EGR and the boost-pressure control). This permits compensation of the differences in atmospheric pressure encountered at different altitudes. The atmospheric-pressure sensor measures the absolute pressure (60...115 kPa, 0.6...1.15 bar).

Oil-pressure and fuel-pressure sensors

There are oil-pressure sensors installed in the oil filter for measuring the absolute oil pressure. This information is applied for determining engine loading as required for the Service Display. The sensor's pressure range is 50...1000 kPa (0.5...10.0 bar).
The sensor cell's high resistance to the measured medium means that it can also be used for the fuel-pressure measurement in the low-pressure stage. The sensor is fitted either in the fuel filter or on it, and its signal is used to monitor the degree of fuel contamination (measuring range 20...4000 kPa or 0.2...40 bar).

Design and construction

A sensor element is the heart of the micromechanical pressure sensor (Fig. 2) together with the sensor cell (Fig. 1). This is comprised of a micromechanical silicon chip (2) into which a thin diaphragm (1) has been etched. Four measuring resistors (R_1, R_2), whose electrical resistances change when mechanical pressure is applied, are arranged on the diaphragm.
A temperature sensor can also be integrated in the pressure sensor (Fig. 4, Pos. 1), whose signal can be evaluated

Fig. 1

Sensor cell of the DS-LDF4 micromechanical pressure sensor (schematic diagram)

1 Diaphragm, **2** Silicon chip, **3** Reference vacuum, **4** Glass (Pyrex), **5** Wheatstone bridge.
p Pressure, U_0 Supply voltage, U_A Measurement voltage, Measuring resistors R_1 (compressed) and R_2 (stretched).

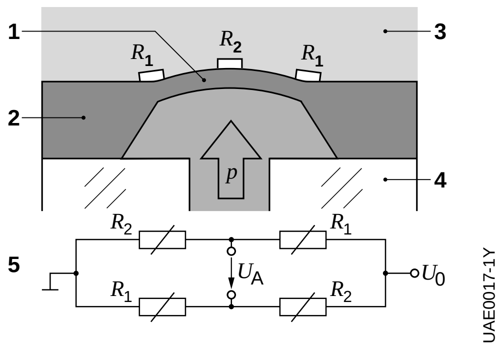
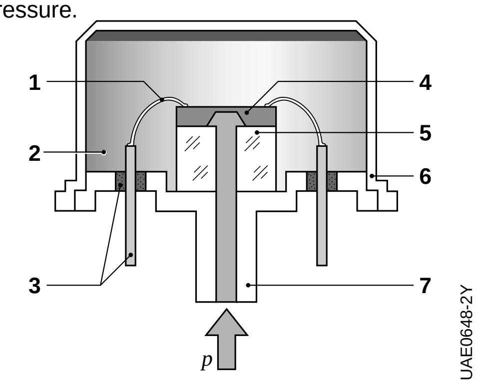


Fig. 2

Sensor element of the DS-LDF4 micromechanical pressure sensor (construction)

1 Electrical connections, **2** Reference vacuum, **3** Glass-encapsulated electrical lead-in, **4** Sensor cell (chip) with evaluation electronics, **5** Glass base, **6** Cap, **7** Pressure connection.
p Pressure.



separately. This has the advantage that only a single sensor need be installed when both temperature and pressure are to be measured.

Operating concept

The sensor-cell diaphragm bends by several µm as a function of the applied pressure. The resulting mechanical tension causes the four measuring resistors on the diaphragm to change their resistance (piezoresistive effect).
These measuring resistors are arranged on the diaphragm so that when the diaphragm deforms (due to pressure application), the electrical resistance of two of the resistors increases, and that of the other two decreases. Since the resistors are part of a Wheatstone bridge (Fig. 1, Pos. 5), when the resistance values change so does the voltage ratio across the measuring resistors, and with it the measurement voltage U_A which thus becomes a measure of the pressure applied to the diaphragm.
Using a bridge circuit enables a higher measurement voltage to be generated than would be possible with a single resistor. The Wheatstone bridge, therefore, permits a higher level of sensitivity.
The side of the diaphragm to which no pressure is applied is subjected to a reference vacuum (Fig. 2, Pos. 2) with the result that the sensor measures absolute pressure.
The complete evaluation electronics is integrated on the chip and has the job of amplifying the bridge voltage, compensating for temperature fluctuations, and linearizing the pressure curve. Output voltage is 0...5 V and via the sensor's electrical plug-in connection (Fig. 4, Pos. 5) is inputted to the ECU where the pressure is calculated by means of a programmed characteristic curve.

DS-LDF4 micromechanical boost-pressure sensor (construction)

1 Temperature sensor (NTC), **2** Housing base, **3** Intake manifold, **4** O-ring, **5** Electrical connection, **6** Housing cover, **7** Sensor element.

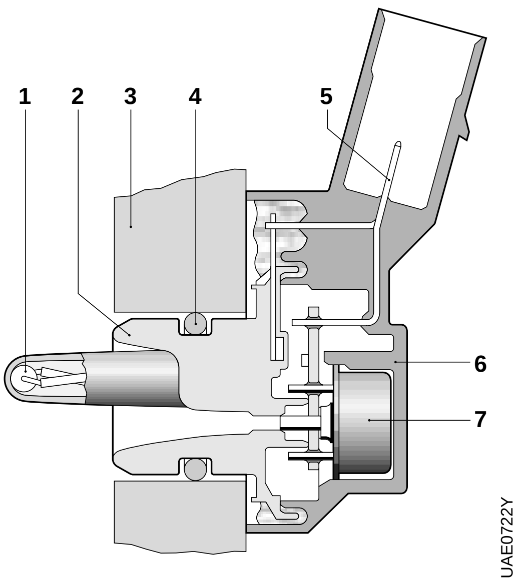


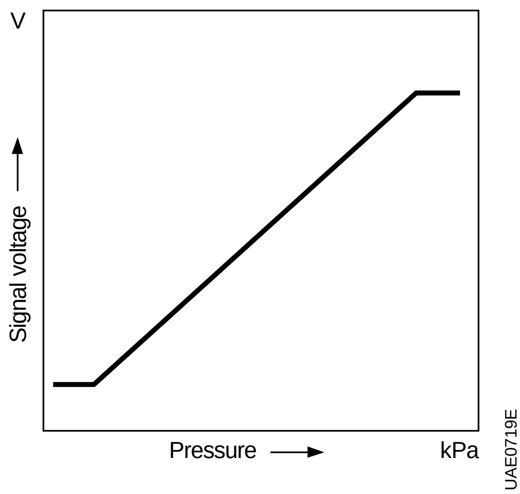
Fig. 4

Fig. 3

Sensor element of the DS-LDF4 micromechanical boost-pressure sensor

Fig. 5

Characteristic curve of a micromechanical boost-pressure sensor



Inductive rotational-speed sensors and angle-of-rotation sensors

Applications

Rotational-speed sensors are used for determining:
- Crankshaft position (for the position of the engine pistons), and
- Plunger position in solenoid-valve-controlled distributor injection pumps.

The rotational speed is calculated from the sensor's signal frequency. The output signal from the rotational-speed sensor is one of the most important quantities in electronic engine management.

Design and operating concept

The sensor is mounted directly opposite a ferromagnetic trigger wheel from which it is separated by a narrow air gap (Fig. 1). It contains a soft-iron core (pole pin) (4), which is enclosed by the solenoid winding (5). The pole pin is also connected to a permanent magnet (1), and a magnetic field extends through the pole pin and into the trigger wheel (8). The level of the magnetic flux through the winding depends upon whether the sensor is opposite a trigger-wheel tooth or gap. Whereas the magnet's stray flux is concentrated by a tooth and leads to an increase in the working flux through the winding, it is weakened by a gap. When the trigger wheel rotates therefore, this causes a fluctuation of the flux which in turn generates a sinusoidal voltage in the solenoid winding which is proportional to the rate of change of the flux. The amplitude of the AC voltage increases strongly along with increasing trigger-wheel speed. It is adequate as from about 30 rpm.
The number of teeth on the trigger wheel depends upon the particular application. On modern engine-management systems, a 60-pitch trigger wheel is normally used, although 2 teeth are omitted (8) so that the trigger wheel has 60 – 2 = 58 teeth. The extended tooth gap (Fig. 1, Pos. 8) is allocated to a defined crankshaft position and serves as a reference mark for synchronizing the ECU. The geometries of the trigger-wheel teeth and the pole pin must be matched to each other. The evaluation electronics circuitry in the ECU converts the sinusoidal voltage, which is characterized by strongly varying amplitudes, into a constant-amplitude square-wave voltage for evaluation in the ECU microcontroller.

Fig. 1

Inductive rotational-speed sensor

1 Permanent magnet, **2** Housing, **3** Engine block, **4** Soft-iron core, **5** Solenoid winding, **6** Air gap, **7** Magnetic field, **8** Trigger wheel with reference-mark gap.

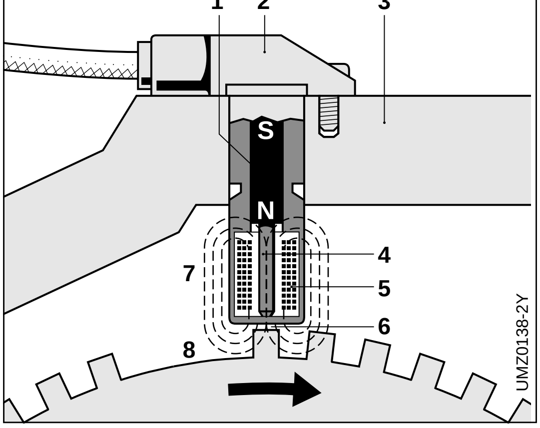
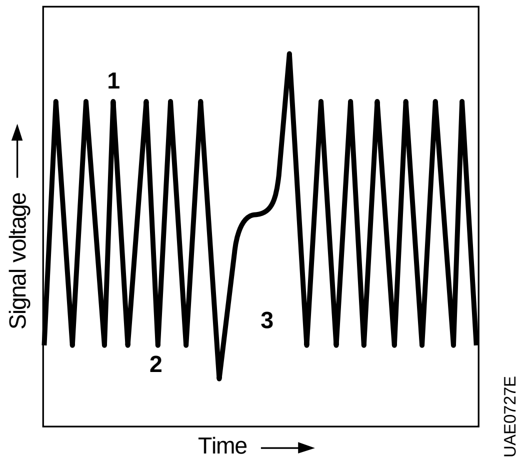


Fig. 2

Signal from an inductive rotational-speed sensor

1 Tooth, **2** Tooth gap, **3** Reference-mark.



Hall phase sensors

Application

If a given engine piston is moving in the direction of TDC, the camshaft position defines whether it is in the compression or exhaust stroke. The phase sensor on the camshaft provides the ECU with this information.

Design and operating concept

The phase sensor utilises the Hall effect. There are ferromagnetic teeth on the camshaft, and when one of these teeth passes the phase sensor's current-carrying sensor element (chip), its magnetic field realigns the chip's electrons so that they are vertical to the direction of current flow (Fig. 1). This results in a voltage signal (Hall voltage) which provides the ECU with information on the cylinder 1 working cycle. The sensor's output voltage is in the millivolt range and is independent of the relative speed between trigger wheel and sensor. Before being outputted it is conditioned by the evaluation electronics integrated in the sensor.

Differential Hall principle
In addition to the conventional Hall sensors, use is also made of so-called differential Hall elements. These are comprised of two Hall elements which are spatially offset from each other, and provide an output signal which is proportional to the difference in flux density between the measuring points. The advantages of differential evaluation lie in the larger air-gap range and in its good temperature-compensation qualities. One disadvantage that must be taken into account with this Hall sensor though is the increased accuracy with regard to its installation point, and the need for a dual-track trigger wheel for the generation of a signal in each Hall sensor.

Hall rod-type sensor
Here, the Hall element is located directly on the pole of a permanent magnet. When a ferromagnetic mass passes by, the magnetic flux through the Hall element changes, and with it the sensor voltage.

Digital output
A digital sensor-output signal is also possible.

Fig. 1

Hall sensor element: Circuit

U_H Hall voltage,
U_R Applied longitudinal voltage,
B Magnetic induction,
α Deflection of the electrons by the magnetic field.

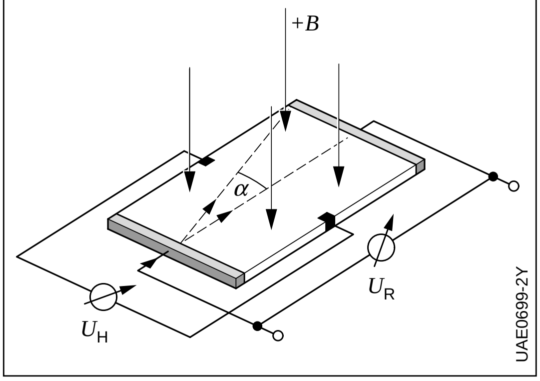
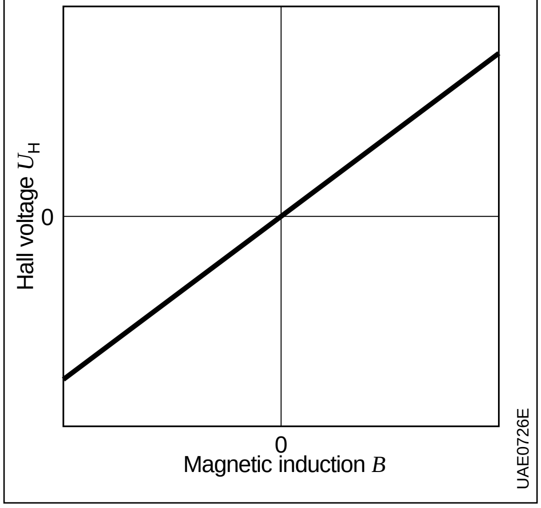


Fig. 2

Hall sensor element: Characteristic curve

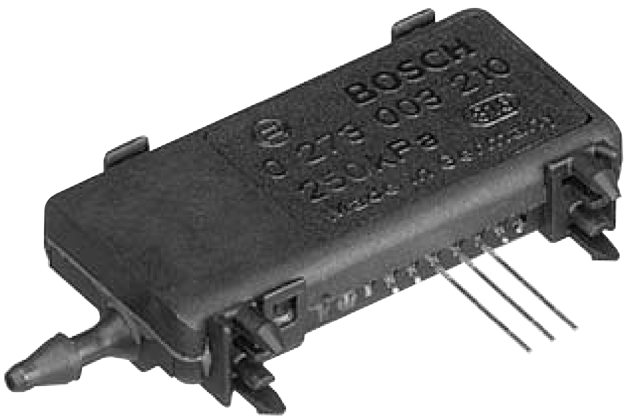


Integrated sensors

Due to the advances in modern microtechnology, sensors are not only becoming smaller and smaller, but also faster and more precise. Depending upon the level of integration, the signal conditioning, the A/D conversion, and even a small microcomputer for further signal processing will in future be directly integrated in the sensor itself. This will have the following advantages:

– Less computing power is needed in the ECU,
– A uniform, flexible, bus-compatible interface permits the use of a variety of different sensors,
– A given sensor can be used by several ECU's via the data bus,
– Small measuring effects (e.g. the piezo effect) can be registered (local amplification),
– Simple calibration is possible.

Atmospheric-pressure sensor 1996



Atmospheric-pressure sensor 1999

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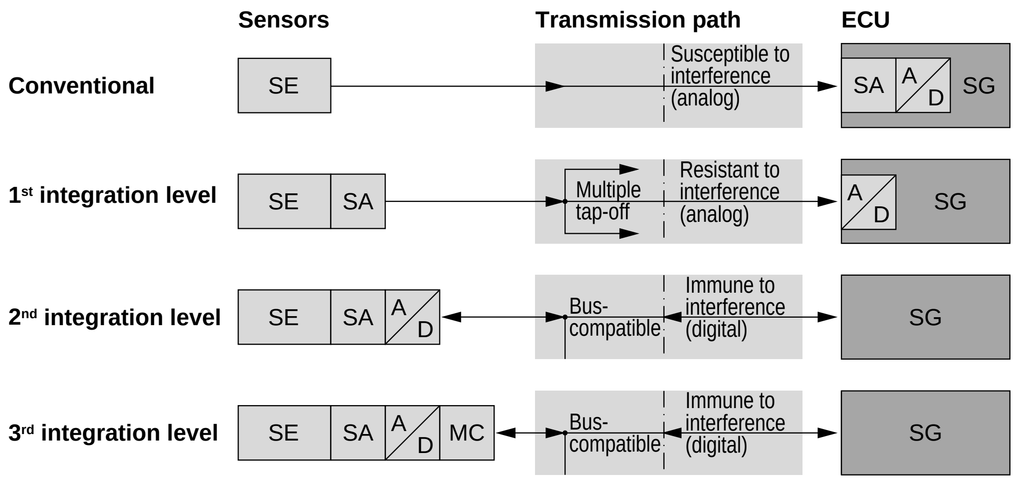
Sensor integration levels

SE Sensor(s), **SA** Analog signal conditioning, **A/D** Analog-digital converter, **SG** Digital ECU, **MC** Microcomputer (evaluation electronics).



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Accelerator-pedal sensors

Application

With modern electronic engine-management systems, the driver's wishes (e.g. for acceleration, or constant speed) are not transmitted to the engine management by Bowden cable or mechanical linkage. Instead, an accelerator-pedal sensor (also known as a pedal-travel sensor PWG) registers the accelerator-pedal setting and transmits this to the ECU.

Design and operation

The heart of the accelerator-pedal sensor is a potentiometer across which there is a voltage which is a function of the accelerator-pedal setting. In the ECU, a programmed characteristic curve is used to calculate the pedal position from this voltage. A second (redundant) sensor is used for diagnosis purposes and if necessary for implementating equivalent functions. There are two different versions:

Low-idle and kick-down switch
Even for very small pedal movements, the low-idle switch changes its status from the "idle-speed range signal" to the "full-load range signal". In the case of automatic-gearbox vehicles, a second switch can generate a kick-down signal.

Second potentiometer
At all operating points, a second, redundant, potentiometer is used to provide half the voltage of the first potentiometer ("Dual potentiometer factor 2") (Fig. 2).

Accelerator-pedal sensors are installed either as individual sensors (Fig. 1a), or as a complete module (Fig. 1, b and c), whereby here no adjustments are needed between pedal setting and sensor.

Characteristic curve of an accelerator-pedal sensor with redundant potentiometer

1 Potentiometer 1 (master potentiometer),
2 Potentiometer 2 (50 % of voltage).

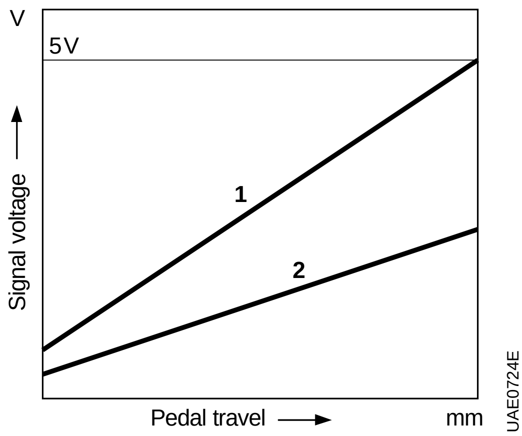
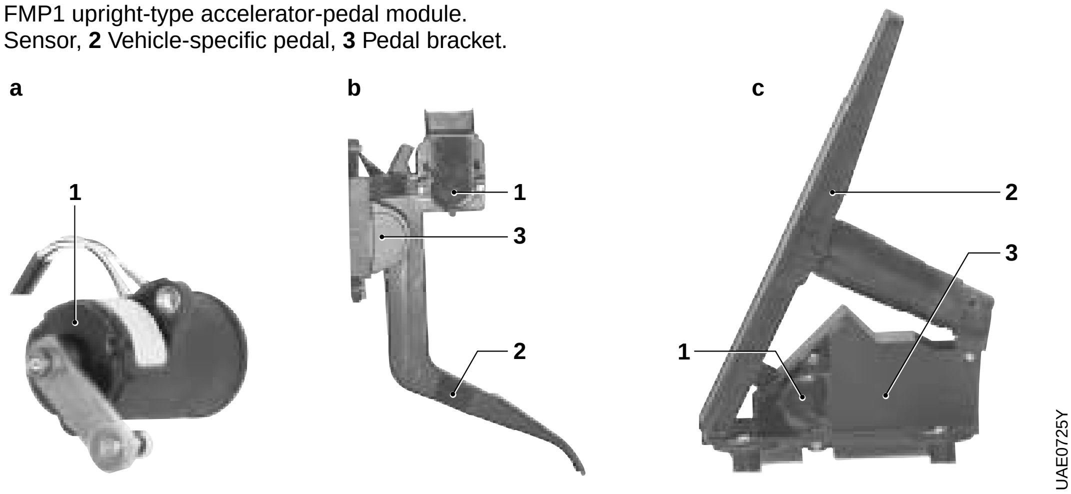


Fig. 2

Fig. 1

Acelerator-pedal-sensor versions

a PWG3 accelerator-pedal sensor, **b** FMP1 pendant-type accelerator-pedal module,
c FMP1 upright-type accelerator-pedal module.
1 Sensor, **2** Vehicle-specific pedal, **3** Pedal bracket.



Hot-film air-mass meter HFM5

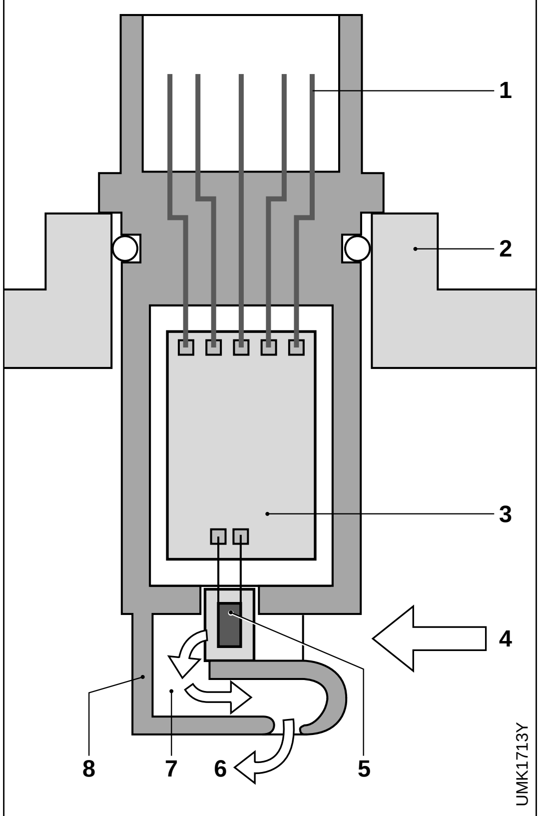
Application

In order to comply with the emission regulations imposed by legislation, it is imperative that precisely the necessary air mass is inducted for the engine's operating state. Particularly on passenger cars, this requires a sensor which precisely measures the air mass flow actually drawn in by the engine. This high accuracy necessitates the detection of the pulsation and the return flows resulting from the opening and closing of the intake and exhaust valves. The meter's measuring accuracy must also remain unaffected by changes in the intake-air temperature. These stipulations are all fulfilled by the HFM5 hot-film air-mass meter.

Fig. 1

HFM5 hot-film air-mass meter (schematic)

1 Electrical plug-in connection, **2** Measuring tube or air-filter housing, **3** Evaluation electronics (hybrid circuit), **4** Air inlet, **5** Sensor element, **6** Air outlet, **7** Bypass passage, **8** Sensor housing.



Design and construction

A measuring tube is integrated in the HFM5 hot-film air-mass meter (Fig. 1, Pos. 2) which, depending upon the engine's air-mass requirements, features different diameters (for 370...970 kg/h). It is installed in the intake tract downstream from the air filter. Plug-in versions are also available which are installed inside the air filter.
The incoming air in the intake manifold flows across a sensor element (5) which, together with the integrated evaluation electronics (3), forms the heart of the HFM5. Vapor-deposition is used to apply the sensor-element components to a semiconductor substrate, and the evaluation-electronics components to a ceramic substrate. This principle permits a very compact design. The incoming air flows through a bypass passage (7) and past the sensor element. Sensor response during strongly pulsating input flow can be improved by appropriate design of the bypass passage. Return flows are also detected. The HFM5 is connected to the ECU through electrical connections (1).

Operating concept

The hot-film air-mass meter is a “thermal sensor” and operates according to the following principle:
A micromechanical sensor diaphragm (Fig. 3, Pos. 5) on the sensor element (3) is heated by a central heating resistor. The temperature drops sharply on each side of the heating zone (4).
The temperature distribution on the diaphragm is registered by two temperature-dependent resistors which are attached upstream and downstream of the heating resistor so as to be symmetrical to it (measuring points M_1, M_2). Without the flow of incoming air, the temperature characteristic (1) is the same on each side of the heating zone.
As soon as air flows over the sensor

element, the temperature distribution at the diaphragm changes (2). On the intake side, the temperature characteristic is steeper since the incoming air flowing past this area cools it off. Initially, on the opposite side (the side nearest to the engine), the sensor element cools off. The air heated by the heater element then heats up the sensor element. The change in temperature distribution (ΔT) leads to a temperature differential between the measuring points M_1 and M_2.
The heat dissipated to the air, and therefore the temperature characteristic at the sensor element is a function of the air mass flow. The temperature differential is a measure of the air mass flow, and is independent of the absolute temperature of the air flowing past. Apart from this, the temperature differential is directional, which means that the air-mass meter not only registers the mass of the incoming air but also its direction.
Due to its very thin micromechanical diaphragm, the sensor features a highly dynamic response (<15 ms), a point which is of particular importance when the incoming air is fluctuating heavily.
The resistance differential at the measuring points M_1 and M_2 is converted into an analog signal of 0...5 V by the evaluation electronics (hybrid circuit) integrated in the sensor. This voltage level is suitable for processing by the ECU. Using the sensor characteristic (Fig. 2) programmed into the ECU, the measured voltage is converted into a value representing the air mass flow [kg/h]. The shape of the characteristic curve is such that the diagnosis facility incorporated in the ECU can detect such malfunctions as an open-circuit line.
A temperature sensor for auxiliary functions can also be integrated in the HFM5. It is located in the plastic housing and is not required for measuring the air mass.

HFM5 signal voltage as a function of the air mass flowing past it

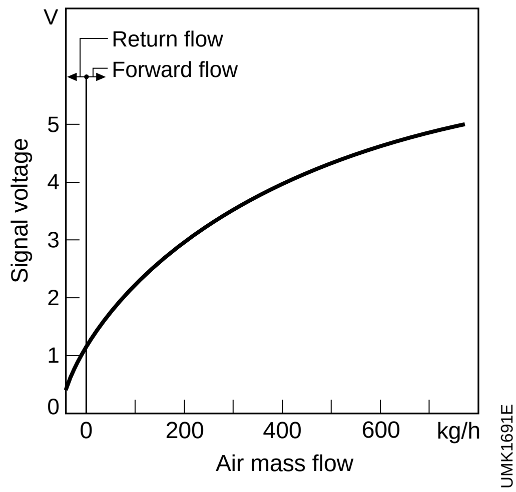
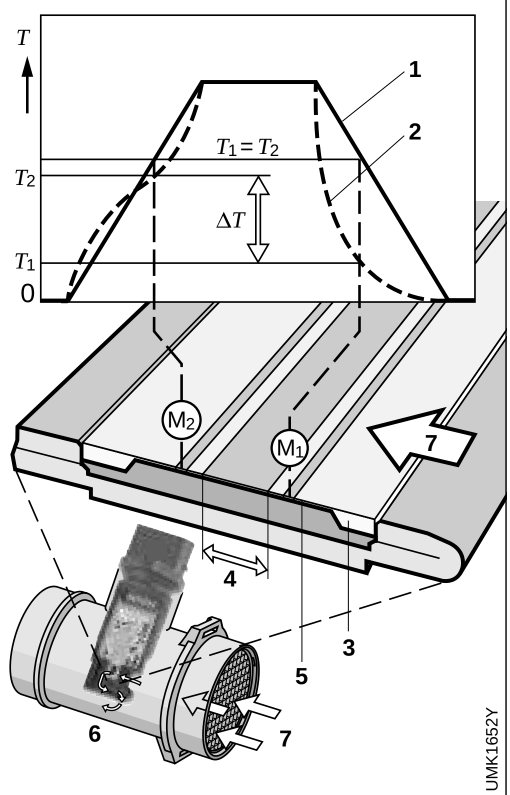


Fig. 2

Fig. 3

Hot-film air-mass meter: Measuring principle

1 Temperature profile without air stream,
2 Temperature profile with air stream,
3 Sensor element, **4** Heating zone,
5 Sensor diaphragm, **6** HFM5 with measuring tube, **7** Air stream. M_1, M_2 measuring points,
T_1, T_2 temperature values at the measuring points M_1 and M_2, ΔT Temperature differential.



ECU

Modern digital technology permits the implementation of a wide range of control functions in the vehicle. Many influencing variables can be taken into account simultaneously so that the various systems can be operated at maximum efficiency. The ECU (Electronic Control Unit) receives the electrical signals from the sensors and desired-value generators, evaluates them, and then calculates the triggering signals for the actuators. The control program is stored in a special memory, and a microcontroller is responsible for implementing the program.

Operating conditions

The ECU is subjected to very high demands with respect to

- Surrounding temperatures (during normal operation −40...+85 °C for commercial vehicles, and −40...+70 °C for passenger cars),
- Resistance to the effects of such materials as oil and fuel etc.,
- Surrounding dampness,
- Mechanical loading due for instance to vibrations from the engine.

To the same degree, very high demands apply regarding EMC (electromagnetic compatibility) and the limitation of HF interference-signal radiation.

Design and construction

The ECU (Fig. 1) is installed in a metal case, and connected to the sensors, actuators, and power supply through a multi-pole plug-in connection (1). The power-electronics components for the direct triggering of the actuators are integrated in the ECU case in such a manner that excellent heat dissipation to the case is ensured. When the ECU is mounted directly on the engine, an integrated heat sink is used to dissipate the heat from the ECU case to the fuel which permanently flushes the ECU (→ ECU cooler, commercial vehicles only). The majority of the components use SMD technology (SMD = Surface-Mounted Device). Conventional wiring is only used on some of the power-electronics components and at the plug-in connections, so that a particularly space-saving and weight-saving design can be implemented.

Data processing

Input signals

In addition to the actuators on the periphery, the sensors represent the interface between the vehicle and the ECU in its role as the processing unit.
The ECU receives the electrical signals from the sensors through the vehicle's wiring harness and the plug-in connections. These signals can be of the following type:

Analog input signals
Within a given range, analog input

signals can assume any voltage value. Examples of physical quantities which are available as analog measured values are intake air mass, battery voltage, intake-manifold and boost pressure, coolant and intake-air temperature. An A/D converter in the ECU microcontroller converts these values to digital values with which the microprocessor performs its calculations. Signal resolution depends on the number of stages used during the conversion.

Digital input signals
These input signals only have two states. They are either “high” or “low”. Examples of digital input signals are on/off switching signals, or digital sensor signals such as the rotational-speed pulses from a Hall generator. Such signals are processed directly by the microcontroller.

Pulse-shaped input signals
The pulse-shaped signals from inductive sensors containing information on rotational speed and reference mark are conditioned in their own ECU circuit. Here, spurious pulses are suppressed and the pulse-shaped signals converted into digital rectangular signals.

Signal conditioning

Protective circuitry is used to limit the input signals to a permissible maximum voltage. By applying filtering techniques, the superimposed interference signals are for the most part removed from the useful signal which, if necessary, is then amplified to the permissible input-signal level for the ECU.
Signal conditioning can take place completely or partially in the sensor depending upon the level of integration.

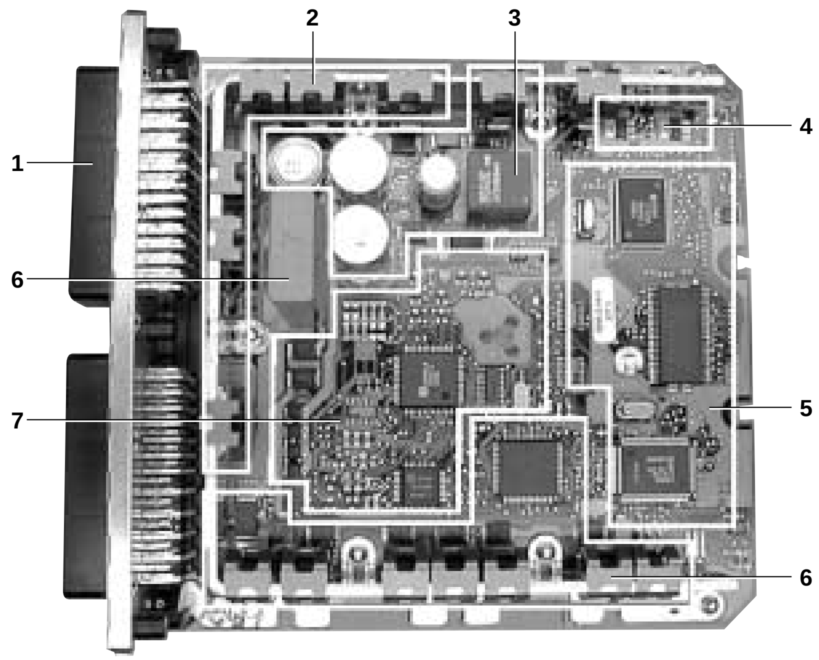
Signal processing

The ECU is the system control center, and is responsible for the functional sequences. The closed and open-loop control functions are executed in the microcontroller. The input signals provided by sensors, desired-value generators, and by interfaces to other systems, serve as the input variables. They are subjected to a further

Fig. 1

ECU: Design and construction

1 Plug-in connection, **2** Low-power driver stages, **3** Switched-mode power supply (SMPS),
4 CAN interface, **5** Microcontroller core, **6** High-power driver stages, **7** General input and output circuitry.



plausibility check in the computer. The output signals are calculated using the program, the characteristic curves, and the maps. The microcontroller is clocked by a quartz circuit.

Program memory

To operate, the microcontroller needs a program which is stored in a read-only memory (ROM or EPROM).

This memory also contains specific data (individual data, characteristic curves, and maps). These are fixed data which cannot be changed during vehicle operation.

The wide variety of vehicle variants which need different data records, makes it imperative that a method is available to limit the number of different ECU types required by a given automaker. Here, the complete memory area of the Flash EPROM (FEPROM) can be programmed with the program and the variant-specific data record when the vehicle leaves the production line (this is termed EoL = End of Line programming). It is also possible to store a number of data variants (e.g. for specific countries) in the memory, which can then be selected by EoL programming.

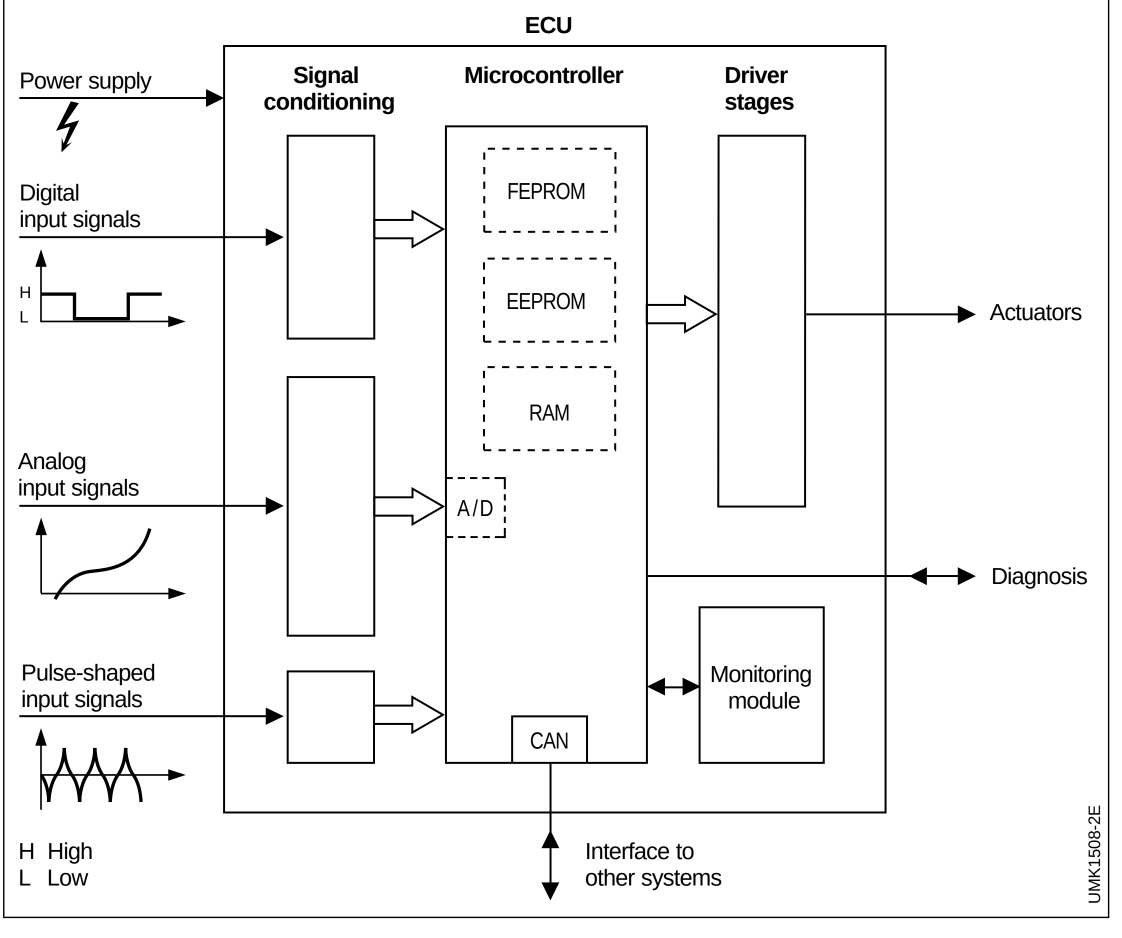
Data storage

A random-access memory (RAM) is required in order to store such changeable data as arithmetic and signal values. The RAM needs a permanent power supply to operate correctly. When the ECU is switched off by means of the ignition and starting switch, therefore, this memory loses its entire stock of data (it is a volatile memory). Adaptation values (that is, values which the system "learns" during operation) concerning engine and operating states, would in this case have to be "re-learned" after switching on the ECU again.

Data which must not be lost (for instance, codes for the immobilizer and data in the

Fig. 2

Signal processing in the ECU



fault store) must be permanently stored in an EEPROM. In this case, the stock of data in this memory is not lost, even when the battery is disconnected.

ASIC

The ever-increasing complexity of ECU functions means that the microcontroller's computing power has become inadequate. The solution here is to use so-called ASIC modules (Application-Specific Integrated Circuit). These IC's are designed and produced in accordance with data from the ECU development department and, as well as being equipped with an extra RAM, and inputs and outputs, they can generate and transmit pwm signals.

Monitoring module

The ECU is provided with a monitoring circuit which is integrated in an ASIC. The microcontroller and the monitoring module supervise each other, and as soon as a fault is detected each of them can switch off the fuel-injection independently.

Output signals

With its output signals, the microcontroller triggers the driver stages. These are usually powerful enough to operate the actuators directly, or to trigger a relay. The driver stages are protected against short-circuits to ground or battery voltage, as well as against destruction due to electrical overload. Such malfunctions, together with open-circuit lines or sensor faults are detected by the driver-stage controller and reported to the microcontroller.

Switching signals

These are used to switch the actuators on and off (for instance, for the engine fan).

PWM signals

Digital output signals can be in the form of pwm (pulse-width modulated) signals. These are rectangular signals with constant frequency but variable on-times

PWM signals

a Fixed frequency, **b** Variable on-time.

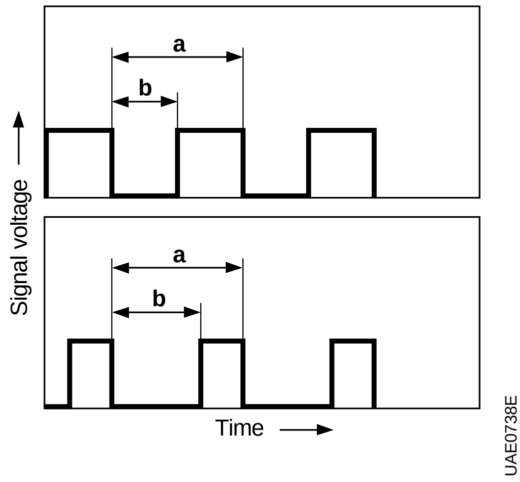


Fig. 3

(Fig. 3) which can be used to trigger the electropneumatic transducers to any angle (e.g. the EGR valve).

Communication within the ECU

In order to be able to support the microcontroller in its work, the peripheral components must be able to communicate with it. This takes place using an address/data bus, through which the microcomputer issues, for instance, the RAM address whose contents are to be accessed. The data bus is then used to transmit the relevant data. For former automotive applications, an 8-bit bus topology sufficed whereby the data bus comprised 8 lines which together can transmit 256 values simultaneously. The 16-bit address bus commonly used with such systems can access 65,536 addresses. Today, more complex systems demand 16 bits, or even 32 bits, for the data bus. In order to save on pins at the components, multiplexing can be used for the data and address buses. That is, data and addresses are dispatched through the same lines but offset from each other with respect to time.

Integrated diagnostics

Sensor monitoring

In order to ascertain whether their power supply is adequate and whether their output signal is within the permissible range (e.g. with a temperaure sensor this is between –40 and +150 °C), the sensors are monitored by an integrated diagnosis facility. As far as this is feasible, the most important signals are redundant, in other words they are provided 2 or 3 times. That is, in case of malfunction another similar signal can be used, or a 2 from 3 selection can be made.

Fault detection

This is possible within the particular sensor's monitoring range. In the case of functions featuring a closed control loop (e.g. pressure monitoring), it is also possible to diagnose the deviation from a given control range.

A signal path is said to be defective once a malfunction is present for longer than a defined period. Once this period has been exceeded, the malfunction is stored in the ECU fault store together with details of the conditions under which it occurred (e.g. coolant temperature, engine speed etc.).

For many malfunctions, it is possible for the sensor to be assessed as serviceable again once the signal path in question has been monitored as faultless for a defined period.

Reaction in case of fault

If a sensor's signal output is outside the permissible range, changeover takes place to a default value. This procedure is used for the following input signals:

- Battery voltage,
- Coolant, intake-air, and oil temperature,
- Boost pressure, and
- Atmospheric pressure and intake-air quantity.

In the case of certain very important driving functions, a switch-over is made to substitute functions which permit the driver to reach the next workshop for instance. If one of the potentiometers of the accelerator-pedal module should fail, the signals from the second potentiometer can be used for calculations provided they are plausible, or the engine can be switched to a non-variable, low speed.

EDC: Operating concept

The ECU evaluates the signals from the external sensors and limits them to the permissible voltage level.
Using this input data and stored maps, the microprocessor calculates the injection times (duration), and the starts (instants) of injection, and converts these times into signal characteristics as a function of time which are then adapted to piston motion. Considering the engine's high dynamic forces and speed, a high level of computing power is necessary to comply with the demands for accuracy. The output signals are used to trigger driver stages which supply adequate power for all the actuators (e.g. solenoid valves), including those for such engine functions as EGR and boost-pressure actuator, and for auxiliary functions such as glow relay and A/C. The driver stages are protected against destruction or damage due to short circuits and electrical overload. Such malfunctions, including cable open-circuits, are reported back to the microprocessor.

The diagnosis functions of the solenoid-valve driver stages also detect faulty signal characteristics. In addition, a number of output signals are sent to other vehicle systems via interfaces. The ECU also monitors the complete injection system within the framework of a safety concept.

Operating-state control

In order that the engine can always operate with optimum combustion, the appropriate injected fuel quantity for each operating state has to be calculated in the ECU. A number of quantities must be taken into account in the process (Fig. 1).

Start quantity

The injected fuel quantity for starting is calculated as a function of the coolant temperaure and the engine's rotational (cranking) speed. The ECU outputs the signal “start quantity” from the moment the glow-plug and starter switch is turned (Fig. 1, switch in Pos. A) until a given minimum engine speed is reached. The driver has no influence on the start quantity.

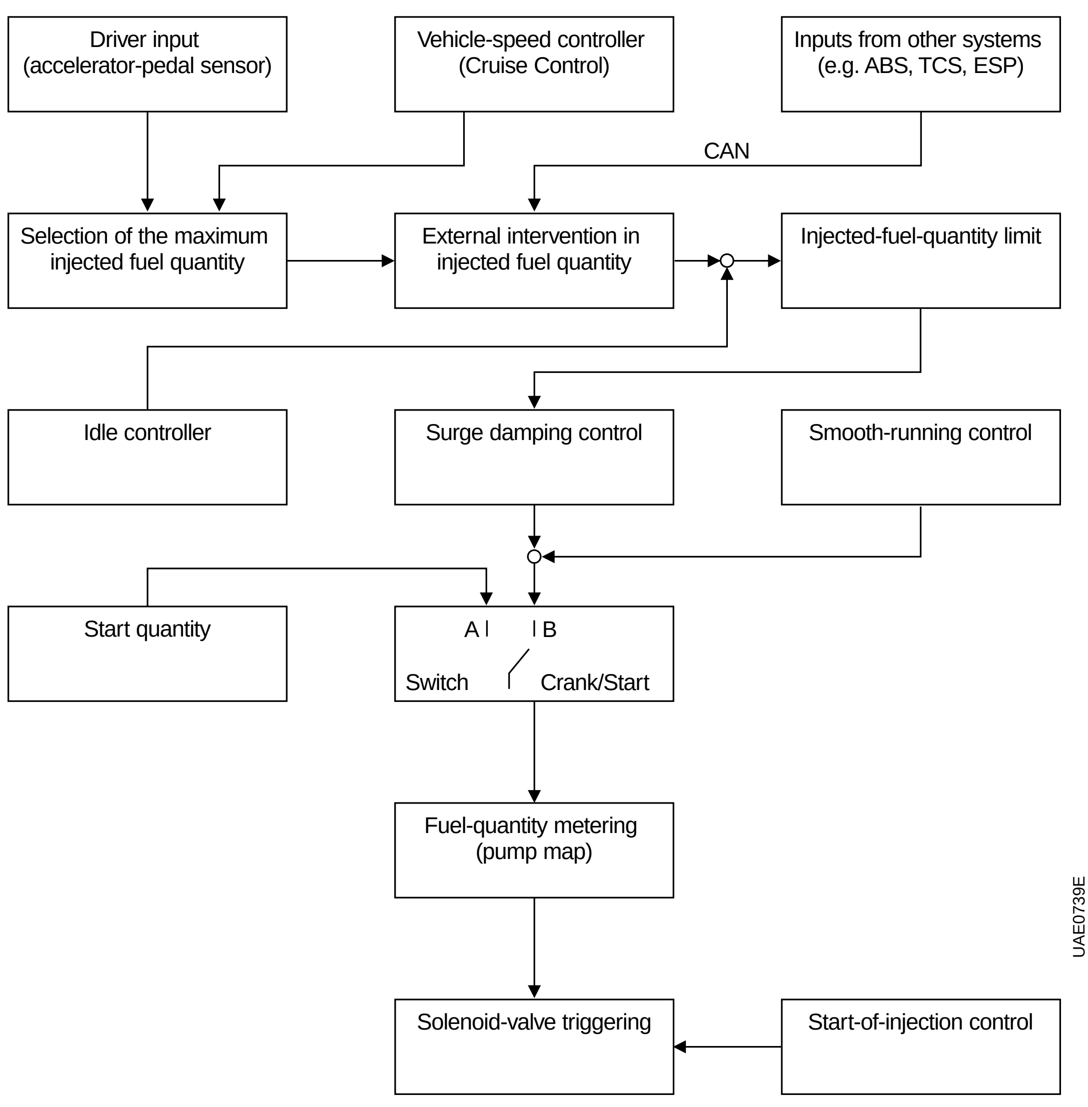
Driving

With the vehicle actually being driven, the injected fuel quantity is calculated as a function of the accelerator-pedal setting (accelerator-pedal sensor) and engine speed (Fig. 1, switch in Pos. B), and uses the vehicle-handling map. This enables the driver's wishes and the vehicle's power to be optimally adapted to each other.

Fig. 1

Calculation of the injected fuel quantity in the ECU

Switch position A: Start; Switch position B: Drive.



Idle-speed control

At idle, fuel consumption is determined mainly by the engine's efficiency and idle speed.

In today's dense stop-and-go traffic, a major portion of a vehicle's fuel consumption is attributable to operation at idle. This means, therefore, that on the one hand the idle speed should be kept to a minimum. On the other hand though, irrespective of loading (A/C switch-on, gear selected on automatic gearbox, operative power steering etc.), it should never drop below a given minimum so that the engine starts to run roughly or even stalls.

In order to set the desired idle speed, the idle-speed controller varies the injected fuel quantity until the idle speed as measured corresponds to the desired idle speed. Here, the desired idle speed and the control characteristic are influenced by the selected gear (on automatic gearboxes) and the engine temperature (coolant-temperature sensor).

In addition to the externally applied load torques, internal friction torques must also be taken into account and compensated for by the idle-speed controller. As well as being highly dependent upon temperature, these increase slightly but steadily throughout the life of the engine.

Smooth-running control

Due to mechanical tolerances and changes which take place during the life of the engine, not all of its cylinders develop the same torque. Particularly during idle, this can result in the engine running unevenly. The smooth-running control measures the rotational-speed changes after each ignition and compares them with each other. The injected fuel quantities for each cylinder are then adjusted as a function of the speed differences so that each cylinder can as far as possible make the same contribution to the engine's torque output.

Vehicle-speed control (Cruise Control)

The so-called Tempomat or Cruise Control enables the vehicle to be driven at a constant speed. It adjusts the vehicle's speed to a selected level which is set via a lever on the instrument panel. The injected fuel quantity is increased, or decreased, until the measured speed corresponds to the selected speed. As soon as the driver hits the brake or clutch pedal, this automatically switches off the control process. The accelerator pedal can be used to accelerate beyond the presently desired speed. Upon releasing the accelerator pedal, the Cruise Controller adjusts the vehicle speed to the last-valid desired speed. Similarly, with the Cruise Control switched off, the lever can be set to “Reactivate” so that it adjusts the vehicle's speed to the last-valid level.

Step by step changes to the desired speed can also be made using the Cruise Control lever.

Control of the injected-fuel-quantity limit

There are a number of reasons why the the physically possible amount of fuel, or the amount of fuel as wished for by the driver, should <u>not</u> be injected.

These include the danger of

– Excessive pollutant emissions,
– Development of too much soot,
– Mechanical overload resulting from excessive torque, or excessive speed,
– Thermal overload due to high coolant, lube-oil, or exhaust-gas turbocharger temperatures.

The injected-fuel-quantity limit is generated on the basis of a number of input variables, for instance the intake air mass, the engine rotational speed, and the coolant temperature.

Surge damping control
Suddenly releasing or depressing the accelerator pedal results in a rapid change of the injected fuel quantity and with it engine output torque. As a result of this abrupt load change, the resilient engine suspension and the drivetrain generate surge oscillations which lead to fluctuations in engine speed (Fig. 2).
The surge damping control option reduces these periodic engine-speed fluctuations by varying the injected fuel quantity with the same period of oscillation. When speed increases, less fuel is injected, and vice versa. The surge movements are considerably reduced as a result.

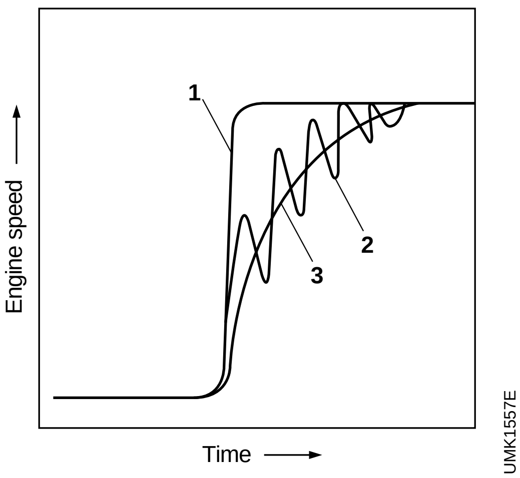
Altitude compensation
The atmospheric pressure influences the boost-pressure control and the torque limitation. Using the atmospheric-pressure sensor, it can be measured by the ECU so that at high altitudes the injected fuel quantity can be reduced and with it the smoke emission.

Cylinder shutoff
Instead of injecting very little fuel to reduce torque at high engine speeds, cylinder shutoff can be opted for. Here, half of the injectors are switched off (UIS, UPS, CR) and the remaining injectors supplied with a correspondingly higher amount of fuel which can be injected with even more accuracy.
When the cylinders are switched on and off, special software algorithms are applied to provide soft transitions, that is, torque fluctuations are not generated.

Fig. 2

Surge damping control

1 Sudden accelerator-pedal movement (driver input), **2** Speed characteristic without surge damping control, **3** Speed characteristic with surge damping control.



Engine shutoff
Diesel-engine operation is based on the auto-ignition principle. This means that the engine can only be stopped by switching off the supply of fuel.
In the case of Electronic Diesel Control (EDC), the engine is stopped by the ECU stipulating “Injected fuel quantity: Zero” (no triggering of the solenoid valves). There are also a number of (redundant) shutoff paths available. The UIS and UPS are intrinsically safe. In other words, unintentional injection can only occur once at the most. Shutoff takes place, therefore, by switching off the solenoid valves.

Exchange of information

Communication between the engine ECU and the other ECUs in the system takes place through the CAN-Bus (Controller Area Network). This serves to transmit the desired and setpoint values, operating data, and status information as required for error control and efficient operation (refer to “Data transmission to other systems!”).

External intervention in injected fuel quantity
Here, intervention in the injected fuel quantity is influenced by another ECU (e.g. ABS, TCS) which informs the engine ECU whether the engine torque is to be changed (and therefore the injected fuel quantity), and if so, by how much.

Electronic immobilizer

To support the theft-deterrence measures in the vehicle, an immobilizer ECU can be installed which prevents engine start.
The driver can use a remote signal to indicate to this ECU that he/she is authorized to use the vehicle. The immobilizer ECU then instructs the engine ECU to permit the injection of fuel so that the engine can be started and the vehicle driven.

Air conditioner

When outside temperatures are very high, the air conditioner cools the air inside the vehicle to a pleasant level by means of a refrigerating compressor.
Depending upon the engine and the particular driving situation, the compressor's power demands can total up to 30 % of the engine's output power.
The EDC briefly switches off the compressor immediately the driver hits the accelerator hard (in other words he/she requires maximum torque).
This releases full engine power for accelerating the vehicle, and has negligible effect upon the interior temperature.

Glow control unit

The engine ECU provides the glow control unit with the information on when the glow plugs are to be heated and for how long. The glow control unit monitors the glow process, and reports any malfunctions to the engine ECU for diagnosis purposes.

UI/UP solenoid valves: Triggering

The triggering of the solenoid valves places severe demands upon the driver stages. The necessity for low tolerances and high reproducibility of the injected fuel quantities demands that the current pulses feature steep leading and trailing flanks. Triggering uses current control which divides the triggering process into a pickup-current phase and a holding-current phase. Between these two phases, constant voltage is applied for a brief period in order to detect the solenoid-valve closing point. The current control must be so accurate that the injection pump or the injector always produces reproducible injection results in every operating range. The current control is also responsible for reducing the ECU and solenoid-valve power losses. In order to ensure defined, high-speed opening of the solenoid valve at the end of the injection process, the energy stored in the solenoid valve is abruptly quenched by applying a high voltage across the terminals.
The microcomputer is responsible for calculating the individual triggering phases. It is assisted by a so-called gate array featuring very high computing power which implements this requirement by generating two real-time digital triggering signals (MODE signal and ON signal). In turn, these triggering signals cause the driver stages to generate the necessary triggering-current sequence (Fig. 1).

Control of the beginning of the injection period (BIP)

BIP is defined as the instant in time at which the solenoid valve closes and the buildup of pressure starts in the pump's high-pressure chamber. As soon as the pressure exceeds the nozzle-needle opening pressure the nozzle opens and injection starts (start of injection). The actual metering of fuel takes place between the start of delivery and the end of solenoid-valve triggering. It is termed the delivery period.

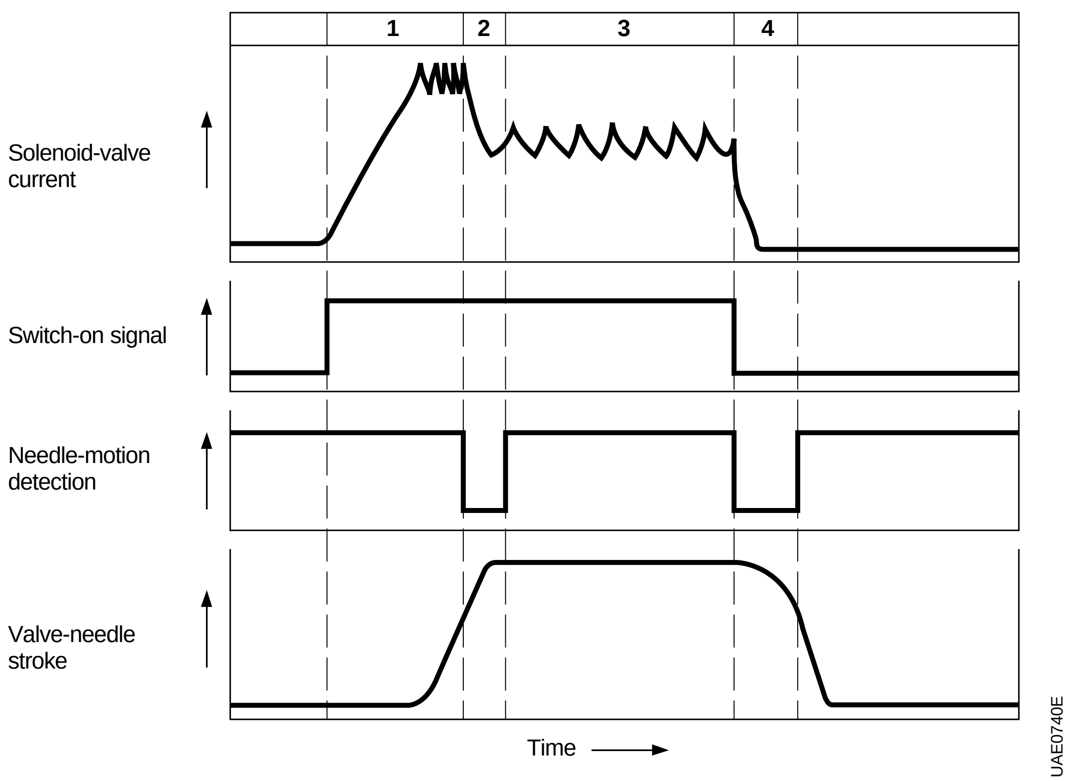
The BIP has a pronounced effect upon the engine's power ouput, fuel consumption, noise, and emissions. Its setpoint value is a function of the engine speed and the injected fuel quantity, and is stored in characteristic maps in the ECU. It can be corrected as a function of the coolant temperature.
Due to manufacturing tolerances and the changes which take place in the solenoid valves during their service life, minor differences can exist between the switching times of the solenoid-valves in a given engine. This leads to different starts of injection for the individual pumps.
To comply with emission-control legislation, and to achieve good smooth-running qualities, it is therefore necessary to compensate for these irregularities by means of suitable control strategy.
Considering the direct correlation between start of delivery and start of injection as described above, for the exact control of the start of injection it suffices to have exact data on the start of delivery.

Electronic evaluation of the solenoid-valve current is used to precisely define the start of delivery, and additional sensor technology (e.g. a needle-motion sensor) is not required. Solenoid-valve triggering is performed with constant voltage around the instant at which the valve is expected to close. Inductive effects occurring when the solenoid valve closes, give the valve's current curve a specific characteristic at this point. This is evaluated by the ECU, and deviations from the expected setpoint for each solenoid valve's instant of closing are stored to be used as compensation data for the next injection sequence.

Fig. 1

Triggering sequence of the solenoid valves

1 Pickup current, **2** BIP detection, **3** Holding current, **4** Abrupt energy quenching.



Data transmission to other systems

System overview

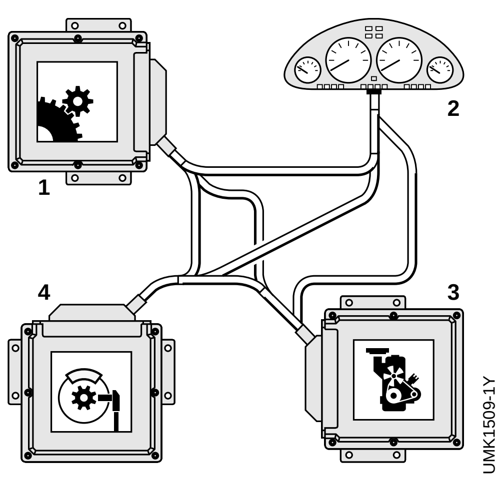
Increasingly widespread application of electronic control systems for automotive functions such as
- Electronic engine-management and injection-pump controls,
- Electronic transmission-shift control,
- Antilock braking system (ABS),
- Traction control system (TCS),
- Electronic Stability Program (ESP),
- Engine drag-torque control (MSR),
- Electronic immobilizers (EWS), and
- On-board computers etc.,

has made it vital to interconnect the individual ECUs by means of networks. The exchange of information between the various control systems reduces the number of sensors while also promoting exploitation of the performance potential which is inherent in the individual systems. The interfaces of the communication systems which have been specifically developed for automotive applications can be subdivided into two categories:
- Conventional interfaces, and
- Serial interfaces, e.g. Controller Area Network (CAN).

Fig. 1

Conventional data transmission

1 Transmission-shift control, **2** Instrument cluster, **3** Engine management, **4** ABS/ESP.



Conventional data transmission

In conventional automotive data-communications systems each signal is assigned to a single line (Fig. 1). Binary signals can only be transmitted as one of two conditions: “l” or “0” (“high” or “low” respectively). An example would be the vehicle's a/c compressor, which can be “on” or “off.”
Pulse-duty factors can be employed to relay continually varying data, such as that on the position of the accelerator-pedal sensor.
The increasing data traffic between various on-board electronic components means that conventional interfaces can no longer provide satisfactory performance. The complexity of current wiring harnesses and the sizes of the associated plugs is already very difficult to manage, and the requirements for data communications between ECUs are on the rise. In some vehicles, the ECUs are each networked to as many as 30 different components, an assignment which would be practically impossible to solve at reasonable cost with conventional wiring.

Serial data transmission (CAN)

The problems associated with the exchange of data using a multitude of wires and conventional interfaces can be solved by using bus systems. CAN is a bus system (bus bar) specially designed for automotive applications. Data is relayed in serial form, that is, the items of information are transmitted one after another on a single line. Provided the ECUs are equipped with a CAN serial interface, they can receive and transmit data through the CAN bus line.

Areas of application
In the vehicle there are four basic areas of application for CAN:

Multiplex applications

Multiplex is suitable for use with applications controlling the open and closed-loop control of components in the sectors of body electronics, and comfort and convenience. These include climate control, central locking, and seat adjustment.

Transfer rates are typically between 10 kbit/s and 125 kbit/s (low-speed CAN).

Mobile communications applications

In the area of mobile communications, such components as navigation system, telephone, and audio installations are networked with central display and operating units. The object here is to standardise operational sequences as far as possible and to concentrate status information at one point so that driver distraction is reduced to a minimum.

Transfer rates are up to 125 kbit/s. The direct transmission of audio or video data is impossible here.

Diagnosis applications

The diagnosis applications using CAN are aimed at using the already existing network for the diagnosis of the connected ECUs. The presently common form of diagnosis using the K line (ISO 9141) then becomes invalid.

A data transfer rate of 500 kbit/s is planned.

Real-time applications

Real-time applications serve to control the vehicle's movements. Here, electrical systems such as engine management, transmission-shift control, and electronic stability program (ESP) are networked with each other.

Commonly, data transfer rates of between 125 kbit/s and 1 Mbit/s (high-speed CAN) are needed to guarantee the required real-time response. The following chapters are restricted to real-time applications.

ECU networking

With this strategy, such electronic systems as the engine-management system, antilock braking system (ABS), traction control system (TCS), electronic stability program (ESP), and electronic transmission-shift control, etc., are interlinked with each other through the CAN interface. The ECUs are ranked as equal partners within a linear bus topology (Figure 2). The advantage of this structure, known as the “Multi-Master” principle, is that failure of one subscriber will not affect access for the others. The probability of total failure is thus substantially lower than with other logical configurations such as loop or star structures in which failure of one of the subscribers, or the central CPU, will provoke total system failure.

Typical data transfer rates lie between 125 kbit/s and 1 Mbit/s. They must be so high in order to guarantee the stipulated real-time response. This means for instance that the data on engine load from the engine ECU arrives at the gearbox ECU in just a few milliseconds.

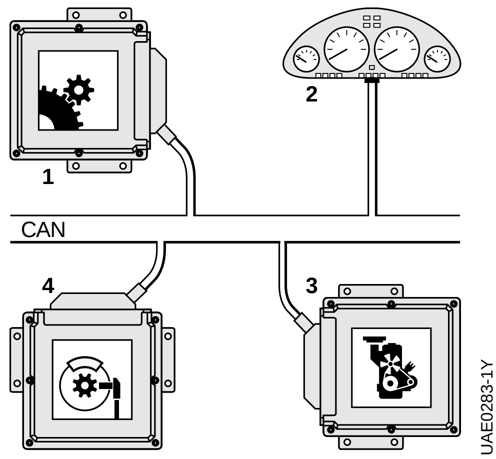
Content-based addressing

The CAN bus system does not address each station individually, but instead allocates each “message” a fixed “identifier” with a length of 11 bits (standard format for passenger cars) or 29 bits (extended format for commercial vehicles). As the name implies, this identifies the contents of the message (e.g. engine speed). Several signals can be included in a

Fig. 2

Linear bus topology

1 Transmission-shift control, **2** Instrument cluster, **3** Engine management, **4** ABS/ESP.

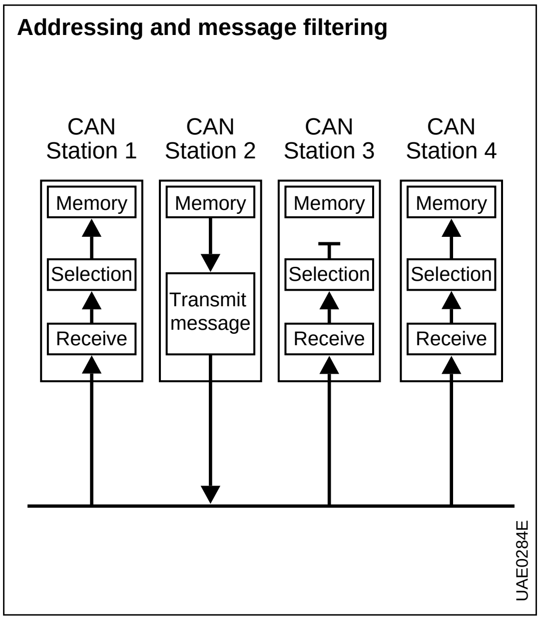


single message (for instance a number of switch positions).
Each station processes only that data whose identity is stored in its own list of messages to be accepted (message filtering, Fig. 3). All other messages are simply ignored. This function can be performed by a special CAN module (Full-CAN), so that less load is placed on the microcontroller. Basic CAN modules read all messages, and the microcontroller then accesses the respective memory location.
With content-based addressing, a single signal can be sent to a number of stations. The transmitter in question merely needs to send its signal directly to the bus network via an ECU, so that the signal is available to all receivers. Apart from this, since further stations can be added to an already existing CAN system, a multitude of equipment variants can be implemented. If an ECU requires additional information which is available on the Bus, all it needs to do is to call it up.

Priority assignment

The identifier not only indicates the data content, but also defines the message's priority rating. Signals subject to rapid variation (for instance, engine speed) obviously need to be forwarded without delay and without loss of data. As a result, these fast-changing signals are assigned a higher priority rating than signals with contents that shift at a relatively slow pace (for instance, engine temperature). In addition, the messages are sorted according to their “importance” (for instance, safety-relevant functions are allocated high “importance” ratings). There are never two (or more) messages of identical priority in the bus.

Fig. 3



Bus arbitration

Each station can begin transmitting its highest priority message as soon as the bus is unoccupied. If several stations start to transmit simultaneously, the resulting bus-access conflict is resolved by granting first access to the message with the highest priority rating, without any form of delay and without loss of data bits (nondestructive protocol). This takes place using “recessive” (logical 1) and “dominant” (logical 0) bits, whereby the dominant bits “overwrite” the recessive bits. The transmitters with low-priority messages automatically become receivers, and repeat their transmission attempt as soon as the bus is vacant again. In order that all messages have a chance of entering the bus, the bus speed must be appropriate to the number of stations participating in the bus. A cycle time is defined for those signals which fluctuate permanently (e.g. engine speed).

Message format

A data frame of maximum 130 bits in length (standard format) or 150 bits (extended format) is generated for transmissions to the bus. This ensures that the queue time until the next – possibly extremely urgent – data transmission is held to a minimum. The data frames consist of seven consecutive fields (Fig. 4).

"Start of frame" indicates the beginning of a message and synchronises all stations.

The "arbitration field" consists of the message's identifier and an additional control bit. While this field is being transmitted, the transmitter accompanies the transmission of each bit with a check to ensure that a higher-priority message is not being transmitted by another station. The control bit defines whether the message is a "Data frame" (message with data) or a "Remote frame" (request for a message).

The "control field" contains the code indicating the number of data bytes in the "data field". This enables the receiver to determine whether all bits have been received.

The "data field's" information content is comprised of between 0 and 8 bytes. A message with data length = 0 is used to synchronise distributed processes.

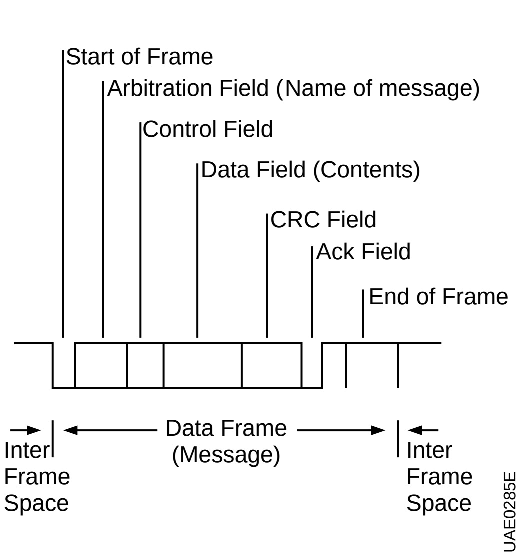
The "CRC (Cyclic Redundancy Check) field" contains the check word for detecting possible transmission interference.

The "Ack field" contains the acknowledgement signals from all receiver stations which have received the message in non-corrupted form – irrespective of whether they have processed the contents or not.

"End of frame" marks the end of the message.

Fig. 4

Message format



Integrated diagnosis

The CAN bus system incorporates a range of control mechanisms for error detection. These include such features as the check signal in the data frame, as well as the monitoring function in which each signal is routed back to its transmitter of origin, which can then detect any discrepancies.

When a station detects a problem, it responds by transmitting an error flag to interrupt the transmission which is in progress. This prevents other stations from accepting the faulty transmission data.

A potential problem is that a defective station could start to abort all transmissions, including the valid ones, by planting error flags. To avoid this problem, the CAN bus system is equipped with a mechanism designed to distinguish between intermittent and extended interference or malfunction. This facility can also localize station failures. The process is based on statistical analysis of the error conditions.

Standardization

The International Organization for Standards (ISO) and SAE have issued CAN standards for data exchange in automotive applications:

– For low-speed applications up to 125 kbit/s: ISO 11519-2, and
– For high-speed applications over 125 kbit/s: ISO 11898 and SAE J 22584 (passenger cars) and SAE J 1939 (trucks and buses).

Furthermore, an ISO Standard on CAN Diagnosis (ISO 15756 – Draft) is being prepared.

Actuators

Actuators convert the electrical output signals from the ECU into mechanical quantities (e.g. for setting the EGR valve or the throttle valve).

Electropneumatic transducers

Boost-pressure actuator

In order to provide for high engine torque at low engine speeds, the exhaust-gas turbocharger is designed to generate high boost pressure in this rotational-speed range.
Without some form of control, the boost pressure would be excessive at high speeds. The solution is to divert a portion of the exhaust gas past the turbocharger's turbine by means of a bypass valve (the so-called "wastegate") Fig. 1.
Instead of the wastegate, variable turbine geometry (VTG) can be applied to adapt the turbocharger's output. VTG varies the angle of the turbine blades in the exhaust-gas passage.

EGR valve

With exhaust-gas recirculation (EGR) a portion of the exhaust gas is led into the engine's intake tract with the object of reducing toxic emissions (refer also to the "Diesel Combustion" Chapter).The quantity of exhaust gas directed back to the engine is controlled by an electropneumatic valve situated between the exhaust tract and the intake tract.

Throttle valve

The throttle valve is controlled by an electropneumatic valve, and in the diesel engine has a very different function to that in the gasoline engine. On the diesel engine it serves to increase the EGR rate by reducing the overpressure in the intake manifold. Throttle-valve control is only operative in the lower speed range.

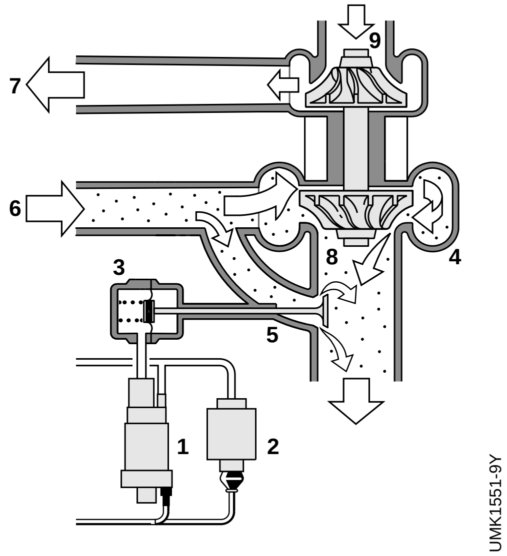
Intake-manifold flap

On the passenger-car UIS, the intake-manifold flap cuts off the supply of air when the engine is switched off so that less air is compressed and the engine stops smoothly. The flap is controlled by an electropneumatic valve.

Fig. 1

Boost-pressure control with boost-pressure actuator

1 Boost-pressure actuator, **2** Vacuum pump,
3 Pressure actuator, **4** Exhaust-gas turbocharger,
5 Bypass valve, **6** Exhaust-gas flow,
7 Intake-air flow, **8** Turbine, **9** Compressor.



Swirl controller

In a passenger car, the swirl control influences the swirl motion of the intake air in the cylinder. The swirl itself is usually generated by spiral-shaped intake ports. Since it determines the mixing of fuel and air in the combustion chamber, it has considerable influence upon the combustion quality. As a rule, a pronounced swirl is generated at low speeds, and a weak swirl at high speeds. The swirl can be modified by the swirl controller (flap or slide valve) near to the throttle valve.

Continuous-operation braking systems

These braking systems are used for heavy trucks for reducing their speed without braking-component wear. They cannot stop the vehicle though. In contrast to service brake systems, due to them being able to adequately dissipate the braking heat even when they are applied over a long period, continuous-operation braking systems are most suitable for slowing down the vehicle on extended downhill gradients. As a result, the friction brakes are used less and remain cool so that they can be applied to full effect in an emergency. The continuous-operation braking system is controlled by the engine-management ECU.

Exhaust brake

The supply of fuel to the engine by the injection system is cut off when the exhaust brake is switched on, and intake air which is drawn into the cylinder is forced out again without having mixed with fuel. An electropneumatic valve operates a rotary valve or a flap in the exhaust pipe which serves as an obstacle to the intake air (no fuel is injected at this point) attempting to leave the engine through the exhaust pipe. The resulting air cushion generated in the cylinder brakes the piston in the compression and exhaust strokes. With the exhaust brake, there is no means of varying the degree of braking intensity.

Auxiliary engine brake

When the engine is to be braked, an electrohydraulic valve-lifting device opens the exhaust valve at the end of the compression stroke. The compression pressure collapses as a result and energy is removed from the system. Lube oil is used as the hydraulically switched medium.

Retarder

The retarder is an auxiliary braking system which is completely independent of the engine. It is installed in the drivetrain downstream of the gearbox and is thus also effective when passing through neutral during gear changes. There are two different systems:

Hydrodynamic retarder
Comprises a movable turbine wheel (rotor) and at the opposite end a fixed turbine wheel (stator). The rotor is mechanically connected to the vehicle drive. When the brakes are applied, the blade chambers in the stator and rotor fill with oil. This oil is accelerated by the (rotating) rotor and decelerated by the (fixed) stator. The kinetic energy is converted to heat and dissipated to the engine coolant. The quantities of oil entering the rotor and stator chambers can be used for infinite variation of the braking effect.

Electrodynamic retarder
This comprises an air-cooled soft-iron disk which rotates in a controllable electromagnetic field generated by the vehicle battery. The resulting eddy currents brake the disk and with it the vehicle wheels. The braking effect is infinitely variable.

Engine-fan control

As a function of coolant temperature, the ECU switches the engine's fan on and off as required using an electromagnetic clutch.

Start-assist systems

Compared to gasoline, diesel fuel is far more easily ignited. This is why a warm diesel engine starts immediately when cranked. The DI diesel engine even starts immediately at temperatures down to 0 °C. When starting, the 250 °C auto-ignition temperature is reached when the engine is cranked at its starting speed. Below 0 °C, DI diesel engines need some form of start assistance, as do prechamber (IDI) diesel engines. The cylinders of IDI and swirl-chamber engines have a sheathed-element glow plug (GSK) in their auxiliary combustion chamber which functions as a "hot spot". On small DI engines (up to 1 l/cylinder), this "hot spot" is located on the combustion chamber's periphery. Large DI truck engines on the other hand have the alternative of using air pre-heating in the intake manifold (flame start), or special, easily ignitable fuel (Start Pilot) which is sprayed into the intake air. Today, sheathed-element glow plugs are used practically without exception.

Intake-air pre-heating

Flame glow plug

The flame glow plug burns fuel in the intake tract to heat the incoming air. Normally, the injection system's supply pump delivers fuel to the flame plug through a solenoid valve. The flame plug's connection fitting has a filter, and a metering device which permits passage of precisely the correct amount of fuel appropriate to the particular engine. This fuel then evaporates in an evaporator tube surrounding the tubular heating element and mixes with the intake air. The resulting mixture ignites on the 1000 °C heating element at the flame-plug tip. The heating power is limited since the heater flame must not consume more than a fraction of the oxygen needed for subsequent combustion in the engine cylinder.

Electrical heating

A number of heater elements in the air-intake system are switched on and off by a relay.

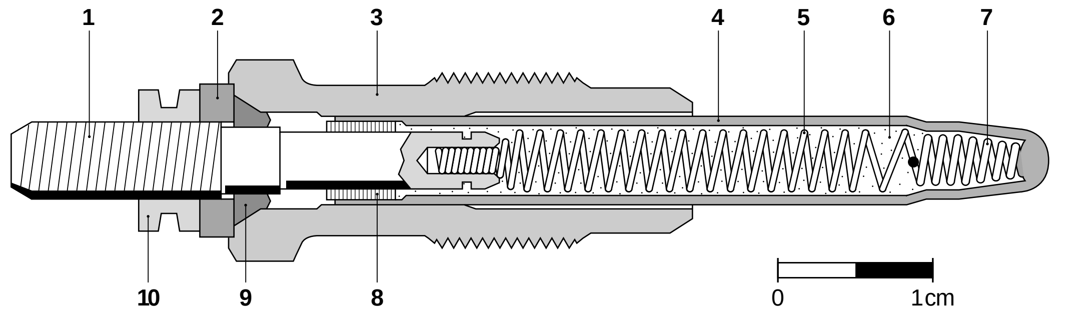
Sheathed-element glow plug

The glow plug's (Fig. 1) glow element is so firmly pressed into the glow-plug shell (3) that a gas-tight seal is formed. The element is a metal glow tube (4) which is resistant to corrosion and hot gases, and which contains a heater (glow) element embedded in magnesium-oxide powder (6). This heater element comprises two series-connected resistors: the helical heating wire (7) in the glow-tube tip, and the control filament (5). Whereas the helical heating wire maintains virtually constant electrical resistance regardless of temperature, the control filament is made of material with a positive temperature coefficient (PTC). On newer-generation

Fig.1

Sheathed-element glow plug GSK2

1 Electrical connector terminal, **2** Insulating washer, **3** Shell, **4** Glow tube, **5** Control filament,
6 Filling powder, **7** Helical heating wire, **8** Heater-element gasket, **9** Double gasket, **10** Round nut.



glow plugs (GSK2), its resistance increases even more rapidly with rising temperature than was the case with the conventional S-RSK glow plug. This means that the newer GSK2 glow plugs are characterized by reaching the temperature needed for ignition far more quickly (850 °C in 4 s). They also feature a lower steady-state temperature which means that the glow plug's temperature is limited to a non-critical level. The result is that the GSK2 glow plug can remain on for up to 3 minutes following engine start. This post-glow feature improves both the warm-up and run-up phases with considerable improvements in noise and exhaust-gas emissions.

Glow control unit

The glow control unit (GZS) uses a power relay for triggering the glow plugs. Its start pulse comes from the engine ECU via a temperature sensor. The glow control unit controls the glow duration of the glow plugs, as well as having safety and monitoring functions. Using their diagnosis functions, more sophisticated units are also able to recognise the failure of individual glow plugs and inform the driver. Multiple plugs are used as the control inputs to the glow control units.

Functional sequence

The diesel engine's glow plug and starter switch, which controls the preheat and starting sequence, functions in a similar manner to the ignition and starting switch on the gasoline engine. Switching to "ignition on" starts the preheating process (Fig. 3). When the indicator lamp goes out, this indicates that the glow plugs are hot enough for the engine to start, and cranking can begin. In the following starting phase, the droplets of injected fuel ignite in the hot compressed air. The heat thus released leads to initiation of combustion. In the warm-up phase following a successful start, post-glow contributes to faultless engine running (no misfiring) and therefore to practically smokeless engine run-up and idle.

EDC-controlled glow system for a DI diesel engine

1 Sheathed-element glow plug, **2** Glow control unit, **3** Glow plug and starter switch, **4** To battery, **5** Indicator lamp, **6** Control line to the engine ECU, **7** Diagnosis line.

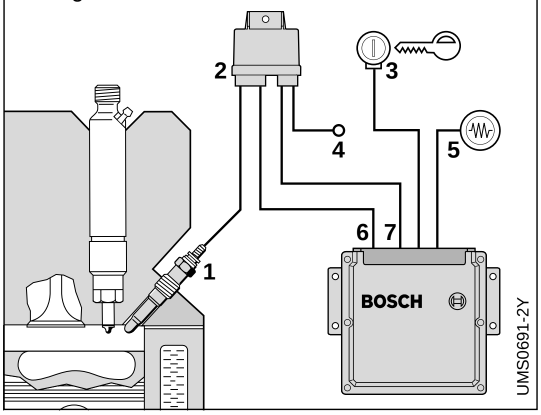
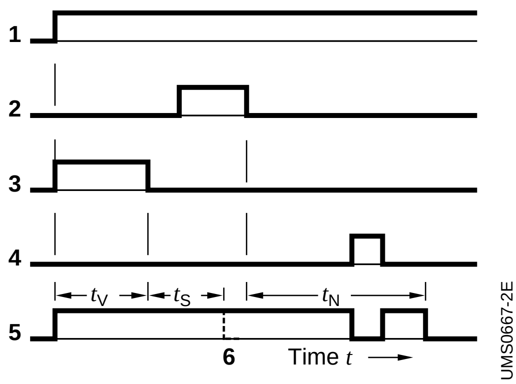


Fig. 2

Fig. 3

Typical preheating sequence

1 Glow-plug and starter switch, **2** Starter, **3** Glow-plug indicator lamp, **4** Load switch, **5** Glow plugs, **6** Self-sustained engine operation, t_V Preheating time, t_S Ready to start, t_N Postheating time.



At the same time, with the engine cold, preheating reduces combustion noise. A glow-plug safety switchoff prevents battery discharge if the engine cannot be started. The glow control unit can be coupled to the ECU of the Electronic Diesel Control (EDC) so that information available in the EDC control unit can be applied for optimum control of the glow plugs in line with the particular operating conditions. This is yet another possibility for reducing the blue-smoke and noise levels.