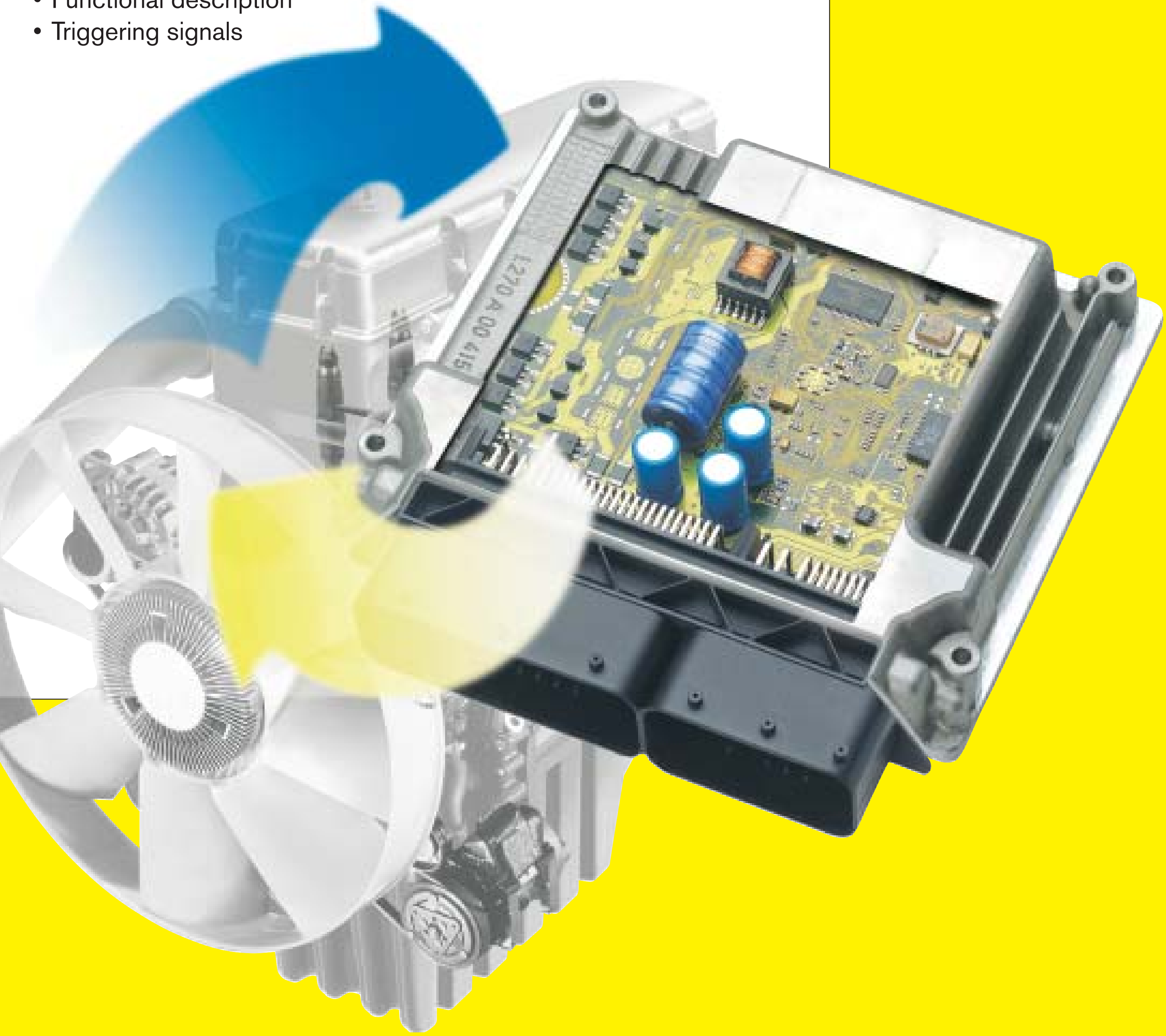
The Bosch Yellow Jackets **Edition 2001** | Technical Instruction | Diesel-Engine Management

Electronic Diesel Control EDC

BOSCH

Automotive Technology

- Lambda closed-loop control for passenger-car diesel engines
- Functional description
- Triggering signals



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Robert Bosch GmbH

Electronic Diesel Control EDC

Bosch

Contents

Electronics is coming more and more to the forefront in the control and management of the diesel engine, whereby the question is often raised “Is it really necessary to fill the vehicle with so much electronics ?”

The point is though, without electronics it would be impossible to detect a large number of important variables, such as engine speed, quickly enough for them to be used for engine management. Electronic control is behind the modern diesel engine having become more powerful, more efficient, quieter, cleaner, and more economical. These facts hold true irrespective of the engine’s operating range or mode.

Electronic **D**iesel **C**ontrol, EDC, permits the implementation of such auxiliary functions as smooth-running control (SRC).
EDC is applied for all modern diesel injection systems:

- In-line injection pumps, PE,
- Distributor injection pumps, VE, VR,
- Unit Injector System, UIS,
- Unit Pump System, UPS,
- Common Rail System, CRS.

Although these injection systems differ in many respects, and are installed in a wide variety of different vehicles, they are all equipped with a similar form of EDC.

This “Technical Instruction” manual describes the Electronic Diesel Control and all its components. The differences between the individual injection systems are shown in tabular form (Pages 12 through 17). The manual thus provides the reader with a comprehensive overview of the various diesel fuel-injection systems from the point of view of their open and closed-loop electronic control.

Diesel fuel-injection systems: An overview

Diesel engines are characterized by their high levels of economic efficiency. Since the first series-production injection pumps were introduced by Bosch in 1927, injection-system developments have continued unceasingly.

Diesel engines are employed in a wide range of different versions (Figure 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 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 diesel engine’s combustion chamber at a very high pressure (today, this is between 350 and 2,050 bar), and the injected fuel quantity 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 (flyweight) governor is increasingly being superseded by the Electronic Diesel Control (EDC). In the passenger-car and commercial-vehicle sector, the new diesel fuel-injection systems are all EDC-controlled.

1 Bosch diesel fuel-injection systems. Areas of application

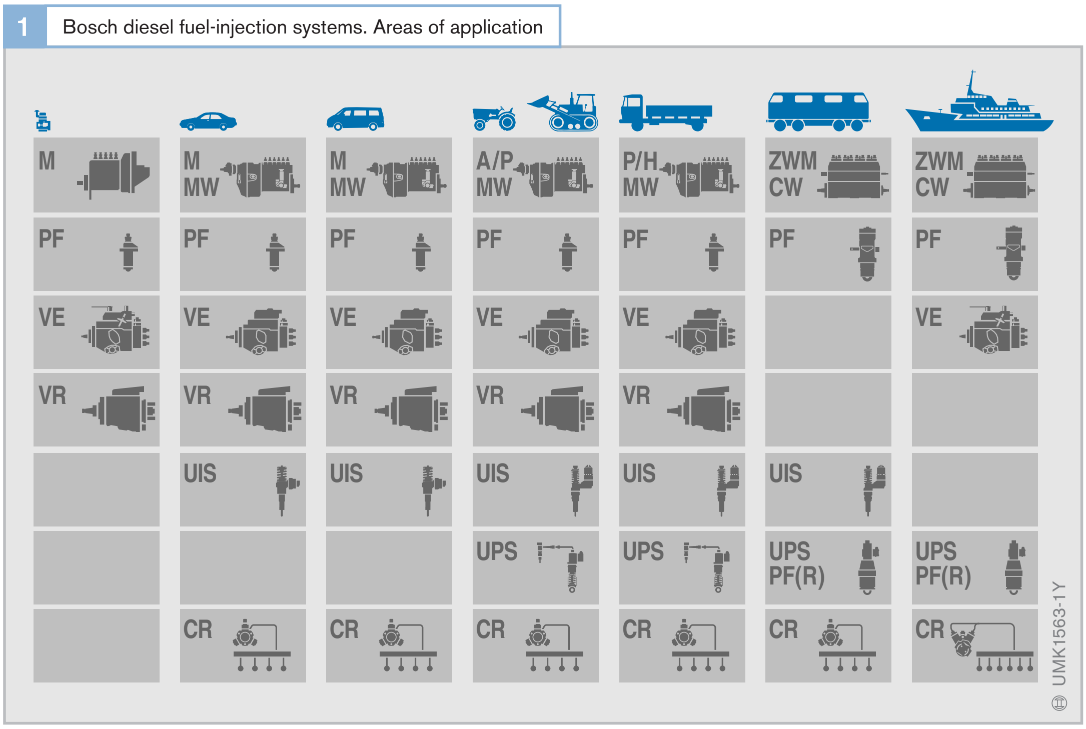


Figure 1
M, MW,
A, P, H,
ZWM,
CW In-line injection pumps in order of increasing size;
PF Single-plunger injection pumps
VE Axial-piston distributor injection pumps
VR Radial-piston distributor injection pumps
UPS Unit Pump System
UIS Unit Injector System
CR Common Rail System

1 The most important diesel-engine high-pressure fuel-injection systems: Properties and characteristic data

Fuel-injection system	Application	Fuel injection				Engine-related data			
Type	P Passenger cars and light trucks N Comm. vehs. & buses O Off-Highway[1] S Ships/Locomotives	Injected fuel quantity per stroke mm³	Max. permissible nozzle pressure bar (0.1 MPa)	PI Pilot injection POI Post Injection	m Mechanical e Electronic em Electromechanical MV Solenoid valve	DI Direct injection IDI Indirect injection	No. of engine cylinders	Max. speed min⁻¹	Max. power per engine cylinder kW
In-line injection pumps									
M	P	60	550	–	m, e	IDI	4…6	5000	20
A	O	120	750	–	m	DI/IDI	2…12	2800	27
MW	P, O	150	1100	–	m	DI	4…8	2600	36
P3000	N, O	250	950	–	m, e	DI	4…12	2600	45
P7100	N, O	250	1200	–	m, e	DI	4…12	2500	55
P8000	N, O	250	1300	–	m, e	DI	6…12	2500	55
P8500	N, O	250	1300	–	m, e	DI	4…12	2500	55
H1	N	240	1300	–	e	DI	6…8	2400	55
H1000	N	250	1350	–	e	DI	5…8	2200	70
ZWM	S	900	850	–	m	DI/IDI	6…12	1500	150
CW	S	1500	1000	–	m	DI/IDI	6…10	1600	260
Axial-piston distributor pumps									
VE … F	P	70	350	–	m	IDI	3…6	4800	25
VE … F	P	70	1205	–	m	DI	4…6	4400	25
VE … F	N, O	125	800	–	m	DI	4, 6	3800	30
VP37 (VE-EDC)	P	70	1250	–	em	DI	3…6	4400	25
VP37 (VE-EDC)	O	125	800	–	em	DI	4, 6	3800	30
VP30 (VE-M)	P	70	1400	PI	e, MV	DI	4…6	4500	25
VP30 (VE-M)	O	125	800	PI	e, MV	DI	4, 6	2600	30
Radial-piston distributor pumps									
VP44 (VR)	P	85	1850	PI	e, MV	DI	4, 6	4500	25
VP44 (VR)	N	175	1500	–	e, MV	DI	4, 6	3300	45
Single-plunger injection pumps									
PF(R)…	O	13… 120	450… 1150	–	m, em	DI/IDI	Arbitrary	4000	4… 30
PF(R)… Large diesel engines	P, N, O, S	150… 18000	800… 1500	–	m, em	DI/IDI	Arbitrary	300… 2000	75… 1000
UIS P1	P	60	2050	PI	e, MV	DI	5[2, 2a]	4800	25
UIS 30	N	160	1600	–	e, MV	DI	8[2]	4000	35
UIS 31	N	300	1600	–	e, MV	DI	8[2]	2400	75
UIS 32	N	400	1800	–	e, MV	DI	8[2]	2400	80
UPS 12	N	180	1600	–	e, MV	DI	8[2]	2400	35
UPS 20	N	250	1800	–	e, MV	DI	8[2]	3000	80
UPS (PF[R])	S	3000	1600	–	e, MV	DI	6…20	1500	500
Common Rail accumulator injection system									
CR[3]	P	100	1350	–	PI, POI[4]	DI	3…8	4800[5]	30
CR[6]	P	100	1600	–	PI, POI[7]	DI	3…8	5200	30
CR	N, S	400	1400	–	PI, POI[8]	DI	6…16	2800	200

Table 1

1 Stationary engines, building and construction machines, agricultural and forestry machines

2 With two ECUs, larger numbers of cylinders are possible

2a As from EDC16: 6 cylinders

3 1st generation

4 Pilot injection (PI) up to 90° cks before TDC; post injection (POI) possible

5 Up to 5,500 min⁻¹ during overrun

6 2nd generation

7 Pilot injection (PI) possible up to 90° cks before TDC; post injection (POI) up to 210° after TDC

8 Pilot injection (PI) up to 30° cks before TDC; post injection (POI) possible

Injection-pump designs

The diesel engine's injection system has the task of injecting the diesel fuel into the engine's cylinders at very high pressure, in the correct quantities, and at exactly the right instant in time.

Depending upon the particular combustion process, the nozzle extends into either the main or the auxilary combustion chamber. It opens at a fuel pressure which is specific to the particular injection system, and closes as soon as the pressure drops again. The major difference between the various injection systems is to be found in the high-pressure generation process.

The very high injection pressures involved necessitate the precision manufacture of all the injection components from high-tensile materials. All components must be exactly matched to each other.

Electronic closed-loop control functions enable the inclusion of numerous auxiliary functions (for instance, active surge damping, Cruise Control, and boost-pressure control).

In-line injection pumps

PE standard in-line injection pumps

The standard PE in-line injection pumps (Figure 1) have a plunger-and-barrel assembly for each engine cylinder. As the name implies, this comprises the pump barrel (1) and the corresponding pump plunger (4). The pump camshaft (7) is integrated in the pump and driven by the engine, and forces the pump plunger in the delivery direction (in this case upwards). The plunger is returned by its spring (5). The individual plunger-and-barrel assemblies (also known as pumping elements) are normally arranged in-line, and plunger lift is invariable.

During the plunger's upward travel, high-pressure generation starts when the inlet port (2) is closed by the plunger's top edge. This instant in time is termed the start of delivery. The plunger continues to move beyond this point and in doing so increases the fuel pressure to such an extent that the nozzle opens and fuel is injected into the engine cylinder.

A helix has been mechanically machined into the plunger, and as soon as it opens the inlet port the fuel pressure collapses, the nozzle needle closes and injection stops.

1 In-line fuel-injection pump: Principle of functioning

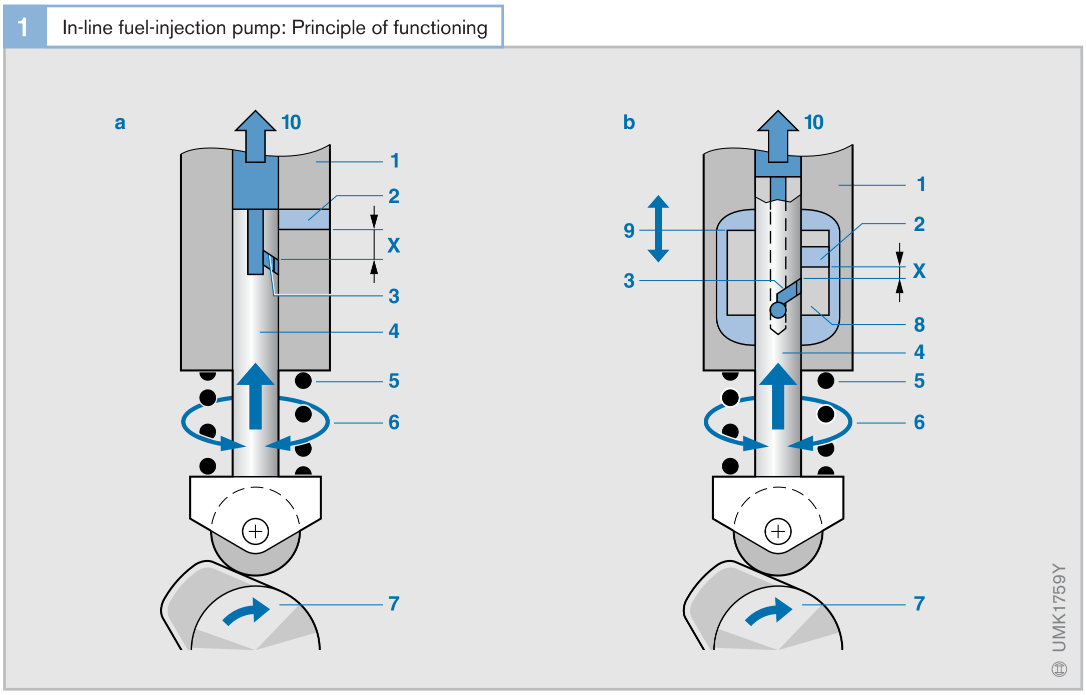


Figure 1

a	PE standard in-line injection pump
b	Control-sleeve in-line injection pump
1	Pump barrel
2	Inlet port
3	Helix
4	Pump plunger
5	Plunger return spring
6	Rotational travel due to action of control rack (injected fuel quantity)
7	Camshaft
8	Control sleeve
9	Adjustment travel due to actuating shaft (start of fuel delivery)
10	Flow of fuel to the nozzle
X	Effective stroke

2 Port-and-helix-controlled axial-piston distributor pump: Principle of functioning

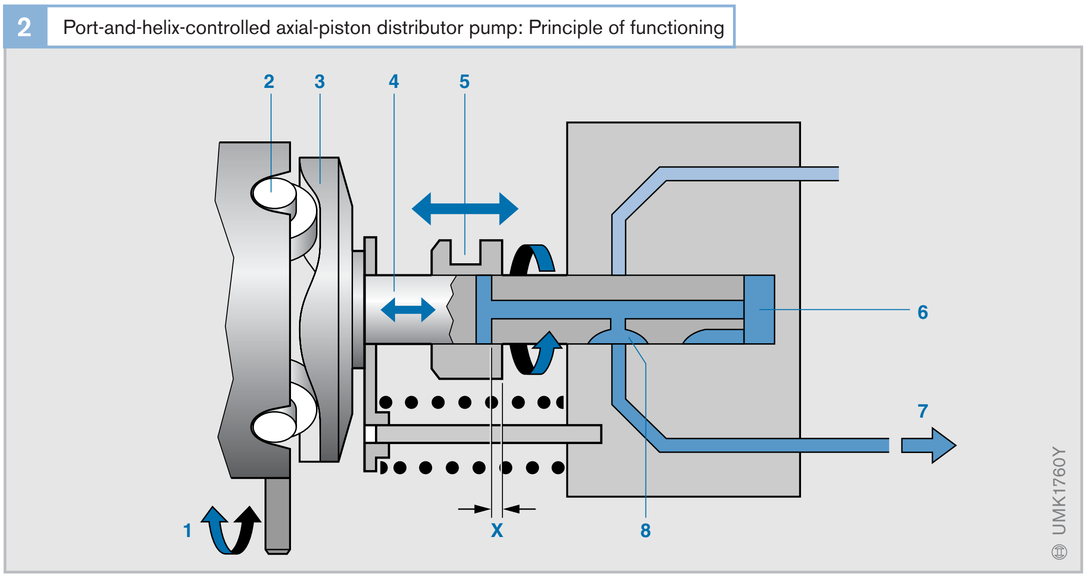


Figure 2

1	Timing-device travel on the roller ring
2	Roller
3	Cam plate
4	Axial piston
5	Control collar
6	High-pressure chamber
7	Fuel outlet to the injection nozzle
8	Metering slot
X	Effective stroke

The plunger travel between the closing and opening of the inlet port is termed the effective stroke (X).

The pump is equipped with a control rack (6) which rotates the plunger so that the position of the helix relative to the inlet port is changed. This changes the plunger's effective stroke, and along with it the injected fuel quantity. The control rack is controlled by either a mechanical (flyweight) governor or an electrical actuator mechanism.

Control-sleeve in-line injection pump

The control-sleeve in-line injection pump differs from a conventional in-line injection pump by having a “control sleeve” (Figure 1, Pos. 8) which slides up and down the pump plunger. By way of an actuator shaft (Figure 1, Pos. 9), this varies the plunger lift to (inlet) port closing, and with it the start of injection.

Since the start of injection can be varied independent of engine speed, the control-sleeve version features an additional degree of freedom compared to the standard PE in-line injection pump.

Distributor injection pumps

The distributor pump has only one plunger-and-barrel asembly for all the engine's cylinders (Figures 2 and 3). A vane-type supply pump delivers fuel to the high-pressure chamber (6). High-pressure generation is the responsibility of either an axial piston (Figure 2, Pos. 4) or several radial pistons (Figure 3, Pos. 4). A rotating distributor plunger opens and closes the metering slots (8) and spill ports, and in the process distributes the fuel to the individual engine cylinders via the injection nozzles (7). The duration of injection (injection time) can be varied using a control collar (Figure 2, Pos. 5) or a high-pressure solenoid valve (Figure 3, Pos. 5).

Axial-piston distributor pump

The drive for the cam plate (Figure 2, Pos. 3) comes from the vehicle's engine. The number of cams on the underside of the cam plate corresponds to the number of engine cylinders. These cams ride on the rollers (2) of the roller ring with the result that a rotating-reciprocating movement is imparted to the plunger. For one revolution of the driveshaft, the piston performs as many strokes as there are engine cylinders.

3 Solenoid-valve-controlled radial-piston distributor pump: Principle of functioning

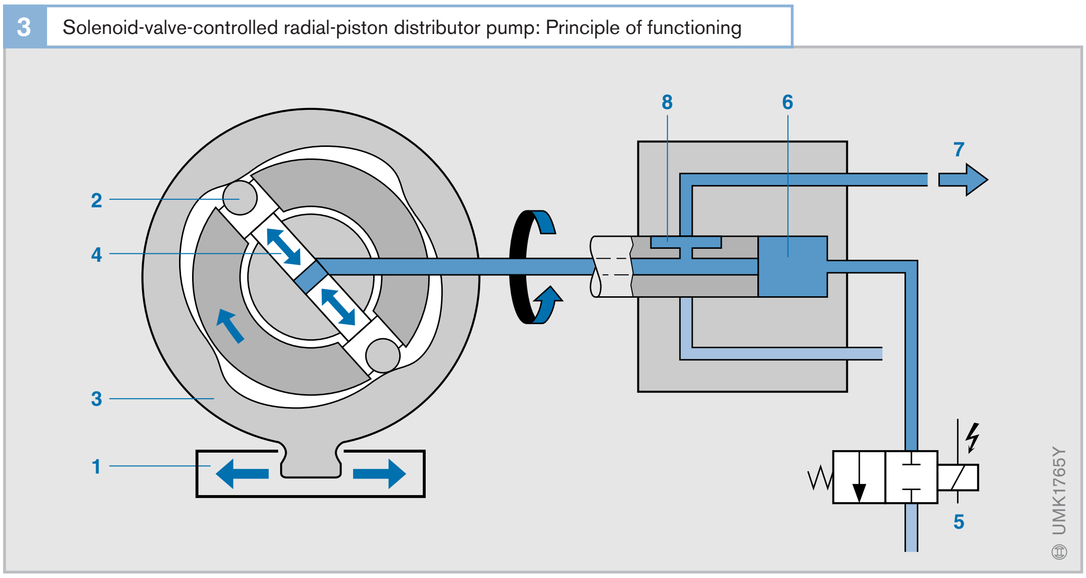


Figure 3

1 Timing device on roller ring
2 Roller
3 Cam ring
4 Radial piston
5 High-pressure solenoid valve
6 High-pressure chamber
7 Fuel outlet to the injection nozzle
8 Metering slot

On the port-and-helix-controlled VE axial-piston distributor pump with mechanical (flyweight) governor, or electronically controlled actuator, the control collar (5) defines the effective stroke and with it the injected fuel quantity.

The timing device adjusts the pump's start of delivery by rotating the roller ring (1).

Radial-piston distributor pumps

Here, instead of the cam plate as used on the axial-piston distributor pump, a radial-piston pump with cam ring (Figure 3, Pos. 3) and two to four radial pistons (4) is responsible for high-pressure generation. Higher pressures can be achieved with the radial-piston pump than with the axial-piston version, although this necessitates the pump having to be much stronger mechanically.

The cam ring is rotated by the timing device (1). On all radial-piston distributor pumps, start of injection and duration of injection (injection time) are solenoid-valve-controlled.

Solenoid-valve-controlled distributor pumps

On the solenoid-valve-controlled distributor pump, an electronically controlled high-pressure solenoid valve (5) is used to meter the injected fuel quantity and to change the start-of-injection point. With the solenoid valve closed, pressure can build up in the high-pressure chamber (6). Once the valve opens, fuel escapes so that there is no fuel-pressure buildup and no fuel is injected. The open and closed-loop control signals are generated in either one or two ECU's (pump ECU and engine ECU, or only in the pump ECU).

Single-plunger injection pumps

PF single-plunger pumps

PF single-plunger pumps are used principally for small engines, diesel locomotives, marine engines, and construction machinery. Single-plunger pumps are also suitable for operation with viscous heavy oils.

Although these pumps have no camshaft of their own (the F in their designation stands for external drive) their basic operating concept corresponds to that of the PE in-line pumps. The cams for actuating the individual PF single-plunger injection pumps are on the engine camshaft. 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 pumps are on the engine camshaft, and this means that injection timing cannot be implemented by rotating the camshaft. 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. Due to the direct connection to the engine's camshaft, this cannot be turned to implement injection timing. Instead, injection timing takes place by adjusting an intermediate element, whereby an advance angle of several angular degrees can be obtained. Adjustment is also possible using solenoid valves.

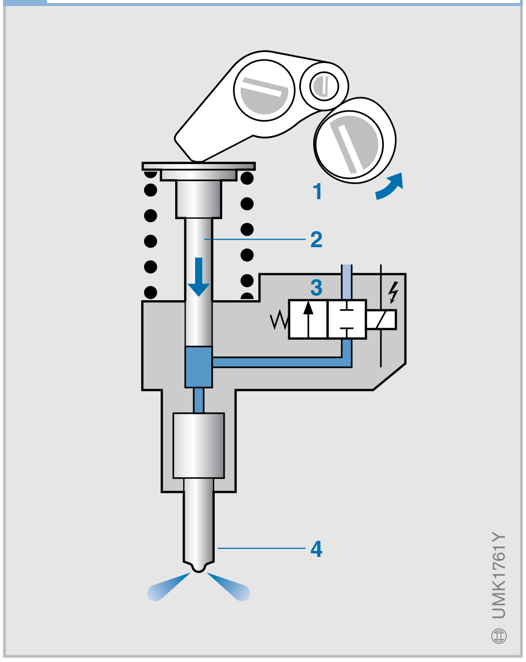
Unit-Injector System (UIS)

In the Unit Injector System (UIS), injection pump and injection nozzle form a single unit (Fig. 4). One of these units is installed in the engine's cylinder head for each engine cylinder, and driven directly by tappet or indirectly from the engine 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 high-pressure lines. The fuel-injection parameters are calculated by the ECU, and injection is controlled by opening and closing the high-pressure solenoid valve.

Unit-Pump System (UPS)

The modular Unit Pump System (UPS) uses the same operating concept as the UIS. In contrast to the UIS, pump and nozzle holder (2) are joined by a short high-pressure delivery line (3) precisely matched to the respective components. Separation of high-pressure-generation stage and nozzle holder simplifies installation at the engine. The UPS system features an injection unit for each cylinder comprised of pump, delivery line, and nozzle holder. The pump is driven from the engine's camshaft (6).
On the UPS too, injection duration and start of injection are controlled electronically by a high-speed high-pressure solenoid valve (4).

4 High-pressure components of the Unit Injector System (UIS): Principle of functioning



5 High-pressure components of the Unit Pump System (UPS): Principle of functioning

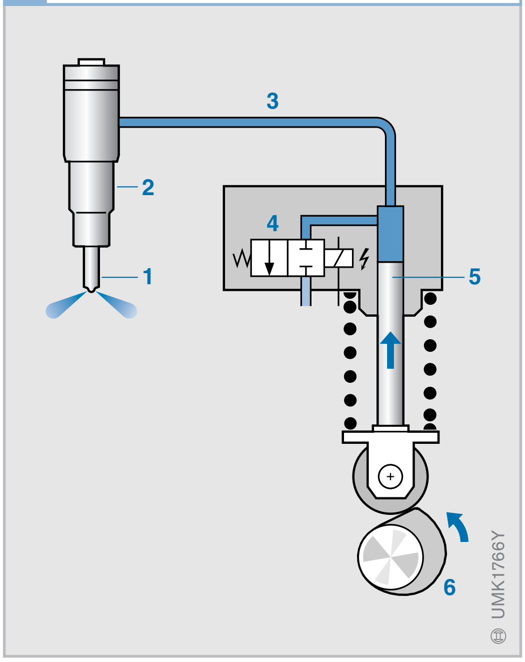


Figure 4
1 Actuating cam
2 Pump plunger
3 High-pressure solenoid valve
4 Injection nozzle

Figure 5
1 Injection nozzle
2 Nozzle holder
3 High-pressure line
4 High-pressure solenoid valve
5 Pump plunger
6 Actuating cam

Accumulator injection system

Common-Rail System CRS

In this system the processes of pressure generation and fuel injection are decoupled from each other (Figure 6). Injection pressure is generated and controlled by a high-pressure pump (1), and is for the most part independent of engine speed and injected fuel quantity. It is permanently available in the "rail" (fuel accumulator, 2) for injection.

The CRS thus provides maximum flexibility in the injection-process design.

Each engine cylinder is provided with an injector (4) which forms the injection unit. Opening and closing the high-pressure solenoid valve (3) controls the injection process. The instant of injection and the injected fuel quantity are calculated in the ECU.

6 High-pressure components of the Common Rail System (CRS): Principle of functioning

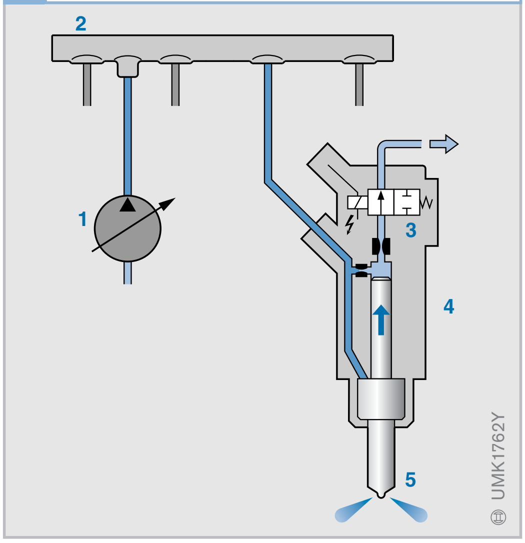


Figure 6
1 High-pressure pump
2 Rail (high-pressure fuel accumulator)
3 High-pressure solenoid valve
4 Injector
5 Injection nozzle

7 Examples of the high-pressure components as used in Bosch diesel injection systems

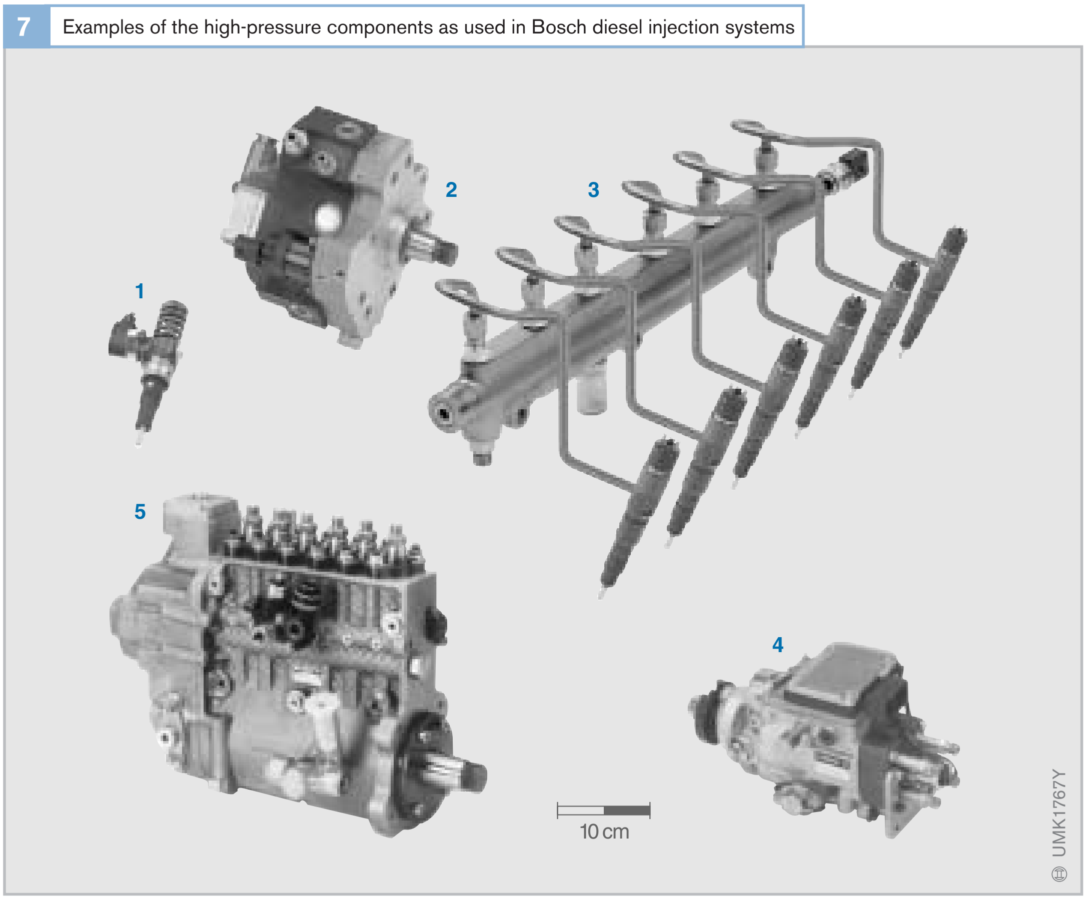


Figure 7
1 P1 Unit Injector (passenger cars)
2 CP2 Common Rail high-pressure pump (commercial vehicles)
3 Rail with injectors (commercial-vehicle CRS)
4 VP30 distributor pump (passenger cars)
5 RP39 control-sleeve in-line pump (commercial vehicles)

A brief history of diesel injection

Bosch started at the end of 1922 with the development of a fuel-injection system for diesel engines. All technical factors were favorable: Bosch had experience with internal-combustion engines, production engineering was highly developed, and above all it was possible to apply the know-how that Bosch had accumulated in the manufacture of lubrication pumps. Notwithstanding these facts, for Bosch there was considerable risk involved in this development work, and numerous challenges had to be surmounted.

The first injection pumps went into series production in 1927. At that time, the precision achieved in their manufacture was absolutely unique. They were small and of lightweight design, and were behind the diesel engine now being able to run at high speeds. These in-line pumps were installed as from 1932 in commercial vehicles, and as from 1936 in passenger cars. From this point onwards, there was not letup in the development of the diesel-engine and its injection equipment.

In 1976, the diesel engine was given a new lease of life when Bosch introduced the distributor injection pump with automatic timing device. And a decade later, after years of intensive development work to bring it to the volume-production stage, Bosch brought the Electronic Diesel Control (EDC) onto the market.

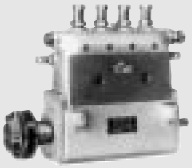
Development engineers are constantly faced with the need for the even more precise injection of minute quantities of diesel fuel, at exactly the right instant in time, and under higher and higher injection pressures. This has led to a number of innovative injection-system developments (see adjacent Figure).

The diesel engine is still at the forefront regarding fuel economy and efficient utilization of fuel.

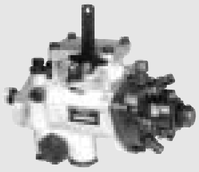
New injection systems make even better use of this potential. In addition, the internal-combustion engine's power output is continuously increasing, while its noise and emissions figures have continued to drop.

Milestones in diesel injection technology

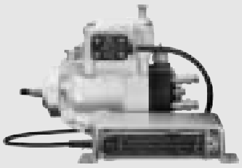
1927
First series-production in-line pump



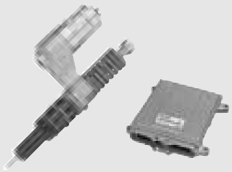
1962
First axial-piston distributor pump,
the EP-VM



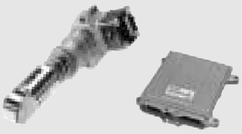
1986
The first electronically controlled axial-piston distributor pump



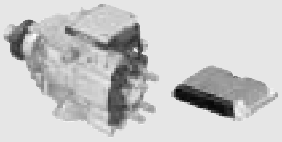
1994
First Unit Injector System (UIS) for commercial vehicles



1995
First Unit Pump System (UPS)

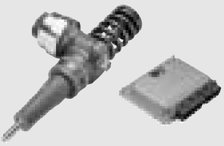


1996
First radial-piston distributor pump



1997
First Common Rail accumulator injection system (CRS)

1998
First Unit Injector System (UIS) for passenger cars



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,
- Pilot injection and possibly post injection,
- Adaptation of injected fuel quantity, boost pressure, and injected fuel quantity 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,
- Intervention from other systems (e.g. TCS),
- 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 (**O**n-**B**oard-**D**iagnosis) and EOBD (**E**uropean **O**n-**B**oard **D**iagnosis) stipulations.

System blocks

The EDC system comprises three system blocks: (Fig. 1):

1. *Sensors and desired-value generators* (1) for the detection of operating conditions (e.g. engine rpm) and of desired values (e.g. switch position). These convert the various physical quantities into electrical signals

2. *Electronic control unit (ECU)* (2) 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 (4) and to the vehicle diagnosis facility (5).

3. *Solenoid actuators* (3) 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).

1 Major EDC components

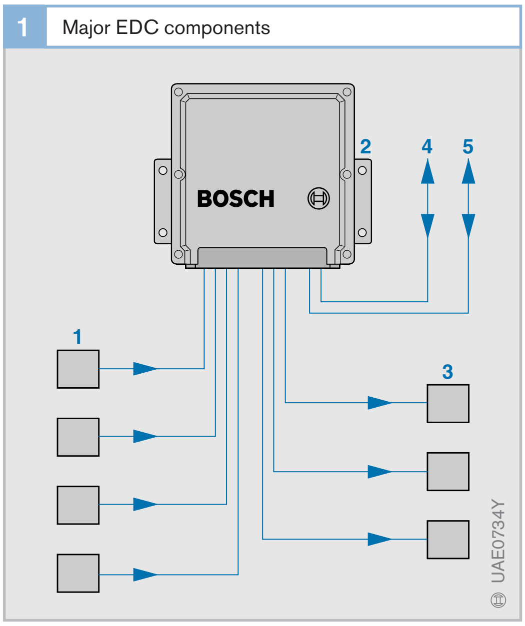
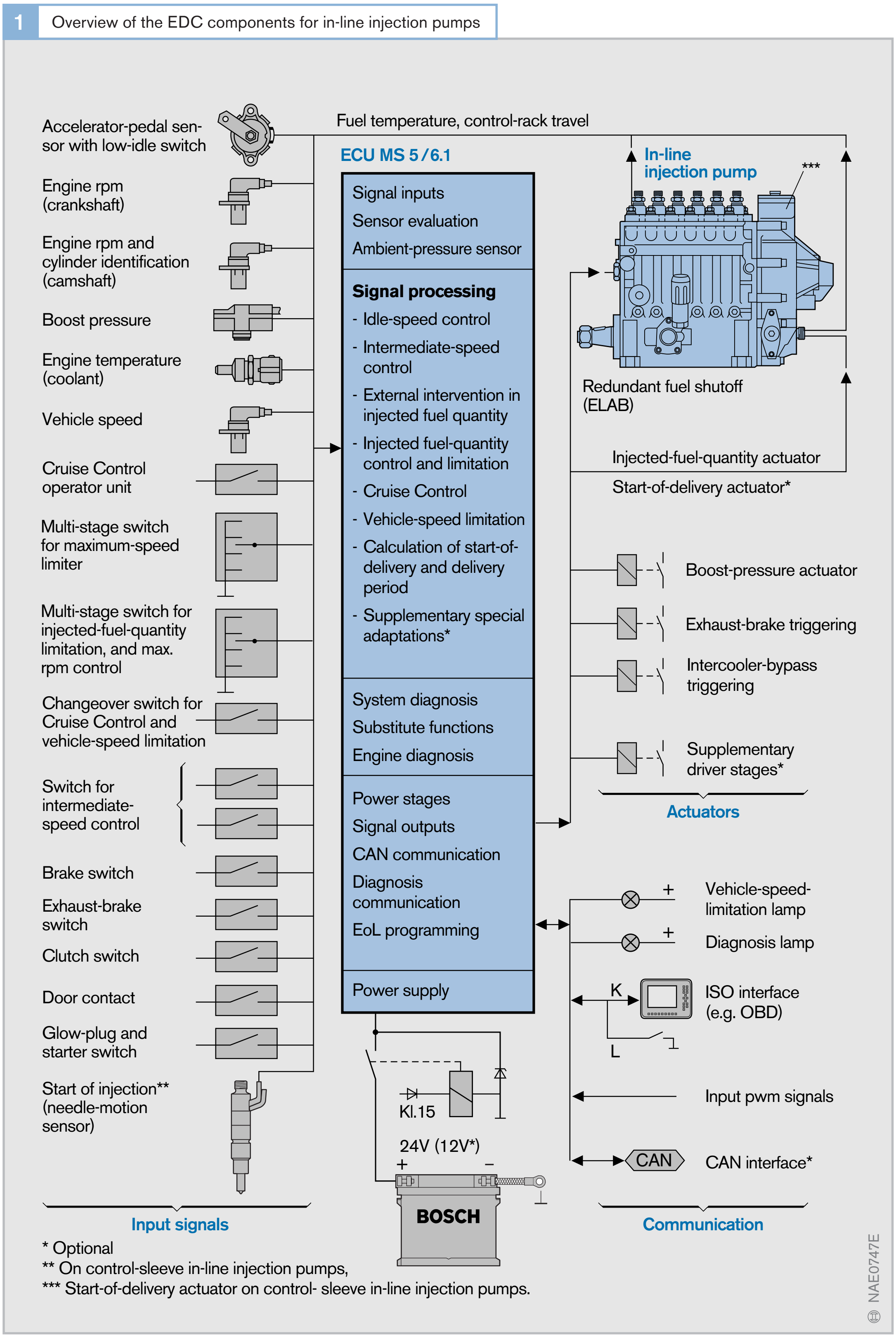


Figure 1
1 Sensors and desired-value generators (input signals)
2 ECU
3 Actuators
4 Interface to other systems
5 Diagnosis interface

In-line injection pumps

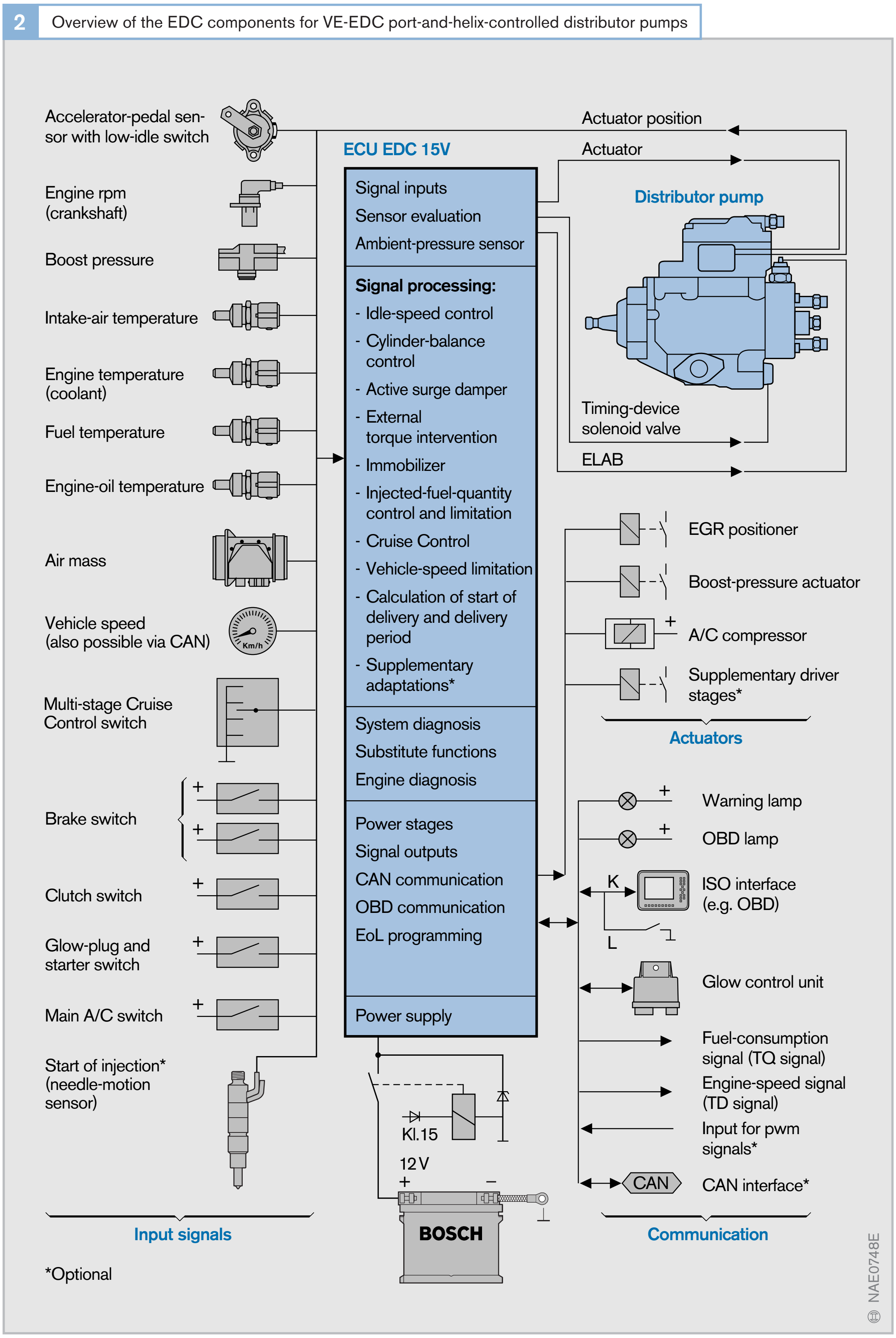
1 Overview of the EDC components for in-line injection pumps



* Optional
** On control-sleeve in-line injection pumps,
*** Start-of-delivery actuator on control- sleeve in-line injection pumps.

Port-and-helix-controlled axial-piston distributor pumps

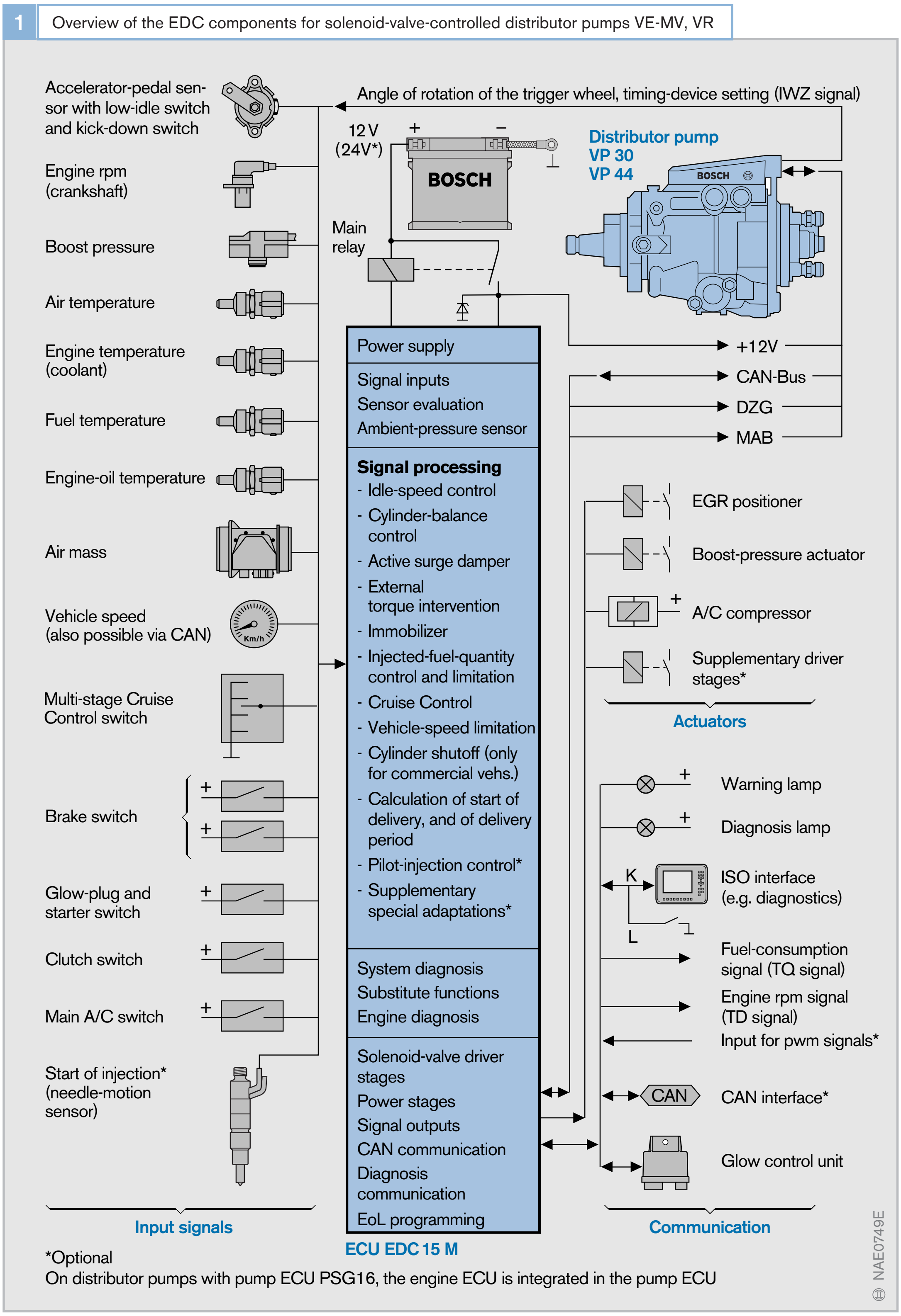
2 Overview of the EDC components for VE-EDC port-and-helix-controlled distributor pumps



*Optional

Solenoid-valve-controlled axial-piston and radial-piston distributor pumps

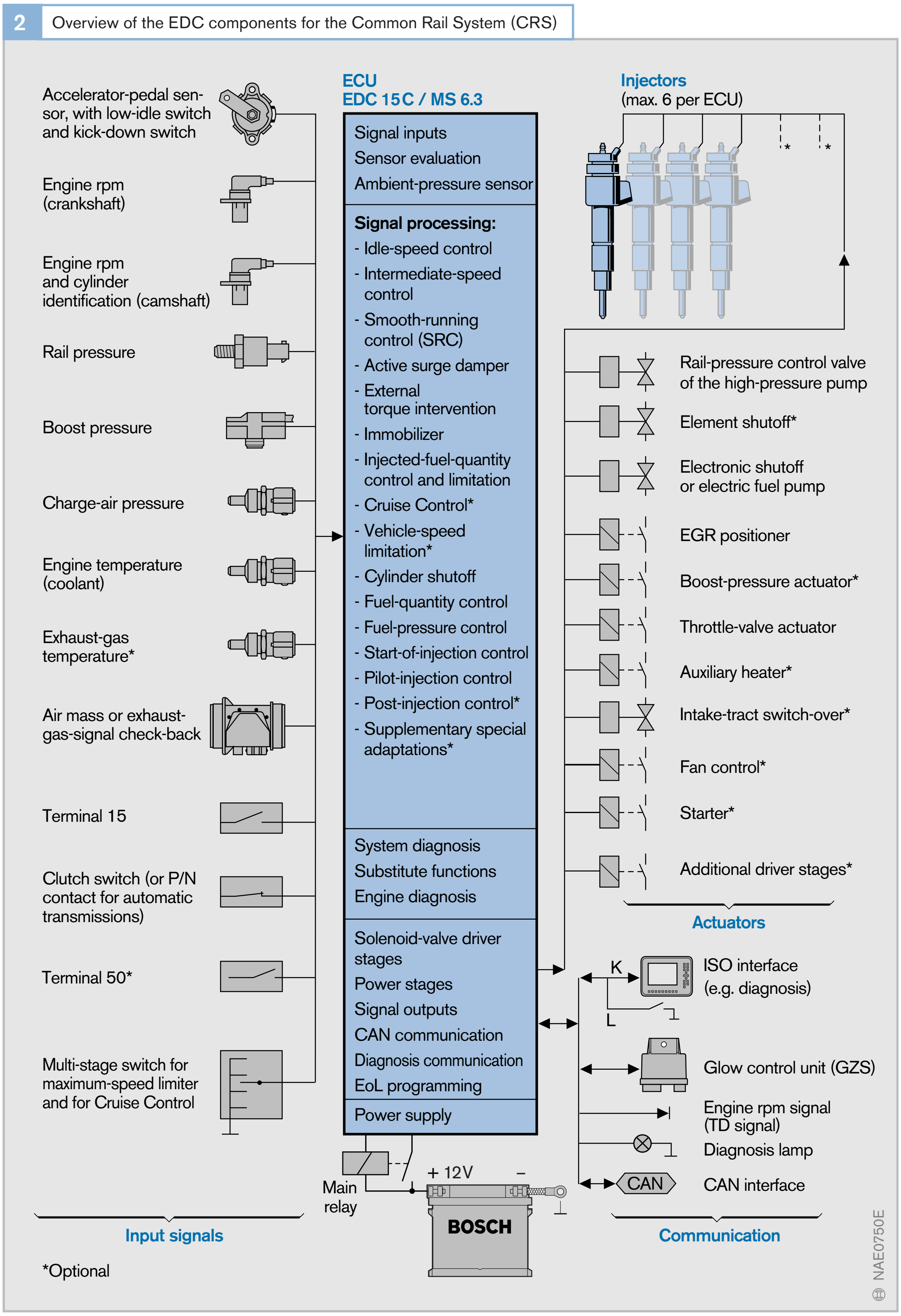
1 Overview of the EDC components for solenoid-valve-controlled distributor pumps VE-MV, VR



*Optional
On distributor pumps with pump ECU PSG16, the engine ECU is integrated in the pump ECU

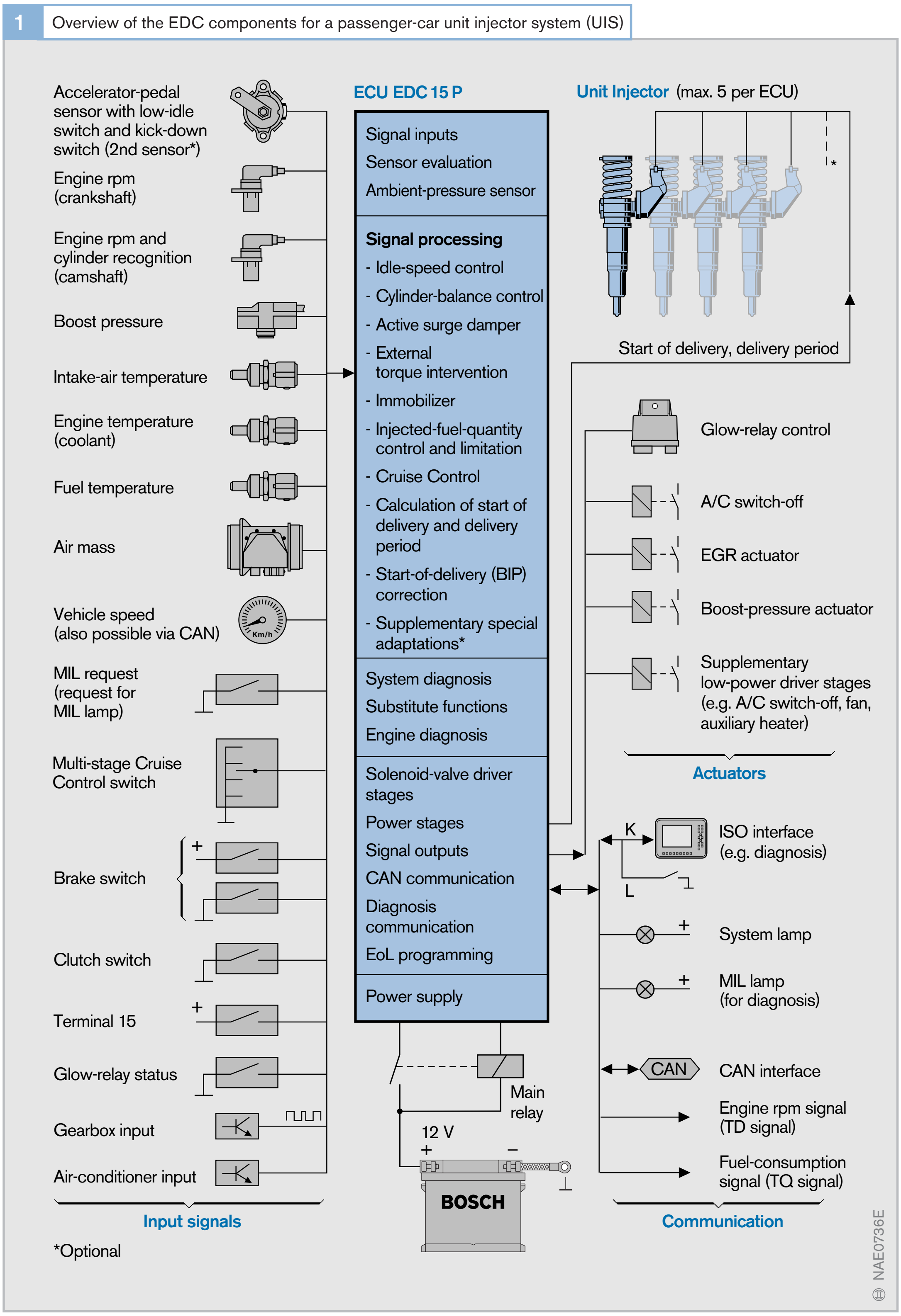
Common Rail System (CRS)

2 Overview of the EDC components for the Common Rail System (CRS)



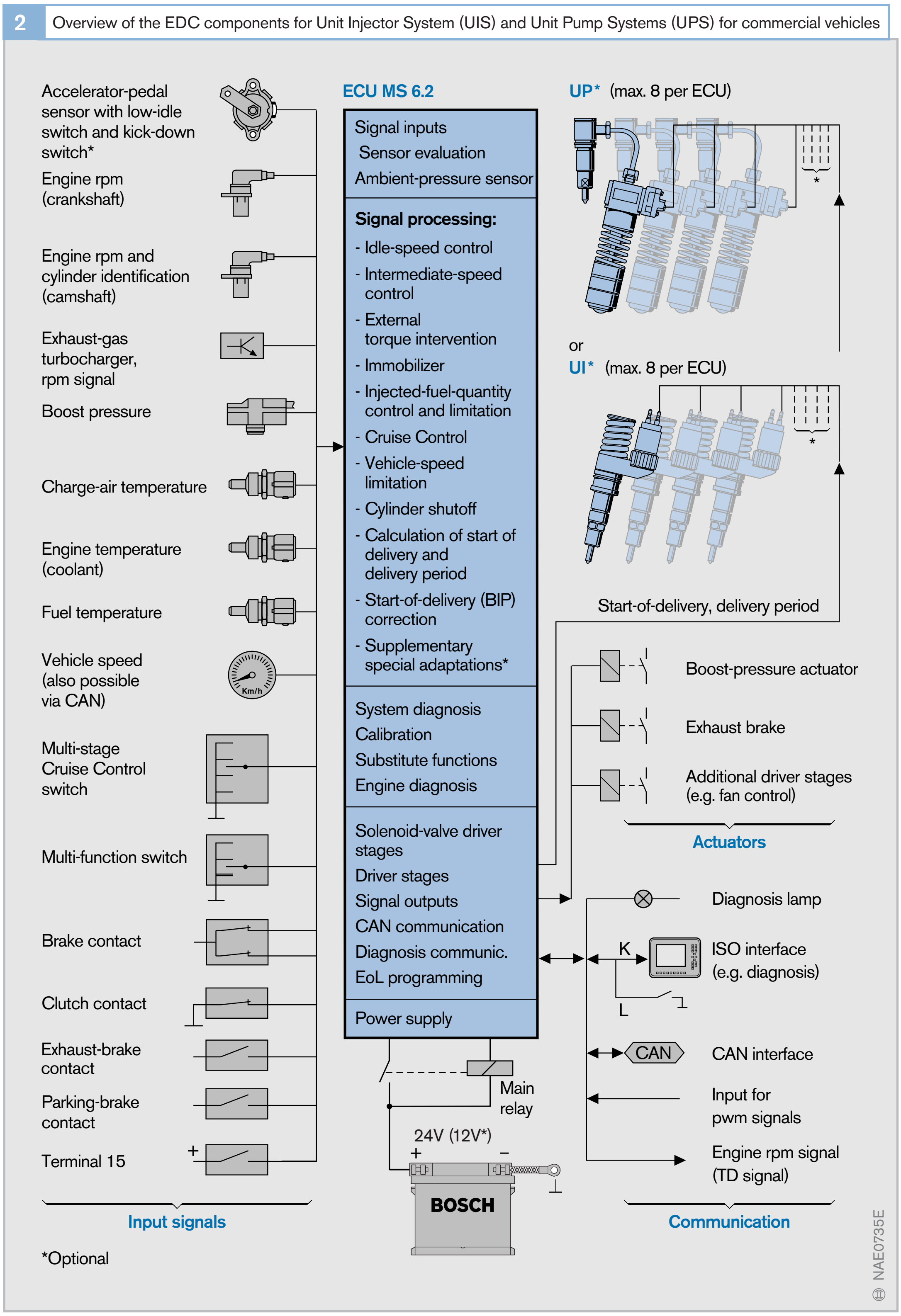
Unit Injector System (UIS) for passenger cars

1 Overview of the EDC components for a passenger-car unit injector system (UIS)



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

2 Overview of the EDC components for Unit Injector System (UIS) and Unit Pump Systems (UPS) for commercial vehicles



Sensors

Sensors register operating states (e.g. engine speed) and setpoint/desired values (e.g. accelerator-pedal position). They convert physical quantities (e.g. pressure) or chemical quantities (e.g. exhaust-gas concentration) into electric signals.

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 (for instance, the Engine Management, the Electronic Stability Program ESP, and the air conditioner). As a rule, a matching circuit in the sensor converts the signals so that they can be processed by the ECU.

The field of mechatronics, in which mechanical, electronic, and data-processing components are interlinked and cooperate closely with each other, is rapidly gaining in importance. They are integrated in modules (e.g. in the crankshaft CSWS (Composite Seal with Sensor) module complete with rpm sensor).

Since their output signals directly affect not only the engine's power output, torque, and emissions, but also vehicle handling and safety, sensors, although they are becoming smaller and smaller, must also fulfill demands that they be faster and more precise. These stipulations can be complied with thanks to mechatronics.

Depending upon the level of integration, signal conditioning, analog/digital conversion, and self-calibration functions can all be integrated in the sensor (Fig. 1), and in future a small microcomputer for further signal processing will be added. The advantages are as follows:

- Lower levels of computing power are needed in the ECU,
- A uniform, flexible, and bus-compatible interface becomes possible for all sensors,
- Direct multiple use of a given sensor through the data bus,
- Registration of even smaller measured quantities,
- Simple sensor calibration.

1 Sensor integration levels

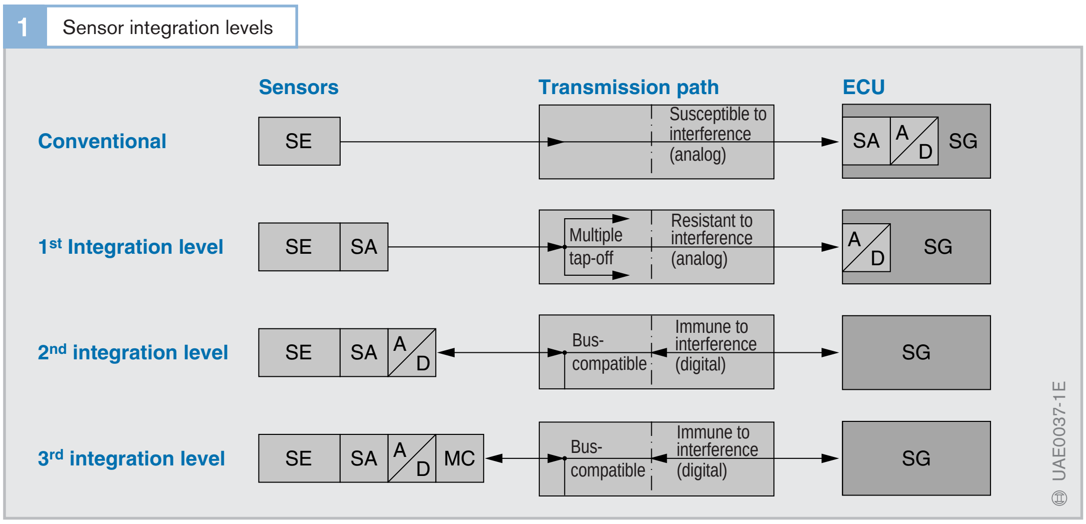


Figure 1
SE Sensor(s)
SA Analog signal conditioning
A/D Analog-digital converter
SG Digital ECU
MC Microcomputer (evaluation electronics)

1 Coolant-temperature sensor

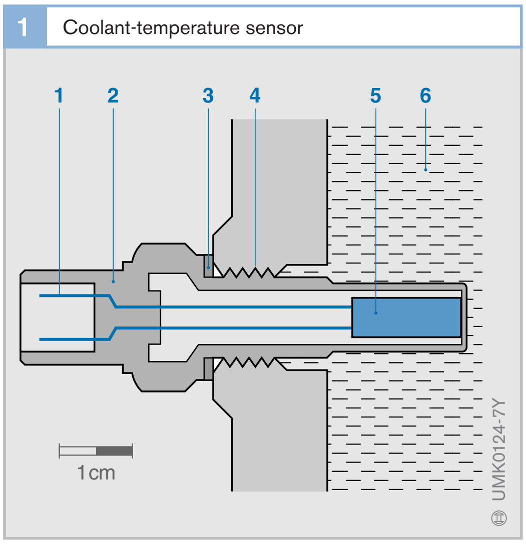
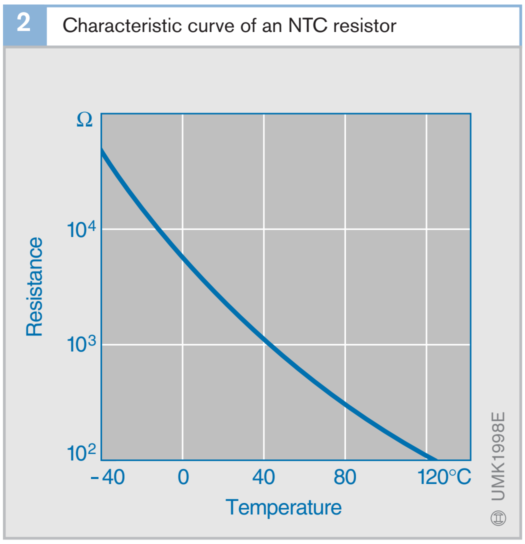


Figure 1

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

2 Characteristic curve of an NTC resistor



Temperature sensors

Applications

Engine-temperature sensor

This is incorporated in the coolant circuit and measures the coolant temperature as an indication of engine temperature (Fig. 1). This information is needed for the engine-management system. The measurable temperature range is between – 40 and +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 between – 40 and +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 between – 40 and +170 °C.

Fuel-temperature sensor

This sensor is installed in the low-pressure stage of the fuel system. The fuel temperature is an important factor in precisely defining the correct injected fuel quantity. The measurable temperature range is between – 40 and +120 °C.

Exhaust-gas temperature sensor

This sensor is installed at a point in the exhaust system which is critical with regard to temperature. It is used in the control of the exhaust-gas treatment system. Platinum is usually used for the measuring resistor. The measurable temperature range is between – 40 and +1000 °C.

Design and operating concept

Depending upon the particular application, these temperature sensors are available in a variety of different shapes and versions. A temperature-dependent semiconductor measuring resistor is mounted inside the sensor housing. This resistor is usually of the NTC (**N**egative **T**emperature **C**oefficient) type, or less commonly of the PTC (**P**ositive **T**emperature **C**oefficient) type. In other words, when subjected to increasing temperature, its electrical resistance decreases (NTC) or increases (PTC) dramatically.

The measuring resistor is part of a voltage-distributor circuit to 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 incorporates a characteristic curve which allocates a specific temperature to each output-voltage value or resistance (Fig. 2, Page 21).

Micromechanical pressure sensors

Applications

Intake-manifold sensor or boost-pressure sensor

This sensor measures the absolute pressure in the intake manifold (typically 250 kPa or 2.5 bar) between the supercharger and the engine. The 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.

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 the differences in atmospheric pressure encountered at different altitudes to be taken into account. The atmospheric-pressure sensor measures absolute pressure (60...115 kPa, 0.6...1.15 bar).

Oil-pressure and fuel-pressure sensors

Oil-pressure sensors are 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 element's high resistance to the measured medium means that it can also be used for the fuel-pressure measurement in the fuel-system low-pressure stage. The sensor is fit-

1 Sensor element of a pressure sensor with reference vacuum on the component-buildup side (schematic)

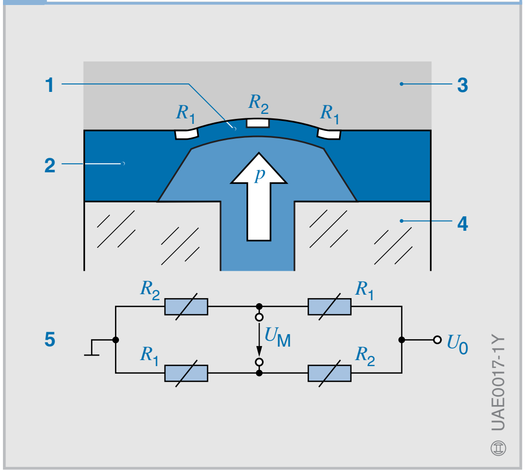


Figure 1
1 Diaphragm
2 Silicon chip
3 Reference vacuum
4 Glass (Pyrex)
5 Wheatstone bridge
p Measured pressure
U_0 Supply voltage
U_M Measurement voltage
R_1 Measuring resistors (compressed) and
R_2 Measuring resistors (stretched)

2 Sensor element of the pressure sensor with cap and reference vacuum on the component side (design)

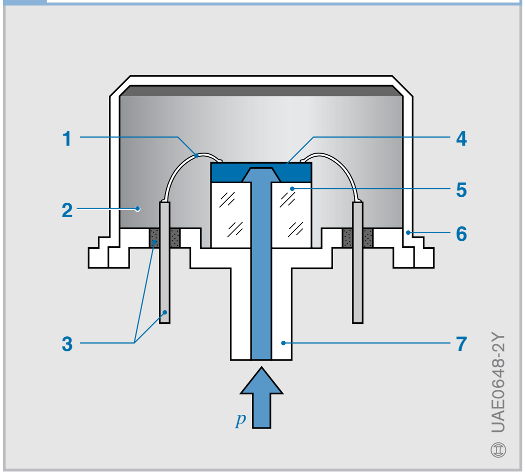
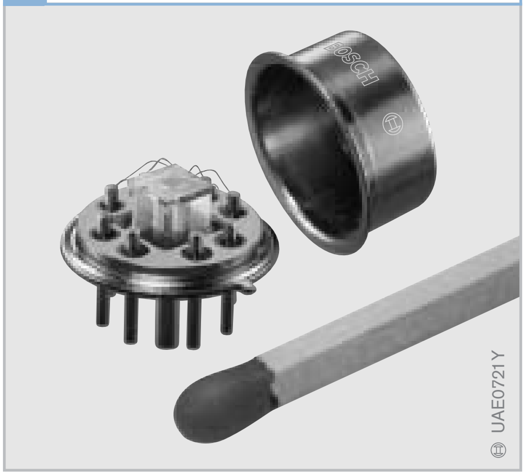


Figure 2
1, 3 Electrical connections with glass-enclosed lead-in
2 Reference vacuum
4 Sensor element (chip) with evaluation electronics
5 Glass base
6 Cap
7 Pressure connection for measured pressure p

3 Sensor element of the pressure sensor with cap and reference vacuum on the component side



ted either in the fuel filter or on it, and its signal is used to monitor the degree of fuel contamination (measuring range 20...400 kPa or 0.2...4 bar).

Design with the reference vacuum on the component side

Design

The measuring element is the heart of the micromechanical pressure sensor, and is comprised of a silicon chip (Fig. 1, Pos. 2) into which a thin diaphragm (1) has been etched micromechanically. Four measuring resistors (R_1, R_2), whose electrical resistances change when mechanical pressure is applied, are arranged on the diaphragm. On its structure side, the sensor element is surrounded and sealed off by a cap which encloses the reference vacuum (Figs. 2 and 3). A *temperature sensor* can also be integrated in the pressure sensor (Fig. 4, Pos. 1), whose signals can be evaluated separately. This has the advantage that only a single sensor housing is needed when both temperature and pressure are to be measured.

Operating concept

The sensor-element diaphragm bends by several µm (10...1000 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 silicon chip 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_M 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 sensor sensitivity.

4 Micromechanical pressure sensor with reference vacuum on the component side

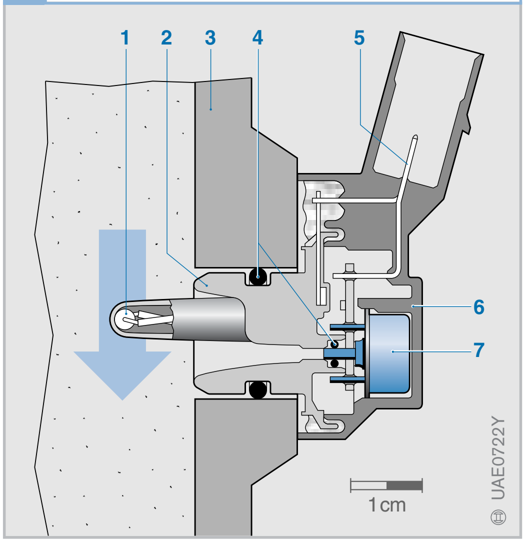
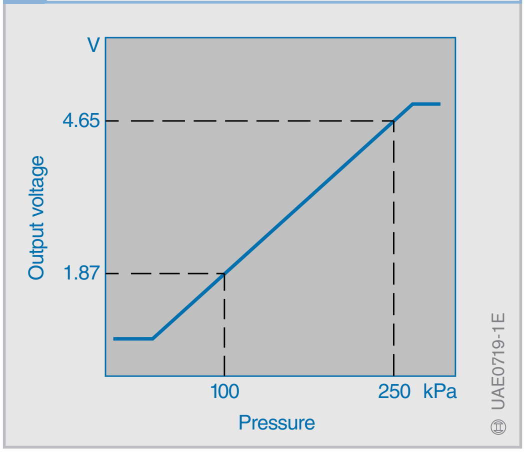


Figure 4
1 Temperature sensor (NTC),
2 Housing base
3 Intake-manifold wall
4 O-rings
5 Electrical plug-in connection
6 Housing cover
7 Sensor element

5 Characteristic curve of a micromechanical boost-pressure sensor (example)



The component side of the diaphragm to which no pressure is applied is subjected to a reference vacuum (Fig. 2, Pos. 2) so that the sensor measures absolute pressure.

The signal-conditioning electronics are integrated on the chip and have 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) it is inputted to the ECU which uses it to calculate the pressure curve (Fig. 5).

Version with the reference vacuum in a cavity

Design

The *pressure sensor* with reference vacuum inside a cavity (Figs. 6 and 8) is used as an intake-manifold or boost-pressure sensor. It is simpler in design than the version with the reference vacuum on the component side. A silicon chip with etched diaphragm and four measuring resistors in a bridge circuit is mounted as the sensor element on a glass base similar to the sensor version with cap and reference vacuum on the component side. In contrast to the latter version though, there is no hole in the cavity-type sensor's glass base for transmitting the measured pressure from the sensor's rear side to the sensor element. Instead, pressure is applied to the silicon chip at the side containing the evaluation electronics. This side must therefore be sealed off with a special gel to protect it against environmental effects (Fig. 7, Pos. 1). The reference vacuum is located in the hollow space (cavity) between the silicon chip (6) and the glass base (3). The complete measuring element is mounted on the ceramic hybrid (4) which is provided with solder surfaces for connections within the sensor.

It is also possible to integrate a *temperature sensor* inside the pressure sensor's housing. This extends into the air stream and is thus able to react extremely quickly to temperature changes.

Operating concept

Operating concept, signal conditioning and amplification, as well as the characteristic curve, are all identical to those of the sensor with cap and reference vacuum on the component side. The sole difference is that the sensor-element's diaphragm, and with it the measuring resistors, is deformed in the opposite direction.

6 Micromechanical pressure sensor with reference vacuum in a cavity

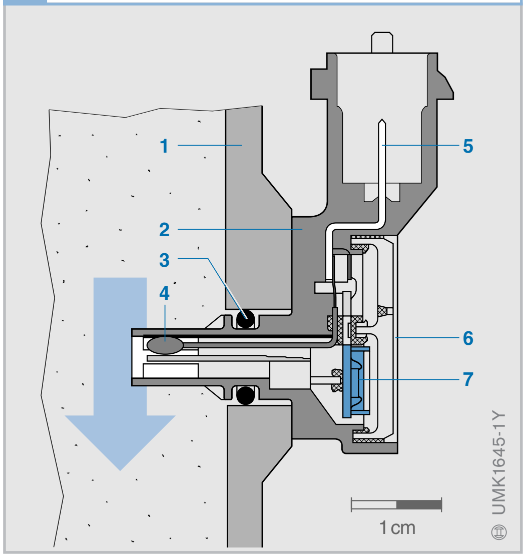


Figure 6
1 Intake-manifold wall
2 Housing
3 Seal ring
4 Temperature sensor (NTC)
5 Electrical plug-in connection
6 Housing cover
7 Sensor element

7 Sensor element with reference vacuum in a cavity

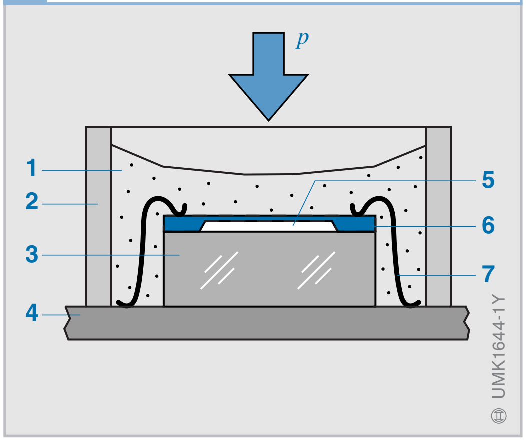


Figure 7
1 Protective gel
2 Gel frame
3 Gass base
4 Ceramic hybrid
5 Cavity with reference vacuum
6 Sensor element (chip) with evaluation electronics
7 Bonded connection
p Measured pressure

8 Micromechanical pressure sensor with reference vacuum in a cavity and integrated temperature sensor

Rail-pressure sensors

Application

In the Common-Rail injection system and the gasoline direct-injection system MED-Motronic, these sensors are used to measure the fuel pressure in the high-pressure fuel accumulator (or rail, from which the system took its name). Strict compliance with the stipulated fuel pressure is of extreme importance with regard to emissions, noise, and engine power. The fuel pressure is regulated in a control loop, and deviations from the desired pressure level are compensated for by a pressure-control valve.

The rail-pressure sensors feature very tight tolerances, and in the main measuring range the measuring accuracy is better than 2% of the measuring range.

These rail-pressure sensors are used in the following engine systems:

- *Common-Rail diesel injection system (CRS)*
  Maximum operating pressure $p_{\max}$ (rated pressure) is 160 MPa (1600 bar).
- *Gasoline direct injection MED-Motronic*
  For this gasoline direct-injection system, operating pressure is a function of load and rotational speed, and is 5...12 MPa (50...120 bar).

Design and operating concept

The heart of this sensor is a steel diaphragm on which measuring resistors in the form of a bridge circuit have been vapor-deposited (Fig. 1, Pos. 3). The sensor's measuring range is a function of diaphragm thickness (thicker diaphragms for higher pressures, thinner diaphragms for lower pressures). As soon as the pressure to be measured is applied to the diaphragm through the pressure connection (Fig. 1, Pos. 4), this bends and causes a change in the resistance of the measuring resistors (approx. 20 µm at 1500 bar). The output voltage generated by the bridge is in the range 0...80 mV and is inputted to the evaluation circuit (2) in the sensor. This amplifies the bridge signal to 0...5 V and transmits it to the ECU which uses it together with a stored characteristic curve to calculate the pressure (Fig. 2).

1 Rail-pressure sensor

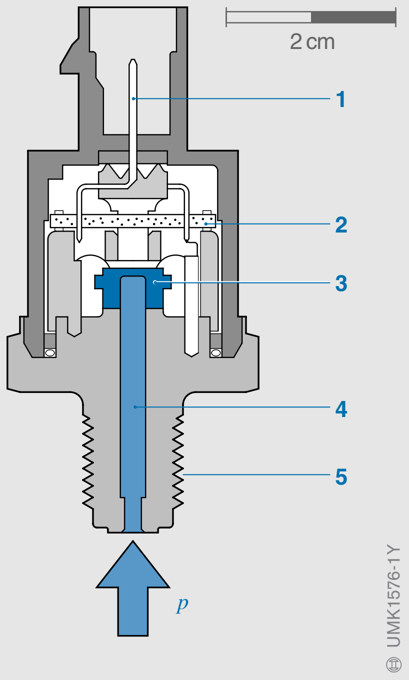
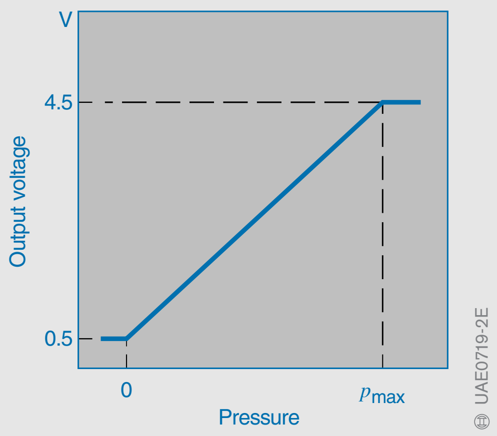


Figure 1
1 Electrical plug-in connection
2 Evaluation circuit
3 Steel diaphragm with measuring resistors
4 Pressure connection
5 Mounting thread

2 Rail-pressure sensor: Characteristic curve



Inductive engine-speed (rpm) sensors

Applications

Such engine-speed sensors are used for measuring:

- Engine rpm,
- Crankshaft position (for information on the position of the engine pistons).

The rotational speed is calculated from the intervals between the signals from the rpm sensor. The output signal from the rpm 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 (Fig. 1, Pos. 7) from which it is separated by a narrow air gap. It has 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. 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 (Fig. 2). The amplitude of the AC voltage increases strongly along with increasing trigger-wheel speed (several mV...>100 V). At least about 30 rpm are needed to generate an adequate signal level.

1 Inductive rpm sensor (principle)

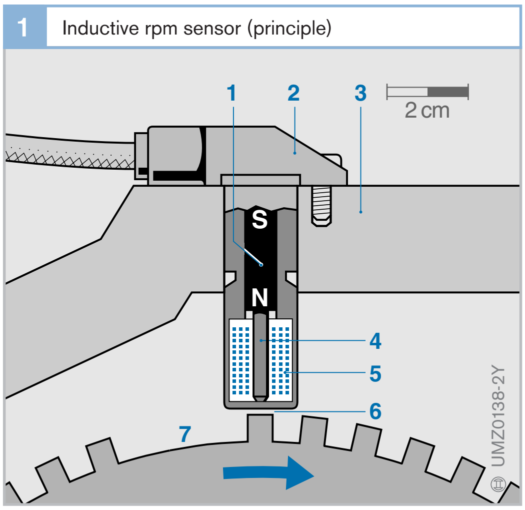


Figure 1
1 Permanent magnet
2 Sensor housing
3 Engine block
4 Pole pin
5 Solenoid winding
6 Air gap
7 Trigger wheel with reference-mark gap

2 Signal from an inductive rpm sensor

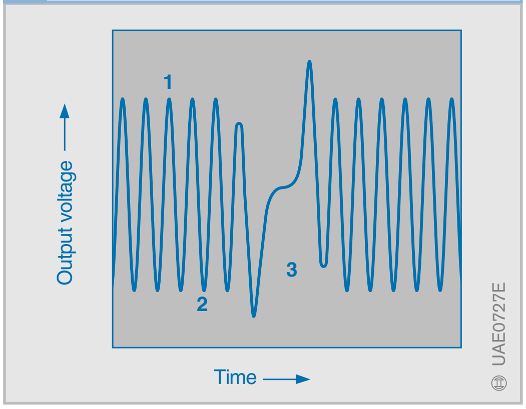


Figure 2
1 Tooth
2 Tooth gap
3 Reference mark

The number of teeth on the trigger wheel depends upon the particular application. On solenoid-valve-controlled engine-management systems for instance, a 60-pitch trigger wheel is normally used, although 2 teeth are omitted (Fig. 1, Pos. 7) so that the trigger wheel has 60 – 2 = 58 teeth. The very large tooth gap (7) is allocated to a defined crankshaft position and serves as a reference mark for synchronizing the ECU.

There is another version of the trigger wheel which has one tooth per engine cylinder. In the case of a 4-cylinder engine, therefore, the trigger wheel has 4 teeth, and 4 pulses are generated per revolution.

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.

Rotational-speed (rpm) sensors and incremental angle-of-rotation sensors

Application

The above sensors are installed in distributor injection pumps with solenoid-valve control. Their signals are used for:

- The measurement of the injection pump's speed,
- Determining the instantaneous angular position of pump and camshaft,
- Measurement of the instantaneous setting of the timing device.

The pump speed at a given instant is one of the input variables to the distributor pump's ECU which uses it to calculate the triggering time for the high-pressure solenoid valve, and, if necessary, for the timing-device solenoid valve.

The triggering time for the high-pressure solenoid valve must be calculated in order to inject the appropriate fuel quantity for the particular operating conditions. The cam plate's instantaneous angular setting defines the triggering point for the high-pressure solenoid valve. Only when triggering takes place at exactly the right cam-plate angle, can it be guaranteed that the opening and closing points for the high-pressure solenoid valve are correct for the particular cam lift. Precise triggering defines the correct start-of-injection point and the correct injected fuel quantity.

The correct timing-device setting as needed for timing-device control is ascertained by comparing the signals from the camshaft rpm sensor with those of the angle-of-rotation sensor.

Design and operating concept

The rpm sensor, or the angle-of-rotation sensor, scans a toothed pulse disc with 120 teeth which is attached to the distributor pump's driveshaft. There are tooth gaps, the number of which correspond to the number of engine cylinders, evenly spaced around the disc's circumference. A double differential magnetoresistive sensor is used.

Magnetoresistors are magnetically controllable semiconductor resistors and similar in design to Hall-effect sensors.

The double differential sensor has four resistors connected to form a full bridge circuit. The sensor has a permanent magnet, the magnet pole face opposite the toothed pulse disc being homegenized by a thin ferromagnetic wafer on which are mounted the four magnetoresistors, separated from each other by half a tooth gap. This means that alternately there are two magnetoresistors opposite tooth gaps and two opposite teeth (Fig. 1). The magnetoresistors for automotive applications are designed for operation in temperatures of ≤ 170 °C (≤ 200 °C briefly).

1 Rotational-speed/angle-of-rotation sensor

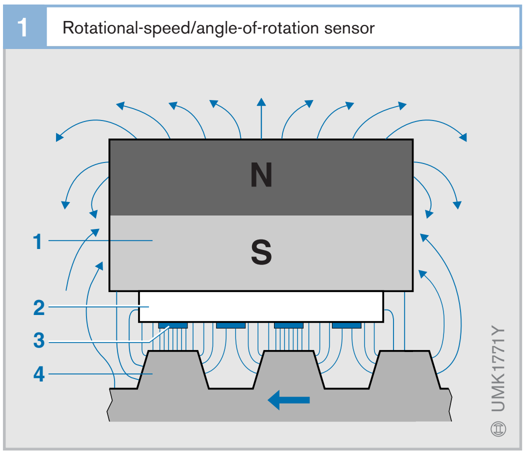


Figure 1
1 Magnet
2 Homogenization wafer (Fe)
3 Magnetoresistor
4 Toothed pulse disc

2 Rotational-speed/angle-of-rotation sensor (installed)

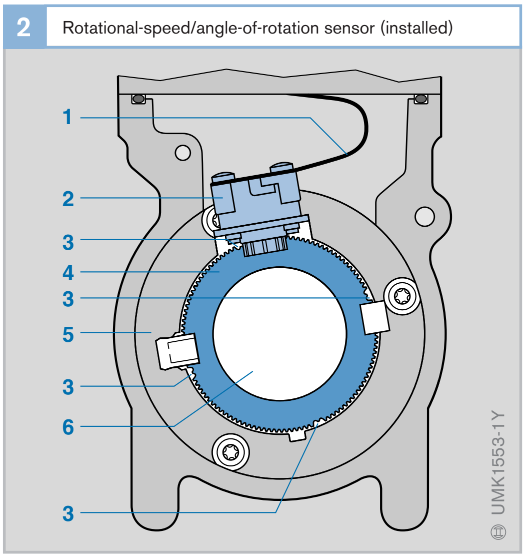


Figure 2
1 Flexible conductive strip
2 Rotational-speed (rpm)/angle-of-rotation sensor
3 Tooth gap
4 Toothed pulse disc (trigger wheel)
5 Rotatable mounting ring
6 Driveshaft

Hall-effect phase sensors

Application

The engine's camshaft rotates at half the crankshaft speed. Taking a given piston on its way to TDC, the camshaft's rotational position is an indication whether the piston is in the compression or exhaust stroke. The phase sensor on the camshaft provides the ECU with this information.

Design and operating concept

Hall-effect rod sensors

As the name implies, such sensors (Fig. 2a) make use of the Hall effect. A ferromagnetic trigger wheel (with teeth, segments, or perforated rotor, Pos. 7) rotates with the camshaft. The Hall-effect IC (6) is located between the trigger wheel and a permanent magnet (5) which generates a magnetic field perpendicular to the Hall element.

If one of the trigger-wheel teeth (Z) now passes the current-carrying rod-sensor element (semiconductor wafer), it changes the field strength. This causes the electrons, which are driven by a longitudinal voltage across the element, to be deflected perpendicularly to the direction of current (Fig. 1, angle α).

This results in a voltage signal (Hall voltage) in the millivolt range, which is independent of the relative speed between sensor and trigger wheel. The evaluation-electronics stage integrated in the sensor's Hall IC conditions the signal and outputs it in the form of a rectangular-pulse signal (Fig. 2b "High"/"Low").

Differential Hall-effect rod sensors

Rod sensors operating as per the differential principle are provided with two Hall elements. These elements are offset from each other either radially or axially (Fig. 3, S1 and S2), and generate an output signal which is proportional to the difference in magnetic flux at the element measuring points. A two-track perforated plate (Fig. 3a) or a two-track trigger wheel (Fig. 3b) are needed in order to generate the opposing signals in the Hall elements (Fig. 4) as needed for this measurement.

Such sensors are used when particularly severe demands are made on accuracy. Further advantages are their relatively wide air-gap range and good temperature-compensation characteristics.

1 Hall element (Hall-effect vane switch)

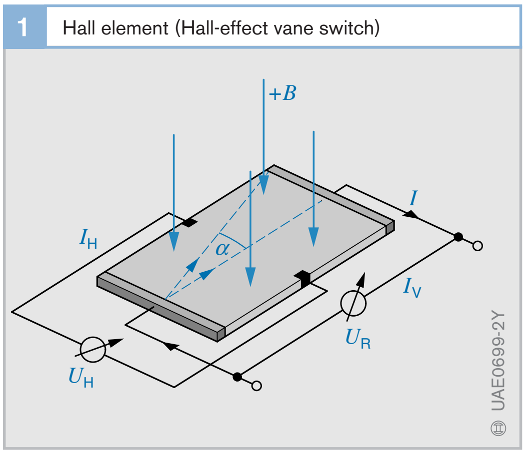


Figure 1

I	Wafer current
I_H	Hall current
I_V	Supply current
U_H	Hall voltage
U_R	Longitudinal voltage
B	Magnetic induction
α	Deflection of the electrons by the magnetic field

2 Hall-effect rod sensor

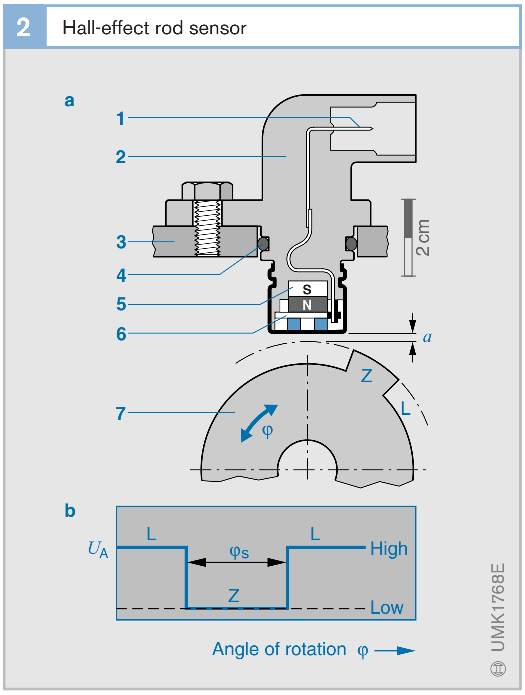


Figure 2

a	Positioning of sensor and single-track trigger wheel
b	Output signal characteristic U_A
1	Electrical plug-in connection
2	Sensor housing
3	Engine block
4	Seal ring
5	Permanent magnet
6	Hall-IC
7	Trigger wheel with tooth/segment (Z) and gap (L)
a	Air gap,
φ	Angle of rotation

3 Differential Hall-effect rod sensors

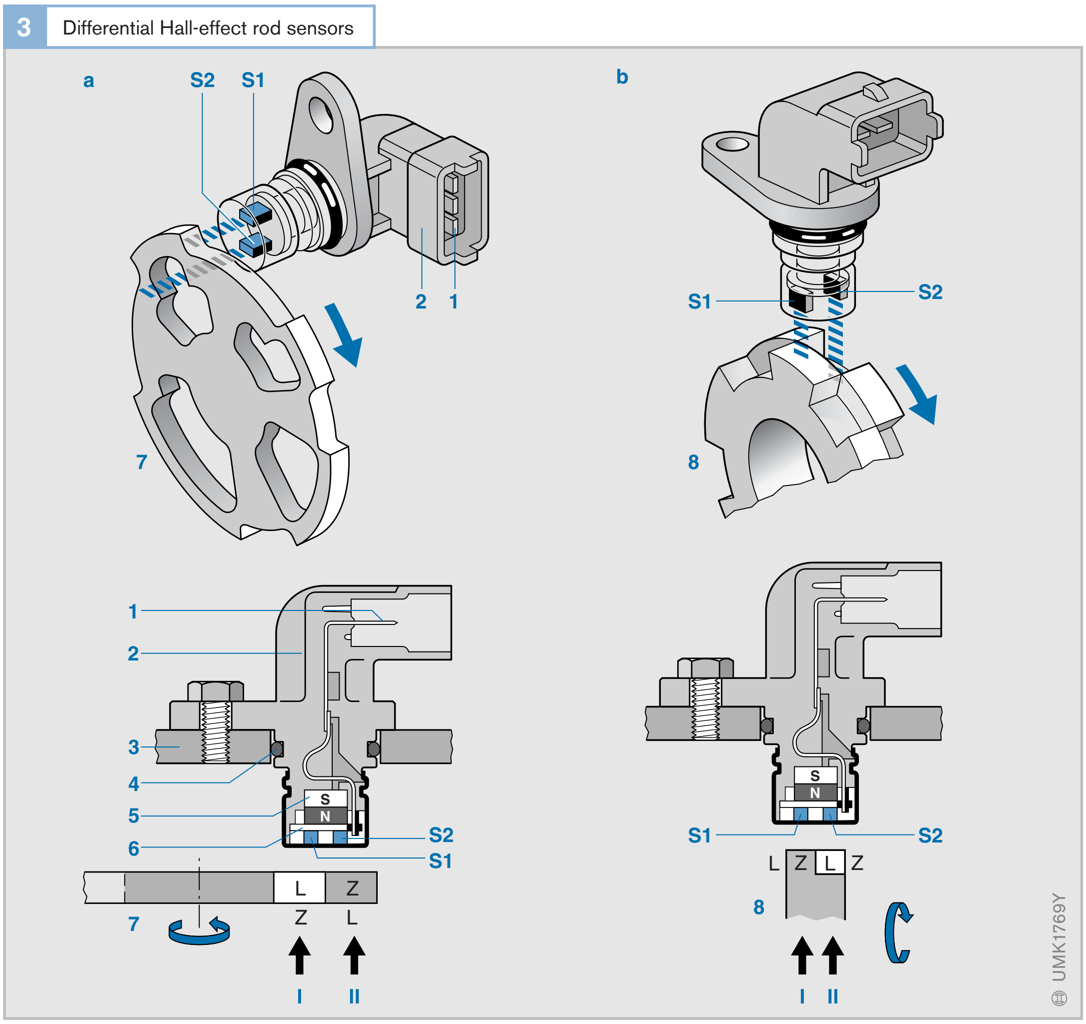


Figure 3

a Axial tap-off (perforated plate)
b Radial tap-off (two-track trigger wheel)

1 Electrical plug-in connection
2 Sensor housing
3 Engine block
4 Seal ring
5 Permanent magnet
6 Differential Hall-IC with Hall elements S1 and S2
7 Perforated plate
8 Two-track trigger wheel
I Track 1
II Track 2

4 Characteristic curve of the output signal U_A from a differential Hall-effect rod sensor

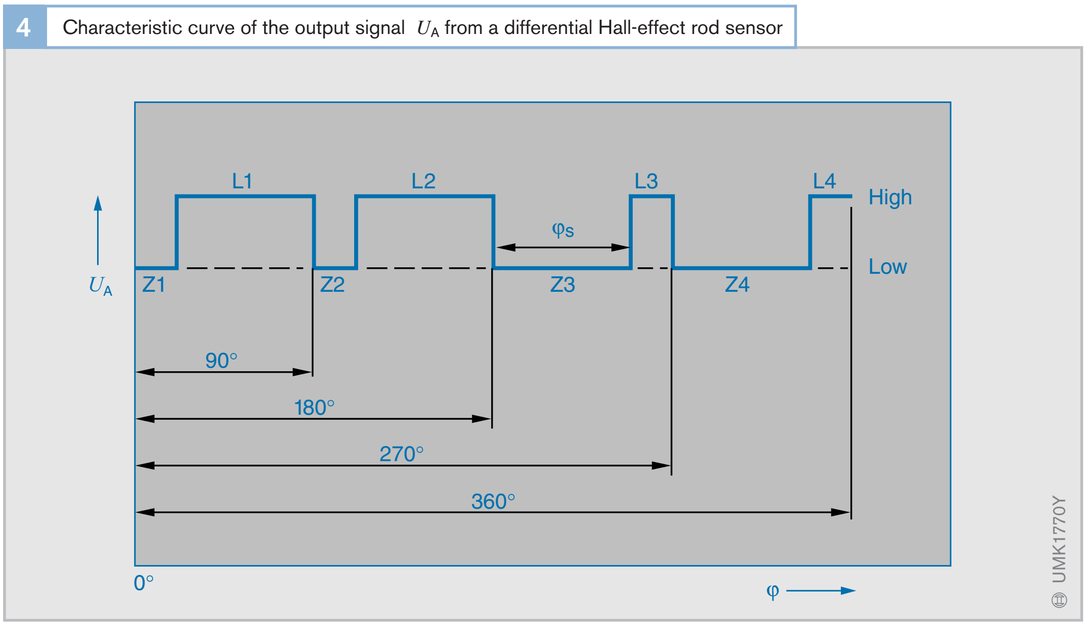


Figure 4

Output signal "Low": Material (Z) in front of S1, gap (L) in front of S2;

Output signal "High": Gap (L) in front of S1, material (Z) in front of S2

φ_S signal width

Half-differential short-circuiting-ring sensors

Application

The above sensors are applied as position sensors for travel or angle. They are very precise and very robust, and are used as

- Rack-travel sensors (RWG) for measuring the control-rack setting in in-line diesel injection pumps, and as
- Angle-of-rotation sensors in the injected-fuel quantity actuators for diesel distributor pumps.

Design and operating concept

These sensors (Figs. 1 and 2) are comprised of a laminated soft-iron core on each limb of which are wound a measuring coil and a reference coil.

When the alternating current (AC) outputted by the ECU flows through these coils, alternating magnetic fields are generated. The copper short-circuiting rings surrounding the limbs of the soft-iron core, though, screen these against the alternating magnetic fields. Whereas the reference short-circuiting rings are fixed in position, the measuring short-circuiting rings are attached to the control rack or to the control-collar shaft (in-line pumps and distributor pumps respectively) and are free to move (control-rack travel s, and adjustment angle φ).

When the measuring short-circuiting ring moves, the magnetic flux changes and, since the ECU maintains the current constant (load-independent current), the voltage across the coil also changes.

The ratio of the output voltage U_A to the reference voltage U_{Ref} (Fig. 3) is calculated by an evaluation circuit. This ratio is proportional to the deflection of the measuring short-circuiting ring and can be processed by the ECU. Bending the reference short-circuiting ring adjusts the characteristic-curve gradient, and the basic position of the measuring short-circuiting ring defines the zero point.

2 Design of the half-differential short-circuiting-ring sensor for diesel distributor pumps

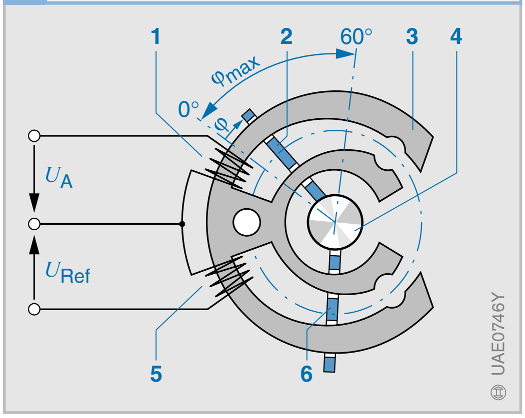


Figure 2
1 Measuring coil
2 Measuring short-circuiting ring
3 Soft-iron core
4 Control-collar shaft
5 Reference coil
6 Reference short-circuiting ring
φ_{max} Adjustment angle for the control-collar shaft
φ Measured angle

1 Design of the rack-travel sensor for diesel in-line injection pumps

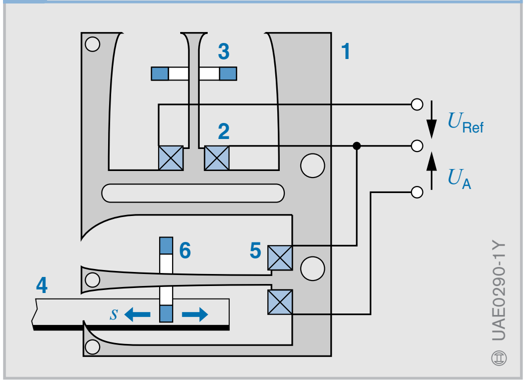


Figure 1
1 Soft-iron core
2 Reference coil
3 Reference short-circuiting ring
4 Control rack
5 Measuring coil
6 Measuring short-circuiting ring
s Control-rack travel

3 Voltage ratio as a function of control-rack travel

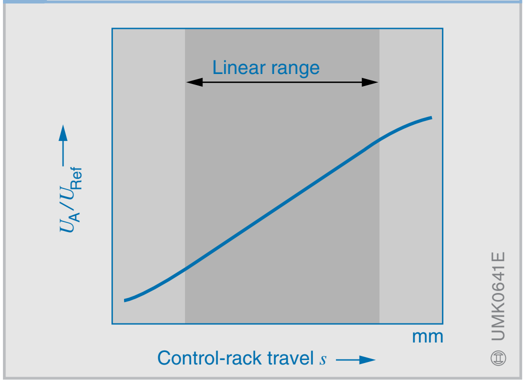


Figure 3
U_A Output voltage
U_{Ref} Reference voltage

Nozzle holders with needle-motion sensor

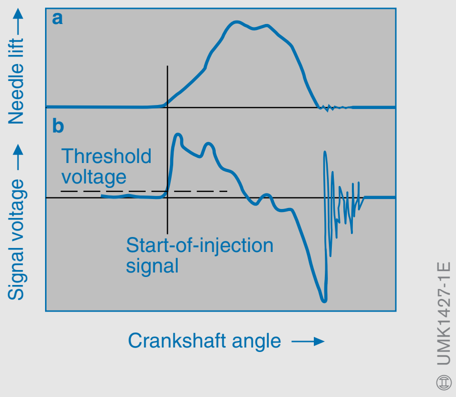
Application

The start-of-injection point is an important parameter for optimum diesel-engine operation. Its evaluation, for instance, permits load and speed-dependent injection timing, and/or the control of the exhaust-gas recirculation (EGR), as well as diagnosis in the ECU. Here, a nozzle holder with needle-motion sensor (Fig. 2) is used which outputs a signal as soon as the nozzle needle lifts off its seat.

Design and operating concept

When the needle lifts, the extended pressure pin (12) enters the coil (11). The degree to which it enters the coil (immersion length “X” in Fig. 2), determines the strength of the magnetic flux in the coil. Nozzle-needle movement causes a change in the coil’s magnetic flux so that a signal voltage is induced which is proportional to the needle’s speed of movement but not to the distance it has travelled. This signal is processed directly in the evaluation circuit. When a given threshold voltage is exceeded (Fig. 1), the evaluation circuit uses this as the signal for the start of injection.

1 Needle-motion sensor: Signal



2 Two-spring nozzle holder with needle-motion sensor for direct-injection (DI) engines

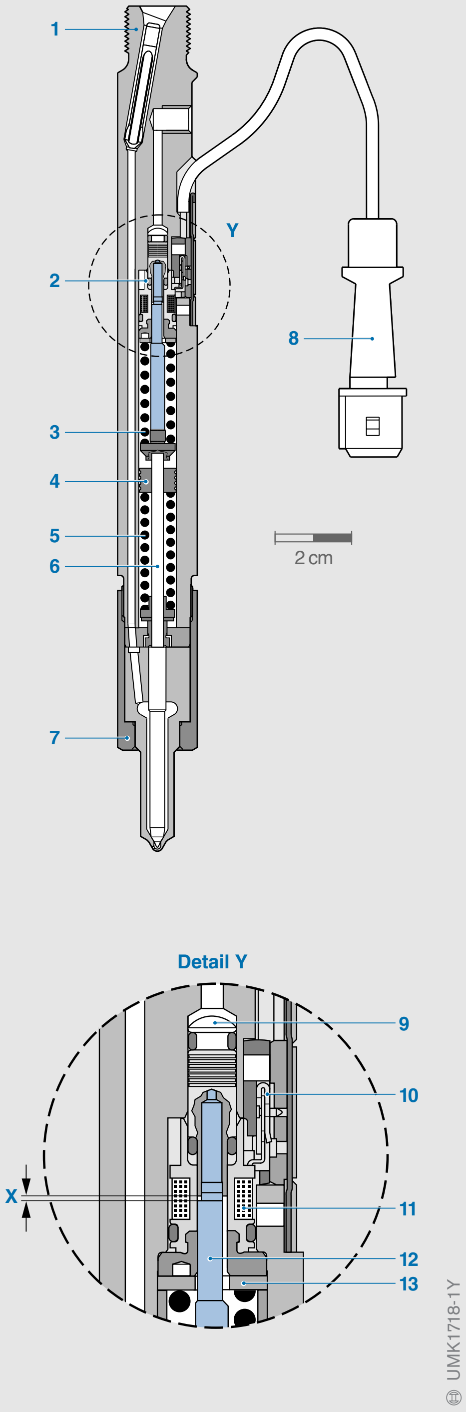


Figure 1

a Needle-lift curve,
b Corresponding signal-voltage curve at the coil

Figure 2

1 Nozzle-holder body
2 Needle-motion sensor
3 Spring
4 Guide element
5 Spring
6 Pressure pin
7 Nozzle-retaining nut
8 Connection to the evaluation circuit
9 Setting pin
10 Contact lug
11 Coil (sensor coil)
12 Pressure pin
13 Spring seat

Accelerator-pedal sensors

Application

In conventional engine-management systems, the driver transmits his/her wishes for acceleration, constant or lower speed, to the engine by using the accelerator pedal to intervene mechanically at the throttle plate (gasoline engine) or injection pump (diesel engine). Intervention is transmitted from the accelerator pedal to throttle plate or injection pump by means of a Bowden cable or linkage.

On today's engine-management systems, the Bowden cable and/or linkage have been superseded and the driver's accelerator-pedal inputs are transmitted to the ECU by an accelerator-pedal sensor. This registers the pedal travel, or its angular setting, and sends this to the engine ECU in the form of an electrical signal.

1 Characteristic curve of an accelerator-pedal sensor with redundant potentiometer

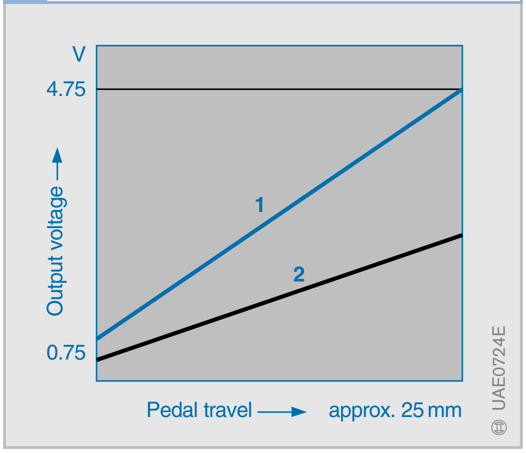


Figure 1
1 Potentiometer 1 (master potentiometer)
2 Potentiometer 2 (50% of voltage)

The accelerator-pedal module (Fig. 2b and c) is available as an alternative to the individual accelerator-pedal sensor (Fig. 2a). The module is a ready-to-install unit comprising accelerator pedal and sensor. Such modules mean that adjustments on the vehicle have become unnecessary.

Design and operating concept

Potentiometer-type accelerator-pedal sensor

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 accelerator-pedal travel or its angular setting from this voltage.

A second (redundant) sensor is incorporated for diagnosis purposes and for use in case of malfunction. It is a component part of the monitoring system. One version of the accelerator-pedal sensor operates with a second potentiometer. The voltage across this potentiometer is always half that across the first potentiometer. This provides two independent signals which are used for trouble-shooting (Fig. 1). Instead of the second potentiometer, another version uses a low-idle switch which provides a signal for the ECU when the accelerator pedal is in the idle position. For automatic-transmission

2 Accelerator-pedal-sensor versions

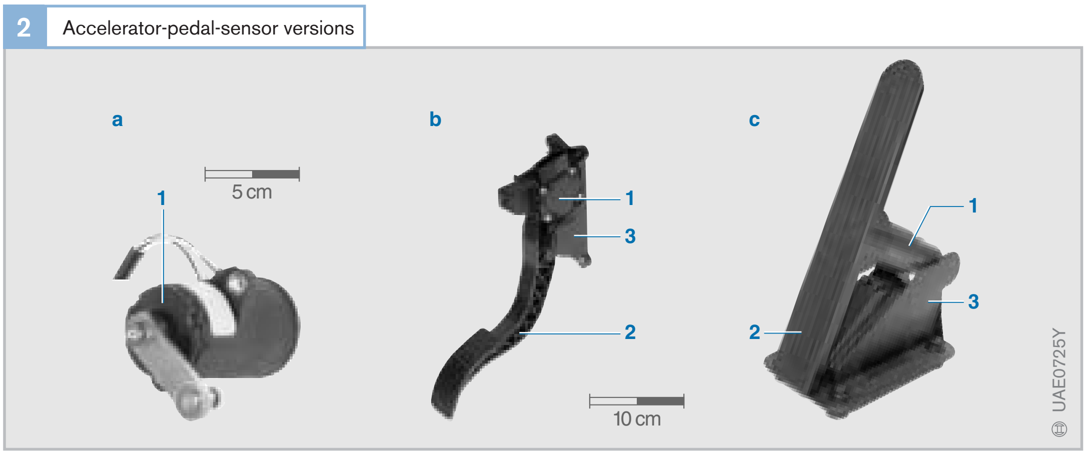


Figure 2
a Individual accelerator-pedal sensor
b Top-mounted accelerator-pedal module
c Bottom-mounted accelerator-pedal module FMP1
1 Sensor
2 Vehicle-specific pedal
3 Pedal bracket

vehicles, a further switch can be incorporated for a kick-down signal.

Hall-effect angle-of-rotation sensors

This Hall-effect angle-of-rotation sensor (ARS1) is based on the movable-magnet principle. It has a measuring range of approx. 90° (Figs. 3 and 4).

A semicircular permanent-magnet rotor (Fig. 4, Pos. 1) generates a magnetic flux which is returned back to the rotor via a pole shoe (2), two conductive elements (3) and the magnetically soft shaft (6). In the process, the amount of flux which is returned through the conductive elements is a function of the rotor's angle of rotation φ. There is a Hall-effect sensor (5) located in the magnetic path of each conductive element, so that is it possible to generate a practically linear characteristic curve in the measuring range.

On the ARS2 sensor, a simpler design is used without magnetically soft conductive elements. Here, a magnet rotates around the Hall-effect sensor. The path it takes is in the form of a circular arc. Since only a small section of the resulting sinusoidal characteristic curve features good linearity, the Hall-effect sensor is located slightly outside the center of the arc. This causes the characteristic curve to deviate from its sinusoidal form so that the linear section of the curve is increased to more than 180 °.

Mechanically, this sensor is highly suitable for installation in an accelerator-pedal module (Fig. 5).

3 Hall-effect angle-of-rotation sensor ARS1

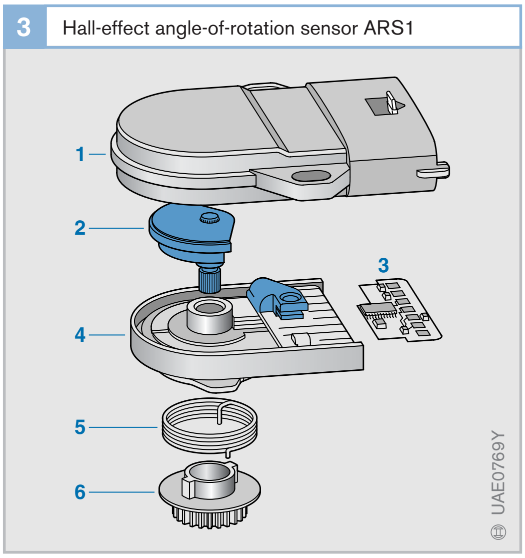


Figure 3

1	Housing cover
2	Rotor (permanent magnet)
3	Evaluation electronics with Hall-effect sensor
4	Housing base
5	Return spring
6	Coupling element (e.g. gear)

4 Hall-effect angle-of-rotation sensor ARS1 (shown with angular settings a...d)

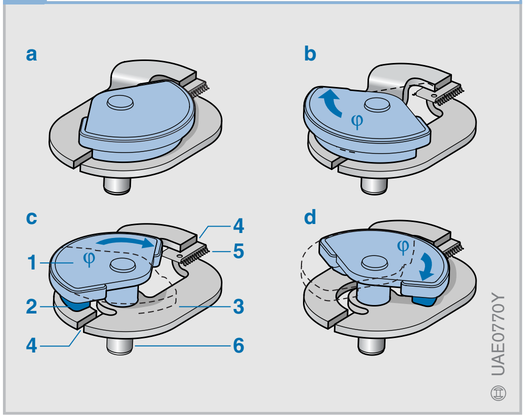


Figure 4

1	Rotor (permanent magnet)
2	Pole shoe
3	Conductive element
4	Air gap
5	Hall-effect sensor
6	Pedal shaft (magnetically soft)
φ	Angle of rotation

5 Hall-effect angle-of-rotation sensor ARS2

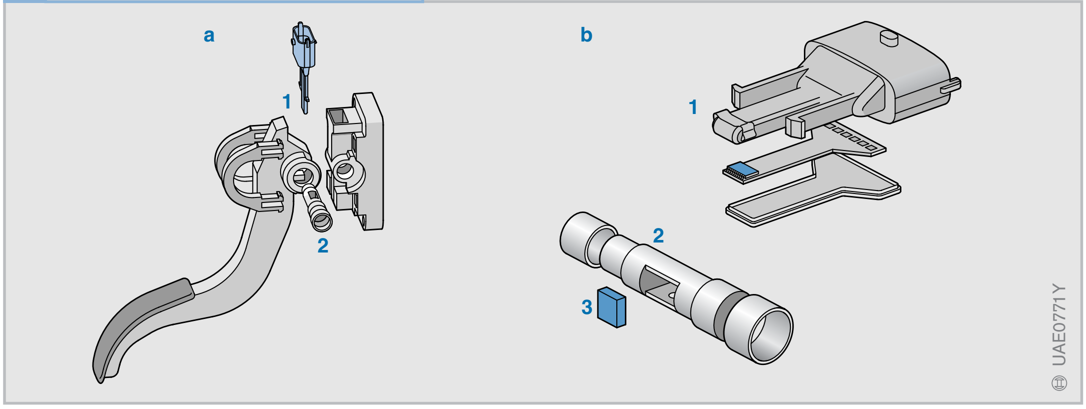


Figure 5

a	Installation in accelerator-pedal module
b	Components
1	Hall-effect sensor
2	Pedal shaft
3	Magnet

Hot-film air-mass meter HFM5

Application

For the optimal combustion as needed to comply with the emission regulations imposed by legislation, it is imperative that precisely the necessary air mass is inducted as dictated by the engine's operating state.

To this end, part of the total air flow which is actually inducted through the air filter or the measuring tube is measured by a hot-film air-mass meter. Measurement is very precise and takes into account the pulsations and reverse flows caused by the opening and closing of the engine's intake and exhaust valves. Intake-air temperature changes have no effect upon measuring accuracy.

Design and construction

The housing of the HFM5 hot-film air-mass meter (Fig. 1, Pos. 5) projects into a measuring tube (2) which, depending upon the engine's air-mass requirements, can have a variety of diameters (for 370...970 kg/h). This tube 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 most important components in the sensor are the sensor element (4), situated in the air intake (8), and the integrated evaluation electronics (3).

Vapor-deposition is used to apply the sensor-element components to a semiconductor substrate, and the evaluation-electronics (hybrid circuit) components to a ceramic substrate. This principle permits a very compact design. The evaluation electronics are connected to the ECU through the plug-in connection (1). The partial-flow measuring tube (6) is shaped so that the air flows past the sensor element smoothly (without whirl effects) and back into the measuring tube via the air outlet (7). This method ensures efficient sensor operation even in case of extreme pulsation, and in addition to forward flow, reverse flows are also detected (Fig. 2).

1 Hot-film air-mass meter HFM5

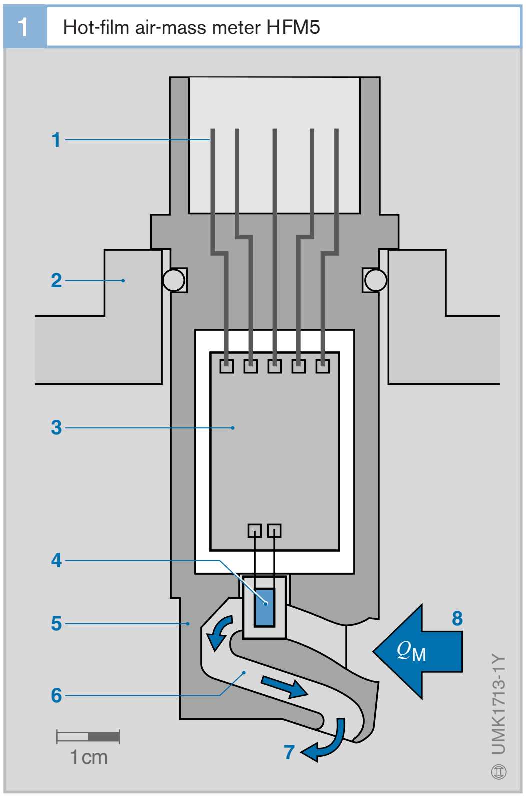


Figure 1
1 Electrical plug-in connection
2 Measuring tube or air-filter housing wall
3 Evaluation electronics (hybrid circuit)
4 Sensor element
5 Sensor housing
6 Partial-flow measuring tube
7 Air outlet for the partial air flow Q_{M}
8 Intake for partial air flow Q_{M}

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 and held at a constant temperature. The temperature drops sharply on each side of this controlled heated 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 heated zone ($T_1 = T_2$).

As soon as air flows over the sensor element, the uniform 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 leads to a temperature differential (ΔT) 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.

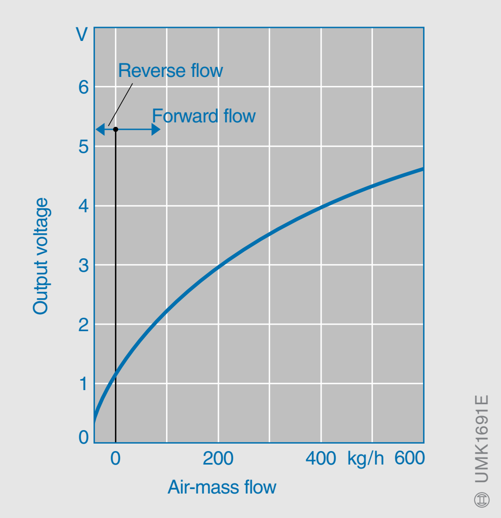
Due to its very thin micromechanical diaphragm, the sensor has a highly dynamic response (<15 ms), a point which is of particular importance when the incoming air is fluctuating heavily.

The resistance differential at the measuring points M_1 and M_2 is converted by the evaluation electronics integrated in the sensor into an analog signal of 0...5 V which 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 on the sensor element upstream of the heated zone, and is not required for measuring the air mass.

For applications on specific vehicles, supplementary functions such as improved separation of water and contamination are provided for (inner measuring tube and protective grid).

2 Output voltage of the hot-film air-mass meter as a function of the partial air mass flowing past it



3 Hot-film air-mass meter: Measuring principle

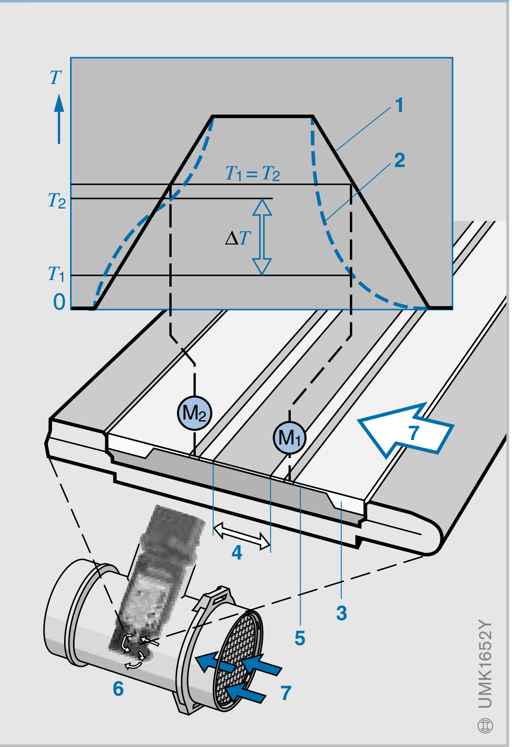


Figure 3

1	Temperature profile without air flow across sensor element
2	Temperature profile with air flow across sensor element
3	Sensor element
4	Heated zone
5	Sensor diaphragm
6	Measuring tube with air-mass meter
7	Intake-air flow
M_1, M_2	measuring points
T_1, T_2	Temperature values at the measuring points M_1 and M_2
ΔT	Temperature differential

Planar broad-band Lambda oxygen sensor LSU4

Application

As its name implies, the broad-band Lambda sensor is used across a very extensive range to determine the oxygen concentration in the exhaust gas. The figures provided by the sensor are an indication of the air-fuel (A/F) ratio in the engine's combustion chamber. The excess-air factor λ is used when defining the A/F ratio. The broad-band Lambda sensor is capable of making precise measurements not only at the "stoichiometric" point $\lambda = 1$, but also in the lean range ($\lambda > 1$) and the rich range ($\lambda < 1$). In the range from $0.7 < \lambda < \infty$ (∞ = air with 21 % O_2) these sensors generate an unmistakable, clear electrical signal (Fig. 2).

These characteristics enable the broad-band Lambda sensor to be used not only in engine-management systems with two-step control ($\lambda = 1$), but also in control concepts with rich and lean air-fuel (A/F) mixtures. This type of Lambda sensor is also suitable for the Lambda closed-loop control used with lean-burn concepts on gasoline engines, as well as for diesel engines, gaseous-fuel engines and gas-powered central heaters and water heaters (this wide range of applications led to the designation LSU: Lambda Sensor Universal (taken from the German), in other words Universal Lambda Sensor). The sensor projects into the exhaust pipe and registers the exhaust-gas flow from all cylinders. In a number of systems, several Lambda sensors are installed for even greater accuracy. Here, for instance, they are fitted upstream and downstream of the catalytic converter as well as in the individual exhaust tracts (cylinder banks).

Design and construction

The LSU4 broad-band Lambda sensor (Fig. 3) is a planar dual-cell limit-current sensor. It features a zirconium-dioxide measuring cell (Fig. 1) which is a combination of a Nernst concentration cell (sensor cell which functions the same as a two-step Lambda sensor) and an oxygen pump cell for transporting the oxygen ions.

The oxygen pump cell (Fig. 1, Pos. 8) is so arranged with respect to the Nernst concentration cell (7) that there is a 10 ... 50 μm diffusion gap (6) between them which is connected to the exhaust gas through a gas-access passage (10). A porous diffusion barrier (11) serves to limit the flow of oxygen molecules from the exhaust gas.

On the one side, the Nernst concentration cell is connected to the atmosphere by a ref-

1 Planar broad-band Lambda sensor (installation in the exhaust pipe and schematic design of the measuring cell)

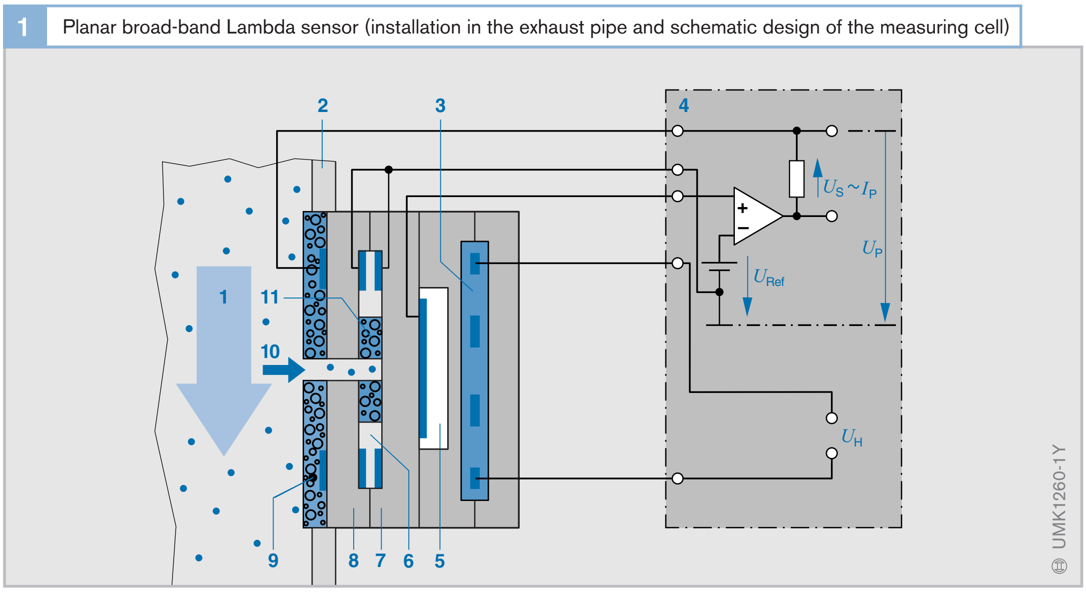


Figure 1

1	Exhaust gas
2	Exhaust pipe
3	Heater
4	Control electronics
5	Reference cell with reference-air passage
6	Diffusion gap
7	Nernst concentration cell
8	Oxygen pump cell with internal and external pump electrode
9	Porous protective layer
10	Gas-access passage
11	Porous diffusion barrier

I_P	Pump current
U_P	Pump voltage
U_H	Heater voltage
U_{Ref}	Reference voltage (450 mV, corresponds to $\lambda = 1$)
U_S	Sensor voltage

erence-air passage (5), and on the other, it is connected to the exhaust gas in the diffusion gap.
The sensor must have heated up to at least 600 ... 800 °C before it generates a usable signal. It is provided with an integral heater (3), so that the required temperature is reached quickly.

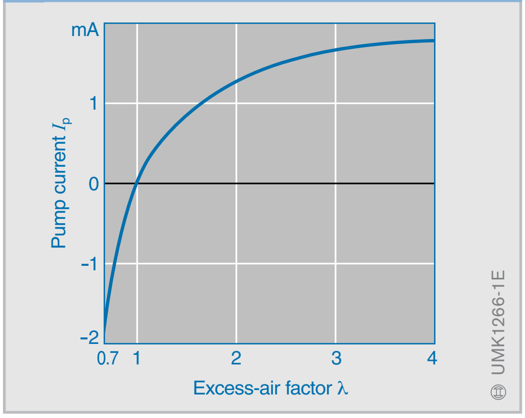
Operating concept

The exhaust gas enters the actual measuring chamber (diffusion gap) of the Nernst concentration cell through the pump cell's gas-access passage. In order that the excess-air factor λ can be adjusted in the diffusion gap, the Nernst concentration cell compares the exhaust gas in the diffusion gap with the surrounding air in the reference-air passage.

The process as a whole functions as follows:

By applying the pump voltage U_P across the pump cell's platinum electrodes, oxygen from the exhaust gas can be pumped through the diffusion barrier and into or out of the diffusion gap. With the help of the Nernst concentration cell, an electronic circuit in the ECU controls the voltage U_P across the pump cell in order that the composition of the gas in the diffusion gap remains constant at $\lambda = 1$. If the exhaust gas is lean, the pump cell pumps the oxygen to the outside (positive pump current). On the other hand, if it is rich, due to the decomposition of CO_2 and H_2O at the exhaust-gas electrode the oxygen is pumped from the surrounding exhaust gas and into the diffusion gap (negative pump current). Oxygen transport is unnecessary at $\lambda = 1$ and pump current is zero. The pump current is proportional to the exhaust-gas oxygen concentration and is thus a measure for the non-linear excess-air factor λ (Fig. 2).

2 Pump current I_P of a broad-band Lambda sensor as a function of the exhaust-gas excess-air factor λ



3 LSU4 planar broad-band sensor

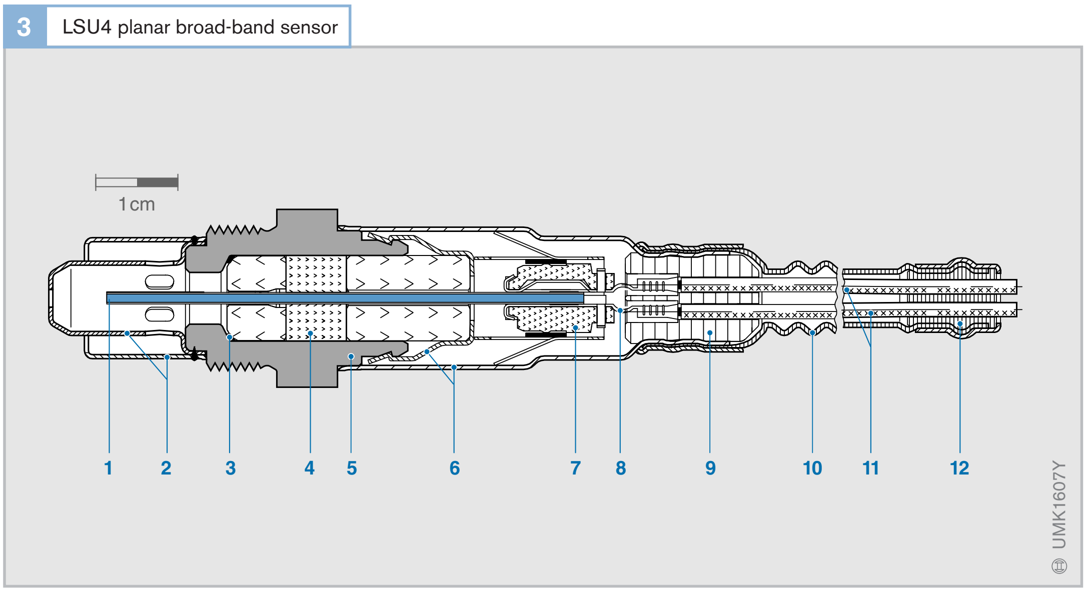


Figure 3
1 Measuring cell (combination of Nernst concentration cell and oxygen-pump cell)
2 Double protective tube
3 Seal ring
4 Seal packing
5 Sensor housing
6 Protective sleeve
7 Contact holder
8 Contact clip
9 PTFE sleeve
10 PTFE shaped sleeve
11 Five connecting leads
12 Seal ring

Electronic Control Unit (ECU)

Digital technology permits the implementation of a wide range of open and closed-loop control functions in the vehicle. An extensive array of 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, evaluates them, and then calculates the triggering signals for the actuators. The control program, the "software", is stored in a special memory and implemented by a microcontroller.

Operating conditions

The ECU is subjected to very high demands with respect to

- Surrounding temperatures (during normal operation from – 40 °C to between +60 °C and +125 °C)
- Resistance to the effects of such materials as oil and fuel etc.,
- Surrounding dampness,
- Mechanical loading due for instance to engine vibration.

Even when cranking the engine with a weak battery (cold start), the ECU must operate just as reliably as when operating voltage is at a maximum (fluctuations in on-board voltage supply).

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

More details on the severe standards applying to the ECU are given in the box at the end of this Chapter.

Design and construction

The pcb (printed-circuit board) with the electronic components (Fig. 1) is installed in a metal case, and connected to the sensors, actuators, and power supply through a multi-pole plug-in connector (4). The high-power driver stages (6) 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. This ECU cooler is only used on commercial vehicles. Compact, engine-mounted hybrid-technology ECUs are available for even higher levels of temperature loading.

The majority of the electronic components use SMD technology (SMD, **S**urface-**M**ounted **D**evice). Conventional wiring is only applied at some of the power-electronics components and at the plug-in connections, so that a particularly space-saving and weight-saving design can be used.

Data processing

Input signals

In their role as peripheral components, the actuators and 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 connection. These signals can be of the following type:

Analog input signals

Within a given range, analog input signals can assume practically 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 analog/digital (A/D) converter in the ECU microcontroller converts these values to the digital values used by the microprocessor to perform its calculations. The maximum resolution of these signals is in steps of 5 mV per bit (approx. 1000 steps).

Digital input signals

Digital input signals only have two states. They are either “high” or “low” (logical 1 and logical 0 respectively). Examples of digital input signals are on/off switching signals, or digital sensor signals such as the rotational-speed pulses from a Hall generator or a magnetoresistive sensor. 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 stage. 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 to a great extent removed from the useful signal which, if necessary, is then amplified to the permissible input-signal level for the microcontroller (0 ... 5 V).

Signal conditioning can take place completely or partially in the sensor depending upon the sensor’s level of integration.

Signal processing

The ECU is the system control center, and is responsible for the functional sequences of the engine management (Fig. 2, next page). The closed and open-loop control functions are executed in the microcontroller. The input signals from the sensors and the interfaces to other systems serve as the input variables, and are subjected to a further plausibility check in the computer.

1 ECU: Design and construction

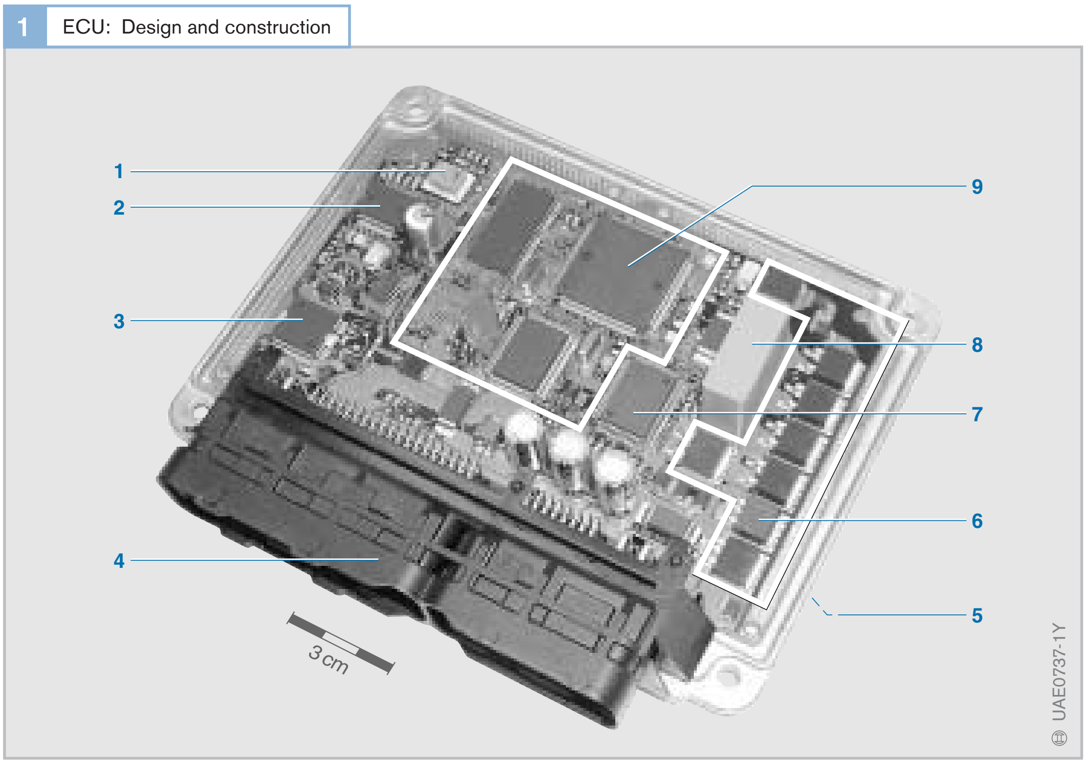


Figure 1
1 Atmospheric-pressure sensor
2 Switched-mode power supply (SMPS) with voltage stabilization
3 Low-power driver stage
4 Plug-in connection
5 CAN interface and general input and output circuitry (underneath the pcb, therefore not visible here)
6 High-power driver stages
7 ASIC for driver-stage triggering
8 Booster-voltage store (Common Rail)
9 Microcontroller core

The output signals are calculated using the program.

Microcontroller

The microcontroller is the ECU's central component and controls its operative sequence. Apart from the CPU (**C**entral **P**rocessing **U**nit), the microcontroller contains not only the input and output channels, but also timer units, RAMs, ROMs, serial interfaces, and further peripheral assemblies, all of which are integrated on a single microchip. Quartz-controlled timing is used for the microcontroller.

Program and data memory

In order to carry out the computations, the microcontroller needs a program - the "software". This is in the form of binary numerical values arranged in data records and stored in a program memory.

These binary values are accessed by the CPU which interprets them as commands which it implements one after the other (refer also to the Chapter "Electronic open and closed-loop control").

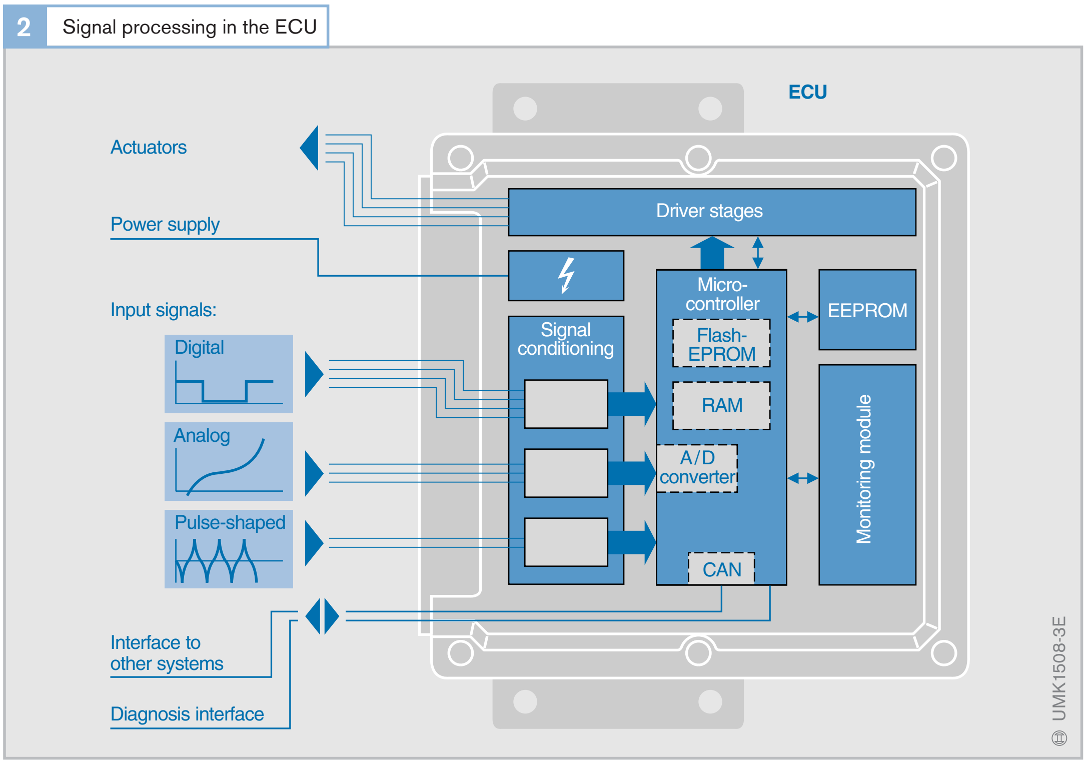
This program is stored in a Read-Only Memory (ROM, EPROM, or Flash-EPROM) which also contains variant-specific data (individual data, characteristic curves, and maps). This is non-variable data which cannot be changed during vehicle operation. It is used to regulate the program's open and closed-loop control processes.

The program memory can be integrated in the microcontroller and, depending upon the particular application, expanded by the addition of a separate component (e.g. by an external EPROM or a Flash-EPROM).

ROM

Program memories can be in the form of a ROM (**R**ead **O**nly **M**emory). This is a memory whose contents have been defined permanently during manufacture and thereafter remain unalterable. The ROM installed in the microcontroller only has a restricted memory capacity, which means that an additional ROM is required in case of complicated applications.

2 Signal processing in the ECU



EPROM
The data on an EPROM (**E**rasable **P**rogrammable **ROM**) can be erased by subjecting the device to UV light. Fresh data can then be entered using a programming unit.

The EPROM is usually in the form of a separate component, and is accessed by the CPU through the Address/Data-Bus.

Flash-EPROM (FEPROM)
The Flash-EPROM is often referred to merely as a “Flash”. lt can be erased electrically so that it becomes possible to reprogram the ECU in the service workshops without having to open it. In the process, the ECU is connected to the reprogramming unit through a serial interface.

lf the microcontroller is also equipped with a ROM, this contains the programming routines for the Flash programming. Flash-EPROMs are available which, together with the microcontroller, are integrated on a single microchip (as from EDC16).

Its decisive advantages have helped the Flash-EPROM to largely supersede the conventional EPROM.

Variable-data or main memory

Such a read/write memory is needed in order to store such variable data (variables) as the computational and signal values.

RAM
Instantaneous values are stored in the RAM (**R**andom **A**ccess **M**emory) read/write memory. If complex applications are involved, the memory capacity of the RAM incorporated in the microcontroller is insufficient so that an additional RAM module becomes necessary. lt is connected to the ECU through the Address/Data-Bus.

When the ECU is switched off by turning the “ignition” key, the RAM loses its complete stock of data (volatile memory).

EEPROM (also known as the E^{2}PROM)
As stated above, the RAM loses its information immediately its power supply is removed (e.g. when the "ignition switch " is turned to OFF). Data which must be retained, for instance the codes for the vehicle immobilizer and the fault-store data, must therefore be stored in a non-erasable (non-volatile) memory. The EEPROM is an electrically erasable EPROM in which (in contrast to the Flash-EPROM) every single memory location can be erased individually. lt has been designed for a large number of writing cycles, which means that the EEPROM can be used as a non-volatile read/write memory.

ASIC

The ever-increasing complexity of ECU functions means that the computing powers of the standard microcontrollers available on the market no longer suffice. The solution here is to use so-called ASIC modules (**A**pplication **S**pecific **I**ntegrated **C**ircuit). These IC's are designed and produced in accordance with data from the ECU development departments and, as well as being equipped with an extra RAM for instance, and inputs and outputs, they can also generate and transmit pwm signals (see “PWM signals” below).

Monitoring module

The ECU is provided with a monitoring module. Using a “Question and Answer” cycle, the microcontroller and the monitoring module supervise each other, and as soon as a fault is detected one of them triggers appropriate back-up functions independent of the other.

Output signals

With its output signals, the microcontroller triggers driver stages which are usually powerful enough to operate the actuators directly. The driver stages can also trigger specific relays. The driver stages are proof against shorts to ground or battery voltage, as well as against destruction due to electrical or thermal overload. Such malfunctions, together with open-circuit lines or sensor faults are identified by the driver-stage IC as an error 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 (**p**ulse-**w**idth **m**odulated) signals. These are constant-frequency rectangular signals with variable on-times (Fig. 3), and are used to shift the actuators to the desired setting (e.g. EGR valve, fan, heating element, boost-pressure actuator).

3 PWM signals

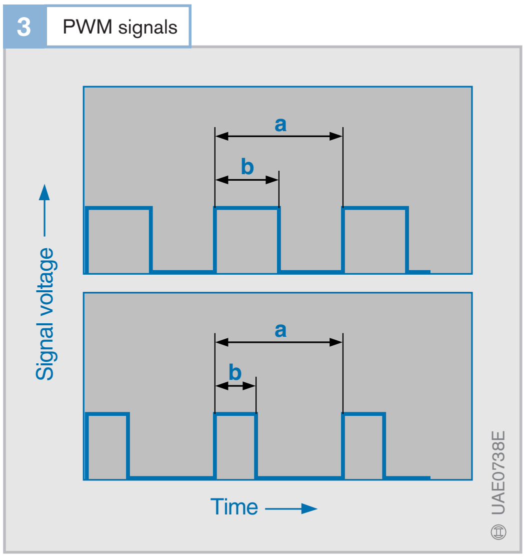


Figure 3
a Fixed frequency
b Variable on-time

Communication within the ECU

In order to be able to support the microcontroller in its work, the peripheral components must communicate with it. This takes place using an address/data bus which, for instance, the microcomputer uses to issue 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 structure 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. Presently, more complex systems demand 16 bits, or even 32 bits, for the data bus. In order to save on pins at the components, the data and address buses can be combined in a multiplex system. That is, data and addresses are dispatched through the same lines but offset from each other with respect to time.

Serial interfaces with only a single data line are used for data which need not be transmitted so quickly (e.g. data from the fault storage).

EoL programming

The extensive variety of vehicle variants with differing control programs and data records, makes it imperative to have a system which reduces the number of ECU types needed by a given manufacturer. To this end, the Flash-EPROM's complete memory area can be programmed at the end of production with the program and the variant-specific data record (this is the so-called **E**nd-**o**f-**L**ine, or EoL, programming). A further possibility is to have a number of data variants available (e.g. gearbox variants), which can then be selected by special coding at the end of the line (EoL). This coding is stored in an EEPROM.

Very severe demands are made on the ECU

Basically, the ECU in the vehicle functions the same as a conventional PC. Data is entered from which output signals are calculated. The heart of the ECU is the printed-circuit board (pcb) with microcontroller using high-precision microelectronic techniques. The automotive ECU though must fulfill a number of other requirements.

Real-time compatibility

Systems for the engine and for road/traffic safety demand very rapid response of the control, and the ECU must therefore be "real-time compatible". This means that the control's reaction must keep pace with the actual physical process being controlled. It must be certain that a real-time system responds within a fixed period of time to the demands made upon it. This necessitates appropriate computer architecture and very high computer power.

Integrated design and construction

The equipment's weight and the installation space it requires inside the vehicle are becoming increasingly decisive. The following technologies, and others, are used to make the ECU as small and light as possible:

- **Multilayer:** The printed-circuit conductors are between 0.035 and 0.07 mm thick and are “stacked” on top of each other in layers.
- **SMD components** are very small and flat and have no wire connections through holes in the pcb. They are soldered or glued to the pcb or hybrid substrate, hence SMD (**S**urface **M**ounted **D**evices).
- **ASIC:** Specifically designed integrated component (**A**pplication-**S**pecific **I**ntegrated **C**ircuit) which can combine a large number of different functions.

Operational reliability

Very high levels of resistance to failure are provided by integrated diagnosis and redundant mathematical processes (additional processes, usually running in parallel on other program paths).

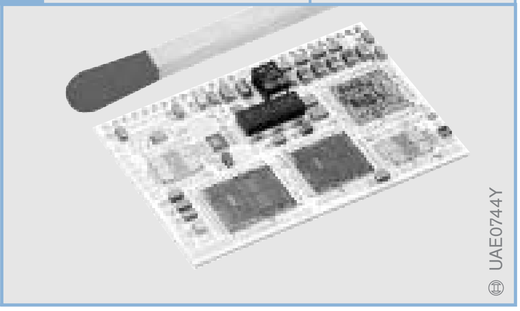
Environmental influences

Notwithstanding the wide range of environmental influences to which it is subjected, the ECU must always operate reliably.

- **Temperature:** Depending upon the area of application, the ECUs installed in vehicles must perform faultlessly during continual operation at temperatures between −40 °C and +60 ... 125 °C. In fact, due to the heat radiated from the components, the temperature at some areas of the substrate is considerably higher. The temperature change involved in starting at cold temperatures and then running up to hot operating temperatures is particularly severe.
- **EMC:** The vehicle's electronics have to go through severe electromagnetic compatibility testing. That is, the ECU must remain completely unaffected by electromagnetic disturbances emanating from such sources as the ignition, or radiated by radio transmitters and mobile telephones. Conversely, the ECU itself must not negatively affect other electronic equipment.
- **Resistance to vibration:** ECUs which are mounted on the engine must be able to withstand vibrations of up to 30 *g* (that is, 30 times the acceleration due to gravity).
- **Sealing and resistance to operating mediums:** Depending upon installation position, the ECU must withstand damp, chemicals (e.g. oils), and salt fog.

The above factors and other requirements mean that the Bosch development engineers are continually faced by new challenges.

Hybrid substrate of an ECU



Open and closed-loop electronic control

The most important assignment of the Electronic Diesel Control (EDC) is the control of the injected fuel quantity and the instant of injection. The "Common Rail" accumulator injection system also controls the injection pressure. Furthermore, on all systems, the engine ECU also controls a number of actuators. For all components to operate efficiently, it is imperative that the EDC functions be precisely matched to every vehicle and every engine (Fig. 1).

Open and closed-loop electronic control

In both forms of control, one or more input quantities influence one or more output quantities

Open-loop control

With open-loop control, the actuators are triggered by the output signals which the ECU has calculated using the input variables, stipulated data, characteristic maps, and algorithms. The final results are not checked (open control loop). This principle is used for instance for the glow-plug sequence control.

Closed-loop control

On the other hand, as its name implies, closed-loop control is characterized by a closed control loop. Here, the actual value at the output is continually checked against the desired value, and as soon as a deviation is detected this is corrected by a change in the actuator control. The advantage of closed-loop control lies in the fact that disturbances from outside are detected and taken into account. Closed-loop control is used for instance to control the engine's idle speed.

In fact, therefore, the EDC Electronic Control Unit (ECU) is really an "open and closed-loop control unit". The term ECU "Electronic Control Unit" has become so widespread though, that it is still used even though the word "control" alone is not explicit enough.

Data processing (DP)

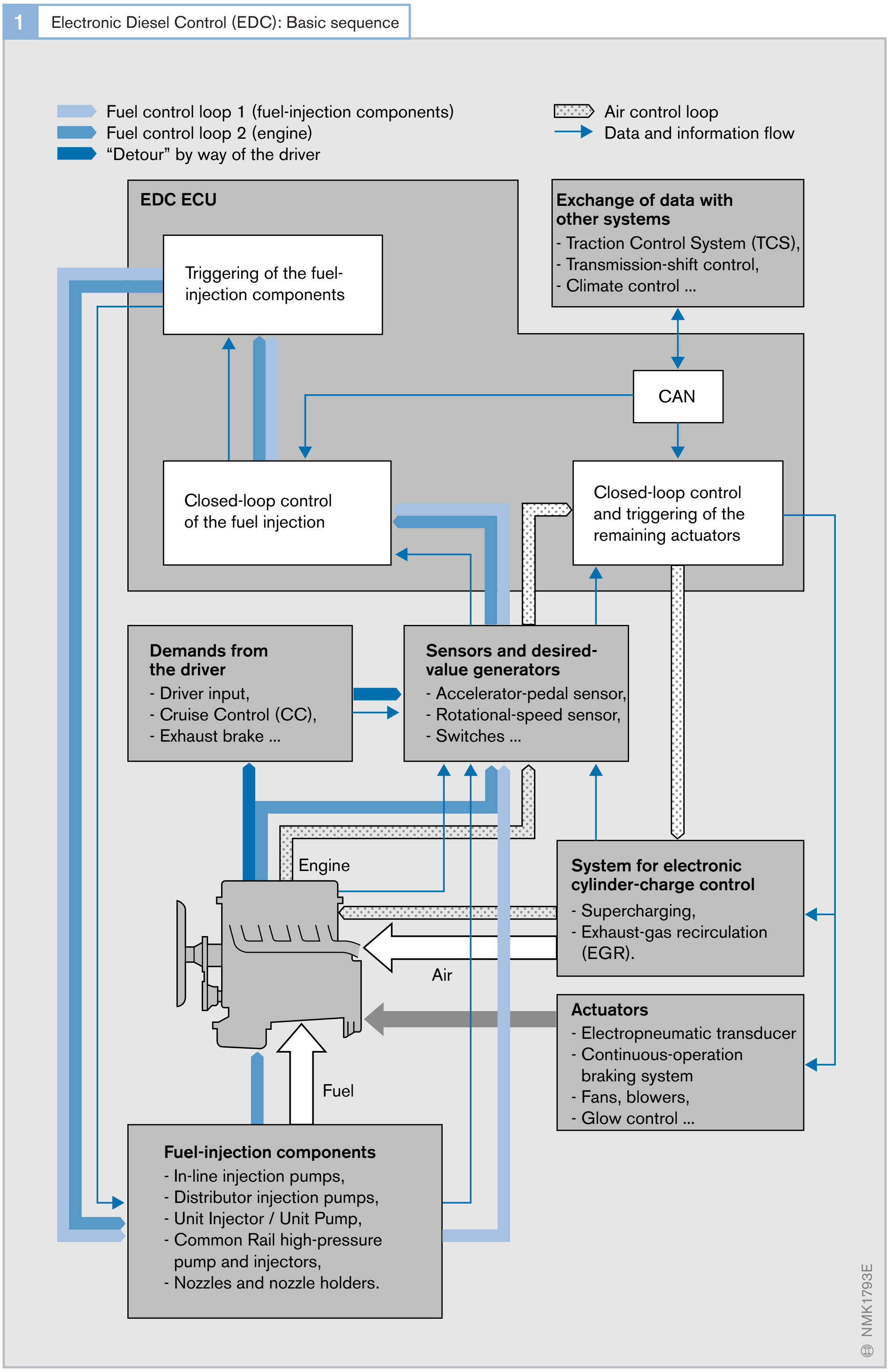
The ECU processes the incoming signals from the external sensors and limits them to the permissible voltage level. A number of the incoming signals are also checked for plausibility.

Using these input data, together with stored characteristic curves, the microprocessor calculates the injection's timing and its duration. This information is then converted to a signal characteristic which is aligned to the engine's piston movements. This calculation program is termed the "ECU software".

The required degree of accuracy together with the diesel engine's outstanding dynamic response necessitate high-level computing power. The output signals are applied to output stages which provide adequate power for the actuators (for instance the high-pressure solenoid valves for fuel injection, EGR positioner, or boost-pressure actuator). Apart from this, a number of other auxiliary-function components (e.g. glow relay and air conditioner) are triggered.

Faulty signal characteristics are detected by the output-stage diagnosis functions. Furthermore, signals are exchanged with other systems in the vehicle via the interfaces. The engine ECU monitors the complete injection system within the framework of a safety concept.

1 Electronic Diesel Control (EDC): Basic sequence



Data exchange with other systems

Fuel-consumption signal

The engine ECU (Fig. 1, Pos. 3) detects the engine fuel consumption and transmits the signal via CAN to the instrument cluster, or to an independent on-board computer (6), where the driver is informed of the current fuel consumption and/or the remaining range with the fuel still in the tank. Older systems used pulse-width modulation (pwm) for the fuel-consumption signal.

Starter control

The starter (8) can be triggered from the engine ECU. This ensures that the driver cannot operate the starter with the engine already running. The starter only turns long enough for the engine to have reliably reached self-sustaining speed. This function leads to a lighter and thus lower-priced starter.

Glow control unit

The glow control unit (GZS, 5) receives information from the engine ECU on when glow is to start and for how long. It then triggers the glow plugs accordingly and monitors the glow process, as well as reporting back to the ECU on any faults (diagnosis function). The pre-glow indicator lamp is usually triggered from the ECU.

Electronic immobilizer

To prevent unauthorized starting and drive-off, the engine cannot be started before a special immobilizer (7) ECU removes the block from the engine ECU.

Either by remote control or by means of the glow-plug and starter switch ("Ignition" key), the driver can signal the immobilizer ECU that he/she is authorised to use the vehicle. The immobilizer ECU then removes the block on the engine ECU so that engine start and normal operation become possible.

1 Possible components involved in the exchange of data with the Electronic Diesel Control (EDC)

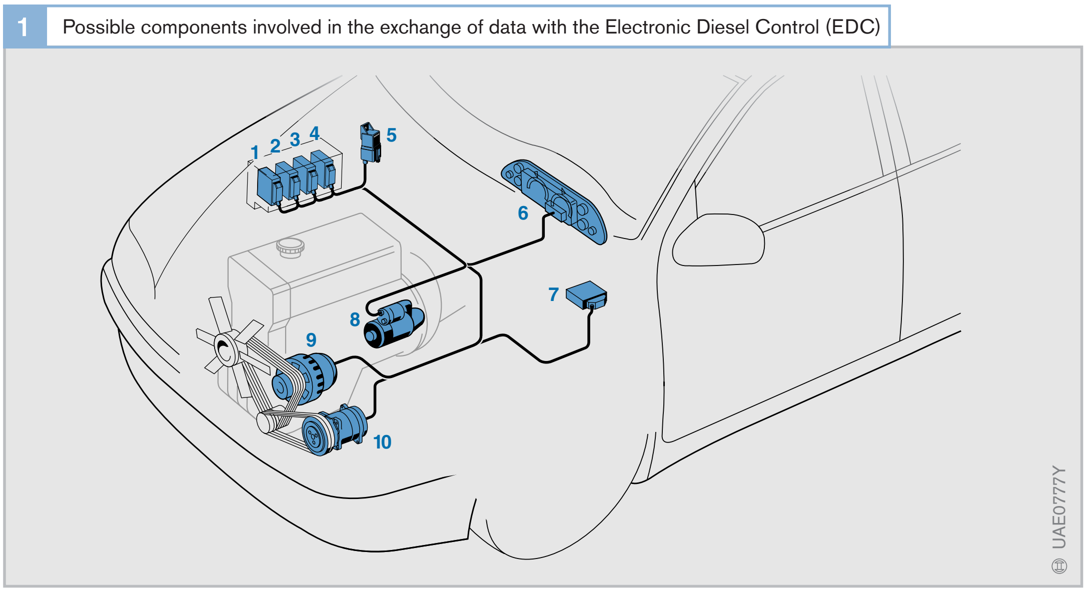


Figure 1
1 ESP ECU (with ABS and TCS)
2 ECU for transmission-shift control
3 Engine ECU (EDC)
4 A/C ECU
5 Glow control unit
6 Instrument cluster with on-board computer
7 Immobilizer ECU
8 Starter
9 Alternator
10 A/C compressor

External torque intervention

In the case of external torque intervention, the injected fuel quantity is influenced by another (external) ECU (for instance the ECU for transmission shift, or for TCS). This informs the engine ECU whether the engine torque is to be changed, and if so, by how much (this defines the injected fuel quantity).

Alternator control

By means of a standard serial interface, the EDC can remotely control and remotely monitor the alternator (9). The regulator voltage can be controlled, just the same as the complete alternator assembly can be switched off. In case of a weak battery for instance, the alternator's charging characteristic can be improved by increasing the idle speed. It is also possible to perform simple alternator diagnosis through this interface.

Air conditioner

In order to maintain comfortable temperatures inside the vehicle when it is very hot outside, the air conditioner (A/C) cools down the air with the help of a refrigerating compressor (10). Depending upon the engine and the operating conditions, the A/C compressor can need as much as 30% of the engine's output power.

Immediately the driver hits the accelerator pedal (in other words he/she wishes maximum torque), the compressor can be switched off briefly by the engine ECU, so that all the engine's power is available at the wheels. Since the compressor is only switched off very briefly, this has no noticeable effect upon the passenger-compartment temperature.

▶ Where does the word "Electronics" come from?

This term really originates from the ancient Greeks. They used the word electron for "amber" whose forces of attraction for wool and similar materials had already been described by Thales von Milet 2,500 years ago.

The term "electronics" originates directly from the word "electrons". The electrons, and therefore electronics as such, are extremely fast due to their very small mass and their electrical charge.

The mass of an electron has as little effect on a gram of any given substance as a 5 gram weight has on the total mass of our earth.

Incidentally, the word "electronics" is a product of the 20th century. There is no evidence available as to when the word was used for the first time. Sir John Ambrose Fleming, one of the inventors of the electron tube could have used it around 1902.

The first "Electronic Engineer" though goes back to the 19th century. He was listed in the 1888 Edition of a form of "Who's Who", published during the reign of Queen Victoria. The official title was "Kelly's Handbook of Titled, Landed and Official Classes". The Electronic Engineer is to be found under the heading "Royal Warrant Holders", that is the list of persons who had been awarded a Royal Warrant.

And what was this Electronic Engineer's job? He was responsible for the correct functiong and cleanliness of the gas lamps at court. And why did he have such a splendid title ? Because he knew that "Electrons" in ancient Greece stood for glitter, shine, and sparkle.

Source:
"Basic Electronic Terms" ("Grundbegriffe der Elektronik") – Bosch publication (reprint from the "Bosch Zünder" (Bosch Company Newspaper))..

Fuel-injection control

An overview of the various control functions which are possible with the EDC control units is given in Table 1. Fig. 1 opposite shows the sequence of fuel-injection calculations with all functions, a number of which are special options. These can be activated in the ECU by the workshop when retrofit equipment is installed.

In order that the engine can run with optimal combustion under all operating conditions, the ECU calculates exactly the right injected fuel quantity for all conditions. Here, a number of parameters must be taken into account. On a number of solenoid-valve-controlled distributor pumps, the solenoid valves for injected fuel quantity and start of injection are triggered by a separate pump ECU (PSG).

1 EDC variants for road vehicles: Overview of functions

Fuel-injection system	**In-line injection pumps** PE	**Helix-controlled distributor injection pumps** VE-EDC	**Solenoid-valve-controlled distributor injection pumps** VE-M, VR-M	**Unit Injector System and Unit Pump System** UIS, UPS	**Common Rail System** CR
Function					
Injected-fuel-quantity limitation	●	●	●	●	●
External torque intervention	●[3]	●	●	●	●
Vehicle-speed limitation	●[3]	●	●	●	●
Vehicle-speed control (Cruise Control)	●	●	●	●	●
Altitude compensation	●	●	●	●	●
Boost-pressure control	●	●	●	●	●
Idle-speed control	●	●	●	●	●
Intermediate-speed control	●[3]	●	●	●	●
Active surge damping	●[2]	●	●	●	●
BIP control	–	–	●	●	–
Intake-tract switch-off	–	–	●	●[2]	●
Electronic immobilizer	●[2]	●	●	●	●
Controlled pilot injection	–	–	●	●[2]	●
Glow control	●[2]	●	●	●[2]	●
A/C switch-off	●[2]	●	●	●	●
Auxiliary coolant heating	●[2]	●	●	–	●
Cylinder-balance control	●[2]	●	●	●	●
Control of injected fuel quantity compensation	●[2]	–	●	●	●
Fan (blower) triggering	–	●	●	●	●
EGR control	●[2]	●	●	●[2]	●
Start-of-injection control with sensor	●[1, 3]	●	●	–	–
Cylinder shutoff	–	–	●[3]	●[3]	●[3]

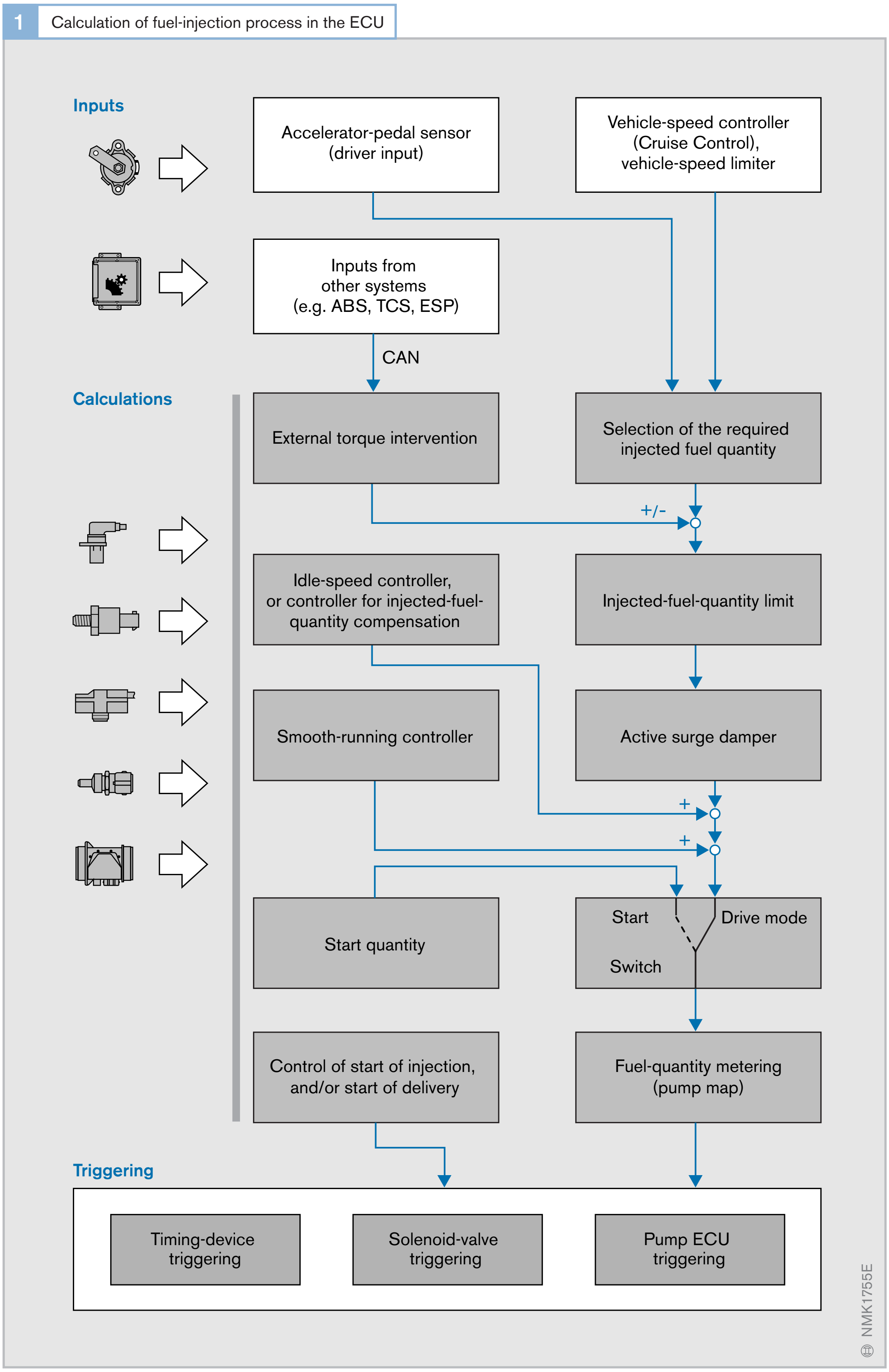
Table 1

1 Only control-sleeve in-line injection pumps

2 Passenger cars only

3 Commercial vehicles only

1 Calculation of fuel-injection process in the ECU



Start quantity

For starting, the injected fuel quantity is calculated as a function of coolant temperature and cranking speed. Start-quantity signals are generated from the moment the starting switch is turned (Fig. 1, switch in “Start” position) until a given minimum engine speed is reached.
The driver cannot influence the start quantity.

Drive mode

When the vehicle is being driven normally, the injected fuel quantity is a function of the accelerator-pedal setting (accelerator-pedal sensor) and of the engine speed (Fig. 1, switch in “Drive” position). Calculation depends upon maps which also take other influences into account (e.g. fuel and intake-air temperature). This permits best-possible alignment of the engine’s output to the driver’s wishes.

Idle-speed control

When the accelerator is not depressed, it is the job of the idle-speed control to ensure that a given idle speed is maintained. This can vary depending upon the engine’s particular operating mode. For instance, with the engine cold the idle speed is usually set higher than when it is warm. There are further instances when the idle speed is held somewhat higher. For instance when the vehicle‘s electrical-system voltage is too low, when the air-conditioner is switched on, or when the vehicle is rolling freely. When the vehicle is driven in stop-and-go traffic, together with stops at traffic lights, the engine runs a lot of the time at idle. Considerations concerning emissions and fuel consumption dictate therefore that idle speed should be kept as low as possible. This of course is a disadvantage with respect to smooth-running and pull-away.

When adjusting the stipulated idle speed, the idle-speed control must cope with heavily fluctuating requirements. The input power needed by the engine-driven auxiliary equipment varies extensively.

At low electrical-system voltages for instance, the alternator consumes far more power than it does when the voltages are higher. In addition, the power demands from the A/C compressor, the steering pump, and the high-pressure generation for the diesel injection system must all be taken into account. Added to these external load moments is the engine’s internal friction torque which is highly dependent upon engine temperature, and which must also be compensated for by the idle-speed control.

In order to regulate the desired idle speed, the controller continues to adapt the injected fuel quantity until the actual engine speed corresponds to the desired idle speed.

Maximum-rpm control

The maximum-rpm control ensures that the engine does not run at excessive speeds. To avoid damage to the engine, the engine manufacturer stipulates a permissible maximum speed which may only be exceeded for a very brief period.

Above the rated-power operating point, the maximum-rpm controller reduces the injected fuel quantity continually, until just above the maximum-rpm point fuel-injection stops completely. In order to prevent engine surge, a ramp function is used to ensure that the drop off in fuel injection is not too abrupt. This becomes all the more difficult the nearer the rated-power point is to the maximum-rpm point.

Intermediate-speed control

The intermediate-speed control is used only for trucks and small commercial vehicles with auxiliary power take-offs (e.g. for crane operation) or for special vehicles (e.g. ambulances with electrical power generator). With the control in operation, the engine is regulated to a load-independent intermediate speed. With the vehicle stationary, the intermediate-speed control is activated via the Cruise Control operator panel.

A fixed rotational speed can be called up from the data store at the push of a button. In addition, this operator panel can be used for preselecting specific engine speeds. The intermediate-speed control is also applied on passenger cars with automated gearboxes (e.g. Tiptronic) to control the engine speed during gearshifts.

Vehicle-speed controller (Cruise Control)

The Cruise Control is taken into operation when the vehicle is to be driven at a constant speed. It controls the vehicle speed to that selected by the driver without him/her needing to press the accelerator pedal. The driver can input the required speed either through an operating lever or through the steering-wheel keypad. The injected fuel quantity is either increased or decreased until the desired (set) speed is reached.

On some Cruise Control applications, the vehicle can be accelerated beyond the current set speed by pressing the accelerator pedal. As soon as the accelerator pedal is released again, the Cruise Control regulates the speed back down to the previously set speed.

If the driver depresses the clutch or brake pedal while the Cruise Control is activated, the control is terminated. On some applications, the control can be switched off by the accelerator pedal.

If the Cruise Control has been switched off, the driver only needs to shift the lever to the reactivate setting in order to again select the last speed which had been set.

The operator's controls can also be used for a step-by-step change of the selected speed.

Vehicle-speed limiter

Variable limitation

The vehicle-speed limiter limits the vehicle's maximum speed to a set value even if the accelerator is depressed further. On very quiet vehicles, in which the engine can hardly be heard, this is a particular help for the driver who can then no longer exceed speed limits inadvertently.

The vehicle-speed limiter keeps the injected-fuel quantity down to a limit which is in line with the selected maximum speed. It can be switched off by the lever or by the kick-down switch. In order to again select the last speed which had been set, the driver only needs to shift the lever to the reactivate setting. The operator's controls can also be used for a step-by-step change of the selected speed.

Fixed limitation

In a number of countries, fixed maximum speeds are mandatory for certain classes of vehicles (for instance, for heavy trucks). The vehicle manufacturers also limit the maximum speeds of their heavy vehicles by installing a fixed speed limit which cannot be switched off.

In the case of special vehicles, the driver can also select from a range of fixed, programmed speed limits (for instance, when there are workers on the garbage truck's rear platform).

Active surge damping

Sudden engine-torque changes excite the vehicle's drivetrain, which as a result goes into surge oscillation. These oscillations are registered by the vehicle's occupants as unpleasant periodic changes in acceleration (Fig. 2, a). It it the job of the active surge damper to reduce them (b). Two separate methods are used:

- In case of sudden changes in the torque required by the driver (through the accelerator pedal), a precisely matched filter function reduces the drivetrain excitation (1).
- The speed signals are used to detect drivetrain oscillations which are then damped by an active control. In order to counteract the drivetrain oscillations (2), the active control reduces the injected fuel quantity when rotational speed increases, and increases it when speed drops.

Smooth-running control (SRC)/Control of injected-fuel-quantity compensation (MAR)

Presuming the same duration of injection, not all of the engine's cylinders generate the same torque. This can be due to differences in cylinder-head sealing, as well as differences in cylinder friction and in the hydraulic injection components. These differences in torque output lead to rough engine running and an increase in toxic emissions.

The smooth-running control (SRC), or the control of injected-fuel-quantity compensation (MAR), use the resulting rotational-speed fluctuations when detecting such torque fluctuations. By selected variation of the injected fuel quantities at the cylinders concerned, they compensate for the torque variation. Here, the rotational speed at a given cylinder after injection is compared to a mean speed. If the particular cylinder's speed is too low the injected fuel quantity is increased, and if it is too high the fuel quantity is reduced (Fig. 3).

2 Active surge damper (ARD): Example

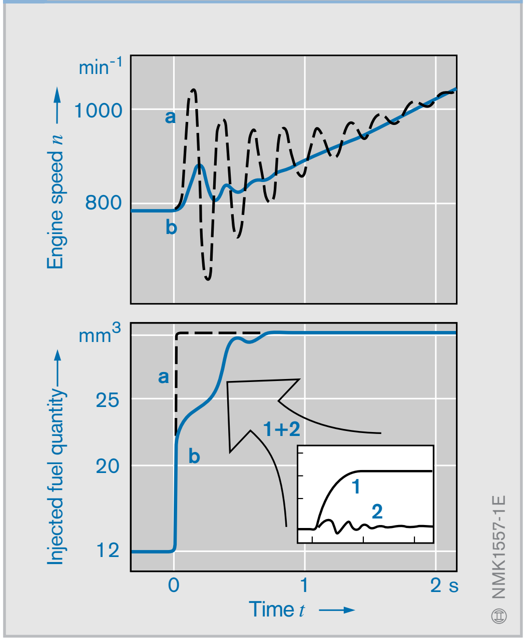
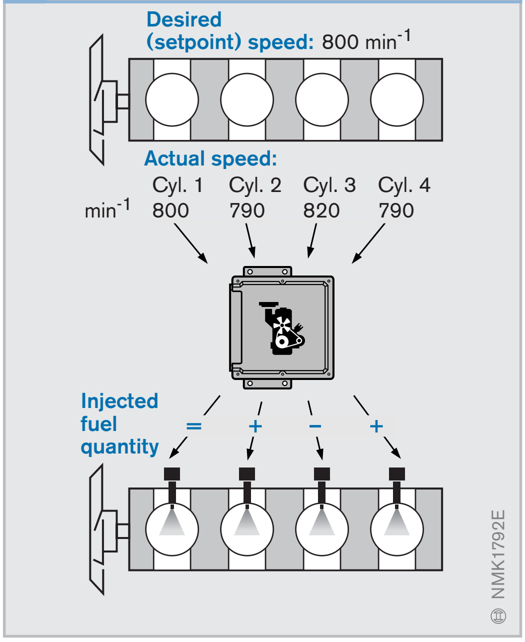


Figure 2
a Without active surge damper
b With active surge damper
1 Filter function
2 Active correction

3 Smooth-running control (SRC): Example



The smooth-running control is a comfort function, the primary object of which is to ensure that the engine runs smoothly in the vicinity of idle. The injected-fuel-quantity compensation function is aimed at not only improving comfort at idle but also at reducing the emissions in the medium speed ranges by ensuring identical injected fuel quantities for all cylinders. On commercial vehicles, the smooth-running control is also known as the AZG (adaptive cylinder equalization).

Injected-fuel-quantity limit

There are a number of reasons why the fuel quantity actually wished for by the driver, or that which is physically possible, should not always be injected. The injection of such fuel quantities could have the following effects:

- Excessive emissions,
- Excessive soot,
- Mechanical overloading due to high torque or excessive engine speed,
- Thermal overloading due to excessive temperatures of the exhaust gas, coolant, oil, or turbocharger,
- Thermal overloading of the solenoid valves as a result of them being triggered too long.

To avoid these negative effects, a number of input variables (for instance intake-air quantity, engine speed, and coolant temperature) are used in generating this limitation figure. The result is that the maximum injected fuel quantity is limited and with it the maximum torque.

Engine-brake function

When a truck’s engine brake is applied, the injected fuel quantity is either reduced to zero or the idle fuel quantity is injected. For this purpose, the ECU registers the setting of the engine-brake switch.

Altitude compensation

Atmospheric pressure drops along with increasing altitude so that the cylinder is charged with less combustion air. This means that the injected fuel quantity must be reduced accordingly, otherwise excessive soot will be emitted.

In order that the injected fuel quantity can be reduced at high altitudes, the atmospheric pressure is measured by the ambient-pressure sensor in the ECU. Atmospheric pressure also has an effect upon boost-pressure control and torque limitation.

Cylinder shutoff

If less torque is required at high engine speeds, very little fuel must be injected. As an alternative, cylinder shutoff can be applied for torque reduction. Here, half of the injectors are switched off (commercial-vehicle UIS, UPS and CRS). The remaining injectors then inject correspondingly more fuel which can be metered with even higher precision.

When the injectors are switched on and off, special software algorithms ensure smooth transitions without noticeable torque changes.

Start-of-injection control

The start of injection has a critical effect on power output, fuel consumption, noise, and emissions. The desired value for start of injection depends on engine speed and injected fuel quantity, and it is stored in the ECU in special maps. Adaptation is possible as a function of coolant temperature and ambient pressure.

Tolerances in manufacture and in the pump mounting on the engine, together with changes in the solenoid valve during its lifetime, can lead to slight differences in the solenoid-valve switching times which in turn lead to different starts of injection. The response behaviour of the nozzle-and-holder assembly also changes over the course of time. Fuel density and temperature also have an effect upon start of injection. This must be compensated for by some form of control strategy in order to stay within the prescribed emissions limits. The following closed-loop controls are employed (Table 2):

Table 2

2 Start-of-injection control

Closed-loop control	**Control using needle-motion sensor**	**Start-of-delivery control**	**BIP control**
Injection system			
In-line injection pumps	●	–	–
Helix-controlled distributor pumps	●	–	–
Solenoid-valve-controlled distributor pumps	●	●	–
Common Rail	–	–	–
Unit Injector/Unit Pump	–	–	●

The start-of-injection control is not needed with the Common Rail System, since the high-voltage triggering used in the CRS permits highly reproducible starts of injection.

Closed-loop control using the needle-motion sensor

The inductive needle-motion sensor is fitted in an injection nozzle (reference nozzle, usually cylinder 1). When the needle opens (and closes) the sensor transmits a pulse (Fig. 4). The needle-opening signal is used by the ECU as confirmation of the start of injection. This means that inside a closed control loop the start of injection can be precisely aligned to the desired value for the particular operating point.

The needle-motion sensor's untreated signal is amplified and interference-suppressed before being converted to precision square-wave pulses which can be used to mark the start of injection for a reference cylinder.

The ECU controls the actuator mechanism for the start of injection (for in-line pumps the solenoid actuator, and for distributor pumps the timing-device solenoid valve) so that the actual start of injection always corresponds to the desired/setpoint start of injection.

The start-of-injection signal can only be evaluated when fuel is being injected and when the engine speed is stable. During starting and overrun (no fuel injection), the needle-motion sensor cannot provide a signal which is good enough for evaluation. This means that the start-of-injection control loop cannot be closed because there is no signal available confirming the start-of-injection.

4 Conditioning of the signal from the needle-motion sensor

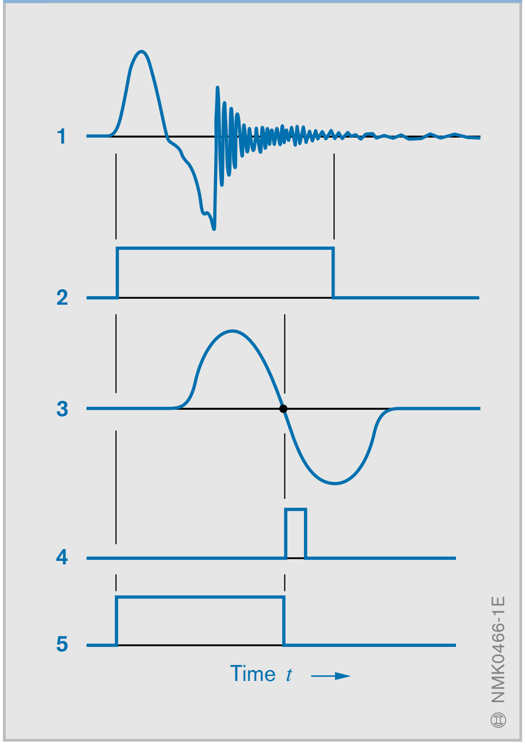


Figure 4
1 Untreated signal from the needle-motion sensor (NBF),
2 Signal derived from the NBF signal,
3 Untreated signal from the inductive engine-speed sensor
4 Signal derived from untreated engine-speed signal,
5 Evaluated start-of-injection signal

In-line injection pumps
On in-line pumps, a special digital current controller improves the control's accuracy and dynamic response by aligning the current to the start-of-injection controller's setpoint value practically without any delay at all.

In order to ensure start-of-injection accuracy in open-loop-controlled operation too, the start-of-delivery solenoid in the control-sleeve actuator mechanism is calibrated to compensate for the effects of tolerances. The current controller compensates for the effects of the temperature-dependent solenoid-winding resistance. All these measures ensure that the setpoint value for current as derived from the start map leads to the correct stroke of the start-of-delivery solenoid and to the correct start of injection.

Start-of-delivery control using the incremental angle/time signal (IWZ)

On the solenoid-valve-controlled distributor pumps (VP30, VP44), the start of injection is also very accurate even without the help of a needle-motion sensor. This high level of accuracy was achieved by applying positioning control to the timing device inside the distributor pump. This form of closed-loop control serves to control the start of delivery and is referred to as start-of-delivery control. Start of delivery and start of injection have a certain relationship to each other and this is stored in the so-called wave-propagation-time map in the engine ECU.

The signal from the crankshaft-speed sensor and the signal from the incremental angle/time system (IWZ signal) inside the pump, are used as the input variables for the timing-device positioning control.

The IWZ signal is generated inside the pump by the rotational-speed or angle-of-rotation sensor (1) on the trigger wheel (2) attached to the driveshaft. The sensor shifts along with the timing device (4) which, when it changes position, also changes the position of the tooth gap (3) relative to the TDC pulse of the crankshaft-speed sensor. The angle between the tooth gap, or the synchronization pulse generated by the tooth gap, and the TDC pulse is continually registered by the pump ECU and compared with the stored reference value. The difference between the two angles represents the timing device's actual position, and this is continually compared with its setpoint/desired position. If the timing-device position deviates, the triggering signal for the timing-device solenoid valve is changed until actual and setpoint position coincide with each other.

Since all cylinders are taken into account, the advantage of this form of start-of-delivery control lies in the system's rapid response. It has a further advantage in that it also functions during overrun when no fuel injection takes place which means that the timing device can be preset for when the next injection event occurs.

In case even more severe demands are made on the accuracy of the start of injection, the start-of-delivery control can have an optional start-of-injection control with needle-motion sensor superimposed upon it.

5 Rotational-speed/Angle-of-rotation sensor for the IWZ signal

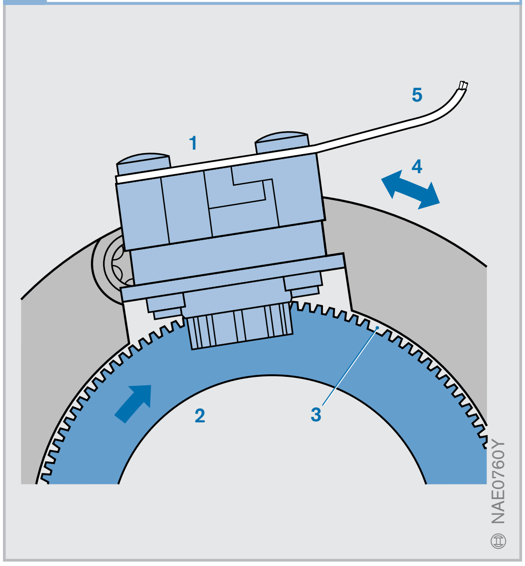


Figure 5
1 Rotational-speed/angle-of-rotation sensor inside the injection pump
2 Trigger wheel
3 Trigger-wheel tooth gap
4 Shift due to timing device
5 Electrical plug-in connection

BIP control

BIP control is used with the solenoid-valve-controlled **U**nit **I**njector System (UIS) and **U**nit **P**ump System (UPS). The start of delivery – or BIP (**B**egin of **I**njection **P**eriod) – is defined as the instant in time in which the solenoid closes. As from this point, pressure buildup starts in the pump high-pressure chamber. The nozzle opens as soon as the nozzle-opening pressure is exceeded, and injection can commence (start of injection). Fuel metering takes place between start of delivery and end of solenoid-valve triggering. This period is termed the delivery period.

Since there is a direct connection between the start of delivery and the start of injection, all that is needed for the precise control of the start of injection is information on the instant of the start of delivery.

So as to avoid having to apply additional sensor technology (for instance, a needle-motion sensor), electronic evaluation of the solenoid-valve current is used in detecting the start of delivery. Around the expected instant of closing of the solenoid valve, constant-voltage triggering is used (BIP window, Fig. 6, Pos. 1). The inductive effects when the solenoid valve closes result in the curve having a specific characteristic which is registered and evaluated by the ECU. For each injection event, the deviation of the solenoid-valve closing point from the theoretical setpoint is registered and stored, and applied for the following injection sequence as a compensation value.

If the BIP signal should fail, the ECU changes over to open-loop control.

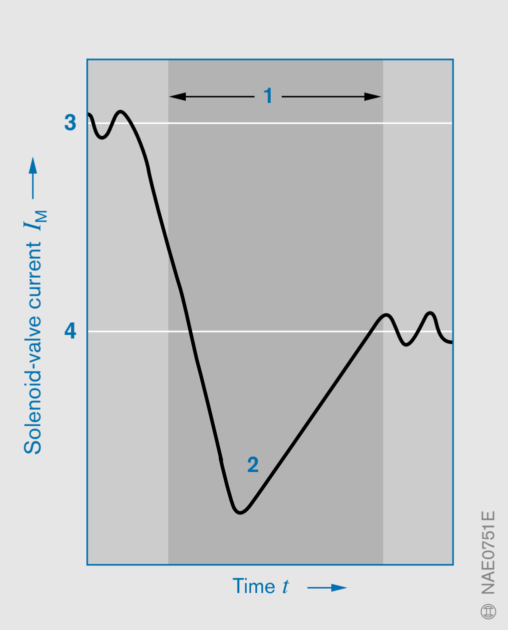
Shutoff

The “auto-ignition” principle of operation means that in order to stop the diesel engine it is only necessary to cut off its supply of fuel. With EDC (**E**lectronic **D**iesel **C**ontrol), the engine is switched off due to the ECU outputting the signal “Fuel quantity zero” (that is, the solenoid valves are no longer triggered, or the control rack is moved back to the zero-delivery setting).

There are also a number of redundant (supplementary) shutoff paths (for instance, the electrical shutoff valve (ELAB) on the port-and-helix controlled distributor pumps).

The UIS and UPS are intrinsically safe, and the worst thing that can happen is that one single unwanted injection takes place. Here, therefore, supplementary shutoff paths are not needed.

6 BIP detection



Firgure 6

1 BIP window
2 BIP signal
3 Level of pickup current
4 Holding-current level

Lambda closed-loop-control for passenger-car diesel engines

Applications

The lawmakers are continually increasing the severity of the legislation governing the exhaust-emission limit values for diesel engines. Apart from the measures taken to optimize the engine's internal combustion, the open and closed-loop control of those functions which are relevant with regard to the exhaust emissions are continuing to gain in importance. The introduction of the Lambda closed-loop control opens up immense potential for reducing the diesel engine's exhaust emissions.

The broad-band Lambda oxygen sensor in the exhaust pipe (Fig. 1, Pos. 7) measures the residual oxygen in the exhaust gas. This is an indicator for the A/F ratio (excess-air-factor Lambda l). A high level of signal accuracy is ensured throughout the sensor's service life by adapting the Lambda-sensor signal during actual operations. The Lambda-sensor signal is used as the basis for a number of Lambda functions which will be described in more detail in the following.

A Lambda closed-loop control circuit is imperative for the regeneration of NO_X accumulator-type catalytic converters.

The Lambda closed-loop-control is suitable

1 System overview of Lambda closed-loop control for passenger-car engines (Example)

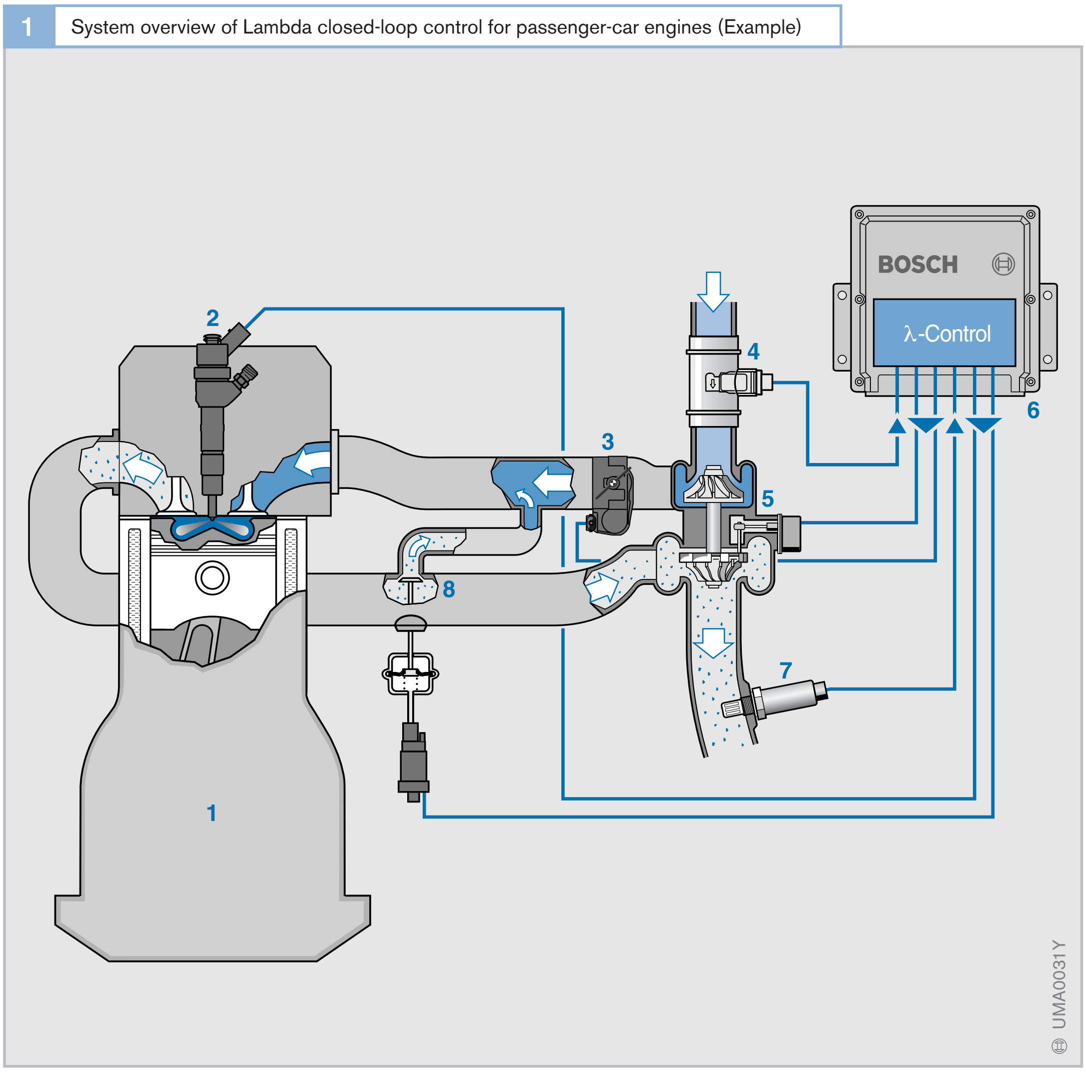


Figure 1

1 Diesel engine
2 Diesel injection component (here Common Rail injector)
3 Throttle valve
4 Hot-film air-mass meter
5 Exhaust-gas turbocharger (here, VTG version)
6 Engine ECU for EDC
7 Broad-band Lambda oxygen sensor
8 EGR valve

for all passenger-car diesel injection systems controlled by the EDC16 generation.

Basic functions

Pressure compensation

The untreated Lambda-sensor signal is a function of the oxygen concentration in the exhaust gas and of the exhaust-gas pressure at the sensor's installation point. The influence of the pressure on the sensor signal must therefore be compensated for.

The pressure-compensation function incorporates two maps, one for the exhaust-gas pressure and one for the pressure-dependence of the lambda sensor's output signal. These two maps are used for the correction of the sensors output signal with reference to the particular operating point.

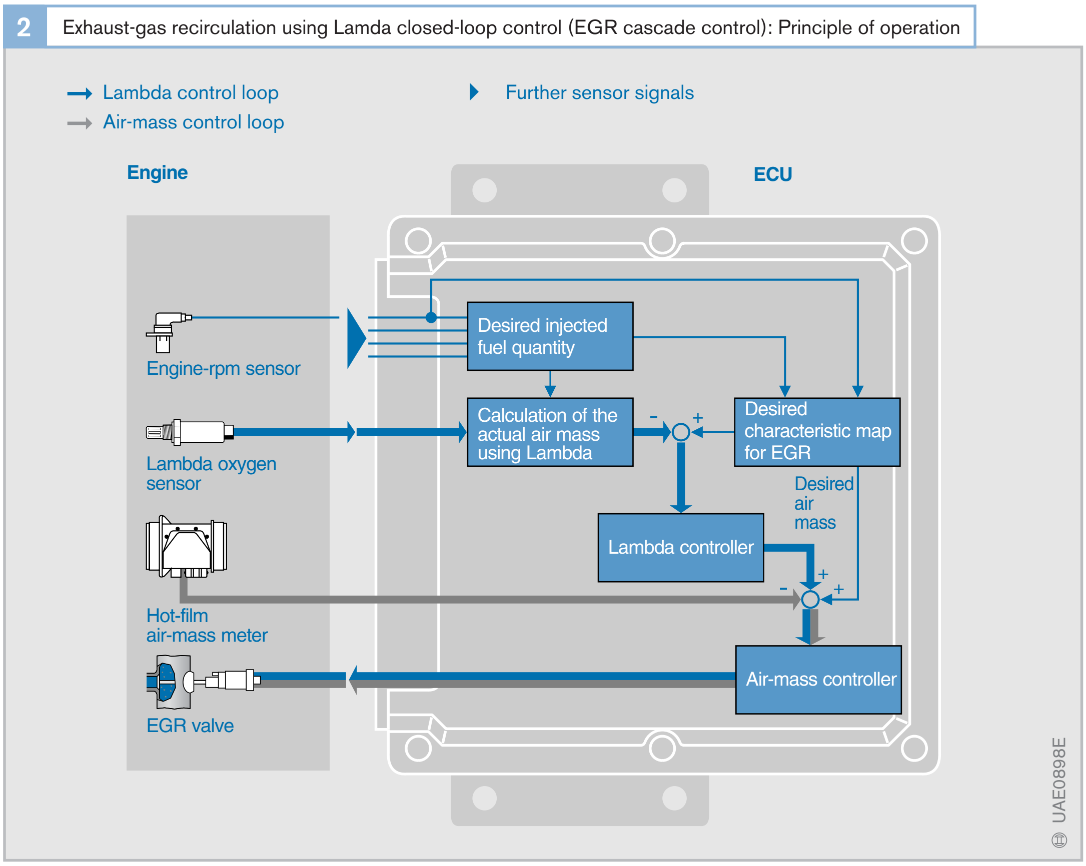
Adaptation

In the overrun (trailing throttle) mode, the Lambda sensor's adaptation takes into account the deviation of the measured oxygen concentration from the fresh-air oxygen concentration (approx. 21%). As a result, the system "learns" a correction value which at every engine operating point is used to correct the measured oxygen concentration. This leads to a precise, drift-compensated Lambda output signal throughout the sensor's service life.

Lambda-based EGR control

Regarding emissions, compared with the conventional EGR method based on air mass, using the Lambda oxygen sensor to measure the residual oxygen in the exhaust gas permits a tighter tolerance range for the complete vehicle fleet. In the MNEFZ (modified new European driving cycle) exhaust-gas test, therefore, from the exhaust-emissions viewpoint this equates to an improvement of 10...20% with regard to the fleet as a whole.

2 Exhaust-gas recirculation using Lamda closed-loop control (EGR cascade control): Principle of operation



Cascade control

With the cascade control (Fig. 2), the conventional air-mass control loop as used in present-day series production has a Lambda control loop superimposed upon it (refer to the section “Control and triggering of the remaining actuators”).

The dynamic response is excellent when air-mass control is used (that is, the air-mass meter responds far more quickly). The external Lambda closed-loop control circuit improves the EGR-system accuracy.

The actual air-mass figure is calculated from the Lambda oxygen sensor signal and from the desired value for the injected fuel quantity. The system deviation between the calculated air mass and the desired air mass taken from the EGR desired-value characteristic map, is compensated for by the Lambda controller.

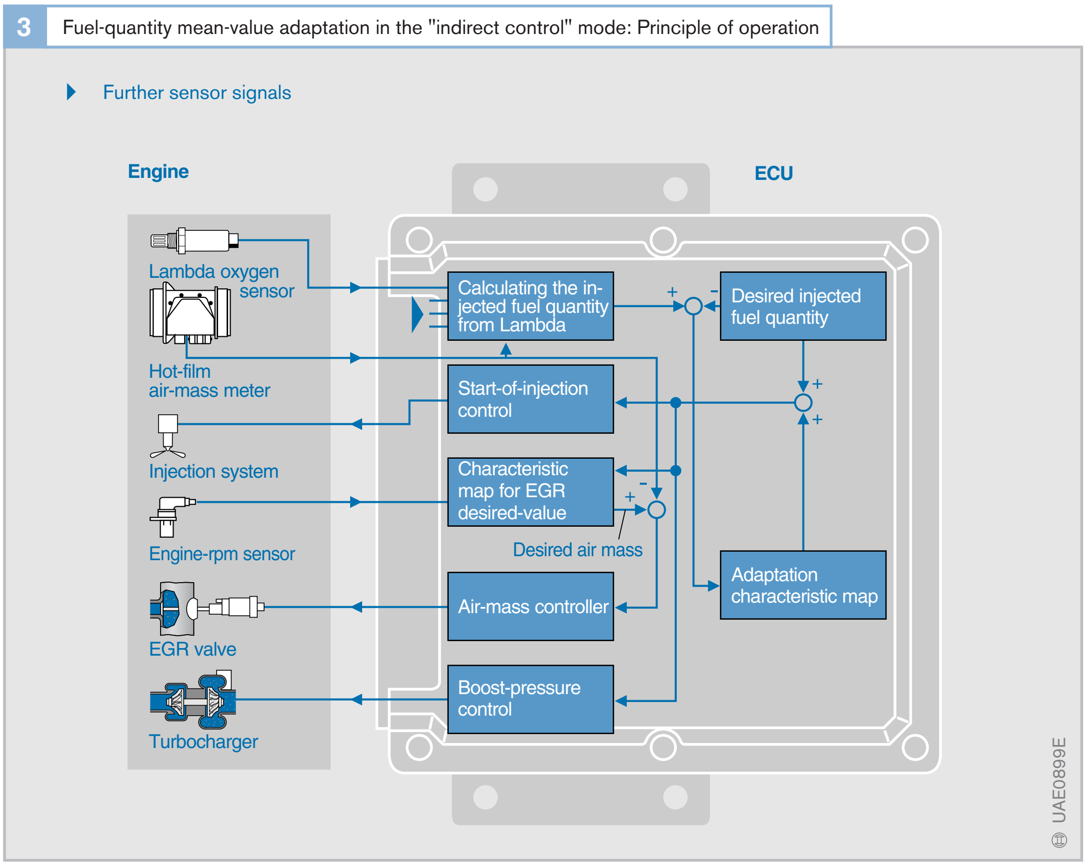
Notwithstanding the change to the calculated air mass as the reference (command) variable for the EGR, in its physical effects, this control architecture acts as a Lambda closed-loop control (in contrast to the Lambda closed-loop control used on gasoline engines in which the fuel mass is taken as the reference (command) variable).

Fuel-quantity mean-value adaptation

The fuel-quantity mean-value adaptation (MMA) provides a precise injected-fuel-quantity signal for the setpoint generation as needed for those control loops which are relevant for exhaust-gas emission (e.g. EGR control, boost-pressure control, and start-of-injection control). The MMA operates in the lower part-load range and determines the average deviation in the injected fuel quantity of all cylinders together.

Fig. 3 shows the basic structure of the MMA and its intervention in the control loops

3 Fuel-quantity mean-value adaptation in the "indirect control" mode: Principle of operation



which are relevant for the exhaust-gas emissions.

The Lambda-sensor signal and the air-mass signal are used in calculating the actually injected fuel mass which is then compared with the desired injected fuel mass. Differences are then stored in an adaptation map in defined “learning points”. This procedure ensures that when the operating point necessitates an injected fuel quantity correction, this can be implemented without delay even during dynamic changes of state.

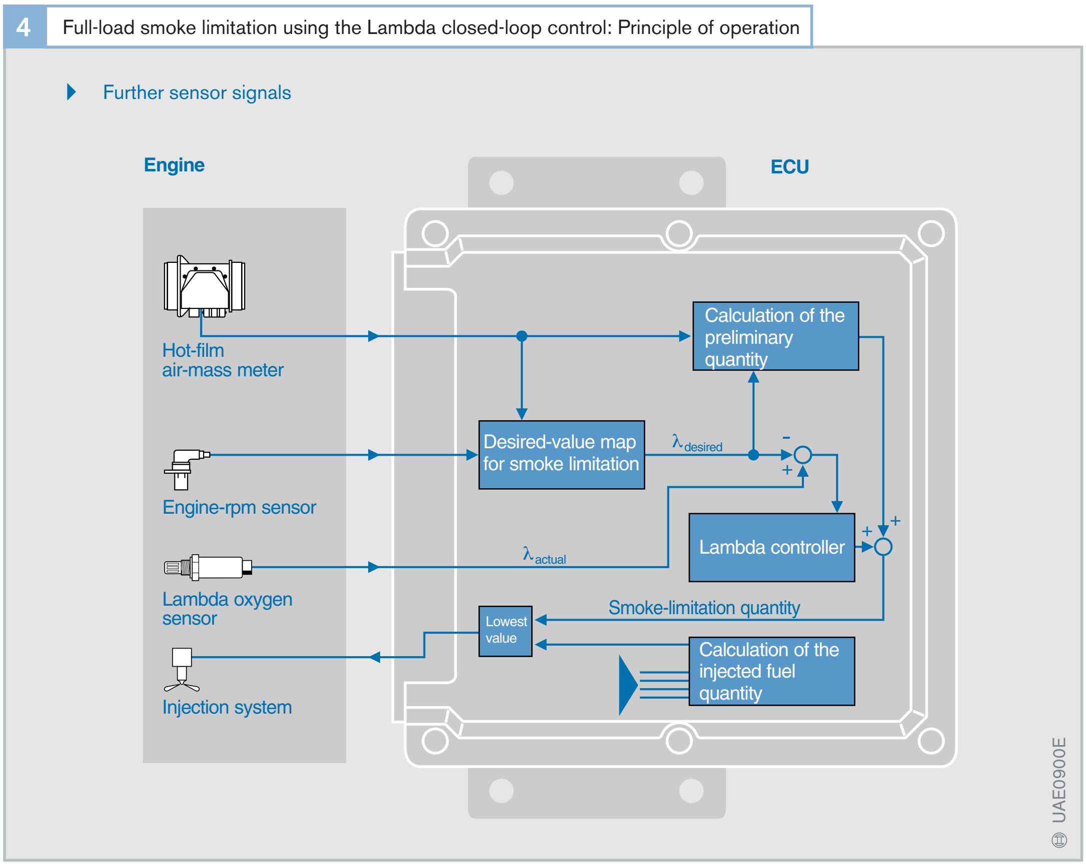
These correction quantities are stored in the EEPROM of the ECU and are available immediately the engine is started.

Basically speaking, there are two MMA operating modes. These differ in the way they apply the detected deviations in injected fuel quantity:

Operating mode: Indirect control
In the “indirect control” mode (Fig. 3), a precise desired injected fuel quantity is used as an input variable in the desired-value characteristic maps which are relevant for exhaust emissions. The injected fuel quantity is not corrected during the fuel-metering process.

Operating mode: Direct control
In the “direct control” mode, in order that the amount of fuel actually injected corresponds as closely as possible to the desired quantity, the fuel-quantity deviation is used to correct the injected fuel quantity during the fuel-metering process. In this case, this is (indirectly) a closed fuel-quantity loop.

4 Full-load smoke limitation using the Lambda closed-loop control: Principle of operation



Full-load smoke limitation

Fig. 4 shows the block diagram of the control structure for full-load smoke limitation using a Lambda oxygen sensor. The objective here is to determine the maximum amount of fuel which may be injected without exceeding a given smoke value.

The signals from the air-mass meter and the engine rpm sensor are applied together with a smoke-limitation map in determining the desired Lambda value $\lambda_{\mathrm{DESIRED}}$. This, in turn, is applied together with the air mass in order to calculate the preliminary value for the maximum permissible injected fuel quantity.

This form of control is already in series production, and has a Lambda closed-loop control imposed upon it. Using the difference between $\lambda_{\mathrm{DESIRED}}$ and the actually measured residual oxygen in $\lambda_{\mathrm{ACTUAL}}$ the Lambda controller calculates the correction fuel quantity. The maximum full-load injected fuel quantity is the total of the preliminary quantity and the correction quantity.

This control architecture permits a high level of dynamic response due to the pilot control, and improved precision due to the superimposed Lambda control loop.

Detection of undesirable combustion

During overrun (trailing throttle), if the Lambda-sensor signal drops below a given, specially calculated threshold this indicates that undesirable combustion is taking place. In this case, the engine can be switched off by closing a control flap and the EGR valve. The detection of undesirable combustion represents an additional engine safeguard function.

Summary

Using Lambda-based EGR it is possible to considerably reduce a vehicle fleet’s exhaust-gas emissions scatter. Here, either fuel-quantity mean-value adaptation (MMA) can be used or cascade control.

MMA provides a precise injected-fuel-quantity signal for generating the desired (setpoint) values for the control loops which are relevant for emissions (for instance, for EGR control, boost-pressure control, start-of-injection control). The precision of these control loops is increased as a result.

In addition, the application of Lambda closed-loop control permits the precise definition of the full-load smoke quantity as well as the detection of undesirable combustion in the overrun (trailing throttle) mode.

Furthermore, the Lambda sensor’s high-precision signal can be used in a Lambda control loop for the regeneration of NO_X catalytic converters.

Engine dynamometer

Every injection system is tested using an engine-dynamometer setup featuring a high degree of engine accessibility.

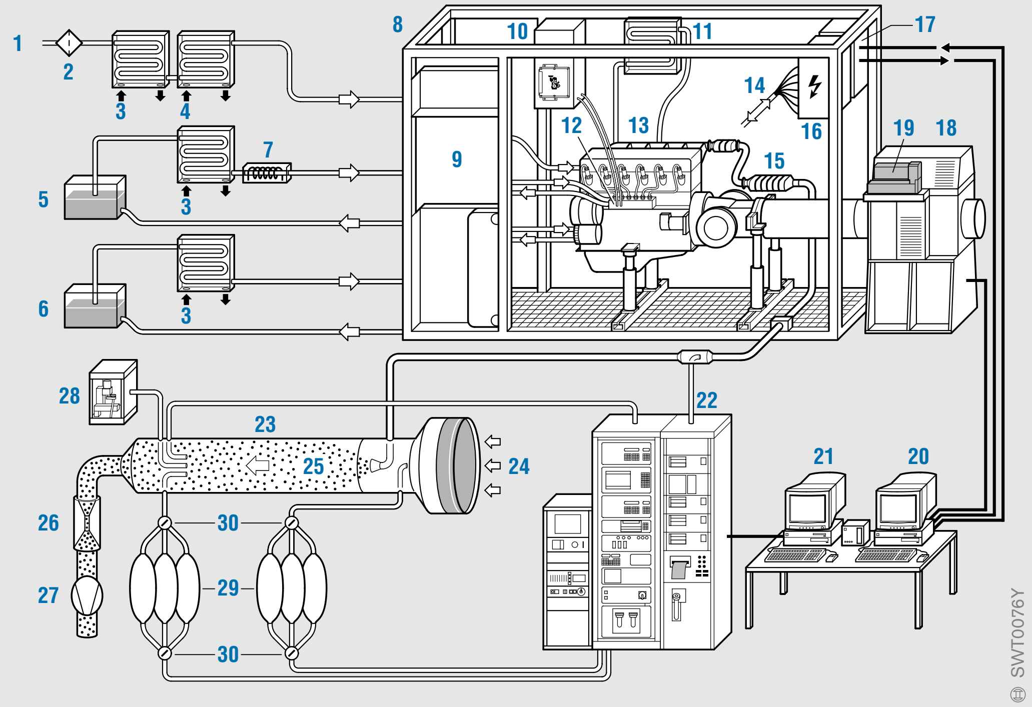
By conditioning intake, air, fuel, and coolant with respect to temperature and pressure etc., it is possible to obtain reproducible test results.

Increasingly, dynamic tests with rapid load and rpm changes must be run through in addition to steady-state tests. Here, test stands with an electrical dynamometric brake (dynamometer) are the best solution, as they can also “drive” the test specimen (as takes place on the road during overrun or trailing-throttle operation on a downhill gradient). Using the appropriate simulation software, the passenger-car exhaust-gas tests demanded by law can then be run through on the engine dynamometer instead of on the roller-type test bench.

The dynamometer computer (20) is responsible for the control and monitoring of the engine and the test equipment. It also takes over data acquisition and data storage. Highly efficient application-engineering work (map measurements) can be carried out with the help of automation software.

By means of suitable quick-change systems (8), it is possible to change engine pallets within about 20 minutes, a feature which increases the dynamometer’s utilization time.

Engine dynamometer: Basic design



1 Intake air
2 Filter
3 Cold-water supply
4 Hot-water supply
5 Fuel
6 Coolant
7 Heater
8 Quick-change system
9 Transfer module for coolant, water, fuel, etc.
10 Engine management (EDC)
11 Intercooler
12 Injection system
13 Engine
14 Triggering and sensor signals
15 Catalytic converter
16 Power supply
17 Interface for measurement techniques
18 Electrical dynamometer
19 Accelerator-pedal actuator
20 Test-bench computer
21 Indicating system (high-speed angle-synchronous measured-value acquisition)
22 Exhaust-gas analysis equipment (e.g. Analysis equipment for gaseous emissions, opacimeter, Fourier-transformed infrared (FTIR) spectroscope, mass spectrometer, particle-counting system)
23 Dilution tunnel
24 Dilution air
25 Mixing chamber
26 Volume meter
27 Blower
28 Particle sampling system
29 CVS bag sampling system
30 Change-over valve

Further special adaptations

In addition to those described here, EDC permits a wide range of other functions. For instance, these include:

Drive recorder

On commercial vehicles, the Drive Recorder is used to record the engine's operating conditions (for instance, how long was the vehicle driven, under what temperatures and loads, and at what engine speeds). This data is used in drawing up an overview of operational conditions from which, for instance, individual service intervals can be calculated.

Special application engineering for competition trucks

On race trucks, the 160 km/h maximum speed may be exceeded by no more than 2 km/h. On the other hand, this speed must be reached as soon as possible. This necessitates special adaptation of the ramp function for the vehicle-speed limiter.

Adaptations for off-highway vehicles

Such vehicles include diesel locomotives, rail cars, construction machinery, agricultural machinery, boats and ships. In such applications, the diesel engine(s) is/are far more often run in the full-load range than is the case with road vehicles (90% full-load operation compared with 30%). The power output of such engines must therefore be reduced in order to ensure an adequate service life.

The mileage figures which are often used as the basis for the service interval on road vehicles are not available for such equipment as agricultural or construction machinery, and in any case if they were available they would have no useful significance. Instead, the Drive Recorder data is used here.

Port-and-helix-controlled fuel-injection systems: Triggering

Electronically controlled in-line injection pumps, PE-EDC

As with the mechanically (flyweight) governed in-line fuel-injection pumps, the injected fuel quantity here is also a function of the control-rack position and the engine speed. The control rack is shifted to the desired position by the linear magnet of the actuator mechanism directly attached to the pump (Fig. 1 on the next page, Pos. 3).

On the control-sleeve in-line pump, an additional electrical actuator in connection with start-of-injection control can be used to arbitrarily adjust the injected fuel quantity and the start of delivery. This necessitates an extra actuator mechanism (4).

Triggering the control-rack actuator mechanism

With the solenoid de-energized, a spring forces the control rack to the stop position and thus interrupts the fuel supply. When the current through the solenoid increases, the solenoid gradually overcomes the force of the spring and control-rack travel increases so that more fuel is injected.

This means that the level of current permits the continuous adjustment of control-rack travel between zero and maximum delivery quantity (pwm signal = pulse-width-modulated signal).

The corresponding pump characteristic map is programmed into the ECU. Using this map, and depending on engine speed, the control-rack travel appropriate to the desired fuel quantity is calculated. In order to improve driveability, a control characteristic can be provided which is familiar from the mechanical (flyweight) RQ and RQV governors.

Using a sensor (rack-travel sensor (RWG)), the position control in the ECU registers the actual control-rack setting so that the system deviation can be calculated.

This enables the position control to quickly and accurately correct the rack setting.

Triggering of the control-sleeve actuator mechanism

A power stage which is triggered directly from the processor with a pwm signal provides the power needed to energize the start-of-delivery solenoids. A low-level current causes minor travel of the start-of-delivery solenoid, and retards the start of delivery or start of injection. On the other hand, a high level of current advances the start-of-delivery point.

The injected-fuel-quantity controls as applied to the control-sleeve in-line pumps and the conventional in-line pumps (both with EDC) are identical. The more extensive functional scope in the ECU for the control-sleeve pump results to a great extent from expanded programs.

Key stop

The key stop function using the “ignition” key supersedes the conventional mechanical shutoff device. It stops the supply of fuel by interrupting the power supply to the electrical shutoff valve (ELAB, redundant shutoff path) and to the control-rack linear solenoids.

Port-and-helix-controlled axial-piston distributor pumps, VE-EDC

Solenoid actuator for injected-fuel-quantity control

The solenoid actuator (moving-magnet actuator) engages the delivery-piston control collar via a shaft (Fig. 2, Pos. 3). Similar to the mechanically governed distributor pumps, the cutoff bores are exposed sooner or later depending upon the position of the control collar.

The injected fuel quantity can be continually varied between zero and maximum. By means of an angle sensor (Hall short-circuiting-ring sensor, HDK), information on the angle of rotation of the actuator, and therefore on the setting of the control collar with respect to the cutoff ports, is reported back to the ECU and used to calculate the correct fuel quantity as a function of engine speed.

In the de-energized state, the fuel delivery is set to zero by return springs on the actuator mechanism.

1 PE control-sleeve in-line fuel-injection pumps: Injection-triggering components

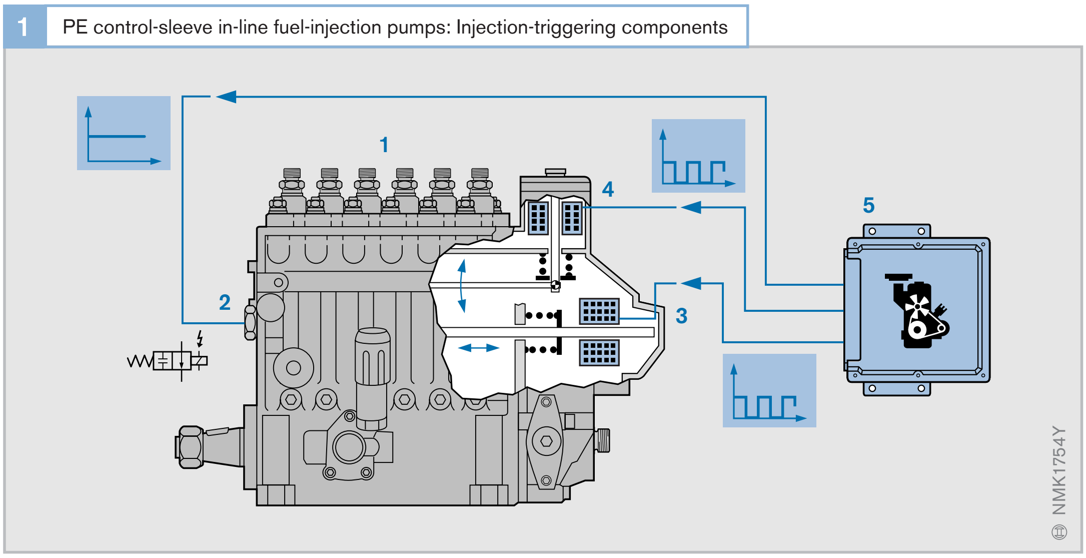


Figure 1
1 In-line injection pump
2 Electrical shutoff valve (ELAB)
3 Control-rack actuator mechanism (injected fuel quantity)
4 Control-sleeve actuator mechanism (start of delivery)
5 Engine ECU

2 VE-EDC axial-piston distributor pumps: Injection-triggering components

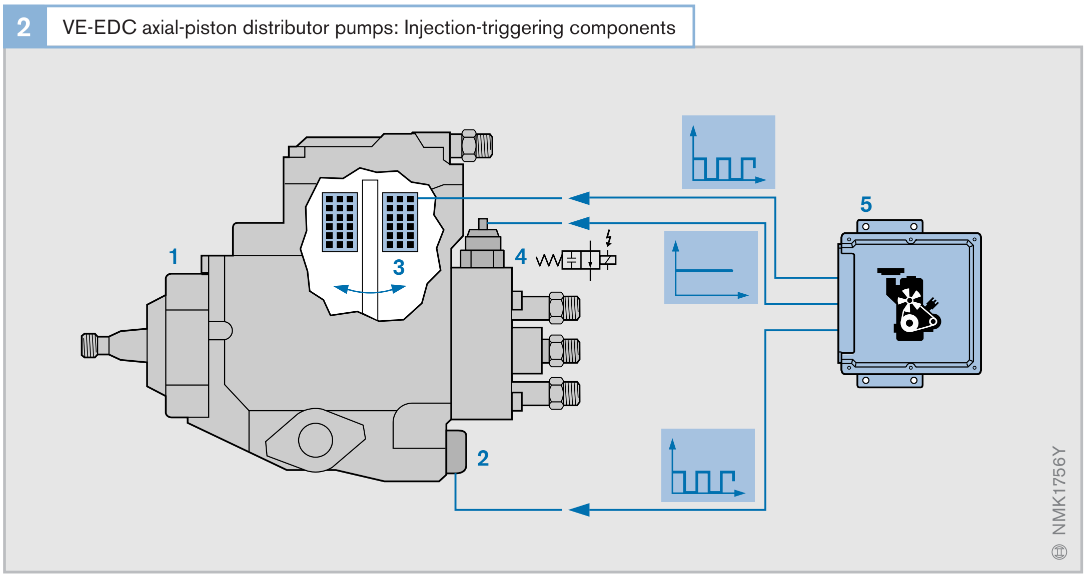


Figure 2

1 Distributor pump
2 Timing-device solenoid valve (start of injection)
3 Moving-magnet actuator (injected fuel quantity)
4 Electric shutoff valve (ELAB)
5 Engine ECU

Solenoid valve for start-of-injection control

The pump's internal pressure is proportional to the pump speed and, similar to the mechanical timing device, is effective at the timing-device piston. This pressure is applied to the timing-device pressure side and is modulated by the clocked timing-device solenoid valve (2). The on/off ratio (ratio of the solenoid's open time to its closed time) for the triggering of the solenoid valve is taken from a programmed control map.

A permanently opened solenoid valve (pressure reduction) results in later start-of-injection points, and with the solenoid valve permanently closed (pressure increase) the start-of-injection points take place earlier. In between these two extremes, infinite variation of the on/off ratio can be implemented by the ECU.

Deviations between actual and desired start-of-injection points, as detected with the help of the needle-motion sensor, result in a change of the on/off ratio for triggering the timing-device solenoid valve. This ratio is changed continually until the system deviation is "zero", and ensures a dynamic response which is comparable to that of the mechanical start-of-injection adjustment.

Shutoff

As a rule, shutoff is by means of the injected-fuel-quantity actuator ("zero" fuel delivery). The redundant electrical shutoff valve (ELAB) provides a further degree of safety (4).

On the distributor pump, the redundant electrical shutoff valve is mounted on the upper side of the pump's distributor head. When switched on (that is, with the engine running), the solenoid keeps the inlet port to the high-pressure chamber open (the armature with sealing cone is pulled in). When switch off takes place using the "ignition switch", the solenoid winding is de-energized and the sealing cone is forced back onto its seat by a spring so that the inlet port to the high-pressure chamber is interrupted.

On marine engines, the ELAB is open when de-energized. This means that the engine can still run even though the on-board power supply has failed. Apart from this, the number of electrical consumers is kept to a minimum since continuous current aggravates the effects of saltwater corrosion.

Solenoid-valve-controlled injection systems: Triggering

The solenoid-valve-controlled injection-system family includes the following:

- Axial-piston distributor pumps, VE-M (VP30),
- Radial-piston distributor pumps, VR (VP44),
- Common Rail System CRS,
- Unit Injector System, UIS
- Unit Pump System, UPS

These solenoid-valve-controlled injection systems are all triggered by similar signals. The characteristic features of the individual systems are described in the following sections, together with the differences between them and conventional injection systems.

Due to better EMC (ElectroMagnetic Compatibility) characteristics, the high-pressure solenoid valves are triggered by analog signals. Since the triggering signal must feature steep current edges in order to ensure narrow tolerances and a high degree of reproducibility for the injected fuel quantity, this form of triggering makes severe demands on the output stages.

In addition, the triggering process must ensure a minimum of power loss in the ECU and in the high-pressure solenoid valve. In other words, the triggering currents must be as low as possible.

Irrespective of operating range, injection control must be extremely accurate in order that the injection pump and solenoid injector inject precisely and with a high level of reproducibility.

The injection system must respond extremely quickly to changes, which means that the calculations in the microcontroller and the triggering-signal implementation in the output stages must take place at very high speed. Data processing is therefore referred to as being “real-time compatible” (resolution time 1 μs).

Solenoid-valve-controlled distributor pumps

On the distributor pumps equipped with a high-pressure fuel-quantity solenoid valve (VP44 and VP30), a pump ECU (PSG) attached to the pump housing is responsible for triggering the solenoid valves at the calculated start-of-delivery point (Fig. 1a, Pos. 1a). This takes place in accordance with the requirements of the engine ECU (6) which is responsible for the engine and vehicle functions. The two ECUs communicate with each other through the CAN bus.

The latest generation of the VP44 system features only a single ECU (PSG 16) which has united all the EDC functions in a single unit, and which is situated directly on the pump (Fig. 1b, Pos. 1b).

The timing-device solenoid valve (4) used on the distributor pumps is triggered using a pulse-width-modulated (pwm) signal. In order to avoid malfunctions due to resonance effects, the clock frequency is not held constant thoughout the complete rotational-speed range but instead, at given speed ranges, it is switched to a different frequency (window technique).

The high-pressure fuel-quantity solenoid valve is triggered via current control (Fig. 2)

1 Solenoid-valve-controlled distributor pumps: Injection-triggering components

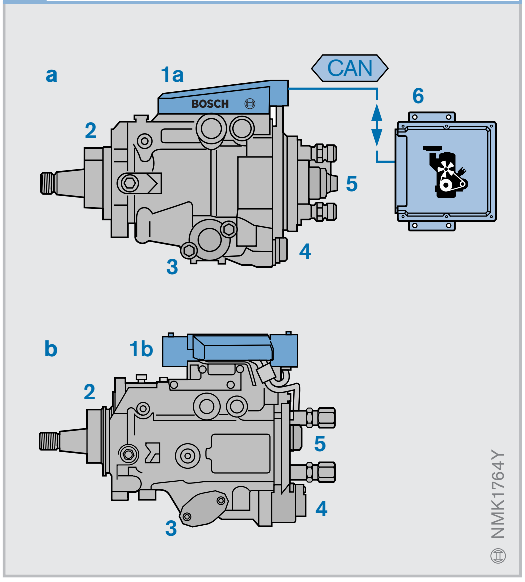


Figure 1

a	With separate pump and engne ECU
b	With integral pump and engine ECU
1a	Pump ECU (PSG5)
1b	Pump ECU (PSG16)
2	Distributor pump
3	Timing device
4	Timing-device solenoid valve
5	High-pressure fuel-quantity solenoid valve
6	Engine ECU (MSG)

which subdivides the triggering process into a pickup-current phase (a) of approx. 18 A, and a holding-current phase (c) of approx. 10 A. At the beginning of the controlled holding-current phase (after 200 ... 250 μs), the BIP evaluation circuit detects the solenoid-valve needle closing against the valve seat (BIP = **B**eginning of the **I**njection **P**eriod).

The latest generation uses the PSG16 pump ECU, and is also provided with a BIP current (b) between the pickup and holding-current phases which is at the optimum level for the BIP detection function.

In order that the pump's injection characteristics are always reproducible irrespective of operating conditions, the triggering circuitry as a whole, and the current control, must be extremely accurate. Furthermore, they must keep the power loss in ECU and solenoid valve down to a minimum.

Defined, rapid opening of the solenoid valve is required at the end of the injection process. To this end, high-speed quenching (d) using a high quenching voltage (1) is applied at the valve to dissipate the energy stored in its solenoid.

The solenoid valve can also be used to control pilot injection (PI) for reduction of combustion noise. Here, the solenoid valve is operated ballistically between the PI point and the MI (main injection) point. In other words it is only partially opened, which means that it can be closed again very quickly. The resulting injection spacing is very short so that even at high rotational speeds, adequate cam pitch remains for the main injection process.

The subdivision into the individual triggering phases is calculated by the microcontroller in the pump ECU.

2 High-pressure solenoid valves: Triggering sequence using current control

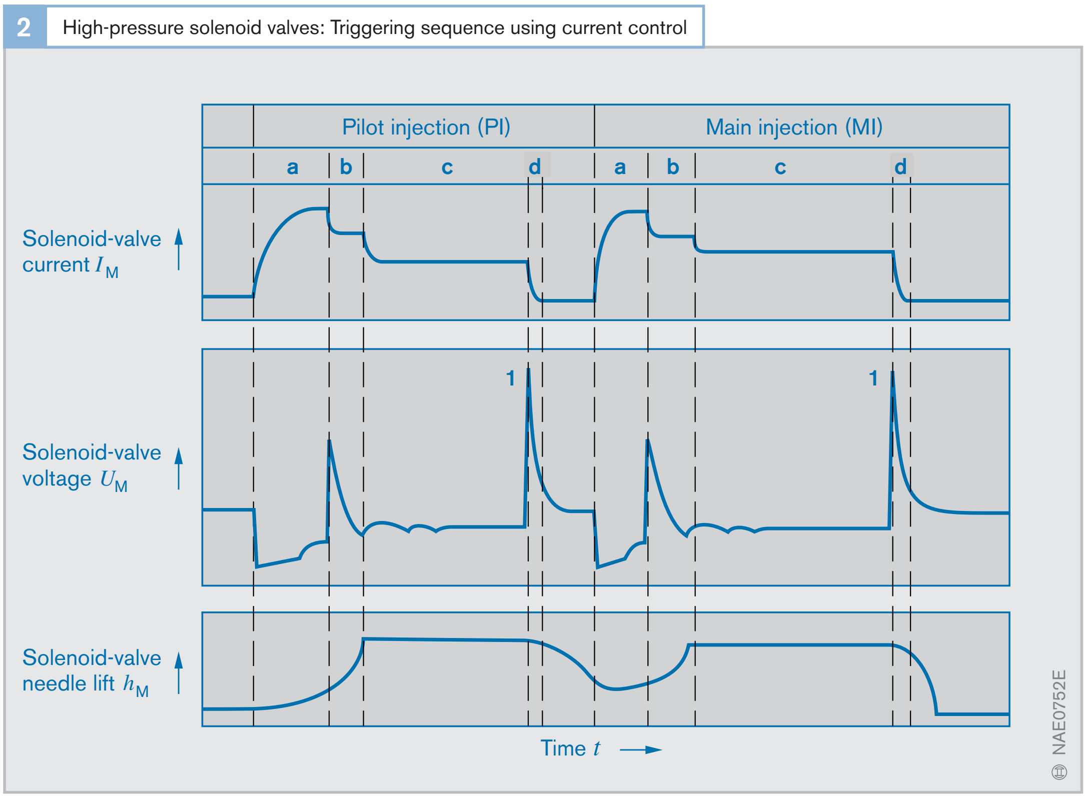


Figure 2
- a Pickup-current phase
- b BIP detection
- c Holding-current phase
- d High-speed quenching
- 1 Quenching voltage

Common Rail System CRS

In the Common Rail System (CRS), the fuel pressure in the rail (Fig. 3, Pos. 3) and with it the injection pressure, are determined by the rail-pressure valve (Pos. 8), and if required by a throttle upstream of the high-pressure pump (1). The injector's (6) high-pressure solenoid valve (7) defines the injection point and the duration of injection in accordance with the various operating parameters. This means, therefore, that injection pressure is decoupled from injection point and duration of injection. Decoupling the injection pressure from injection point and duration of injection means that in addition to the main injection (MI), which is responsible for the generation of torque, other injection processes independent of the injection pressure can also be triggered. On the one hand these are for the most part pilot injections (PI) with the principle objective of reducing the combustion noise, and on the other secondary injection processes (post injection (POI))which serve to reduce exhaust emissions. The injected fuel quantity is the product of injection pressure and duration of injection.

Post injection involves minute quantities of fuel. Injection is not carried out individually at stipulated cylinders, but rather the minute quantities concerned are added together in the ECU until the smallest quantity is reached which can be handled by the injector. When this is reached, it is injected at the next possible opportunity.

Rail-pressure control

The permanent pressure in the rail is generated by a continuously operating high-pressure pump. The closed control loop for the rail pressure comprises the rail-pressure sensor (4) the engine ECU (5) and the rail-pressure control valve (8).

The microcontroller in the engine ECU receives the sensor signal and uses it to calculate the desired pressure. This is outputted to a driver stage which triggers the rail-pressure control valve by means of a pwm signal. The level of the applied current corresponds to the desired pressure. The higher the triggering current the higher the rail pressure. The microcontroller compares the actual pressure at the sensor with the desired pressure and takes appropriate closed-loop control action in case of deviation.

In a number of versions, at high speeds and low levels of required fuel, one of the high-pressure pump's three pumping elements can be switched off (element shutoff). In this case, a triggering current flows through the element-shutoff solenoid valve. Switching off one of the elements reduces the strain on the pump as well as increasing the engine's efficiency.

3 Common Rail System (CRS): Injection-triggering components

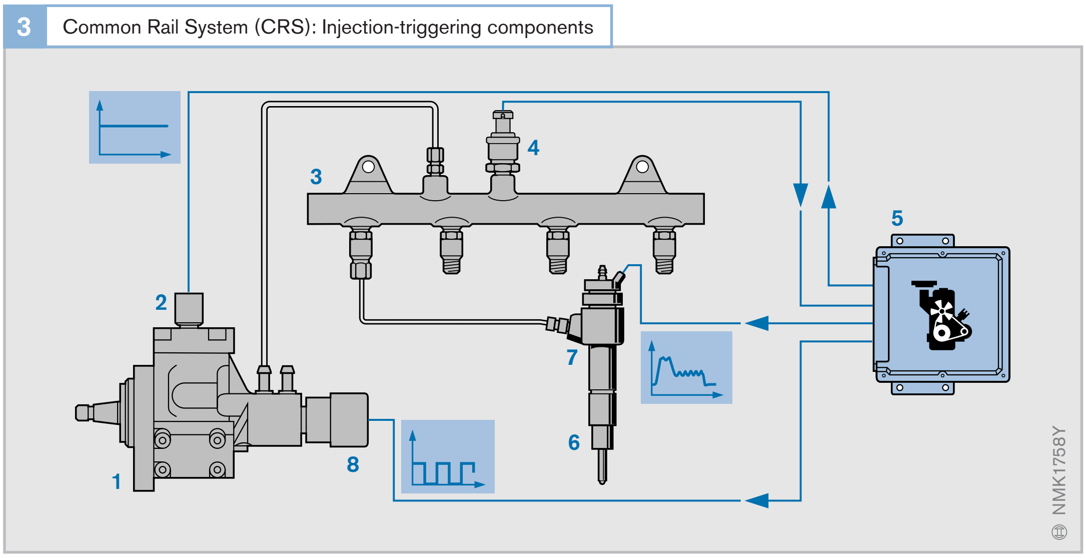


Figure 3
1 High-pressure pump
2 Element shutoff valve
3 Rail
4 Rail-pressure sensor
5 Engine ECU (for higher numbers of cylinders, it is also possible to use a "master slave alliance" with 2 ECUs)
6 Injector
7 High-pressure solenoid valve
8 Rail-pressure control valve

4 Triggering sequence of a high-pressure solenoid valve for a single injection event

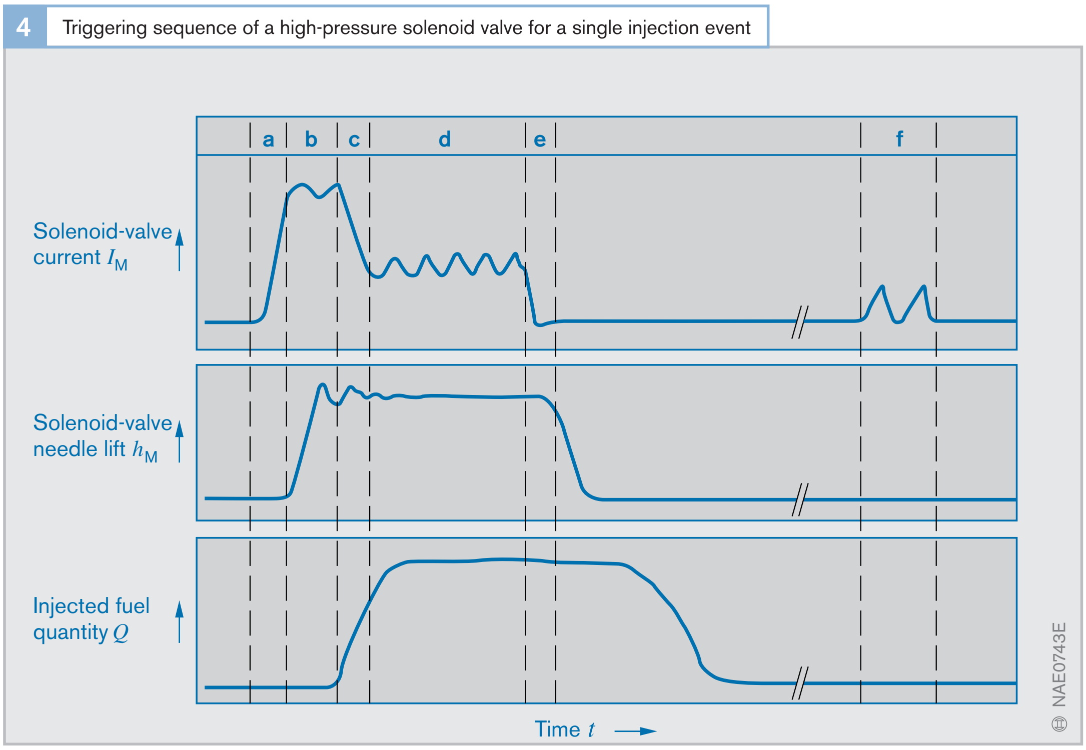


Figure 4
a Opening phase
b Pickup-current phase
c Transition to holding-current phase
d Holding-current phase
e Switch off,
f Recharge

Injector triggering

In the inoperative mode, the injector's high-pressure solenoid valve is not triggered and is therefore closed.

The injector injects when the solenoid valve opens. Solenoid-valve triggering is subdivided into five phases (Figs. 4 and 5).

Opening phase
Initially, in order to ensure tight tolerances and high levels of reproducibility for the injected fuel quantity, the current for opening the valve features a steep, precisely defined flank and increases rapidly up to approx. 20 A. This is achieved with a so-called "booster voltage" of up to as much as 100 V which is generated in the ECU and stored in a capacitor (boost-voltage store). When this voltage is applied across the solenoid valve, the current increases several times faster than it does when only battery voltage is used.

Pickup-current phase
During the pickup-current phase, battery voltage is applied to the solenoid valve, and assists in opening it quickly. Current control limits pickup current to approx. 20 A.

Holding-current phase
In order to reduce the power loss in ECU and injector, the current is dropped to approx. 12 A in the holding-current phase. The energy which becomes available when pickup current and holding current are reduced is routed to the booster-voltage store.

Switch off
When the current is switched off in order to close the valve, the surplus energy is also routed to the booster-voltage store.

Recharge
Between the actual injection events, a sawtooth waveform is applied to the injectors which are not injecting (Fig. 5, f_1). Maximum current level is so low that there is no danger of the injector opening. Energy stored in the solenoid valve as a result is then routed to the booster-voltage store (Fig. 5, f_2), which it recharges until the original voltage is reached as required for opening the solenoid valve.

5 Common Rail System: Block diagram of the triggering phase in the control for a single cylinder group

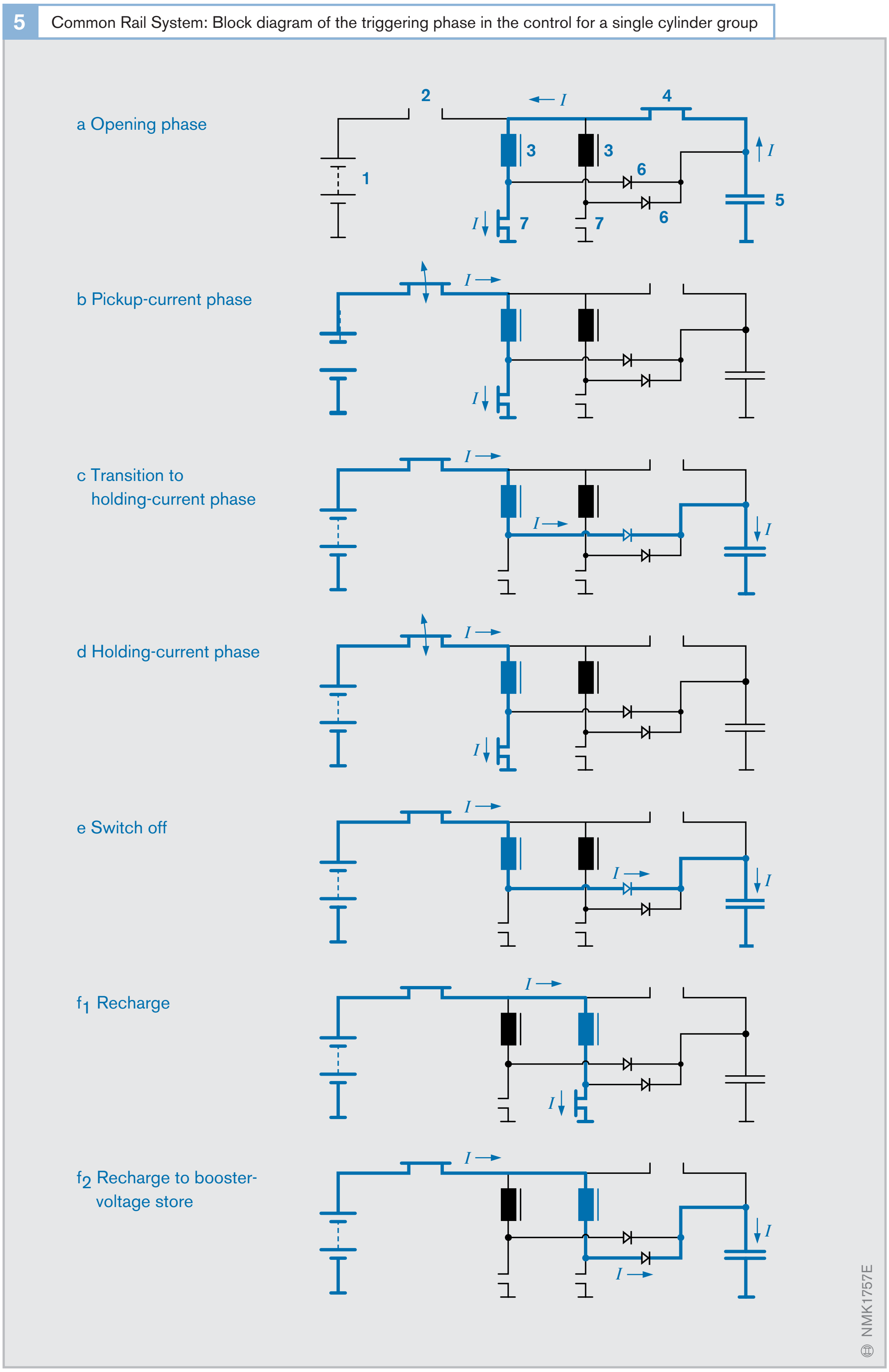


Figure 5

1 Battery
2 Current control
3 Solenoid windings of the high-pressure solenoid valves
4 Booster switch
5 Booster-voltage store (capacitor)
6 Free-wheeling diodes for energy recovery and high-speed quenching
7 Cylinder selector switch
I Current flow

Unit Injector Systems and Unit Pump Systems (UIS/UPS)

The triggering of the high-pressure solenoid valve places severe demands on the output stages. Close tolerances and high reproducibility of the injected fuel quantity demand that the triggering signal features a particularly steep edge.

The Unit Injector and Unit Pump high-pressure solenoid valves are triggered in a similar manner using current control (Figs. 6 through 8) which divides the triggering process into the pickup-current phase (a) and the holding-current phase (c). This form of triggering permits very fast switching times and reduces the power loss. For a brief period between these two phases, constant triggering current is applied to permit the detection of the solenoid-valve closing point (refer to section “BIP control”, b).

In order to ensure high-speed, defined opening of the solenoid valve at the end of the injection event, a high voltage is applied across the terminals (d) for rapid quenching of the energy stored in the solenoid valve.

The microcontroller is responsible for the calculation of the individual triggering phases. An ASIC module (gate array) with high computing power assists the microcontroller by generating two digital triggering signals (MODE signal and ON signal). These triggering signals then instruct the

6 Unit Injector and Unit Pump Systems (UIS/UPS): Triggering components

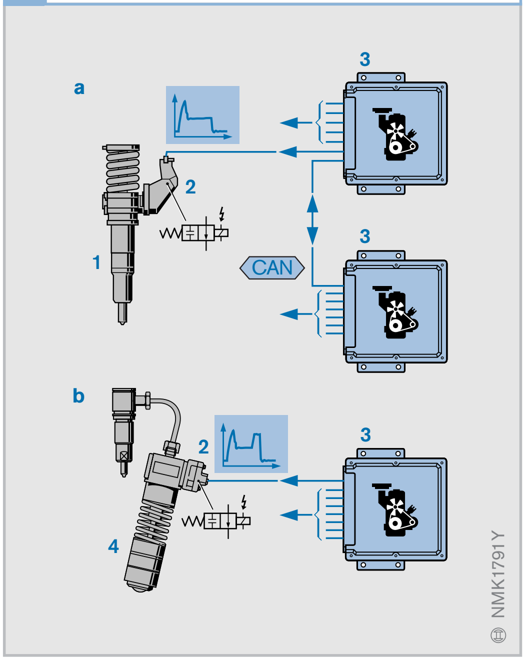


Figure 6

a Unit Injector System (UIS) with 2 ECUs
b Unit Pump System (UPS)
1 Unit Injector (UI)
2 High-pressure solenoid valve
3 Engine ECU
4 Unit Pump (UP)

7 High-pressure solenoid valve: Triggering sequences

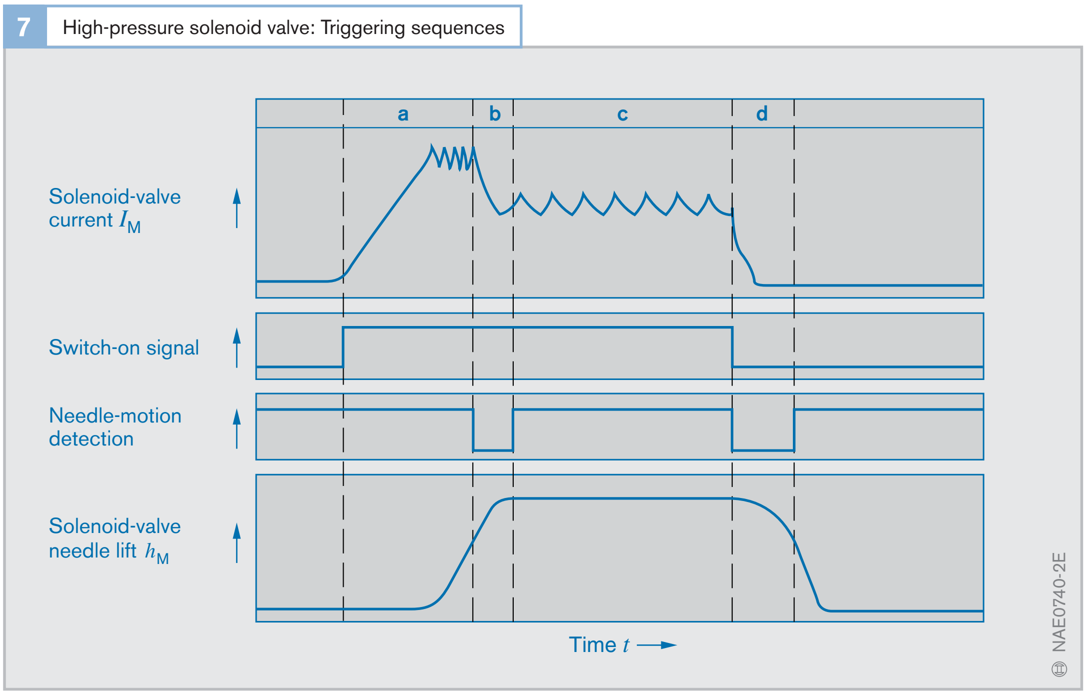


Figure 7

a Pickup current (commercial-vehicle UIS/UPS: 12...20 A; passenger-car UIS: 20 A)
b BIP detection,
c Holding current (commercial-vehicle UIS/UPS: 8...14 A; passenger-car UIS: 12 A)
d High-speed quenching

output-stage drivers to generate the required triggering-current sequence.

Boot-shaped injection characteristic

Future systems will provide the possibility of a special "boot-shaped" injection characteristic (with the main injection (MI) immediately following the pilot injection (PI Fig. 8). Here, the solenoid-valve current is held at a precise intermediate level (approx. 4...6 A, c_1) between the pickup-current and holding-current phases. This leads to the solenoid valve being held in an intermediate position so that a "boot-shaped" injection characteristic is the result.

ECU coupling

The passenger-car Unit Injector System can also be used on engines with more than 6 cylinders. In order to be able to cope with the requirement for more driver stages for injector triggering, and for increased microcontroller computing power, such engines can be equipped with two ECUs coupled together to form a "master-slave alliance". Similar to the Common Rail System (CRS), the ECUs are coupled together by means of an internal CAN-Bus operating at a baud rate of up to 1 Mbaud (1,000,000 bit/s).

Some of the functions are allocated to a specific ECU which is then solely responsible for their processing (for instance, the injected-fuel-quantity compensation). Other assignments though can be flexibly processed in this configuration by either of the ECUs (for instance, the registration of sensor signals). This configuration cannot be changed during operation.

Using this master-slave concept, it is possible to implement both Biturbo control and active exhaust-gas treatment.

8 Triggering sequences of the high-pressure solenoid valves for the "boot-shaped" injection characteristic

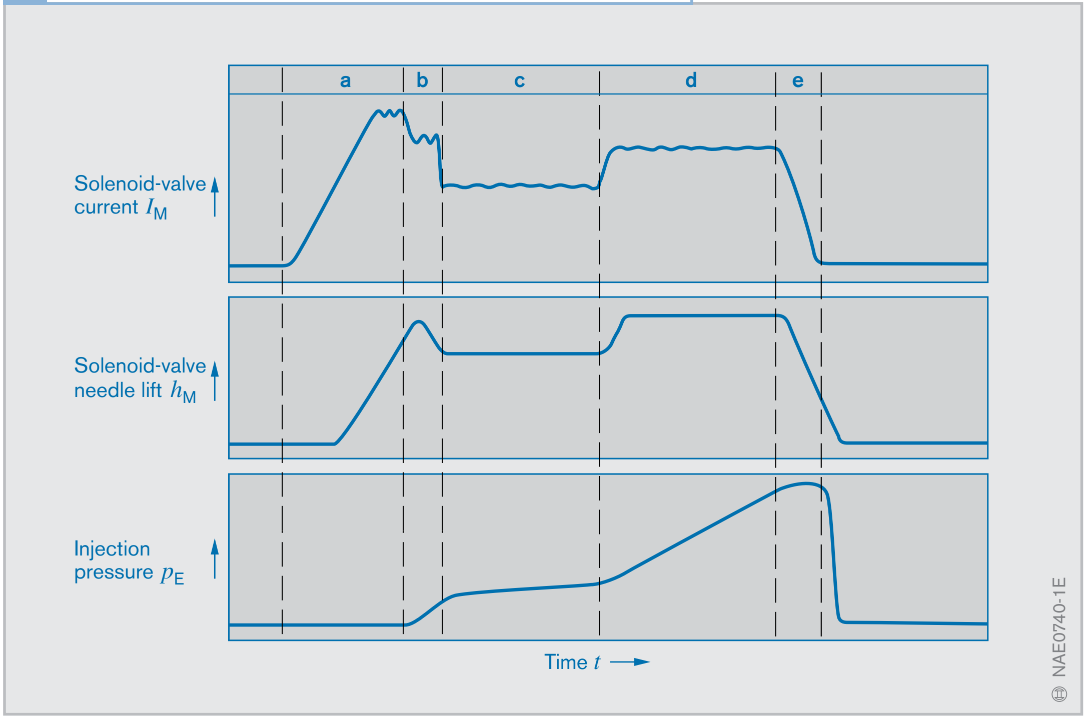


Figure 8
- a Pickup current (commercial-vehicle UIS/UPS: 12...20 A)
- b BIP detection
- c1 Holding current for "boot-shaped" injection characteristic
- c2 Holding current (commercial-vehicle UIS/UPS: 8...14 A)
- d High-speed quenching

Control and triggering of the remaining actuators

In addition to the fuel-injection components themselves, EDC is responsible for the control and triggering of a large number of other actuators. These are used for cylinder-charge control, or for the control of engine cooling, or are used in diesel-engine start-assist systems. Here too, as is the case with the closed-loop control of injection, the inputs from other systems (such as TCS) are taken into account.

A variety of different actuators are used, depending upon the vehicle type, its area of application and the type of fuel injection. This chapter deals with a number of examples, and further actuators are covered in the Chapter “Actuators”.

A variety of different methods are used for triggering:

- The actuators are triggered directly from an output (driver) stage in the engine ECU using appropriate signals (e.g. the EGR valve).
- If high currents are involved (for instance for fan control), the ECU triggers a relay.
- The engine ECU transfers signals to an independent ECU, which is then used to trigger or control the remaining actuators (for instance, for glow control).

The advantage of incorporating all engine-control functions in the EDC ECU lies in the fact that not only the injected fuel quantity and instant of injection can be taken into account in the engine control concept, but also other engine functions such as EGR and boost-pressure control. This leads to a considerable improvement in engine management. Apart from this, the engine ECU has a vast amount of information at its disposal as needed for other functions (for instance, engine and intake-air temperature as used for glow control on the diesel engine).

1 Intake-duct switch-off

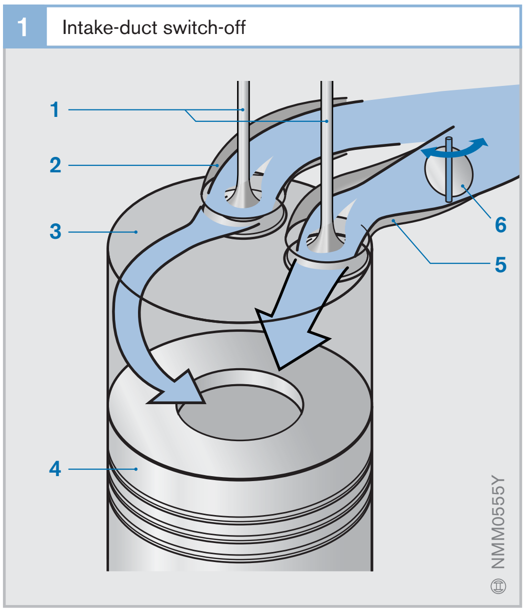


Figure 1

1	Intake valve
2	Turbulence duct
3	Cylinder
4	Piston
5	Intake duct
6	Flap

Auxiliary coolant heating

High-performance diesel engines are very efficient, and under certain circumstances do not generate enough waste heat to adequately heat the vehicle’s interior. One solution for overcoming this problem is to install auxiliary coolant heating using glow plugs. Depending upon the power available from the alternator, this system is triggered in a number of steps. It is controlled by the engine ECU as used for EDC.

Intake-duct switch-off

In the lower engine-rpm ranges and at idle, a flap (Fig. 1, Pos. 6) operated by an electropneumatic transducer closes one of the intake ducts (5). Fresh air in then only inducted through the turbulence duct (2). This leads to improved air turbulence in the lower rpm ranges which in turn results in more efficient combustion. In the higher rpm ranges, the engine’s volumetric efficiency is improved thanks to the open intake duct (5) and the power output increases as a result.

Boost-pressure control

Boost-pressure control applied to the exhaust-gas turbocharger improves the engine's torque curve in full-load operation, and its exhaust and refill cycle in the part-load range.The optimum (desired) boost pressure is a function of engine speed, injected fuel quantity, coolant and fuel temperature, and the surrounding air pressure. This optimum (desired) boost pressure is compared with the actual value registered by the boost-pressure sensor and, in the case of deviation, the ECU either operates the bypass valve's electropneumatic transducer or the guide blades of the VTG (**V**ariable **T**urbine **G**eometry) exhaust-gas turbocharger (refer also to the Chapter "Actuators").

Fan triggering

When a given engine temperature is exceeded, the engine ECU triggers the engine cooling fan, which continues to rotate for a brief period after the engine is switched off. This run-on period is a function of the coolant temperature and the load imposed on the engine during the preceding driving cycle.

Exhaust-gas recirculation (EGR)

In order to decrease the NO_X emissions, exhaust gas is directed into the engine's intake duct through a channel, the cross section of which can be varied by an EGR valve. The EGR valve is triggered by an electropneumatic transducer or by an electric actuator.

Due to the high temperature of the exhaust gas and its high proportion of contamination, it is difficult to precisely measure the exhaust-gas flow which is recirculated back into the engine. Control, therefore, takes place indirectly through an air-mass meter located in the flow of fresh intake air. The meter's output signal is then compared in the ECU with the engine's theoretical air requirement which has been calculated from a variety of data (e.g. engine rpm). The lower the measured mass of the incoming fresh air compared to the theoretical air requirement, the higher is the proportion of recirculated exhaust gas.

Currently, EGR is only used on passenger cars, although work is proceeding on the development of a commercial-vehicle version.

Substitute functions

If individual input signals should fail, the ECU is without the important information it needs for calculations. In such cases, substitute functions are used. Two examples are given below:

Example 1: The fuel temperature is needed for calculation of the injected fuel quantity. If the fuel-temperature sensor fails, the ECU uses a substitute value for its calculations. This must be selected so that excessive soot formation is avoided, although this can lead to a reduction of engine power in certain operating ranges.

Example 2: Should the camshaft sensor fail, the ECU applies the crankshaft-sensor signal as a subsitute. Depending on the vehicle manufacturer, there are a variety of different concepts for using the crankshaft signal to determine when cylinder 1 is in the compression cycle. The use of substitute functions leads to engine restart taking slightly longer.

Substitute functions differ according to vehicle manufacturer, so that many vehicle-specific functions are possible.

The diagnosis function stores data on all malfunctions that occur. This data can then be accessed in the workshop (refer also to the Chapter "Electronic Diagnosis (OBD)").

Torque-controlled EDC systems

The engine-management system is continually being integrated more closely into the overall vehicle system. Through the CAN-Bus, vehicle dynamics systems such as TCS, and comfort and convenience systems such as Cruise Control, have a direct influence on the Electronic Diesel Control (EDC). Apart from this, much of the information registered and/or calculated in or by the engine management system must be passed on to other ECUs through the CAN-Bus.

In order to be able to incorporate the EDC even more efficiently in a functional alliance with other ECUs, and implement other changes rapidly and effectively, it was necessary to make far-reaching changes to the newest-generation controls. These changes resulted in the torque-controlled EDC which was introduced with the EDC16. The main feature is the change over of the module interfaces to the parameters as commonly encountered in practice in the vehicle.

Engine parameters

Essentially, an IC engine's output can be defined using the three parameters: Power P, rpm n, and torque M.

For 2 diesel engines. Fig. 1 compares typical curves of torque and power as a function of engine rpm. Basically speaking, the following formula applies:

$$P = 2 \cdot \pi \cdot n \cdot M$$

In other words, it suffices to use the torque as the reference (command) variable. Engine power then results from the above formula. Since power output cannot be measured directly, torque has turned out to be a suitable reference (command) variable for engine management.

Torque control

When accelerating, the driver uses the accelerator pedal (sensor) to directly demand a given torque from the engine. At the same time, but independent of the driver's requirements, via the interfaces other vehicle systems submit torque demands resulting from the power requirements of the particular component (e.g. air conditioner, alternator). Using these torque-requirement inputs, the engine management calculates the output torque to be generated by the engine and controls the fuel-injection and air-system actuators accordingly. This method has the following advantages:

- No single system (for instance, boost pressure, fuel injection, pre-glow) has a direct effect upon the engine management. This enables the engine management to also take into account higher-level optimization criteria (such as exhaust emissions and fuel consumption) when processing external requirements, and thus control the engine in the most efficient manner,
- Many of the functions which do not directly concern the engine management can be designed to function identically for diesel and gasoline engines.
- Extensions to the system can be implemented quickly.

1 Example of the torque and power-output curves as a function of engine speed for two passenger-car diesel engines with approx. 2.2 l displacement

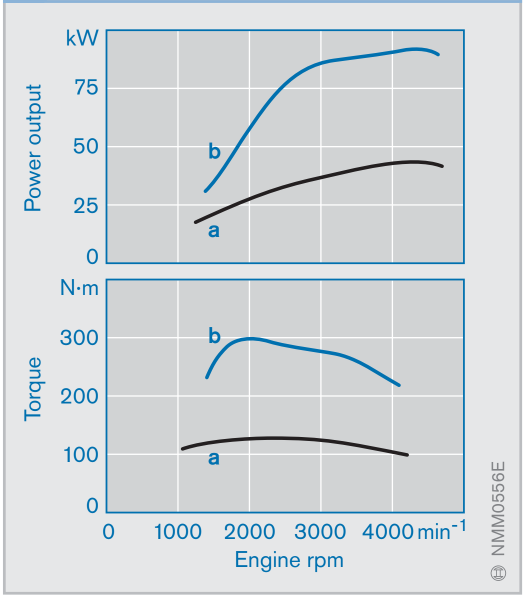


Figure 1
a Year of manufacture 1968
b Year of manufacture 1998

Engine-management sequence

Fig. 2 shows (schematically) the processing of the setpoint inputs in the engine ECU. In order to be able to fulfill their assignments efficiently, the engine management's control functions all require a wide range of sensor signals and information from other ECUs in the vehicle.

Propulsion torque

The driver's input (that is, the signal from the accelerator-pedal sensor), is interpreted by the engine management as the request for a propulsive torque. The inputs from the Cruise Control and the Vehicle-Speed Limiter are processed in exactly the same manner.

Following this selection of the desired propulsive torque, should the situation arise, the vehicle-dynamics system (TCS, ESP) increases the desired torque value when there is the danger of wheel lockup and decreases it when the wheels show a tendency to spin.

Further external torque demands

The drivetrain's torque adaptation must be taken into account (drivetrain transmission ratio). This is defined for the most part by the ratio of the particular gear, or by the torque-converter efficiency in the case of automatic gearboxes. On vehicles with an automatic-gearbox, the gearbox control stipulates the torque requirement during the actual gear shift. Apart from reducing the load on the gearbox, reduced torque at this point results in a comfortable, smooth gear shift. In addition, the torque required by other engine-powered units (for instance, air-conditioner compressor, alternator, servo pump) is determined. This torque requirement is calculated either by the units themselves or by the engine management.

Calculation is based on unit power and rotational speed, and the engine management adds up the various torque requirements. The vehicle's driveability remains unchanged notwithstanding varying requirements from the auxiliary units and changes in the engine's operating status.

Internal torque demands

At this stage, the idle-speed control and the active surge damper intervene.

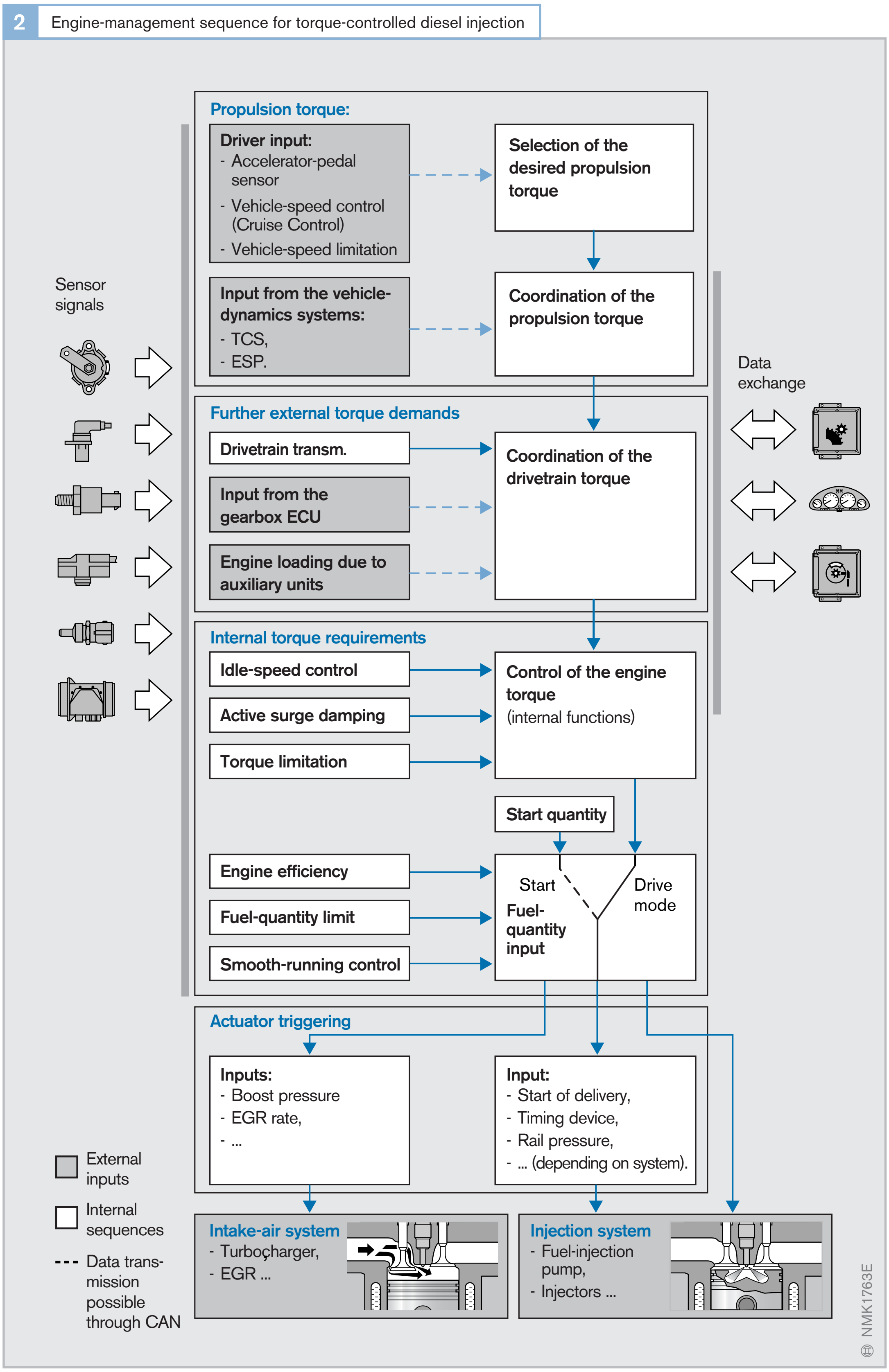
For instance, if demanded by the situation, in order to prevent mechanical damage, or excessive smoke due to the injection of too much fuel, the torque limitation reduces the internal torque requirement. In contrast to the previous engine-management systems, limitations are no longer only applied to the injected fuel-quantity, but instead, depending upon the required effects, also to the particular physical quantity involved.

The engine's losses are also taken into account (e.g. friction, drive for the high-pressure pump). The torque represents the engine's measurable effects to the outside. The engine management though can only generate these effects in conjunction with the correct fuel injection together with the correct injection point, and the necessary marginal conditions as apply to the air-intake system (e.g. boost pressure and EGR rate). The required injected fuel quantity is determined using the current combustion efficiency. The calculated fuel quantity is limited by a protective function (for instance, protection against overheating), and if necessary can be varied by the smooth-running control (SRC). During engine start, the injected fuel quantity is not determined by external inputs such as those from the driver, but rather by the separate “start-quantity control” function.

Actuator triggering

Finally, the desired values for the injected fuel quantity are used to generate the triggering data for the injection pump and/or the injectors, and for defining the optimum operating point for the intake-air system.

2 Engine-management sequence for torque-controlled diesel injection



Electronic diagnosis

ECU-integrated diagnostics belong to the basic scope of electronic engine-management systems. During normal vehicle operation, input and output signals are checked by monitoring algorithms, and the overall system is checked for malfunctions and faults. If faults are discovered in the process, these are stored in the ECU. When the vehicle is checked in the workshop, this stored information is retrieved through a serial interface and provides the basis for rapid and efficient trouble-shooting and repair.

Operating concept

Originally, it was intended that the self-diagnosis of the engine-management system (on-board diagnostics/OBD) should merely be a help in rapid and efficient fault-finding in the workshop. Increasingly severe legal stipulations, and the more wide-ranging functional scope of the vehicle's electronic systems though, led to the emergence of a more extensive diagnostics system within the engine-management system.

Input-signal monitoring

Here, the analysis of the input signals is applied for monitoring the sensors and their connection lines to the ECU (Table 1). These checks serve to uncover not only sensor faults, but also short-circuits to the battery voltage U_{Batt} and to ground, as well as open circuits in lines. The following processes are applied:

- Monitoring the sensors' power supply.
- Checking that the measured values are inside the correct range (e.g. engine temperature –40 °C...+150 °C.
- If auxiliary information is available, the registered value is subjected to a plausibility check (e.g. the camshaft and/or crankshaft speed).
- Important sensors (such as the accelerator-pedal sensor) are designed to be redundant which means that their signals can be directly compared with each other.

Output-signal monitoring

Here, in addition to the connections to the ECU, the actuators are also monitored. Using the results of these checks, open-circuits and short-circuits in the lines and connections can be detected in addition to actuator faults. The following processes are applied here:

- Hardware monitoring of the output-signal circuit using the driver stage. The circuit is checked for open circuit, and for short circuits to battery voltage U_{Batt} and to ground.
- The actuator's influence on the system is checked for plausibility. In the case of exhaust-gas recirculation (EGR) for instance, a check is made whether intake-manifold pressure is within given limits and that it reacts accordingly when the actuator is triggered.

Monitoring ECU communication

As a rule, communication with the other ECUs takes place via CAN-Bus (**C**ontroller **A**rea **N**etwork). The diagnostics integrated in the CAN module are described in the Chapter "Data transfer between electronic systems". A number of other checks are also performed in the ECU. Since most CAN messages are sent at regular intervals by the particular ECUs, monitoring the time intervals concerned leads to the detection of ECU failure.

In addition, when redundant information is available in the ECU, the received signals are checked the same as all input signals.

Monitoring the internal ECU functions

In order that the functional integrity of the ECU is ensured at all times, monitoring functions are incorporated in the hardware (e.g. “intelligent driver-stage modules”) and in the software.

These check the individual ECU components (e.g. microcontroller, Flash-EPROM, RAM). Many of these checks are performed immediately the engine is switched on. During normal operations, further checks are performed regularly so that the failure of a component is detected immediately. Sequences which require extensive computing capacity (for instance for checking the EPROM), are run through immediately the engine is switched off (only possible at present on gasoline engines).

This method ensures that the other functions are not interfered with. On the diesel engine, the switch-off paths are checked in the same period.

1 Monitoring the most important input signals

Signal path	Monitoring
Accelerator-pedal sensor	Check of the power supply and the signal range
	Plausibility with regard to a redundant signal
	Plausibility with regard to the brakes
Crankshaft-rpm sensor	Checking the signal range
	Plausibility with the camshaft-rpm sensor
	Checking the changes as a function of time (dynamic plausibility)
Engine-temperature sensor	Checking the signal range
	Logical plausibility as a function of rpm and injected fuel quantity or engine load
Brake-pedal switch	Plausibility with regard to redundant brake contact
Speed signal	Checking the signal range
	Plausibility with regard to rpm and injected fuel quantity or engine load
EGR positioner	Checks for short circuits and open circuits in lines
	EGR control
	Checking the system's reaction to valve triggering
Battery voltage	Checking the signal range
	Plausibility with regard to engine rpm (at present, only possible with gasoline (SI) engines)
Fuel-temperature sensor	Checking the signal range (at present, only possible with diesel engines)
Boost-pressure sensor	Checking the power supply and the signal range
	Plausibility with regard to ambient-pressure sensor and/or further signals
Boost-pressure actuator	Checking for short circuits and open-circuit lines
	Control deviation of boost-pressure control
Air-mass meter	Checking the power supply and the signal range
	Logical plausibility
Air-temperature sensor	Checking the signal range
	Logical plausibility with regard to the engine-temperature sensor for instance
Clutch-signal sensor	Plausibility with regard to vehicle speed
Ambient-pressure sensor	Checking the signal range
	Logical plausibility of the intake-manifold-pressure sensor

Table 1

Dealing with a fault

Fault recognition

When a fault remains in a signal path longer than a defined period, the signal path is classified as being defective. Until it is finally classified as defective, the last valid value is utilised in the system. Normally, as soon as it is classified as defective, a substitute function is triggered (refer to the Chapter "Closed-loop and open-loop electronic control").

Most faults can be revoked and the signal path classified as serviceable again provided the signal path remains without fault for a defined period of time.

Fault storage

Each fault is stored as a malfunction code in the non-volatile area of the data memory. In the fault entry, each malfunction code is accompanied by auxiliary information in the so-called "freeze-frame" containing the operating and environmental conditions at the moment the fault occurred (e.g. engine rpm, engine temperature). Information is also stored on the fault type (for instance short circuit, conductor open circuit) and the fault status (in other words, permanent fault or sporadic fault).

The lawmaker has prescribed specific malfunction codes for many of the faults which have an effect on the vehicle's toxic emissions. Further fault information not covered by legislation can also be stored for retrieval by the vehicle workshop.

Following storage of the fault entry, the diagnosis for the system or component concerned continues. If the fault does not occur again in the further course of the diagnosis (in other words it was a sporadic fault), it is then erased from the fault memory provided that certain conditions are complied with.

Fault retrieval

The faults can be retrieved from the fault memory with a specified workshop tester provided by the vehicle manufacturer, or by using a System Tester (e.g. Bosch KTS500), or a scan tool. Once the fault information has been retrieved in the workshop and the fault repaired, the fault memory can be cleared again using the tester.

Diagnostic interface

A communication interface is needed for "Off-board testers" in order for them to be able evaluate the "On-Board Diagnosis". This serial interface is mandatory and is defined in ISO 9141 (diagnostic interface through the K-line). The interface operates with a transfer rate (baud rate) of between 10 baud and 10 kbaud, and is either a single-wire interface with common send and receive lines, or a two-wire interface with separate data line (K-line) and initiate line (L-line). A number of ECUs can be connected together at a single diagnostic connector.

The tester sends an initiate address to all the ECUs, one of which recognises this address and replies with a baud-rate identification word. Using the interval between the pulse edges, the tester determines the baud rate, adjusts itself accordingly and sets up the communication with the ECUs.

Actuator diagnosis

An actuator diagnosis facility is incorporated in the ECU so that the workshops can selectively actuate individual actuators and check their correct functioning. This test mode is triggered by the tester and only functions with the vehicle at standstill, and with the engine running at below a given speed or with it stopped. Actuator functioning is checked either acoustically (e.g. clicking of the valve), visually (e.g. movement of a flap), or by other uncomplicated methods.

On-Board-Diagnostics (OBD)

In the past years there has been a continual reduction in toxic emissions per vehicle. In order for the emission limits defined by the vehicle manufacturers to be maintained during continuous in-field operations, it is necessary that the engine and its components are monitored continually. This was the reason for the lawmaker defining specifications to regulate the diagnosis scope for the exhaust-gas-relevant components and systems in the vehicle.

1988 marked the coming into force of OBD I in California, that is, the first stage of CARB legislation (**C**alifornia **A**ir **R**esources **B**oard). All newly registered vehicles in California were forced to comply with these statutory regulations. OBD II, that is the second stage, came into force in 1994.

Since 1994, in the remaining US States the laws of the Federal Authority EPA (**E**nvironmental **P**rotection **A**gency) have applied. The scope of these diagnostics comply for the most part with the CARB legislation (OBD II), although the requirements for compliance with the emissions limits are less severe.

The OBD adapted to European requirements is known as the EOBD and is based on the EPA-OBD. At present, the EOBD stipulations are even less severe than those of the EPA-OBD.

OBD I

The electrical components which are relevant for exhaust-gas emissions are checked for short circuits and breaks by the first stage of the CARB-OBD. The resulting electrical signals must remain within the stipulated plausibility limits.

When a fault/error is discovered, the driver is warned by a lamp in the instrument cluster. Using “on-board devices” (for instance, a diagnosis lamp which displays a blink code), it must be possible to read out which component has failed.

OBD II

The diagnostic procedure for Stage 2 of the CARB-OBD is far more extensive than OBD I. Monitoring no longer stops at the check of the electrical signals from the components, but has been extended to include the check of correct system functioning. For instance, it is no longer sufficient to check that the signal from the engine-temperature sensor does not exceed certain fixed limits. OBD II registers a fault if the engine temperature remains too low (for instance below 10 °C) for a longer period of time (plausibility check).

OBD II demands that all those systems and components be checked which in case of malfunction can lead to a noticeable increase in toxic emissions. In addition, all the components which are actually used for OBD must also to be checked, and every detected fault must be stored. The driver must be warned of malfunctions by a lamp in the instrument cluster. The stored faults are then retrieved by testers which are connected for trouble-shooting.

OBD II legislation stipulates the standardization of the information stored in the fault memory in accordance with the ruling of the SAE (**S**ociety of **A**utomotive **E**ngineers). The means that provided they comply with the standards, commercially available testers can retrieve fault information from the fault memory (so-called “scan tools”).

Diagnosis-sequence control

As a rule, the diagnostic functions for all the systems and components to be tested must be run through at least once during each exhaust-gas test cycle (e.g. ECE/EU test cycle).

Depending on the driving status, the diagnostics-system management can dynamically change the order of the diagnosis functions. The target here is that all diagnosis functions are run through often enough during everyday operations.

Data transfer between automotive electronic systems

Today's vehicles are being equipped with a constantly increasing number of electronic systems. Along with their need for extensive exchange of data and information in order to operate efficiently, the data quantities and speeds concerned are also increasing continuously.

For instance, in order to guarantee perfect driving stability, the Electronic Stability Program (ESP) must exchange data with the engine management system and the transmission-shift control.

System overview

Increasingly widespread application of electronic communications systems, and electronic open and closed-loop control systems, for automotive functions such as

- Electronic engine-management (EDC and Motronic),
- Electronic transmission-shift control (GS),
- Antilock braking system (ABS),
- Traction control system (TCS),
- Electronic Stability Program (ESP),
- Adaptive Cruise Control (ACC), and
- Mobile multimedia systems together with their display instrumentation

has made it vital to interconnect the individual ECUs by means of networks.

The conventional point-to-point exchange of data through individual data lines has reached its practical limits (Fig. 1), and the complexity of current wiring harnesses and the sizes of the associated plugs are already very difficult to manage. The limited number of pins in the plug-in connectors has also slowed down ECU development work.

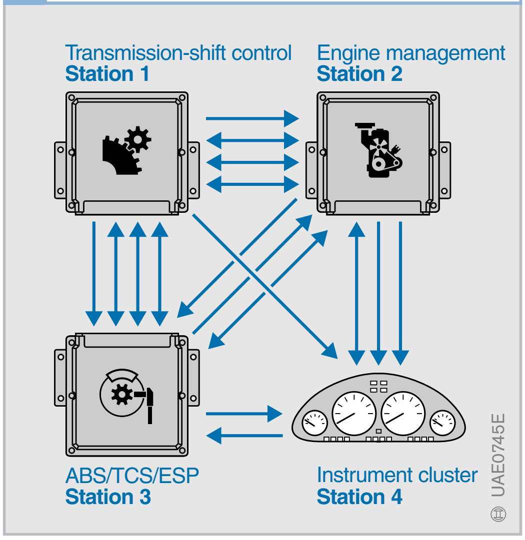
To underline this point:
Apart from being about 1 mile long, the wiring harness of an average middle-class vehicle already includes about 300 plugs and sockets with a total of 2000 plug pins. The only solution to this predicament lies in the application of specific vehicle-compatible Bus systems. Here, CAN has established itself as the standard.

Serial data transfer (CAN)

Although CAN (Controller Area Network) is a linear bus system (Fig. 2) specifically designed for automotive applications, it has already been introduced in other sectors (for instance, in building installation engineering).

Data is relayed in serial form, that is, one after another on a common bus line. All CAN stations have access to this bus, and via a CAN interface in the ECUs they can receive and transmit data through the CAN bus line. Since a considerable amount of data can be exchanged and repeatedly accessed on a single bus line, this networking results in far fewer lines being needed.

1 Conventional data transfer



Applications in the vehicle

For CAN in the vehicle there are four areas of application each of which has different requirements. These are as follows:

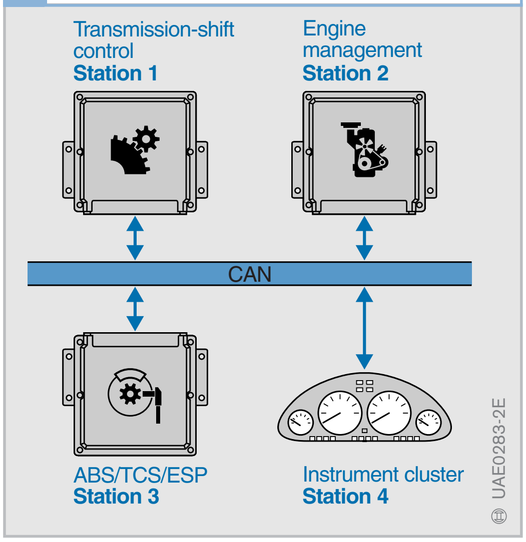
Multiplex applications

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 kbaud and 125 kbaud (1 kbaud = 1 kbit/s) (low-speed CAN).

Mobile communications applications

In the area of mobile communications, CAN networks such components as navigation system, telephone, and audio installations with the vehicle’s central display and operating units. Networking here is aimed at standardizing operational sequences as far as possible, and at concentrating status information at one point so that driver distraction is reduced to a minimum. With this application, large quantities of data are transmitted, and data transfer rates are in the 125 kbaud range. It is impossible to directly transmit audio or video data here.

2 Linear bus topology



Diagnosis applications

The diagnosis applications using CAN are aimed at applying the already existing network for the diagnosis of the connected ECUs. The presently common form of diagnosis using the special K line (ISO 9141) then becomes invalid. Large quantities of data are also transferred in diagnostic applications, and data transfer rates of 250 kbaud and 500 kbaud are planned.

Real-time applications

Real-time applications serve for the open and closed-loop control of the vehicle's movements. Here, such electronic systems as engine management, transmission-shift control, and electronic stability program (ESP) are networked with each other.
Commonly, data transfer rates of between 125 kbaud and 1 Mbaud (high-speed CAN) are needed to guarantee the required real-time response.

Bus configuration

Configuration is understood to be the layout and interaction between the components in a given system. The CAN bus has a linear bus topology (Fig. 2) which in comparison with other logical structures (ring bus and/or star bus) features a lower failure probability. If one of the stations fails, the bus still remains fully accessible to all the other stations. The stations connected to the bus can be either ECUs, display devices, sensors, or actuators. They operate using the Multi-Master principle, whereby the stations concerned all have equal priority regarding their access to the bus. It is not necessary to have a higher-order administration.

Content-based addressing

The CAN bus system does not address each station individually according to its features, but rather according to its message contents. It allocates each “message” a fixed *“identifier”* (message name) which identifies the contents of the message in question (for instance, engine speed). This identifier has a length of 11 bits (standard format) or 29 bits (extended format).

With content-based addressing each station must itself decide whether it is interested in the message or not (“message filtering” Fig. 3). This function can be performed by a special CAN module (Full-CAN), so that less load is placed on the ECU’s central microcontroller. Basic CAN modules “read” all messages. Using content-based addressing, instead of allocating station addresses, makes the complete system highly flexible so that equipment variants are easier to install and operate. If one of the ECUs requires new information which is already on the bus, all it needs to do is call it up from the bus. Similarly, provided they are receivers, new stations can be connected (implemented) without it being necessary to modify the already existing stations.

Bus arbitration

The identifier not only indicates the data content, but also defines the message’s priority rating. An identifier corresponding to a low binary number has high priority and vice versa. Message priorities are a function for instance of the speed at which their contents change, or their significance with respect to safety. There are never two (or more) messages of identical priority in the bus.

Each station can begin message transmission as soon as the bus is unoccupied. Conflict regarding bus access is avoided by applying bit-by-bit identifier arbitration (Fig. 4), whereby the message with the highest priority is granted first access without delay and without loss of data bits (nondestructive protocol).

The CAN protocol is based on the logical states “dominant” (logical 0) and “recessive” (logical 1). The “Wired And” arbitration principle permits the dominant bits transmitted by a given station to overwrite the recessive bits of the other stations. The station with the lowest identifier (that is, with the highest priority) is granted first access to the bus.

3 Addressing and message filtering (acceptance check)

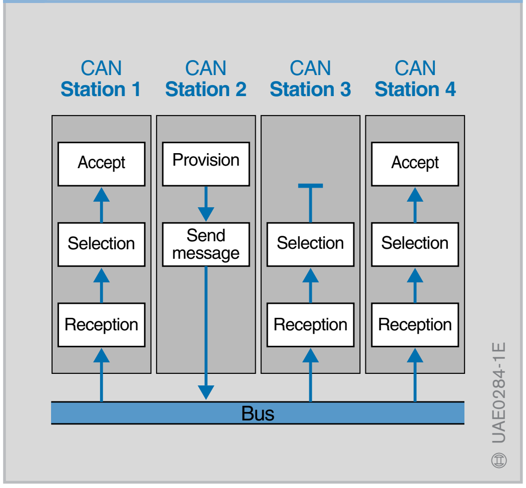


Figure 3
Station 2 transmits, Station 1 and 4 accept the data.

4 Bit-by-bit arbitration (allocation of bus access in case of several messages)

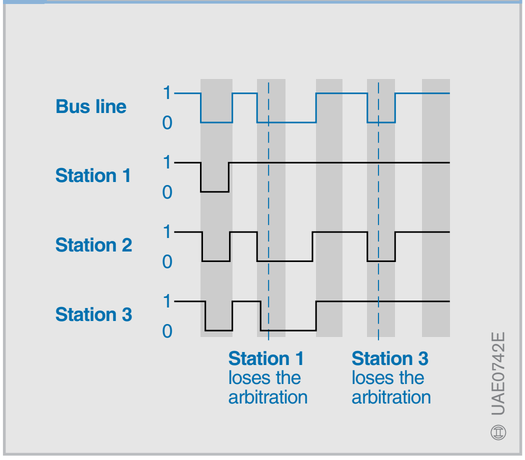


Figure 4
Station 2 gains first access
(Signal on the bus = signal from Station 2)

0 Dominant level
1 Recessive level

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

CAN permits two different formats which only differ with respect to the length of their identifiers. The standard-format identifier is 11 bits long, and the extended-format identifier 29 bits. Both formats are compatible with each other and can be used together in a network. The data frame comprises seven consecutive fields (Fig. 5) and is a maximum of 130 bits long (standard format) or 150 bits (extended format).

The bus is recessive at idle. With its dominant bit, the *"Start of frame"* indicates the beginning of a message and synchronises all stations.

The *"Arbitration field"* consists of the message's identifier (as described above) 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 it is still authorized to transmit or whether another station with a higher-priority message has accessed the Bus. The control bit following the identifier is designated the RTR-bit (**R**emote **T**ransmission **R**equest). It defines whether the message is a "Data frame" (message with data) for a receiver station, or a "Remote frame" (request for data) from a transmitter station.

The *"Control field"* contains the IDE bit (**Id**entifier **E**xtension **B**it) used to differentiate between standard format (IDE = 0) and extended format (IDE = 1), followed by a bit reserved for future extensions. The remaining 4 bits in this field define the number of data bytes in the next data field. This enables the receiver to determine whether all data has been received.

The *"Data field"* contains the actual message information comprised of between 0 and 8 bytes. A message with data length = 0 is used to synchronise distributed processes. A number of signals can be transmitted in a single message (e.g. engine rpm and engine temperature).

The *"CRC Field"* (**C**yclic **R**edundancy **C**heck) contains the frame check word for detecting possible transmission interference.

The *"ACK Field"* contains the **ack**nowledgement signals used by the receiver stations to confirm receipt of the message in non-corrupted form. This field comprises the ACK slot and the recessive ACK delimiter. The ACK slot is also transmitted recessively and overwritten "dominantly" by the receivers upon the message being correctly received. Here, it is irrelevant whether the message is of significance or not for the particular receiver in the sense of the message filtering or acceptance check. Only correct reception is confirmed.

5 CAN message format

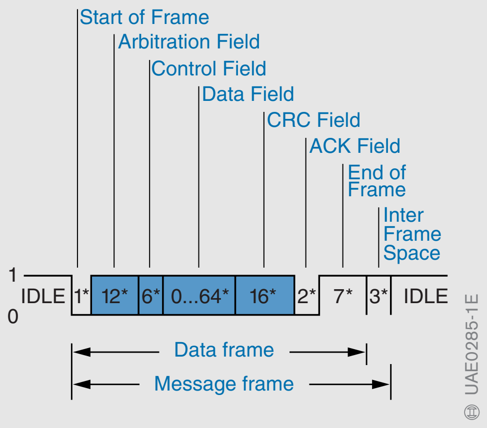


Figure 5
0 Dominant level,
1 Recessive level.
* Number of bits

The *"End of frame"* marks the end of the message and comprises 7 recessive bits.

The *"Inter-frame space"* comprises three bits which serve to separate successive messages. This means that the bus remains in the recessive IDLE mode until a station starts a bus access.

As a rule, a sending station initiates data transmission by sending a "data frame". It is also possible for a receiving station to call in data from a sending station by transmitting a "remote frame".

Detecting errors

A number of control mechanisms for detecting errors are integrated in the CAN protocol.

In the *"CRC field"*, the receiving station compares the received CRC sequence with the sequence calculated from the message.

With the *"Frame check"*, frame errors are recognized by checking the frame structure. The CAN protocol contains a number of fixed-format bit fields which are checked by all stations.

The *"ACK check"* is the receiving stations' confirmation that a message frame has been received. Its absence signifies for instance that a transmission error has been detected.

"Monitoring" indicates that the sender observes (monitors) the bus level and compares the differences between the bit that has been sent and the bit that has been checked.

Compliance with *"Bitstuffing"* is checked by means of the "Code check". The stuffing rule stipulates that in every *"data frame"* or *"remote frame"*, a maximum of 5 successive equal-priority bits may be sent between the *"Start of frame"* and the end of the *"CRC field"*. As soon as five identical bits have been transmitted in succession, the sender inserts an opposite-priority bit. The receiving station erases these opposite-polarity bits after receiving the message. Line errors can be detected using the "bitstuffing" principle.

If one of the stations detects an error, it interrupts the actual transmission by sending an "Error frame" comprising six successive dominant bits. Its effect is based on the intended violation of the stuffing rule, and the object is to prevent other stations accepting the faulty message.

Defective stations could have a derogatory effect upon the bus system by sending an "error frame" and interrupting faultless messages. To prevent this, CAN is provided with a function which differentiates between sporadic errors and those which are permanent, and which is capable of identifying the faulty station. This takes place using statistical evaluation of the error situations.

Standardization

The International Organization for Standardization (ISO) and SAE (Society of Automotive Engineers) 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 above 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 15765 – Draft) is being prepared.

Prospects

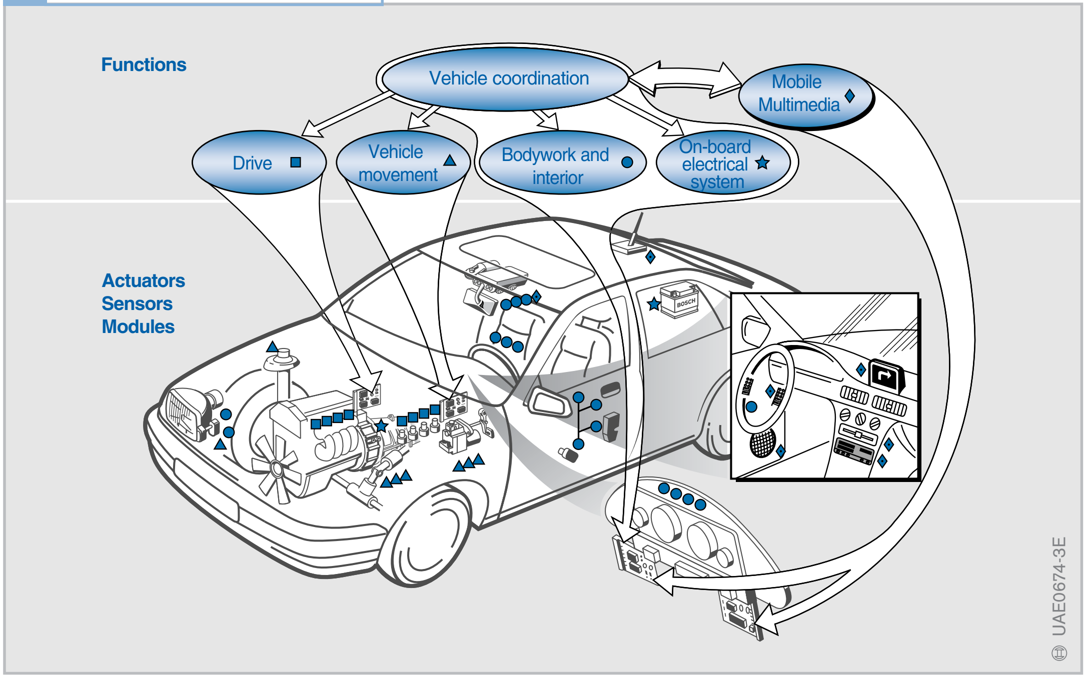
Along with the increasing levels of system-component performance and the rise in function integration, the demands made on the vehicle's communication system are also on the increase. And new systems are continually being introduced, for instance in the consumer-electronics sector. All in all, it is to be expected that a number of bus systems will establish themselves in the vehicle, each of which will be characterized by its own particular area of application.

In addition to electronic data transmission, optical transmission systems will also come into use in the multimedia area. These are very-high-speed bus systems and can transmit large quantities of data as needed for audio and video components.

Individual functions will be combined by networking to form a system alliance covering the complete vehicle, in which information can be exchanged via data buses. The implementation of such overlapping functions necessitates binding agreements covering interfaces and functional contents. The CARTRONIC® from Bosch is the answer to these stipulations, and has been developed as a priority-override and definition concept for all the vehicle's closed and open-loop control systems. The possible sub-division of the functions which are each controlled by a central coordinator can be seen in Fig. 1. The functions can be incorporated in various ECUs.

The combination of components and systems can result in completely novel functions. For instance, the exchange of data between the transmission-shift control and the navigation equipment can ensure that a change down is made in good time before a gradient is reached. With the help of the navigation facility, the headlamps will be able to adapt their beam of light to make it optimal for varying driving situations and for the route taken by the road (for instance at road intersections). Car radios, sound-carrier drives, TV, telephone, E-mail, Internet, as well as the navigation and terminal equipment for traffic telematics will be networked to form a multimedia system.

1 CARTRONIC®: Design schematic



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

EGR valve

With exhaust-gas recirulation (EGR) a portion of the exhaust gas is led back into the engine's intake tract with the object of reducing toxic emissions.

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. In future, electric valves will be used for this purpose.

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. To prevent the generation of excessive boost pressure at high engine turbocharger speeds, the boost-pressure control's actuator diverts some of the exhaust gas around the exhaust-gas turbocharger's turbine by means of a so-called wastegate (Fig. 1).

Instead of the wastegate, turbines with variable turbine geometry (VTG) can be used to adapt the turbocharger's output. In the case of VTG, an electrical or electropneumatic valve varies the angle of the turbine blades in the exhaust-gas passage.

Swirl controller

In the passenger car, swirl control is applied to influence 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 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 intake valve.

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.

Throttle valve

The throttle valve is controlled by an electropneumatic valve, and in the diesel engine its function is very different 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.

1 Boost-pressure control with boost-pressure actuator

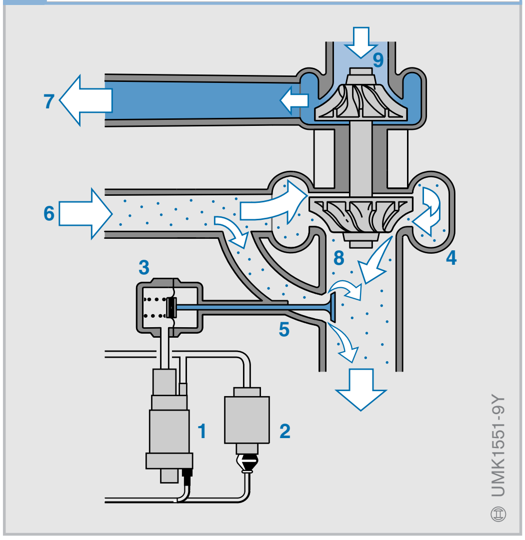


Figure 1
1 Boost-pressure actuator
2 Vacuum pump
3 Pressure actuator
4 Exhaust-gas turbocharger
5 Bypass valve
6 Exhaust-gas flow
7 Intake-air flow
8 Turbine
9 Compressor

Continuous-operation braking systems

These braking systems are used for reducing the speed of heavy trucks without causing wear of the conventional braking components. They cannot stop the vehicle though. Since, in contrast to service brake systems with friction wheel brakes, they 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 injection of fuel into the engine 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 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 hydraulic switching 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 rotatable turbine wheel (brake rotor) and at the opposite end a fixed turbine wheel (brake 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. In the process, 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 engine ECU switches the engine's fan on and off as required using an electromagnetic clutch.

Electrically powered fans are being used increasingly. Since they are not driven by the engine V-belt, this permits innovative solutions regarding their location in the engine compartment.

Start-assist systems

Compared to gasoline, diesel fuel is far more easily ignited. This is why the warm diesel engine starts immediately when cranked. The DI (direct injection) 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. Prechamber engines (IDI – indirect injection) engines need some form of start-assist system when starting "cold". DI engines on the other hand only need assistance when starting below 0 °C. The cylinders of prechamber and swirl-chamber engines are equipped with 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 preheating 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 in start-assist systems.

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 is provided with a filter, and a metering device which permits passage of precisely the right 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 sheathed-element glow plug's (GSK) glow element is so firmly pressed into the glow-plug shell (Fig. 1, Pos. 3) that a gas-tight seal is formed. The element is a metal glow tube (4) which is resistant to both 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

1 Sheathed-element glow plug GSK2

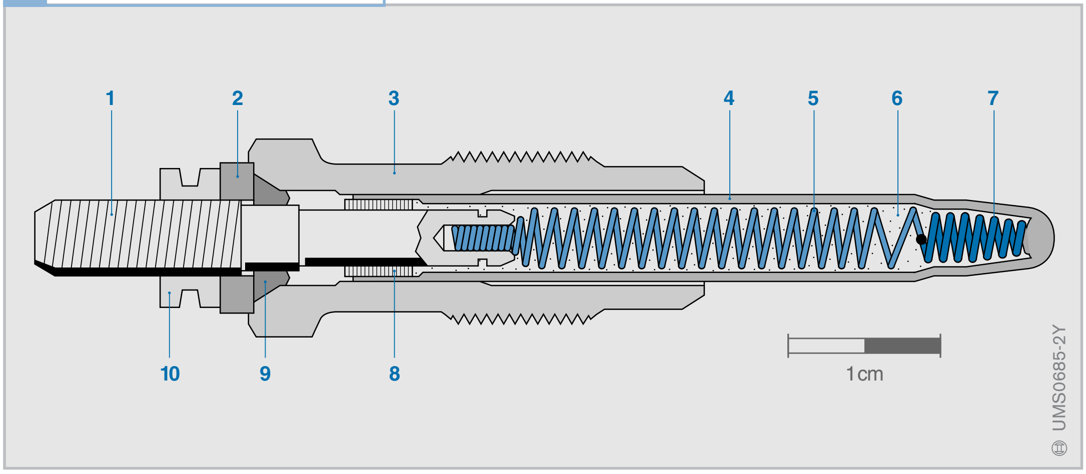


Figure 1
1 Electrical connector terminal
2 Insulating washer
3 Glow-plug shell
4 Glow tube
5 Control filament
6 Filling powder
7 Helical heating wire
8 Heater-element gasket
9 Double gasket
10 Round nut

constant electrical resistance regardless of temperature, the control filament is made of material with a positive temperature coefficient (PTC). On newer-generation 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 their 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. It receives its start pulse 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 glow control units are also able to recognise the failure of individual glow plugs and inform the driver accordingly. 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 the "ignition on" position starts the preheating process (Fig. 3). When the glow-indicator lamp extinguishes, 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 released as a result leads to the initiation of the combustion process.

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. At the same time, when the engine is cold, pre-heating reduces combustion noise. A glow-plug safety switchoff prevents battery discharge in case the engine cannot be started.

The glow control unit can be coupled to the ECU of the **E**lectronic **D**iesel **C**ontrol (EDC) so that information available in the EDC control unit can be applied for optimum control of the glow plugs in accordance with the particular operating conditions. This is yet another possibility for reducing the levels of blue smoke and noise.

2 EDC-controlled glow system in a direct-injection (DI) diesel engine

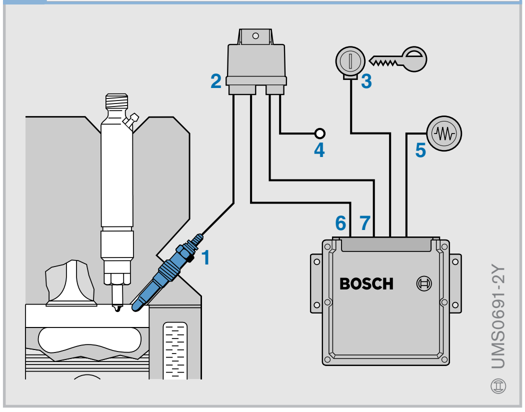


Figure 2

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

3 Typical preheating sequence

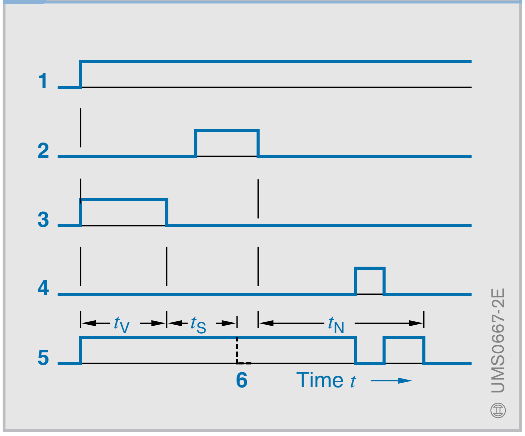


Figure 3

1	Glow-plug and starter switch
2	Starter
3	Indicator lamp
4	To battery
5	Glow plugs
6	Self-sustained engine operation
t_V	Preheating time
t_S	Ready to start
t_N	Postheating time

Index of Technical Terms

An arrow → indicates a term in italics (e.g. → *Common Rail System*) which is a synonym or related term.

Technical term

Abbreviations

A
ABS: Antilock Braking System
ACC: Adaptive Cruise Control
A/D: Analog/Digital
ADF: Atmospheric-pressure sensor
AGR: → *Exhaust-gas recirculation (EGR)*
ARD: → *Active surge-damping control*
ARF: → *Exhaust-gas recirculation (EGR)*
ARS: Angle-of-rotation sensor → *Accelerator-pedal sensor*
ASIC: Application Specific Integrated Circuit
ASR: Traction Control System (TCS)
AZG: Adaptive cylinder balancing

B
BIP signal: Signal for Beginning of the Injection Period (also known as Begin of Injection Period) → (*BIP control*)

C
CAN: → *Controller Area Network*
CO: Carbon monoxide
CO_2: Carbon dioxide
CR System: → *Common Rail System*

D
DI: Direct Injection
DZG: Rotational-speed sensor (→ *Sensors)*

E
EAB: → ELAB
ECE: Economic Commission for Europe
EDC: Electronic Control Unit (→ *Electronic Diesel Control*)
EG: European Union
ELAB: Electrical shutoff valve (In-line and distributor pumps)
EMV: Electromagnetic compatibility (EMC)
EOBD: European → *On-Board Diagnosis*
EOL programming: → *End-of-Line programming*
ESP: Electronic Stability Program
EU: European Union

F
FGB: → *Vehicle-speed limitation*
FGR: → *Vehicle-speed control (Cruise Control)*

G
GSK: → *Sheathed-element glow plug*
GZS: → *Glow control unit*

H
HC: Generic term for hydrocarbons
HDK: Half-differential short-circuiting-ring sensor → *Sensors*
HE: Main Injection → *MI*
HFM: (→ *Hot-film air-mass meter*)
HGB: (→ *Vehicle-speed limitation*)

I
IDI: Indirect Injection (Prechamber engines)
ISO: International Organization for Standardization
IWZ-Signal: → *Incremental angle/time signal*

K
KW: Crankshaft (cks)

L
LDR: → *Boost-pressure control*
LLR: → *Idle-speed control*
LRR: → *Smooth-running control*

M
MAB: Fuel shutoff
MAR: → *Smooth Running Control (SRC)*
MI: → *Main Injection*
MIL: Malfuction Indicator Lamp (diagnosis lamp)
MMA: → *Fuel-quantity mean-value adaptation* (Lambda closed-loop control)
MNEFZ: Modified new European driving cycle (exhaust-gas test)
MSG: Engine ECU
MV: Solenoid valve

N

NBF: Needle-motion sensor → *Sensors*

NBS: → Needle-motion sensor

NE: → *Post injection* → *POI*

NO_X: Generic term for oxides of nitrogen

NTC: Negative Temperature Coefficient

NW: Camshaft (cms)

O

O_2: Oxygen

OBD: → *On-Board Diagnosis*

OT: Top Dead Center (TDC)

P

PDE: → *Unit Injector System*

PE pump: → *In-line fuel-injection pumps*

PF pump: → *Single-plunger fuel-injection pumps*

PI: Pilot Injection

PLD: → *Unit Pump system (UPS)*

POI: Post Injection

PSG: Pump ECU → *Distributor injection pumps*

PTC: Positive Temperature Coefficient

PWG: Accelerator-pedal sensor → *Sensors*

PWM signal: → *Pulse-width-modulated (pwm) signal*

R

RWG: → *Rack-travel sensor*

S

SAE: Society of Automotive Engineers

SRC: → *Smooth Running Control*

T

TCS: → (ASR)

TD signal: Rotational-speed signal

TQ signal: Fuel-consumption signal

U

UIS: → *Unit Injector System*

UPS: → *Unit Pump System*

UT: Bottom Dead Center (BDC)

V

VE → *Distributor injection pump*

VP30: Solenoid-valve-controlled axial-piston → *Distributor injection pump*

VP44: Radial-piston pump → *Distributor injection pump*

VR pump: Radial-piston- → *Distributor injection pump*

VTG: Turbocharger with Variable Turbine Geometry

Z

ZDR: → *Intermediate-speed control*