Electronic Control

"Motronic" is the name of an engine-management system that facilitates open- and closed-loop control of gasoline engines within a single ECU. The first Motronic system went into volume production at Bosch in 1979. Essentially, it comprised the functions of electronic fuel injection and electronic ignition. With the advances made in the field of microelectronics, it has been possible to continuously expand the capabilities of Motronic systems over the course of time. The range of functions has been continuously adapted in response to prevailing demands and the complexity of successive Motronic systems has consequently increased.

Although cost considerations limited application of early Motronic versions to luxury-class cars, progressively more stringent demands for clean emissions is gradually leading to widespread use of this system. Since the mid-1990s, all new engine projects in which Bosch has been involved use Motronic systems.

Open- and closed-loop electronic control

Motronic comprises all the components which control the gasoline engine (Fig. 1). The torque requested by the driver is adjusted by means of actuators or converters. The main individual components are

- The electrically actuated throttle valve (air system): This controls the air-mass flow to the cylinders and thus the cylinder charge.
- The fuel injectors (fuel system): These meter the correct amount of fuel for the cylinder charge.
- The ignition coils and spark plugs (ignition system): These provide for correctly timed ignition of the air/fuel mixture in the cylinder.

Modern-day engines are subject to exacting demands with regard to

- Exhaust-emission behavior
- Power output
- Fuel consumption
- Diagnostic capability, and
- Comfort/user-friendliness

Where necessary, additional components are installed on the engine for this purpose. All the manipulated variables are calculated in accordance with prespecified algorithms in the Motronic ECU. The actuating signals for the actuators are generated from these variables.

Acquisition of operating data

Sensor and setpoint generators

Motronic uses sensors and setpoint generators to collect the operating data required for open- and closed-loop control of the engine (Fig. 1).

Setpoint generators (e.g., switches) record settings made by the driver, such as

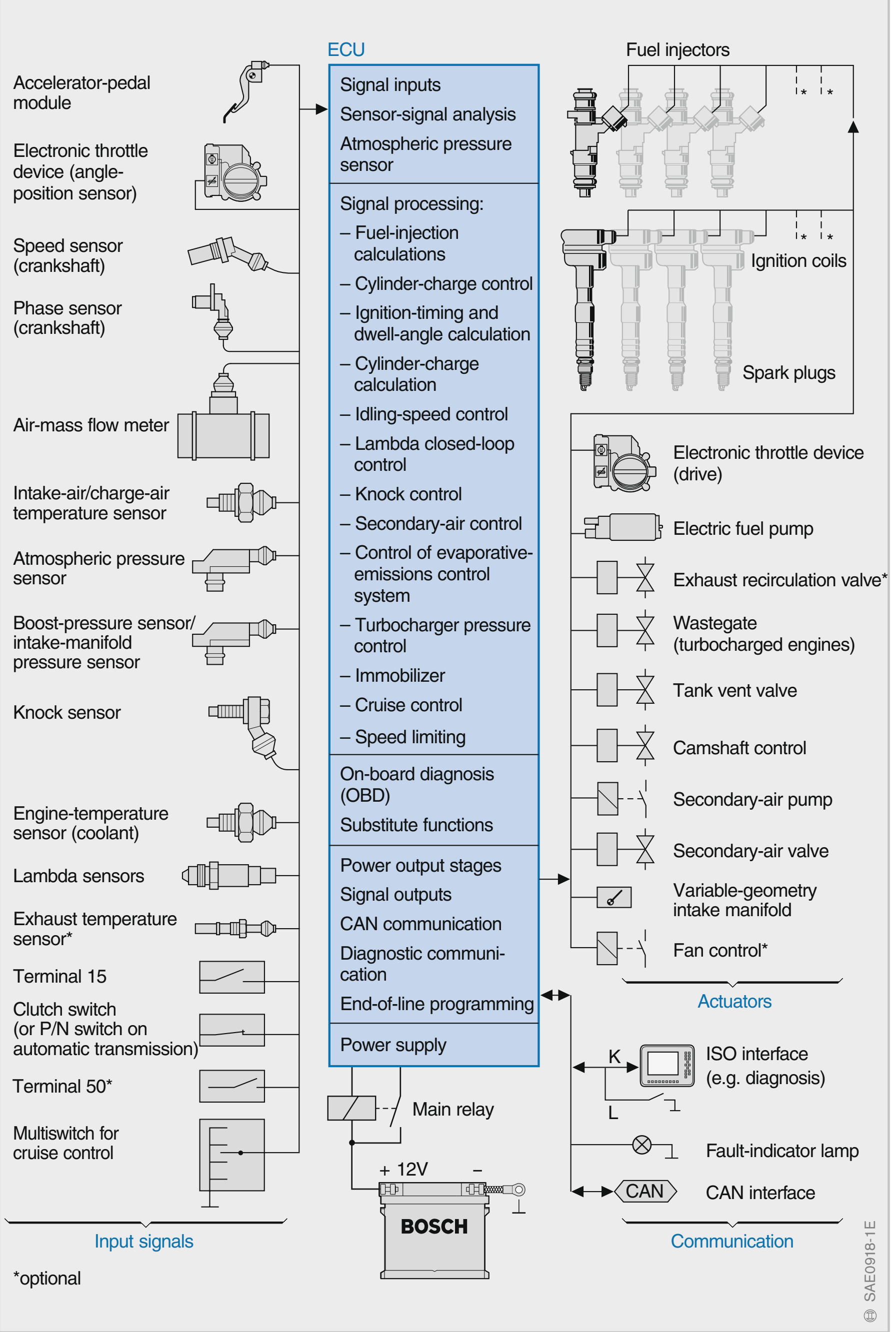
- The position of the ignition key in the ignition lock (terminal 15)
- The positions of A/C-control switches
- The cruise-control lever setting

Sensors detect physical and chemical variables, thus providing information about the engine's current operating state. Examples of such sensors are:

- Engine-speed sensor for detecting the crankshaft position and calculating the engine speed
- Phase sensor for detecting the phase angle (engine operating cycle) or the camshaft position
- Engine-temperature sensor and intake-air temperature sensor for calculating temperature-dependent correction variables
- Knock sensor for detecting engine knock
- Air-mass meter, and/or
- Intake-manifold pressure sensor for charge recording
- Lambda oxygen sensor for lambda closed-loop control

K. Reif (Ed.), *Gasoline Engine Management,* Bosch Professional Automotive Information,
DOI 10.1007/978-3-658-03964-6_14, © Springer Fachmedien Wiesbaden 2015

1 Components used for open- and closed-loop electronic control of a Motronic system



Signal processing in the ECU

The signals produced by the sensors can take the form of digital, pulse-type or analog voltage signals. Input circuits in the ECU, or in the sensors – which will increasingly be the case in the future – process these signals. These circuits transform voltages to the levels required for subsequent processing in the ECU's microprocessor.

Digital input signals are read in directly in the microcontroller and stored as digital information. Analog signals are converted into digital signals by an analog/digital converter.

Processing of operating data

From the input signals, the engine ECU detects the engine's current operating state of the engine and uses this information in conjunction with requests from auxiliary systems and from the driver (pedal-travel sensor and operating switches) to calculate the command signals for the actuators.

The tasks performed by the engine ECU are subdivided into functions. The algorithms are stored as software in the ECU's program memory.

ECU functions

Motronic has two basic functions: Firstly, metering the correct mass of fuel in accordance with the air mass drawn into the engine, and secondly, triggering the ignition spark at the best possible moment in time. In this way, fuel injection and ignition can be optimally matched.

The performance of the microcontrollers used in Motronic permits a wealth of further open- and closed-loop control functions to be integrated. Progressive tightening of emissions limits simultaneously spurs the demand for functions capable of improving the engine's exhaust behavior and exhaust-gas treatment. Functions that are capable of making a contribution here include:

- Idle-speed control
- Lambda closed-loop control
- Control of the evaporative-emissions control system (canister purge)
- Knock control
- Exhaust-gas recirculation for reducing NO_X emissions, and
- Control of the secondary-air system to ensure that the catalytic converter quickly reaches full operational readiness

Where there are increased demands on the drivetrain, the system can also be extended by the following additional functions:

- Control of the exhaust-gas turbocharger, and
- Variable-tract intake manifold in order to increase engine power and torque
- Camshaft control in order to reduce exhaust-gas emissions and fuel consumption, and to increase engine power
- Torque- and speed-limiting functions to protect engine and vehicle
- Control of gasoline direct injection in order to reduce exhaust-gas emissions and fuel consumption, and to increase engine power

Ever-increasing priority is being given in the design and development of motor vehicles to the driver's comfort and convenience. This also affects engine management. Examples of typical comfort and convenience functions are:

- Cruise control (vehicle-speed controller), and
- Adaptive Cruise Control (ACC)
- Torque adaptation during gearshifts on automatic transmissions, and
- Load-reversal damping (reducing abruptness of driver control commands)

Actuator triggering

The ECU functions are executed in accordance with the algorithms stored the program memory of the Motronic ECU. This produces variables (e.g., fuel mass to be injected), which are set by means of actuators (e.g., defined-time actuation of fuel injectors). The ECU generates the electrical actuating signals for the actuators.

Torque structure

The torque-based system structure was first introduced with ME7-Motronic. All performance requirements (Fig. 2) placed on the engine are consistently converted into a torque demand. The torque coordinator prioritizes the torque demands from internal and external loads/consumers and other requirements relating to engine efficiency. The resulting desired torque is allocated to the components of the air, fuel and ignition systems.

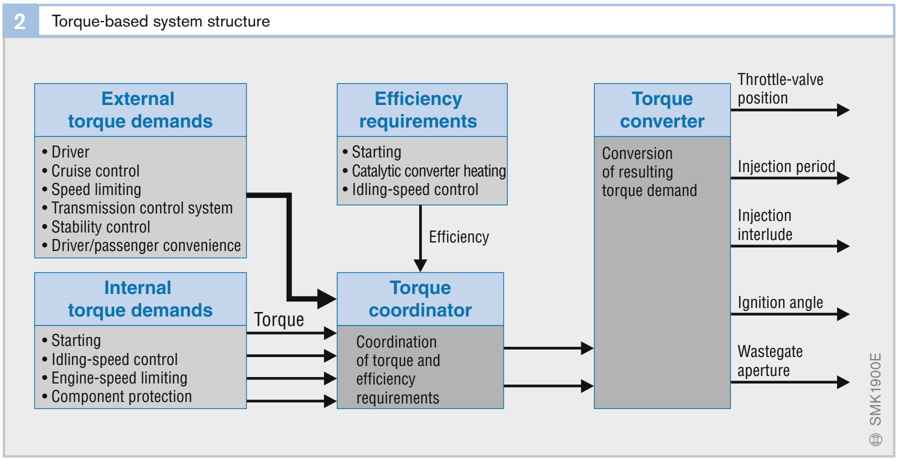
The charge component (air system) is implemented by varying the throttle-valve aperture and – in the case of turbocharged engines – by actuating the wastegate valve. The fuel component is essentially determined by means of the injected fuel, taking account of canister purge (evaporative-emissions control system).

The torque is adjusted via two channels. The air channel (main channel) involves calculating the required cylinder charge from the torque to be converted. From the required cylinder charge, the required throttle-valve aperture is calculated. The required injected-fuel mass is directly related to the cylinder charge due to the fixed lambda value specified. The air channel only permits gradual changes in torque (e.g. integral component of idle-speed control).

The crankshaft-synchronized channel uses the cylinder charge currently available to calculate the maximum possible torque for this operating point. If the desired torque is less than the maximum possible torque, a rapid reduction in torque (e.g., differential component of idle-speed control differential component, torque reduction during gear shifting, surge damping) can be achieved by retarding the ignition or blanking out one or more cylinders altogether (injection blank-out, e.g., TCS intervention or when the engine is overrunning).

On earlier M-Motronic systems without a torque structure, a reduction in torque (e.g., at the request of the automatic transmission when changing gear) is performed directly by the function concerned, for example, by retarding the ignition angle. There is no coordination between individual requests or of command implementation.

2 Torque-based system structure



Monitoring concept

It is imperative that, when the vehicle is in motion, it is never able to accelerate when the driver does not want it to. Consequently, the monitoring concept for the electronic engine-power control system must meet exacting requirements. To this end, the ECU includes a monitoring processor in addition to the main processor, and the two processors monitor one another.

Electronic diagnosis

The diagnosis functions integrated in the ECU monitor the Motronic system (ECU, sensors and actuators) for malfunctions and faults, store details of any faults detected in the data memory, and initiate substitute functions where necessary. A diagnosis lamp or a display within the instrument cluster alerts the driver to the faults.

System testers (e.g., KTS650) are connected via a diagnosis interface in the service garage/workshop. These allow the fault information stored in the ECU to be read out.

The diagnosis function was originally intended only to assist mechanics in conducting vehicle inspections and services in service garages/workshops. However, with the introduction of the Californian OBD (On-Board Diagnosis) emission-control legislation, diagnosis functions were now stipulated which check the entire engine system for exhaust-related faults and indicate these faults by way of a fault indicator lamp. Examples of such functions are catalytic-converter diagnosis, lambda-sensor diagnosis, and misfire detection. These requirements were later adopted in modified form in European legislation (EOBD).

Vehicle management

Motronic can communicate with the ECUs of other vehicle systems via bus systems, such as CAN (Controller Area Network). Figure 3 shows some examples. The ECUs can process the data from other systems in their control algorithms as input signals (e.g., Motronic reduces engine torque in response to a gearshift operation by the transmission to ensure a smoother gear change).

3 Data communication with Motronic

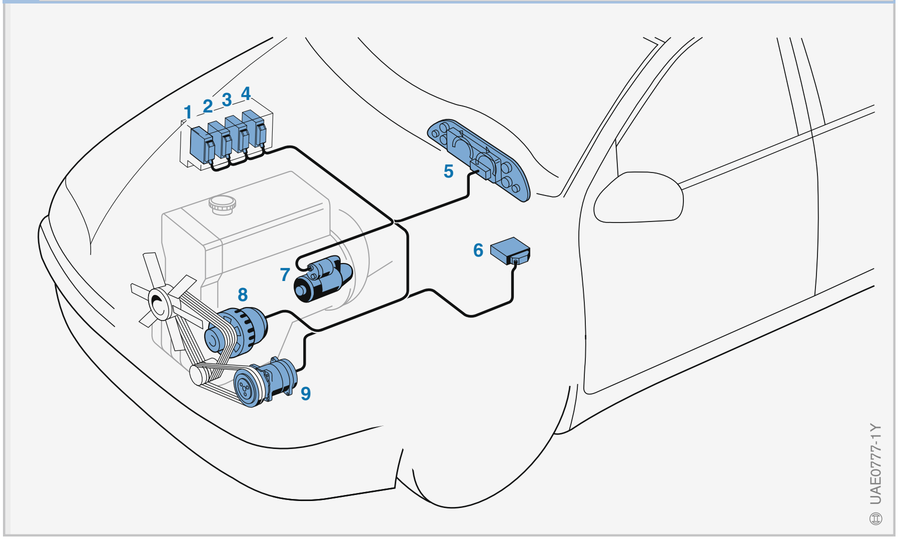


Fig. 3
1 Engine ECU (Motronic)
2 ESP ECU (Electronic Stability Program)
3 Transmission ECU
4 A/C ECU
5 Instrument cluster module with on-board computer
6 Immobilizer ECU
7 Starter
8 Alternator
9 A/C compressor

Motronic systems in motorsport

Simultaneously with the introduction of the Motronic systems on production vehicles, modified versions were also used on racing engines. Whereas the development objectives for production versions are aspects such as convenience, safety, reliability, emission limits and fuel consumption, the main focus in motor-racing applications is on maximum performance over a short period. The production costs with regard to choice of materials and dimensioning of components are a secondary consideration.

But the production and racing versions of the Motronic system are still based on identical principles because in both cases similar functions achieve contrasting aims. The excess-air factor and knock control systems are examples of this.

Environmental protection regulations are increasingly a consideration even in motorsport. The cars in the German Touring Car Championship, for example, are now fitted with catalytic converters. Noise and fuel-consumption levels have to be limited in more and more classes of racing. Consumption-reducing developments used on production cars quickly transfer to motor racing where shorter or less frequent refueling stops can make the difference between winning and losing. The 2001 Le Mans 24-hour race, for example, was won for the first time by a car with a Bosch gasoline direct-injection system.

The high revving speed of racing engines minimizes the time available during each operating cycle. The vast amount of process data requires high processor clock frequencies and the use of multiprocessor systems to a greater extent.

Not only the ECU but also the ignition and fuel-injection components have to operate at extremely high speeds. This requires ignition coils with fast charging times and fuel-system components that are capable of quicker throughput and higher pressures. Spark plugs with smaller thread diameters made of materials adapted to the operating temperatures encountered allow higher compression ratios.

During the race, data can be transmitted by radio from the car to the pits. Known as telemetry, this technology allows constant monitoring of operating parameters such as pressures and temperatures.

UAV0059Y

Motronic versions

Motronic comprises all the components which are needed to control a gasoline engine. The scope of the system is determined by the requirements with regard to engine power (e.g., exhaust-gas turbocharging), fuel consumption, and the stipulations of the relevant emission-control legislation. Californian emission-control and diagnosis legislation (Californian Air Resources Board, CARB) places particularly stringent requirements on the Motronic diagnosis system. Some emissions-related systems can only be diagnosed with the aid of additional components (e.g., evaporative-emissions control system).

In the course of the development history of Motronic systems, successive Motronic generations (e.g., M1, M3, ME7) have differed mainly in the design of the hardware. The basic distinguishing features are the microcontroller family, the peripheral modules and the output-stage modules (chipset). The hardware variations arising from the requirements of different vehicle manufacturers are distinguished by manufacturer-specific identification numbers (e.g., ME7.0).

In addition to the versions described in the following, there are also Motronic systems with integrated transmission management (e.g., MG and MEG-Motronic). However, these are not in extensive use, as the demands on hardware are considerable.

M-Motronic

M-Motronic is an engine-management system for manifold-injection gasoline engines. It is characterized by the fact that the air is supplied through a mechanically adjustable throttle valve.

The accelerator pedal is connected to the throttle valve by way of a linkage or a Bowden cable. The position of the accelerator pedal determines how far the throttle valve opens. This controls the air mass flowing through the intake manifold to the cylinders.

An idle actuator allows a defined air-mass flow to bypass the throttle valve. This provides a means with the additional air of holding the engine speed at a constant level, for example, when idling (idle-speed control). To do so, the engine ECU controls the opening cross-section of the bypass channel.

M-Motronic is no longer of significance to new developments in the European and North American markets, since it has been superseded by ME-Motronic.

ME-Motronic

ME-Motronic is characterized by electronic engine-power control. In this system, there is no longer a mechanical connection between the accelerator pedal and the throttle valve. The position of the accelerator pedal, i.e., the driver command, is detected by a potentiometer attached to the accelerator pedal (pedal-travel sensor in the accelerator-pedal module, Fig. 4 Pos. 23) and read in by the engine ECU (12) in the form of an analog voltage signal. In response, the ECU generates output signals that set the opening cross-section of the electrically actuated throttle valve (3) so that the engine produces the desired torque.

A system that regulates engine power in this way was first introduced by Bosch in 1986. In addition to the engine ECU, the original system also had a separate ECU for engine-power control.

The increasingly higher integration density of electronic systems allowed the combination of Motronic functions and engine-power control in a single ECU (1994). Nevertheless, functions remained divided between two microcontrollers. The next step was taken in 1998 with the launch of the new Motronic generation, the ME7, which executes all engine-management functions in a single microcontroller. This advance was made possible by the ever-increasing processing capacity of microcontrollers.

4 Components used for open- and closed-loop electronic control of an ME-Motronic system (system diagram)

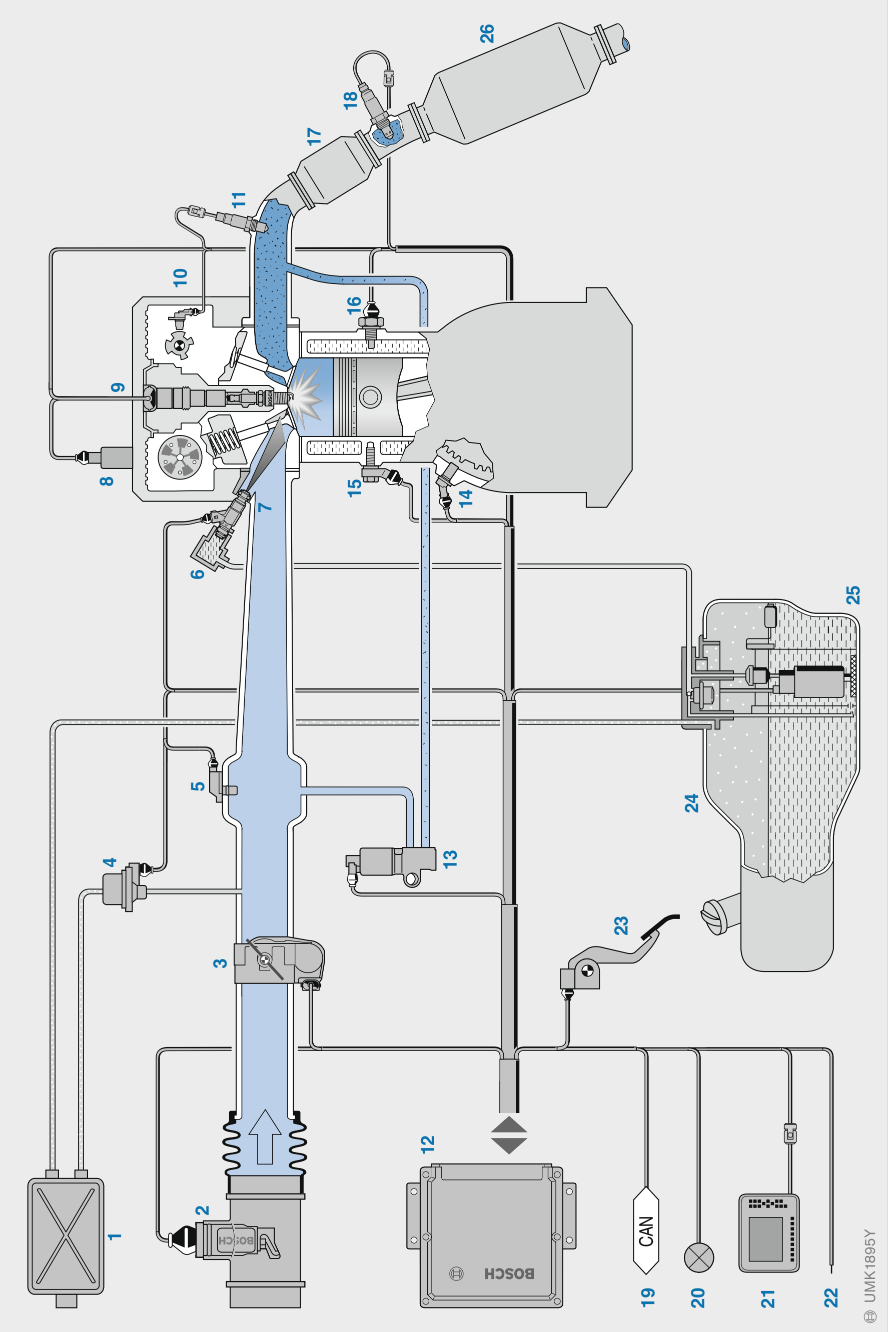


Fig. 1
1 Carbon canister
2 Hot-film air-mass meter with integrated temperature sensor
3 Throttle device (ETC)
4 Canister-purge valve
5 Intake-manifold pressure sensor
6 Fuel rail
7 Fuel injector
8 Actuators and sensors for camshaft control
9 Ignition coil and spark plug
10 Camshaft phase sensor
11 Lambda sensor upstream of primary catalytic converter
12 Engine ECU
13 Exhaust-gas recirculation valve
14 Speed sensor
15 Knock sensor
16 Engine-temperature sensor
17 Primary catalytic converter (three-way catalytic converter)
18 Lambda sensor downstream of primary catalytic converter
19 CAN interface
20 Fault indicator lamp
21 Diagnosis interface
22 Interface with immobilizer ECU
23 Accelerator-pedal module with pedal-travel sensor
24 Fuel tank
25 In-tank unit comprising electric fuel pump, fuel filter and fuel-pressure regulator
26 Main catalytic converter (three-way)

The on-board-diagnosis system configuration illustrated by the diagram reflects the requirements of EOBD

DI-Motronic

The introduction of direct injection in the gasoline engine necessitated a control concept which facilitates both homogeneous and stratified-charge operation.

In homogeneous mode, the fuel injector is actuated in such a way as to produce homogeneous mixture distribution in the combustion chamber. The fuel is injected during the induction stroke for this purpose. In stratified-charge mode, the process of retarding injection until the compression stroke, shortly before ignition, creates a locally limited mixture cloud in the area of the spark plug.

In addition to the systems which facilitate both stratified-charge and homogeneous operation, there are also purely homogeneous systems, in which the engine is operated homogeneously and stoichiometrically ($\lambda = 1$) over the entire operating range. These latter systems are increasingly being used in conjunction with supercharging.

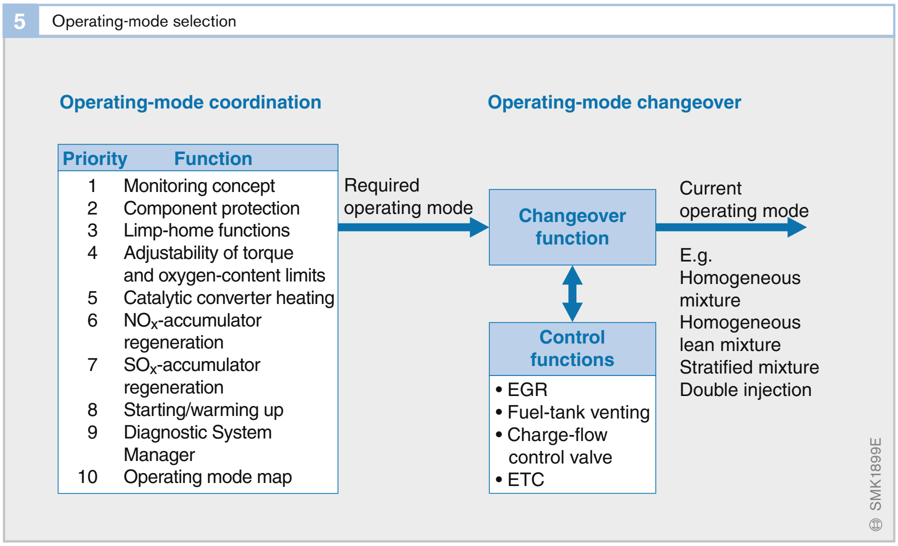
The system diagram (Fig. 6) shows an example of a DI-Motronic system. The first series-production DI-Motronic was launched in the Volkswagen Lupo in 2000.

Operating-mode coordination and changeover

Further operating modes in addition to homogeneous and stratified-charge modes are also possible. Injection of a basic quantity of fuel during the induction stroke together with subsequent injection during the compression stroke result in a stratified charge at the spark plug, surrounded by a homogeneous lean mixture spread through the whole combustion chamber (homogeneous-lean). Further operating modes, for instance for heating the catalytic converter, are set by means of highly retarded injection points and moments of ignition.

DI-Motronic incorporates an operating-mode coordinator, which enables changeover to a different operating mode when engine requirements demand. The basis for selecting an operating mode is the operating-mode map, which plots operating mode against engine speed and torque. Deviating operating-mode requirements are evaluated in the priority list (Fig. 5). This produces the required operating mode. But before ignition and fuel injection can be changed over to the new operating mode, control functions for exhaust-gas recirculation, tank ventilation (canister purge), charge-flow control

5 Operating-mode selection



Priority	Function
1	Monitoring concept
2	Component protection
3	Limp-home functions
4	Adjustability of torque and oxygen-content limits
5	Catalytic converter heating
6	NO_x-accumulator regeneration
7	SO_x-accumulator regeneration
8	Starting/warming up
9	Diagnostic System Manager
10	Operating mode map

- EGR
- Fuel-tank venting
- Charge-flow control valve
- ETC

E.g.
Homogeneous mixture
Homogeneous lean mixture
Stratified mixture
Double injection

6 Components used for open- and closed-loop electronic control of an DI-Motronic system (system diagram)

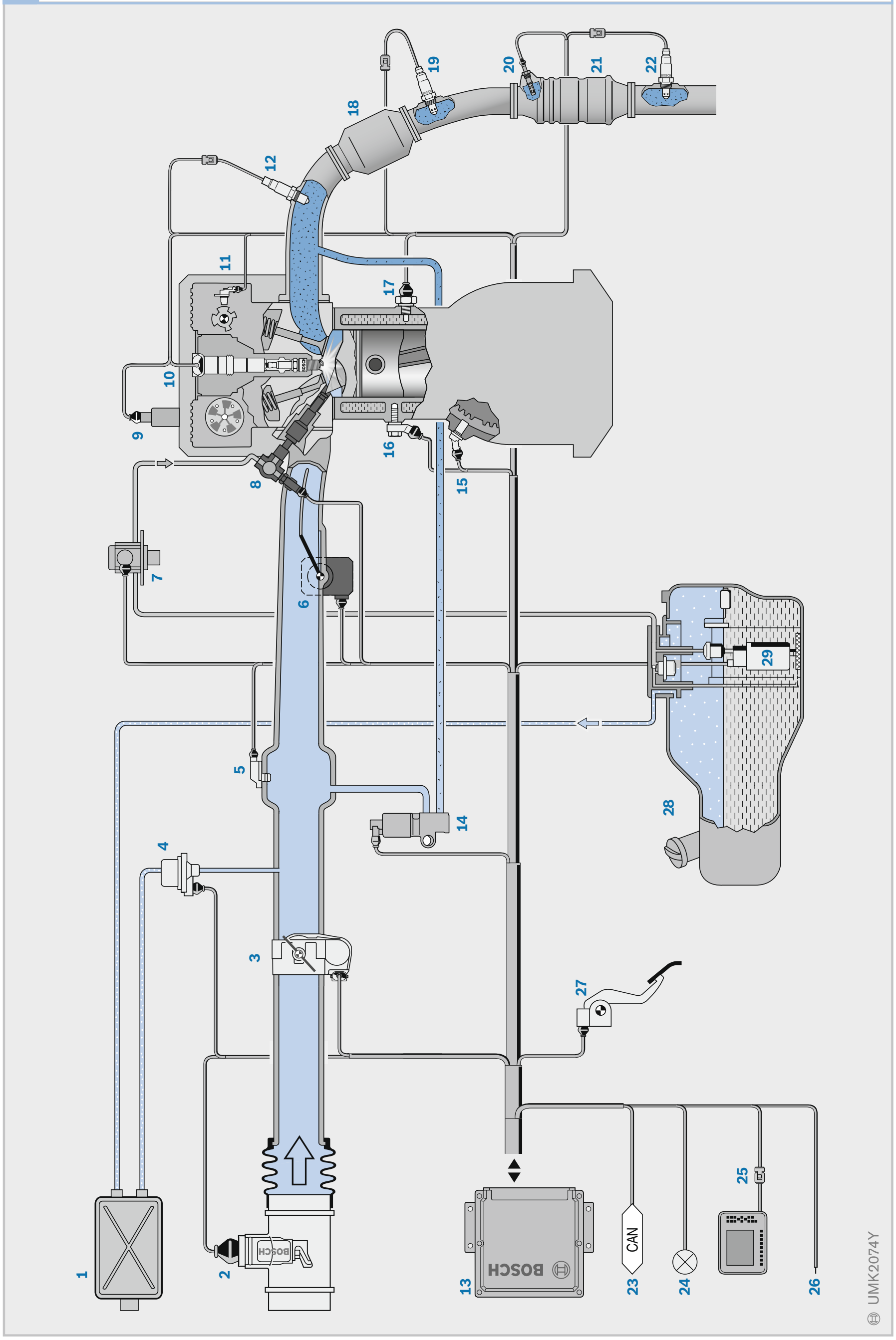


Fig. 6

1 Carbon canister
2 Hot-film air-mass meter
3 Throttle device (ETC)
4 Canister-purge valve
5 Intake-manifold pressure sensor
6 Charge-flow control valve
7 High-pressure pump
8 Fuel rail with high-pressure injector
9 Camshaft adjuster
10 Ignition coil with spark plug
11 Camshaft phase sensor
12 Lambda sensor (LSU)
13 Motronic ECU
14 Exhaust-gas recirculation valve
15 Speed sensor
16 Knock sensor
17 Engine-temperature sensor
18 Primary catalytic converter
19 Lambda sensor
20 Exhaust-gas temperature sensor
21 NO_X accumulator-type catalytic converter
22 Lambda sensor
23 CAN interface
24 Diagnosis lamp
25 Diagnosis interface
26 Interface to immobilizer ECU
27 Accelerator-pedal module
28 Fuel tank
29 Fuel-supply module with electric fuel pump

valve and throttle-valve setting are initiated if required. The system then waits for acknowledgement.

In stratified-charge mode at $\lambda > 1$, the throttle valve is fully open and the inducted air can enter the engine virtually unthrottled. The torque is proportional to the injected fuel mass.

During changeover to homogeneous mode, the air mass, which now determines the torque to a large extent, must be reduced very quickly and a desired lambda value set – for a stoichiometric mixture of $\lambda = 1$ (Fig. 7). The torque output by the engine now varies in relation to the accelerator-pedal position, although the driver is unaware of any change.

Brake-booster vacuum control

When the engine is operating with an unrestricted intake air flow, there is insufficient vacuum in the intake manifold to provide the vacuum required by the brake booster. A vacuum switch or pressure sensor is used to detect whether there is sufficient vacuum in the brake booster. If necessary, the engine has to be switched to a different operating mode in order to provide the required vacuum for the brake booster.

7 Changeover from stratified-charge to homogeneous mode

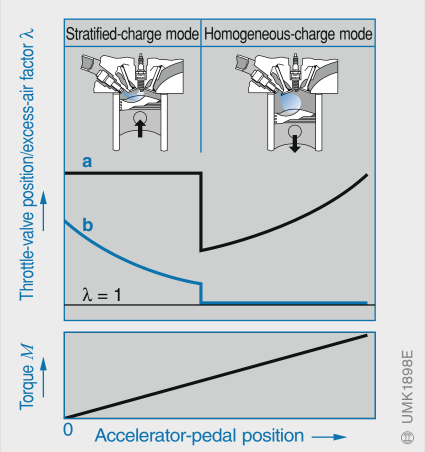


Fig. 7
a Throttle-valve position
b Excess-air factor λ

Bifuel-Motronic (natural gas/gasoline)

Bifuel-Motronic has been developed from ME-Motronic and therefore contains all the components for manifold injection familiar from ME-Motronic. Bifuel-Motronic also contains the components for the natural-gas system (Fig. 8).

Whereas in retrofit systems natural-gas operation is controlled by means of an external unit, with Bifuel-Motronic the CNG functionality is integrated in the engine-management system. The desired engine torque and the variables characterizing the operating state are generated only once in the Bifuel ECU. The physically based structure of the engine-management system makes it possible to easily integrate the parameters specific for gas operation.

Changeover

Depending on the engine design, it can be useful in the case of high load demands to switch automatically to the fuel type which provides the maximum engine power. Further automatic changeovers may also be useful in order, for example, to implement an optimized exhaust-gas strategy and to heat up the catalytic converter more quickly, or basically to effect fuel management. However, it is important in the case of automatic changeovers that these be implemented on a torque-neutral basis, i.e., they are not noticeable to the driver.

The 1-ECU concept enables fuel changeover to be performed in different ways. One option is direct changeover, comparable with a switch. Here, injected must not be interrupted, as this would increase the risk of misfiring during operation. However, the sudden injection of gas in comparison with gasoline operation results in a greater volume displacement to such an extent that the intake-manifold pressure increases and the cylinder charge decreases as a result of changeover by roughly 5 %. This displacement effect must be compensated for by a larger throttle-valve angle. In order to keep the engine torque constant during changeover under load conditions, it is necessary to effect an additional

8 Components used for open- and closed-loop electronic control of a Bifuel-Motronic system (system diagram)

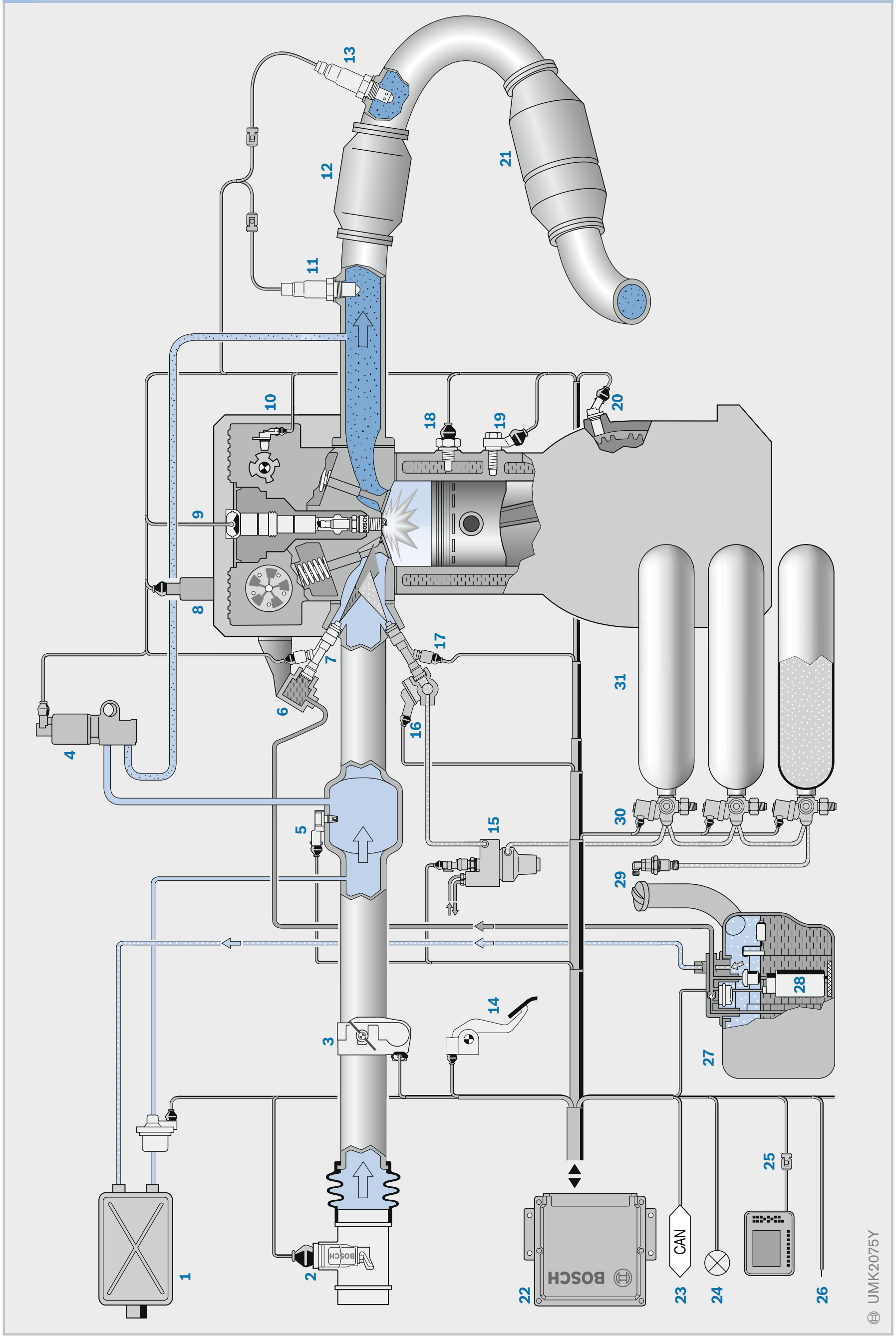


Fig. 8

1 Carbon canister with canister-purge valve
2 Hot-film air-mass meter
3 Throttle device (ETC)
4 Exhaust-gas recirculation valve
5 Intake-manifold pressure sensor
6 Fuel rail
7 Gasoline injector
8 Camshaft adjuster
9 Ignition coil with spark plug
10 Camshaft phase sensor
11 Lambda sensor
12 Primary catalytic converter
13 Lambda sensor
14 Accelerator-pedal module
15 Natural-gas pressure regulator
16 Natural-gas rail with natural-gas pressure and temperature sensor
17 Natural-gas injector
18 Engine-temperature sensor
19 Knock sensor
20 Speed sensor
21 Main catalytic converter
22 Bifuel-Motronic ECU
23 CAN interface
24 Diagnosis lamp
25 Diagnosis interface
26 Interface to immobilizer ECU
27 Fuel tank
28 Fuel-supply module with electric fuel pump
29 Filler neck for gasoline and natural gas
30 Tank shutoff valves
31 Natural-gas tank

intervention in the ignition angles, which facilitates a fast change of torque.

Another option for changeover is fading from gasoline to gas operation. In order to switch to gas operation, gasoline injection is reduced by a dividing factor and gas injection increased accordingly. In this way, jumps in the air charge are avoided. There is also the option of correcting an altered gas quality with lambda closed-loop control during changeover. With this method, it is possible to effect the changeover even at high load without a noticeable change of torque.

Retrofit systems often do not offer the option of switching between the gasoline and natural-gas operating modes under coordinated conditions. For this reason, many systems effect the changeover only during the overrun phases in order to avoid torque jumps.

European On-Board Diagnosis

Current EOBD legislation stipulates separate detection, handling and transmission of faults during operation with gasoline or CNG. This calls for the fault memory to be doubled in size. An alternative suggestion provides for a scenario where faults which are identified independently of the fuel (e.g., speed sensor faulty) are handled independently of the fuel. New fault paths are added for gas-specific faults so that these can also be stored and read out in the fault memory.

System structure

A few years ago, it was still possible to represent the functionality of Motronic systems with “simple” system and function descriptions. Now the open- and closed-loop control operations for gasoline engines have become so complex that a structured system description is necessary.

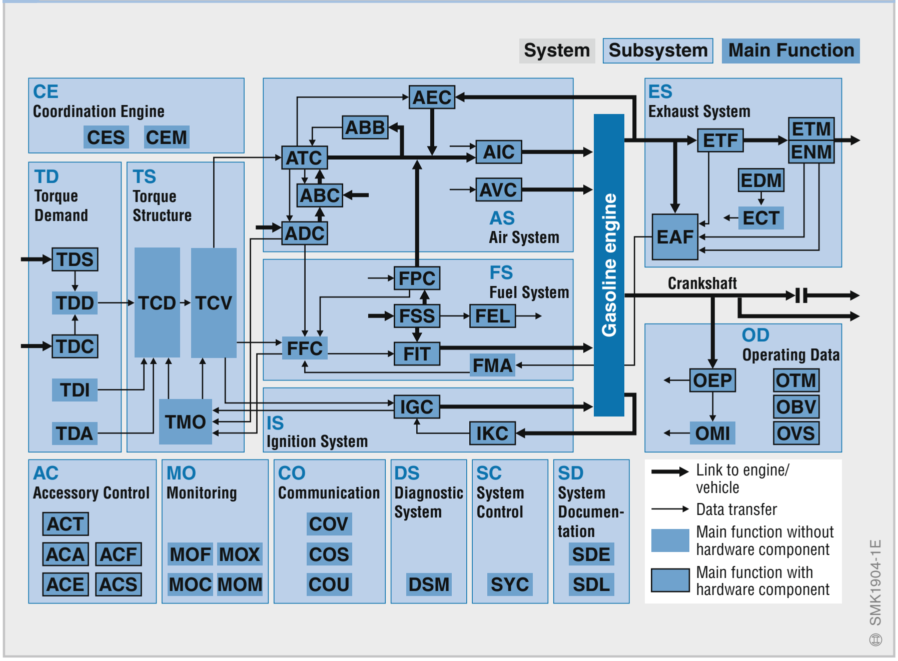
All torque demands placed on the engine are handled by Motronic as torque values and centrally coordinated. The requested torque is calculated and set by means of

- The electrically actuated throttle valve (air system)
- The ignition angle (ignition system)
- The fuel quantity in the case of gasoline direct injection (fuel system)
- The use of injection blank-outs, and
- Controlling the wastegate on exhaust-gas-turbocharged engines

Figure 9 shows the system structure used for new Motronic systems and their various subsystems.

In Figure 9, Motronic is referred to as the system. The different areas within the system are referred to as subsystems. Some subsystems are purely software constructs in the ECU (e.g., Torque Structure), while others also incorporate hardware components (e.g., Fuel System and Fuel Injectors). The various subsystems are interconnected by defined interfaces.

9 Motronic system structure



The system structure describes the Motronic engine-management system from the functional-sequence point of view. The system comprises the ECU (with hardware and software) and external components (actuators, sensors and mechanical components), which can be electrically connected to the ECU.

The system structure divides this mechatronic system hierarchically according to functional criteria into 14 subsystems (e.g., Air System, Fuel System), which in turn are subdivided into a total of 52 main functions (e.g., Boost-pressure Control, Closed-loop Lambda Control) (Fig. 9).

Since the introduction of Electronic Throttle Control (ETC) in the ME7, the torque demands on the engine have been centrally coordinated in the *Torque Demand* and *Torque Structure* subsystems. The control of cylinder charge by the electrically controlled throttle valve allows adjustment of the torque demand made by the driver via the accelerator pedal (driver command). At the same time, all other torque demands that arise from vehicle operation (e.g., when the A/C compressor is switched on) can be coordinated within the torque structure.

Subsystems and main functions

The description which follows provides a very general summary of the essential features of the main functions implemented in a Motronic system. A more detailed presentation is not possible within the scope of this publication.

System Documentation (SD)

System Documentation consists of technical documents which describe the customer project (e.g. description of ECUs, engine and vehicle data, and configuration descriptions).

System Control (SC)

The functions controlling the computer are combined in *System Control.*

The *System Control, SYC* main function defines the microcontroller states:

- Initialization (system run-up)
- Running state (normal operation) – this is the status in which the main functions are executed
- ECU run-on (e.g., for fan run-on, hardware test)

Coordination Engine (CE)

Both the engine status and the engine operating data are coordinated in *Coordination Engine.* This is done at a central point, because many further functionalities are affected in the overall engine-management, depending on this coordination.

The *Coordination Engine States, CES* main function contains both the various engine states, such as starting, running operation and switched-off engine, and coordination functions for injection activation (overrun fuel cutoff/restart) and for start/stop systems.

The operating modes for gasoline direct injection (DI-Motronic) are coordinated and changed over in the *Coordination Engine Operation, CEM* main function. In order to determine the required operating mode, the requirements for various functionalities are coordinated on the basis of defined priorities in the operating-mode coordinator.

Torque Demand (TD)

All the torque demands on the engine are consistently coordinated on the torque level in the system structure of ME-Motronic and DI-Motronic. The *Torque Demand (TD)* subsystem detects all torque demands and makes them available to the *Torque Structure (TS)* subsystem as input variables.

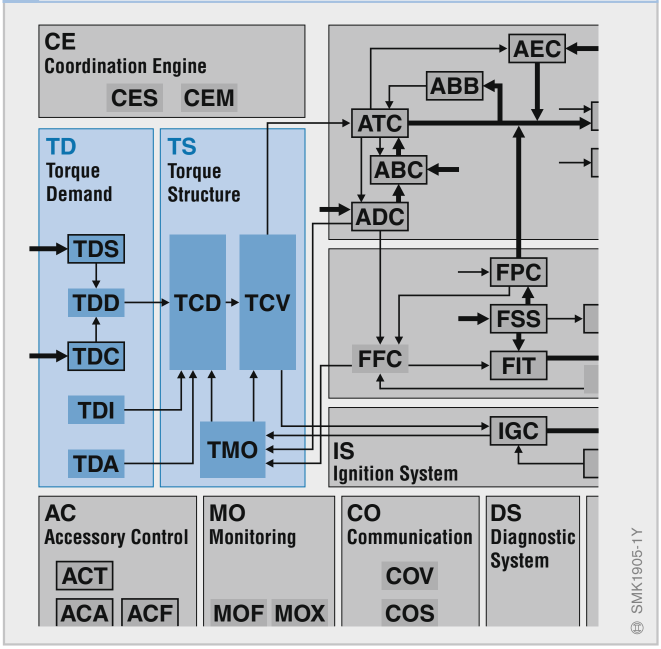
The *Torque Demand Signal Conditioning, TDS* main function essentially consists of detecting the accelerator-pedal position. The pedal position is detected by two independent angle-position sensors and converted into a standardized accelerator-pedal angle. A number of plausibility checks are carried out to ensure that, in the event of a single fault, the standardized accelerator-pedal angle cannot adopt a greater value than the actual accelerator-pedal position.

The *Torque Demand Driver, TDD* main function calculates a setpoint value for the engine torque from the accelerator-pedal position. In addition, it defines the accelerator-pedal characteristic.

Torque Demand Cruise Control, TDC (vehicle-speed controller) holds the vehicle at a constant speed as long as the accelerator pedal is not depressed, assuming this is possible with the available engine torque. The most important shutdown conditions for this function include operating the “Off” button on the driver’s control lever, operating the brakes or disengaging the clutch, and failure to reach the required minimum road speed.

Torque Demand Idle Speed Control, TDI regulates the speed of the engine at idle when the accelerator pedal is not depressed. The setpoint value for idle speed is defined to obtain even and smooth engine running at all times. Accordingly, the setpoint idle speed is set higher than the nominal idle speed under certain operating conditions

10 Excerpt from the structure diagram: *Torque Demand* and *Torque Structure* subsystems showing their main functions



(e.g., when the engine is cold). A higher idle speed may also be used to assist catalytic-converter heating, to increase the output of the A/C compressor, or if the battery charge level is low.

The *Torque Demand Auxiliary Functions, TDA* main function generates internal torque limitations and demands (e.g., engine-speed limitation, damping engine-bucking oscillations).

Torque Structure (TS)

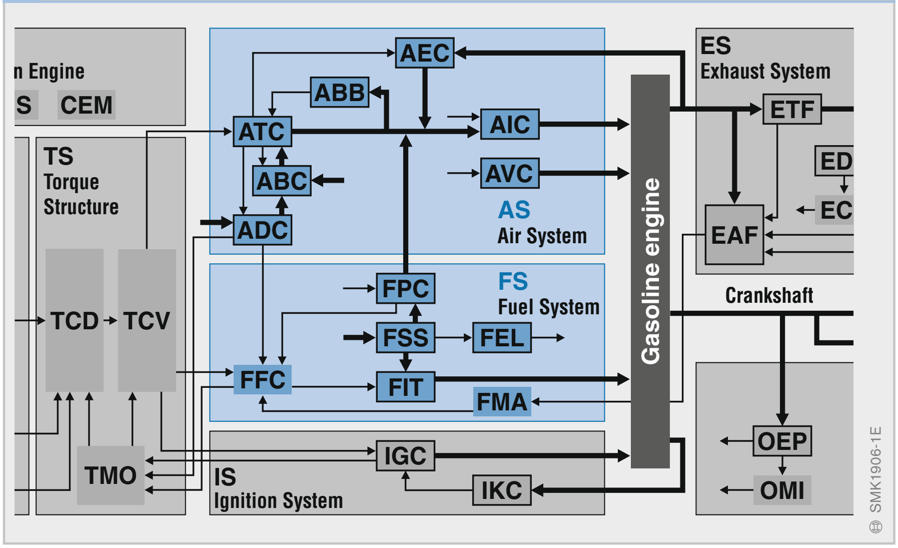
The *Torque Structure* subsystem is where all torque demands are coordinated. The required torque is then set by the air, fuel and ignition systems.

Torque Coordination, TCD coordinates all torque demands. The various demands (e.g., from the driver, engine-speed limitation) are prioritized and converted into setpoint torque values for the various control channels, depending on the current operating mode.

Torque Conversion, TCV calculates from the desired-torque input variables the setpoint values for the relative air mass, the air/fuel ratio λ, the ignition angle, and injection blank-out (e.g., for overrun fuel cutoff). The setpoint air-mass value is calculated so that the setpoint for the air mass/torque is obtained at precisely the moment when the specified oxygen content and the specified ignition timing are applied.

Torque Modeling, TMO calculates a theoretically optimum indicated engine torque from the current values for cylinder charge, oxygen content (lambda), ignition timing, reduction stage, and engine speed. An indicated actual torque is determined with the aid of an efficiency chain. The efficiency chain consists of three different efficiency levels: the blank-out efficiency (proportional to the number of firing cylinders), the ignition-timing efficiency (resulting from the shift in the actual ignition angle relative to the optimum ignition angle), and the oxygen-content efficiency (obtained from plotting the efficiency characteristic against the air/fuel ratio).

11 Excerpt from the structure diagram: *Air System* and *Fuel System* subsystems showing their main functions



Air System (AS)

The *Air System* subsystem is where the required cylinder charge for the torque to be implemented is set. In addition, the exhaust-gas recirculation, boost-pressure control, variable-tract intake-manifold geometry, charge-movement control and valve-timing functions are also part of the air system.

In *Air System Throttle Control, ATC*, the setpoint position for the throttle valve determining the air-mass flow entering the intake manifold is created from the setpoint air-mass flow.

Air System Determination of Charge, ADC determines the cylinder charge composed of fresh air and inert gas with the aid of the available load sensors. The air-mass flows are used to model the pressure conditions in the intake manifold (intake-manifold pressure model).

Air System Intake Manifold Control, AIC calculates the setpoint positions for the intake-manifold and charge-flow control valves.

The vacuum in the intake manifold allows exhaust-gas recirculation, which is calculated and adjusted in *Air System Exhaust Gas Recirculation, AEC.*

Air System Valve Control, AVC calculates the setpoint values for intake- and exhaust-valve positions and controls these settings. This influences the quantity of residual exhaust gas that is recirculated internally.

Air System Boost Control, ABC is responsible for calculating the charge-air pressure in exhaust-gas-turbocharged engines and controls the actuators for this system.

Engines with gasoline direct injection are run in stratified-charge mode with the throttle fully open at low loads. Consequently, the pressure in the intake manifold under such conditions is virtually atmospheric pressure. *Air System Brake Booster, ABB* ensures that there is sufficient vacuum in the brake booster by requesting a required amount of flow restriction.

Fuel System (FS)

The *Fuel System* (FS) subsystem calculates the output variables for the fuel-injection system relative to crankshaft position, i.e., the point(s) at which fuel is injected and the quantity of fuel injected.

Fuel System Feed Forward Control, FFC calculates the fuel mass from the setpoint cylinder charge, the setpoint oxygen content and additional corrections (e.g., transient compensation) or multiplicative corrections (e.g., corrections for engine start, warm-up and restart). Other corrections arise from the closed-loop lambda control, canister purge and mixture adaptation. In DI systems, specific values are calculated for the operating modes (e.g., fuel injection during the induction stroke or during the compression stroke, multiple injection).

Fuel System Injection Timing, FIT calculates the injection duration and the fuel-injection position. It ensures that the fuel injectors are open at the correct time relative to crankshaft rotation. The injection duration is calculated on the basis of previously calculated fuel mass and status variables (e.g., intake-manifold pressure, battery voltage, fuel-rail pressure, combustion-chamber pressure).

Fuel System Mixture Adaptation, FMA improves the pilot-control accuracy of the oxygen content by adjusting the longer-term lambda-controller errors relative to the neutral value. For smaller cylinder charges, the lambda-controller error is used to calculate an additive correction value. On systems with a hot-film air-mass meter, this normally reflects small amounts of intake-manifold leakage. On systems with an intake-manifold pressure sensor, the lambda controller corrects the pressure-sensor residual exhaust gas or offset error. For larger cylinder charges, a multiplicative correction factor is calculated. This essentially represents the hot-film air-mass meter gain error, fuel-rail pressure regulator inaccuracies (on DI systems) and fuel-injector characteristic-gradient errors.

Fuel Supply System, FSS has the function of delivering fuel from the fuel tank to the fuel rail at the required pressure and in the required quantity. In demand-controlled systems, the pressure can be regulated between 200 and 600 kPa. A pressure sensor provides feedback of the actual value.

In the case of gasoline direct injection, the fuel-supply system also includes a high-pressure circuit consisting of an HDP1-type high-pressure pump and a pressure-control valve (DSV), HDP2- and HDP5-type demand-controlled high-pressure pumps with fuel-supply control valve (MSV). This allows pressure in the high-pressure circuit to be varied between 3 and 11 MPa, depending on the engine operating point. The setpoint value is calculated depending on engine operating point and the actual pressure is detected by a high-pressure sensor.

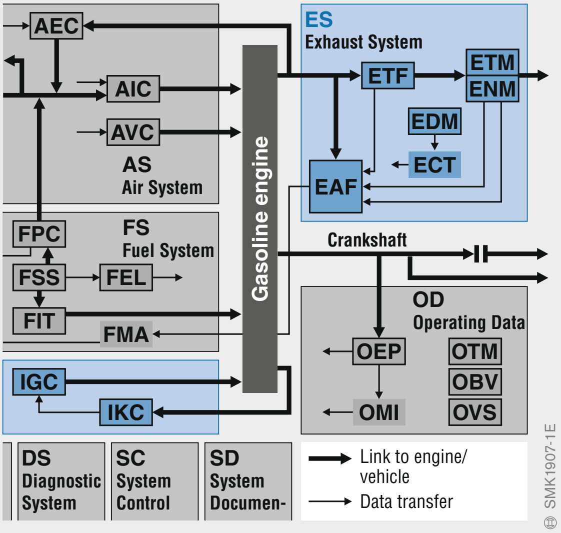
Fuel System Purge Control, FPC controls regeneration during engine operation of the fuel that evaporates from the fuel tank and that is collected in the carbon canister of the evaporative-emissions control system. On the basis of the specified on/off ratio for operating the canister-purge valve and the pressure conditions, an actual value for the total mass flow through the valve is calculated. This is taken into account by the Air System Throttle Control (ATC) function. An actual fuel-content value is also calculated and is subtracted from the setpoint fuel mass.

Fuel System Evaporation Leakage Detection, FEL checks the gas-tightness of the fuel tank in accordance with the requirements of the Californian OBD II legislation. The design and method of operation of this diagnostic system are described in the chapter headed “Diagnosis/OBD functions”.

Ignition System (IS)

The *Ignition System* subsystem calculates the output variables for ignition and actuates the ignition coils.

12 Excerpt from the structure diagram: *Ignition System* and *Exhaust System* subsystems showing their main functions



Ignition Control, IGC calculates the current setpoint ignition angle from the engine operating conditions, taking account of intervention by the torque structure. It then generates an ignition spark across the spark-plug electrodes at the required time. The resulting ignition angle is calculated from the basic ignition angle and the operating-point-dependent ignition-angle corrections and demands. When determining the engine-speed and load-dependent basic ignition angle, the effects of camshaft control, charge-flow control valve, cylinder-bank distribution, and special direct-injection operating modes are taken into account where applicable. In order to calculate the most advanced possible ignition angle, the basic ignition angle is corrected by the advance angles for engine warm-up, knock control and – where applicable – exhaust-gas recirculation. The point at which the ignition driver stage needs to be triggered is calculated from the current ignition angle and the required charge time for the ignition coil. The driver stage is activated accordingly.

Ignition System Knock Control, IKC runs the engine at the knock limit for optimum efficiency, but prevents potentially damaging engine knock. The combustion process in all cylinders is monitored by means of knock sensors. The structure-borne noise signal detected by the sensors is compared with a reference level that is obtained for individual cylinders via a low-pass filter from previous combustion strokes. The reference level therefore represents the background engine noise when the engine is running free of engine knock. The comparison analyzes how much louder current combustion is than the background level. Above a certain threshold, engine knock is assumed to occur. Both calculation of the reference level and detection of engine knock can take account of changes in operating conditions (engine speed, engine-speed dynamics, engine-load dynamics).

The knock-control function generates an ignition-timing adjustment for each individual cylinder. This is taken into account when calculating the current ignition angle (ignition retard). When engine knock is detected, this ignition-timing adjustment is increased by an applicable amount. The ignition-timing retard is then reduced in small increments if, over an applicable time period, engine knock does not occur.

If a hardware fault is detected, a safety function is activated (safety ignition-timing retard).

Exhaust System (ES)

The *Exhaust System* subsystem intervenes in the mixture-formation system, adjusts the excess-air factor, and controls the capacity utilization of the catalytic converters.

The prime functions of *Exhaust System Description and Modeling, EDM* are to model physical variables in the exhaust-gas system, analyze signals and diagnose the exhaust-gas temperature sensors (where present), and supply key exhaust-gas system data for tester output. The physical variables that are modeled are temperature (e.g., for component-protection purposes), pressure (primarily for residual-gas detection) and mass flow (for closed-loop lambda control and catalytic-converter diagnosis). In addition, the exhaust-gas excess-air factor is calculated (for NO_X accumulator-type catalytic-converter control and diagnosis).

The purpose of *Exhaust System Air Fuel Control, EAF* using the lambda sensor upstream of the front catalytic converter is to regulate the excess-air factor to a specified level. This minimizes harmful emissions, prevents engine-torque fluctuations and keeps the exhaust-gas composition on the right side of the lean-mixture limit. The input signals from the closed-loop lambda control system downstream of the main catalytic converter allows further minimization of emissions.

The *Exhaust System Three-Way Front Catalyst, ETF* main function uses the lambda sensor downstream of the front catalytic converter (if fitted). Its signal is a measure of the oxygen content in the exhaust gas and serves as the basis for reference-value regulation and catalytic-converter diagnosis. Reference-value regulation can substantially improve mixture control and permit optimum conversion response by the catalytic converter.

The *Exhaust System Three-Way Main Catalyst, ETM* main function basically operates in the same way as the ETF function described above. Reference-value regulation, however, may take different forms depending on the system. A NO_X accumulator-type catalytic converter operated at $\lambda = 1$ displays optimum conversion response with a specific oxygen-accumulator content. The reference-value regulation function sets the capacity usage to this level. Deviations are corrected by compensation components.

The function of *Exhaust System NO_X Main Catalyst, ENM* is to ensure that NO_X emission requirements in particular are complied with when the engine is running on a lean mixture by means of adapted control of the mixture to the requirements of the NO_X accumulator-type catalytic converter.

Depending on the condition of the catalytic converter, the NO_X storage phase is terminated and the engine switched over to an operating mode ($\lambda < 1$) in which the NO_X accumulator is emptied and the stored NO_X emissions converted to N_2. Regeneration of the NO_X accumulator-type catalytic converter is terminated in response to the change of signal from the sensor downstream of the NO_X accumulator-type catalytic converter. In systems with a NO_X accumulator-type catalytic converter, changeover to a special mode allows desulfurization of the catalytic converter.

Exhaust System Control of Temperature, ECT controls the temperature of the exhaust-gas system. Its aim is to speed up the time it takes the catalytic converters to reach operating temperature after the engine is started (catalytic-converter heating), prevent the catalytic converters from cooling down during operation (catalytic-converter temperature retention), heat up the NO_X accumulator-type catalytic converter for desulfurization, and prevent thermal damage to exhaust-gas system components (component protection). A torque reserve for the TS *(Torque Structure)* subsystem is determined from the heat flow required for a temperature increase. The temperature increase is then achieved by retarding the ignition, for example. When the engine is idling, the heat flow can also be increased by raising the idle speed.

Operating Data (OD)

The *Operating Data* subsystem records all important engine operating parameters, checks their plausibility and provides substitute data where required.

Operating Data Engine Position Management, OEP calculates the position of the crankshaft and the camshaft using the processed input signals from the crankshaft and camshaft sensors. It calculates the engine speed from this information. The crankshaft timing wheel (two missing teeth) and the characteristics of the camshaft signal are used to synchronize the engine and the ECU and to monitor synchonization while the engine is running.

The camshaft signal pattern and the engine shutoff position are analyzed in order to optimize the start time. This allows rapid synchronization.

Operating Data Temperature Measurement, OTM processes the temperature readings provided by the temperature sensors, performs plausibility checks on them, and provides substitute data in the event of faults. The ambient temperature and the engine-oil temperature may also be detected in addition to the temperature of the engine and the intake air. The input voltage signals are assigned to a temperature reading. This is followed by calculation of a characteristic curve.

Operating Data Battery Voltage, OBV function is responsible for providing the supply-voltage signals and performing diagnostic operations on them. The raw signal is detected at terminal 15 and, if necessary, the main relay.

Misfire Detection Irregular Running, OMI monitors the engine for ignition and combustion misses (see the chapter entitled "Diagnosis/OBD functions").

Operating Data Vehicle Speed, OVS is responsible for detecting, conditioning and diagnosing the vehicle speed signal. This variable is needed, among others, for cruise control, for speed limiting ($v_{\max}$) and in the case of the hand switch for gear recognition. Depending on the configuration, there is the option of using the variables supplied via the CAN by the instrument cluster or the ABS/ESP ECU.

Communication (CO)

The *Communication* subsystem encompasses all Motronic main functions that communicate with other systems.

Communication User Interface, COU provides the connection to diagnostic (e.g., engine analyzer) and calibration equipment. Communication takes place via the K-line, though the CAN interface can also be used for this purpose. Different communication protocols are available for various applications (e.g., KWP2000, McMess).

Communication Vehicle Interface, COV looks after communication with other ECUs, sensors and actuators.

Communication Security Access, COS provides for communication with the immobilizer and – as an option – enables access control for reprogramming the Flash-EPROM.

Accessory Control (AC)

The *Accessory Control* subsystem controls the auxiliary systems.

Accessory Control Air Condition, ACA controls operation of the A/C compressor and analyzes the signals from the pressure sensor in the air conditioner. The A/C compressor is switched on when, for example, a request is received from the driver or the A/C ECU via a switch. The A/C ECU signals to the Motronic that the A/C compressor needs to be switched on. It is switched on shortly afterwards. When the engine is idling, the engine-management system has sufficient time to develop the required torque reserves.

Various conditions can result in the air conditioner being switched off (e.g., critical pressure in the air conditioner, fault in the pressure sensor, low ambient temperature).

Accessory Control Fan Control, ACF controls the radiator fan in response to demand and detects faults in the fan and the control system. Under certain circumstances, the fan may be required to run on when the engine is not running.

Accessory Control Thermal Management, ACT regulates the engine temperature according to operating conditions. The required engine temperature is determined depending on engine power, driving speed, engine operating state, and ambient temperature. This helps the engine to reach its operating temperature more quickly and is then adequately cooled. The coolant volumetric flow through the radiator is calculated and the map-controlled thermostat is operated accordingly based on the temperature setpoint.

Accessory Control Electrical Machines, ACE is responsible for controlling the “electrical machines”, i.e. the starter motor and alternator.

The function *Accessory Control Steering, ACS* is to control the power-steering pump.

Monitoring (MO)

Function Monitoring, MOF monitors all Motronic elements that affect engine torque and speed. The core function is torque comparison. This compares the permissible torque calculated on the basis of driver request with the actual torque calculated from the engine data. If the actual torque is too large, suitable measures are initiated to ensure that a controllable status is reestablished.

Monitoring Module, MOM combines all the monitoring functions that contribute to or perform reciprocal monitoring between the function processor and the monitoring module. The function processor and the monitoring module are components of the ECU. Reciprocal monitoring between them takes place by means of continuous query-and-response communication.

Microcontroller Monitoring, MOC combines all the monitoring functions that can detect a fault or malfunction in the processor and its peripherals. Examples include:

- Analog-digital converter test
- Memory test for RAM and ROM
- Program-run monitoring
- Command test

Extended Monitoring, MOX contains functions for expanded function monitoring. These function determine the maximal torque which the engine can plausibly output.

Diagnostic System (DS)

Component and system diagnosis are performed by the main functions of the subsystems. The *Diagnostic System* (DS) is responsible for coordinating the various diagnosis results.

The function of the *Diagnostic System Manager (DSM)* is to:

- Store details of faults and associated ambient conditions
- Switch on the malfunction indicator lamp
- Establish communication with the diagnostic tester
- Coordinate execution of the various diagnostic functions (taking account of priorities and bars) and verify faults