Lambda Control and Changing Pressure Drop

When the lambda valve's duty cycle increases so that it is open longer and returning more fuel to the tank, lower-chamber pressure is reduced. The differential-pressure valve diaphragms deflect further, reducing upper-chamber pressure. This increases the pressure drop at each metering slit and more fuel flows through the slits for any given plunger lift. In short, the greater the duty cycle, the richer the mixture.

On the other hand, reduced duty cycle means less fuel bleeds off from the lower chamber; that increases chamber pressure and decreases deflection of the diaphragm. This reduces the pressure drop and fuel flow at the slits. So, less duty cycle means a leaner mixture. See Fig. 5-8.

Lambda Closed-Loop Control

The control of enrichment of the basic mixture by the lambda-control system is closed-loop, based on the signal from the lambda sensor. The control system continuously corrects the air-fuel mixture for a given plunger lift so that the mixture is held near the ideal, stoichiometric ratio necessary for catalytic converter operation.

As exhaust gas passes the lambda sensor, oxygen-content signals are sent to the lambda control unit. The control unit changes the duty cycle of the lambda-control valve to change pressure drop at the slits and adjust the mixture. The resulting change in exhaust-gas oxygen content changes the lambda-sensor signal. The control unit senses the change and continuously changes the duty cycle of the lambda valve. The cycle is continuous. See Fig. 5-9.

The oxygen content of the exhaust is continuously changing, so the lambda-control system averages to achieve the ideal mixture. It tends to correct to either side of the stoichiometric ratio, but always in a very narrow range. For more on closed-loop systems and the operation of the lambda sensor, see chapter 3.

Lambda Thermoswitch

Because lambda sensor operation depends on high temperature, the system operates open-loop before the sensor warms up. This can cause driveability problems and increased exhaust emissions due to imprecise mixture control. To correct this, many cars have a lambda thermoswitch, located in the coolant (or on the cylinder head of air-cooled Porsches) to give the control unit an additional input and insure proper fuel metering during engine warm-up.

When the engine is cold, the thermoswitch is closed. The control unit sends a fixed, slightly-rich duty-cycle signal of 60% to the lambda control valve. When the thermoswitch warms enough to open, the control unit sends a fixed middle signal, 50% duty cycle. When the lambda sensor reaches operating temperature so its signals are valid, the control unit switches to closed-loop operation. Remember, in closed-loop the duty-cycle signals are constantly changing, cycling back-and-forth between about 45% and 55%, so that the air-fuel ratio is maintained near stoichiometric; lambda (λ) = one.

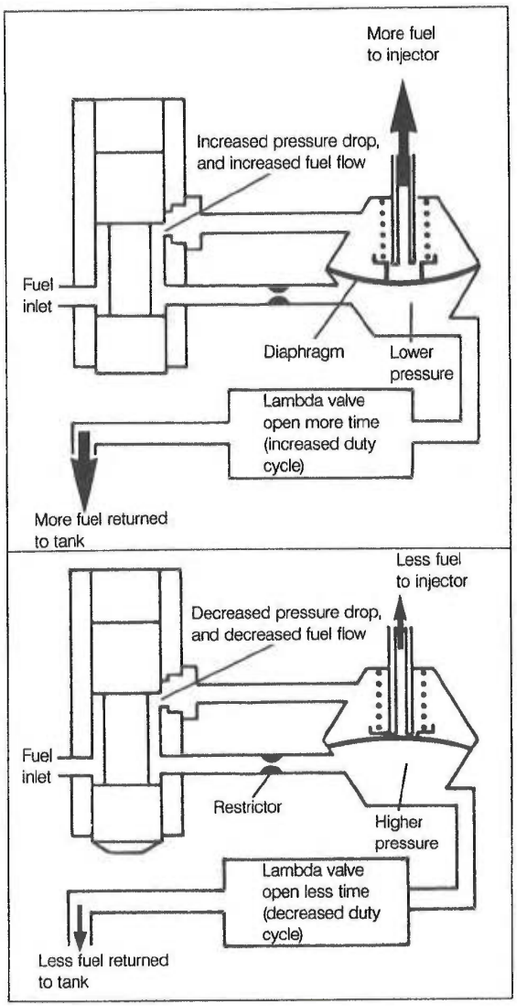


Fig. 5-8. K-lambda valve adjusts mixture by changing pressure drop at the metering slits. **Top**: More open valve returns more fuel, decreases lower and upper chamber pressure, and increases pressure drop and fuel delivery at slits, enriching the mixture. **Bottom**: Decreased opening of valve decreases fuel return, increases lower and upper chamber pressure, and decreases pressure drop and fuel delivery at slits, leaning the mixture. Note that fuel is metered at the slits, not at the diaphragm.

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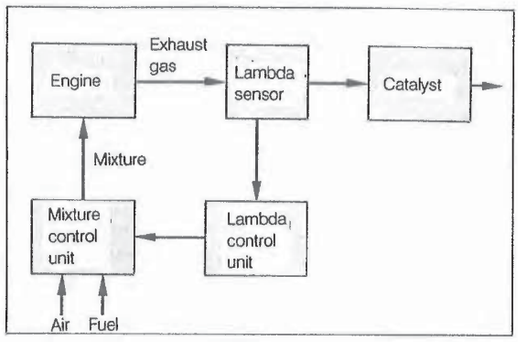


Fig. 5-9. When K-lambda operates closed-loop, the lambda sensor in the exhaust signals oxygen content to the lambda control unit. Signals to the lambda valve on the mixture-control unit change the air-fuel ratio to achieve stoichiometric mixture as burned in the engine.

5.3 KE Systems—Changing Pressure Drop

The KE control system adjusts the basic air-fuel mixture in only one way, by changing pressure drop at the control-plunger slits. KE systems do not have a control-pressure regulator or lambda-control valve. Instead, these controls are replaced by the KE control system—a series of sensors similar to those used in pulsed fuel injection, a control unit to monitor those sensors, and a pressure actuator on the fuel distributor, operated by the control unit.

For any given air flow, slit size in KE systems is governed only by the basic fuel metering—by the lift of the sensor plate. The KE control system changes pressures in the chambers of the differential-pressure valves, and therefore pressure-drop at the slits, to handle all adjustments to the basic air-fuel mixture to compensate for warm-up, emission control demands, and all other operating conditions.

On KE systems, the counterforce on the plunger that balances the air-flow force is system pressure, which is constant. So for any given air flow, plunger lift and slit size is constant. See Fig. 5-10. That's in contrast to K-basic and K-lambda, where reducing control pressure allows the plunger to rise further for a given air flow, increasing slit size to increase fuel delivery.

KE Differential-Pressure Valves and Separate Fuel Flows

In order to achieve more accurate pressure control by the KE control system, there are two fuel flow paths into the chambers of the differential-pressure valves. See Fig. 5-11. In one path, fuel enters the control-plunger barrel at system pressure. It then flows through each slit into each separate upper chamber at reduced pressure, and out to the injectors. I'll call this injector fuel. The basic rate of injector fuel flow is determined by the lift of the control plunger by the air-flow sensor, just as in the other systems.

Control Systems

In the other path, fuel at system pressure first flows to something called the pressure actuator. Fuel then flows at reduced pressure through the lower chambers and a restrictor and back to the fuel tank. I'll call this actuator fuel. The fixed restrictor controls the rate of flow out of the lower chambers. The variable pressure actuator controls the amount of fuel throughflow passing into the lower chambers, and therefore controls lower-chamber pressure and pressure drop at the slits. The operation of this control system is in addition to the basic fuel metering of the control plunger.

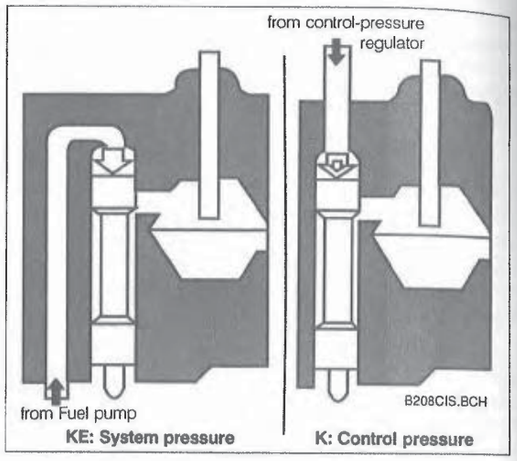


Fig. 5-10. KE meters with constant system pressure on the control plunger, so for any given air flow plunger lift is constant and slit size stays the same.

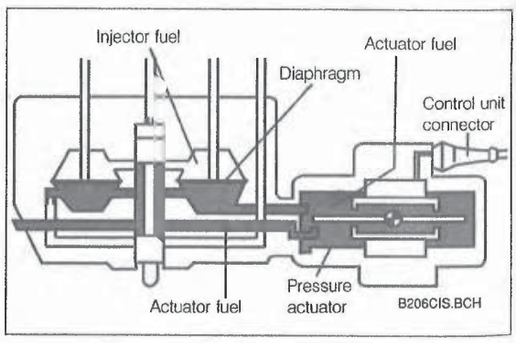


Fig. 5-11. KE injected fuel flow through each upper chamber is separated from actuator fuel flow below the diaphragm, which is spring loaded from below. KE actuator fuel flows continuously through the lower chambers. This throughflow is controlled by the pressure actuator.

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KE Differential Pressure and Pressure Drop

In KE systems, the pressure drop at the slits, and therefore adjustment of the basic fuel metering, is controlled by the pressure drop at the entrance to the pressure actuator. This is also known as the Differential Pressure, the difference between actuator fuel pressure in the lower chambers and system pressure entering the pressure actuator.

The differential pressure directly affects the deflection of the differential-pressure valve diaphragms and so controls the pressure drop at the slits. Remember, by changing the pressure drop at the metering slits of the control plunger, fuel flow is changed for a given air flow and slit size.

The differential pressure is controlled by changing the flow of actuator fuel through the lower chambers. This control of throughflow is by the pressure actuator at its inlet. See Fig. 5-12.

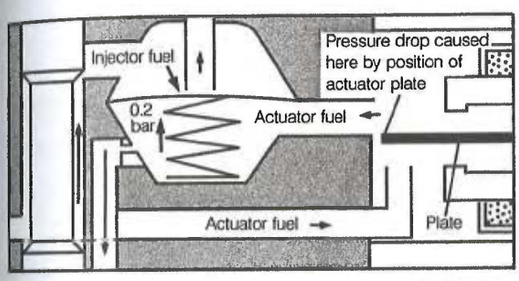


Fig. 5-12. In KE systems, pressure drop at the slits is related through the diaphragm to pressure in the lower chamber. The differential pressure – the difference between system pressure and lower-chamber pressure – determines the pressure drop. Pressure drop at the slits is differential pressure minus 0.2 bar upward spring pressure.

Pressure Actuator

The pressure actuator is part of the mixture-control unit that controls actuator fuel flow through the lower chambers. For any given air flow and its related control-plunger slit opening, the actuator compensates the mixture by changing actuator fuel flow to change the differential pressure. The actuator is shown mounted on the fuel distributor in Fig. 5-13.

The key to the operation of the pressure actuator is the small plate valve that controls fuel throughflow. See Fig. 5-14. A small electromagnet causes the plate to move closer to or farther away from the fuel inlet to the actuator. For example, fuel flows to the actuator inlet at system pressure. Increased current flow through the electromagnet increases the magnetic force and pulls the plate closer to the inlet. This reduces the flow and pressure of the actuator fuel in the lower chambers, changing the differential pressure. The actuator plate valve is controlled by the electronic control unit, as you'll see later. The valve is very small so that it can move rapidly in response to changing engine conditions.

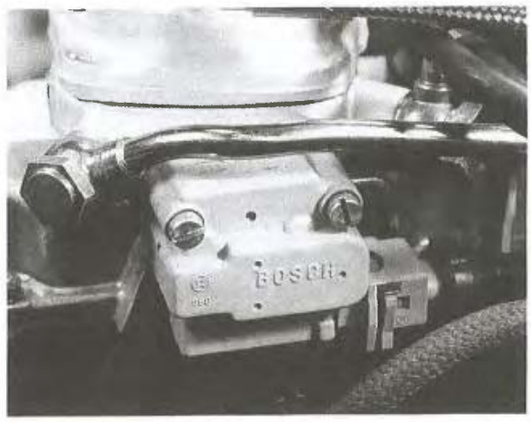


Fig. 5-13. KE pressure actuator controls mixture by controlling flow of actuator fuel through the lower chambers.

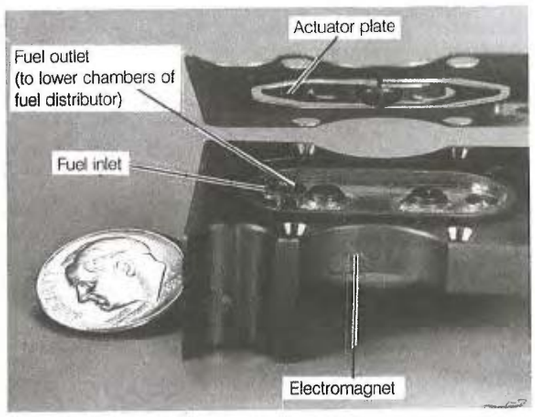


Fig. 5-14. KE pressure-actuator plate valve controls fuel flow through pressure actuator.

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Pressure Actuator and Mixture Adjustment

Fig. 5-15 shows the relationship of differential pressure and pressure drop at the metering slits and how it affects basic fuel metering. When the plate is closer to the actuator inlet it restricts the flow of actuator fuel. Differential pressure increases and the diaphragms deflect further. This increases the pressure drop at the control-plunger slits and increases the flow of injector fuel for a given plunger lift. When the plate is further away from the inlet the differential pressure is less so the diaphragms deflect less. This decreases pressure drop at the slits and reduces the flow of injector fuel for a given plunger lift.

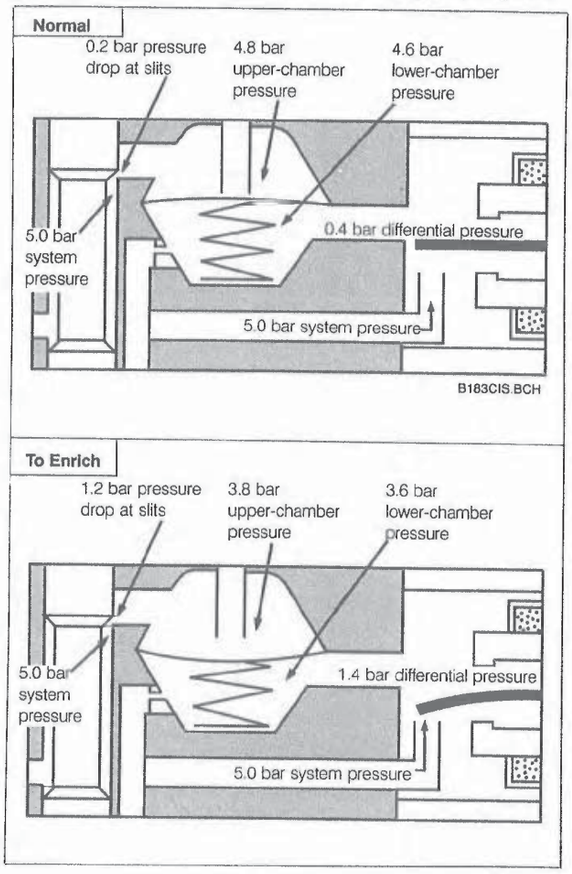


Fig. 5-15. Pressures in the KE differential-pressure valve chambers compared to differential pressure. **Top**: With little deflection of actuator plate differential pressure is low. Actuator fuel flow increases to increase upper-chamber pressure. Pressure drop at the slits drops, restricting the flow of injector fuel. **Bottom**: On the other hand, increased magnetic force increases differential pressure, increases pressure drop at slits, and increases fuel flow.

You can think of the pressure function of the actuator this way: Pressure drop at the metering slits is equal to system pressure minus upper-chamber pressure. Upper-chamber pressure is equal to system pressure plus the 0.2 bar spring pressure, minus the differential pressure. See Fig. 5-16. Remember, differential pressure is the difference between system pressure and pressure in the lower chambers controlled by the pressure actuator. As you'll see in chapter 6, you can't test differential pressure directly. You have to first measure system pressure and then subtract measured lower-chamber pressure to get the differential.

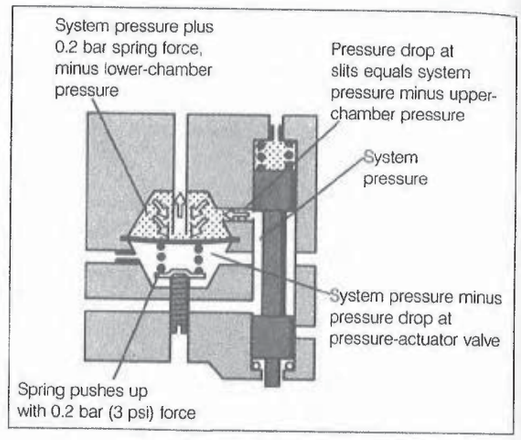


Fig. 5-16. Relationship of pressures in KE differential-pressure valves.

Control Unit and Sensors

The amount of current supplied to the pressure-actuator electromagnet for mixture control is determined by the KE control unit. To determine the correct current, the control unit depends on inputs from sensors much like those used on pulsed systems. See Fig. 5-17. These inputs include those from the ignition circuit for engine-speed, the lambda sensor, the engine-temperature sensor, the intake-air temperature sensor (on Mercedes-Benz, beginning 1986), the sensor-plate potentiometer for acceleration, and the throttle switch for closed and wide-open throttle indications. Control-unit outputs include the pressure-actuator signal and, on some models, signals to an idle-speed stabilizer.

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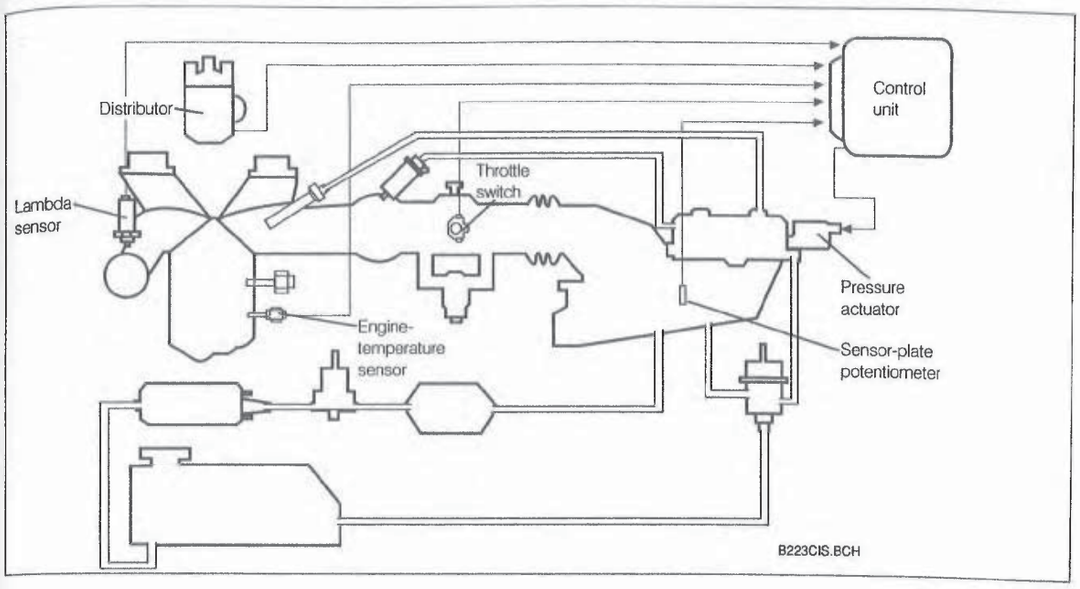


Fig. 5-17. Most KE inputs to control unit are similar to those of pulsed systems. Sensor-plate potentiometer is unique to KE, operating something like a throttle-position sensor. For more information see **6. Functions and Compensation.**

Actuator Current, Pressures, and Air-Fuel Ratios

When troubleshooting, a digital meter can be used to measure the control-unit actuator current. It's very small, measured in milliamps (mA), so be aware that small milliamp currents are affected by oxidation on connectors. The connectors must remain clean and must not be bent by probes inserted to read small currents. The following are some examples of how the control current relates to pressure-actuator mixture adjustment.

For typical warm-engine operation, current flow is about 10 mA. If you remember the discussion above, this causes a small deflection of the plate valve for a small difference between system pressure and lower-chamber pressure. The differential on a fuel gauge would be about 0.4 bar. Pressure drop and injector fuel flow at the slits is normal.

To lean the mixture, the plate is allowed to move away as the current is reduced, to perhaps only 1 mA. The differential pressure falls to only 0.2 bar, so injector fuel decreases.

To enrich the mixture, as in engine warm-up, the plate is pulled closer with more current, say 70 mA. Differential pressure increases to 1 bar, so injector fuel increases. More actuator current means more differential pressure, more deflection of the differential-pressure valve diaphragms, and more pressure drop at the metering slits, so more fuel is injected. When you've got that, you've got the basic idea of the KE-Jetronic control system's adjustment of the basic fuel mixture.

The graph shown in Fig. 5-18 looks complicated, but a moment of study will give you a good summary of actuator current as it affects the air-fuel ratio. This typical curve does not apply to any specific car.

On the baseline, read the pressure-actuator current in milliamps (mA). On the left, one vertical scale shows the pressure drop at the slit: the difference between system pressure and upper-chamber pressure. The other vertical scale shows the specified differential-pressure, the difference between system pressure and lower-chamber pressure. These numbers are 0.2 bar higher than corresponding pressure drop numbers, the result of the 0.2 bar pressure from the spring in the lower chamber.

The right column shows the corresponding air-fuel ratios. Follow the curved line to see how changing pressure-actuator current changes the air-fuel ratio.

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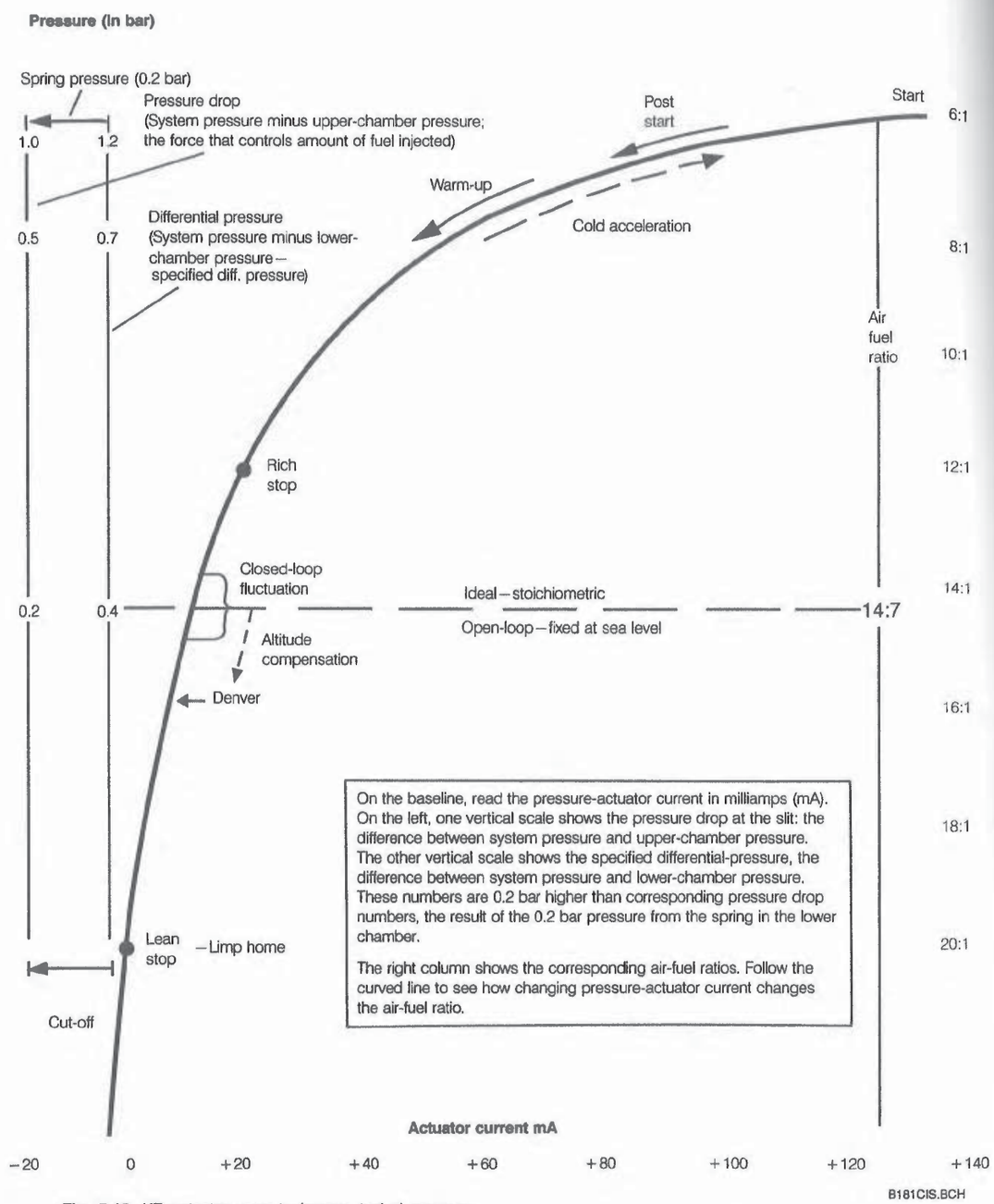


Fig. 5-18. KE actuator current changes typical pressure drop at the slits, and therefore the differential pressure (system pressure minus lower-chamber pressure) and the air-fuel ratio. Notice small closed-loop fluctuation around stoichiometric air-fuel ratio at 8–12 mA, and the limp-home setting at lean stop. These values do not apply to any specific car.

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Limp-Home Mode

The actuator plate is designed to rest at a "limp-home" position if the control-unit current is interrupted. The engine will continue to run, but slightly leaner than normal since the actuator current is not fine-tuning the mixture. In this circumstance, mixture is determined solely by the basic mechanical metering of the air-flow sensor and control plunger. The uncontrolled plate in the pressure actuator allows just enough pressure drop at the slits to keep a warm engine running. The engine may not start, but if it's running, it will get you home. You can simulate the limp-home condition on a running warm engine by disconnecting the pressure-actuator connector.

Logic Circuits

Beginning in 1986, some KE systems have logic circuits in the control unit which help it to recognize and ignore erroneous signals. The computer recognizes rapid changes in input from some sensors as improper and switches to pre-programmed outputs. For example, the coolant temperature signal does not normally change rapidly. If it does, the computer interprets this as a short or an open circuit, and switches to a predetermined value associated with a warm engine. Because this capability is so new and so vehicle-specific, refer to your car service manual for more information.

5.4 Summary of Control Systems: K-Basic, K-Lambda, KE

Now that I've discussed how the control systems of the three types of continuous fuel injection fine-tune the basic fuel metering of the air-flow sensor and control plunger, I'll summarize these systems according to the two important factors: changing control-plunger slit size for a given air flow, and changing pressure drop at the slits for a given plunger lift. In all cases, pressure drop at the slits is the difference between system pressure inside the slit and upper-chamber pressure in the differential-pressure valves.

In all three types of continuous systems, the air-flow sensor and the control plunger meter the basic amount of proportional fuel to match the air flow. The control systems then manipulate pressures in the system to adjust the basic air-fuel mixture to compensate for different operating conditions. Refer to Fig. 5-19 on the next page for comparison of the manipulation of pressures in the differential-pressure valves of the three systems. Note that the following control descriptions are not for any specific air flow or operating condition.

Table b illustrates these comparisons with numbers. The table uses the same system pressure of 5.0 bar (73 psi) for clarity, but be aware that system pressures do vary.

K-Basic

K-basic systems increase fuel delivery to enrich the mixture for a given air flow by reducing counterforce on the plunger, allowing it to rise higher. When the engine is cold, the control-pressure regulator opens more and increases return flow from the control-pressure circuit. This reduces control-pressure counterforce and the plunger rises higher for the same air-flow force. A larger portion of the plunger slit is exposed and fuel flow to the injectors increases.

Table b. CIS Upper-Chamber and Lower-Chamber Pressures

System	System pressure	Lower-chamber pressure	Upper-chamber pressure	Pressure drop at slit (system pressure minus upper-chamber pressure)	Enrichment method
K-Basic	5.0 bar (73 psi)	5.0 bar (73 psi)	4.9 bar (71.5 psi) (lower-chamber pressure minus 0.1 bar (1.5 psi) spring pressure	0.1 bar (1.5 psi)	Increase slit size (by reducing control pressure)
K-Lambda	5.0 bar (73 psi)	5.0 bar (73 psi) minus reduction caused by return of fuel at lambda valve	Lower-chamber pressure minus 0.1 bar (1.5 psi) spring pressure	Varies: 0.1 bar (1.5 psi) plus the reduction in lower-chamber pressure	Increase slit size (by control pressure), increase pressure drop (by lambda valve)
KE	5.0 bar (73 psi)	5.0 bar (73 psi) minus reduction caused by pressure actuator	5.0 bar (73 psi) plus 0.2 bar (3 psi) spring pressure, minus differential pressure (difference between system pressure and lower-chamber pressure)	Varies: differential pressure minus 0.2 bar (3 psi) lower spring force	Increase pressure drop (by pressure actuator)

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Pressure drop at the metering slits of the control plunger is a constant 0.1 bar (1.5 psi), maintained by the spring in the upper chamber pressing down on the diaphragm of the differential-pressure valve. Each flexible diaphragm of the differential-pressure valves moves with a change in fuel flow, so upper-chamber pressure is always 0.1 bar less than system pressure in the lower chamber.

K-Lambda

K-lambda systems use control pressure to change the mixture, just as in K-basic. They also have an additional control system. K-lambda changes the pressure drop at the slit by changing the lower-chamber pressure in the differential-pressure valve.

Fuel pressure in the lower chambers is controlled by the lambda control system. To enrich as a result of lean signal from the lambda sensor, the control unit increases the duty cycle of the lambda-control valve. More fuel is returned from the lambda-control circuit so lower-chamber pressure drops. Through the movement of the differential-pressure valve diaphragm, this decreases upper-chamber pressure and increases the pressure drop at the slits. More fuel flows for a given plunger lift and slit size.

With the spring in the upper chamber pressing down, each diaphragm moves so the pressure drop at the slit is always 0.1 bar (1.5 psi) less than lower-chamber pressure. Upper-chamber pressure is always 0.1 bar less than lower-chamber pressure as lower-chamber pressure varies according to action of the lambda control valve.

KE Systems

KE systems adjust the basic mixture only by changing the pressure drop at the slit. KE slit size does not vary for a given air-flow force because the counterforce on the plunger is system pressure, which is constant. The fuel flow through the lower chambers, and therefore lower-chamber pressure, is controlled by the pressure actuator. This KE control system compensates for all operating conditions, as well as maintaining a stoichiometric air-fuel ratio for emission control.

To enrich, increased current from the control unit pulls down the pressure-actuator plate valve to reduce lower-chamber pressure. This increases differential pressure—the difference between system pressure and pressure in the lower chambers. For any given air flow, this increases diaphragm deflection in the differential-pressure valves. The pressure drop at the slits increases, increasing fuel delivery to the injectors.

With a spring pushing up on each differential-pressure valve, upper-chamber pressure is 0.2 bar (3 psi) higher than lower-chamber pressure. Lower-chamber pressure is system pressure minus differential pressure. Vehicle specifications will list differential pressures for corresponding actuator currents in milliamps (mA).

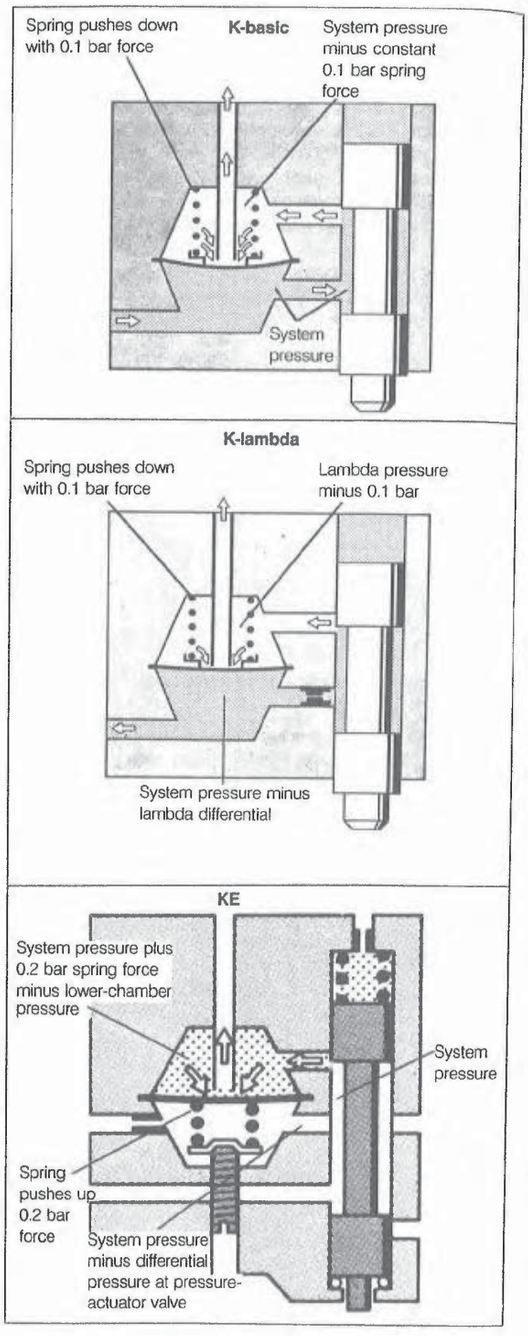


Fig. 5-19. Comparison of differential-pressure valve pressures in continuous systems. Lift of plunger by air flow determines basic fuel quantity. Control systems then manipulate pressure to change mixture. All three have system pressure inside the control-plunger slit.

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6. FUNCTIONS AND COMPENSATIONS

You've seen how each control system adjusts the basic air-fuel mixture. Now you'll see how that control is applied for all operating conditions, and you'll also see how other components add additional enrichment as necessary.

6.1 Starting

When the key is turned to start, the fuel pump is turned on through the safety circuit to build system pressure; if the engine stops turning for more than one second (as when the engine will not start) the pump shuts off, even with the ignition key on. For starting enrichment, extra fuel is delivered to the port injectors. In K-basic and K-lambda, reduced control pressure allows more plunger lift, increasing slit size to deliver more fuel. In KE systems, the control unit sends more current to the pressure actuator for start enrichment, lasting about one second. The current is high for maximum pressure drop at the metering slits, enriching the mixture delivered to the port injectors.

Cold Starting

For cold starting, in addition to enrichment at the port injectors, continuous systems enrich the mixture with a cold-start injector system, similar to that used on pulsed systems. Also, an auxiliary-air valve or idle-speed stabilizer adds air, bypassing the throttle plate to increase idle rpm. See chapter 3 for more information. Beginning about 1985, some KE systems ground the start injector through the control unit, so the thermo-time switch is eliminated.

Hot-Start Pulse Relay

Some cars—notably VWs beginning about 1985—have a special hot-start pulse relay. See Fig. 6-1. The relay bypasses the thermo-time switch and grounds the cold-start injector in short pulses when a warm engine is started, spraying fuel into the manifold. This provides additional fuel in the intake manifold to aid starting when the port injectors are delivering less fuel because of high temperatures and vapor in the lines.

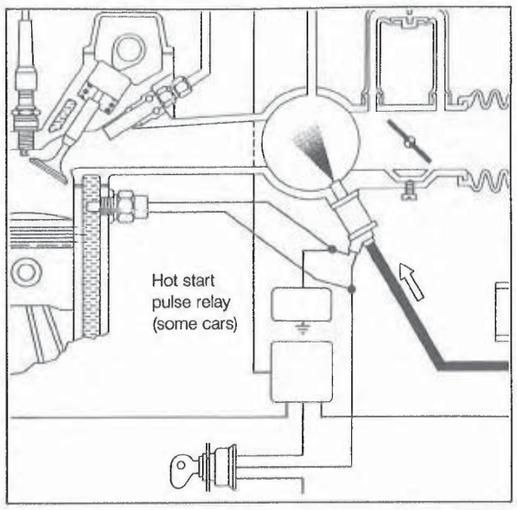


Fig. 6-1. In some VWs and Audis, hot-start pulse relay adds fuel by energizing cold-start injector during hot-engine cranking.

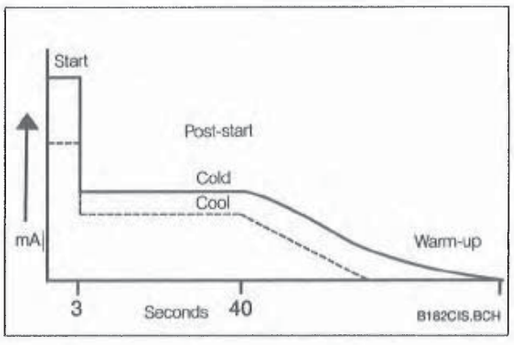


Fig. 6-2. KE enrichment at start and post-start depends on temperature. Warm-up enrichment also depends on time since starting.

6.2 Post-Start/Warm-Up

When the key is released to run, enrichment changes from engine-crank needs to engine-run needs. On K-basic and K-lambda, the control-pressure regulator warms up, gradually increasing control pressure on the plunger. This cuts back the enrichment factor in a few minutes.

KE post-start enrichment is determined by the control unit based on input from the engine temperature sensor. Increased actuator current keeps the engine running, right after starting. Then enrichment tapers off during warm-up, depending on engine temperature. See Fig. 6-2.

6.3 Acceleration

In all systems, rapid opening of the throttle increases air flow and causes the air-flow sensor plate to overreact, in a manner similar to that of pulsed systems vane-type air-flow sensor flaps. Overswing of the sensor plate allows the plunger to momentarily rise higher and enriches the mixture enough to prevent lean-mixture flat-spots and hesitation. See Fig. 6-3.

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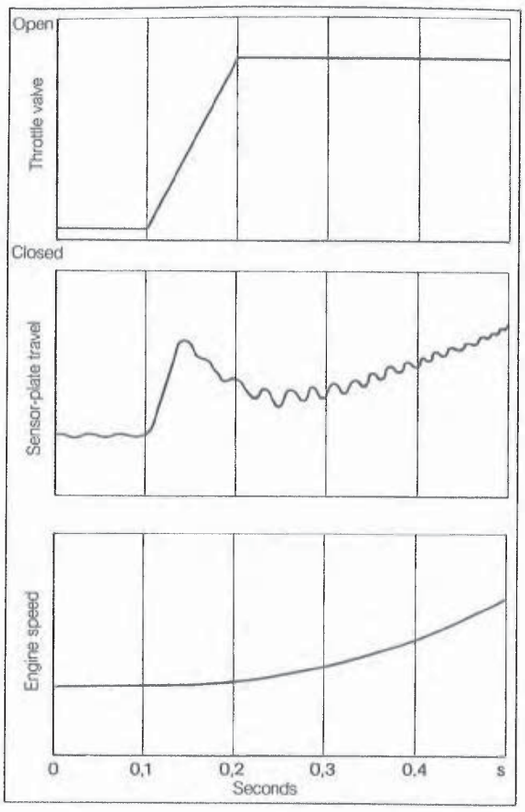


Fig. 6-3. Sudden opening of throttle causes overswing of sensor plate, adding acceleration enrichment for K-basic and K-lambda.

Part-Throttle Acceleration

In K-basic and K-lambda, cold-engine overswing is greater than that of a warm engine because reduced control pressure on the plunger allows more lift. In addition, some control-pressure regulators sense manifold pressure to further reduce control pressure and add acceleration enrichment.

KE systems use an additional sensor, the sensor-plate potentiometer (also called the air-flow sensor position indicator), to signal the need for extra enrichment during cold-engine part-throttle acceleration. The potentiometer signals how fast and how far the sensor plate moves as air flow increases. See Fig. 6-4.

The potentiometer has an arm with sliding contacts that is connected to the sensor-plate pivot. As the arm moves, it changes a voltage signal. See Fig. 6-5. From this input, the control unit sends a compensation output to the pressure actuator. For about one second, pressure-actuator current increases, depending on sensor plate movement and on engine temperature and rpm. The greatest enrichment is when the engine is cold; middle enrichment when the engine is cool; no enrichment when engine temperature is above 175°F (80°C). Mercedes-Benz has added an Intake Air Temperature Sensor to further compensate acceleration-enrichment for cold air, a refinement for better driveability.

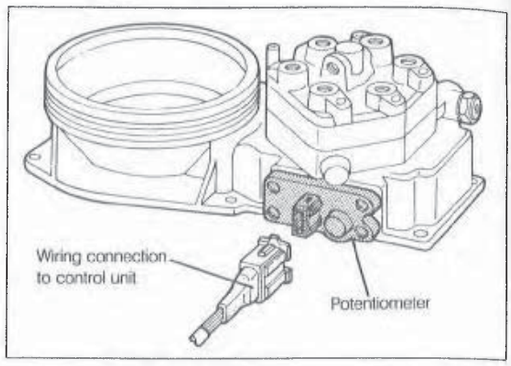


Fig. 6-4. Location of potentiometer on KE mixture-control unit.

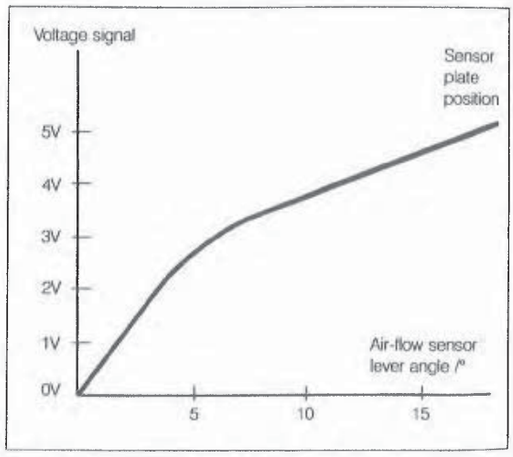


Fig. 6-5. KE adds signal from sensor-plate potentiometer to enrichment from sensor-plate overswing. The more the lever angle changes, the greater the voltage signal to the control unit.

Full-Throttle Acceleration

On K-basic and K-lambda, enrichment is supplied only on systems with control-pressure regulators linked to manifold pressure.

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KE enrichment usually continues as long as the throttle switch signals a full-load condition, adding enrichment by control of the pressure actuator. Some engines, particularly VW, need full-throttle enrichment only during limited rpm ranges, so the control unit is programmed accordingly. The control unit adds about 3 mA to the actuator current to compensate the mixture for full-load acceleration, depending on the full-load signal, on rpm and on engine temperature.

6.4 Lambda Control

K-lambda closed-loop operation is described under **5. Control Systems**. Note that closed-loop operation switches to open-loop under these conditions:

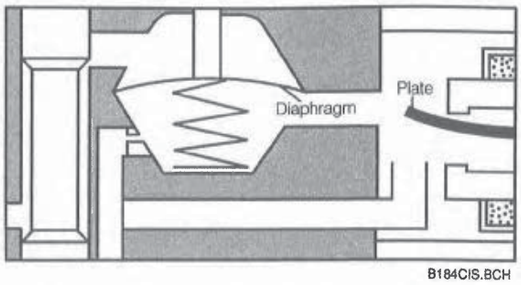
- lambda sensor cool, not ready to send valid signals
- engine cool, usually below about 105°F (40°C)
- WOT, full-load
- coasting cut-off
- acceleration enrichment (some cars)

KE systems also operate closed-loop with a lambda sensor. The lambda-sensor signals are processed with the other inputs to determine pressure-actuator current. The plate valve is always moving; either slightly toward the inlet or slightly away from it, the result of constantly changing pressure actuator current. With the engine warm, and the lambda sensor hot, look for actuator current to change back and forth in a narrow range, typically from 8 to 12 mA. This fluctuation during closed-loop operation is normal; the system is adjusting to maintain the ideal air-fuel ratio. During open-loop operation, with the lambda sensor disconnected and the engine warm, actuator current should be about in the middle of the fluctuations, according to engine specifications. When you see no change in actuator current, you know the system is running open-loop.

6.5 Cut-off

(KE only)

In KE, to cut off fuel injection, such as during coasting or for rpm limitation, actuator current is reversed to move the plate valve completely away from the inlet. With no limit to the amount of actuator fuel flowing through the lower chamber, both chambers rise to system pressure. Each spring pushes its diaphragm up, as shown in Fig. 6-6, closing the outlet and cutting off injector fuel. On some cars, such as Mercedes, rpm limitation is also handled by cutting power to the fuel-pump relay. On most cars, coasting cut-off is inhibited during cruise-control operation.



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Fig. 6-6. To cut off fuel in KE systems, pressure actuator current is reversed (to approximately −40 mA), pushing plate away from inlet. Zero differential pressure causes lower-chamber spring to raise diaphragm, shutting off fuel to injectors.

6.6. Altitude

On some K-basic and K-lambda systems, altitude compensation is built into the control-pressure regulator, as described in **5. Control Systems**.

In KE systems on higher-priced cars, an altitude sensor signals the control unit to reduce pressure-actuator current to reduce fuel delivery when the air is thinner. The decrease is about 1 mA actuator current for each thousand feet above sea level. KE-Motronic systems with adaptive air-fuel mixture control "learn" to adjust themselves and therefore need no altitude sensor.

7. KE3-JETRONIC AND KE-MOTRONIC

KE3-Jetronic and KE-Motronic systems combine the control of KE-type fuel injection with the control of ignition timing. The difference between the two systems is that KE3-Jetronic has two separate control units – one for fuel injection, one for ignition timing – and operates with standard KE-Jetronic fuel injection. KE-Motronic is a true "Motronic" system; it has both fuel injection and ignition control combined into one control unit, and has a special data-point map in the control unit that determines actuator current for all operating conditions. Ignition-timing control for both KE3-Jetronic and KE-Motronic also uses maps. For more information on timing control, Motronic systems, and control-unit maps, see the Motronic section of chapter 3.

The first application of KE3-Jetronic is on some 1987 Audi 5000s, and all 1988 5-cylinder Audis. Audi calls this system CIS-E III. The first use of KE-Motronic is on the 1988 4-cylinder Audi 80; Audi calls this system CIS-Motronic.

In the two system diagrams, shown in Fig. 7-1 and Fig. 7-2, you can see the ignition timing input (the Hall-effect sender in the ignition distributor) that makes these systems different from KE-Jetronic. The ignition outputs to the ignition coil with power stage are: 1) close-circuit to begin charging the coil and 2) open circuit to fire the spark plug.

KE3-Jetronic and KE-Motronic

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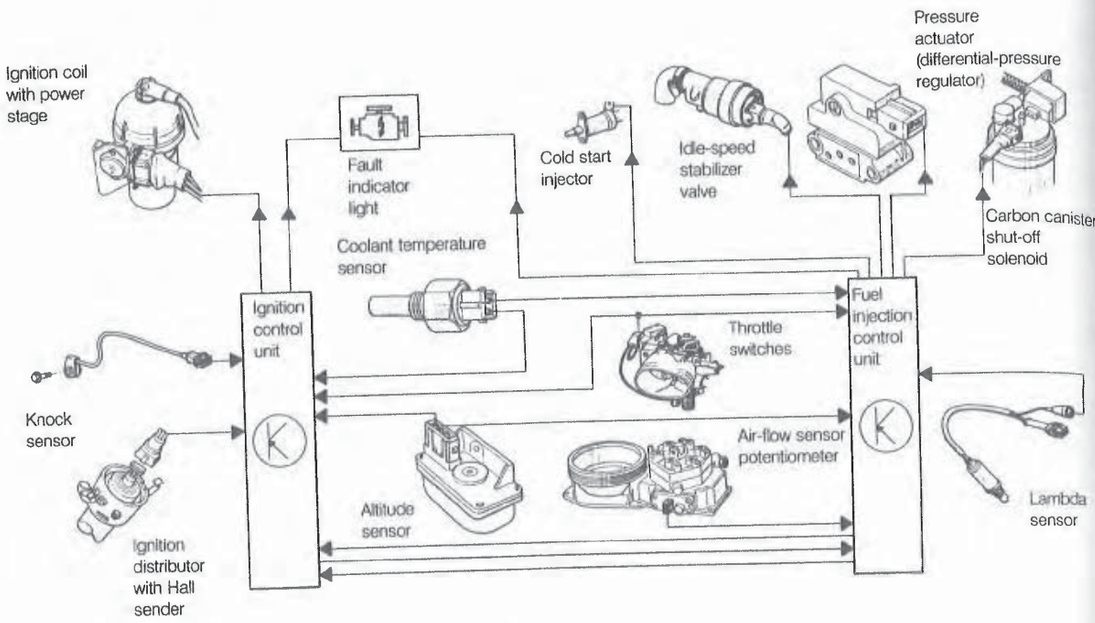


Fig. 7-1. KE3-Jetronic system used in recent Audi and Mercedes includes diagnostics, but controls fuel injection with normal Jetronic control unit. Ignition is controlled by separate control unit.

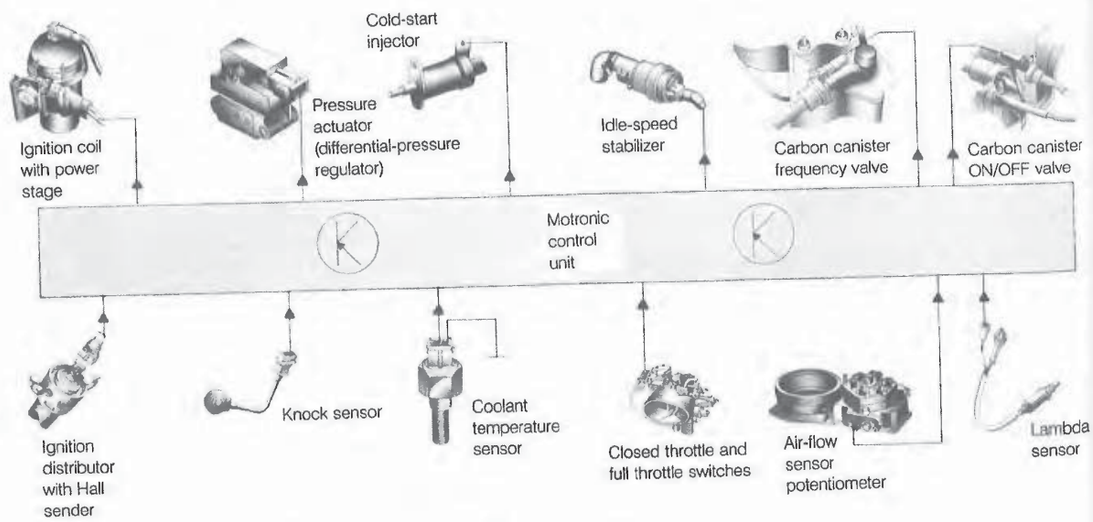


Fig. 7-2. KE-Motronic has special Motronic control unit with special internal data maps to determine operating points for actuator current and other functions. Inputs include Hall sender in distributor, and knock sensor. Outputs include ignition coil for ignition timing control.

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The other KE3-Jetronic and KE-Motronic inputs are the same as KE-Jetronic: coolant temperature sensor, closed throttle (idle) and full-throttle switches, air-sensor potentiometer, and lambda sensor. Most of these inputs are used to control ignition timing as well as fuel injection.

The outputs are also the same: pressure actuator (called a differential-pressure regulator by VW/Audi) current, and idle-speed stabilizer control. In addition, the control unit manages the vapor-canister frequency valve and the canister on-off valve; parts of the evaporative emission control system.

Actuator Current

Both systems have a different range of control-unit current for the pressure actuator. For KE3-Jetronic, a typical rich limit is +10 mA, with a lean limit of −10 mA. The nominal adjustment point is 0 mA, to provide for the widest range of adaptation.

For KE-Motronic, a typical rich limit is +23 mA, with a lean limit of −16 mA. This provides for the operation of the adaptive circuitry. The system can compensate for broader changes beyond just lambda control, including all engine operating conditions, altitude, intake leaks and other variations. A typical actuator current for a new engine running open-loop (lambda sensor disconnected) might be 2 mA. As the engine ages, perhaps with minor intake air leaks, typical open-loop actuator current might be 7 mA. See Fig. 7-3.

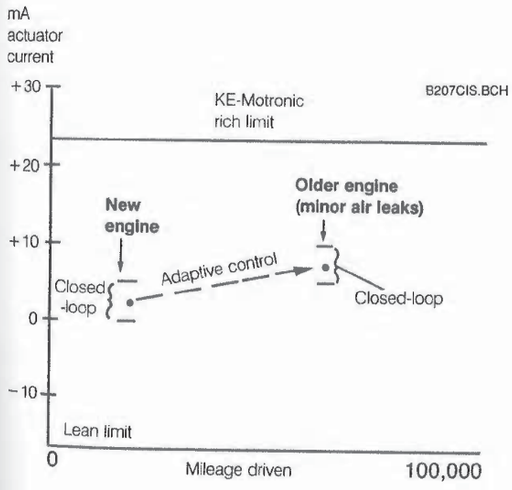


Fig. 7-3. KE-Motronic adaptive control can adjust actuator current to match changing conditions. Older engine may need greater actuator current for enrichment to counter minor air leaks.

KE-Motronic Adaptive Control

Adaptive control means that the control unit "learns" to make automatic mixture adjustment. The control-unit circuitry senses nominal warm-engine cruise values. It stores those values as the normal open-loop operation, and then uses those values as a basis for both closed-loop and open-loop actuator current. The control unit continually "relearns" the compensations necessary for changes in engine condition, or even intake air leaks.

The air-fuel ratio values are stored in the control unit's volatile memory, so they are lost any time the battery is disconnected. If the engine runs differently after service, even if that service was as seemingly unrelated as the installation of a radio or theft alarm, be ready to drive the car normally for about 10 minutes to re-store the nominal air-fuel mixture values in the volatile memory of the KE-Motronic control unit.

Fault Memory
(Diagnostic Codes)

Diagnostic codes (fault memories) are stored in the control unit. The control unit continually checks all systems for incorrect signals. If one is found, the fault is stored in the control-unit fault memory as a series of electrical pulses. On KE3-Jetronic systems you can read these fault-memory pulses at the indicator light on the dash panel as shown in Fig. 7-4. On KE-Motronic systems, you connect a test light between the battery and the test lead next to the fuel distributor on the engine. See Fig. 7-5. The fault codes are read out by inserting a spare fuse into the top of the fuel-pump relay.

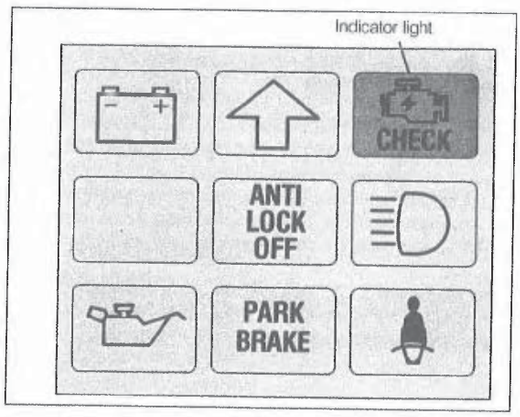


Fig. 7-4. On KE3-Jetronic, diagnostic codes from the control unit fault memory are read out at the dashboard.

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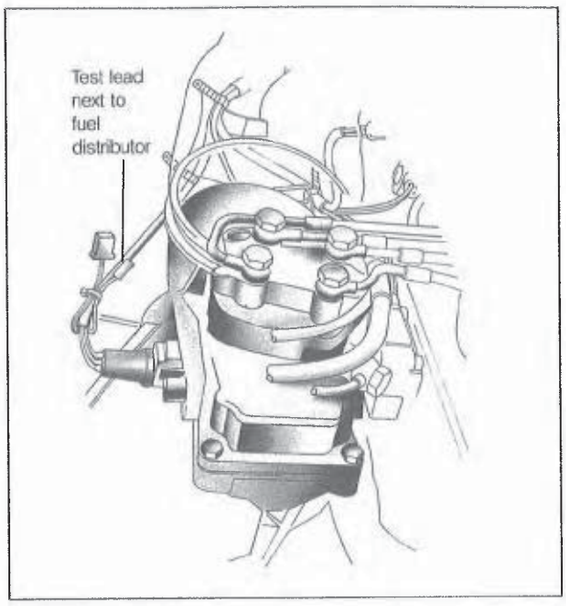


Fig. 7-5. On KE-Motronic, diagnostic read-out of fault memory is by voltage pulses at test lead near mixture-control unit.

KE3-Jetronic codes in all cars except California are erased when the ignition is turned off. Fault codes are restored by driving for 5 minutes (at at least 3,000 rpm, and once at full-throttle) or by cranking the engine for 6 seconds. If the fault is emission related, the indicator light on California cars remains on as long as the fault is present; in all other cars the code is stored, but will not come on until the fuse is inserted. When you activate the fault memory, injection faults read out first, and then ignition faults.

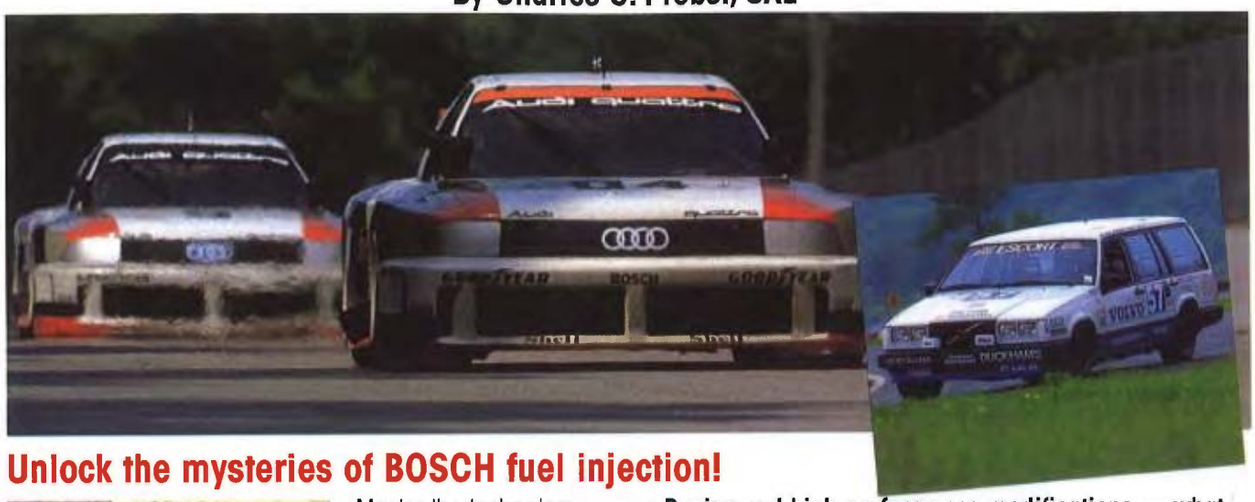
In KE-Motronic, if the fault is emission related, all cars except California will store the fault in memory until it is erased. California cars flash the fault light as long as a fault is present. This helps in finding intermittent faults. For non-emission related faults, all cars store the fault until the engine is restarted. Troubleshooting can be done before engine is shut off, or with ignition OFF. Fault codes can be restored by driving for 5 minutes (at at least 3,000 rpm, and at least once at full throttle), or by cranking for 6 seconds. For more information on the fault memory and reading trouble codes, see chapter 6.

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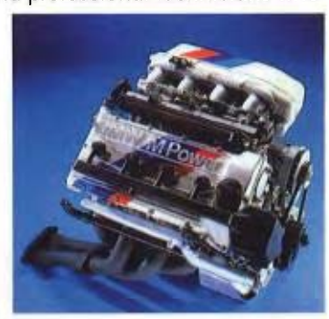


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Modeling and Control of Advanced Technology Engines

by

Anna Stefanopoulou

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Electrical Engineering:Systems)
in The University of Michigan
1996

Doctoral Committee:
Professor Jessy W. Grizzle, Co-Chair
Associate Professor James S. Freudenberg, Co-Chair
Professor Michael G. Parsons
Professor William B. Ribbens
Associate Professor Jeffrey L. Stein
Jeffrey A. Cook Principal Engineering Specialist, Ford Research Laboratory

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ABSTRACT

Modeling and Control
of Advanced Technology Engines

by
Anna Stefanopoulou

Co-Chairs: Jessy W. Grizzle and James S. Freudenberg

Over the last two decades there has been a dramatic evolution in powertrain control systems, largely driven by government regulations aimed at improving fuel economy and reducing emissions. One way to potentially meet these performance requirements is to introduce additional design parameters via innovative mechanical configurations (new actuators). The design parameters, control variables in system terminology, provide additional degrees of freedom to optimize the performance of the engine over its wide range of operation.

In this dissertation, we study control design issues for two advanced technology engines: (i) a spark-ignition (SI) engine with secondary throttles placed in the intake ports of the cylinders, and (ii) an SI engine equipped with a variable cam timing (VCT) mechanism. Both engine configurations are multivariable and nonlinear, thus imposing challenging control problems associated with control authority, long sensor delays, and strongly coupled subsystems. We develop and validate dynamic engine models, study the subsystem interactions, identify performance tradeoffs, and apply classical and modern control techniques to improve engine performance. Moreover, we study the impact of modular controller architecture on the engine dynamic response, and demonstrate that even if the controller is eventually implemented in independent software modules, coordinating the design and analysis allows for a better assessment of the tradeoffs among the dynamic performance of different subsystems. Our results demonstrate the advantages of a systematic approach to developing advanced technology powertrain control systems.

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Dedicated to George, Kaite, and Dolly.

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There were many days during the three years of my studies that I found myself working innumerous hours in the 4402 computer laboratory. This laboratory became my home, and my lab-mates Meera, Jon, Raga, Cecilia, Brian, Al, Craig, Erich, Manish, Tyrone, Steve R., Yi-Liang, and Steve H. became my family. I want to thank them for their willingness to help with any problem that arose, and I wish them the best.

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And, finally, my ultimate thanks go to my loving companion Paul, who stood by my side through all these years.

This thesis is dedicated to my father, George, who had decided that I will become an

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engineer even before I was born, to my mother, Kaite, who encouraged all my ambitions, and to my sister, Dolly, who always argued that engineering is a world bleak and monochrome, and filled me with stories of magic, adventure and mystery.

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CHAPTER 1

Introduction.

1.1 Background on Advanced Technology Engines.

Over the last two decades there has been a dramatic evolution in powertrain control systems, largely driven by government regulations : (i) stringent Federal and California emissions standards, (ii) increased fuel economy to comply with mandated Corporate Average Fuel Economy (CAFE), and (iii) minimum safety and reliability standards that are independent of age, environment, and varying fuel properties. These requirements create challenging control problems for two reasons:

- It is increasingly important to achieve control over transient behavior and meet performance objectives over the life of the vehicle. This requires the development of high performance and robust powertrain controllers.
- The performance objectives are often conflicting, or at best interrelated. One way to potentially meet these requirements is to introduce additional design parameters via innovative mechanical configurations (new actuators). The design parameters, control variables in system terminology, provide additional degrees of freedom to optimize the performance of the engine over its wide range of operation. The continuously variable transmission is an example of a recently implemented actuator that affects overall powertrain performance. Other actuators currently under consideration are electronic throttle, variable cam timing, camless valves, and direct injectors.

Historically, new actuators (exhaust gas recirculation valve, air bypass valve, fuel injectors) and sensors (exhaust gas oxygen sensor, mass air flow meter) have been introduced each time designers needed to meet additional engine performance requirements [15]. Performance standards and convenience pressed for the development of spark timing control. This additional control was used to advance or retard spark timing resulting in improved fuel economy and power. During the Eisenhower administration, federal emission legislation required emission control. This was accomplished by positive crankcase ventilation systems (PCV) used to minimize emissions from the crankcase, and secondary air systems used to oxidize hydrocarbons (HC) in feedgas emissions. Stricter emissions standards were met by

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introducing external exhaust gas recirculation (EGR) to reduce oxides of nitrogen (NO_x) formation in feedgas emissions. Mandates in fuel economy led to the development of the idle speed regulation by the introduction of the air bypass valve. Development of the catalytic converter allowed further emission reduction, but required precise air-fuel ratio control, which was accomplished with the introduction of the exhaust gas oxygen sensor, and fuel injectors. The development and implementation of the corresponding control strategies were based on the relative independence of the different subsystems at low frequencies. Individual feedback loops were wrapped around sensors and actuators available for each subsystem (multiple single-input single output, SISO approach). In advanced technology automotive engines, the coupling between subsystems is strong, and imposes performance tradeoffs. Without knowledge of this interaction the powertrain control problem involves an extensive scheduling effort to define the new optimum operating points, and requires a laborious tuning process to calibrate the subsystem controllers to avoid unintentional excitations. Good control design in advanced technology automotive engines requires informed decisions of the performance tradeoffs early in the design process, and it is one of the subjects addressed by this dissertation.

In this dissertation we show that control design in advanced technology automotive engines necessitates a systematic modern control theoretical approach. In advanced technology automotive engines, the multiple SISO approach (decentralized controller architecture) reaches its limitations. In the following chapters we present a feasibility analysis of the engine control system for two innovative mechanical configurations of the spark ignition (SI) engine : (i) an SI engine equipped with secondary throttles placed in the intake ports of the cylinders, and (ii) an SI engine equipped with a variable cam timing (VCT) mechanism. Both mechanical designs affect the breathing process of the engine and are introduced to reduce emissions, increase fuel economy, and maintain drivability during rapid changes in the throttle position imposed by the driver (acceleration/ deceleration). Both actuators can be viewed as special cases of camless engine; the functionality of the secondary throttles is similar to the variable intake valve timing and lift, and the variable cam timing engine addresses the case of a variable intake and exhaust valve timing with fixed valve overlap. This study is an assessment of the achieved performance when compared to conventional engines, and an investigation of the effects of the new technology on the implementation of the complete powertrain control strategy. This work is based on the systematic approach of (i) deriving or identifying the dynamic model for the advanced technology engine design, (ii) validating the model using engine-dynamometer experimental data, (iii) studying the subsystem interconnections and making decisions on the performance tradeoffs in transient and steady-state engine operation, (iv) designing a controller that achieves a reasonable tradeoff in the performance requirements, and (v) investigating the controller complexity and the associated engine performance.

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1.2 Engine Control.

Engine performance is primarily characterized by emission production, fuel efficiency and drivability. These in turn are affected by four fundamental engine variables: air charge, air-fuel ratio (A/F), exhaust gas recirculation (EGR) and spark timing. Automatic control of these variables has improved engine performance allowing optimum operation independent of aging, history, or environment [66], and has increased the convenience and safety level of the modern automobile [15]. A key contributor to the accomplishments in the area of engine control has been the availability of accurate and simple (control oriented) engine models. In the early 70's, control applications in the automotive industry paralleled achievements in engine and powertrain modeling. In this dissertation we model two innovative mechanical configurations of the SI engine, and use them for the analysis and synthesis of A/F and EGR controllers to achieve engine performance requirements. To serve as an introduction to this work, we review the most significant engine modeling efforts, and provide a brief description of the A/F and EGR control tasks and existing control designs.

1.2.1 Engine Modeling.

In this section we discuss the accomplishments in the area of engine modeling and its contributions to the analysis and development of engine control. The evolution of the engine models has three significant phases: (i) thermodynamic models, (ii) input-output models, specific to each application or engine configuration, and (iii) nonlinear models, physically based (generalized) for wide range of operation.

In the first of these phases, detailed thermodynamic methods were employed to understand the exact phenomena, to identify the variables that govern them, and ultimately to represent them with compact mathematical equations [3]. Numerical simulations allowed the designers to gain understanding of the engine behavior by performing numerical experiments, and testing the engine performance. The first non-thermodynamic models can be found in [32, 33, 34], where the authors developed crankangle event based models for compression ignition engine to perform stability analysis studies. Nonlinear dynamical models for SI engines have been developed in [65, 66], where spark, A/F, and EGR were optimized to minimize emissions while maintaining fuel economy. In these articles, the authors used control theoretical techniques to achieve performance improvements. Modern control methods were applied to linear engine models in [7] demonstrating the capabilities of control theoretical approaches in automotive applications. The need for precise transient A/F control emerged from the increasingly demanding emission requirements. Unknown fuel dynamics often misled control engineers to over-compensate for lean or rich A/F responses, so identification of fuel puddling and wall-wetting became a pressing problem. The first efforts led to the derivation of an input-output model of the fuel dynamics [75], and later to a more detailed characterization of transient A/F response [85, 1].

In the early 80's nonlinear dynamic models with wide range of operation (covering most

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urban driving cycles) were developed [18, 17, 86, 58]. The work in [17] provides the most comprehensive model including actuator and sensors, and [86] incorporates exhaust emission and rotational dynamics. The effort in engine modeling has been expanded to include transmission and driveline characterization [60, 11]. In [13] the authors derive linearized models and study an important issue of engine control, namely, how multi-rate sampling affects engine control design. By the end of the 80's control engineers had developed a significant number of engine models, and a comprehensive list of them and discussion of their development can be found in [60] and in [62].

Currently, stringent requirements on emission, fuel economy, and safety require high performance and robust controllers. Complete, but generic, powertrain models are developed in [11, 23, 16, 35, 52], and are combined with modern control techniques in [10, 12, 76] to satisfy these requirements. Meeting the new performance requirements often requires accurate information and characterization of complicated phenomena [48], which is facilitated by the increased computational power in on-board control systems. In [61] the author addresses the challenging problem of reducing the development time needed to obtain accurate models, and provides a systematic approach to powertrain modeling and control effort.

1.2.2 Air-Fuel Ratio Control.

Vehicle feedgas emissions consist of carbon monoxides (CO), hydrocarbons (HC), and oxides of nitrogen (NO_x). In the early 1970s, three-way catalytic (TWC) converters were introduced to oxidize (HC and CO) and reduce (NO_x) pollutant species in the exhaust gases. The efficiency with which the undesirable exhaust gases are reduced to acceptable levels, or are converted to desirable gases, is a function of A/F. The sensitivity of the catalytic converter efficiency to A/F is shown in Figure 1.1. In this figure it can be seen that there is a very narrow range of A/F where high conversion efficiency for the primary three pollutants is attained. The A/F value were the highest efficiency is attained is the stoichiometric value (for standard fuels, $A/F = 14.64$). Due to this sensitivity, A/F control is an important task in controlling vehicle tailpipe emissions. In the 70's, A/F was based on regulation of fuel flow into the cylinders via carburaters [73], and later, with fuel injectors [69, 88]. After the development of the exhaust gas oxygen (EGO) sensor, electronic feedback fuel control was possible. Electronic feedback fuel control has since been used to keep A/F close to the stoichiometric value based on the A/F signal at the EGO sensor. Achieving precise A/F in both steady-state and transient engine operations is a challenging problem due to unpredictable inputs of the driver, the switching type EGO sensor, transport delays that limit accurate response during transients and the combined dynamics of the hot-wire anemometer used for the mass air flow sensing, the throttle body, the intake manifold, and fuel puddling dynamics.

For this reason, many studies have been conducted on A/F feedback control. These studies may be divided into two categories, the first of which addresses the scarcity and

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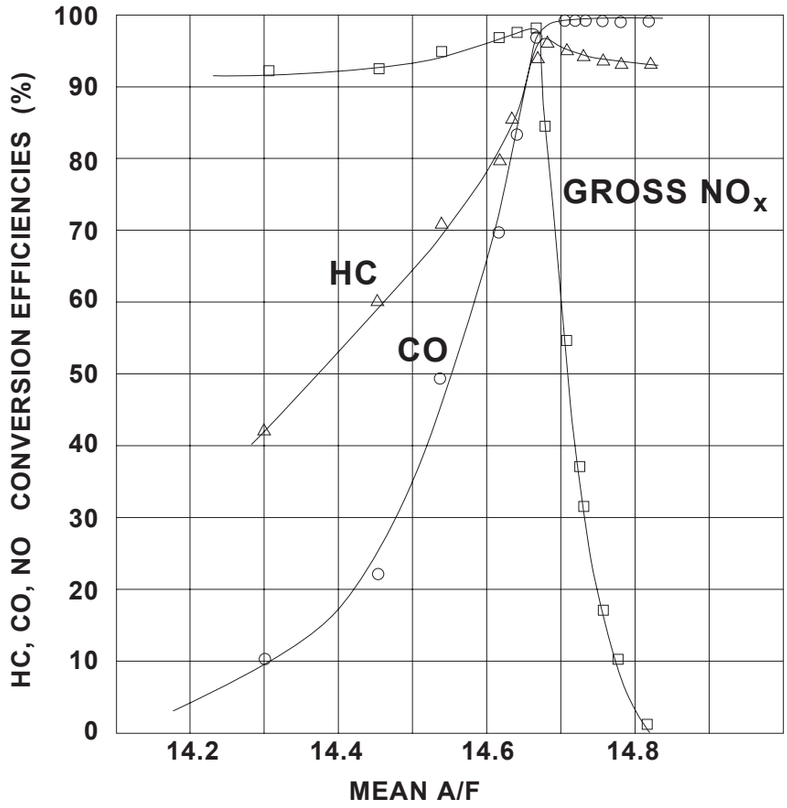


Figure 1.1: Typical three-way catalytic converter efficiency curves

nonlinearity of the conventional sensors. The emphasis in these studies is on the reconstruction of signals available for feedback, and the accurate and robust knowledge of the system states. The second category of studies addresses new engine configurations, i.e., modification of combustion parameters [3], and introduction of new actuators [8, 5] and sensors [64]. The new parameters in these engine configurations can improve A/F, but they often affect other engine variables. In this category of A/F control problems, the control designer has to identify and account for these interactions in order to meet the overall engine performance requirements. The work in this dissertation lies in the second category of A/F control studies. We control A/F for two different engine configurations after the introduction of new actuators. In the first problem, A/F excursions are minimized by the implementation of secondary throttles used to control air flow into the cylinders. The presence of the secondary throttles however can adversely affect drivability by making the engine seem sluggish. In the second problem, VCT is used to reduce feedgas emissions. This new control variable may cause disturbances in the A/F response of the engine. Both of these actuator configurations impose challenging multivariable problems that must be addressed by the control designer.

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Previous work on the first category of A/F control studies consists of proportional-integral control and classical pole placement techniques, both in the discrete and continuous time domains [59, 46]. Furthermore, nonlinear analysis using describing functions has been used to study limit cycle behavior of the A/F response due to the switching type EGO sensor [63]. Multi-variable control with observers [57, 36] has been suggested as solutions to the problem of high performance and robust A/F control. Nonlinear sliding mode fuel injection controllers have been developed and tested in [10, 12, 54] providing an elegant alternative to the traditional gain scheduling of linear controllers, and show promising results even when using a switching EGO sensor. Individual A/F cylinder control using a single EGO sensor based on multi-rate sampling and periodic control techniques have given an answer to the alleviation of air charge maldistribution problems [28]. In related work, estimation of the air charge maldistribution in the cylinders is used in [47] along with a novel nonlinear observer technique. Use of nonlinear estimation also occurs in [36], were an extended Kalman filter is used for compensating the dynamics of fuel puddling. Adaptive compensation for the fuel dynamics has been successfully employed in [49] and [82]. In both studies the objective is the reconstruction of the A/F signal using a switching EGO sensor based on a fuzzy logic algorithm in [49], and a model-based approach in [82]. On-line identification techniques of the model used in [81, 39, 71] give promising results. In [71] the authors use a neural network that deals effectively with the long delay in the A/F process. On-line identification, observer design, and robust nonlinear control design techniques are areas of great importance to transient A/F control.

The second category of A/F control studies includes primarily engine control based on in-cylinder pressure measurements [64], and an electronically throttled engine [8, 39, 5]. The development of the electronic throttle control (ETC) or drive-by-wire (DBW) throttle system is an important research tool that provides a way of regulating the changes in air flow into the manifold caused by the primary throttle movement. These schemes show very good results in regulating A/F, and reducing emissions. In Chapter 2 we use this idea, and introduce secondary throttles in the inlet runners to allow coordination of air flow and fuel flow to achieve good A/F response during transients. The A/F performance improvement is shown to be achieved without slowing the engine torque response, and thus no tradeoff is made with drivability.

1.2.3 Exhaust Gas Recirculation.

Exhaust gas recirculation (EGR) was introduced in the early 1970s to suppress the formation of oxides of nitrogen (NO_x). The inert exhaust gases dilute the inducted air-fuel charge and lower the combustion temperature which reduces NO_x feedgas emissions.

Conventionally, exhaust gas recirculation is accomplished by controlling the exhaust gas that is supplied from the exhaust manifold to the intake manifold through a vacuum actuated valve. The EGR control algorithm is a simple PI or PID loop that adjusts the

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amount of exhaust gas to the scheduled steady-state point which is a function of engine speed, coolant temperature and engine load (or another load related variable). EGR alters the breathing process dynamics and consequently the torque response. Careful steady-state and transient control design is necessary to maintain good engine torque response, and for this reason, EGR is typically turned off in transient engine operations, engine warm-up, and idling.

An innovative mechanical design approach to controlling EGR is the development of the variable cam timing (VCT) mechanism. By retarding the cam timing, combustion products which would otherwise be expelled during the exhaust stroke are retained in the cylinder during the subsequent intake stroke. This is a method of phasing the camshaft to control residual dilution and achieve the same results with the conventional external EGR system, thus providing an innovative solution to an old problem. The development of the VCT engine model and controller is addressed in Chapter 3 (engine model), Chapter 4 (control design), and Chapter 5 (implementation issues). With this work we show that dynamic VCT control is feasible.

1.3 Dynamic Interactions and Performance Tradeoffs.

To meet their stringent performance requirements, automotive engines have to be operated efficiently during both steady-state and transient operations. Past and current practice has been to optimize the additional design parameters that new actuators introduce only in steady-state using static engine mapping. The optimum operating points are defined by overlaying static maps of components that have to cooperate. Performance compromises in steady-state are alleviated with the introduction of feedforward terms that allow more freedom in achieving the design goals. However, the new Federal Test Procedure (FTP) for driving cycles consists of transient and high speed maneuvers, where the dynamic engine response is as important as the static engine behavior. These performance requirements press automotive engine designers to consider interactions between different processes at higher frequencies. Furthermore, the new actuators in the advanced technology automotive engines affect several subsystems, and cause severe performance tradeoffs. In this dissertation we show that the interaction between subsystems is a decisive factor in the control design of these highly multivariable engines. In the following chapters we identify the interactions that the secondary throttles and variable cam timing actuators introduce to the engine. These interactions are manifested through performance tradeoffs that the control engineer has to account for early in the design process. Briefly stated, *the secondary throttles and variable cam timing alter the engine breathing process which in turn affects fuel economy, emissions, and engine torque response over a wide range of operating conditions.* In designing controllers, we shall encounter three fundamental performance tradeoffs which are inherent to the advanced technology automotive engines.

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(i) Fuel economy and emissions.
An approach for increasing fuel economy is to reduce energy losses. Engine operation (maintaining the same load) in high manifold pressure reduces the intake stroke pumping work required from the cylinders. High manifold pressure is associated with faster manifold filling dynamics, and therefore, changes in the throttle position are followed by rapid changes in the air charge. These changes introduce high bandwidth disturbances to the A/F response. Unless A/F control can successfully reject these disturbances, fuel economy (the initial design goal) will be followed by emission degradation.

(ii)NO_x feedgas emissions and catalytic converter efficiency.
Exhaust gas recirculation, used to suppress NO_x formation, alters the engine volumetric efficiency, and changes the breathing process dynamics. Exhaust gas recirculation and mass air flow into the cylinders are interconnected over a wide range of frequencies. High bandwidth control of feedgas NO_x rapidly alters the air charge and causes A/F excursions. In these cases, reduction in feedgas emissions is associated with reduction of the catalytic converter efficiency and may cause an increase in tail pipe emissions.

(iii) NO_x feedgas emissions and engine torque response.
NO_x feedgas reduction using exhaust gas recirculation affects the engine breathing process. Exhaust gas recirculation affects adversely the air charge and the mixture formation which is crucial to good engine torque response. The EGR control design must address the affects of the mixture dilution to the engine torque response both in steady-state and transient operations. Moreover, an open loop design is necessary since the conventional automobile is not equipped with an on-line torque sensor.

1.4 Overview.

Chapter 2 addresses the problem of controlling an engine equipped with secondary throttles. The new control variables affect the nonlinear breathing process and are introduced to allow joint management of air and fuel flow into the cylinders. A nonlinear feedforward map is developed as a solution to a control authority problem inherent to the two distinct operating regimes of the breathing process. A linear multivariable feedback is designed to limit air fuel excursions and track a torque command during transient operations. This novel approach provides an alternative to current drive-by-wire schemes and possesses major advantages for enhancing the safety level of the modern automobile.

Another innovative engine design is the variable cam timing engine. The effects of cam timing and secondary throttles in the breathing process are similar. The understanding gained from the control problem in Chapter 2 is applied to the modeling of the VCT engine. A mathematical representation for the variable cam timing engine is identified in Chapter 3. The variable cam timing engine allows the joint management of fuel flow and internal exhaust gas recirculation to minimize exhaust emissions, increase fuel economy and satisfy drivers' performance requirements over a wide range of operating conditions. The

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mathematical representation is formulated by physically based differential equations; all parameters and key nonlinearities used are determined from regressed engine data. The models are experimentally validated by engine dynamometer testing.

In Chapter 4, a control scheme is developed to minimize feedgas NO_x and HC emissions and to maintain air fuel ratio at stoichiometry, while providing satisfactory torque response during rapid changes in throttle position. Control of the VCT engine is a challenging problem due to the strong interconnections between the cam phasing and A/F loop, and sensor limitations. Consequently we design a multivariable and a decentralized controller, and analyze how the multivariable controller achieves better performance than the decentralized controller. The impact of the control architecture (multivariable vs. decentralized) upon the dynamic response of the VCT engine is analyzed in Chapter 5. Finally, in Chapter 6 we summarize the results of this dissertation and discuss directions for future research.

1.5 Contributions of this Dissertation

The contributions of this dissertation are :

- An existing nonlinear dynamical engine model by Crossley and Cook [16] was modified to include the effects of secondary throttles placed before the intake ports of the cylinders on the performance of the SI engine. The model, based on physical engine characteristics, is a powerful tool in studying the effects of innovative actuation that can affect the breathing process of the SI engine.

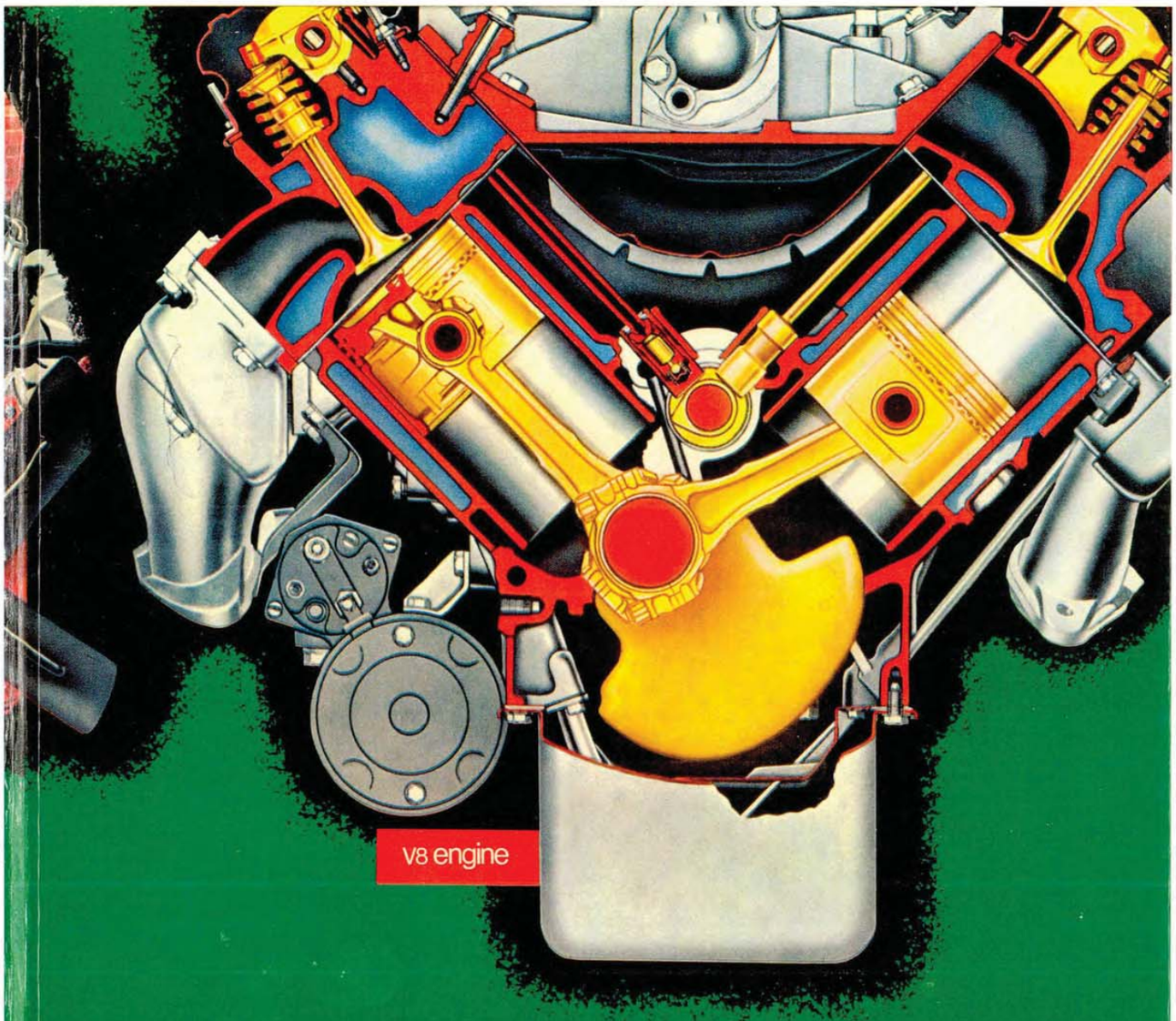
- Identification of different control authority regions for regulating the steady-state air flow into the cylinders. This result, although well known in the thermodynamic community [37], has not been acknowledged by control engineers. Our ability to affect (or not affect) the air flow into the cylinders is an important consideration in engine control, because the air flow into the cylinders is a variable that affects the overall engine performance in the following manner: (i) drivability, by altering the air charge, (ii) fuel economy, by changing the pumping losses during the intake event, and (iii) emissions, by causing A/F excursions.

- Derivation of a new control-oriented engine model that represents an SI engine equipped with a variable cam timing mechanism over a wide range of operating conditions. The model includes the breathing process, torque and emission generation, and sensor/actuator dynamics. Based upon extensive laboratory measurements, a phenomenological engine model structure was elucidated. With respect to the basic model of [16], the VCT mechanism alters the mass air flow into the cylinders, the self-EGR, the torque response, and the emissions of the engine. The developed model reflects all these innovations. It has been validated with engine-dynamometer experimental data and used in the design and development of the VCT engine controller.

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- A rigorous analysis of the consequences of the multivariable versus decentralized controller architecture on the dynamic response of the VCT engine. A multivariable and a decentralized controller were designed, and it was demonstrated that the multivariable controller can manage the performance tradeoffs better than the decentralized controller. Moreover, the multivariable controller structure was simplified, without detrimental consequences in the system dynamic response, providing a paradigm of how a control designer may carry out her/his task in light of the requirement for a modular controller architecture implementation.

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automotive encyclopedia

fundamental principles, operation, construction, service, repair

WILLIAM K. TOBOLDT

Author of Diesel, Fundamentals, Service, Repair; Fix Your Ford; Fix Your Chevrolet; Auto Body Repairing and Repainting. Member, Society of Automotive Engineers. Associate Member, Automotive Engine Rebuilders Association. Associate Member, Association of Diesel Specialists.

LARRY JOHNSON

Author of Fix Your Volkswagen. Certified General Automobile Mechanic by National Institute for Automotive Service Excellence. Affiliate Member, Society of Automotive Engineers.

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INTRODUCTION

The automotive service field offers excellent career opportunities for anyone who is mechanically inclined and has the necessary educational background, including extensive training in the fundamentals of service and repair work.

The AUTOMOTIVE ENCYCLOPEDIA is a book of fundamentals. It covers construction details, principles of operation, latest mechanical advances and basic service procedures. This is the foundation on which a sound, thorough knowledge of auto mechanics is based. Once you learn these fundamentals, you can quickly acquire the know-how, through experience, that will enable you to diagnose trouble and perform the service or repair needed on any make of car.

The ENCYCLOPEDIA tells you how each system works. It explains what happens when you turn the ignition key or "step on the gas" or apply the brakes. It shows by clear illustration how the energy in fuel is converted into power, and how that power is transmitted to the driving wheels of the car.

This book helps you explore the sciences involved in vehicle operation: the fundamentals of electricity, hydraulics, pneumatics, internal combustion and exhaust emission control. It also gives basic information on hand tools, fasteners, measuring instruments, service equipment and meters.

The purpose of the AUTOMOTIVE ENCYCLOPEDIA is to provide instruction in auto mechanics as recommended by the Standards for Automotive Service Instruction in Schools, prepared by the Automotive Service Industry - - Vocational Educational Conference. It is intended, too, as a guide for car owners and prospective car owners who want to learn more about the mechanical features of their cars.

William K. Toboldt

Larry Johnson

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PRINCIPLES OF CARBURETION

The purpose of the fuel supply system, Fig. 21-1, is to provide a combustible mixture of fuel and air to the engine cylinders. The ratio of fuel to air must always be in the correct proportion regardless of the speed and load on the engine.

Major elements of the fuel supply system include: fuel tank and cap, fuel system emission controls, fuel lines, fuel pump, fuel filter, carburetor, air cleaner and manifold. In addition, there is the fuel gauge, which indicates the amount of fuel in the tank.

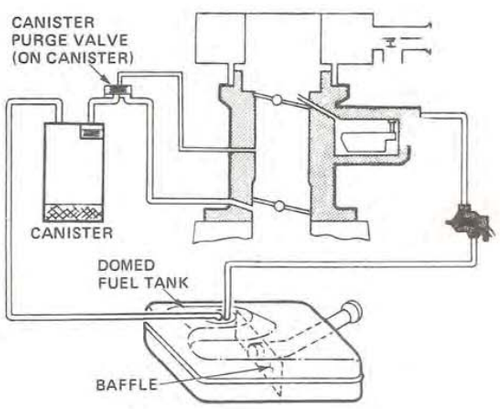


Fig. 21-1. Details of fuel system on late model car.

PURPOSE OF CARBURETOR

The purpose of the carburetor is to prepare and supply a mixture of fuel vapor and air, in proper proportion for efficient combustion, to the engine cylinders.

Because of varying conditions of temperature, engine speed and load on the engine, perfect carburetion is difficult to attain. When an internal combustion engine is started, it is cold and an air-fuel mixture containing a larger proportion of fuel is required. When the engine reaches operating temperatures, better vaporization of the fuel is attained and, as a result, the initial mixture of fuel and air is too "rich." This mixture contains more fuel than is normally required. It is not efficient and the engine will not operate satisfactorily, particularly at idling speed.

Still another difficulty must be overcome by the carburetor. When the engine is idling or operating at low speed, a richer mixture is required than when operating at medium speed and power. Then, when maximum power is required, the amount of fuel in relation to air must be increased. Similarly, during periods of acceleration, a richer mixture is needed.

A problem encountered in designing carburetors results from the fact that the rate of air flow through the carburetor changes in a ratio of more than 100 to 1. This is a direct result of the changes of engine speed. At low speed, the flow of air through the carburetor is at a minimum. At maximum engine speed, it will be at least 100 as great.

Variations in types and characteristics of fuels also complicate the carburetor design operation. Gasoline is a blend of various parts or fractions of crude petroleum. As a result, some fractions contained in commercial gasoline will boil or vaporize at 100 deg. F, others have boiling points ranging up to 400 deg. F.

Depending on the temperature of various parts of the intake manifold, some cylinders may receive a mixture with some portions of the fuel completely vaporized, while other portions of the fuel may be in liquid form. In addition, some cylinders will receive fuel having greater antiknock qualities than others. Consider, too, that when the engine and manifold are cold, the problem is still more difficult.

AIR-FUEL RATIO

For normal operating conditions, the best economy is obtained by a mixture of 1 part by weight of gasoline to between 16 to 17 parts of air. For quick acceleration and maximum power, a richer mixture of about 1 part of gasoline to 12 to 13 parts of air is needed. For idling, a somewhat richer-than-normal mixture is required. When starting a cold engine, an extremely rich mixture is needed. (See the chapter on MANUAL AND AUTOMATIC CHOKES.)

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EVAPORATION

All substances, whether solid, liquid or gas, are made of molecules. In solids such as steel and copper, the particles are so close together they seem to have no motion. In liquids, the molecules are not held together so tightly. They can move with respect to each other and, as a result, liquids flow. In gases, such as air, there is even less tendency for the molecules to hold together, so they move quite freely.

When molecules of a liquid move from the liquid into the air, the liquid is said to evaporate. As this continues, the liquid disappears from its container and forms vapor in the air.

Rapidity of evaporation varies with a number of factors. These factors, include temperature, the pressure above the liquid, the amount of liquid that has already evaporated into the air and the volatility of the liquid.

The term volatility refers to the ease with which a liquid vaporizes. For example, alcohol and benzene are more volatile than water because they evaporate more easily. A highly volatile liquid evaporates rapidly. A liquid of low volatility evaporates slowly.

At higher temperatures, molecules move faster. As a result, the rate of vaporization is increased. Furthermore, when there is little pressure above the liquid, the molecules can escape from the liquid more easily. If evaporation takes place in a closed chamber, the evaporation of the liquid will soon stop because the closed space above the liquid becomes filled with escaped molecules of the liquid. When this occurs, the space above the liquid is said to be saturated.

If a liquid is broken up into tiny particles or globules, it will vaporize more easily. Breaking a liquid into tiny particles is known as vaporization. Spray guns of the type used for spraying insecticides or paint will vaporize a liquid. For example, if gasoline is placed in an ordinary spray gun, Fig. 21-2, the fuel will be broken into a fine mist that will change into vapor almost instantly.



Fig. 21-2. Fuel leaving jet in a carburetor is vaporized like a spray from a conventional spray gun.

PRINCIPLES OF CARBURETOR OPERATION

Both air and gasoline are drawn through a carburetor and into the engine combustion chambers by suction created by the pistons moving downward in the cylinders. As the piston moves down, a partial vacuum is created in the cylinder and combustion chamber. The difference between this low pressure within the cylinder and the atmospheric pressure outside of the carburetor causes air and fuel to flow into the cylinder from the carburetor.

Directly related to this air flow into the carburetor is the principle or method whereby the moving air draws fuel from the carburetor jet and fuel supply. It is called the venturi principle, a means by which the suction within the carburetor is increased. Actually, a venturi is an hour-glass shaped constriction placed in a carburetor, so that incoming air must pass through it on its way to the intake manifold and engine cylinders, Fig. 21-3.

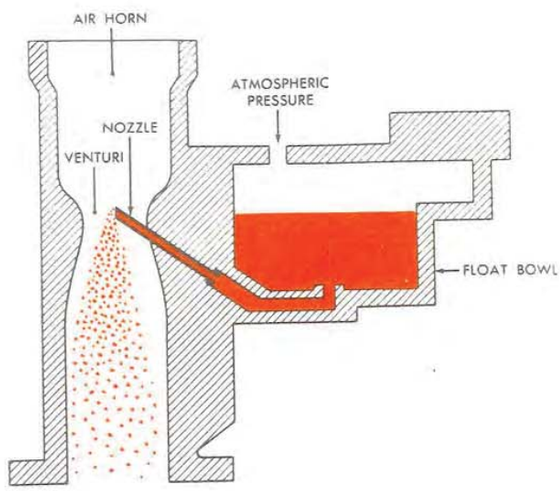


Fig. 21-3. Simplified carburetor consisting only of air horn, venturi, float bowl and nozzle.

A venturi is simply a specially designed section of a pipe line or tube where the area of the tube is reduced. This reduction in area increases the speed of the air that is passing through the tube. The same volume of air or fluid flows through all sections of the tube. Therefore, if the area of the tube is decreased, the velocity of the air or fluid must increase as it passes through the restricted area.

The venturi not only increases the velocity of the flow of air which passes through it, but it also produces a vacuum at its point of maximum restriction, Fig. 21-4. The outlet of a fuel jet is placed at that point, so that fuel is drawn from the jet and immediately mixes with the passing air.

This mixing of the fuel with air is known as vaporization, and it closely resembles the action of the familiar spray gun used for spraying insecticides, Fig. 21-2.

Some carburetors have as many as three venturies, Fig. 21-15 and Fig. 21-37. This design permits a more accurate metering of the flow of air and fuel for different conditions of engine operation. It improves the efficiency of combustion, which has become increasingly important in reducing exhaust emissions.

Remember that the difference between the pressure at the open carburetor jet at the venturi and surface pressure on the fuel in the float bowl, Fig. 21-3, causes the fuel to flow.

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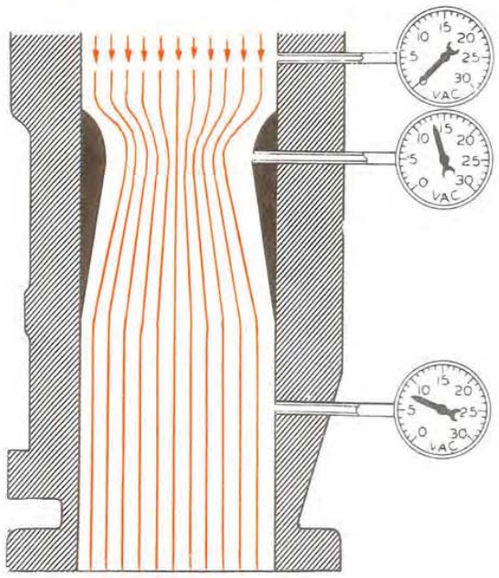


Fig. 21-4. Note how vacuum varies through different sections of carburetor.

CARBURETOR CIRCUITS

In order to supply an air-fuel mixture suitable for all the different operating conditions of low to high speeds, and light loads to full loads, a carburetor must be provided with additional circuits and controls. These circuits include: float system, idle system, main metering system, accelerating system and high speed system. Under controls, there are: the throttle, anti-percolator, fast idle, unloader, anti-icing, hot idle compensator and anti-stall dashpot.

THROTTLE

One of the important controls on a carburetor is the throttle valve, or valves. The throttle valve is a device for varying the amount of air-fuel mixture that enters the intake manifold. This control is necessary so the speed of the vehicle can be changed.

The throttle valve, Fig. 21-5, is simply a round disk mounted on a shaft, so that it can be tilted at various angles in the carburetor throttle valve body. It is connected by means of suitable linkage to the accelerator pedal in the driving compartment of the vehicle. Depressing the pedal opens the throttle valve, permitting an increased amount of air-fuel mixture to reach the manifold.

FLOAT CIRCUIT

Fuel in the carburetor must be maintained at a specified level for correct fuel metering under all operating conditions. This is the function of the float circuit, Fig. 21-6. Maintenance of the desired fuel level is accomplished by the float or pontoon when its attached lever forces the needle valve closed and shuts off the flow of fuel.

Then, as soon as fuel is withdrawn from the float bowl, the float drops, the needle valve opens and fuel again flows into the bowl. In that way the fuel level is maintained at the opening of the main discharge nozzle.

The float level must be set with a high degree of accuracy. If the level is too low, insufficient fuel will be supplied to the system and engine performance will suffer. On the other hand, if the level is too high, excessive fuel will flow from the nozzle.

Under conditions of a high fuel level in the float bowl, excessive fuel consumption results and carbon will accumulate in the combustion chambers of the engine. In actual operation, the float and needle valve maintain a position that permits the fuel coming into the float bowl to balance the fuel issuing from the carburetor jets.

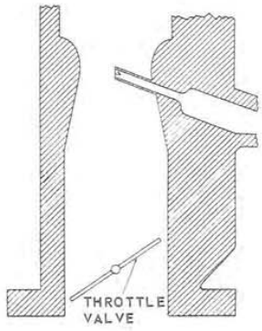


Fig. 21-5. Illustrating position of throttle valve or plate.

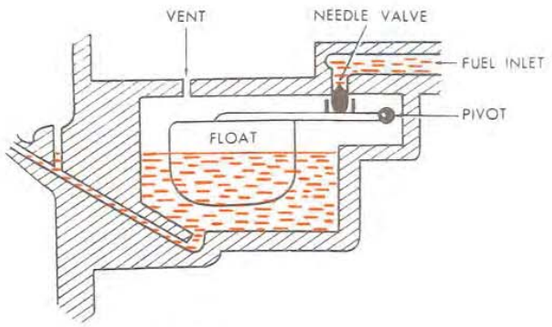


Fig. 21-6. Typical carburetor float system.

LOW-SPEED CIRCUIT

The idle system or low-speed circuit, Fig. 21-7, is designed to supply the proper amount of mixture for the engine at idle and extremely low speeds. It operates from idle speed to approximately 25 mph. Above that speed, the idle system gradually passes out of operation and fuel is supplied by the main metering system.

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When the throttle valve is almost closed, there will be very little air passing through the venturi. Consequently, there will be very little vacuum to draw fuel from the fuel nozzle.

However, on the manifold side of the throttle valve, the vacuum will be at a maximum as long as the throttle is in the closed position. A fuel discharge port is located immediately below the closed position of the throttle, Fig. 21-7. It is supplied by fuel from the float bowl. Atmospheric pressure in the float bowl will force fuel from the idle discharge port as long as there is some degree of vacuum of the port.

When the throttle valve is opened, vacuum at the discharge port decreases. It continues to decrease as the valve opens further until there is no flow of fuel from that port. An adjustable needle valve is provided, so that the amount of fuel discharged from the idle port can be governed.

Immediately above the venturi is another port, Fig. 21-7, which is designed to permit air to bleed into the idle circuit as long as the idle circuit is operating. The air mixes with fuel to help atomize it before the fuel leaves the idle discharge port.

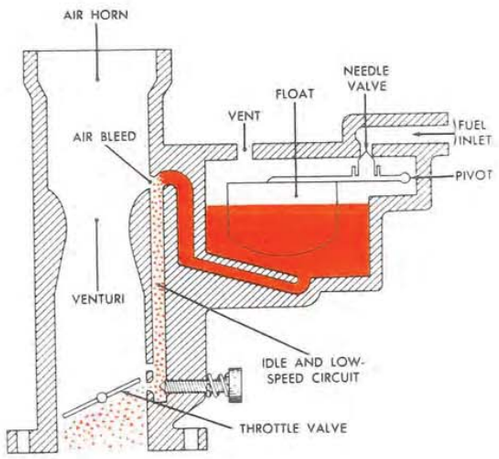


Fig. 21-7. Details of carburetor idle system.

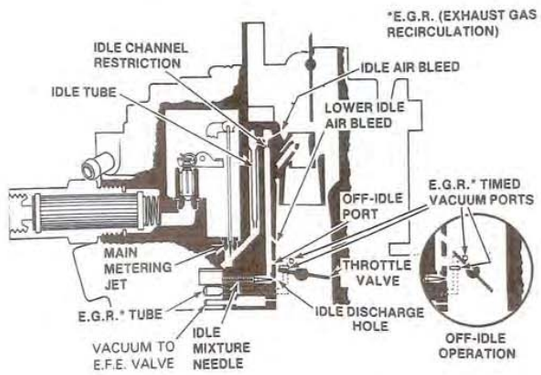


Fig. 21-8. Note location of idle discharge ports on this Rochester M2ME carburetor.

OFF IDLE OPERATION

In addition to the basic idle system, some carburetors (Rochester 2GC and M2ME) are provided with an off idle system. As the throttle valves are opened during acceleration, more fuel is supplied by the off idle discharge port, Fig. 21-8.

The off idle port gradually is exposed to manifold vacuum and supplies the additional fuel needed for the increase in engine speed. Improved fuel control is achieved by an adjustable off idle air bleed screw. The adjustment screw, which regulates air passing from a separate channel into the idle channel, is factory adjusted.

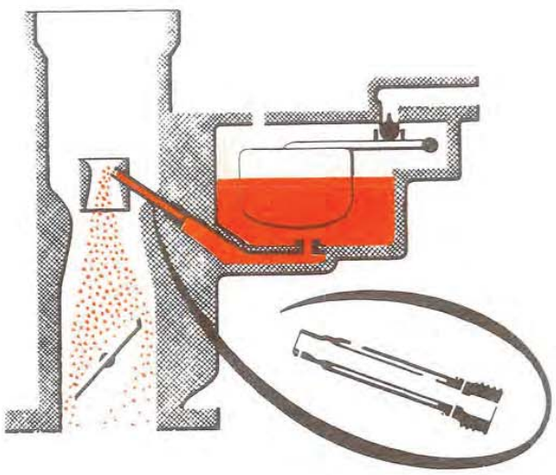


Fig. 21-9. Main or high-speed system.

AIR FLOW IS RESTRICTED

When the throttle is opened a little, the flow of air is still too restricted for the venturi to discharge fuel from the main jet or nozzle, Fig. 21-5. However, with the increased movement of air through the carburetor, more fuel must be supplied in order to maintain the correct proportions of air and fuel.

To supply additional fuel during this stage of low-speed operation, another port is included in the idle circuit. This hole is positioned slightly above the closed position of the throttle valve, Fig. 21-7. As soon as the valve is opened a small amount, the port will be uncovered, intake manifold vacuum will act on it and the additional fuel needed will be obtained.

Another type of idling system is used on Zenith carburetors on many industrial engines. In this system, air mixes with the fuel in proportions determined by the position of an idle-adjusting needle valve. The tube of the idling jet projects down into a well filled with fuel when the engine is at rest. As more air is admitted by means of the needle valve adjustment, less fuel will flow.

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MAIN CIRCUIT

As the throttle is opened, the flow of fuel from the idle ports gradually decreases in volume. However, vacuum at the venturi gradually increases, so fuel starts to flow from the main or high-speed system. The main system consists essentially of the main nozzle or jet, which is centered in the venturi, Fig. 21-9, and supplies fuel from partly open to fully open throttle positions.

Remember, as the rate of flow of the air through the carburetor increases, the flow of the fuel also increases at a much faster rate. This results from the fact that the density of the fuel does not change, while that of the air does. So the mixture in a simple carburetor will be much too rich under wide-open throttle valve conditions. In fact, with a simple carburetor, the correct mixture of air and fuel would be provided at only one position of the throttle valve. So provision must be made to supply the correct ratio of air to fuel for all positions of the throttle valve.

POWER ENRICHMENT SYSTEM

To supplement the main metering system, some carburetors are provided with a power enrichment system, Fig. 21-10. Power enrichment is designed to provide proper mixtures

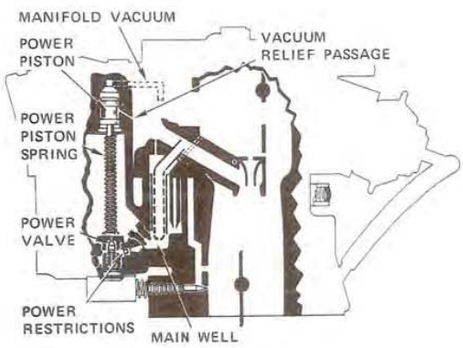


Fig. 21-10. Details of a Rochester power enrichment system.

when more power is desired, or for extreme high-speed driving. The system consists of a vacuum-operated power piston in the air horn and a power valve located in the bottom of the float bowl. The power piston cylinder is exposed to engine manifold vacuum at all times through a connecting vacuum passage from the base of the carburetor.

During idle and part throttle operation, the relatively high vacuum holds the power piston against spring pressure, and the power valve remains closed. The increase in engine load lowers the manifold vacuum. When it has dropped sufficiently, the power piston spring overcomes the upward pull of vacuum. Under spring pressure, the power piston moves downward. This opens the power valve to allow additional fuel to flow through calibrated restrictions into the main well.

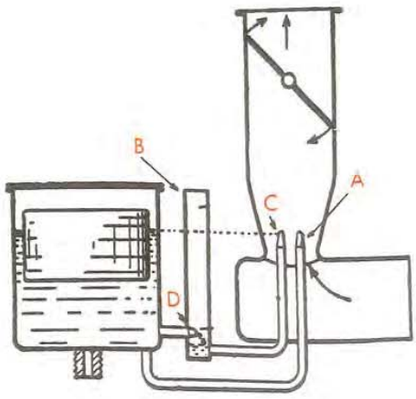


Fig. 21-11. Main nozzle A secures fuel directly from float chamber. Compensating nozzle C receives fuel from standpipe B. Fuel supplied by nozzle C depends on size of metering orifice D which delivers fuel to standpipe B.

COMPENSATION OR DOUBLE NOZZLE PRINCIPLE

One method of controlling the mixture of fuel and air is to provide, in addition to the main nozzle, another nozzle with a constant rate of discharge. In combination, the two nozzles give a substantially constant mixture.

In Fig. 21-11, the main nozzle is supplied with fuel directly from the float chamber. The compensating nozzle, which has a constant rate of discharge, is supplied from a standpipe that receives its fuel from the float chamber. The upper end of the standpipe is open to the atmosphere.

Fuel enters the standpipe through a metered opening. Since the fuel in the float chamber is at a constant level, the flow to the standpipe will be constant. In addition, the rate at which fuel can be drawn from the compensating nozzle also will be constant. At high engine speed, the compensating nozzle delivers less fuel than at low engine speed. In this way, it compensates for the natural tendency of the main nozzle to deliver a mixture that is too rich at high speed.

Also at high engine speed, and when the compensating nozzle is delivering smaller amounts of fuel (due to reduced vacuum), the level of the fuel in the standpipe will rise until its level is equal to that in the float chamber. Then, as suction on the compensating nozzle draws fuel from it, the fuel level in the standpipe will be lowered. If the throttle valve is maintained at the same opening for a sufficient length of time, all the fuel will be drawn from the standpipe. Then the compensating nozzle will be supplied directly from the compensating jet or submerged metering orifice.

AIR BLEED PRINCIPLE

The use of air bleeds is another method of compensating for the increased richness of the mixture caused by increased air velocity through the carburetor throat. Fig. 21-12 shows

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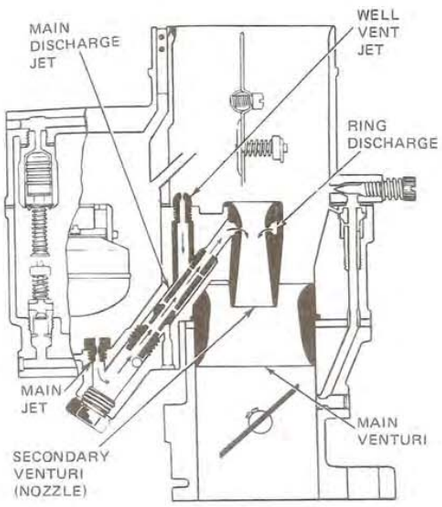


Fig. 21-12. Illustrating air bleed principle used on Model 228 Zenith carburetor.

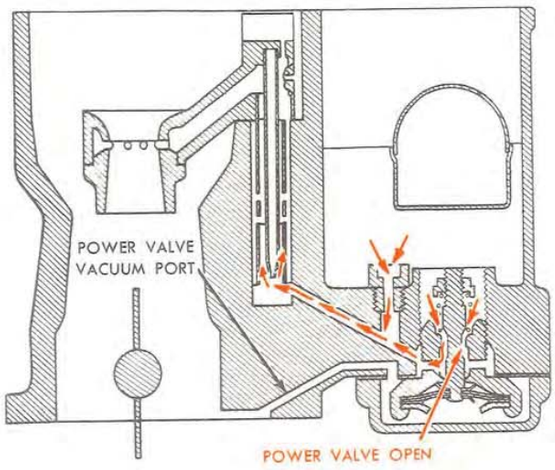


Fig. 21-13. Motorcraft 2150 carburetor power valve, or economizer valve, which supplies additional fuel needed for wide open throttle.

the air bleed system used on a Zenith carburetor. In this case, the high-speed system of the carburetor consists of a primary venturi, a secondary venturi, a main jet, a well jet and a discharge jet.

The main jet controls the fuel mixture from about one-fourth to about three-fourths throttle valve opening. The mixture is controlled by a small amount of air admitted through the well vent or high speed bleeder. The air bleed holes are located in the upper section of the discharge jet at a point below the level of the fuel in the jet.

Introduction of air at that point reduces the surface tension of the fuel and helps fuel flow at low pressures. This bleed also restricts fuel flow through the main jets under high vacuum conditions. In combination, these two factors control the air-fuel ratio and offset the tendency toward increased richness of mixture that occurs when a plain nozzle is subjected to increased air velocity.

FULL POWER CIRCUIT

With its air bleed maintaining the air-fuel ratio at a constant rate, the main circuit provides economical operation for all speeds, from low speed up to but not including wide-open throttle. However, for maximum speed and power, additional fuel must be supplied. There are several ways that this additional fuel is provided for maximum power. These methods include the economizer valve or power jet, and the metering rod.

POWER VALVE

The power valve, or economizer valve, depends upon manifold vacuum for its operation. It is connected to a vacuum port on the engine side of the throttle valve, Fig. 21-13. By design, when full throttle operation is approached, engine vacuum acting on the diaphragm or plunger of the power valve will permit the required amount of fuel to pass through the main nozzle.

Another type of power valve is shown in Fig. 21-14. In this design, the power jet valve is controlled by a vacuum-actuated piston assembly, operating in accordance with throttle valve opening. With the throttle closed (high manifold vacuum), atmospheric pressure in the float chamber moves the vacuum-controlled piston assembly to the top of its cylinder against the tension of a spring. This closes the power valve. When the throttle valve is opened to a point where additional fuel is required, manifold vacuum has decreased sufficiently so that

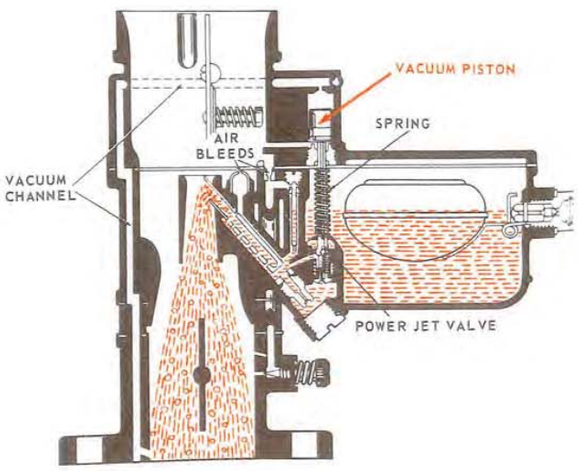


Fig. 21-14. Another type of power jet valve is controlled by vacuum piston.

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the spring moves the piston down, opening the power jet to feed additional fuel into the high-speed circuit.

Mechanical means are also used on some carburetors for supplying the additional fuel needed for high-speed operation. In this design, the power jet is opened by the accelerator pump when the pump is at the bottom, or end, of its stroke.

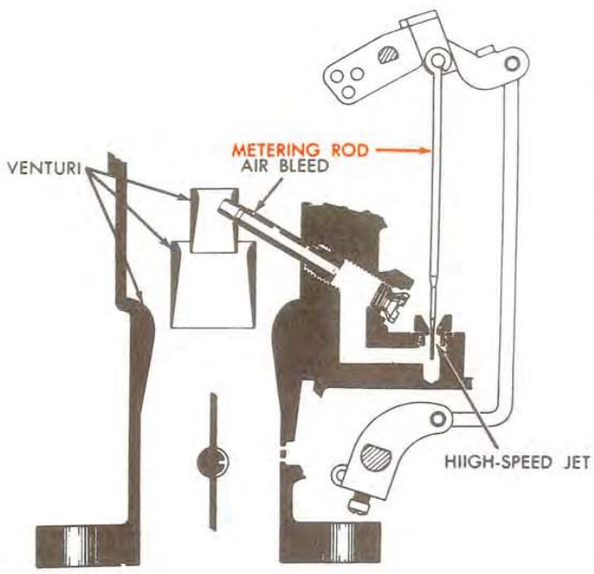


Fig. 21-15. Metering rod varies amount of fuel flowing from a jet.

METERING ROD

Instead of using a power jet, some carburetors accomplish the same results by employing a metering rod that varies the size of the high-speed jet openings. In this design, Fig. 21-15, fuel from the float bowl is metered to the high-speed circuit through the calibrated orifice provided by the high-speed jet and the metering rod within it. From this point, the fuel is conducted to the nozzle extending into the venturi.

As the throttle valve is opened, its linkage raises the metering rod in the jet. The rod has several steps, or tapers, on the lower end. As it is raised in the jet, it makes the effective size of the fuel orifice greater, permitting more fuel to flow through the circuit. Obviously, metering rod position must be carefully synchronized with every throttle position so that the correct air-fuel ratio is maintained throughout all engine speeds.

Metering rods are also operated by means of a vacuum controlled piston as shown in Fig. 21-16.

VACUUM STEP-UP

The vacuum step-up circuit, Fig. 21-17, operates much like the power jet. It consists of a step-up piston fastened to a step-up rod. When high vacuum develops in the intake

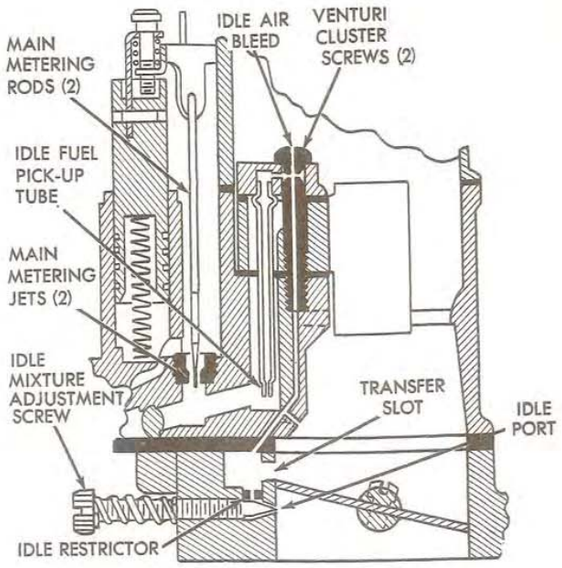


Fig. 21-16. Metering rods (2) are operated by a vacuum piston on a Carter BBD carburetor.

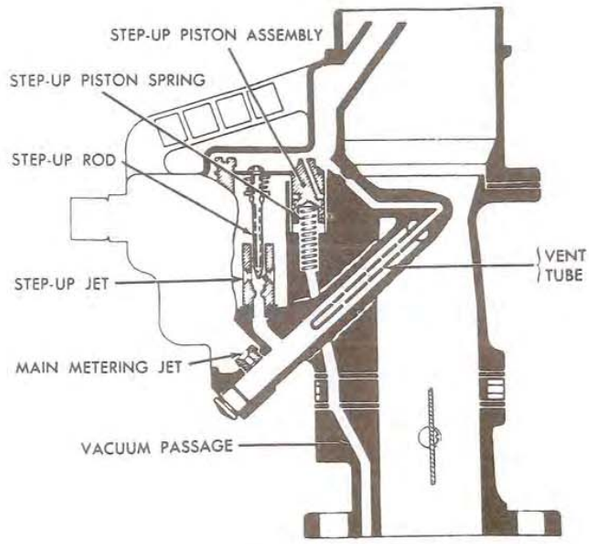


Fig. 21-17. Details of vacuum step-up circuit designed to supply additional fuel needed for full power operation.

manifold (part throttle operation), atmospheric pressure holds the step-up piston down against spring pressure. This, in turn, holds the step-up rod down in the step-up jet, closing the jet.

With low vacuum in the intake manifold (wide-open throttle), the difference in pressure above and below the piston is small. Consequently, the piston is moved up by spring pressure and the rod is raised out of its jet. In this way, additional fuel is supplied for maximum power.

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ACCELERATING PUMP

When a throttle valve is opened quickly to produce rapid acceleration of the engine, the carburetor fuel mixture tends to become too lean and a "flat spot" occurs. This results from the fact that the fuel is of greater weight than air. Consequently, when the accelerator is opened suddenly the flow of fuel will lag behind the flow of the air.

To supply the additional fuel needed to overcome this condition, a small accelerating pump is incorporated in the design of the carburetor, Fig. 21-18. This pump is operated by the throttle linkage. In some designs, the strokes of the pump can be adjusted to any one of three positions. The longest stroke provides the maximum amount of fuel, so this is the setting usually used during cold weather.

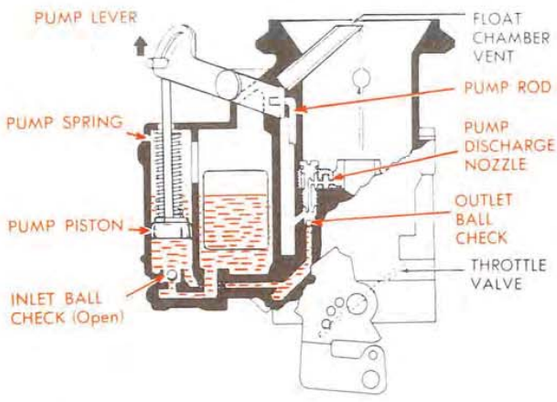


Fig. 21-18. Accelerator pump supplies additional fuel for rapid acceleration.

The accelerating pump circuit generally consists of:

1. A pump cylinder.
2. A plunger, mechanically actuated by a lever mounted on throttle shaft, or vacuum-operated by intake manifold vacuum.
3. An intake check valve located in bottom of pump cylinder to control passage of fuel from bowl to pump cylinder.
4. A discharge or outlet check valve.
5. An accelerating jet to meter fuel used.

When the throttle is opened, the pump plunger moves downward in its cylinder. In the mechanically-operated design, the downward movement is obtained by direct linkage with the throttle. In the vacuum-actuated design, a sudden throttle opening will cause the manifold vacuum to drop, allowing the accelerating pump spring to force the pump plunger down in the cylinder.

In either case, the downward travel of the plunger forces the fuel past the discharge check valve of the acelerating jet.

Fuel is supplied to the pump cylinder through the intake check valve at the bottom. This valve permits a supply of fuel to reach the cylinder, but closes on the down stroke of the plunger to prevent fuel in the cylinder from being pushed back into the float bowl.

ANTI-PERCOLATOR

During extremely hot weather, there is a tendency for the fuel to vaporize in the fuel line, the fuel pump or within the carburetor. When this condition occurs in the carburetor, it is known as "percolation."

To overcome percolation when it occurs, special provisions

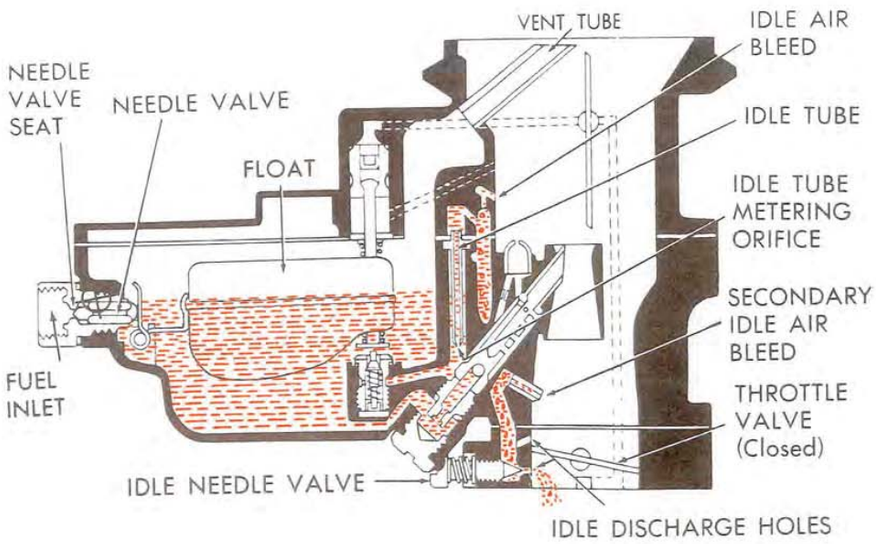


Fig. 21-19. Vent tube from float bowl to air horn prevents vapor lock and equalizes effect of a clogged air filter. This illustration also shows a typical idling system.

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are made. One method is to provide a passageway or vent tube between the top of the float bowl chamber and the upper part of the air horn, Fig. 21-19. By this means, any vapor developing in the float bowl chamber will be drawn into the air stream in the air horn. From there, it will pass through the carburetor and into the intake manifold.

Venting the float bowl in this manner has the added advantage that it will equalize the effect of a clogged air filter. A clogged filter will cause a somewhat greater vacuum at the venturi and consequent increased flow of fuel. Venting the float bowl into the carburetor air horn relieves this condition.

Another method vents the float bowl chamber directly into the atmosphere, Fig. 21-16. In this carburetor design, the vent is provided with a cap to prevent dust and dirt from entering the float bowl chamber.

Still another design incorporates a special valve that vents the main discharge nozzle to the atmosphere. Linkage is arranged so that closing of the throttle valve will open an anti-percolator valve. Another method designed to accomplish the same thing provides a vent for the passages to the discharge nozzle without the use of a valve.

With the coming of evaporative emission controls, venting of fuel vapors to the atmosphere was discontinued. See Chapter 29.

FAST IDLE

To prevent an engine from stalling before it reaches operating temperature, it must be operated at a faster-than-normal speed. This is done by preventing engine speed from dropping below a predetermined rpm. To accomplish this, the choke shaft is linked to a cam on the outside of the carburetor, Fig. 21-20. The linkage is arranged so that as long as the choke is in a partially closed position, the high spot on the cam comes under the fast idle speed adjusting screw. In this way, the throttle valve will be held open a sufficient amount to prevent stalling.

After the engine reaches operating temperature, opening of the choke valve will move the cam from under the fast idle speed adjusting screw, and the engine will idle at normal speed.

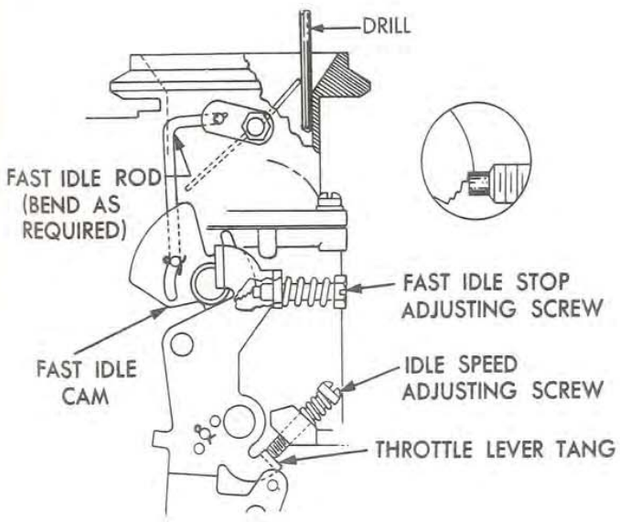


Fig. 21-20. Showing fast idle and choke linkage, together with fast idle adjustment and idle speed adjustment.

CARBURETOR UNLOADER

When an engine does not start immediately, prolonged cranking will result in a flooded condition. The air-fuel mixture in the manifold and engine is so rich that it is no longer a vapor. Consequently, the spark plugs cannot fire it. To overcome this condition, linkage is provided on the carburetor which will hold the choke valve open when the accelerator is pushed to the floor, Fig. 21-21. Then, as the engine is cranked again, air will enter the manifold and cylinders to clear excessive gasoline from the system. This is accomplished by special linkage between the throttle and choke levers, Fig. 21-21.

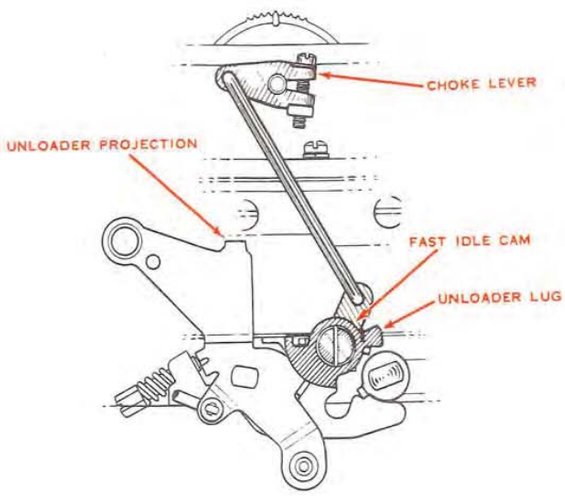


Fig. 21-21. Showing relationship of unloader lug or cam, unloader projection, choke lever and fast idle cam.

ANTI-ICING

When fuel is evaporated, it absorbs heat from the surrounding air and metal parts of the carburetor. When the humidity of the air is high and temperatures are at approximately the freezing point, the evaporation of fuel in the carburetor often causes "icing." The ice forms around the closed position of the throttle plate, and the idle port becomes closed with ice. This, in turn, will cause the engine to stall at low speeds.

To overcome this icing condition, some carburetors are provided with special passages that carry hot exhaust gases around the carburetor, heating the area surrounding the

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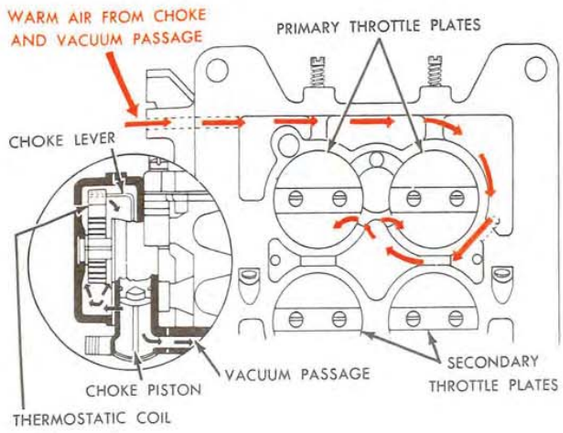


Fig. 21-22. Showing path of warm air from choke passing around throttle valves to prevent formation of ice.

throttle plate, Fig. 21-22.

Another method of overcoming this difficulty is to provide a water jacket for the carburetor. This water jacket, of course, is connected to the cooling system of the vehicle.

HOT IDLE COMPENSATOR

During long periods of idling with an extremely hot engine, the fuel in the carburetor bowl becomes hot enough to form vapors. These vapors enter the carburetor bores by way of the inside bowl vents, mixing with the idle air and causing an extremely rich mixture. This will result in loss of engine rpm and, eventually, in stalling. To overcome this condition (on Carter AFB carburetors, for example), a hot idle compensator valve is placed in the secondary side of the carburetor. This is calibrated to permit additional air to enter the manifold below the secondary throttle valve, where it mixes with the fuel vapors to provide a more combustible mixture.

On Rochester 4GC carburetors, the hot idle compensator is placed on the secondary side of the float bowl and permits additional air to enter the primary bores under extreme hot idle conditions, Fig. 21-23.

ANTI-STALL DASHPOT

Most older cars with automatic transmissions have an anti-stall dashpot connected to the carburetor linkage, Fig. 21-24. The purpose of this dashpot is to prevent the throttle valve from closing too fast. Too rapid closing often causes the engine to stall. Installation of the dashpot prevents the throttle from being closed too quickly, thereby avoiding stalls.

This condition would not occur with a manual transmission since the momentum of the vehicle would continue to drive the engine through the stall period.

Also, to insure easy starting, some engines have special carburetor linkage designed to automatically hold the throttle valve slightly open during cranking.

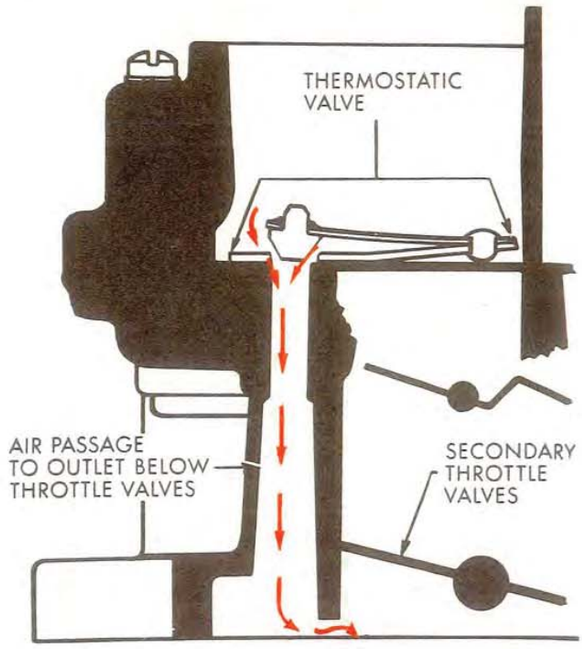


Fig. 21-23. Hot idle compensator permits additional air to enter primary bores of carburetor under extreme hot idle conditions.

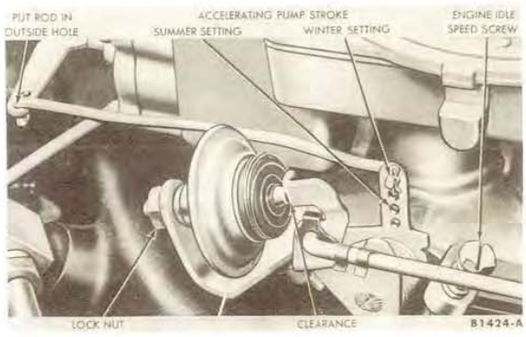


Fig. 21-24. Showing anti-stall dashpot mounted on side of Ford carburetor. Some carburetors have anti-stall dashpot built into carburetor. Note provision for adjustment of accelerator pump.

VACUUM ADVANCE

Vacuum from the carburetor is used to control the spark advance on the Ford Loadomatic distributor. By design, vacuum is transmitted to the distributor diaphragm from three interconnected passages in the carburetor, Fig. 21-25. All manifold vacuum to the distributor passes through the spark control valve.

Under normal load conditions, the spark valve is held open against spring pressure by a combination of atmospheric

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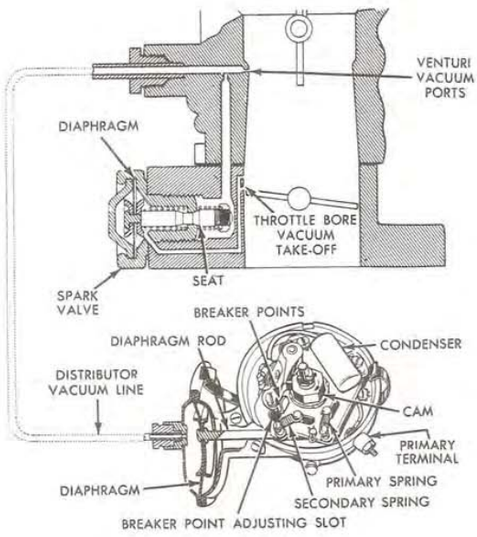


Fig. 21-25. Method of using vacuum at venturi and at throttle valve to control spark advance.

pressure and manifold vacuum. When accelerating, manifold vacuum drops and spring pressure closes the spark valve which shuts off the vacuum and prevents excessive spark advance. Venturi vacuum prevents full retard. When manifold vacuum increases, the spark valve will again allow a higher vacuum to advance the distributor.

GOVERNORS

Governors are used principally on industrial engines and commercial vehicles so that economical and safe speeds are not exceeded. One type of Holley unit, Fig. 21-26, is inserted between the carburetor and the intake manifold, where it is actuated by the pressure differential acting against the governor diaphragm. The differential is provided by vacuum below the governor throttle plates and atmospheric pressure above the plates.

At low engine rpm, the governor control valve weight is held away from its seat by the tension of the valve weight spring. During this period, the valve is wide open to allow outside air to flow to the governor so that no governing action occurs. As engine speed increases, the differential between atmospheric pressure and engine vacuum decreases, causing the governor diaphragm to exert a pull on the governor lever. This turns the throttle shaft and partly closes the throttle.

Another method of limiting the speed of an engine is by means of a velocity type governor. In this design, the unit is inserted adjacent to the throttle. As the gas goes through the manifold, its velocity acts on a spring-loaded floating obstruction in the form of a ball or disk attached to the throttle As engine speed increases, the gas flowing through the manifold tends to carry the obstruction along with it. Since this disk or ball is attached to the throttle plate of the carburetor, its movement closes the throttle against the tension of a spring. In this way, the speed of the engine is controlled.

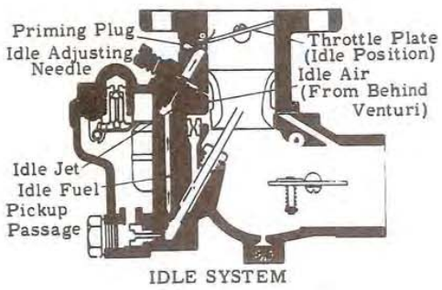


Fig. 21-27. Sectional view of updraft carburetor. Air enters at right and passes upward through venturi and past throttle plate.

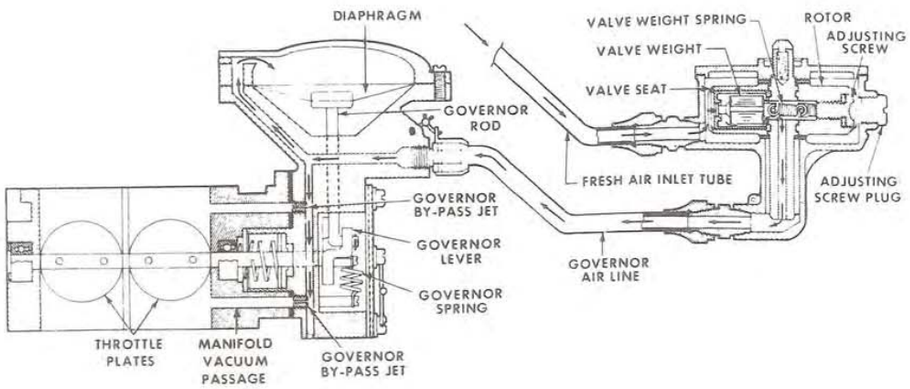


Fig. 21-26. This Holley governor uses vacuum below governor throttle plates and atmosphere above to control speed of vehicle.

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TYPES OF CARBURETORS

While there are many variations in the design and construction of carburetors, there are three basic types:

1. Updraft.
2. Downdraft.
3. Sidedraft.

The direction of the air flow at the carburetor outlet to the manifold determines the classification.

The updraft carburetor, Fig. 21-27, is placed low on the side of the engine. It is supplied with fuel by gravity feed. However, the fuel mixture must be lifted from the carburetor, through the manifold and into the engine. Air velocities must be high; a requirement that can be attained only by using carburetors and manifold passages of small diameter. As a result, power output is limited.

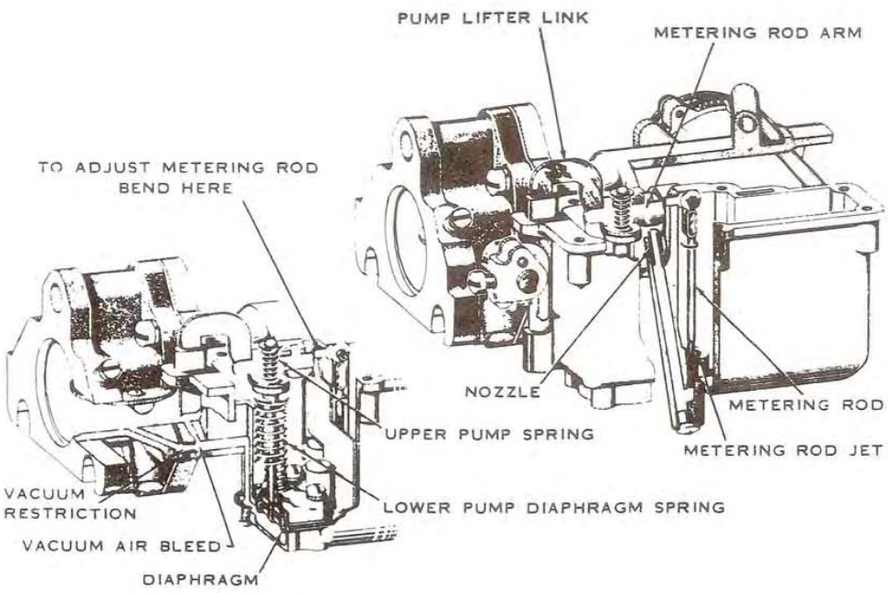


Fig. 21-28. Typical sidedraft, or crossdraft, carburetor.

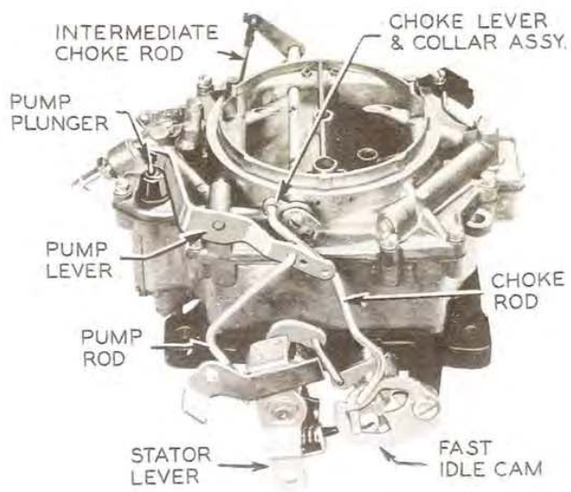


Fig. 21-29. Typical single-barrel, downdraft carburetor.

The sidedraft, or crossdraft, carburetor shown in Fig. 21-28 is used where there is little space over the engine. The air cleaner naturally is positioned lower in a sidedraft carburetor installation. Another application of this carburetor is where the vaporized mixture is heated by water in the engine water jacket.

U.S. passenger car engines are equipped almost exclusively with the downdraft carburetor, Figs. 21-14 and 21-29. In this design, the air-fuel mixture will reach the engine even though the air velocity is low. The carburetor throat and manifold can be made larger, by design. This, in turn, increases the size of the air-fuel intake system, making high speeds and high specific output possible.

SINGLE-BARREL CARBURETOR

While there are three basic types of carburetors, they also may be classed by number of throats, or barrels. A single-barrel carburetor, Fig. 21-29, has one outlet to the intake manifold. It is designed to take care of all the requirements of the engine for all operating conditions. Such carburetors are used extensively on engines having six cylinders or less.

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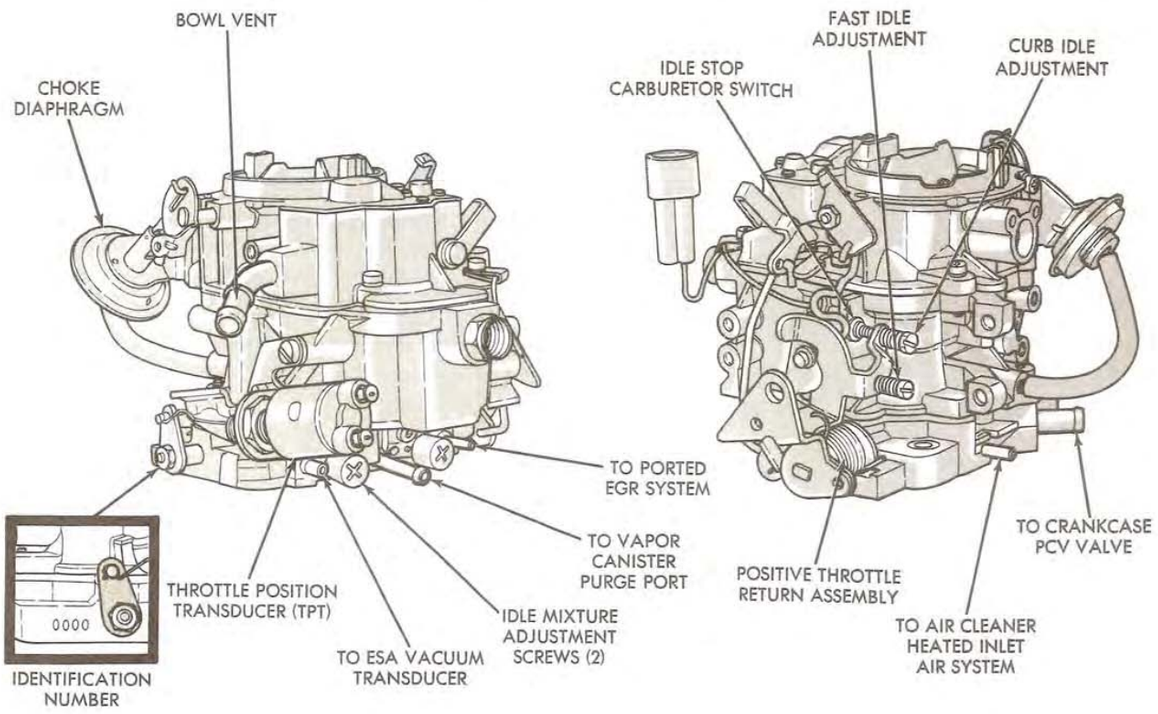


Fig. 21-30. Two views of Holley 2280 dual venturi carburetor as installed on Chrysler 318 cu. in. (5.2 litre) V-8 engine. This carburetor has four basic metering systems: idle system provides mixture for idle and low speed; accelerator pump system pumps additional fuel for acceleration; main metering system meters an economical mixture for normal cruising conditions; power enrichment system which combines a mechanical and vacuum operated power valve to provide additional fuel for maximum power.

TWO-BARREL CARBURETOR

Carburetors with two outlets to the intake manifold are known as two-barrel or two-throat carburetors, Fig. 21-30. Basically, these units are two carburetors in one, with two complete idling systems, two high-speed systems, two power systems, two accelerating systems, two throttle valves, two choke valves, but only one float system.

With a two-barrel carburetor, each barrel or mixing tube supplies alternate cylinders in the firing order. In a conventional six cylinder engine, one barrel supplies cylinders 1, 3 and 2, while the other barrel supplies cylinders 5, 6 and 4.

FOUR-BARREL CARBURETOR

In the four-barrel carburetor, Fig. 21-31, generally used on V-8 engines, there are four openings to the intake manifold within the single unit. Some systems, such as the float system, may be common to all four barrels. In some four-barrel carburetor designs, half of the carburetor operates as a two-barrel unit during light load and cruising speeds, while the other half of the carburetor is supplemental for top speed and full-throttle operation. The two barrels supplying fuel for light load operation are known as the primary side, while the supplementary two barrels are known as the secondary side.

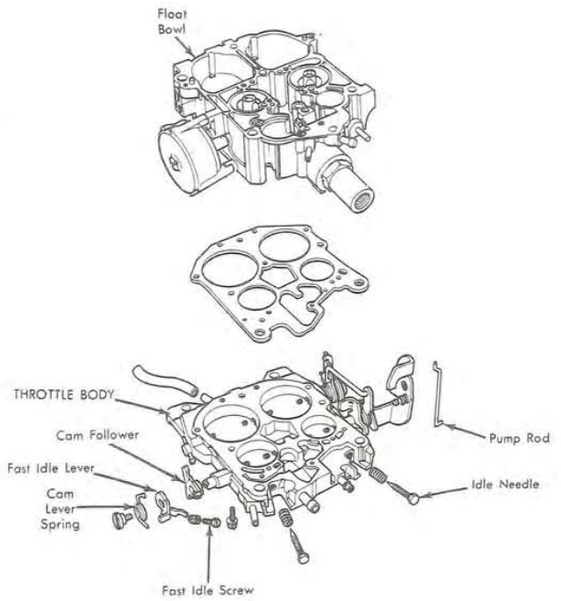


Fig. 21-31. Four-barrel carburetor. Note four openings to manifold.

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When two barrels of a four-barrel carburetor supply fuel to the engine throughout the entire speed range, a portion of the idle system fuel is routed to the secondary barrels for satisfactory fuel distribution. Also in this design, the secondary throttle plates remain closed at lower engine speeds. As engine speed increases, the throttle plates of the secondary barrels are opened.

In some designs, the secondary throttle plates are operated mechanically through linkage. On other models, the secondary throttle plates are controlled automatically by a vacuum-operated diaphragm. In general, the secondary throttle plates will start to open when the primary plates are open 50 deg.

In a four-barrel carburetor on a V-8 engine, primary and secondary barrels form a pair to supply cylinders 1-7-4-6, while the other primary and secondary barrels will supply fuel to cylinders 3-5-2-8. However, this applies only to an engine having a firing order of 1-8-4-3-6-5-7-2.

In general, manifolding for both two-barrel and four-barrel carburetors is designed as follows: One half of the carburetor supplies fuel to the end cylinders on one side of the engine and two center cylinders on the other side. The other half of the carburetor supplies fuel to the remaining cylinders.

MULTIPLE CARBURETORS

Maximum engine performance requires perfect distribution of large quantities of the air-fuel mixture. One way to attain this is by using several carburetors. One installation on a V-8 engine uses three two-barrel carburetors.

In this installation (Chevrolet), the center carburetor is known as the primary, Fig. 21-32. It takes care of all engine requirements up to 60 deg. opening of the throttle. Above that, the secondary carburetors come into operation to supply the additional fuel required for maximum performance.

The primary carburetor is a complete unit, containing all the usual carburetor systems (float, idle, choke, port throttle, power and accelerator pump). The front and rear carburetors do not include idle, part throttle or choke systems.

A combined mechanical and vacuum linkage is used to operate the throttle valves. The primary carburetor throttle valves are operated mechanically. When they are opened 60 deg., a vacuum slider valve causes vacuum to act on a diaphragm which, in turn, operates the throttle valves on the secondary carburetors.

AUTOLITE 4300 CARBURETOR

The Autolite model 4300 4-V carburetor, Fig. 21-33, is a three-piece, separately cast design consisting of the air horn, main body and throttle body.

A cast-in center fuel inlet has provision for a supplementary fuel inlet system. The fuel bowl is vented by an internal balance vent; and a mechanical atmospheric vent operates during idle.

The idle bypass system is designed to provide a more consistent idle, and a hot idle compensator, Fig. 21-33, is used to help idle stability.

These adjustments for idle air and idle fuel must be made at the same time. Opening the idle air screw to increase engine rpm leans the air-fuel mixture. Consequently, the idle fuel mixture must also be adjusted to provide the correct air-fuel mixture for smooth engine idle.

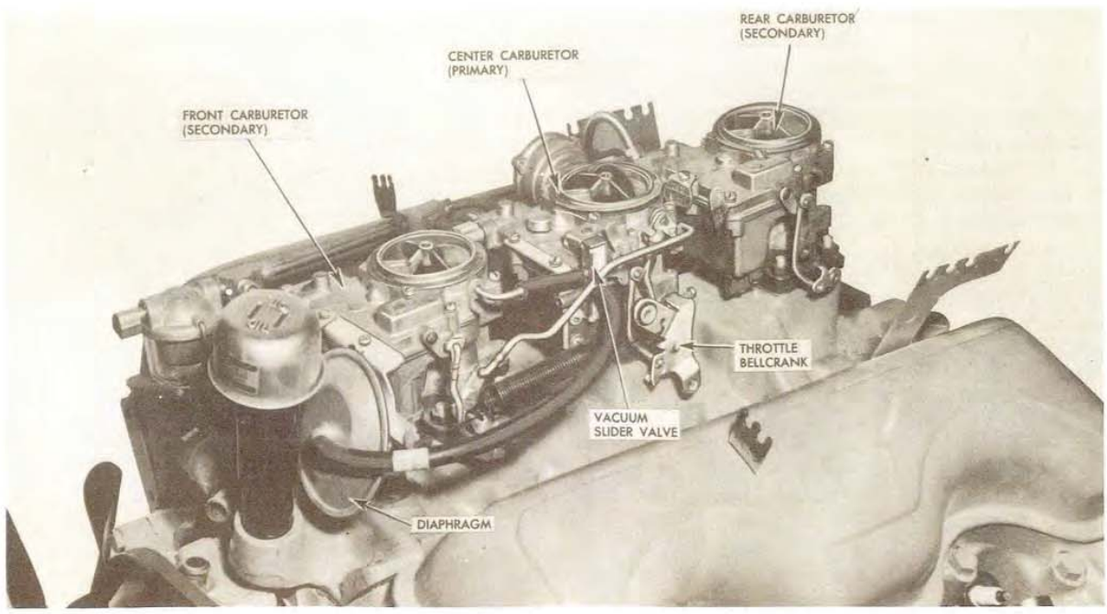


Fig. 21-32. Showing installation of three two-barrel carburetors on a Chevrolet V-8 engine.

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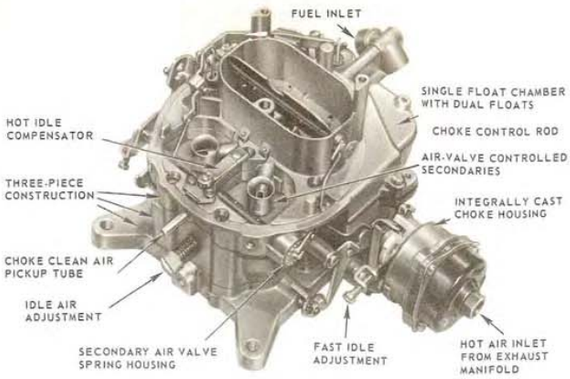


Fig. 21-33. Details of Autolite 4300 4-V carburetor. Note idle air adjustment.

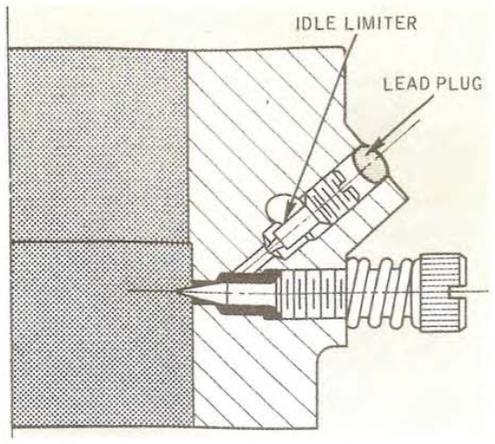


Fig. 21-35. Details of idle fuel limiter on Carter model YF carburetor.

Starting with 1968 models, most carburetors have been modified or recalibrated to provide leaner air-fuel mixtures to conform to the Federal regulations governing exhaust emissions.

These leaner mixtures result primarily from better control of the idle mixture, and from better combustion during periods of deceleration. In some cases the idle mixture screws have a finer pitch, making for more accurate control of the air-fuel ratio.

On Autolite carburetors, idle mixture adjustments are provided with an idler limiter device, Fig. 21-34, which sets a limit on enrichment of the idle mixture. Holley and single-venturi Carter carburetors contain a preset fixed mixture restriction in idle fuel passages that accomplishes the same thing, Fig. 21-35.

In the case of the Monojet carburetor used on six cylinder Chevrolet, Buick, Pontiac and Oldsmobile engines with automatic transmissions, an idle stop solenoid is used to stop engine "dieseling" after the ignition is turned off.

Idle rpm with exhaust emission control carburetors is slightly higher than normal and, in every case, must be accurately set to specified value. On the Monojet, Fig. 21-36, the idle speed is adjusted with the transmission in "drive"

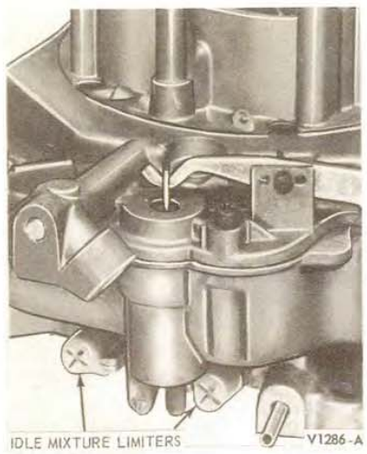


Fig. 21-34. Note idle mixture limiters on Autolite carburetor.

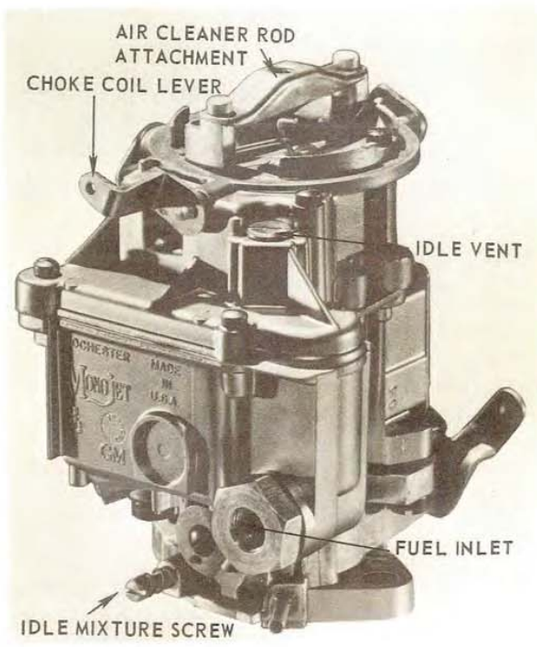


Fig. 21-36. Rochester Monojet carburetor is used on six cylinder Buick, Chevrolet, Oldsmobile and Pontiac engines.

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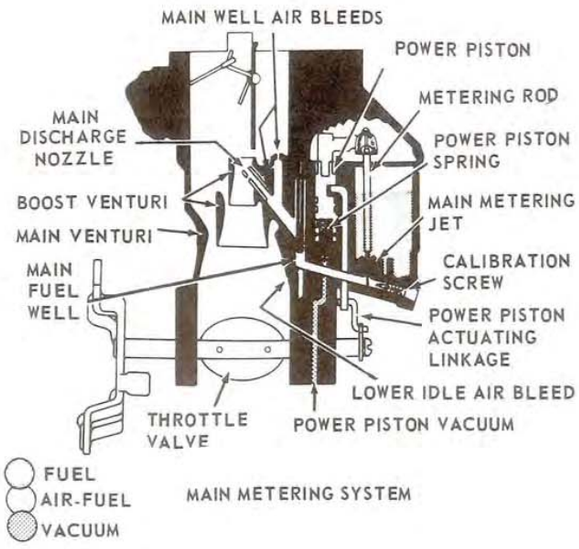


Fig. 21-37. Details of main metering system on Monojet carburetor.

position. When the owner is about to turn off the ignition, he places the transmission in "park" or "neutral." With the load off the engine, idle speed will rise to the 700 rpm range. With the engine running at that speed, plus higher operating temperatures and slightly retarded spark, "dieseling" may occur. The idle stop solenoid eliminates the possibility by closing the throttle valve when the ignition key is turned off.

The main metering system of the Monojet carburetor, Fig. 21-37, feeds fuel whenever air flow through the venturi is great enough to maintain fuel flow through the main discharge nozzle. The triple venturi stack-up is particularly sensitive to air flow. This means finer and more stable metering control from light to heavy loads, an important factor in the control of exhaust emissions.

The main metering system consists of the metering jet, a mechanical and vacuum-operated metering rod, main fuel well, main well air bleeds, fuel discharge nozzle and the triple venturi.

Power enrichment in the Monojet is obtained by the movement of a spring-loaded vacuum piston that senses changes in manifold vacuum. The amount of enrichment is controlled by the clearance between the groove in the power piston and the diameter of the power piston drive rod.

CARTER THERMO-QUAD CARBURETOR

One method of controlling hydrocarbon end carbon monoxide is to reduce the heat transfer to the fuel. The Carter Thermo-Quad carburetor installed on some Chrysler, Dodge and Plymouth engines has a float bowl made of molded phenolic resin which acts as an effective heat insulator, Fig. 21-38. A reduction of 20 deg. F over all-metal carburetors is claimed. The Thermo-Quad carburetor and others of the

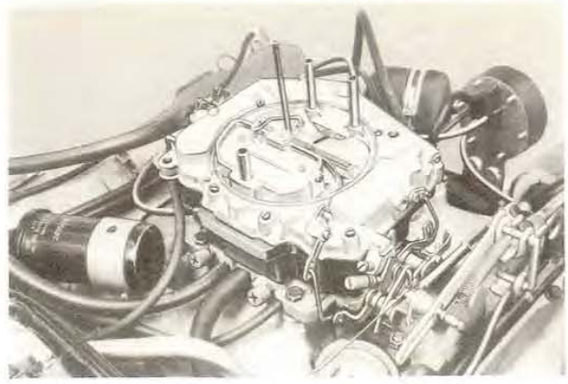


Fig. 21-38. Float bowl of this Carter Thermo-Quad carburetor is made of molded phenolic resin to reduce heat transfer.

Chrysler line form a part of the proportional exhaust gas recirculation (EGR) system, Fig. 21-39. The system includes a recirculation control valve and a vacuum sensor to insure proper flow of exhaust gas is proportional to vacuum sensed in the carburetor.

In this EGR system, a slot type port in the carburetor throttle body is exposed to an increasing percentage of manifold vacuum as the throttle valve opens. This throttle bore port is connected through an external nipple direct to the EGR valve. The flow rate is dependent on the manifold vacuum, throttle position and exhaust back pressure.

Recycling of exhaust gases is eliminated at wide-open throttle. This is done by calibrating the valve opening point above manifold vacuum available when the throttle valves are wide open, since port vacuum cannot exceed manifold vacuum. Elimination of wide-open throttle recycle provides maximum performance.

ROCHESTER 2GV CARBURETOR

The current Rochester 2GV carburetor has many features designed to reduce exhaust gas emissions. This carburetor uses calibrated cluster design that places the main well tubes, idle tubes, mixture passages, air bleeds and pump jets in a compact assembly. The cluster is removable for cleaning and inspection purposes.

The venturi cluster fits on a flat portion of the carburetor bowl in front of the main venturi with a gasket underneath. The idle and main well tubes are permanently installed in the cluster body by means of a precision press fit.

The main nozzles and idle tubes are suspended in the main wells of the float bowl. Removable plastic main well inserts surround the main fuel nozzles to insulate the nozzles and prevent percolation. The plastic inserts also provide smooth fuel flow through the main metering system during hot engine operation.

Rochester 2GC-2GE carburetors have similar construction. A sectional drawing in Fig. 21-40 shows the major parts of these carburetors.

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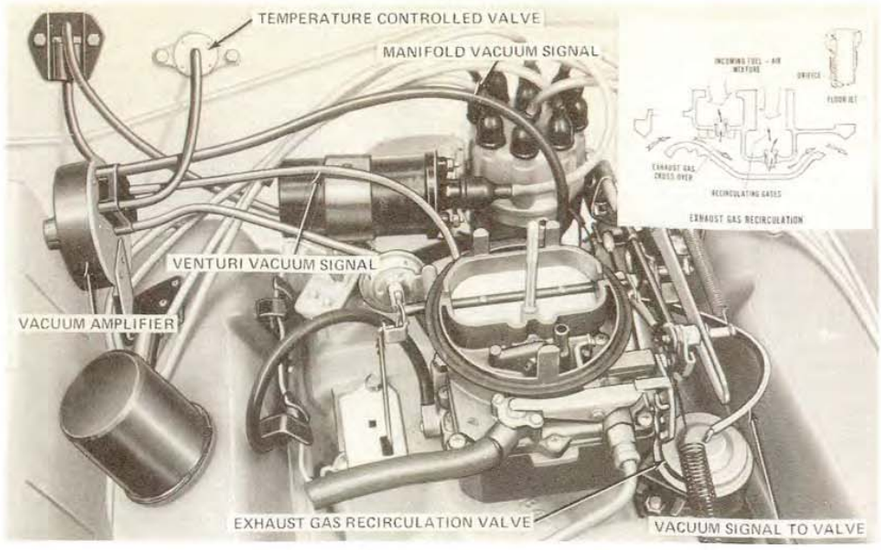


Fig. 21-39. Note details of proportional exhaust gas recirculation system installed on late model Chrysler Corp. engines.

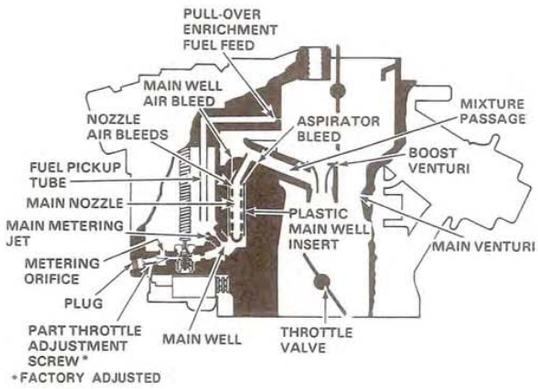


Fig. 21-40. Details of major parts of Rochester 2GC-2GE carburetors.

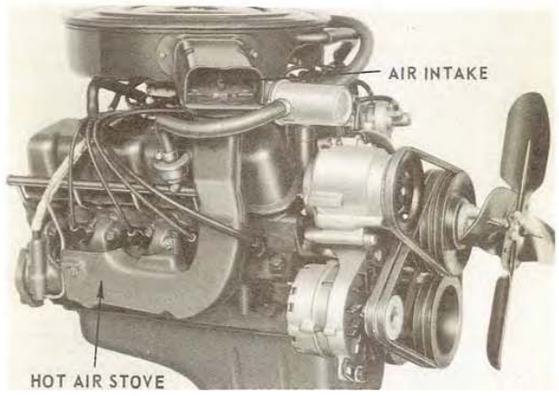


Fig. 21-41. Thermostatically controlled heated air intake is provided on modern carburetors. Ford 302 cu. in. V-8 is shown.

HOT AIR INTAKE – RAM AIR

Many of the carburetors designed for exhaust emission control have thermostatically controlled air intake systems. Hot air intake provides advantages ranging from improved cold start-up through warm-up and, more particularly, in more complete combustion and reduced exhaust by-products. The warm air is obtained from a heat stove on the exhaust manifold. See Ford design in Fig. 21-41. (Also see the chapters on AIR CLEANERS and EMISSION CONTROL.)

The Ford carburetor heated air intake system is equipped with a vacuum override control that opens the upper valve for direct air intake of unheated air for maximum air volume at full throttle opening. The override operates only when maximum air volume is needed for rapid acceleration. When high air volume is no longer needed, the override releases and the selector valve returns to the position indicated by underhood temperatures.

By placing carburetor intake air scoops at the front of the vehicle, full advantage is taken of air motion due to the speed of the car. This provides a ramming effect to the air entering the carburetor, and a degree of supercharging is obtained. Some Oldsmobiles with 400 cu. in. (6.6 litre), 10.5 to 1 compression ratio V-8 engines have scoops with 13 in. x 2 in. openings to feed ram air to the twin snorkels of the air cleaner.

FORD'S VARIABLE VENTURI CARBURETOR

Ford's Motorcraft model 2700 variable venturi carburetor, Figs. 21-42 and 21-43, varies the area of the venturi as a function of speed and load. Most other carburetors have

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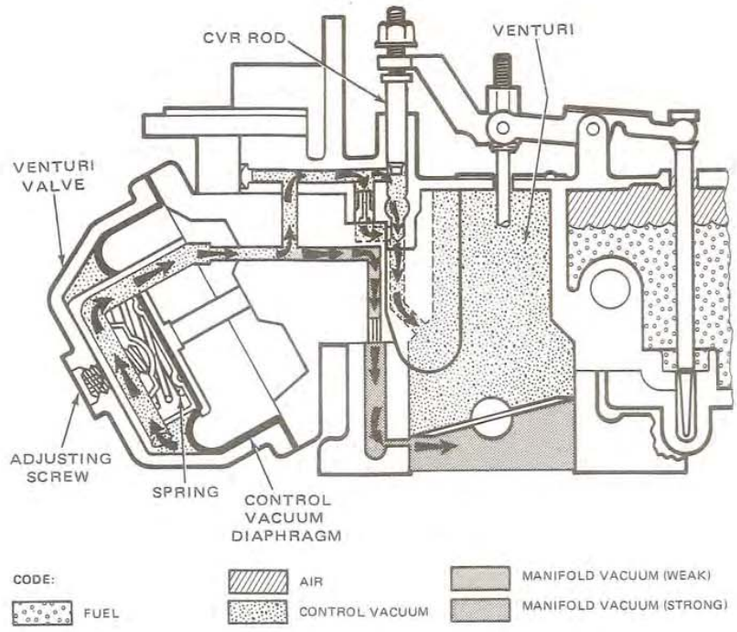


Fig. 21-42. In Ford's variable venturi carburetor, the venturi valve position is controlled by spring pressure and control vacuum. The spring pressure tends to close the valve. Control vacuum acts through a rubber diaphragm to open the valve. Control vacuum is vacuum below the venturi valve and above the throttle valves. See arrows in diagram.

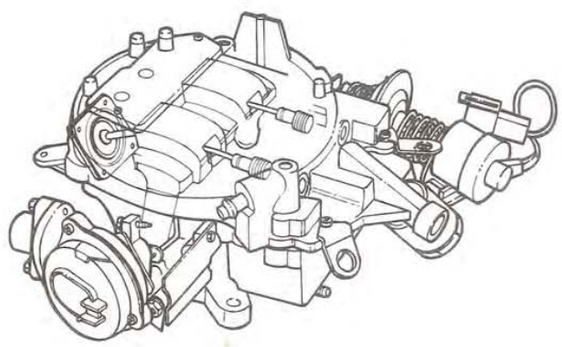


Fig. 21-43. Ford's Motorcraft variable venturi carburetor.

venturis that are fixed. In this design, changing the size of the venturi maintains sufficient air velocity and pressure drop to the main metering system. This is accomplished by means of tapered metering rods attached to the venturi valve, which changes the area of the venturi.

There is one rod and one jet for each bore of the carburetor. The rod moves back and forth in the jet when the air valve moves. When the venturi valve is closed, the largest diameter of the rod is in the jet. When the valve is wide open, the smallest diameter of the rod is in the jet. In that way, effective metering of the fuel is controlled by the position of the rod, Fig. 21-42.

SPECIAL FEATURES

Float spring: A requirement of fuel metering systems is that the fuel level in the float bowl be maintained at as near a constant level as possible. In the Holley 4150C carburetor, a float spring is incorporated under the float to keep the float in a stable position, Fig. 21-44.

Float needle valves: Instead of using steel for float needle valves, most carburetors are now using nylon or a similar material for their construction. A better seal is obtained and, in addition, the material has better wearing qualities. Also it is not readily affected by small foreign particles.

Secondary throttles: Four-barrel carburetors have two primary bores supplying air-fuel mixtures throughout the entire engine operation, while the two secondary bores function only when speed and load require them. At lower speeds, the secondary throttle plates remain closed.

When engine speed increases to a point where additional breathing capacity is required, vacuum is used to open the secondary throttle plates. Vacuum taken from one of the primary barrels, and the secondary barrels, acts on a diaphragm which controls the secondary throttle plates, Fig. 21-45.

CARBURETOR DEGASSER

The degasser, Fig. 21-46, is an auxiliary device built into the carburetor. It is used to correct the over-rich mixture condition that occurs when the throttle is closed suddenly.

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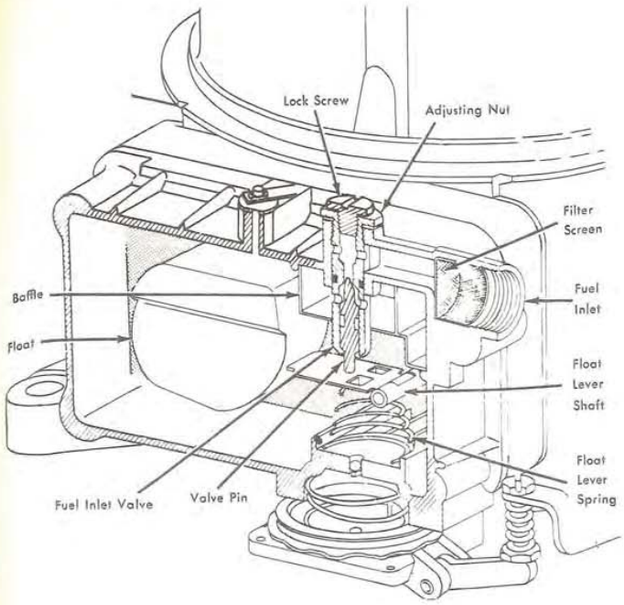


Fig. 21-44. Float lever spring helps steady action of float in maintaining a constant fuel level in float bowl.

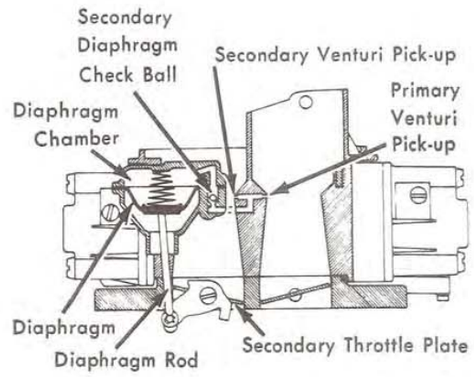


Fig. 21-45. Showing connections for operation of secondary throttle plate in a Holley carburetor.

Under this condition, abnormally high vacuum builds up above the throttle valve, resulting in too much fuel being drawn into the engine through the idle system.

The degasser consists of two die-cast housings clamped together with a diaphragm sandwiched between them. The diaphragm is attached to a plunger which actuates a walking beam, the end of which bears against a needle valve. Normally the valve is held off its seat by the spring. The upper diaphragm chamber is connected, by a bypass line, to an opening into the intake manifold above the throttle.

With the throttle in the idle position and the engine turning

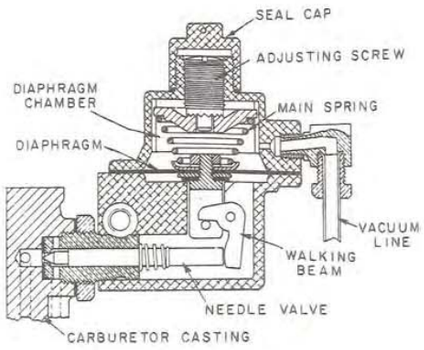


Fig. 21-46. Details of Bendix degasser.

over at idle speed, the proper amount of fuel is drawn through the idle jet. During periods of deceleration, the engine rpm will be much higher than normal idle rpm, causing the vacuum in the passages above the throttle plate to rise much higher than at normal idle speeds.

With the degasser in operation, the abnormally high vacuum during deceleration is transferred to the chamber above the diaphragm, raising the plunger and compressing the diaphragm spring. This movement actuates the walking beam to force the needle valve against its seat to shut off the flow of fuel through the idle hole.

As engine speed approaches idle, and intake manifold vacuum decreases to normal, the diaphragm is forced down by the spring. This backs off the walking beam, which unseats the needle valve and restores the flow of fuel to the idle hole.

DECEL VALVE

Some recent model cars, such as the Ford Pinto, are equipped with a decel valve which is designed to meter to the engine an additional amount of fuel and air during engine deceleration. This additional amount of fuel and air together with engine modification, permits more complete combustion with resultant lower levels of exhaust emissions.

During periods of engine deceleration, manifold vacuum forces the diaphragm assembly against the spring, Fig. 21-47, which, in turn, raises the decel valve. With the valve open, existing manifold vacuum pulls a metered amount of air and fuel from the carburetor through the valve body assembly into the intake manifold. The decel valve remains open and continues to feed additional air and fuel for a specified time.

THROTTLE SOLENOID

The Autolite-Weber model 5200 carburetor installed on the Ford Pinto 2000 cc engine is equipped with a throttle solenoid adjustment designed to control idling speed on automatic transmission-equipped cars. The curb idle is adjusted by turning the throttle solenoid plunger. First disconnect the throttle solenoid wire, then, set the lower curb idle speed screw. Connect the throttle solenoid wire, open the throttle

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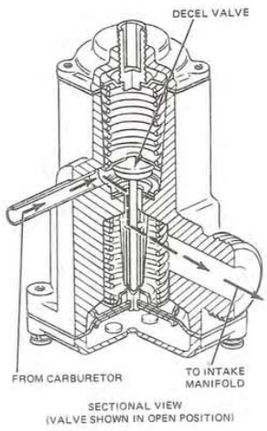


Fig. 21-47. Sectional view of decel valve showing valve in open position.

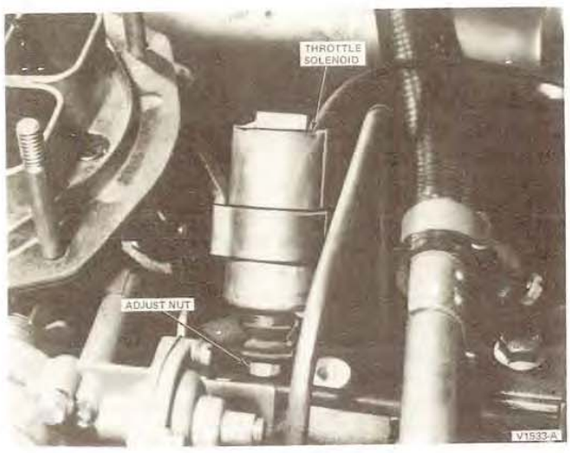


Fig. 21-48. Throttle solenoid adjustment on Autolite-Weber model 5200 carburetor.

slightly by hand to allow the plunger to extend, then, set the higher curb idle speed by turning the solenoid plunger, Fig. 21-48.

SMALL ENGINE CARBURETORS

Many of the basic principles found in large carburetors are also incorporated in carburetors used on small engines. This is particularly true in the case of engines used on many lawn mowers, Fig. 21-49. Carburetors using the float system of controlling fuel flow are good examples of this similarity.

Two cycle engines designed to operate at varying angles (chain saws) are often equipped with a floatless carburetor. On these installations, a diaphragm type carburetor is used

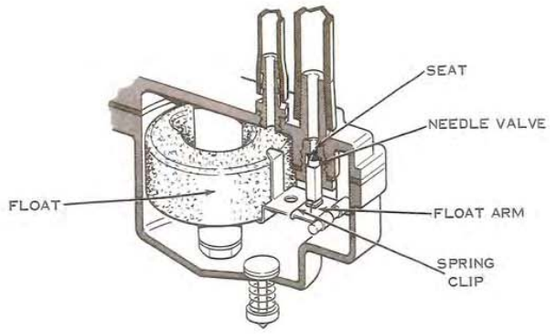


Fig. 21-49. Some small engines use float type carburetors. Note similarity of float bowl parts to large automotive carburetor parts.

because it will function at a steep angle or even in an inverted position for a short time.

Diaphragm type carburetors use the upper part of the unit for carburetion, while the lower part houses a fuel pump. The two parts are bolted together to form a single assembly.

The pump utilizes the positive and negative pressure pulsations in the crankcase for its operation. Fuel is delivered to the inlet supply channel either by the integral fuel tank or by gravity.

When the engine is idling at nearly closed throttle, fuel is drawn through an idle tube or, for inverted operation, past the idle adjusting screw and into the engine via the primary idle discharge port.

As the throttle is opened progressively, the vacuum at idle position is nearly eliminated, but the increase in air velocity through the venturi puts increased vacuum on the nozzle to unseat a nylon ball. The nozzle then delivers the power mixture metered in relation to the demands of the engine.

In the case of the suction feed carburetor fuel system, the fuel tank is mounted below the carburetor, Fig. 21-50.

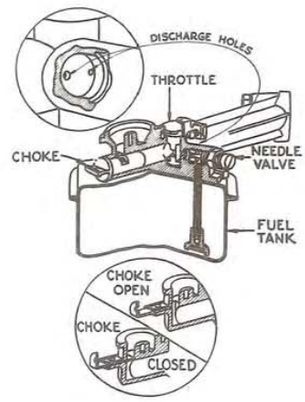


Fig. 21-50. Sectional view of suction feed carburetor used on lawn mowers and similar small engines.

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Atmospheric pressure is utilized as the force to move the fuel. The fuel tank cap is vented to allow pressure in the tank to remain constant. As the piston goes down on the intake stroke with the throttle open, a low pressure is created in the carburetor throat. A slight restriction is placed between the air horn and the carburetor throat and the choke. This helps maintain the low pressure.

Therefore, the difference in pressure in the tank and in the carburetor throat forces the fuel up the fuel pipe, past the needle valve, through the two discharge holes. The throttle is relatively thick on this type of carburetor, so there is in effect a venturi at this point to aid vaporization. A spiral is placed in the throat to help acceleration and also to help keep the engine from dying when the throttle is opened suddenly.

The amount of fuel flowing at operating speed is metered by the needle valve and seat. Because of its compact design, the suction feed carburetor fuel system is used primarily on lawn mower engines.

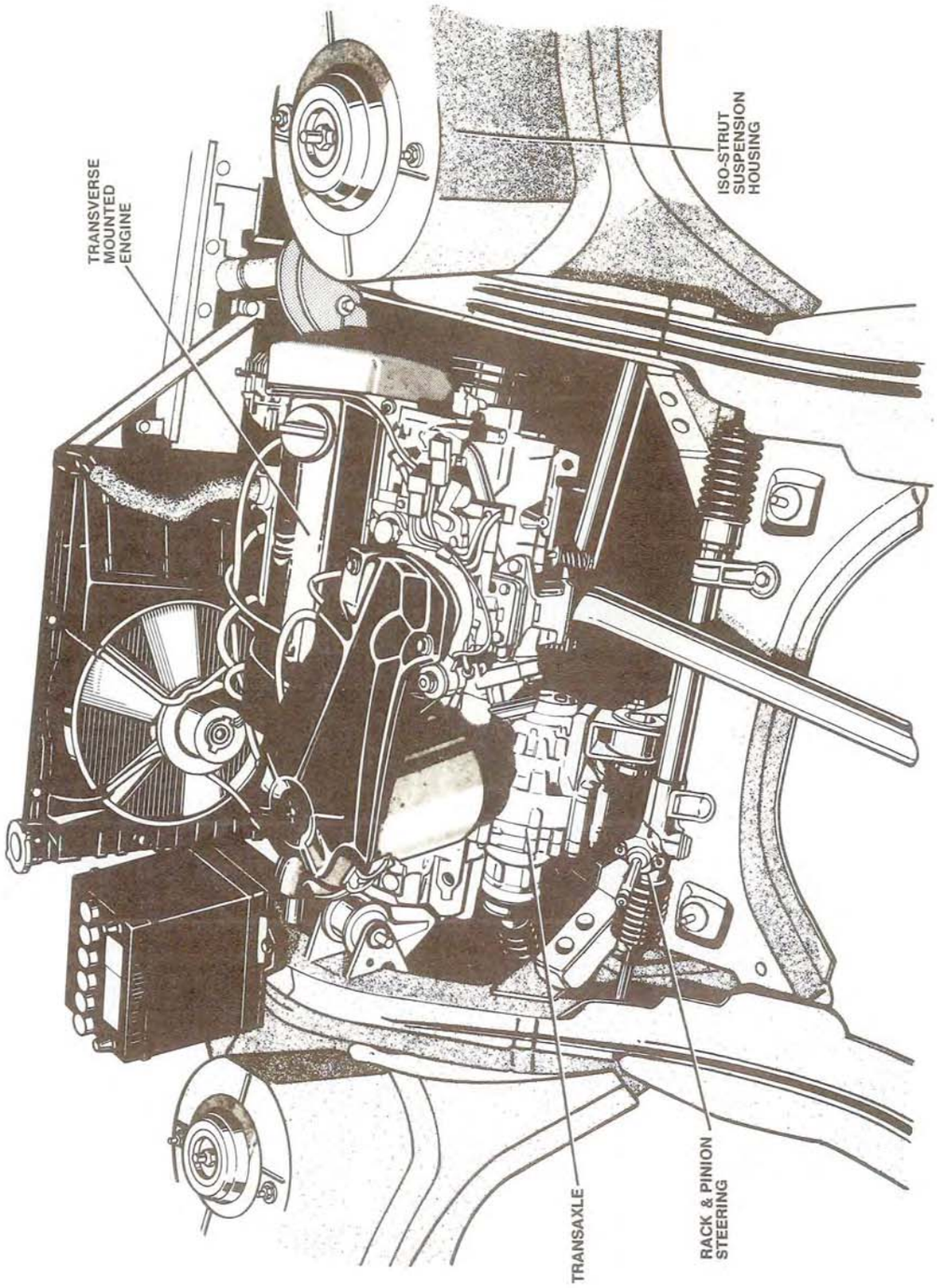
REVIEW QUESTIONS – PRINCIPLES OF CARBURETION

1. What is the purpose of the fuel system in an internal combustion engine?
2. List the main parts of a fuel system.
3. The rate of flow through a carburetor is the same under all operating conditions. True or False?
4. When starting an internal combustion engine, the fuel mixture should be:
   a. Rich.
   b. Lean.
   c. Average.
5. Which speed requires a richer mixture?
   a. Idling.
   b. 30 mph.
6. Will all cylinders of a multi-cylinder engine receive an air-fuel mixture having the same octane rating?
7. For normal operating conditions, what air-fuel ratio will give the best economy?
   a. 16 to 1.
   b. 20 to 1.
   c. 25 to 1.
8. For quick acceleration, what is the best air-fuel ratio?
   a. 5 to 1.
   b. 10 to 1.
   c. 12 to 1.
   d. 20 to 1.
9. Are the molecules forming a gas held more tightly together than those of a metal?
10. Name two factors affecting the rapidity of evaporation.
11. What causes the air-fuel mixture to be drawn into the combustion chamber of an internal combustion engine?
12. The purpose of a venturi in a carburetor is to:
    a. Increase speed of air passing through carburetor.
    b. Maintain correct air-fuel ratio.
    c. Provide extra fuel for acceleration.
13. There are five main circuits in a modern carburetor. Name four of them.
14. In a carburetor venturi, which point has the highest vacuum?
    a. Entrance to the venturi.
    b. Narrowest point of the venturi.
    c. Point one inch beyond the venturi.
15. The idle system of a carburetor supplies fuel at what speeds?
    a. Idle speed only.
    b. Speeds up to 40 mph.
    c. Speeds up to 25 mph.
16. How many fuel discharge ports does the conventional idle system have?
    a. One.
    b. Two.
    c. Three.
    d. Four.
17. When the idle system is no longer supplying fuel to the engine, which system then supplies fuel?
    a. Air bleed system.
    b. Main system.
    c. Vaporizing system.
18. The purpose of an economizer valve is to supply more fuel, or less fuel?
19. The metering rod is designed to vary the size of which jets?
    a. Idle jets.
    b. Accelerating jets.
    c. High speed jets.
    d. Float level jets.
20. Under what conditions is ice most likely to form in a carburetor?
    a. 20 deg. below zero and high humidity.
    b. 32 deg. above zero and high humidity
    c. Zero deg. and low humidity.
21. On what type of car are you most likely to find an anti-stall dashpot?
    a. Cars with automatic transmission.
    b. Cars with conventional transmission.
    c. Cars fitted with 1 Bbl. carburetors.
    d. Cars fitted with 4 Bbl. carburetors.
22. In addition to updraft and downdraft carburetors, what other basic type is there?
23. The calibrated cluster in the Rochester 2GV carburetor cannot be removed from the carburetor. True or False?

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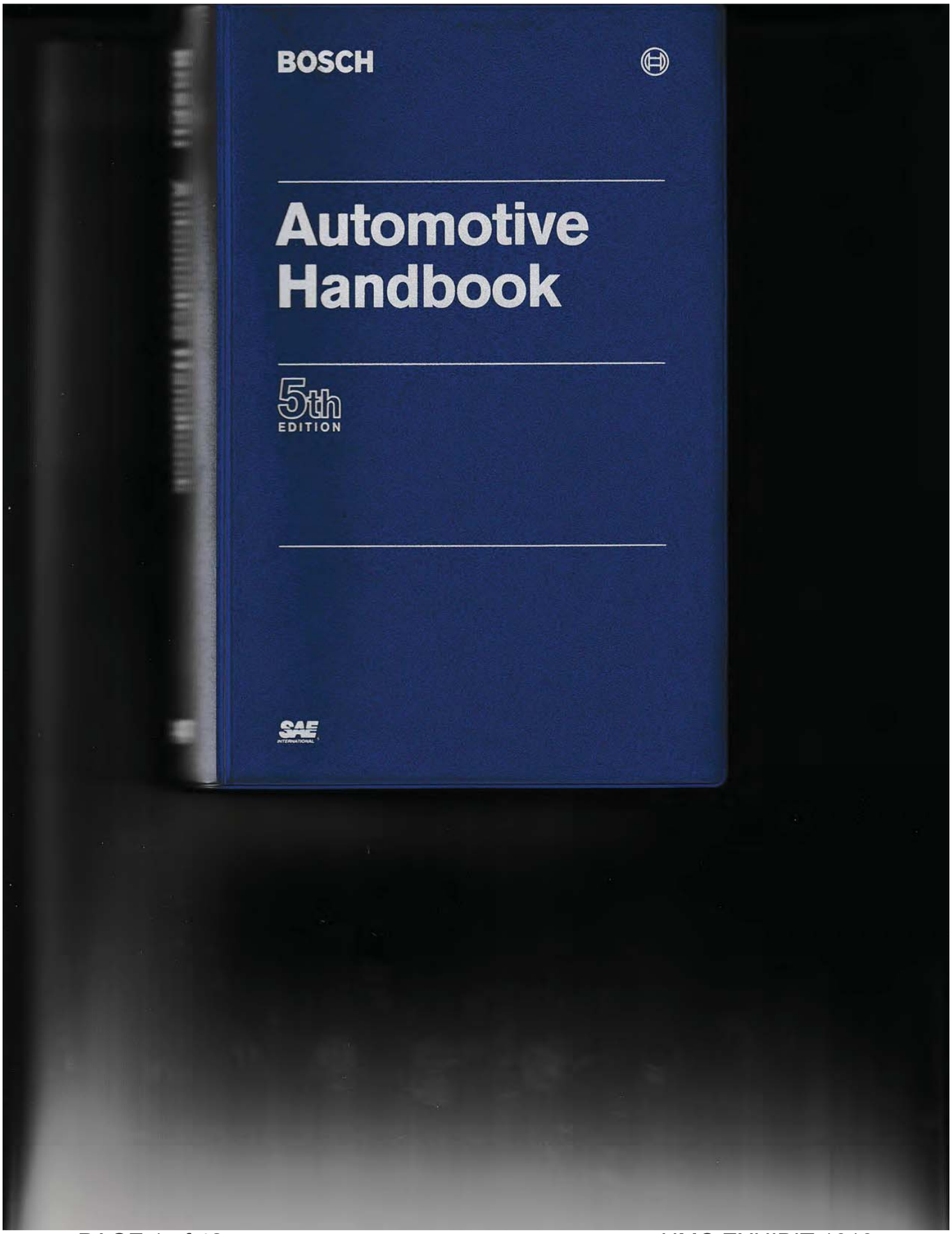


The Dodge Omni four cylinder engine is mounted transversely and is combined with a transaxle to power the front wheels. Note carburetor and unique air cleaner.

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Foreword to the 5th Edition

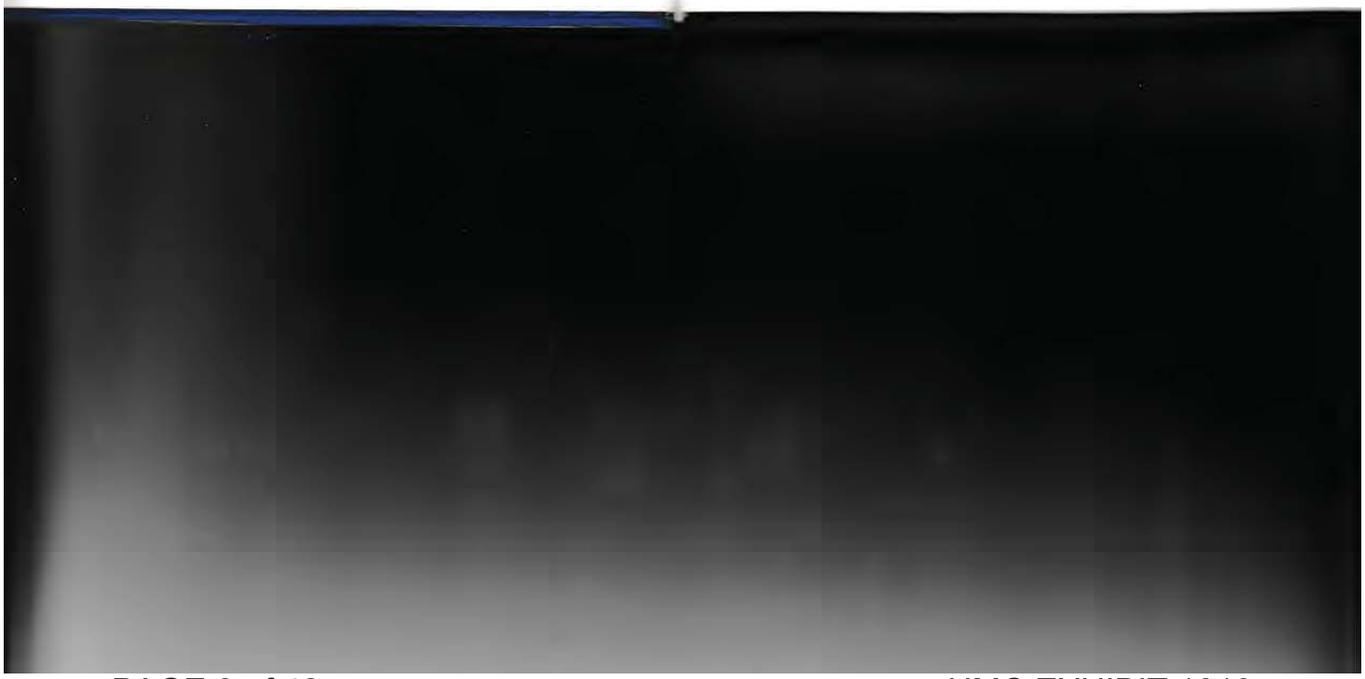
The "Automotive Handbook", a reliable guide full of up-to-date and concise information, has grown over a period of six decades from a calendar supplement of 96 pages to a 960-page reference work. In that time, over a million copies have been produced worldwide and the text translated into numerous languages.
The 5th edition, in common with its predecessors, is supported by two main pillars: the expertise of the technical staff at our company and in the automotive industry. They have fully revised the contents of this manual and brought it completely up to date. Thanks are due to all those involved.
This book is intended primarily as a source of important facts and figures and as a review of present-day technology for the automotive engineer and technician, but also for anyone else with an interest in technical matters. Accordingly, the automotive technology content is restricted to passenger cars and commercial vehicles, and the remaining content to that required for practical purposes.
Within the framework of a pocketbook it is impossible to present detailed coverage of individual technical subjects. On the other hand, bearing in mind the very wide range of readers, we do not want to dispense with generally applicable topics and data. However, we have dispensed with the "Conversion Tables" as the calculator is now an everyday item of equipment and any figure required can easily be calculated using the conversion formulas provided. The chapter "Road Traffic Legislation (Germany)" has also been deleted due to the international usage of the booklet.
These deletions have made way for new and updated topics which have added an extra 70 pages to the book.
We recommend readers to scan through the "Automotive Handbook" in order to gain an overall impression before using it.

The Editors

For your information

The following topics have been updated/extended since the 4th edition:
Vibration • Acoustics • Electronics (integrated circuits, micromechanics, mechatronics, sensors) • Statistics• Reliability • Closed and open-loop control systems • Materials technology (basic principles, materials, lubricants, fuels, consumables) • Corrosion • Hardness • Calculating fuel consumption • Vehicle dynamics.
Internal-combustion engines (direct fuel injection, diesel combustion systems) • Engine cooling (cooling-module technology, thermomanagement, exhaust cooling) • Turbochargers and superchargers (multistage) • Engine management on gasoline engines (mixture control, fuel-injection systems, fuel injectors, spark plugs, ME-Motronic, exhaust gases) • Engine management on diesel engines (axial/radial-piston pumps, injectors, exhaust gases, start-assist systems).
Electric drive units • Drivetrain (transmission, traction control systems (TCS) for passenger cars and commercial vehicles) • Steering • Braking systems (ABS for passenger cars, ABS and EBS for commercial vehicles) • Bodywork, commercial vehicles • Lighting systems (stepped reflectors, Bi-Litronic, headlamps and lights). Car radios • Park Pilot systems • Navigation systems • Vehicle information systems • Mobile phones • Safety and security systems (impact detection, interior-movement detection) • Automotive hydraulics (electric proportional control valves).
Circuit diagrams and symbols • Vehicle electrical system (batteries, battery testers, water-cooled alternators, electromagnetic compatibility (EMC))
Passenger-car specifications.

The following topics have been introduced:
Fuel filters • MED-Motronic • Natural gas operation (spark-ignition engines) • Fuel cells • EHB for passenger cars • Automatic Cruise Control (ACC) • Instrumentation • Traffic telematics • Car radios (DAB) • Connectors • Cartronic.
and the following have been dropped:
Conversion tables • Road traffic legislation (Germany).



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Authors of the 5th Edition[1])

Quantities, units
Dipl.-Ing. G. Brüggen
Vibration and oscillation
Dipl.-Ing. J. Bohrer
Mechanics
Dipl.-Ing. G. Brüggen
Strength of materials
Dr.-Ing. M. Bacher-Höchst
Acoustics
Dr. rer. nat. W. Keiper
Heat
Dipl.-Ing. W. Daniel
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Dr. rer. nat. W. Draxler,
Dipl.-Ing. B. Wörner
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Dr. rer. nat. U. Schaefer;
Dr. rer. nat. P. Egelhaaf;
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Dipl.-Ing. M. Graf
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Dipl.-Math. H.-P. Bartenschlager
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Dr. rer. nat. E. Dilger; Dr. rer. nat. H. Weiler
Data processing in the motor vehicle
Dr. rer. nat. V. Denner
Control engineering
Dr. techn. R. Karrelmeyer

Materials
Dr. rer. nat. J. Ullmann;
Dr. rer. nat. W. Draxler; Dr.-Ing. D. Wicke;
Dipl.-Ing. D. Weidemann,
DaimlerChrysler AG, Sindelfingen;
Dr. rer. nat. H.-J. Spranger;
Dr. rer. nat. H. P. Koch;
Dipl.-Ing. R. Mayer;
Dipl.-Ing. G. Lindemann;
Dipl.-Ing. (FH) W. Hasert; R. Schäftlmeier;
Dipl.-Ing. H. Schneider;
Dipl.-Chem. Dr. W. Reckordt,
BASF Coatings AG, Münster;
Dr. rer. nat. G. Dornhöfer;
Dr. rer. nat. B. Blaich; Dr. rer. nat. D. Welting
Corrosion
Dipl.-Chem. B. Moro
Heat treatment, hardness
Dr.-Ing. D. Liedtke

Tolerances
Ing. (grad.) J. Pfänder
Sliding bearings and rolling bearings
Dr.-Ing. R. Heinz
Spring calculations
Dipl.-Ing. O. Krickau
Gears and tooth systems
Dipl.-Ing. U. v. Ehrenwall
Belt drives
C. Hansen
Basic principles of threaded fasteners
Dipl.-Ing. O. Krickau; Dipl.-Ing. M. Nöcker

Joining and bonding techniques
Dr.-Ing. M. Witt,
Volkswagen AG, Wolfsburg

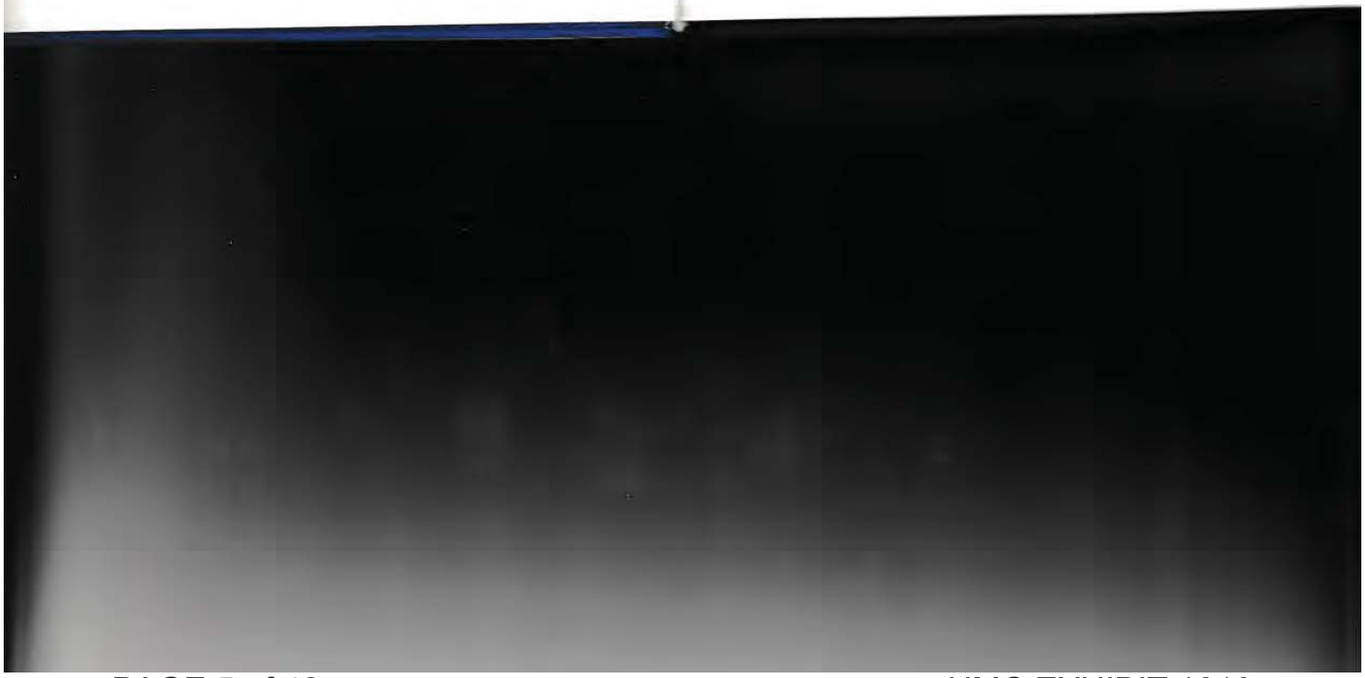
Sheet-metal processing
Ing. W. Gertler, Volkswagen AG, Wolfsburg; Dr.-Ing. M. Witt, Volkswagen AG, Wolfsburg

Tribology, wear
Dipl.-Ing. H. Schorr

Road-going vehicle requirements
Prof. Dr. K. Binder, DaimlerChrysler AG, Stuttgart; Dipl.-Ing. G. Moresche, DaimlerChrysler AG, Stuttgart

Motor-vehicle dynamics
Dipl.-Ing. G. Moresche,
DaimlerChrysler AG, Stuttgart;
Prof. Dr.-Ing. habil. E.-C. v. Glasner,
DaimlerChrysler AG, Stuttgart;
Dr.-Phys. H. Böckenhoff,
DaimlerChrysler AG, Stuttgart;
Dr.-Ing. H. Steinkampf, Institut für Betriebstechnik der FAL, Braunschweig

[1]) Unless otherwise stated, the above are all employees of Robert Bosch GmbH.



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Environmental stresses
Dipl.-Ing. G. Adalbert

Internal-combustion (IC) engines
Prof. Dr. K. Binder,
DaimlerChrysler AG, Stuttgart;
Dr.-Ing. H. Hiereth,
DaimlerChrysler AG, Stuttgart

Engine cooling
Dipl.-Ing. (FH) J.Wolf,
Behr GmbH & Co, Stuttgart

Fuel and air filters
Dr.-Ing. G.-M. Klein, Filterwerk
Mann und Hummel, Ludwigsburg;
Dr.-Ing. M. Tumbrink, Filterwerk
Mann und Hummel, Ludwigsburg

Turbochargers and superchargers
Dipl.-Ing. A. Förster, AG 3K-Warner
Turbosystems GmbH, Frankenthal

Exhaust systems
Dipl.-Ing. W. Steinle,
Eberspächer KG, Esslingen

Engine management for gasoline engines
Dipl.-Ing. J. Gerhardt
Ignition
Dipl.-Ing. R. Schleupen; Dipl.-Ing. D. Betz;
Dipl.-Ing. E. Breuser; Dipl.-Ing. W. Häming
Fuel supply and delivery, mixture formation
Dipl.-Ing. A. Gerhard; Dipl.-Ing. J. Gerhardt
Carburetors
Dr.-Ing. D. Großmann, Neuss
Gasoline fuel-injection systems
Dipl.-Ing. G. Felger;
Dipl.-Ing. M. Lembke;
Ing. (grad.) L. Seebald;
Dipl.-Ing. H. Deichsel

Combined ignition and fuel-injection system (Motronic)
Dipl.-Ing. J. Gerhardt

Gasoline engines for alternative fuels
J. van der Weide,
TNO Road-Vehicles Research Institute,
Delft, Netherlands;
Dipl.-Ing. (FH) T. Allgeier;
Ing. (grad.) L. Seebald;
Dipl.-Ing. M. Klenk

Exhaust emissions from gasoline engines
Dr. rer. nat. M. Streib; Dr.-Ing. G. König;
Dipl.-Ing. E. Schnaibel

Engine management for diesel engines
Dr.-Ing. L. Schulze, Otto-von-Guericke
University (IMKO), Magdeburg;
Dipl.-Ing. K. Hummel; Dr.-Ing. W. Fuchs;
Dr.-Ing. R. Maier, Dr.-Ing. H. Stutzenberger
Start-assist systems
Dipl.-Ing. C. Kern; Dr. rer. nat. H.-P. Bauer
Exhaust emissions from diesel engines
Dr.-Ing. L. Schulze, Otto-von-Guericke
University (IMKO), Magdeburg

Starting systems
Dipl.-Ing.(FH) W. Rühle

Electric drives
Dr.-Ing. B. Sporckmann,
RWE Energie AG, Essen

Hybrid drives
Prof. Dr.-Ing. C. Bader,
DaimlerChrysler AG, Stuttgart
Fuel cells
Dr. rer. nat. U. Alkemade;
Dr. rer. nat. A. Häbich
Drivetrain
Dipl.-Ing. P. Köpf, Zahnradfabrik
Friedrichshafen AG ;
Dr. rer. nat. M. Schwab, Zahnradfabrik
Friedrichshafen AG;
Dr.-Ing. G. Schmidt; Dr.-Ing. H. Schramm

Suspension, suspension linkage
Dipl.-Ing. P. Dick,
Dipl.-Ing. J. Wimberger,
Dipl.-Ing. A. Mrotzek,
Dipl.-Ing. H. Stein,
all authors Bayerische Motoren Werke AG,
Munich

Wheels
Dipl.-Ing. R. Braun,
DaimlerChrysler AG, Stuttgart;
Prof. Dr.-Ing. habil. E.-C. v. Glasner,
DaimlerChrysler AG, Stuttgart

Tires
Dipl.-Ing. B. Meiß,
Continental AG, Hanover;
Prof. Dr.-Ing. habil. E.-C. v. Glasner,
DaimlerChrysler AG, Stuttgart

Steering
Ing. (grad.) D. Elser, Zahnradfabrik
Friedrichshafen AG, Schwäbisch Gmünd
Braking systems
Dr. rer. nat. J. Bräuninger; Prof. Dr.-Ing.
habil. E.-C. v. Glasner, DaimlerChrysler
AG, Stuttgart; Dipl.-Ing. (FH) K.-H. Röß,
DaimlerChrysler AG, Stuttgart;
Dr.-Ing. G. Schmidt; Dr.-Ing. H. Schramm;
Dipl.-Ing. W. Brühmann

Electronic Stability Program (ESP)
Dr.-Ing. A. van Zanten; Dipl.-Ing. G. Pfaff;
Dr.-Ing. R. Erhardt
Adaptive Cruise Control (ACC)
Dr. rer. nat. H. Winner;
Dr. rer. nat. H. Olbrich

Road-vehicle systematics
Dipl.-Ing. D. Weidemann, DaimlerChrysler
AG, Sindelfingen

Vehicle bodies, passenger cars
Dipl.-Ing. D. Weidemann, DaimlerChrysler
AG, Sindelfingen
Vehicle bodies, commercial vehicles
Dr.-Phys. H. Böckenhoff,
DaimlerChrysler AG, Stuttgart

Lighting
Dr.-Ing. M. Hamm; Dipl.-Ing. D. Boebel;
Dipl.-Ing. T. Spingler
Signaling devices and alarm systems
Dipl.-Betriebsw. C. Giek;
Dipl.-Ing.(FH) H. Hennrich

Windshield and headlamp cleaning
Dr.-Ing. J.-G. Dietrich

Heating, ventilation and air-conditioning (HVAC)
Dipl.-Ing. G. Schweizer,
Behr GmbH & Co, Stuttgart

Instrumentation
Prof. Dr. P. Knoll, Dr.-Ing. B. Herzog
Car radios, DAB
S. Rehlich; Dipl.-Ing. G. Spreitz

Parking systems
Dipl.-Ing. (FH) H. Arnold

Trip recorders
Mannesmann Kienzle GmbH,
PR-Abteilung, Villingen-Schwenningen

Navigation systems, traffic telematics
Dipl.-Ing. E. P. Neukirchner
Mobile radio
Dr.-Ing. J. Wazeck
Motor-vehicle information systems
Dr. rer. nat. D. Elke

Safety, comfort and convenience systems
Dipl.-Ing. B. Mattes;
Dipl.-Ing. R. Kurzmann;
Dr.-Ing. G. Hartz; A. Walther

Automotive hydraulics
Dipl.-Ing. H. Lödige;
Dipl.-Ing. K. Griese;
Ing. (grad.) D. Bertsch;
Dipl.-Ing. W. Kötter;
Dipl.-Ing. M. Bing;
Dipl.-Ing. (FH) W. Steudel;
Dipl.-Ing. G. Bredenfeld

Automotive pneumatics
Ing. (grad.) P. Berg

Symbols, conductor-size calculations
The editorial staff

Plug-in connections
Dipl.-Ing. W. Gansert

Power supply
Dipl.-Ing. F. Meyer

Starter batteries
Dr.-Ing. G. Richter

Alternators
Dr.-Ing. H.-P. Gröter

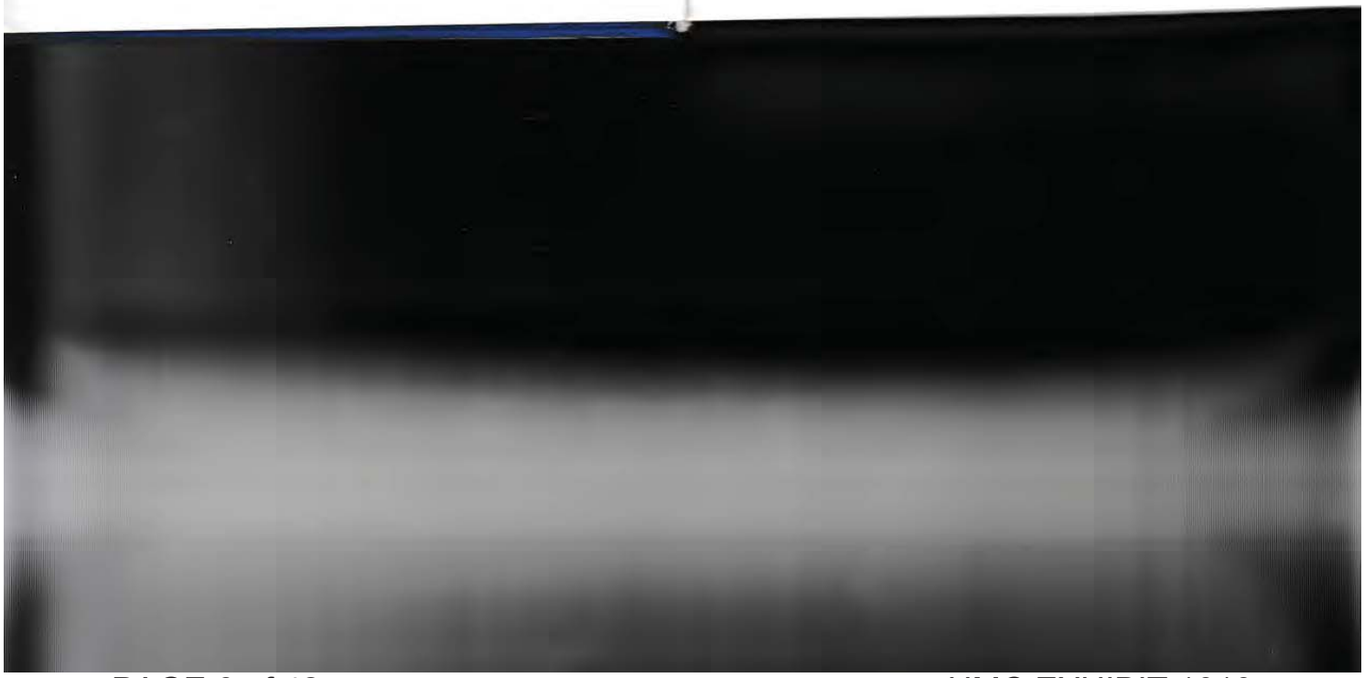
Controller Area Network (CAN)
Dr.-Ing. M. Walther

CARTRONIC
Dr. rer. nat. J. Maier

Electromagnetic compatibility (EMC)
Dr.-Ing. W. Pfaff

Testing technology
Dr. rer. nat. W. Stöffler; R. Heinzmann;
L. Vogel; Dipl.-Ing.(FH) F. Zauner

Passenger-car specifications
R. Helfer



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Heat

Symbols and units

See PP. 12 ... 18 for names of units, P. 26 for conversion of heat units and P. 180 for thermal expansion, heat of fusion, heat of evaporation.

Quantity		SI unit
A	Area, cross-section	m^2
c	Specific heat capacity	J/(kg · K)
	c_p isobaric (constant pressure)	
	c_v isochoric (constant volume)	
H	Enthalpy (heat content)	J
k	Heat transmission coefficient	W/(m² · K)
m	Mass	kg
p	Pressure	Pa = N/m²
Q	Heat	J
$\dot{Q}$	Heat flow = Q/t	W
R_m	Molar gas constant = 8.3145 J/(mol · K) (same for all gases)	J/(mol · K)
R_i	Special gas constant $R_i = R_m/M$ (M = molecular weight)	J/(kg · K)
S	Entropy	J/K
s	Distance	m
T	Thermodynamic temperature $T = t + 273.15$	K
ΔT	Temperature difference $= T_1 - T_2 = t_1 - t_2$	K
	T_1, t_1 higher temperature	
	T_2, t_2 lower temperature	
t	Celsius temperature	°C
V	Volume	m³
v	Specific volume	m³/kg
W	Work	J
z	Time	s
α	Heat transfer coefficient α_a external, α_i internal	W/(m² · K)
ε	Emissivity	–
λ	Thermal conductivity (see P. 17 for values)	W/(m · K)
ϱ	Density	kg/m³

Conversion from outdated units
(see also PP. 16 and 17)
1 kcal (kilocalorie) = 4186.8 J
= 4200 J = 4.2 kJ
1 kcal/(m · h · grd) = 1.163 W/(m · K)

Enthalpy (heat content)

$$H = m \cdot c \cdot T$$

Enthalpy difference (ΔH) is the quantity of heat released (Q) as a result of a change in temperature ($\Delta T = T_1 - T_2$)

$$\Delta H = H_1 - H_2 = Q$$
$$= m \cdot c \cdot \Delta T = V \cdot \varrho \cdot c \cdot \Delta T$$

Heat transfer

Heat is transferred in three different ways:
Thermal conduction: Heat is conveyed inside a solid, liquid or gaseous body by contact between the particles.
Convection: Heat is conveyed by the particles of a moving liquid or gaseous body. In natural or free convection, the state of motion is brought about by the effect of buoyancy; in forced convection, however, the motion is maintained artificially.
Radiation: Heat is transferred from one body to another by electromagnetic waves without a material carrier.

Thermal conduction

The heat flow in a body of constant cross section A between two parallel cross-sectional planes separated by a distance s at a temperature difference ΔT is

$$\dot{Q} = \frac{\lambda}{s} \cdot A \cdot \Delta T$$

Thermal radiation

Empty space and air are pervious to thermal radiation. Solid bodies and most liquids are impervious to thermal radiation, as are various gases to certain wavelengths.

The thermal radiation emitted by the area A at temperature T is

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4$$

where $\sigma = 5.67 \cdot 10^{-8}$ W/(m² · K⁴) is the radiation constant of the black-body radiator[1]) and ε is the emissivity of the surface area (see table on opposite page).

Emissivity ε
up to a temperature of 300 °C (573 K)

Black-body radiator[1])	1.00
Aluminum, unmachined	0.07
Aluminum, polished	0.04
Ice	0.90
Enamel paint, white	0.91
Glass	0.93
Cast iron, rough, oxidized	0.94
Cast iron, turned	0.44
Wood, smooth	0.90
Lime mortar, rough, white	0.93
Copper, oxidized	0.64
Copper, polished	0.05
Brass, matt	0.22
Brass, polished	0.05
Nickel, polished	0.07
Oil	0.82
Paper	0.80
Porcelain, glazed	0.92
Soot	0.93
Silver, polished	0.02
Steel, matt, oxidized	0.96
Steel, polished, oil-free	0.06
Steel, polished, oiled	0.40
Water	0.92
Bricks	0.93
Zinc, matt	0.23
Zinc, polished	0.05
Tin, polished	0.06

Transmission of heat through a wall

The heat flow through a wall of area A and thickness s at a temperature difference ΔT is:

$$\dot{Q} = k \cdot A \cdot \Delta T$$

The heat transmission coefficient k is calculated as follows:

$$1/k = 1/\alpha_i + s/\lambda + 1/\alpha_a$$

Thermal resistance

Thermal resistance is composed of the thermal resistance of the individual layers of the wall:

$$s/\lambda = s_1/\lambda_1 + s_2/\lambda_2 + \ldots$$

See P. 186 for the thermal conductivity λ of various materials.

[1]) A "black-body radiator" completely absorbs all incident light and heat radiation directed against it; and therefore when heated radiates the maximum amount of light which can be emitted by a body. An example of a black-body radiator is the opening in a carbon tube.

Heat transfer coefficients α
(convection + radiation)

Type of material, wall surface etc.	α_i or α_a W/(m² · K)
Natural air movement in a closed room:	
Wall surfaces, interior windows	8
Exterior windows	11
Floors, ceilings:	
from bottom upwards	8
from top downwards	6
Forced air movement on a flat wall	
Mean wind velocity $w = 2$ m/s	15
Mean wind velocity $w > 5$ m/s	$6.4 \cdot w^{0.75}$
Water on a flat wall	
Still	500 ... 2000
Moving	2000 ... 4000
Boiling	2000 ... 6000

Thermal resistance of air layers s/λ
(conduction + convection + radiation)

Position of air layer	Thickness of air layer mm	Thermal resistance s/λ m² · K/W
Vertical air layer	10	0.14
	20	0.16
	50	0.18
	100	0.17
	150	0.16
Horizontal air layer Heat flow from bottom upwards	10	0.14
	20	0.15
	50	0.16
Horizontal air layer Heat flow from top downwards	10	0.15
	20	0.18
	50	0.21

Heat required to heat dwellings

50 to 60 W is required to heat each m² of living area.

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Technical temperature measurement

(VDE/VDI Guideline 3511)

Measurement system	Measurement range	Method of operation	Examples of application
Liquid-in-glass thermometers	–200 ... 1000 °C	Thermal expansion of the liquid is visible in a narrow glass tube. Liquid: Pentane (–200 ... 30 °C). Alcohol (–100 ... 210 °C), Toluene (–90 ... 100 °C), Mercury (–38 ... 600 °C), Gallium (... 1000 °C).	For liquids and gases, for monitoring steam, heating and drying systems; refrigeration equipment; media flowing through pipes.
Pressure-spring thermometers	–50 ... 500 °C	Due to its expansion pressure (mercury, toluene) or vapor pressure (ether, hexane, toluene, xylene), a liquid in an immersion vessel actuates a pointer or a recording instrument via a Bourdon tube.	For monitoring and recording temperatures (including remote applications up to 35 m) in power plants, factories, heating plants, cold rooms.
Solid expansion thermometers	0 ... 1000 °C	Different thermal expansion of two metals (rod in tube).	Temperature regulators.
Bimetallic thermometers	–50 ... 400 °C	Curvature of a strip consisting of two different metals.	Temperature regulators.
Resistance thermometers	–220 ... 850 °C	Change in resistance caused by change in temperature Platinum wires –220 ... 850 °C, Nickel wires –60 ... 250 °C, Copper wires –50 ... 150 °C, Semiconductors –40 ... 180 °C,	Temperature measurements on machines, windings, refrigeration equipment. Remote transmission possible.
Thermistors	0 ... 500 °C (2200°)	Sharp drop in electrical resistance as the temperature increases.	Measurement of minor temperature differences due to high sensitivity.
Thermocouples	–200 ... 1800 °C	Thermoelectromotive force of two metals whose junctions are at different temperatures.	Temperature measurements on and in machines, engines, etc. Remote transmission possible.
Radiation thermometers (pyrometer, infrared camera, high-speed pyrometer)	–100 ... 3500 °C	The radiation emitted by a body is an indicator of its temperature. It is sensed by using either thermocouples or photocells, or by comparing luminance values. Emissions level must be observed.	Melting and annealing furnaces. Surface temperatures. Moving objects, thermogravimetry, extremely rapid response.
Temperature-sensitive paints, temperature-indicating crayons	40 ... 1350 °C	Color changes when specific temperatures are exceeded. Paints and crayons are available with one or more color changes (up to 4). The new color remains after cooling.	Temperature measurements on rotating parts, in inaccessible places, in machining processes; warning of excessive temperature; material testing (cracks).
Suction thermometers, pyrometers	1800 ... 2800 °C	Gas is extracted from the flame.	Measurement of flame temperature (delayed display).

Other temperature-measurement methods: spectroscopy, interferometry, quartz thermometry, noise thermometry, liquid crystals, acoustic and magnetic thermometers.

Thermodynamics

First law of thermodynamics:
Energy can be neither created nor destroyed. Only the form in which energy exists can be changed, e.g., heat can be transformed into mechanical energy.

Second law of thermodynamics:
Heat cannot be completely converted to another form of energy, e.g., mechanical work. All natural and synthetic energy transformation processes are irreversible and occur in a preferred direction (according to the probable state). On its own, heat passes only from warmer to colder bodies, the reverse is possible only if energy is supplied.

Entropy S is a measure of the thermal energy in a system which is no longer capable of performing work. That proportion of energy available for work is referred to as exergy.

For reversible processes, the sum of the entropy changes is equal to zero.

The greatest efficiency in the conversion of heat to mechanical work is achieved in a reversible process. The following then applies for thermal efficiency:

$\eta_{th} = (Q_1 - Q_2)/Q_1 = (T_1 - T_2)/T_1$
(Carnot cycle)

The maximum work to be gained here is:
$W = Q_1 (T_1 - T_2)/T_1$

Changes of state for gases

(general equation of state: $p \cdot v = R_i \cdot T$)

Change of state	Characteristics	Specific heat capacity[1]	Equations (k, K are constants)[1]	Examples
Isobaric	Constant pressure	c_p	$p = k$ $v = K \cdot T$	"Constant pressure" combustion in diesel engines; heating or cooling in once-through boilers.
Isochoric	Constant volume	c_v	$v = k$ $p = K \cdot T$	"Constant volume" combustion in spark-ignition engines; heating or cooling in closed boilers.
Isothermal	Constant temperature	–	$T = k$ $p \cdot v = K$	Slow change of state (heat flows through partitions).
Adiabatic	Heat neither supplied nor dissipated	–	$P \cdot v^{\varkappa} = k$ $T \cdot v^{\varkappa - 1} = k$	Compression or expansion stroke without cooling losses (the ideal condition which is virtually achieved in high-speed machines).
Isentropic	Adiabatic and friction-free (reversible)	–	$T^{\varkappa} \cdot p^{1-\varkappa} = k$	Theoretically optimum attainable comparison processes.
Polytropic	General change of state	$c = \frac{c_v (n - \varkappa)}{n - 1}$	$P \cdot v^n = K$ $T \cdot v^{n-1} = K$ $T^n \cdot p^{1-n} = K$	Compression and power strokes in internal-combustion engines, steam engines (n = 1.2 ... 1.4).

[1] c_p, c_v and $\varkappa = c_p/c_v$ see P. 192, $n = \frac{\lg p_2 - \lg p_1}{\lg v_1 - \lg v_2}$

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Engine management for spark-ignition (SI) engines

Requirements

SI-engine torques
The power output P from a spark-ignition (SI) engine is determined by the available clutch torque and the engine speed.

The clutch torque is produced from the torque generated by the combustion process, reduced by the friction torque (friction losses in the engine) and the charge-cycle losses, and the torque required for operating the auxiliary systems.

The combustion torque is generated in the power cycle and determined by the following variables:
- the air mass that is available for combustion once the intake valves have closed,
- the fuel mass available at the same time, and
- the point at which the ignition spark initiates combustion of the air/fuel mixture.

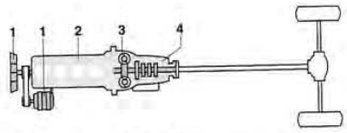
Primary function of engine management
The primary function of engine management is to adjust the torque generated by the engine. For this purpose, all the variables that influence the torque are controlled in the various engine-management subsystems.

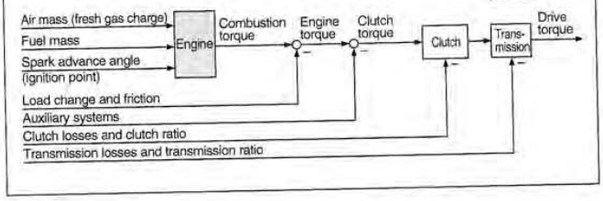
Cylinder-charge control
In Bosch engine-management systems with an electronic accelerator pedal (EGAS), the required charging of the engine cylinders with air is determined and the throttle valve opened accordingly in the "cylinder-charge control" subsystem. In conventional injection systems, the driver directly controls the opening of the throttle valve by pressing the accelerator pedal.

A/F mixture formation
In the "mixture formation" subsystem, the associated fuel mass is calculated and from this the necessary injection time and the optimum injection point are determined.

Ignition
In the "ignition" subsystem, the crankshaft angle is determined at which the ignition spark ignites the mixture at the correct time.

Drivetrain torques
1 Auxiliary systems (alternator, A/C compressor etc.),
2 Engine,
3 Clutch,
4 Transmission.





The objective of this management system is to make available the torque requested by the driver, and at the same time to satisfy the exacting demands placed on exhaust emissions, fuel consumption, power output, comfort and safety.

Cylinder charge

Constituent elements
The gas mixture in the cylinder after the intake valves have closed is termed the cylinder charge. This charge consists of the supplied fresh A/F mixture and residual exhaust gas.

Fresh A/F mixture
The constituent elements of the fresh mixture drawn in are fresh air and the fuel suspended in it. The majority of the fresh air flows through the throttle valve; additional fresh mixture can be drawn in through the evaporative-emissions control system (if fitted). The air supplied via the throttle valve and present in the cylinder after the intake valves have closed is the decisive factor in the work performed at the piston during combustion, and thus in the torque delivered by the engine.

Measures for increasing maximum torque and maximum engine power therefore almost always necessitate an increase in the maximum possible cylinder charge. The theoretical maximum charge is predetermined by the piston displacement.

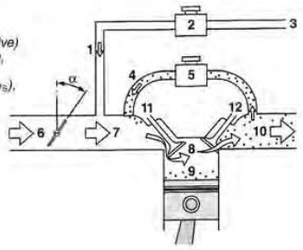
Residual exhaust gas
The share of residual exhaust gas in the charge is formed
- by the exhaust-gas mass which remains in the cylinder and is not discharged during the period when the exhaust valve is open, and
- in systems with exhaust-gas recirculation (EGR), by the mass of the recirculated exhaust gas.

The residual exhaust-gas share is determined by the charge cycle.

The residual exhaust-gas mass does not contribute directly to the combustion process but does influence ignition and the course of the combustion process. This residual exhaust-gas share can therefore be perfectly desirable when the engine is in part-load operation.

In order for a desired torque to be generated, the reduction in the fresh-mixture volume (due to the residual-gas quantity) must be compensated for by increasing the throttle-valve opening. This reduces

Cylinder charge in the SI engine
1 Air and fuel vapor,
2 Purge valve with variable valve-opening cross-section,
3 Connection to evaporative-emissions control system,
4 Exhaust gas,
5 Exhaust-gas recirculation valve (EGR valve) with variable valve-opening cross-section,
6 Air mass flow (ambient pressure p_U),
7 Air mass flow (intake-manifold pressure p_S),
8 Fresh A/F-mixture charge (combustion-chamber pressure p_B),
9 Residual exhaust-gas charge (combustion-chamber pressure p_B),
10 Exhaust gas (exhaust-gas back pressure p_A),
11 Intake valve,
12 Exhaust valve.
α Throttle-valve angle.



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the engine's pumping losses, and fuel consumption drops as a result. A specifically introduced residual exhaust-gas share can likewise influence combustion and thus the emission of nitrogen oxides (NO_x) and unburnt hydrocarbons (HC).

Control

In a spark-ignition engine with external mixture formation, the power output is proportional to the air mass flow drawn in. In future, it will also be possible to directly control the direct-injection SI engine operating with lean A/F mixtures via variation of the injected fuel mass.

Throttle valve

The throttle valve is used when the engine power, and thus (at a specific engine speed) the engine torque, are to be controlled by means of the air mass flow. When the throttle valve is not fully open, the air drawn in by the engine is throttled, thereby reducing the torque generated. This throttling effect is dependent on the position and thus on the opening cross-section of the throttle valve.

The maximum engine torque is achieved when the throttle valve is fully open (see Fig.).

Charge cycle

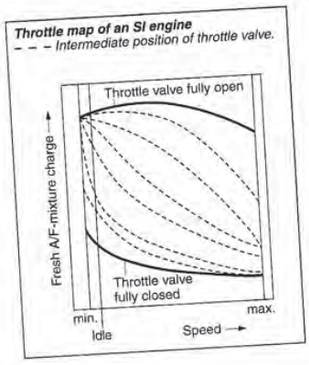
The charge cycle of fresh A/F mixture and residual exhaust gas is controlled by the appropriate opening and closing of the intake and exhaust valves. The cams on the camshaft determine the points at which the valves open and close (valve timing) and the course of the valve lift. This influences the charge-cycle process and thus also the amount of fresh A/F mixture available for combustion.

The valve overlap, i.e. the overlapping of the opening times of the intake and exhaust valves, has a decisive impact on the residual exhaust-gas mass in the cylinder. This situation involves "interior" exhaust-gas recirculation. The residual exhaust-gas mass can also be increased by "exterior" exhaust-gas recirculation. In this case, an additional EGR valve connects the intake manifold and exhaust manifold. When the valve is open, the engine draws in a mix of fresh A/F mixture and exhaust gas.

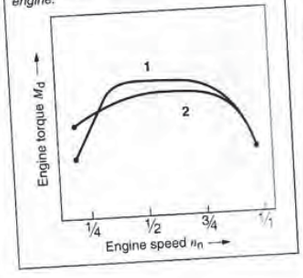
Supercharging

The obtainable torque is proportional to the charge of fresh A/F mixture. It is therefore possible to increase the maximum torque by compressing the air in the cylinder by means of dynamic supercharging, mechanical supercharging, or exhaust-gas turbocharging (P. 392).

Throttle map of an SI engine
– – – Intermediate position of throttle valve.



Torque curve for turbocharged engine compared with naturally aspirated engine at same rated power
1 Turbocharged engine, 2 Naturally aspirated engine.



Fuel delivery with electric fuel pump

Function

The electric fuel pump must deliver sufficient quantities of fuel to the engine and maintain enough pressure for efficient injection under all operating conditions. Essential requirements include:

- maintaining flow rates between 60 and 200 liters/h at the rated voltage,
- maintaining fuel-system pressures of 300...450 kPa,
- the ability to pressurize the system during operation at 50...60 % of the rated voltage, important for cold-starting response.

In addition, the electric fuel pump is increasingly being used as the presupply pump for modern direct-injection systems, both for gasoline and for diesel engines. For gasoline direct-injection systems, at times pressures of up to 700 kPa must to be provided. This, together with the very high viscosity range when pumping diesel fuel, signifies new challenges facing the hydraulic and electric systems of the electric fuel pump.

Design

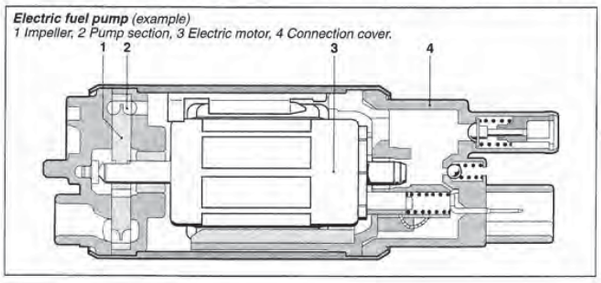
The electric fuel pump consists of:

- the end cover including the electrical connections, non-return valve (to maintain system pressure) and the hydraulic discharge fitting. Most end covers also include the carbon brushes for the drive-motor commutator and interference-suppression elements (inductance coils, with condensers in some applications).
- the electric motor with armature and permanent magnets. Electronically commutated (EC) fuel pumps are being developed for use with special fuels which feature for instance marked electrolytic effects, and for use in other environments which have negative effects on carbon-brush and commutator assemblies.
- a positive-displacement or flow-type pump assembly.

Positive-displacement pump

As the positive-displacement unit's pump element rotates it draws in fluid through the suction side and through a sealed area on its way to the high-pressure side. Electric fuel pumps fall into two categories, the roller cell and the internal-gear unit. Positive-displacement pumps provide good performance in high-pressure (400 kPa and above) systems. They also perform well at low supply voltages, i.e. the flow rate curve remains relatively "flat" and constant throughout a wide range of operating voltages. Efficiency ratings can be as high as 25 %. The unavoidable pressure pulses may cause noise; the extent of this problem varies according to the pump's design configuration and mounting location. Yet another disadvantage may be encountered with hot fuel, when the unit tends to pump gas instead of fuel, leading to reduced flow rates (problem potential varies according to in-

Electric fuel pump *(example)*
1 Impeller, 2 Pump section, 3 Electric motor, 4 Connection cover.



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stallation location). Standard positive-displacement pumps usually incorporate peripheral primary circuits to deal with this problem by discharging the gas.

While the flow-type pump has to a large extent replaced the positive-displacement pump in electronic gasoline injection systems for performing the classical function of the electric fuel pump, a new field of application has opened up for the positive-displacement pump in terms of the above-mentioned presupply for direct-injection systems with their significantly increased pressure requirements and viscosity range. This is especially true for the presupply of diesel and biodiesel.

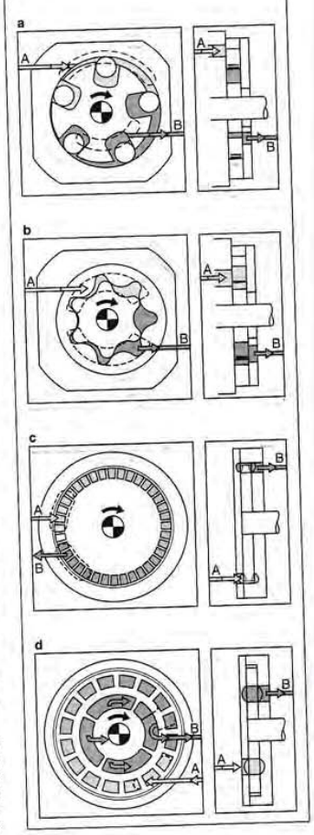
Flow-type pumps

Designs based on the principles used for the peripheral pump and the side-channel pump have become the standard for electric fuel pumps, with a slight preference for the side-channel pump as this tends to provide higher pressures and improved efficiency. An impeller equipped with numerous peripheral vanes rotates within a chamber consisting of two fixed housing sections. Each of these sections features a passage along the path of the impeller's vanes, with the openings on one end of the passage on a plane with the suction openings. From here they extend to the point where the fuel exits the pump at system pressure. Within the passage is a baffle element designed to prevent internal leakage. A small gas-discharge orifice (not necessary in diesel applications) located at a specified angular distance from the suction opening, improves performance when pumping hot fuel; this orifice facilitates the discharge of any gas bubbles which may have formed (with minimal leakage).

The pulses reflected between the impeller vanes and the fluid molecules result in pressurization along the length of the passage, inducing a spiral rotation of the fluid volume in the impellers and in the passages.

Because pressurization is continuous and virtually pulse-free, flow-type pumps are quiet in operation. Pump design is also substantially less complex than that of the positive-displacement unit. Single-stage pumps generate system pressures

Electric fuel-pump designs
a) Roller-cell pump,
b) Internal-gear pump,
c) Peripheral pump,
d) Side-channel pump.



extending up to 450 kPa. Still higher system pressures, as will become necessary for brief periods in future for highly supercharged engines, and for engines with gasoline direct injection (see above), are possible, but under continuous-duty conditions such pressures would overload today's conventional electrical systems (permanent-magnet DC motors with conventional electromechanical commutation) and would result in a significantly reduced service life. The following remedial measures are being considered:

- High-pressure operation only when required → demand control of the electric fuel pump, e.g. with the aid of a timing module or another upstream device.
- Equipping of the fuel-pump motor with a carbon commutator in place of the conventional copper commutator so as to safeguard the service life also at high current and additionally with corrosive and/or high-viscosity fuels.
- For applications where the wide range of operating conditions and fuels place particularly high demands on the pump's versatility, work is proceeding on electronically commutated (EC) fuel-pump drives. Such an electrical system features unlimited service life.

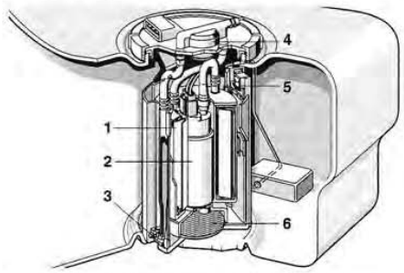
The efficiency ranges between 10 and approx. 20 %. The fuel systems of newly designed vehicles with spark-ignition engines rely almost exclusively on flow-type pumps for fuel delivery.

Electric fuel pumps: integration in injection system and in fuel tank

Whereas the first electronic fuel-injection systems almost always featured electric fuel pumps designed for in-line installation outside the tank, current and more recent applications tend to have in-tank installation as a standard feature. The electric fuel pump is one of the elements within the in-tank units now being designed to include an increasingly wide array of components such as: the suction filter, a fuel-baffle chamber to maintain delivery during cornering (usually with its own "active" supply based on a suction-jet pump or a separate primary circuit in the main electric pump), the fuel gauge sensor, and a variety of electrical and hydraulic connections.

Another advance is the returnless fuel system (RLFS), usually in the form of an in-tank unit with an integral fuel-pressure regulator designed to maintain a continuous return circuit within the in-tank assembly. A pressure-side fine-mesh fuel filter can also be incorporated in this unit. Further functions will in future be integrated in the delivery module, e.g. diagnostic devices for tank leakage, timing module for fuel-pump control.

In-tank unit: complete integrated assembly for returnless fuel systems
1 Fuel filter, 2 Electric fuel pump, 3 Suction-jet pump (regulated), 4 Fuel-pressure regulator, 5 Fuel-gauge sensor, 6 Suction strainer.



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A/F-mixture formation

Influencing variables

Air-fuel (A/F) mixture

To be able to operate, a spark-ignition engine requires a specific air-fuel mixture ratio. Ideal theoretical complete combustion is available at a mass ratio of 14.7:1. This is also termed the stoichiometric ratio. I.e.: an air mass of 14.7 kg is needed to burn a fuel mass of 1 kg. Or expressed as a volume: 1 l fuel burns completely in roughly 9500 l air.

The specific fuel consumption of a spark-ignition engine is essentially dependent on the mixture ratio of the A/F mixture. It is necessary to have an excess of air in order to ensure genuine complete combustion, and thus as low a fuel consumption as possible. Limits are imposed though by the flammability of the mixture and the available combustion time.

The A/F mixture also has a decisive impact on the efficiency of the exhaust-gas treatment systems. State-of-the-art technology is represented by the three-way catalytic converter. This, though, needs a stoichiometric A/F ratio in order to operate with maximum efficiency. Such a catalytic converter helps to reduce harmful exhaust-gas constituents by more than 98%.

The engines available today are therefore operated with a stoichiometric mixture as soon as their operating status permits this.

Certain engine operating states require mixture corrections. Specific corrections of the mixture composition are necessary e.g. when the engine is cold. The mixture-formation (carburation) system must therefore be in a position to satisfy these variable requirements.

Excess-air factor

The excess-air factor λ (lambda) has been chosen to designate the extent to which the actual air-fuel mixture differs from the theoretically necessary mass ratio (14.7:1):

λ = Ratio of supplied air mass to air requirement with stoichiometric combustion.

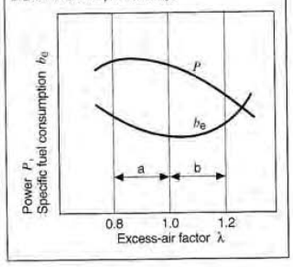
$\lambda = 1$: The supplied air mass corresponds to the theoretically necessary air mass.

$\lambda < 1$: There is an air deficiency and thus a rich mixture. Maximum power output at $\lambda = 0.85...0.95$.

$\lambda > 1$: There is an excess of air or a lean mixture in this range. This excess-air factor is characterized by reduced fuel consumption and reduced power output. The maximum value for λ that can be achieved – the so-called "lean-burn limit" – is very heavily dependent on the engine design and on the mixture-formation system used. The mixture is no longer ignitable at the lean-burn limit. Combustion misses occur and this is accompanied by a marked increase in uneven running.

Spark-ignition engines with manifold injection achieve their peak power output at an air deficiency of 5...15% ($\lambda = 0.95...0.85$), and their lowest fuel consumption at an air excess of 10...20% ($\lambda = 1.1...1.2$).

Effect of excess-air factor λ on power P and specific fuel consumption b_e
a Rich mixture (air deficiency),
b Lean mixture (air excess).



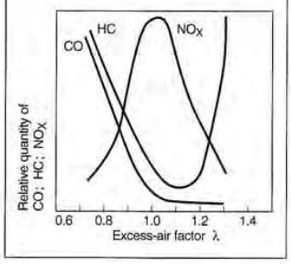
The graphs show the dependence of power output, specific fuel consumption and pollutant buildup on the excess-air factor for a typical engine with manifold injection. It can be deduced from these graphs that there is no ideal excess-air factor at which all the factors assume the most favorable value. For engines with manifold injection, excess-air factors of $\lambda = 0.9...1.1$ have proven effective in realizing "optimal" consumption at "optimal" power output.

Engines with direct injection and charge stratification involve different combustion conditions such that the lean-burn limit is significantly higher. These engines can therefore be operated in the part-load range with significantly higher excess-air factors (up to $\lambda = 4$).

For the treatment of exhaust gas by a three-way catalytic converter, it is absolutely essential to adhere exactly to $\lambda = 1$ with the engine at normal operating temperature. In order to do so, the air mass drawn in must be precisely determined and an exactly metered fuel mass added to it.

For optimum combustion in today's common manifold-injection engines, not only is a precise injected fuel quantity necessary, but also a homogeneous A/F mixture. This necessitates efficient fuel atomization. If this precondition is not satisfied, large fuel droplets will precipitate on the intake manifold or the combustion-chamber walls. These large droplets cannot fully combust and will result in increased hydrocarbon emissions.

Effect of excess-air factor λ on pollutant composition in untreated exhaust gas



Mixture-formation systems

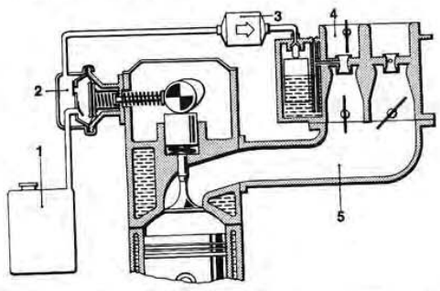
It is the job of fuel-injection systems, or carburetors, to furnish an A/F mixture which is adapted as well as possible to the relevant engine operating state. Injection systems, especially electronic systems, are better suited to maintaining narrowly defined limits for the mixture composition. This is advantageous with regard to fuel consumption, driving performance and power output. The result of increasingly stringent exhaust-emissions legislation in the automotive sector is that today, injection systems have completely superseded carburetors.

Today, the automotive industry almost exclusively uses systems in which the mixture formation takes place outside the combustion chamber. However, systems with interior mixture formation, i.e. where the fuel is injected directly into the combustion chamber, already formed the basis of the first gasoline injection systems. These systems are increasing in importance as they are very well suited to reducing fuel consumption even further.

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Schematic of a carburetor system
1 Fuel tank, 2 Fuel supply pump, 3 Fuel filter, 4 Carburetor, 5 Intake manifold.



Carburetors

Carburetor systems

The fuel is transported from the fuel tank to the carburetor by a fuel pump (generally a diaphragm unit) powered by the camshaft or distributor shaft. The system is designed to limit the maximum supply pressure. A fine-mesh fuel filter can be installed upstream or downstream from the pump as required.

Carburetor types

Downdraft carburetors

Downdraft carburetors are the most common type. Designs featuring optimized float chamber and metering-jet configurations result in efficient units. These designs work in conjunction with the corresponding intake-manifold layouts for optimum mixture formation and distribution.

Horizontal-draft carburetors

Horizontal-draft carburetors (familiar as fixed-venturi and constant-depression units) are useful for minimizing engine height.

Constant-depression carburetors feature venturi cross sections which vary in size during operation to maintain essentially constant vacuum levels at the fuel outlet. The variation in intake cross section is provided by a pneumatically-actuated plunger; attached to the plunger is a needle which regulates the fuel quantity.

Venturi configurations

The single-throat carburetor with one venturi is the least expensive design.

The two-stage carburetor featuring two venturis provides convenient tuning for individual applications and has become the standard in 4-cylinder applications. The first barrel controls part-throttle operation, while the second venturi opens for maximum power.

The double-barrel carburetor features two carburetor sections sharing a single float chamber and operating in parallel, making it ideal for use on 6-cylinder engines. The two-stage four-barrel carburetor has four venturi fed from a single float chamber.

Design and operating principles

The driver uses the accelerator pedal to vary the throttle valve's aperture so that the airflow into the engine is varied and with it the engine's power output. The carburetor varies the amount of fuel metered to the engine to reflect the current intake air flow. Together with the needle valve, the float regulates the fuel flow to the carburetor while maintaining a constant fuel level in the float chamber.

Airflow is monitored by an air funnel designed to induce a venturi effect. The progressively narrower diameter increases the velocity of the air, producing a corresponding vacuum at the narrowest point. The resulting pressure differential relative to the float chamber – which can be further augmented with a boost venturi – is exploited to extract fuel from the float chamber. The jets and metering systems adapt fuel delivery to airflow.

Fuel-metering systems

Main system

The fuel is metered by the main jet. Correction air is added as a delivery aid to the fuel through side orifices in the venturi tube.

Idle and progression system

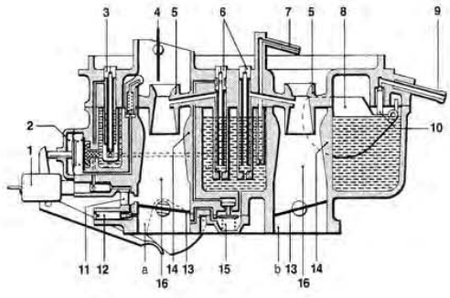
At idle, the vacuum which the air stream produces at the fuel outlet is not sufficient to withdraw fuel from the main system. For this reason, there is a separate idle system with an outlet located downstream from the throttle valve at the point of maximum vacuum. The emulsion required for idling emerges from the idle circuit after initial processing by the idle fuel and air-correction jets.

During transitions to the main metering system the throttle valve controls a series of orifices, or a slit, drawing fuel from the idle circuit.

Other systems

These basic devices are supplemented by a range of additional systems. These are designed to adapt carburetor performance for warm operation (part-throttle control, full-throttle enrichment), to compensate for fuel accumulation within the intake-manifold during acceleration (accelerator pump) and to meet the special engine requirements encountered during starting and in the warm-up phase. Other supplementary systems include lambda closed-loop mixture control and devices to deactivate the fuel supply during trailing-throttle operation.

Schematic of a two-stage carburetor
a) Primary stage, b) Secondary stage.
1 Idle cutoff valve, 2 Accelerator pump, 3 Idle circuit, 4 Choke, 5 Boost venturi, 6 Main systems with venturi tubes, 7 Full-throttle enrichment, 8 Float, 9 Fuel supply, 10 Needle valve, 11 Bypass plug, 12 Idle mixture screw, 13 Throttle valves, 14 Venturi wall, 15 Part-throttle control valve, 16 Venturi chamber.



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Electronically-controlled carburetor system (ECOTRONIC)

Basic carburetor
The basic carburetor is restricted to the throttle valve, float system, idle and transition systems, main system and choke. An idle-air control system with a choke-activated needle jet is also provided.

Additional components and actuators
The throttle-valve actuator is an electropneumatic servo device for controlling the cylinder charge. The actuator's plunger moves the throttle valve via a lever attached to the carburetor's throttle shaft.

The choke valve actuator is a final-control element designed to adapt the mixture in response to variations in engine operating conditions. This unit closes the choke valve to enrich the mixture by raising the pressure differential (vacuum) at the main jets while simultaneously increasing flow rates from the idle circuit.

Sensors
The throttle-valve potentiometer monitors the throttle valve's position and travel. One temperature sensor monitors the engine's operating temperature while a second sensor can be installed if necessary to monitor the temperature within the intake manifold.

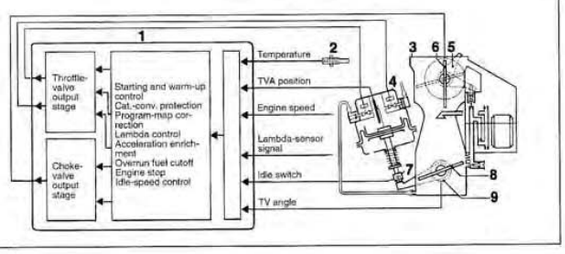
The idle switch serves to identify trailing-throttle operation; it can be replaced by appropriate software in the electronic control unit (ECU).

Electronic control unit (ECU)
The ECU's input circuit converts incoming analog signals into digital form. The processor performs further operations with the input data in order to calculate output values with reference to the programmed data map. The output signals control several functions, including regulation of the servo elements that operate the choke valve and main throttle valve.

Basic functions
The basic carburetor determines the primary functions of the system. The idle, transition and full-throttle systems all contribute to matching performance to the programmed curves. The base calibrations can be intentionally "lean", as the choke-valve control can provide a corrective enrichment.

Electronic functions
Electronic open and closed-loop control circuits regulate a number of secondary operations within the ECU. Several of these are illustrated below. Further functions may include: ignition control, transmission-shift control, fuel consumption displays and diagnosis capabilities.

Schematic of an electronically controlled carburetor (ECOTRONIC)
1 ECU, 2 Temperature sensor, 3 Carburetor, 4 Throttle actuator, 5 Choke actuator, 6 Choke valve, 7 Idle switch, 8 Throttle valve, 9 Throttle potentiometer.



Gasoline injection systems

Systems for external A/F mixture formation

Gasoline injection systems for external mixture formation are identified by the fact that the air-fuel mixture is created outside the combustion chamber (in the intake manifold).

Single-point injection (SPI)
Single-point injection is an electronically controlled injection system in which an electromagnetic fuel injector injects the fuel intermittently into the intake manifold at a central point ahead of the throttle valve. The Bosch single-point injection systems are called Mono-Jetronic and Mono-Motronic.

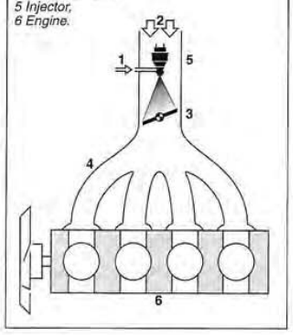
Multipoint injection (MPI)
Multipoint injection creates the ideal preconditions for satisfying the demands placed on a mixture-formation system. In multipoint injection systems, each cylinder is assigned a fuel injector, which injects the fuel directly ahead of that cylinder's intake valve. Examples of such systems are KE- and L-Jetronic with their respective variants.

Mechanical injection system:
The K-Jetronic system operates without a drive and injects the fuel continuously. The injected fuel mass is not determined by the fuel injector but rather prespecified by the fuel distributor.

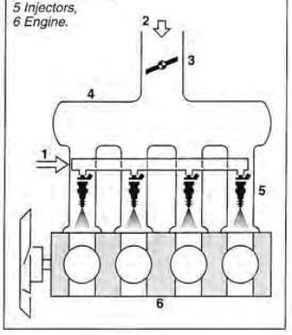
Combined mechanical-electronic injection system:
KE-Jetronic is based on the mechanical basic system of K-Jetronic. Thanks to the extended acquisition of operating data, this system facilitates electronically controlled supplementary functions in order to adapt the injected fuel quantity more exactly to the different engine operating states.

Electronic injection systems:
Electronically controlled injection systems inject the fuel intermittently with electromagnetically actuated fuel injectors. The injected fuel mass is determined by the injector opening time (for a given pressure drop across the injector).

Single-point fuel injection
1 Fuel,
2 Air,
3 Throttle valve,
4 Intake manifold,
5 Injector,
6 Engine.



Multipoint fuel injection
1 Fuel,
2 Air,
3 Throttle valve,
4 Intake manifold,
5 Injectors,
6 Engine.



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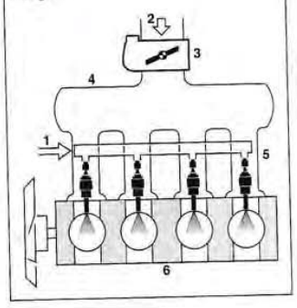
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Examples: L-Jetronic, LH-Jetronic, and Motronic as an integrated engine management system.

The high standards required of a vehicle's smooth running and exhaust-emissions necessitate high demands being made on the A/F mixture composition of each working cycle. Precisely timed injection is significant as well as precise metering of the injected fuel mass in accordance with the air drawn in by the engine.

In modern multipoint injection systems, therefore, not only is each engine cylinder assigned an electromagnetic fuel injector but also this fuel injector is activated individually for each cylinder. In this way, both the fuel mass appropriate to each cylinder and the correct start of injection are calculated by the control unit (ECU). Injecting the precisely metered fuel mass directly ahead of the cylinder intake valve(s) at the correct moment in time improves mixture formation. This, in turn, helps to a large extent in preventing wetting of the intake-manifold walls with fuel, which can result in temporary deviations from the desired lambda value during transient engine operation. The advantages of multipoint injection can thus be fully exploited.

Direct injection (DI)
1 Fuel,
2 Air,
3 Throttle-valve (EGAS),
4 Intake manifold,
5 Injectors,
6 Engine.



The engine intake manifolds thus carry only the combustion air and can therefore be optimally adapted to the gas-dynamic requirements of the engine.

Systems for internal A/F mixture formation

In direct-injection systems for internal mixture formation, the fuel is injected directly into the combustion chambers by electromagnetically actuated fuel injectors. Each cylinder is assigned a fuel injector. Mixture formation takes place inside the cylinder. To ensure efficient combustion, it is essential that the fuel be finely atomized when leaving the injectors.

In normal operation, a direct-injection engine draws in only air and not an air-fuel mixture, as is the case in conventional injection systems. Herein lies an advantage of this new system: no fuel can precipitate on the intake-manifold walls. With external mixture formation, the air-fuel mixture is generally present throughout the entire combustion in a homogeneous state and in a stoichiometric ratio. On the other hand, formation of the mixture in the combustion chamber permits two completely different operating modes:

Stratified-charge operation

In stratified-charge operation, the mixture only has to be combustible in the area around the spark plug. The remaining section of the combustion chamber thus only contains fresh mixture and residual exhaust gas without unburnt fuel. In the idle and part-load ranges, this creates an altogether highly lean mixture and thus a reduction in the fuel consumption.

Homogeneous operation

In homogeneous operation, as with external mixture formation, there is a homogeneous mixture throughout the entire combustion chamber; and the entire fresh air available in the combustion chamber takes part in the combustion procedure. For this reason, this operating mode is used in the full-load range.

MED-Motronic is the management system for direct-injection gasoline engines.

Single-point injection systems

Single-point fuel injection has advanced beyond the compact fuel-injection system stage to become part of a comprehensive engine-management system.

The various single-point injection systems differ in the design of the central-injection unit. All systems feature an injector located above the throttle plate; they differ from multipoint injection units in that they frequently operate at low pressure (0.7...1 bar). This means that an inexpensive, hydrodynamic electric fuel pump can be used which is generally in the form of an in-tank unit. The injector is flushed continuously by the fuel flowing through it in order to inhibit the formation of air bubbles. This arrangement is an absolute necessity in such a low-pressure system. The designation "Single-Point Injection (SPI)" corresponds to the terms Central Fuel Injection (CFI), Throttle Body Injection (TBI) and Mono-Jetronic (Bosch).

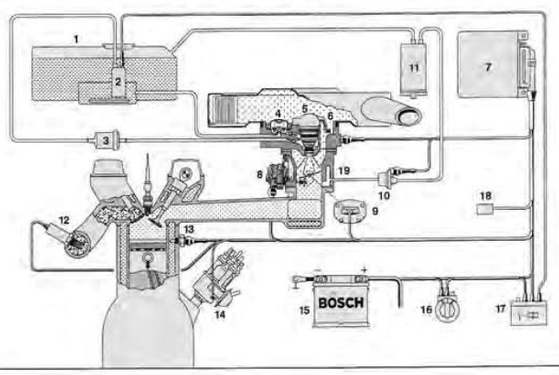
Mono-Jetronic

Mono-Jetronic is an electronically controlled, low-pressure single-point injection system for 4-cylinder engines, and features a centrally located solenoid-controlled fuel injector. At the heart of the system is the central injection unit, which uses the throttle valve to meter the intake air while injecting the fuel intermittently above the throttle valve. The intake manifold then distributes the fuel to the individual cylinders. Various sensors monitor all important engine operating data, which are then are used to calculate the triggering signals for the injectors and other system actuators.

Central injection unit

The injector is located above the throttle, in the intake-air path, in order to ensure homogeneous mixtures and consistent cylinder-to-cylinder distribution. The fuel spray is directed into the sickle-shaped orifice between the housing and throttle plate, whereby fuel wetting of the intake-tract walls is inhibited to a great extent, and the high pressure differential pro-

Schematic of a Mono-Jetronic system
1 Fuel tank, 2 Electric fuel pump, 3 Fuel filter, 4 Pressure regulator, 5 Injector, 6 Air-temperature sensor, 7 ECU, 8 Throttle actuator, 9 Throttle potentiometer, 10 Canister-purge valve, 11 Carbon canister, 12 Lambda sensor, 13 Coolant-temperature sensor, 14 Ignition distributor, 15 Battery, 16 Ignition switch, 17 Relay, 18 Diagnostic connector, 19 Central injection unit.



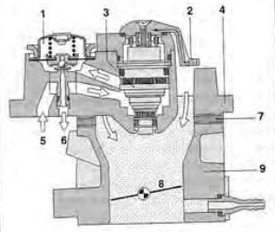
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motes optimum mixture formation. The injector operates at a system pressure of 1 bar (referred to atmospheric pressure). Efficient fuel atomization ensures consistently good mixture distribution, even in the critical full-load range. Injector triggering is synchronized with the ignition pulses.

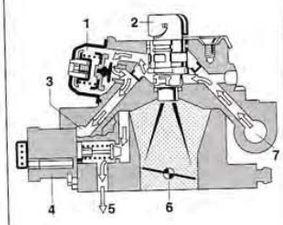
System control
In addition to the engine speed n, the main actuating variables for the injection system can include the air volume/air mass flow, the absolute manifold pressure, and the throttle position α. The (α/n) system applied with Mono-Jetronic can meet stringent emission requirements when used in conjunction with lambda closed-loop control and a 3-way catalytic converter. A self-adaptive system employs the signal from the lambda sensor as a reference to compensate for component tolerances and engine changes, thus maintaining high precision throughout the service life of the system.

Adaptation functions
The injection time is extended to provide additional fuel for cold starts and during the post-start and warm-up phases. When the engine is cold, the throttle actuator adjusts the throttle position to supply more air to the engine, thus maintaining idle speed and exhaust emissions at a constant level. The throttle potentiometer recognizes the change in throttle position and initiates an increase in the fuel quantity via the ECU. The system regulates the enrichment for acceleration and full-throttle operation in the same way. The overrun fuel cutoff provides reductions in fuel consumption and in exhaust emissions during trailing-throttle operation. Adaptive idle-speed control lowers the idle speed and stabilizes it. For this purpose, the ECU issues a signal to the servomotor to adapt the throttle-valve position as a function of engine speed and temperature.

Mono-Jetronic central injection unit
1 Pressure regulator, 2 Air-temperature sensor, 3 Injector, 4 Upper part (hydraulics), 5 Fuel supply, 6 Fuel return, 7 Insulator plate, 8 Throttle valve, 9 Lower part.



Multec central injection unit (Opel)
1 Pressure regulator, 2 Injector, 3 Fuel return, 4 Stepper motor for idle-speed control, 5 To intake manifold, 6 Throttle valve, 7 Fuel inlet.



Multipoint injection systems

K-Jetronic

Operating principle
– Continuous injection,
– Direct air-flow measurement.

K-Jetronic is a mechanical system which does not require an engine-driven injection pump. It meters a continuous supply of fuel proportional to the quantity of air being drawn into the engine.

Because of direct air-flow measurement, K-Jetronic also takes into account changes caused by the engine and permits the use of emission-control equipment, for which precise intake-air monitoring is an essential requirement.

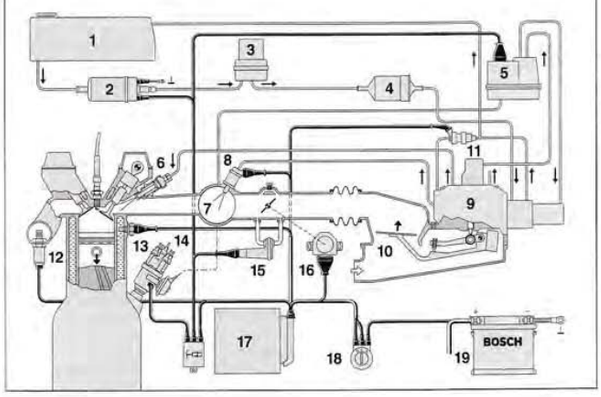
Operation
The intake air flows through the air filter, the air-flow sensor, and the throttle valve, before entering the intake manifold and continuing to the individual cylinders.

The fuel is delivered from the fuel tank by an electric (roller-cell) fuel pump. It then flows through the fuel accumulator and fuel filter to the fuel distributor. A pressure regulator in the fuel distributor maintains the fuel at a constant system pressure. The fuel flows from the fuel distributor to the injectors. Excess fuel not required by the engine is returned to the tank.

Mixture-control unit
The mixture-control unit consists of the air-flow sensor and the fuel distributor.

Air-flow sensor
The air-flow sensor consists of an air funnel and a pivoting air-flow sensor plate . A counterweight compensates for the weight of the sensor plate and pivot as-

Schematic of a K-Jetronic system
1 Fuel tank, 2 Electric fuel pump, 3 Fuel accumulator, 4 Fuel filter, 5 Warm-up regulator, 6 Injector, 7 Intake manifold, 8 Electric start valve, 9 Fuel distributor, 10 Air-flow sensor, 11 Frequency valve, 12 Lambda sensor, 13 Thermo-time switch, 14 Ignition distributor, 15 Auxiliary-air valve, 16 Throttle switch, 17 ECU, 18 Ignition switch, 19 Battery.



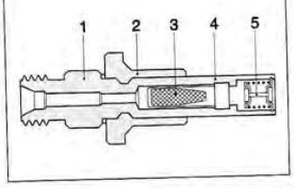
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sembly. The sensor plate is displaced by the air flow, while the control plunger in the fuel distributor exerts hydraulic counterpressure to maintain the system in a balanced state. The position of the air-flow sensor plate provides an index of intake air flow, and is transmitted to the fuel distributor's control plunger by a lever.

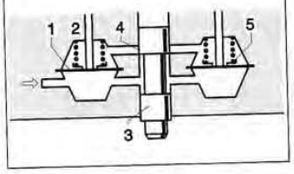
Fuel distributor

The amount of fuel supplied to the individual cylinders is regulated by varying the aperture of the metering slots in the fuel-distributor barrel. The number of rectangular-shaped metering slots in the barrel corresponds to the number of engine cylinders. The specific size of the metering-slot aperture depends on the control-plunger's position. In order to ensure constant pressure drop at the slots for various flow rates, a differential pressure regulator is located downstream of each metering slot.

Fuel injector
1 Hexagon, 2 Rubber molding, 3 Fine-mesh strainer, 4 Valve body, 5 Valve needle.



Fuel distributor in mixture-control unit
1 Diaphragm, 2 To injector, 3 Control plunger, 4 Metering slot, 5 Differential-pressure regulator.



Injector

The injector opens automatically at a pressure of approximately 3.8 bar, and has no metering function. It provides efficient mixture formation by opening and closing at a frequency of approx. 1500 Hz ("chatter").

It is held in place by a rubber molding. It is pressed, not screwed, into position. The hexagon serves to brace the injector when the fuel-supply line is screwed on.

Warm-up regulator

The warm-up regulator is controlled by an electrically-heated bimetallic element; it enriches the mixture in the warm-up phase by reducing the counterpressure (control pressure) exerted against the control plunger. A reduction in this control pressure means that the stroke of the air-flow sensor plate for a given air flow increases (reflected by a correspondingly larger metering-slot aperture). The result is a richer mixture during warm-up.

Where desired, the warm-up regulator can be expanded to incorporate the following functions:
- full-throttle enrichment,
- acceleration enrichment,
- altitude compensation.

Auxiliary-air valve

The auxiliary-air valve, controlled by either a bimetallic spring or an expansion element, supplies the engine with additional air (which is monitored by the air-flow sensor, but bypasses the throttle valve) during the warm-up phase. This supplementary air compensates for the cold engine's higher friction losses; it either maintains the normal idle speed or increases it in order to heat the engine and exhaust more quickly.

Electric start valve, thermo-time switch

The thermo-time switch activates the electric start valve as a function of engine temperature and elapsed time. During low-temperature starts, the start valve injects supplementary fuel into the intake manifold (cold-start enrichment).

Lambda closed-loop control

Open-loop control systems do not regulate the A/F ratio with enough accuracy to allow compliance with stringent emissions limits.

Lambda closed-loop control is required for operation of the 3-way catalytic converter. When it is installed, the K-Jetronic system must include an electronic control unit which uses the Lambda sensor's signal as its main input variable.

A solenoid frequency valve regulates the A/F mixture ratio by controlling the pressure differential at the metering slots. However, this principle cannot be applied to meet the more stringent emissions requirements scheduled for the future.

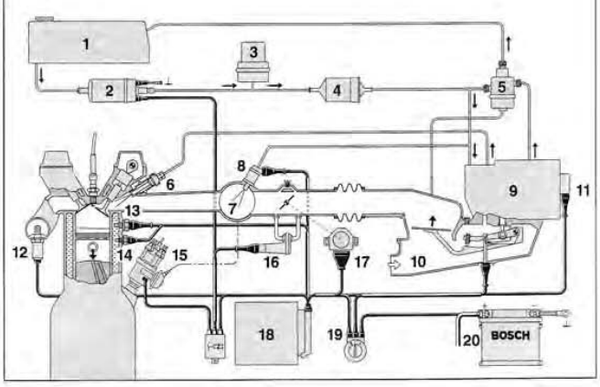
KE-Jetronic

KE-Jetronic is an advanced version of the K-Jetronic system. KE-Jetronic includes an ECU for increased flexibility and supplementary functions. Additional components include:
- a sensor for the intake air flow,
- a pressure actuator for mixture ratio adjustment, and
- a pressure regulator which maintains system pressure at a constant level as well as providing a fuel-cutoff function when the engine is switched off.

Operation

An electric fuel pump generates the system pressure. The fuel flows through the fuel distributor, while a diaphragm regulator maintains the system pressure at a constant level. With K-Jetronic, the control circuit performs mixture corrections via the warm-up regulator. In contrast, with KE-Jetronic the primary pressure and the pressure exerted upon the control plunger are equal. The ratio is corrected by adjusting the pressure differential in all the fuel distributor's chambers simultaneously.

Schematic of a KE-Jetronic system
1 Fuel tank, 2 Electric fuel pump, 3 Fuel accumulator, 4 Fuel filter, 5 Fuel-pressure regulator, 6 Injector, 7 Intake manifold, 8 Electric start valve, 9 Fuel distributor, 10 Air-flow sensor, 11 Electrohydraulic pressure actuator, 12 Lambda sensor, 13 Thermo-time switch, 14 Coolant-temperature sensor, 15 Ignition distributor, 16 Auxiliary-air valve, 17 Throttle switch, 18 ECU, 19 Ignition switch, 20 Battery.

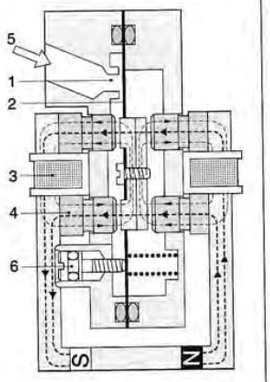


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The system pressure is present upstream from the metering slots, and applies a counterpressure to the control plunger. As with K-Jetronic, the control plunger is moved by an air-flow sensor flap. A damper unit prevents the oscillations that could be induced by the forces generated at the sensor flap. From the control plunger the fuel flows through the pressure actuator, the lower chambers of the differential-pressure valve, a fixed flow restrictor, and the pressure regulator, before returning to the fuel tank. Together with the flow restrictor, the actuator forms a pressure divider in which the pressure can be adjusted electrodynamically. This pressure is present in the lower chambers of the differential-pressure valves.

A pressure drop corresponding to the actuator current occurs between the actuator's two connections. This causes variations in the pressure differential at the metering slots, and alters the amount of fuel injected. The current can also be reversed to shut down the fuel supply completely. This feature can be employed for such functions as overrun fuel cutoff and engine-speed limitation.

Electrohydraulic pressure actuator
1 Nozzle, 2 Valve plate, 3 Coil, 4 Magnetic pole, 5 Fuel inlet, 6 Adjustment screw.



Electrohydraulic pressure actuator

This electrohydraulic actuator is flange-mounted on the fuel distributor. It is an electrically-controlled pressure regulator which operates using the nozzle/flapper-plate system. The mixture enrichment is directly proportional to the current flow.

Electronic control unit (ECU)

The ECU processes signals from the ignition (engine speed), temperature sensor (coolant temperature), throttle potentiometer (intake air flow), throttle switch (idle and overrun, WOT), starter switch, Lambda (O_2) sensor, pressure sensor and other sensors. Its most important functions are the control of:

- starting and post-start enrichment,
- warm-up enrichment,
- acceleration enrichment,
- full-throttle enrichment,
- overrun fuel cutoff,
- engine-speed limitation,
- idle-speed control,
- altitude compensation,
- closed-loop lambda control.

A coding switch (trim plug) makes it possible to select between operation with lambda control (with catalytic converter) and without it. This permits a choice between leaded and unleaded gasoline.

Lambda closed-loop control

The signal from the Lambda sensor is processed in the KE-Jetronic's ECU. The pressure actuator carries out the necessary adjustments.

L-Jetronic

Operating principle

- Air-flow measurement,
- Main controlled variables: air flow and engine speed,
- Intermittent injection.

L-Jetronic combines the advantages of direct air-flow measurement with the unique possibilities afforded by electronics. It is similar to K-Jetronic in that it recognizes all changes in engine condition (due to wear, combustion-chamber deposits, changes in valve setting). This ensures consistently good exhaust-gas composition.

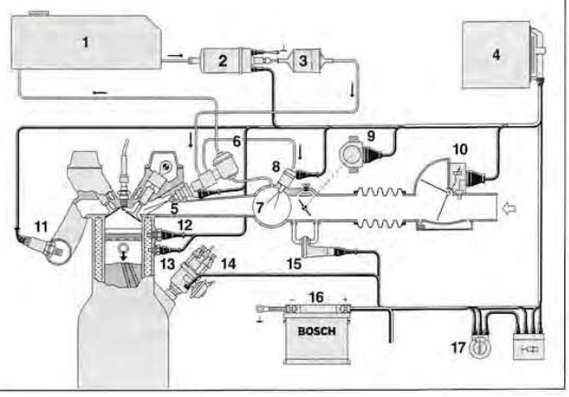
Operation

The fuel is injected through the engine's solenoid-operated injectors. A solenoid valve assigned to each cylinder is triggered once per crankshaft revolution. All of the injectors are wired in parallel to reduce the complexity of the electrical circuit. The pressure differential between fuel and intake-manifold pressures is maintained at a constant level of 2.5 or 3 bar such that the injected fuel quantity is only dependent on the opening period of the valves. For this purpose, the ECU delivers control pulses whose duration is dependent on the intake air flow, the engine speed, and other influencing variables. These are monitored by sensors and processed in the ECU.

Fuel supply

An electric fuel pump supplies the fuel and generates the injection pressure. The fuel is pumped from the fuel tank, through a paper filter, and into a high-pressure supply line at the other end of which there is a pressure regulator (spring-loaded diaphragm). The pressure regulator maintains a constant pressure at the metering orifice, regardless of the injected fuel quantity.

Schematic of an L-Jetronic system
1 Fuel tank, 2 Electric fuel pump, 3 Fuel filter, 4 ECU, 5 Injector, 6 Fuel-pressure regulator, 7 Intake manifold, 8 Electric start valve, 9 Throttle switch, 10 Air-flow sensor, 11 Lambda sensor, 12 Thermo-time switch, 13 Coolant-temperature sensor, 14 Ignition distributor, 15 Auxiliary-air valve, 16 Battery, 17 Ignition switch.



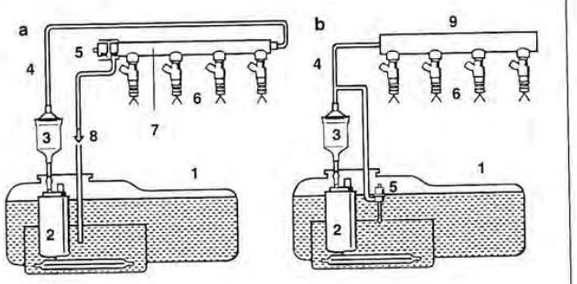
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Standard system:
The fuel flows through the high-pressure line on its way to the engine-mounted fuel rail with the injectors. The pressure regulator is installed on the fuel rail. After flowing through the rail the portion of the fuel not required by the engine flows through the return line attached to the regulator and back to the tank. Because the returning fuel has been warmed on the way back from the engine, fuel temperatures within the tank rise.

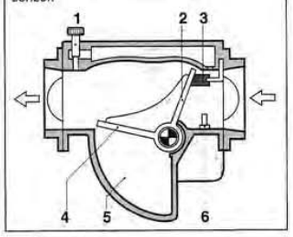
Fuel vapor is generated in the tank as a function of fuel temperature. For environmental purposes these vapors are routed through the tank ventilation system for storage in an activated charcoal canister until they can be returned through the intake manifold for combustion within the engine.

Returnless system:
A returnless fuel-supply system reduces the tendency of the fuel in the fuel tank to heat up, thus making it easier to comply with the legal requirements governing vehicular evaporative emissions. The pressure regulator is located either in the fuel tank or in its immediate vicinity, which means that the return line from the engine to the fuel tank can be dropped. The amount of fuel pumped to the fuel rail is limited to the quantity being used by the injectors. The excess flow volume emerging from the pump returns directly to the tank without the round trip to the engine and back. Assuming equivalent operating conditions, and depending upon the specific vehicular application, this system can reduce in-tank fuel temperatures by up to 10 K, cutting vaporization by roughly one third.

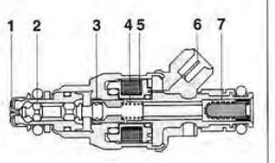
Fuel supply
a) Standard system, b) Returnless system.
1 Fuel tank, 2 Electric fuel pump, 3 Fuel filter, 4 Pressure line, 5 Fuel-pressure regulator, 6 Injectors, 7 Fuel rail (continuous flow), 8 Return line, 9 Fuel rail (no return flow).



Air-flow sensor
1 Idle-mixture adjustment screw, 2 Air-flow sensor flap, 3 Stop, 4 Compensation flap, 5 Damping chamber, 6 Air-temperature sensor.



Injector
1 Pintle, 2 Needle, 3 Armature, 4 Spring, 5 Solenoid winding, 6 Electrical terminals, 7 Fuel strainer.



Air-flow sensor
The intake air flow deflects a sensor flap against the constant return force of a spring to a defined angular position, which is converted by a potentiometer into a voltage ratio. This voltage ratio determines the pulse length of a timing element in the ECU. A temperature sensor in the air-flow sensor indicates changes in air density caused by temperature variations.

Fuel injectors
Fuel injectors serve to meter and atomize the fuel. When the solenoid winding is energized, the nozzle needle is lifted a mere 0.05 mm off its seat.

Throttle-valve switch
This transmits a control signal to the ECU when the throttle valve is either completely closed (idle) or fully opened (full-throttle [WOT]).

Engine-temperature sensor
The engine-temperature sensor is designed as a temperature-sensitive resistor (thermistor) and controls the warm-up enrichment.

Auxiliary-air valve, electric start-valve, thermo-time switch
Design and function are similar to those of the corresponding K-Jetronic components.

Electronic control unit (ECU)
This ECU converts the engine variables into electrical pulses. Transmission intervals for these pulses are correlated with ignition timing, while their duration is basically a function of speed and intake air flow. Since all injectors are activated simultaneously, only a single driver stage is required. The temperature sensors respond to lower engine and air temperatures by increasing the injection duration. The throttle-switch signals allow mixture adaptation for idle and full-throttle operation.

Lambda closed-loop control
The ECU compares the signal from the Lambda sensor with a setpoint value before activating a two-state controller. The control adjustment is then performed, as are all corrections, by modifying the injection duration.

L3-Jetronic
L3-Jetronic incorporates functions extending beyond those provided by the L-Jetronic's analog technology. The L3 system's ECU employs digital technology to adjust the mixture ratios based on a load/engine-speed map. In order to save space, the ECU is installed in the engine compartment, directly on the air-flow sensor, where the two components form a single monitoring and control unit.

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LH-Jetronic

LH-Jetronic is closely related to L-Jetronic. The difference lies in the method of intake air-flow measurement, with LH-Jetronic using a hot-wire air-mass meter to measure the mass of the intake air. Thus, the results no longer depend on the air density, which varies with temperature and pressure.

The other LH-Jetronic components and the basic system concept are to a large extent the same as those in L-Jetronic.

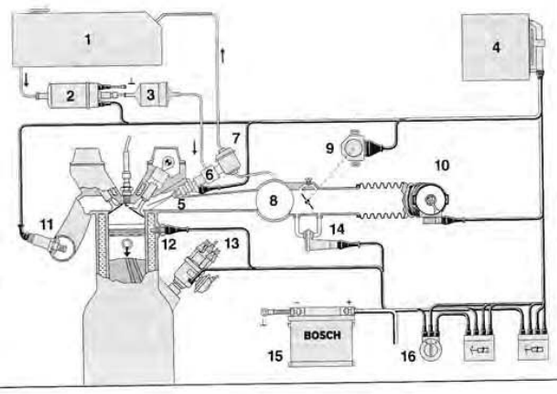
Operating-data processing in the ECU

LH-Jetronic is equipped with a digital ECU. Arrangements for adjusting the mixture ratio vary from those used with L-Jetronic in using a load/engine-speed map programmed for minimum fuel consumption and exhaust emissions. The ECU processes the sensor signals when calculating the injection duration that determines the injected fuel quantity. The ECU includes a microprocessor, a program and data memory, and an A/D converter. The microprocessor is provided with a suitable voltage supply and with a stable clock rate for data processing. The clock rate is defined by a quartz oscillator.

Hot-wire air-mass flow meter

The stream of intake air is conducted past a heated wire (hot wire). This wire forms part of an electrical bridge circuit. The flow of current through the wire serves to maintain it at a constant temperature above that of the intake air. This principle makes it possible to employ the current requirement as an index of the air mass being drawn into the engine. A resistor converts the heating current into a voltage signal, which the ECU then processes along with engine speed as a main input variable. A temperature sensor is mounted in the hot-wire air-mass flow meter to ensure that its output signal is not influenced by the temperature of the intake air. The A/F ratio at idle can be adjusted with a potentiometer. As contamination on the surface of the hot wire could affect the output signal, each time the engine is shut down the wire is electrically heated for one second to burn-off any contamination. The hot-wire air-mass flow meter has no moving parts, and its aerodynamic resistance within the intake tract is negligible.

Schematic of an LH-Jetronic system
1 Fuel tank, 2 Electric fuel pump, 3 Fuel filter, 4 ECU, 5 Injector, 6 Fuel distributor, 7 Fuel-pressure regulator, 8 Intake manifold, 9 Throttle switch, 10 Hot-wire air-mass flow meter, 11 Lambda sensor, 12 Coolant-temperature sensor, 13 Ignition distributor, 14 Idle-speed actuator, 15 Battery, 16 Ignition switch.



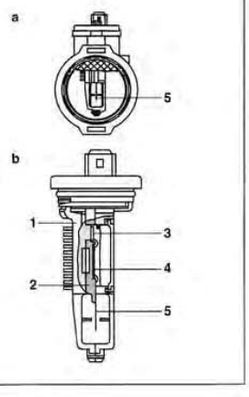
Hot-film air-mass flow meter

The operating principle of the hot-film air-mass flow meter is the same as that of the hot-wire sensor. However, in the interests of simplified design, a substantial portion of the electrical bridge circuit is installed on a ceramic substrate, in the form of thin-film resistors. In addition, there is no need to burn contaminants off the film. The contamination problem is solved by placing the areas on the sensor element which are decisive for thermal transmission at a downstream location. This prevents them from being affected by deposits on the sensor element's leading edge.

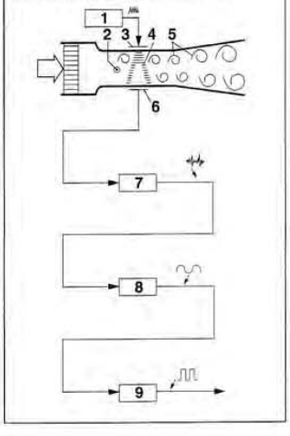
Kármán vortex volumetric flow meter

Yet another option for measuring intake air is provided by a sensor which uses the Kármán vortex principle to measure the volumetric flow rate. This meter monitors vortices generated as the intake air flows past vortex generators. The frequency of these vortices is a measure of the volumetric flow rate. This frequency is measured by emitting ultrasonic waves perpendicular to the direction of the intake-air flow. The propagation velocity of these waves as modified by the vortices is detected by an ultrasonic receiver and the resulting signals are evaluated in the ECU.

Hot-film air-mass flow meter
a Housing, b Hot-film sensor (installed in center of housing). 1 Heat sink, 2 Spacer, 3 Driver stage, 4 Hybrid, 5 Sensor element (metallic film).



Kármán vortex volumetric flow meter
1 Oscillator, 2 Vortex generator, 3 Transmitter, 4 Ultrasonic waves, 5 Eddy currents, 6 Receiver, 7 Amplifier, 8 Filter, 9 Pulse shaper.



HMC EXHIBIT 1010

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Electromagnetic fuel injectors

Design and operation

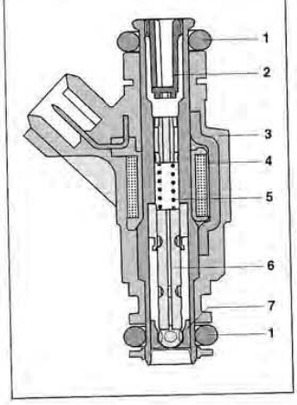
Fuel injectors essentially consist of a valve housing with current coil and electrical connection, a valve seat with spray-orifice disk and a moving valve needle with solenoid armature.

A filter strainer in the fuel feed protects the injector against contamination. Two O-rings seal the injector against the fuel-distribution pipe and the intake manifold. When the coil is de-energized, the spring and the force resulting from the fuel pressure press the valve needle against the valve seat to seal the fuel-supply system against the intake manifold (see Fig.).

When the injector is energized, the coil generates a magnetic field which attracts the armature and lifts the valve needle off of its seat to allow fuel to flow through the injector.

The injected fuel quantity per unit of time is essentially determined by the system pressure and the free cross-section of the spray orifices in the spray-orifice disk. The valve needle closes again when the field current is switched off.

***Fuel injector EV6** (example)*
1 O-rings, 2 Filter strainer, 3 Valve housing with electrical connection, 4 Current coil, 5 Spring, 6 Valve needle with solenoid armature, 7 Valve seat with spray-orifice disk.



Spray formation

The fuel injectors' spray formation, i.e. spray shape, spray angle and droplet size, influences the formation of the A/F mixture. Individual geometries of intake manifold and cylinder head make it necessary to have different types of spray formation.

Tapered spray:

Individual fuel sprays emerge through the openings in the spray-orifice disk. These fuel sprays combine to form a tapered spray. Tapered sprays can also be obtained by means of a pintle projecting through the injector needle tip. Tapered-spray injectors are typically used in engines with one intake valve per cylinder. The tapered spray is directed into the opening between the intake-valve disk and the intake-manifold wall.

Dual spray:

Dual-spray formation is used in engines with two intake valves per cylinder. The openings in the spray-orifice disk are arranged in such a way that two fuel sprays emerge from the injector. Each of these sprays supplies an intake valve.

Air-shrouding:

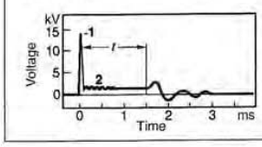
In the case of an air-shrouded injector, the pressure drop between intake-manifold and ambient pressures is used to improve mixture formation. Air is routed through an air-shrouding attachment into the outlet area of the spray-orifice disk. In the narrow air gap, the air is accelerated to a very high speed and the fuel is finely atomized when it mixes with it.

Ignition

The ignition system's function is to initiate combustion in the flammable air-fuel mixture by igniting it at precisely the right moment. In the spark-ignition (Otto) engine, this is achieved with an electrical spark, i.e. an arc generated between the spark plug's electrodes. Consistently reliable ignition under all circumstances is essential for ensuring fault-free catalytic-converter operation.

Misfiring results in damage to or destruction of the catalytic converter due to overheating during afterburning of the uncombusted mixture.

Spark-plug voltage characteristic with stationary or semi-stationary A/F mixture
1 Ignition voltage, 2 Spark voltage, t Spark duration.



Mixture ignition

Provided the composition of the mixture is stoichiometric, an energy of approximately 0.2 mJ is required for each individual ignition of the A/F mixture via electric spark. Over 3 mJ are required for a rich or lean mixture. This energy represents only a fraction of the total energy in the ignition spark, the actual ignition energy. If sufficient ignition energy is not available, there will be no ignition, the mixture cannot ignite, and misfiring will result.

The system must therefore deliver enough ignition energy to ensure consistently reliable ignition of the mixture, even under unfavorable conditions. Igniting a small flammable mixture cloud flowing past the spark can be enough to initiate the process.

This mixture cloud ignites, the flame spreads to the remaining mixture in the cylinder, and the fuel starts to combust. Ignitability is enhanced by efficient fuel atomization and good access of the mixture to the electrodes, as well as through extended spark duration and spark length (large electrode gap).

The spark plug determines the location and length of the spark; spark duration depends upon the type and design of the ignition system, as well as on the momentary ignition conditions.

Spark generation

Adequate voltage must be present before a spark will arc from one electrode to another. At the moment of ignition, the voltage across the electrodes abruptly rises from zero up to the arcing (ignition) voltage and the plug fires. Once the spark has ignited, the spark-plug voltage drops to the sparking voltage. The A/F mixture may ignite at any point during the firing period of the ignition spark (spark duration). Once the spark has broken away, the voltage is damped and drops to zero.

Although intense mixture turbulence is basically desirable, it can extinguish the spark, thus leading to incomplete combustion. The energy stored in the ignition coil should therefore suffice for one or more consecutive sparks, depending on individual requirements.

High-voltage generation and energy storage

Battery-ignition systems generally employ an ignition coil to generate the high-tension voltage needed to generate the spark. The ignition coil operates as an autotransformer but within coil-ignition systems it also assumes the further important function of storing the ignition energy. When the contact breaker closes, energy from the vehicle's electrical system flows into the coil's primary winding. This energy is then stored in a magnetic field until the firing point, when the secondary winding discharges it to one of the engine's spark plugs. The ignition coil is designed to ensure that the available high-tension voltage in the coil is always well in excess of the spark plug's maximum-possible ignition-voltage requirement. Energy levels of 60...120 mJ within the coil correspond to an available voltage of 25...30 kV.

The operational reserves of high volt-

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age and ignition energy are sufficient to compensate for all electrical losses. Inadequate maintenance reduces these high-voltage reserves, and leads to ignition and combustion miss. Engine power drops and fuel consumption increases. In addition, this phenomenon can result in damage to or destruction of the catalytic converter, should one be installed. In extreme cases, the engine either fails to start – especially when cold – or stalls.

Ignition systems are also available with capacitive energy storage (CDI or Capacitor-Discharge Ignition) for use on high-performance and racing engines. These systems store the ignition energy in the electrical field of a capacitor before a special transformer transmits it to the spark plug in the form of a high-voltage ignition pulse.

Ignition timing and adjustment

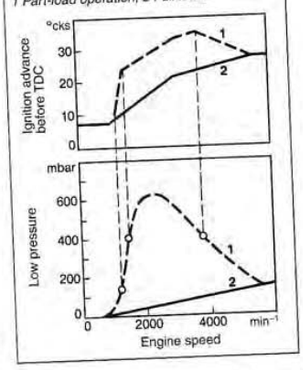
Approximately two milliseconds elapse between the mixture's initial ignition and its complete combustion. The ignition spark must therefore arc early enough to ensure that main combustion, and thus the combustion-pressure peak in the cylinder, occur shortly after piston TDC. The ignition angle should therefore move further in the advance direction along with increasing engine speed. The chosen firing point should ensure that the following requirements are met:

- maximum engine performance
- low fuel consumption
- no engine knock
- clean exhaust gas.

Since it is impossible to obtain optimal compliance with all of these requirements simultaneously; compromises must be found on a case-to-case basis. Optimal ignition timing is defined according to a variety of parameters. The most important are engine speed, engine load, engine design, fuel quality and momentary operating conditions (starting, idle and trailing throttle, etc.). In the simplest case, spark-advance mechanisms sensitive to variations in engine speed and intake-manifold vacuum adapt the ignition timing to suit the engine's current operating conditions.

In modern engine-management systems with extended functions, additional adjustments can be used e.g. for rapid torque adaptation or for swift heating of the catalytic converter.

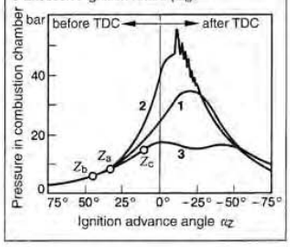
Example of cumulative ignition timing consisting of centrifugal and vacuum advance
1 Part-load operation, 2 Full load.



All the adjustment strategies can operate either individually or simultaneously. The degree to which the ignition timing is advanced or retarded is determined by the ignition-advance curves calibrated specifically for each individual engine configuration.

At full load, the accelerator pedal is depressed fully and the throttle is wide open (WOT). Along with increasing engine speeds, ignition takes place earlier in order to maintain the combustion pressure at the levels required for optimal engine performance. The leaner A/F mixtures encountered during part-throttle operation are more difficult to ignite. Because this means that more time is required for ignition, it must be triggered earlier, with the timing being shifted further in the "advance" direction. The manifold vacuum employed to determine the necessary degree of spark advance is monitored downstream from the throttle valve. If the vacuum bore is located near the throttle valve (P. 489), the vacuum initially increases as the throttle is opened wider and begins to

Combustion-pressure curve for various ignition firing points
1 Correct ignition advance (Z_a),
2 Excessive ignition advance (Z_b),
3 Excessive ignition retard (Z_c).



fall in the proximity of the full-throttle (WOT) position. The progressively wider throttle openings required to increase engine speed on the operating curve for part-throttle road operation are reflected in the relationship between vacuum and min^{-1} shown in the diagram.

Yet another diagram shows the curves for combustion-chamber pressure in a 4-stroke engine with correct and incorrect ignition timing. Even if the timing is initially correct, neglected maintenance can allow it to drift over the course of time. If the timing shifts towards a later firing point ("retard"), the result is a gradual drop in engine power and increased fuel consumption. Excessive "advance" may result in extreme cases in serious damage to spark plugs or to the engine if the engine knocks. The level of exhaust emissions also increases.

Ignition and emissions

Owing to the fact that it directly affects the various exhaust-gas components, the ignition has a significant effect upon exhaust emissions. Because various – and in this context sometimes mutually antagonistic – factors such as fuel economy, driveability, etc., are also potential optimization criteria, it is not always possible to specify the ideal ignition timing for minimum emissions.

Shifts in ignition timing induce mutually inverse response patterns in fuel consumption and exhaust emissions: While more spark advance increases power and reduces fuel consumption, it also raises HC and, in particular, NO_x emissions. Excessive spark advance can cause engine knock and lead to engine damage. Retarded ignition results in higher exhaust-gas temperatures, which can also harm the engine. Electronic engine-management systems featuring programmed ignition curves are designed to adapt ignition timing in response to variations in factors such as min^{-1}, load, temperature, etc. They can thus be employed to achieve the optimum compromise between these mutually antagonistic objectives.

Overview of various ignition systems

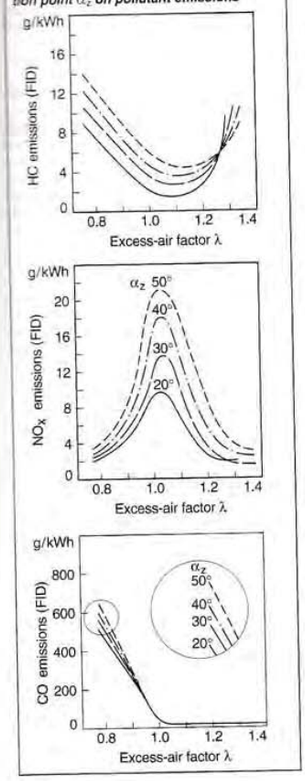
Function	Ignition system			
	CI	TI	EI[1])	DLI
Designation	Coil ignition system	Transistorized ignition system	Engine management: Electronic ignition system	Engine management: Distributorless semiconductor ignition system
High-voltage generation	Inductive			
Ignition triggering	Mechanical	Electronic		
Ignition angle determined from engine speed and load	Mechanical		Electronic	
Spark distribution to appropriate cylinder	Mechanical			Electronic

[1]) Any desired ignition timing is not possible with EI. DLI therefore dominates with integrated engine-management systems.

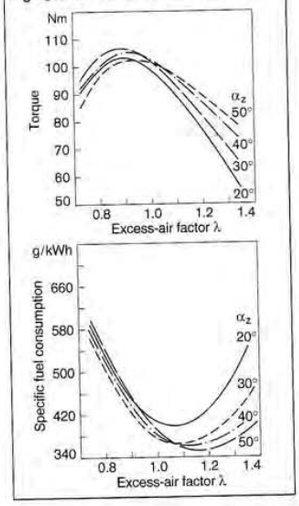
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Influence of excess-air factor λ and ignition point α_z on pollutant emissions



Influence of air factor λ and ignition timing α_z on fuel consumption and torque



Ignition energy

The ignition system generates a high-voltage spark at the spark plug to initiate combustion. An ignition-spark energy of approx. 0.2 mJ is adequate to ignite a stoichiometric air-fuel mixture, while richer or leaner mixtures require substantially higher levels of spark energy. Excess energy, i.e., from an ignition system designed to generate a high-energy spark of extended duration (transistorized or electronic ignition) stabilizes flame propagation and reduces the fluctuations from cycle to cycle. The reduction in fluctuations results in smoother engine operation and lower HC emissions. Increased spark projection, larger electrode gaps and thin electrodes also have a positive influence on the engine's smoothness and HC emissions.

Ignition coil

The ignition coil functions as both an energy-storage device and a transformer. The coil, which is powered by DC voltage from the vehicle's electrical system, supplies the ignition pulses for the spark plugs at the required high voltage and discharge energy. The ignition driver stage with its defined deactivation current combines with a primary winding featuring specific resistance and inductance characteristics to determine the amount of energy stored within the ignition coil's magnetic field. The secondary winding can be designed to provide peak voltage, spark current and discharge duration in accordance with individual requirements.

The contact-breaker points used with coil ignition (CI) can only handle interrupt currents of up to approx. 5 A. TI, EI and DLI ignition systems and Motronic ECUs can handle much higher interrupt currents. The series resistors generally employed with coil ignition (they can be bypassed to increase energy during cold starts) can be omitted in electronic ignition systems. Here the electronic circuitry activates the ignition coil depending on battery voltage, engine speed and other influencing variables in such good time that full energy is available at the ignition point.

Each ignition coil is designed to meet the requirements of a particular application. It must charge quickly in order to furnish the voltages and ignition energies required at high engine speeds. Important priorities thus include low primary inductance and, in some cases, higher primary interrupt currents (for adequate energy storage).

Design and operation

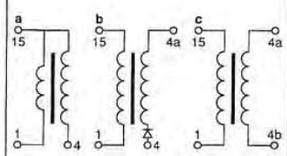
Traditional ignition coils with asphalt or oil insulation enclosed in metal casings are being increasingly replaced by units featuring an epoxy-resin filler. These not only allow more latitude in the selection of geometry, type and number of electrical terminals, but also provide more compact dimensions, better vibration resistance and lower weight. The ignition coil is generally attached by way of the iron core to the engine or vehicle body. Rod-type ignition coils are installed in the cylinder-head recess above the spark plug.

The coil's synthetic materials provide good adhesion between all of the high-voltage components and the molded epoxy resin, which penetrates into all the capillary spaces. Supplementary iron cores are sometimes embedded on the inside of the synthetic molding.

The secondary winding is mostly designed as a disk or sandwich coil, with the

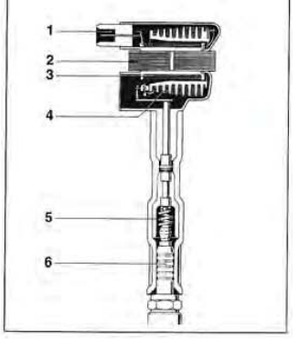
Ignition coils (schematic)

Rotating distribution: a) Single-spark ignition coil. Distributorless ignition: b) Single-spark ignition coil, c) Dual-spark ignition coil.



Single-spark ignition coil

1 External low-voltage terminal, 2 Laminated iron core, 3 Primary winding, 4 Secondary winding, 5 Internal high-voltage connection via spring contact, 6 Spark plug.



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windings distributed among a series of segments. Even distribution of stresses among the insulating elements in all chambers combines with high dielectric strength to permit compact dimensions while at the same time making foil and paper between wire layers redundant. The winding's self-capacitance is also reduced.

Because lower breakdown voltages are required for the negative (relative to engine ground) ignition spark, the positive terminals for the primary and secondary windings are generally combined on those ignition coils used with rotating high-voltage distribution.

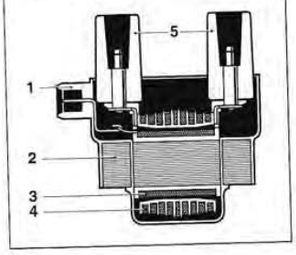
Single and dual-spark ignition coils are an alternative for use in ignition systems with distributorless ignition (DLI).

When a single-spark coil per spark plug is used, the primary current is controlled to furnish the relevant spark plug with an ignition pulse at precisely the right moment in time. High-voltage diodes are used to prevent the positive 1...2 kV high-voltage pulse generated when the primary current is activated from causing the spark plug to fire prematurely.

On the dual-spark coil, the secondary winding is galvanically insulated from the primary winding. Each of the two high-voltage outputs are connected to a spark plug. Ignition sparks are created at the two spark plugs when the primary current is deactivated. As with rotating high-voltage distribution, this system does not usually require any special precautions to prevent activation sparks.

Connection and installation are facilitated by combining several ignition coils in a common casing to form a single assembly. However, the individual coils continue to operate as independent units. The integration of output stages in the ignition coils means that short primary leads can be used (lower voltage drop). This arrangement also prevents power loss in the driver circuits from overheating the ECU.

Dual-spark ignition coil (distributorless ignition)
1 Low-voltage terminal, 2 Laminated iron core, 3 Primary winding, 4 Secondary winding, 5 High-voltage terminals.



Spark plug

Function

The spark plug introduces the ignition energy generated by the ignition coil into the combustion chamber. The high voltage creates an electric spark between the spark-plug electrodes which ignites the compressed A/F mixture. As this function must also be guaranteed under extreme conditions (cold starting, full load), the spark plug plays a decisive role in the optimum performance and reliable operation of a spark-ignition engine. These requirements remain the same over the entire service life of the spark plug.

Requirements

The spark plug must satisfy a variety of extreme performance demands: It is exposed to the varying periodic processes within the combustion chamber as well as external climatic conditions. However, the combustion chamber must remain sealed.

During spark-plug operation with electronic ignition systems, ignition voltages of up to 30,000 V may occur and must not damage the insulator. This insulation capability must also be guaranteed at temperatures in the region of 1000 °C.

Because the spark plug is subjected to mechanical stresses in the form of exposure to periodic pressure peaks (up to

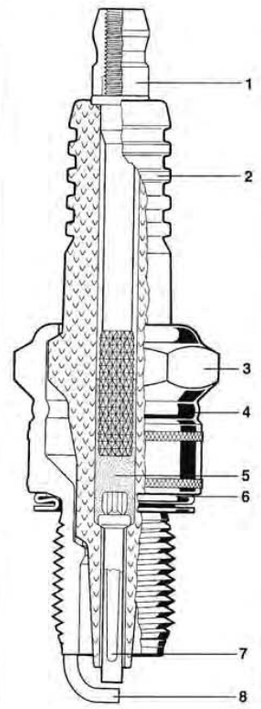
80 bar) within the combustion chamber, its materials must exhibit extreme resistance to thermal loads and continuous vibratory stress. At the same time, that section of the spark plug that protrudes into the combustion chamber is exposed to high-temperature chemical processes, making resistance to aggressive combustion deposits essential. Because it is subjected to rapid variations between the heat of the combustion gases and the cool A/F mixture, the spark-plug insulator must feature high resistance to thermal stresses (thermal shock). Effective heat dissipation at the electrodes and the insulator is also essential for reliable spark-plug performance.

Design

In a special high-grade ceramic insulator, an electrically conductive glass seal forms the connection between the center electrode and terminal stud. This glass element acts as a mechanical support for the components while providing a gas seal against the high-pressure combustion gases. It can also incorporate resistor elements for interference suppression and burn-off.

The connection end of the insulator is glazed for improved protection against contamination. The connection between it and the nickel-plated steel shell is gas-tight. The ground electrode, like the center electrode, is primarily manufactured using nickel-based alloys to cope with the high thermal stresses. It is welded to the shell. The thermal conduction properties of both the center and the ground electrodes are improved by using a nickel-alloy jacket material and a copper core. Silver and platinum, or platinum alloys, are employed as electrode material for special applications. The spark plugs have either an M4 or a standard SAE thread, depending upon the type of high-voltage connection. Spark plugs with metal shields are available for watertight systems and for maximum interference suppression.

Spark plug
1 High-voltage connector (terminal nut), 2 Al_2O_3 Ceramic insulator, 3 Shell, 4 Heat-shrinkage zone, 5 Conductive glass, 6 Captive gasket, 7 Composite center electrode Ni/Cu, 8 Ground electrode.



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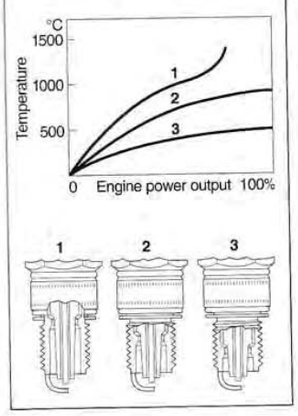
Heat range

The operating temperature of the spark plug represents a balance between heat absorption and dissipation. The aim is to achieve a self-cleaning temperature of approx. 500 °C even at low engine power outputs.

If the temperature drops below this level, there is the danger that unburnt hydrocarbons and oil residue from incomplete combustion sequences will settle on the cold areas of the spark plugs (particularly when the engine is not at normal operating temperature, at low outside temperatures, and during repeated starts). This can create a conductive connection (shunt) between the center electrode and the spark-plug shell by way of which the ignition energy leaks away in the form of short-circuit current (risk of misfires). At higher temperatures, the residues containing carbons burn on the insulator nose; the spark plug thus "cleans" itself.

An upper temperature limit of approx. 900 °C should be observed because in this range wear of the spark-plug electrodes increases markedly (due to hot-gas corrosion) and if this limit is significantly exceeded this increases the risk of auto-ignition (ignition of the air-fuel mixture on hot surfaces). Such auto-ignition subjects the engine to extreme loads and can result in the engine's destruction within a short period of time. The spark plug must therefore be adapted accordingly in terms of its heat-absorption capability to the engine type. The identifying feature of a spark plug's thermal loading capacity is its heat range, which is defined by a code number and determined in comparison measurements with a reference standard source.

Spark-plug temperature response
1 high, 2 medium, and 3 low heat range.



The Bosch ionic-current process presents possibilities for adapting the heat range to each engine. Characteristic changes in the combustion procedure due to increased thermal loading of the spark plugs can be detected using ionic current and used in the assessment of the auto-ignition process. The spark plug must be adapted in such a way as to preclude any possibility of premature ignition.

The use of center-electrode materials with high thermal conductivity (silver or nickel alloys with copper core) makes it possible to substantially extend the insulator nose without changing the plug's heat range, thus extending the plug's operating range downward into a lower thermal-load range and reducing the probability of fouling. These advantages are inherent in all Bosch Super (thermo-elastic) spark plugs.

Reducing the likelihood of combustion miss and ignition miss – with their attendant massive increases in hydrocarbon emissions – provides benefits in exhaust emissions and fuel consumption in part-throttle operation at low load factors.

Electrode gap and ignition voltage

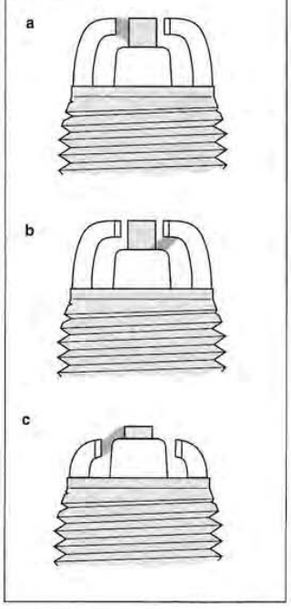
The electrode gap should on the one hand be as large as possible so that the ignition spark activates a large volume element and thus results in reliable ignition of the air-fuel mixture due to the development of a stable flame-core.

It is frequently impossible to achieve a smooth idle when the electrode gap is too narrow. On the other hand, the electrode gap must be narrow enough to guarantee that the ignition voltage will continue to produce a reliable arc, even at the end of the spark plug's service life and under unfavorable circumstances.

The required ignition voltage is influenced not only by the size of the electrode gap, but also by the electrodes' shape and temperature and the materials used in their manufacture. Parameters specific to the combustion chamber such as mixture composition (lambda value), flow velocity, turbulence and density of the gas to be ignited, also play an important role.

On today's high-compression engines, which frequently feature high charge turbulence, electrode gaps must be carefully defined in order to guarantee reliable ignition and thus misfire-free operation throughout the required service life.

Spark gap
a) Spark air gap,
b) Semi-surface gap,
c) Surface gap.



Spark gap

The configuration of the arcing path is defined by the mutual arrangement of the electrodes.

Spark air gap (a):

A linear spark arcing directly between the center and ground electrodes ignites the air/fuel mixture between the electrodes.

Semi-surface gap (b):

The semi-surface gap is created by positioning the ground electrodes (at a defined distance to the insulator end face) to the sides of the center electrode. Under certain conditions, the ignition spark forms between the center electrode and the surface of the insulator tip before arcing across a gas-filled gap to the ground electrode.

Shifting a portion of the spark's propagation travel to this shunt path extends the gap across which any given voltage can produce an arc.

The increased electrode gap improves the ignition properties.

Surface gap (c):

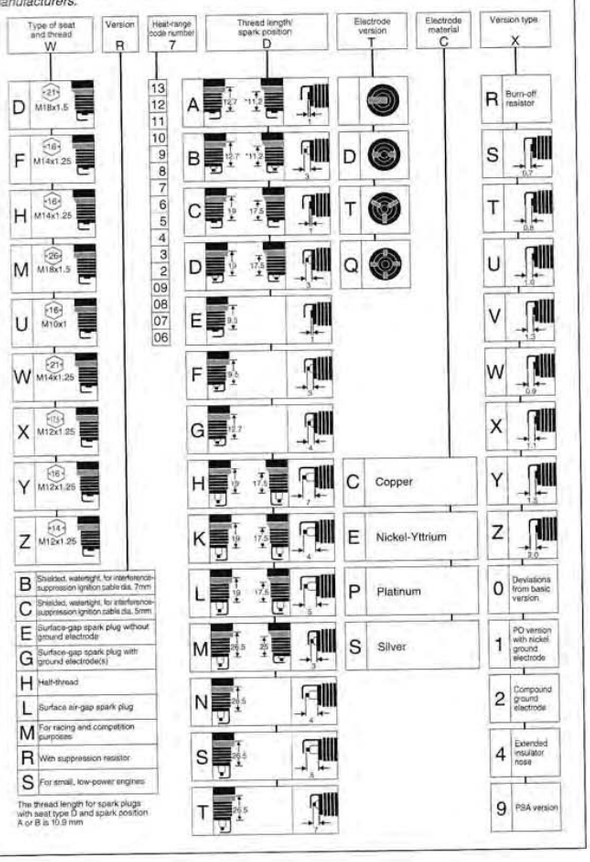
On surface-gap spark plugs, the ground electrodes are positioned to the sides of the ceramic body. The sparks thus form over the surface of the insulator tip before arcing across a small gas-filled gap to the ground electrode. The arrangement of the ground electrode to the side of the ceramic body helps to reduce the quenching losses, i.e. the flame core can extend more effectively into the combustion chamber, thus enhancing the ignition properties of the plug.

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Designation codes for Bosch spark plugs

Individual spark-plug specifications are contained in the designation code. This code includes all vital spark-plug characteristics except the electrode gap, which is indicated on the package. Spark-plug specifications for individual engine applications are defined by Bosch and the engine manufacturers.



Conventional coil ignition (CI)

Many vehicles are still equipped with conventional coil ignition. When the contact breaker closes with the ignition switched on, current from the battery or alternator flows through the ignition coil's primary winding, generating a powerful magnetic field in which the energy is stored. At the ignition point, the contact breaker interrupts the current, the magnetic field collapses and the high voltage necessary for ignition is induced in the secondary winding. This voltage is fed from terminal 4 to the ignition distributor via a high-tension cable and from there to the individual spark plugs.

The following is a basic definition of the relationship between the speed of a four-stroke SI engine and the number of sparks generated per minute:

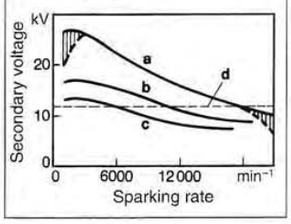
$$f = z \cdot n/2$$

f Spark-generation rate, z Number of cylinders, n Engine speed.

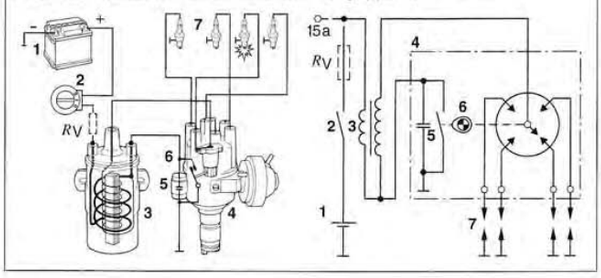
At low engine speeds, the contact-breaker points remain closed long enough to exploit the coil's full energy-storage potential. At higher engine speeds, this contact period – the dwell angle – is shorter, and the primary current is interrupted before maximum energy can be transferred to the coil. The resulting reduction in stored energy means that less high-tension current is then available from the coil.

In response, ignition coils are designed to provide high-tension voltage well in excess of the spark plugs' requirements, even at maximum engine speeds. Contamination on the insulating components acts as a capacitive and ohmic shunt, increasing the ignition loads placed upon the system, with combustion and ignition misfiring as the ultimate consequences.

Secondary voltage as a function of sparking rate
a Without ohmic shunts (R > 10 MΩ),
b Shunt resistance 1 MΩ,
c Shunt resistance 0.5 MΩ,
d Required ignition voltage.



Conventional coil-ignition system (CI), *components at left, circuit diagram at right*
1 Battery, 2 Ignition switch, 3 Coil, 4 Distributor, 5 Ignition condenser, 6 Contact breaker, 7 Spark plugs, R_V Ballast resistor for increased start voltage (optional).



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Ignition coil
Description: see P. 481.

Ignition distributor
The distributor is a separate, self-contained component within the ignition system. It has the following functions:
- it distributes the ignition pulses to the engine's spark plugs in the defined sequence (CI, TI, and electronic ignition),
- triggers the ignition pulse, either when the contact breaker interrupts the primary current, or, with breakerless systems (CI, TI, EI in some cases), using a pulse generator,
- adjusts the ignition timing with a spark-advance mechanism on conventional ignition systems (CI, TI).

In modern electronic ignition systems, operating either alone or in combination with the fuel-injection system (Motronic), the distributor generally comprises only a rotor arm connected to the camshaft and the distributor cap with high-voltage cables.

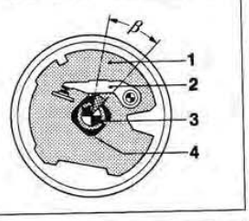
The contact-breaker points and the spark-advance mechanism perform separate functions from those of the distributor proper. They are combined with it in a single unit because they require a synchronized drive.

The ignition pulse passes through the center connection and the carbon brush or the center-tower spark gap to the distributor's rotor arm which then distributes this ignition energy by arcing it to fixed electrodes pressed into the periphery of the distributor cap. From here, the ignition pulses travel through the ignition cables to the spark plugs. A dust cover is sometimes installed to separate this high-voltage section from the rest of the unit.

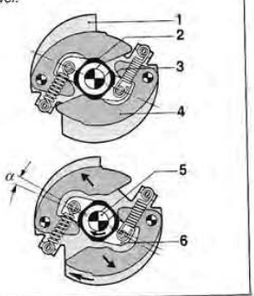
Contact breaker
A cam opens the contact-breaker points to interrupt the flow of primary current to the coil for ignition. The number of cam lobes corresponds to the number of engine cylinders. The portion of the distributor shaft's rotation during which the points remain closed is the dwell angle.

The contact-breaker points are subject to three types of wear:

Contact breaker
1 Moving breaker-plate assembly, 2 Breaker lever, 3 Distributor shaft, 4 Distributor cam.



Centrifugal advance mechanism, at rest (above), in operation (below)
1 Support plate, 2 Distributor cam, 3 Contact path, 4 Advance flyweight, 5 Distributor shaft, 6 Driver.



- contact pitting,
- contact arm (rubbing-block) wear,
- plastic deformation and local compression of the contact metal.

Contact pitting stems from the breaking sparks (residual arcing) induced by induction voltage during interruption of the primary current. The ignition condenser is designed to suppress this type of arcing, but residual sparks continue to occur. Although contact wear and rubbing-block wear are mutually counteractive, the effects of the latter are generally more pronounced, resulting in a tendency for the ignition to drift in the "retard" direction, toward a later ignition point.

Spark-advance mechanism
Ignition distributors are generally equipped with two spark-advance mechanisms: a speed-sensitive centrifugal advance mechanism and a load-dependent vacuum-controlled device.

Centrifugal advance mechanism
The centrifugal advance mechanism adjusts the ignition timing in response to changes in engine speed. The support plate upon which the flyweights are mounted rotates with the distributor shaft. The flyweights move outward as engine speed increases, thereby turning the driver over the contact path to the distributor shaft in the direction of rotation. In this way, the distributor cam also turns towards the distributor shaft by the ignition advance angle α. The point of ignition is advanced by this angle.

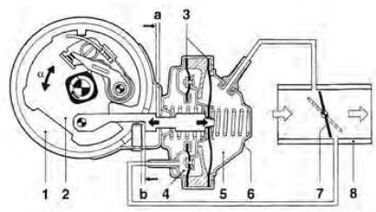
Vacuum adjustment mechanism
The vacuum mechanism adapts the ignition timing to changes in engine output and load factor. Intake manifold vacuum is monitored or tapped off in the vicinity of the throttle valve. The vacuum acts upon two aneroid capsules.

Operation of advance mechanism
Because the air/fuel mixture combusts more slowly during operation at low load factors, it must be ignited earlier to compensate. Meanwhile, the proportion of those residual gases which have been burned but not discharged from the combustion chamber increases, and the mixture leans out. Vacuum for the advance mechanism is tapped off immediately downstream from the open throttle valve. As the engine load decreases, the vacuum in the advance unit rises, causing the diaphragm and its control arm to move to the right. The control arm turns the breaker-plate assembly against the distributor shaft's direction of rotation; the point of ignition is advanced still further.

Operation of retard mechanism
Here the connection with the intake manifold's internal vacuum is downstream from the closed throttle. The ring-shaped vacuum retard unit reduces exhaust emissions by reducing ignition advance under specific operating conditions (e.g. idle, trailing throttle). The ring diaphragm and its control arm move to the left when vacuum is applied. The control arm rotates the breaker-plate assembly together with the contact breaker in the distributor shaft's direction of rotation.

This spark-retard system operates independently of the advance mechanism. The advance mechanism has priority: simultaneous vacuum in both units during part-throttle operation shifts the unit to its "advance" position.

Vacuum advance mechanism with ignition advance and retard units
a Advance adjustment up to stop, b Retard adjustment up to stop
1 Ignition distributor, 2 Breaker-plate assembly, 3 Diaphragm, 4 Vacuum retard unit, 5 Vacuum advance unit, 6 Vacuum unit, 7 Throttle valve, 8 Intake manifold.



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Transistorized ignition (TI)

With conventional coil-ignition systems, ignition energy and maximum voltage are restricted by various electrical and mechanical factors limiting the breaker points' switching capacity. The demands placed upon battery-ignition systems are often more than the contact-breaker assembly can satisfy in its role as a power switch. In electronic ignition systems, the points are assisted or replaced entirely by wear-free control devices. Transistorized (coil) ignition is available in both breaker-triggered and breakerless versions.

Transistorized coil ignition with contact control is especially suitable for upgrading existing coil-ignition systems (CI). Breaker-triggered transistorized coil ignition systems are no longer installed as original equipment.

Breakerless transistorized ignition

On breakerless transistorized ignition systems, the cam-actuated contact breaker is replaced by a magnetic "pulse generator". This generates current and voltage pulses magnetically (without contacts) to trigger the high-voltage ignition pulse through the system electronics. The pulse generator is installed in the ignition distributor.

These triggering devices operate according to various principles.

Induction-type pulse generators (TI-I)

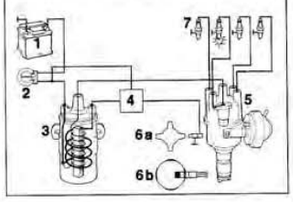
The induction-type pulse generator is a permanently-excited AC generator consisting of stator and rotor. The number of teeth or arms corresponds to the number of cylinders in the engine. The frequency and amplitude of the alternating current generated by the unit vary according to engine speed. The ECU processes this AC voltage and uses it for ignition control.

Hall-effect pulse generators (TI-H)

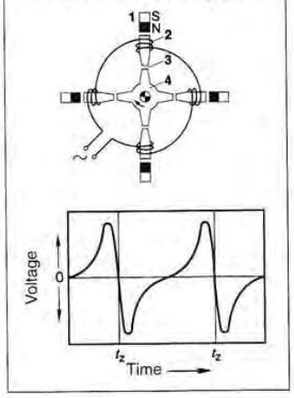
This type of ignition-pulse generator utilizes the Hall effect. A speed-sensitive magnetic field produces voltage pulses in an electrically charged semiconductor layer to control activation of the ECU's primary current.

Ignition pulse generators (impulsers) display clear benefits over mechanical contact breakers: They do not wear, and are thus maintenance-free. They allow precise control of ignition timing with attendant benefits in engine performance.

Breakerless transistorized ignition system
1 Battery, 2 Ignition switch, 3 Coil, 4 Electronic trigger box, 5 Ignition distributor with centrifugal and vacuum advance mechanism, 6a Induction-type pulse generator, 6b Hall-type pulse generator (alternative), 7 Spark plugs.



Ignition distributor with induction-type pulse generator
1 Permanent magnet, 2 Induction winding with core, 3 Variable air gap, 4 Trigger wheel.



Electronic control units

Virtually all of the electronic control units (trigger boxes) in use today are equipped with primary-current regulators and closed-loop dwell-angle control.

The primary-current regulator limits the current in order to protect the ignition coil and the driver stage. When used in conjunction with a coil featuring low primary resistance, it provides high starting current at low battery voltages. This makes it possible to dispense with series resistors upstream of the coil as well as with the bridging function for starting.

Closed-loop dwell-angle control ensures that the desired primary current is obtained in the control range as far as possible at the point of ignition. This reduces the power losses in the ECU. It also compensates for battery-voltage fluctuations and ignition-coil temperature effects. Depending on system design, this dwell-angle control is effective up to medium engine speeds. At high engine speeds, the dwell angle is determined by the break time required to achieve adequate arcing durations. The residual energy remaining in the coil after the break time promotes optimal coil charging with reduced dwell times.

The sparkless closed-circuit current deactivation switches off the primary current with the ignition on and the engine off to ensure that no sparks occur at the spark plug. However, there are also TC-I systems (with induction-type pulse-generator) with intrinsic closed-circuit current deactivation.

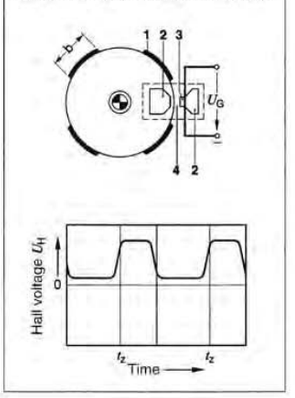
Transistorized ignition is sometimes employed together with auxiliary devices to adjust the spark advance. An example would be the idle-speed control which is installed between the Hall generator and the ECU; below idle speed it reacts to further decreases in engine min^{-1} by advancing the ignition, thus increasing torque and preventing engine speed from dropping any further. The electronic retard device reduces ignition advance at high engine speeds to prevent knocking. It is connected in parallel with the ECU. Today, both of these functions are integrated in the electronically adjusted ignition systems within the engine-management system.

Hybrid units have become the ECU standard for transistorized ignition systems owing to their ability to combine high packaging density with low weight and excellent reliability. Hybrid technology replaces the printed-circuit board, with an Al_2O_3 substrate bearing conductor paths and resistors applied in a silk-screening process. Semiconductor devices and capacitors in chip form complete the circuit. As the Darlington power-transistor chip is mounted insulated on the metallic base plate, cooling is excellent, permitting operation at high temperatures.

Ignition coils (description on P. 481)

The performance specifications of ignition coils for conventional ignition differ from those of ignition coils with electronic circuit-breakers (transistorized ignition, see P. 490). A coil designed for one application should never be employed in the other.

Ignition distributor with Hall sensor
1 Vane with width b, 2 Soft-magnetic conductive elements, 3 Hall IC, 4 Air gap, U_G Sensor voltage (transformed Hall voltage).



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Note: Unlike with breaker-triggered ignition, terminal 1 of the systems mentioned must not be shorted to ground (e.g. during compression testing) as this would overload the low-resistance primary winding of the ignition coil.

Capacitor-discharge ignition (CDI)

The operating concept behind CDI, or "thyristor ignition," as it is also called, differs from that of the ignition systems described above. CDI was developed for use with high-speed, high-output multi-cylinder reciprocating IC engines in high-performance and competition applications and for rotary-piston engines.

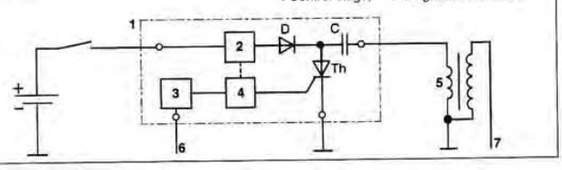
The salient characteristic of the CDI system is that it stores ignition energy in the electrical field of a capacitor. Capacitance and charge voltage of the capacitor determine the amount of energy which is stored. The ignition transformer converts the primary voltage discharged from the capacitor to the required high voltage. Capacitor-discharge ignition is available in both breaker-triggered and breakerless versions.

The major advantage of the CDI is that it generally remains impervious to electrical shunts in the high-voltage ignition circuit, especially those stemming from spark-plug contamination. For many applications, the spark duration of 0.1...0.3 ms is too brief to ensure that the air-fuel mixture will ignite reliably. Thus CDI is only designed for specific types of engine, and today its use is restricted to a limited application range, as transistorized ignition systems now afford virtually the same performance. CDI is not suited for aftermarket installations.

CDI can also be employed for distributorless ignition (DLI) with the installation of one ignition coil per cylinder, with energy distribution taking place at the medium-voltage level.

Capacitor-discharge ignition system with induction-type pulse generator, schematic

1 Control unit, 2 Charger, 3 Pulse shaper, 4 Control stage, 5 Ignition transformer, 6 To induction-type pulse generator, 7 To ignition distributor.



Accident hazard

All electronic ignition systems (including capacitor discharge, transistorized ignition and all systems with partial or comprehensive electronic control) are potentially dangerous. Always switch off the ignition or disconnect the battery before performing any service or maintenance including:

– Replacing components such as spark-plugs, coils, transformers, distributors, high-tension cables, etc.
– Connecting engine test devices such as stroboscopic lamps, dwell-tach testers, ignition oscillographs etc. Dangerously high voltage levels are present throughout the ignition system whenever it is turned on. All service operations should be performed exclusively by qualified technicians.

Electronic ignition (EI and DLI)

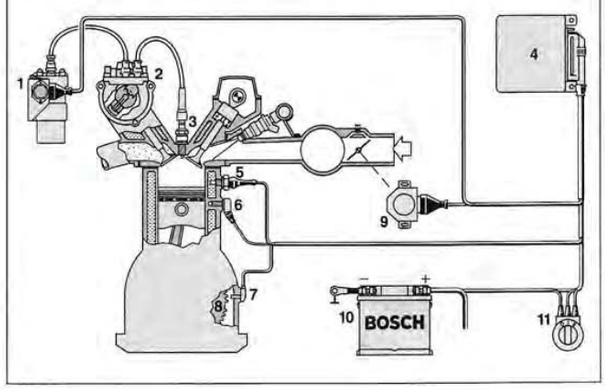
Electronic ignition derives its name from the fact that it calculates the ignition point electronically. The characteristic curves provided by the conventional distributor's centrifugal and vacuum-advance units are replaced by an optimized electronic ignition map. Mechanical high-tension distribution is retained with EI ignition. Fully electronic distributorless semiconductor ignition (DLI) uses stationary electronically controlled components to replace the mechanical, rotating high-tension distributor.

Electronic ignition systems operate more precisely than mechanical systems, with major benefits originating in the fact that the ignition process can be triggered from the crankshaft instead of from a distributor (distributor drive tolerances are no longer a factor). The limitations which mechanical adjustment mechanisms place upon the performance curve (summation of curves for load and engine speed in a single progression) are also avoided. The number of input variables is also theoretically unlimited, usually allowing extensions in the ignition angle's adjustment range. The fixed-drive ignition distributor's limitations regarding the engine's ignition-voltage requirements and ignition-angle adjustment range are such that it has difficulty coping with larger numbers of cylinders; efficient spark distribution cannot always be guaranteed. Corrective measures include dividing the ignition into two circuits (e.g., for 8- and 12-cylinder engines) and static voltage distribution.

Electronic ignition can be combined with electronic fuel-injection (Motronic), knock control, ASR, etc., making it possible to employ sensors and/or signals from other units in more than one system. A serial bus (CAN, P. 884) further reduces the number of inputs and processing circuits on the ECU's input-side.

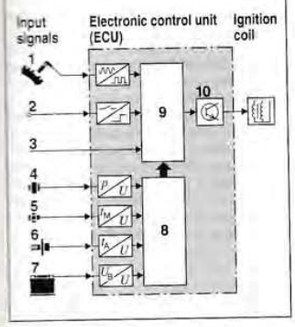
Schematic of an electronic ignition system (EI)

1 Ignition coil with ignition driver stage, 2 High-voltage distributor, 3 Spark plug, 4 ECU, 5 Engine-temperature sensor, 6 Knock sensor, 7 Engine-speed and reference-mark sensor, 8 Ring gear for sensor, 9 Throttle switch, 10 Battery, 11 Ignition switch.

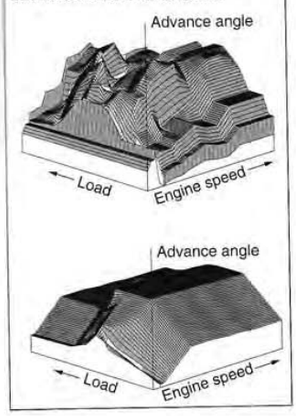


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Electronic ignition, signal processing
1 Engine speed, 2 Switch signals, 3 CAN (serial bus), 4 Intake-manifold pressure, 5 Engine temperature, 6 Intake-air temperature, 7 Battery voltage, 8 Microprocessor, 9 Analog/digital converter, 10 Driver stage.



Ignition maps
Above: electronically optimized, Below: mechanical advance system.



Operation
The engine's speed and crankshaft position are monitored directly at the ring gear, using either a separate rotor or a specific pin sequence employing an inductive, rod-type sensor, with two sensors being employed on older units. Triggering is either incremental or segmentary, according to whether the information is taken from teeth distributed evenly around the crankshaft or a crankshaft segment per cylinder pair:
- Beginning of segment = maximum spark advance angle,
- End of segment = starting angle.

In the incremental system illustrated here, the reference mark (shown as a tooth gap) represents a defined crankshaft position, providing a reference for electrically monitoring crankshaft angle using the ring-gear teeth. A distributor without an advance mechanism can also be employed for triggering; here the control signal is provided by a Hall generator. An absolute-pressure sensor in the intake manifold is the best way to monitor load. This provides a better gauge of cylinder charge than the spark-advance or retard bores on the throttle valve. It is also possible to incorporate load switches, throttle-valve potentiometers or electronic load signals from the mixture-preparation system. The microcomputer in the ECU processes the engine-speed and load signals prior to using them to calculate the precise ignition angle within the ignition map. The computer can also process other input variables, such as e.g. engine temperature, or information on trailing throttle or full-load operation from the throttle-valve switch, to derive correction values and regulate other vehicle-specific functions as required. The dwell angle for charging the ignition coil is also specified by the computer. The battery voltage is monitored here to enable voltage correction. The system responds to deviations in battery voltage from the specified baseline by extending or reducing coil-charging times accordingly. This ensures consistent availability of maximum voltage while at the same time limiting the accumulation of heat in ECU and coil to a minimum. At speeds below the starting speed, the computer interrupts the current flow through the ignition coil in order to prevent overheating. The driver stage can be either integrated inside the ECU or installed externally, e.g. on the ignition coil.

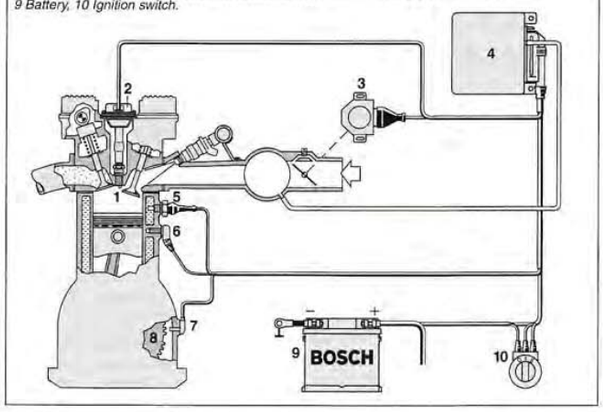
Signal processing in the ECU
After initial processing the digital signals go directly to the processor. Analog signals are first converted into digital form. There are also ECU's which can transmit supplementary digital or analog signals (e.g., for overrun fuel cutoff and exhaust-gas recirculation). There exists a range of EI ignition-system versions of varying complexity. A comparison of the ignition map with the response curve of a distributor shows that it is possible to program each point in the ignition map independently from every other point. Thus the optimum ignition timing (e.g., for maximum fuel economy) can be selected for every operating condition, according to the limits imposed by factors such as exhaust emissions, pre-ignition limit and driveability. The entire system is completely maintenance-free and does not require any adjustments during the engine's service life.

Rotating voltage distribution
A high-voltage distributor distributes the ignition pulses to the spark plugs of the individual cylinders (as described earlier). If the distributor's adjustment range is insufficient for handling a larger number of cylinders, then two ignition circuits are employed, i.e., two 4-cylinder distributors can be used for one 8-cylinder engine. Synchronization through the crankshaft can be used for "two times 4 cylinders", whereas "two times 3 cylinders" with constant ignition-angle spacing (not employed up to now) must be controlled by the camshaft.

Distributorless (stationary) voltage distribution

Systems with single-spark ignition coil
Each cylinder has its own ignition coil with driver output stage, installed either di-

Schematic of a fully-electronic distributorless ignition system (DLI)
1 Spark plug, 2 Single-spark coil, 3 Throttle switch, 4 ECU, 5 Engine-temperature sensor, 6 Knock sensor, 7 Engine-speed and reference-mark sensor, 8 Ring gear for sensor, 9 Battery, 10 Ignition switch.



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rectly above the spark plug or separately. Either synchronization with the camshaft sensor or a method for detecting the compression cylinder is required. On engines with an even number of cylinders, the system reverts to crankshaft triggering in the event of camshaft-sensor failure, although two coils are then always activated simultaneously (one of the sparks is discharged during an exhaust stroke). This system, suitable for engines with any number of cylinders, provides the greatest latitude for adjustment, as there is only one spark per cycle. All these advantages mean that the single-spark ignition coil is being increasingly used and is taking over from the dual-spark ignition coil in spite of costing more.

Systems with dual-spark ignition coil

One ignition coil is required for every two cylinders. The crankshaft can be used for synchronization. The high-voltage end of each ignition coil is connected to the spark plugs for two cylinders whose operating cycles are 360° out of phase with each other.

As there is an additional spark during the exhaust stroke, it is important to ensure that residual mixture or fresh mixture is not ignited. Furthermore, the dual-spark system is only suited for use with even numbers of cylinders. Owing to its cost advantage relative to the single-spark unit, the dual-spark ignition system is the most common distributorless ignition in use today.

Knock control

Application

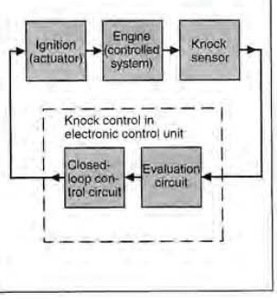
Electronic control of the ignition point offers the possibility of controlling very precisely the ignition angle as a function of engine speed, load and temperature.

Nevertheless, without knock control a clear safety distance to the knock limit is required. This distance is necessary to ensure that even in the most knock-sensitive case with regard to engine tolerances, engine aging, environmental conditions and fuel quality, no cylinder reaches or exceeds the knock limit. The resulting engine design leads to lower compressions with retarded ignition points and thus worsening of fuel consumption and torque figures.

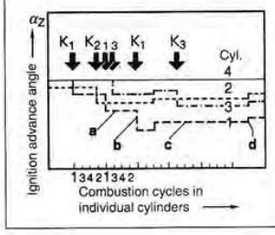
These disadvantages can be avoided through the use of knock control. Experience shows that knock control increases engine compression and significantly improves fuel consumption and torque. However, the pre-control ignition angle now no longer needs to be determined for the most knock-sensitive but rather for the most insensitive conditions (e.g. engine compression at lower tolerance limit, best possible fuel quality, most knock-insensitive cylinder). Each individual engine cylinder can now be operated over its entire service life in virtually all operating ranges at its knock limit and thus at optimal efficiency.

The essential precondition for this ignition-angle configuration is reliable knock detection for each individual cylinder as from a particular knock intensity, and over the entire engine operating range.

Schematic of knock-control system



Knock control *Control algorithm for ignition adjustments with a 4-cylinder engine*
$K_{1...3}$ knock in cylinders 1...3, Cylinder 4, no knock.
a Delay prior to ignition retard, b Retardation, c Delay before return to original ignition point, d Spark advance.



Combustion knock

The characteristic vibrations of combustion knock are detected by knock sensors, converted into electrical signals and forwarded to the Motronic.

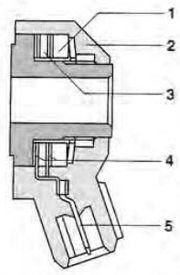
It is essential to work out carefully the number and installation positions of the required knock sensors. Reliable knock detection must be guaranteed for all cylinders and for all engine operating points, particularly at high engine speeds and loads. As a rule, 4-cylinder in-line engines are equipped with one knock sensor, 5- and 6-cylinder engines with two sensors and 8- and 12-cylinder engines with two or more sensors.

Knock detection, evaluation

For the purpose of knock detection, the vibrations characteristic to knocking are converted into electrical signals by one or more knock sensors mounted at appropriate positions on the engine, and then forwarded to the Motronic for evaluation. It is here that the corresponding evaluation algorithm is applied to detect knock for each cylinder and each combustion. Detected combustion knocks result in a retardation of the ignition point by a programmable amount at the cylinder in question. If knock stops, the ignition point is advanced again in stages up to the pre-control value.

The knock-detection and knock-control algorithms are matched in such a way as to eliminate any knocking that is audible and damaging to the engine.

Knock sensor
1 Seismic mass, 2 Potting compound, 3 Piezoceramic element, 4 Contacts, 5 Terminals.



Adaptation

Real engine operation produces different knock limits and thus also different ignition points for the individual cylinders. In order to adapt the ignition-point pre-control values to the particular knock limit, the ignition-point retardation values individual to each cylinder and dependent on the operating point are stored.

They are stored in non-volatile maps of the permanently powered RAM covering load and engine speed. In this way, the engine can also be operated in the event of rapid load and speed changes in each operating point at optimal efficiency and without audible combustion knocks.

The engine can even be approved for fuels with lower anti-knock properties.

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Combined ignition and injection system (Motronic)

The Motronic engine-management system has undergone substantial development since its introduction in 1979. Initially, integration was based on the basic gasoline-injection systems, in combination with distributorless semiconductor ignition, as were available in the following systems:
- KE-Motronic, based on KE continuous gasoline injection (P. 469),
- Mono-Motronic, based on intermittent single-point injection (P. 465),
- M-Motronic, based on intermittent multi-point injection (P. 471).

On the basis of M-Motronic, and by applying further integration steps, the Motronic system assumed control of all the manipulated variables of a spark-ignition engine that influence torque:
- ME-Motronic with electronic accelerator pedal (ETC) for controlling gasoline injection, ignition and fresh-air charge for manifold injection (P. 498).
- MED-Motronic with further integrated open- and closed-loop control functions for the high-pressure fuel circuit. With direct injection and realization of the various operating modes of this engine type (P. 507).

System overview

The Motronic system comprises all the sensors for recording the current engine and vehicle operating data (P. 501, Operating-data acquisition) and all the actuators for the adjustments to be carried out on the SI engine (P. 503, Operating-data processing).

Electronic control unit

The ECU employs sensors to monitor the relevant status of engine and vehicle at extremely short intervals (milliseconds).

Input circuits suppress sensor-signal interference and convert the signals to a single unified voltage scale. An analog-digital converter then transforms the conditioned signals into digital values. Further signals are received by way of a digital interface. Using this information, the microprocessor identifies the operating state desired by the driver and from it calculates for instance:
- the required torque,
- the resulting cylinder charge with the associated injected fuel quantity, and
- the correct ignition timing.

The low-level signal data from the microprocessor outputs are adapted by the driver stages to the levels required by the various actuators. A semiconductor memory chip stores all programs and performance maps, ensuring system consistency which remains completely impervious to fluctuations resulting from signal-level and component tolerances.

Digital accuracy is a function of word length, as well as of the consistency of the quartz's basic clock frequency and the types of algorithms used for the calculations. The consistency and precision of the reference voltages and the components installed in the analog input circuits influence the analog accuracy.

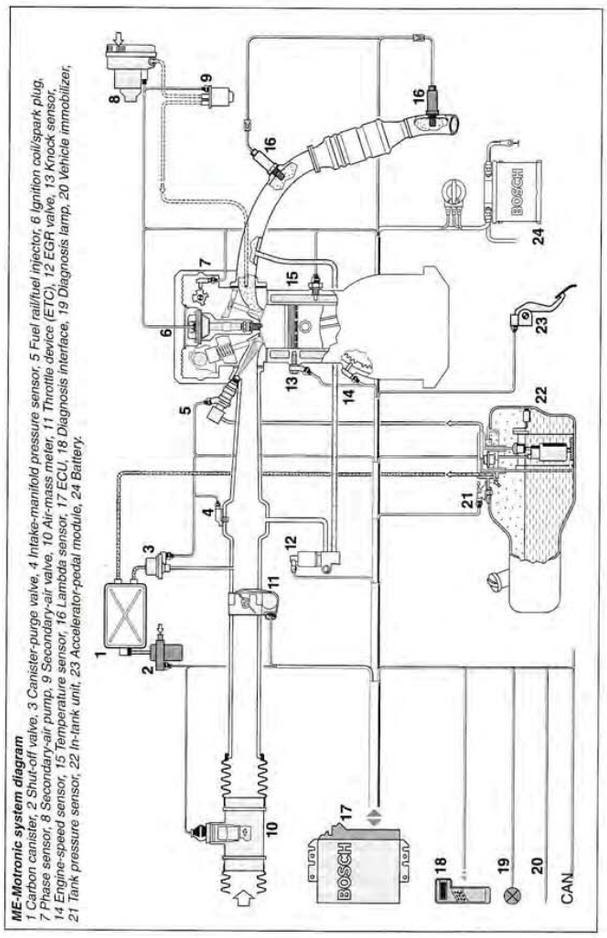
Program design must satisfy the engine's severe real-time demands: in an 8-cylinder engine at maximum speeds, less than 2.5 ms are available between two ignitions. All essential calculations must be completed within this period. In addition to these crankshaft-synchronous processes, there are also time-synchronous operations. Both types can be suspended by interrupts.

ME-Motronic

Design

Basic functions

In order to set the operating state desired by the driver (main function), the position of the gas pedal is converted by the microprocessor into a setpoint value for the engine torque. Then, while taking into consideration the highly varying current operating data from the ME-Motronic, these are converted into the variables for determining the engine torque:
- the charging of the cylinders with air,
- the mass of the injected fuel and
- the ignition angle.



ME-Motronic system diagram
1 Carbon canister, 2 Shut-off valve, 3 Canister-purge valve, 4 Intake-manifold pressure sensor, 5 Fuel rail/fuel injector, 6 Ignition coil/spark plug, 7 Phase sensor, 8 Secondary-air pump, 9 Secondary-air valve, 10 Air-mass meter, 11 Throttle device (ETC), 12 EGR valve, 13 Knock sensor, 14 Engine-speed sensor, 15 Temperature sensor, 16 Lambda sensor, 17 ECU, 18 Diagnosis interface, 19 Diagnosis lamp, 20 Vehicle immobilizer, 21 Tank pressure sensor, 22 In-tank unit, 23 Accelerator-pedal module, 24 Battery.

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Additional function
As well as the basic functions, the ME-Motronic has a large number of additional open- and closed-loop control functions. Examples of such functions are:
- idle-speed control,
- closed-loop lambda control,
- control of evaporative-emissions control system,
- exhaust-gas recirculation for reducing NO_x emissions,
- control of secondary-air system for reducing HC emissions, and
- cruise control.

These functions have been made necessary by the legislation covering the reduction of exhaust emissions, the calls for a decrease in fuel consumption but also increased demands placed on driving comfort and safety.

In addition, the ME-Motronic system can be further extended with the following functions:
- Control of turbocharger control and variable-tract intake manifold for increasing engine power output,
- Camshaft control for reducing exhaust emissions and fuel consumption and for increasing power,
- Knock control, engine-speed limitation and vehicle-speed limitation for protecting components in the engine and vehicle.

Torque-guided control concept
The torque-guidance principle is aimed at simplifying the many and sometimes very different assignments placed on the engine and the vehicle. Only then is it possible, depending on the engine or vehicle type, to determine the required functions in each case and to integrate them in the relevant Motronic version.

Most of the additional open- and closed-loop control functions likewise influence the engine torque. In a torque-guided system, all these functions behave like the driver: they request an engine torque irrespective of each other. The torque-guided ME-Motronic uses torque coordination to sort the often contradictory torque requirements and to then put the most important requirement into effect.

Vehicle management
The ME-Motronic can communicate via the CAN bus system (P. 884) with the ECUs of other vehicle systems. Among other things, in conjunction with the automatic-transmission ECU, it reduces torque at the gear-shift point so that the transmission is subjected to less loading and wear. When wheel spin occurs, the ECU belonging to the Traction Control System (TCS) signals to the ME-Motronic to reduce the generated torque.

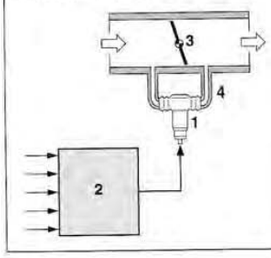
Diagnosis
The ME-Motronic incorporates components for on-board monitoring (OBD). It therefore complies with the most stringent emission limits and the demands placed on the integrated diagnosis functions.

Cylinder-charge control systems

Throttle-valve control
In an SI engine with external A/F mixture formation, the cylinder charge is the factor that determines torque output and thus power output. The throttle valve controls the air-flow intake into the engine and thus the cylinder charge.

In conventional systems, a cable or a linkage transfers the movement of the accelerator pedal to the throttle valve. Requirements for additional air are covered by a bypass air actuator which directs an additional air flow around the throttle valve (see Fig.), or a throttle-valve actuator alters the stop for minimum air quantity. However, the air flow required by the engine can only be electronically influenced to a limited extent (idle-speed control).

Air control with bypass air actuator (principle)
1 Idle actuator (bypass air actuator), 2 ECU, 3 Throttle valve, 4 Bypass.



Systems with ETC (electronic throttle control, integrated in the engine control unit for ignition, injection and other auxiliary functions) detect the position of the accelerator pedal with a pedal-travel sensor (potentiometer).

Taking into account the current engine operating status, the ECU calculates how far the throttle valve needs to open and actuates the throttle-valve drive accordingly (see Fig.). A throttle-valve angle sensor (potentiometer) monitors exact compliance with the desired throttle-valve position. Two potentiometers (for redundancy reasons) at the accelerator pedal and throttle device are part of the ETC monitoring system which, while the engine is running, continually checks all the sensors and calculations which affect throttle-valve opening.

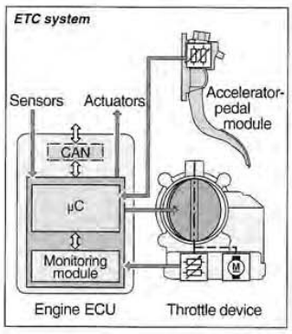
Charge-cycle control
The behavior of the gas columns flowing into and out of the cylinders changes considerably as a function, for instance, of engine speed or throttle-valve opening. With fixed valve timing, the charge cycle can only be optimized for a specific operating range.

Camshaft control or camshaft-lobe control (P. 387) permits not only variable valve timing, and thus adaptation to various engine speeds, but also enables the residual exhaust-gas mass in the cylinder to be influenced ("internal EGR").

("External") EGR effectively reduces the temperature-dependent NO_x emissions. Exhaust gases which have already been combusted are added to the A/F mixture in order to reduce peak combustion temperatures. For this purpose, the Motronic triggers the exhaust-gas recirculation valve as a function of the engine operating point. The EGR valve then adds a partial flow of exhaust gas to the fresh mixture, thereby increasing the total charge while the fresh-air charge remains constant. In this way, the engine must be throttled less heavily in order for a specific torque to be reached (lower fuel consumption).

The achievable torque, which is proportional to the fresh-mixture charge, can be increased still further by compressing the air in the cylinder. This is the purpose of dynamic supercharging, exhaust-gas turbocharging, or mechanical supercharging (P. 390).

ETC system



Operating-data acquisition

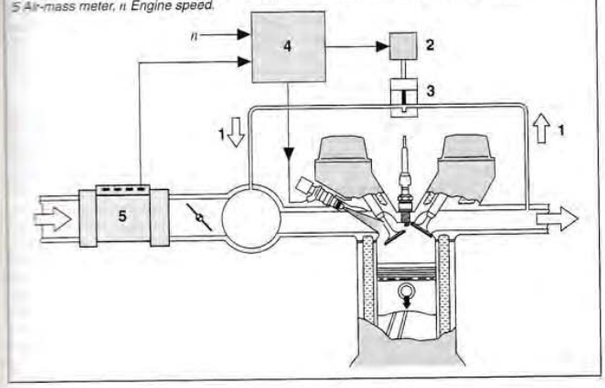
Vehicle-operator command
In the case of engine management with an electronic throttle valve (ETC), there is no longer a mechanical connection between the accelerator pedal and the throttle-valve actuator. Instead, the position of the accelerator pedal is sensed by a pedal-travel sensor or accelerator-pedal module and converted into an electrical signal. The engine-management system interprets this signal as the vehicle-operator command.

Air charge
In engine concepts with manifold injection, there is a linear relationship between the air charge and the torque generated by combustion. In the torque-guided ME-Motronic, the air charge is therefore not just one of the main factors involved in calculating the injected fuel quantity and

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Exhaust-gas recirculation *(example)*
1 Exhaust-gas recirculation (EGR), 2 Electropneumatic converter, 3 EGR valve, 4 ECU, 5 Air-mass meter, n Engine speed.



ignition angle, but also serves to calculate the torque currently being delivered by the engine. The following sensors can be used for this purpose:
– Hot-film air-mass meter,
– Intake-manifold pressure sensor,
– Ambient pressure sensor,
– Boost-pressure sensor (BPS) and
– Throttle-valve sensor.

Engine speed, crankshaft position and camshaft position
A speed sensor on the crankshaft monitors the crankshaft revolutions per minute (rotational speed). It then forwards this information on the crankshaft position, that is, the piston position of all cylinders, as an important input variable to the ME-Motronic. The cylinder's piston position is used, for instance, to determine the injection and ignition points.

To trigger the single-spark ignition coils, the ME-Motronic with static voltage distribution also requires additional information on the camshaft position. This information is mostly monitored with a Hall-effect sensor and forwarded to the ECU as a switch signal.

A/F mixture composition
The lambda factor (λ) is the figure which quantifies the A/F mass ratio of the mixture. The catalytic converter only performs optimally at $\lambda = 1$. The lambda sensor measures the oxygen concentration in the exhaust gas and provides information on the current value of the excess-air factor (P. 458).

Combustion knocks
The characteristic vibrations of combustion knocks are detected by knock sensors, converted into electrical signals and forwarded to the ME-Motronic (P. 498).

Engine and intake-air temperatures
The voltage at the NTC resistor of the engine-temperature sensor is a function of the coolant temperature. It is input via the analog-digital converter and is a measure of the temperature. In the same way, a sensor in the intake port measures the temperature of the intake air.

Operating-data processing

Torque guidance
Torque guidance is a feature of the ME-Motronic. Numerous subsystems within the Motronic (e.g. idle-speed control, engine-speed limitation), and the systems for management of the drivetrain (e.g. TCS or transmission-shift control) or of the complete vehicle (e.g. air-conditioner control), direct their torque requirements to the basic Motronic system with the aim of modifying the engine torque which has just been generated. The ME-Motronic evaluates and coordinates these requirements and implements the resulting setpoint torque using the available manipulated variables (optimum engine operation in terms of exhaust gas and fuel consumption at each operating point).

An essential precondition for torque guidance is the electronic accelerator pedal ETC with the throttle valve controlled independently of the accelerator pedal.

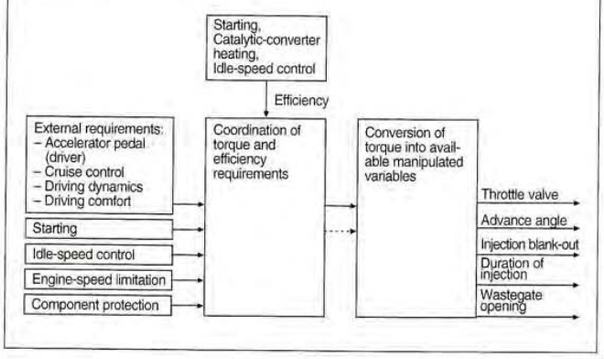
Calculation of setpoint torque
The basic variable for the ME-Motronic torque structure is the internal torque arising from combustion. The function of torque guidance is to set the internal torque, through appropriate selection of the manipulated engine variables, in such a way that the vehicle-operator command is satisfied, and all the losses and additional requirements are covered. Because the Motronic "knows" the optimum values for charge, injection time and ignition angle for each and every desired setpoint torque, it can ensure optimal engine operation in terms of exhaust gas and fuel consumption.

Setting of setpoint torque
For setting the internal torque, the ME-Motronic's torque converter has a slow path (cylinder-charge path, steady-state operation) for the throttle valve (ETC), and a high-speed path (ignition-angle path, dynamic operation) for variation of the ignition angle and/or injection blank-out of individual cylinders.

Calculation of cylinder charge
The air mass in the cylinder after the intake valves have closed is termed the air charge. Referring the actual air charge to the maximum obtainable charge produces a variable that is independent of the engine piston displacement: the "relative (air) charge". The associated injected fuel quantity can be calculated from the relative air charge.

The relative charge cannot be measured directly but it can be determined from the available measurement signals.

Influencing torque in a gasoline engine



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For this purpose, an intake-manifold model calculation is used in which all the air-mass flows into the intake manifold and from the intake manifold to the combustion chamber are calculated. The most important measured variable in this model is either the air flow through the throttle valve (measured with a hot-film air-mass meter) or the absolute intake-manifold pressure (measured with a pressure sensor).

Starting out from this intake-manifold model, it is then also possible to determine the actual relative air charge.

Cylinder-charge control

In today's spark-ignition engines, the relative cylinder charge is also the main factor in influencing the engine torque, and is therefore used in the torque structure as a manipulated variable. The intake-manifold model is also used to control the cylinder charge by means of the throttle valve: for this purpose, a required cylinder charge is first of all calculated from the desired torque (which was calculated by ME-Motronic torque guidance). This cylinder charge is then converted into an associated throttle-valve angle and finally passed on as the setpoint value to the position controller of the throttle-valve actuator.

Calculation of injection period

The fuel mass for a stoichiometric air-fuel ratio can be calculated from the air charge in the cylinder. When the fuel-injector constant (this is a function of the fuel-injector properties) is taken into consideration, this furnishes the duration of injection.

The duration of injection is also dependent on the pressure differential between fuel-supply pressure (approx. 300 kPa) and injection back pressure. Fuel-supply systems with fuel recirculation keep the supply pressure constant with respect to the intake manifold. This ensures that, in spite of a changing intake-manifold pressure, the same pressure differential is applied at the fuel injectors. On the other hand, fuel-supply systems without fuel recirculation keep the supply pressure constant with respect to the environment. As the intake-manifold pressure changes, the pressure differential varies between fuel supply and intake manifold. A compensation function corrects this error.

A further adaptation factor individual to each cylinder serves to accommodate fuel-pressure pulsations caused by the opening and closing of the fuel injectors.

The effective opening duration calculated in this way is valid under the precondition that the fuel injector is already open. It must therefore be extended by the opening and closing time of the injector. An additional, battery-voltage-dependent duration of injection, which is added to the valve-opening period, compensates for this effect.

If the effective injection duration is too short, the influences of the valve-opening and closing time become excessive. In order to ensure exact fuel metering, the injection duration is restricted to a minimum value. This value is below the injection duration associated with the minimum possible cylinder charge.

To ensure optimum combustion, it is necessary to precisely define the injected fuel quantity and the exact point for the start of injection. The fuel is generally injected into the intake manifold while the intake valves are still closed. The end of injection is determined by the "fuel-hold angle", which is specified in "crankshaft degrees". The point at which the intake valve closes serves as the reference point. It is then possible to use the duration of injection for calculating, as a function of engine speed, the start of injection as an angle. The fuel-hold angle is determined taking into account the current operating conditions.

The ME-Motronic triggers a fuel injector for each cylinder. The fuel can thus be held (stored) separately for each cylinder to optimum effect (sequential injection).

Calculation of ignition and dwell angles

When calculating the ignition angle, the first step is to determine the "basic ignition angle" while taking into account the current engine operating conditions. This basic ignition angle can be adapted in specific operating states.

When calculating the dwell angle, the first step is to determine the dwell period from a speed- and battery-voltage-dependent map. Once a temperature-dependent correction has been taken into account, the associated dwell angle is determined by means of a time/angle conversion.

The difference between the end of dwell (determined from the resulting ignition angle) and the dwell angle determines the start of dwell.

Operating states

In some operating states, the fuel requirement differs markedly from the steady-state requirements of an engine at normal operating temperature, with the result that corrective intervention in the mixture formation becomes necessary.

Starting

Intake-air adjustment, fuel injection and ignition are specially calculated during the starting procedure. An increased injected fuel quantity adapted to the engine temperature serves to build up a fuel film on the intake-manifold and cylinder walls and covers the increased fuel demand while the engine is running up. The ignition angle is likewise adapted to the starting procedure. The air charge while the engine is at a standstill is not affected by the throttle valve, which however is opened slightly in anticipation of the post-start phase.

Post-start

In this phase, the still increased charge and injected fuel quantity are reduced as a function of engine temperature and time at the end of the starting procedure. The ignition angle is adapted accordingly.

Warming-up

After starting at low engine temperatures, the engine's increased torque demand is covered up to a specific temperature threshold by adaptation of the charge, fuel injection and ignition.

Catalytic-converter heating

Highly retarded ignition angles generate very hot engine exhaust gas, thereby quickly bringing the catalytic converter up to operating temperature.

Idle

At idle, the engine-generated torque is just enough to permit sustained engine operation and running of the auxiliary systems. With idle-speed control, the desired idle speed remains stable under all conditions.

Full load

At full load, the throttle valve is wide open (WOT) and there are no throttling losses. The engine delivers the maximum torque relative to the current engine speed.

Acceleration and deceleration

Heavy acceleration and deceleration result in rapid changes in the intake-manifold pressure and thus in the conditions for the fuel film on the intake-manifold wall. In order to prevent leaning during acceleration, additional fuel is injected to build up the wall film. During deceleration, the injected fuel quantity is reduced accordingly.

Overrun fuel cutoff and restart

During the transition to no-combustion overrun conditions, the ME-Motronic cuts off the engine torque without jolting, and also provides for a smooth torque build-up when fuel feed starts again.

Additional closed- and open-loop control functions

Idle-speed control

Idle-speed control specifies a torque at which the desired engine speed is maintained under the given operating conditions. This torque increases as engine speed drops and decreases as engine speed rises.

Lambda closed-loop control

It is only possible to convert the noxious exhaust-gas constituents in the three-way catalytic converter in a very narrow range ("lambda window" where $\lambda = 0.99 \ldots 1$). Lambda closed-loop control is essential in order to remain inside this window (P. 522).

Evaporative-emissions control system

The function of evaporative-emissions control systems is to limit the HC emissions. Such systems are equipped with a carbon canister, which accommodates

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the end of the vent line from the fuel tank. Degassing fuel is retained in the canister's activated carbon. When the engine is running, a vacuum is created in the intake manifold which causes air to be drawn in from the environment through the activated carbon and into the intake manifold. The fuel vapors trapped in the canister are entrained with this air and carried to the engine for combustion. A canister-purge valve meters this "scavenging flow".

Knock control
Knock sensors convert the vibrations characteristic to knocking into electrical signals. These are used by the Motronic to adjust the ignition point in order to prevent audible knocking and knocking which could damage the engine (P. 496).

Boost-pressure control
On engines with exhaust-gas turbocharging, the setpoint value of the desired boost pressure is adjusted by electronic boost-pressure control. It is converted into a setpoint value for the desired maximum charge and then by means of torque management into a setpoint value for the throttle-valve angle and a control duty factor for the "wastegate". In the "wastegate", by means of a change in the control pressure and stroke this signal leads to a change in the cross-section at the bypass valve.

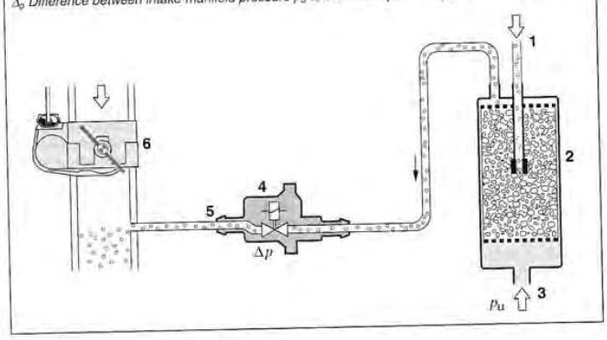
Safety and security, comfort and convenience functions
The safety and security functions include:
- Engine-speed/vehicle-speed limitation,
- Torque/power limitation,
- Limitation of exhaust-gas temperature,
- Vehicle immobilizer.

The comfort and convenience functions include:
- Load-change damping,
- Surge-damping function,
- Cruise control.

Integrated diagnosis (OBD)
"On-board diagnosis" (OBD) is a basic feature of the ME-Motronic. During normal operation, it continually compares the system's responses with the ECU's commands, as well as comparing the various sensor signals with each other for plausibility.

During vehicle inspection, a tester connected to a standardized interface reads out the stored faults and displays them. Due to the demands of the Californian Environmental Protection Agency, an expanded diagnosis system (OBD II; adapted for Europe: EOBD) monitors all those components which if they fail could result in a significant increase in noxious emissions (fault indication with diagnosis lamp).

Evaporative-emissions control system
1 Line from fuel tank to carbon canister, 2 Carbon canister, 3 Fresh air, 4 Canister-purge valve, 5 Line to intake manifold, 6 Throttle device with throttle valve.
Δ_p Difference between intake-manifold pressure p_S and ambient pressure p_u.



Examples of systems subject to diagnosis:
- Air-mass meter,
- ETC throttle-valve actuator,
- Combustion misses,
- Catalytic converter,
- Lambda sensor,
- Fuel supply,
- Tank system,
- Secondary-air injection,
- Exhaust-gas recirculation (EGR).

Fault memory
If exhaust-gas-related faults are detected, an entry is made in the non-volatile fault memory. Apart from the officially stipulated fault codes, each entry includes a "freeze frame", which contains additional information on the general conditions under which the fault occurred (e.g. engine speed, engine temperature). Service-related faults can also be stored.

Limp-home operation
If a fault occurs during driving (e.g. failure of a component), this leads not only to an entry in the fault memory. Substitute values and emergency functions now come into force for calculating cylinder charge, fuel injection and ignition in such a way that the vehicle can continue to be driven, albeit with restricted comfort.

For this purpose, the ETC throttle-valve actuator has a limp-home position, in which the throttle valve is held in place by spring force. The engine speed is then restricted to low values so that the vehicle can continue to be driven (with impaired functions) in spite of this important actuating device having failed.

MED-Motronic

Requirements
With gasoline direct injection in SI engines, fuel consumption can be reduced by up to 20 % when compared with conventional manifold injection, and the CO_2 emissions caused by road traffic can be reduced with lasting effect.

In order for direct injection to be at all feasible, it must be possible during engine operation for coordinated alternation to take place between "charge stratification" at part load and operation with a homogeneous mixture at full load.

Essentially, the features required of the MED-Motronic engine-management system are:
- precise metering of the required injected fuel quantity,
- generation of the necessary injection pressure,
- definition of the start of injection, and
- introduction of the fuel directly and accurately into the engine's combustion chambers.

It must also coordinate the various torque demands on the engine in order then to be able to perform the required adjustments at the engine.

An important system interface delivers the internal torque from combustion. The torque-control structure is divided into the following areas of operation:
- torque demand,
- torque coordination and
- torque conversion.

The most important torque demand derives from the vehicle-operator command generated by the accelerator pedal, from the position of which the engine-management system interprets the demand to be made on the IC engine for a particular torque.

Further torque demands can also originate, for instance, from the transmission-shift control, the traction control system, or the electronic stability program.

Torque coordination is performed centrally in the engine-management system.

Design
As with manifold injection, the high-pressure direct-injection system is designed as a rail, or accumulator-type, injection system. In such systems, the fuel can be directly injected into the cylinders at any

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stipulated moment in time using electromagnetic high-pressure fuel injectors.

In comparison to the ME basic ECU, the ECU for the MED gasoline direct-injection system also incorporates a driver stage for triggering the pressure-control valves.

The intake air mass can be freely adjusted by the electronically controlled throttle valve (ETC). Precision measurement of air mass is made by means of a hot-film air-mass meter. The A/F mixture is monitored by universal lambda sensors LSF and LSU in the exhaust-gas flow upstream and downstream of the catalytic converter. They serve to control $\lambda = 1$ operation and lean-burn operation, and are also responsible for the precise control of catalytic-converter regeneration. It is important to set the exhaust-gas recirculation rate exactly, particularly in dynamic operation.

Operation

Fuel delivery and injection

The MED-Motronic accumulator injection system injects the fuel stored under pressure in the rail. Injection can take place at any moment in time, whereby electromagnetically controlled fuel injectors inject the fuel directly into the combustion chamber. It thus offers the following functions:

– free selection of the injection point,
– variable system pressure.

Low-pressure circuit:

A primary pressure of 0.35 MPa (3.5 bar) is initially generated in a low-pressure circuit on the tank side which comprises an electric fuel pump with a mechanical pressure regulator connected in parallel. This feeds the high-pressure pump driven by the IC engine.

High-pressure circuit:

High-pressure pump: The function of the H.P. pump is to increase the fuel pressure from 0.35 MPa (3.5 bar) primary pressure to 12 MPa (120 bar), to ensure that pressure fluctuations in the rail remain at a minimum, and to ensure operation exclusively with fuel (to prevent any mixing with engine oil).

Rail: The rail must on the one hand feature sufficient elasticity to damp the pressure pulsations arising from the periodic fuel-extraction processes when injection takes place, and from the fuel-delivery pulsation generated by the H.P. fuel pump. On the other hand, it must be rigid enough for the rail pressure to adapt quickly to the requirements of engine operation.

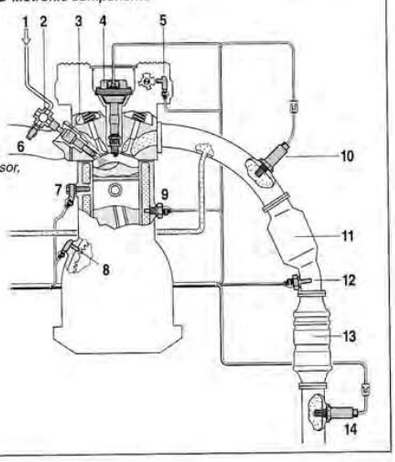
Pressure sensor: The pressure sensor (welded diaphragm of high-grade steel as sensor element with measuring resistors) serves to register the pressure level in the rail.

Pressure-control valve: The pressure-control valve adjusts the system pressure across the entire engine operating range according to the map specifications, and irrespective of the injected fuel quantity and pump delivery rate. Excess fuel is returned to the intake side of the H.P. pump.

Fuel injectors: The fuel injectors are the central components of the gasoline direct-injection system and are directly connected to the rail. Start of injection and injected fuel quantity are defined by the triggering signal for the fuel injectors.

Direct-injection engine with MED-Motronic components

1 Fuel supply (high pressure),
2 Accumulator (rail),
3 Fuel injector,
4 Ignition coil with spark plug,
5 Phase sensor,
6 Pressure sensor,
7 Knock sensor,
8 Engine-speed sensor,
9 Engine-temperature sensor,
10 Lambda sensor (LSU),
11 Three-way catalytic converter,
12 Exhaust-gas temperature sensor,
13 NO_X catalytic converter,
14 Lambda sensor (LSF).



Mixture formation and combustion

A complex engine-management system is necessary for the gasoline direct-injection system to be exploited to the full in terms of low fuel consumption and high engine power output. A distinction is made between two basic operating modes in this respect:

Lower load range

In this range, the engine is run with a heavily stratified cylinder charge and a high level of excess air in order to achieve the lowest-possible fuel consumption. Retarded injection just before the ignition point is used with the aim of achieving the ideal state of having two zones in the combustible air-fuel mixture cloud at the spark plug, embedded in the second zone in the form of an insulating layer of air and residual exhaust gas. In this way, the engine can be run to a large extent unthrottled while gas-exchange losses are avoided. In addition, thermodynamic efficiency increases due to the avoidance of heat losses at the combustion-chamber walls.

Upper load range

As engine load and thus the injected fuel quantity increases, the stratified-charge cloud becomes increasingly richer. This would result in a deterioration in exhaust emissions, particularly with regard to soot. The engine is therefore operated with a homogeneous cylinder charge in this higher torque range.

Lambda coordination assumes the control function between $\lambda = 1$ and lean-burn operation. The fuel is injected during the intake stroke in order to ensure that fuel and air are thoroughly mixed.

Alternation between torque ranges

In the event of a switch between homogeneous and stratified-charge operation, it is crucial to control injected fuel quantity, air charge and ignition angle in such a way that the torque delivered by the engine to the transmission remains constant. The torque structure means that here also the important functions for controlling the electronic throttle valve have been transferred directly from the ME-Motronic. The throttle valve must be closed prior to the actual changeover from stratified to homogeneous operation.

Exhaust-gas treatment, catalytic-converter control

An important consideration with gasoline direct injection is that in stratified-charge operation the NO_X content in the very lean exhaust gas cannot be reduced by a three-way catalytic converter. Exhaust-gas recirculation with a high EGR rate helps to reduce the NO_X content of the exhaust gas by roughly 70 %. To comply with emissions-control legislation, it is also absolutely essential to treat the NO_X emissions. To reduce this exhaust-gas content, the NO_X accumulator-type catalytic converter offers the greatest potential.

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Engine-test technology

Service and maintenance requirements for modern vehicles are declining steadily; electronic systems are essentially maintenance-free. But malfunctions can still occur. Factors such as wear, contamination and corrosion can impair the operation of engine and electronic systems, and settings can drift over time. Rapid and reliable diagnosis of malfunctions is the most important function of any service facility. It is important to distinguish between testing and diagnosis. Testing entails the determination of certain measured values for comparison with the prescribed specifications. Diagnostic procedures (e.g. engine diagnostics) attempt to correlate deviations from specified values with system functions, malfunction patterns and experience in order to determine the failure mode or to locate the defective component.

Engine diagnosis

Engine, ignition and fuel-metering systems are becoming more complex and less accessible. Universal, automated procedures, free from the effects of subjective influences, are thus essential elements of the computer-controlled testing program in the automotive service facility. These include:

- comparison of cylinder output by selective shorting of the ignition or smooth running analysis via current engine speed,
- comparison of compression via the shape of the starter current curve,
- determination of mixture distribution performed by selective measurement of the exhaust-gas HC content,
- analysis of the primary and secondary ignition-voltage patterns.

Electronic-system testing

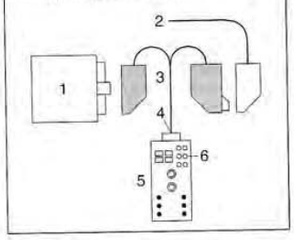
Testing of engine-related electronic systems is carried out using test equipment specifically designed to utilize on-board engine monitoring technology.

The test connection is established by inserting a universal test adapter between the plug and socket at the junction linking the peripheral device with the ECU. If only the peripheral device (sensor, actuator, wiring and power supply) is to be tested, then it is sufficient to connect the tester to the peripheral's plug, while the ECU is also connected for tests embracing dynamic operation. The individual electronic system requires only a single interchangeable, system-specific adapter cable. The program switches on the universal test adapter are then used to establish a logical test sequence specifically tailored to the requirements of the system.

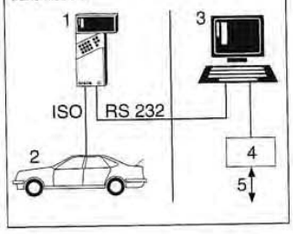
Once connected, the test unit provides a display of both measured values and of signals such as ignition and fuel-injection pulses.

When the ECU remains connected for operational testing, keys can be used to enter simulations of various operating conditions for test-unit evaluation.

Peripheral and functional testing
1 ECU, 2 System wiring harness, 3 System adapter cable, 4 Plug connection, 5 Universal test adapter, 6 Sockets for test unit



System test with ECU diagnostics
1 Test unit, 2 Test vehicle, 3 Information system, 4 Modem, 5 Long-distance data transmission.



ECU diagnostics

The dominant role being assumed by electronic systems in the vehicle makes it necessary to devote increased attention to the problems associated with service. In addition, because essential vehicle functions are becoming increasingly dependent upon electronics, these systems must satisfy stringent reliability requirements, while emergency default programs are required to deal with system errors.

The solution is to incorporate electronic system-diagnosis functions in the ECU. These rely on the electronic "intelligence" already in place in the vehicle to continuously monitor the system, detect faults, store the fault data and perform diagnostics.

For instance, the ECU carries out its own self-check as follows: Programmed memory chips are provided with test patterns which can be retrieved and used for comparisons. For program memories, a comparison with test sums is employed to ensure that data and programs are correctly stored. The data and address buses are included in the test program.

Sensors are tested for plausibility within specified limits, while open and short circuits are also recognized. Final-control elements can be tested during activation using current-draw limits.

The "off-board test units" used for the evaluation of "on-board diagnostics" employ a communications interface as defined in ISO 9141. The serial port can maintain communications at rates ranging from 10 baud to 10 kbaud. It is designed as a single- or two-wire port, allowing connection of several control units to a central diagnosis plug.

A stimulation address is transmitted to all of the connected ECUs, whereupon each unit recognizes its address and responds by transmitting back a baud-rate recognition word.

The test unit monitors the period between pulse flanks to determine the sender's baud rate, which it then adopts automatically. The key bytes that follow (assigned by the DIN Motor-Vehicle Committee) specify the protocol for subsequent data communications.

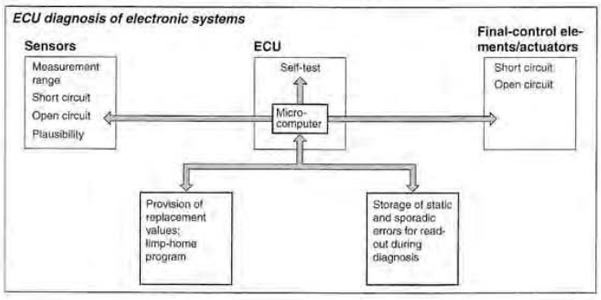
The programmable test unit converts the received data into diagnosis sequences and plain-text information designed specifically for the respective system.

The ECU diagnostic capabilities include:

- identification of system and ECU,
- recognition, storage and readout of static and sporadic malfunctions together with the error path, failure mode and associated parameters,
- readout of current actual values, switching conditions, specifications,
- stimulation of system functions, and
- programming of system variants.

Individual programs for the test unit are stored in plug-in modules, while updates and communications with data systems are supported by a data interface.

ECU diagnosis of electronic systems



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LPG systems

Liquefied petroleum gas

Liquefied petroleum gas assumes a liquid state at pressures of 2...20 bar, depending on the propane/butane ratio and the temperature (see chapter on "Fuels", P. 238).

At the end of the '90s, LPG was being consumed by internal-combustion (IC) engines at a rate of approximately 10.3 million metric tons annually (of which 2.6 million tons were consumed in Europe). Should efforts to utilize the gas contained in petroleum succeed, then these figures could increase exponentially. The mineral-oil tax is a decisive factor in determining the profitability of liquefied petroleum gas.

Natural gas as engine fuel

Reserves of natural gas are extensive. Together with it being used nowhere near as much as crude oil, this fact makes natural gas a very interesting alternative fuel for automotive applications. Both the LPG equipment configurations and the emissions produced would be similar to those for the combination of propane and butane known as LPG (see illustration). Natural gas can be transported in the vehicle either as a high-pressure gas (160...200 bar) or in liquefied form (at –160 °C) in an insulated tank; the disadvantage of the former mode lies in its limited operating range.

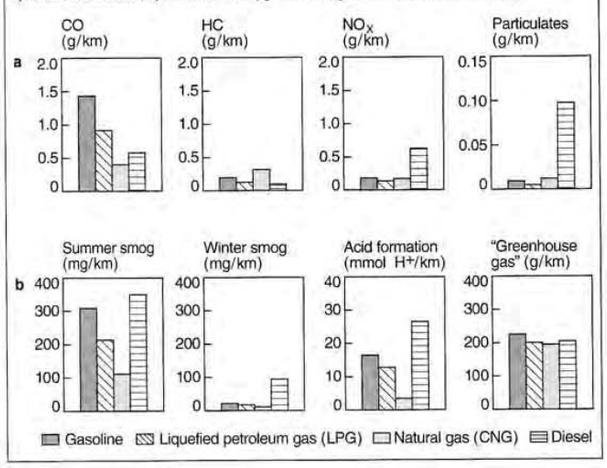
The only real difference between concepts based on natural gas and LPG is the way the gas is transported in the vehicle; actual differences in operating principles are minimal.

Operation on LPG

Any vehicle equipped with an IC engine can be converted for operation on LPG. For the most part, spark-ignition (SI) engines are re-equipped for dual-fuel operation (system can be switched between gasoline and LPG). LPG-powered taxis and buses are generally set up for single-fuel (LPG only) operation, while regulations require this configuration on gas-powered industrial trucks intended for indoor use. When engines are converted, it should be remembered that they operate as naturally aspirated engines while running on LPG (consumption in liters increases by approx. 25% as compared to gasoline).

Exhaust emissions and effects with gasoline, LPG, CNG and diesel

Empirical values taken from five spark-ignition and five diesel-engine vehicles, status 1993 in Europe, including indirect emissions (manufacture, transport, etc.).
a) Pollutant emissions, b) Pollutant effect ("greenhouse gas" assessment, status 1998).



Exhaust emissions

Because LPG mixes well with air, emissions (of CO_2 and other components such as polycyclic aromatic hydrocarbons) are substantially lower than those produced by gasoline-burning engines, and are lower even than those produced by fuel-injection engines equipped with three-way closed-loop catalytic converters. LPG contains no lead or sulphur compounds. It's very good combustion characteristics are complemented by excellent mixture formation and distribution properties. These characteristics are even more significant at low temperatures.

Advantages

- Extremely economical for drivers who cover large distances.
- Assuming the same level of technology (electronic control systems, etc.), emissions from an LPG engine are substantially lower than those achieved with gasoline or diesel fuel.

Disadvantages

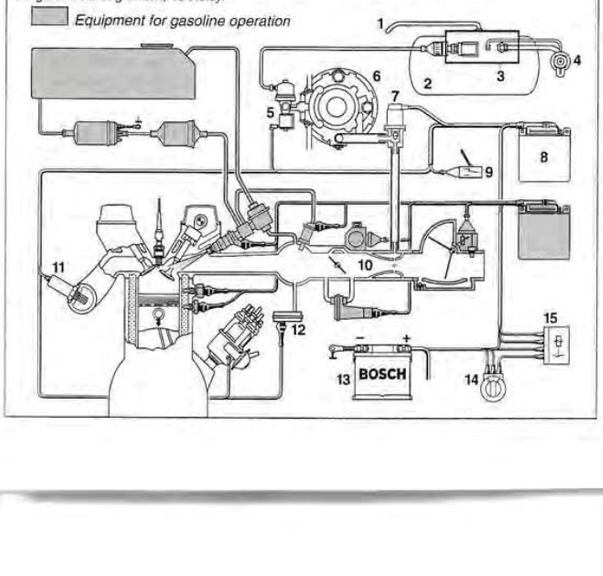
- Lower cruising ranges and increased fuel volumetric consumption compared to gasoline (although actual energy use is not higher than with gasoline, lowest with diesel engine).
- Special safety precautions are necessary, as LPG is pressurized.
- Pressurized gas cylinders require a lot of space, as the actual capacity is only 80% of cylinder volume (the remainder serving as expansion room for the gas).

LPG system

In Germany, professional installation of

Schematic diagram of an LPG system (carburetor principle)

1 Ventilation line for tank fittings, 2 LPG tank, 3 Housing with tank fittings, 4 External filler valve (designed to interrupt refueling at 80% of container capacity), 5 Gas shut-off valve, 6 Pressure regulator for evaporator, 7 Servomotor for gas control, 8 ECU, 9 Gas/gasoline changeover switch, 10 Venturi mixing device, 11 Lambda oxygen sensor, 12 Vacuum sensor, 13 Battery, 14 Ignition/starting switch, 15 Relay.



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the LPG system in a specialist workshop is followed by a trip to the TÜV or TÜA (German inspection authorities) to secure operating approval. This inspection is based on the "Guidelines for inspecting vehicles with engines powered by liquefied gases" as issued by the Federal Minister of Transportation. Uniform regulations for Europe are being drawn up.

A modern LPG system will incorporate the following components:

- LPG tank,
- external filler valve designed to interrupt refueling at 80 % of container capacity,
- flow-interrupt valve,
- evaporator pressure regulator with cooling system,
- venturi mixing unit/injector,
- electronic control unit (ECU),
- servomotor for controlling gas flow,
- switch for alternating between LPG and gasoline operation.

The LPG flows from the LPG tank to the evaporator pressure regulator, where it is vaporized and its pressure reduced. The ECU processes the signals from the Lambda (O_2) and vacuum sensors, which serve as references for controlling the servomotor used to regulate the flow of liquefied gas to the venturi mixing unit.

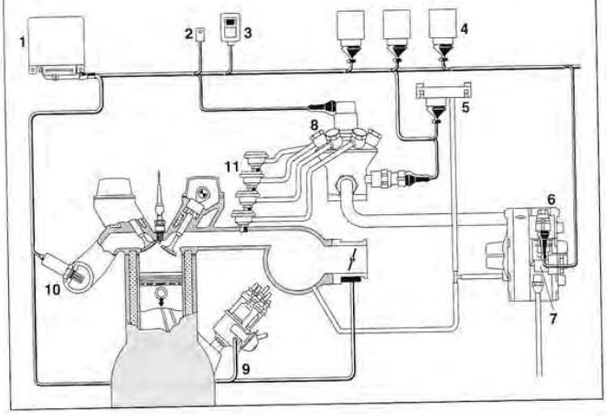
The flow-interrupt valve shuts immediately when the ignition is switched off. A gasoline/LPG switch installed in the instrument panel allows the operator to alternate between the two fuels.

LPG tanks

As LPG tanks are used to store pressurized gas, they are subject in Germany to the "TRG 380" technical regulations. At the factory, each tank receives official technical approval with certification.

They are equipped with an external filler valve (designed to interrupt refueling at 80 % of container capacity) as well as an electromagnetic discharge valve, and have a capacity of 40 ... 128 l for passenger cars.

Schematic diagram of an LPG system (injection principle)
1 ECU, 2 Diagnosis plug, 3 Fuel selection switch, 4 Relay, 5 Air-intake pressure sensor, 6 Evaporator pressure regulator, 7 Flow-interrupt valve, 8 Distributor with step motor, 9 RPM signal, 10 Lambda (O_2) sensor, 11 Gas injector nozzle.



Natural-gas operation of spark-ignition engines

Against the backdrop of worldwide efforts to reduce CO_2 emissions and to comply with ever more stringent exhaust emission limits, natural gas is gaining increasing significance as an alternative fuel.

Properties and storage of natural gas

The main component of natural gas is methane (CH_4), making up 80...99 %. The remainder consists of inert gases such as carbon dioxide, nitrogen and other low-order hydrocarbons. A differentiation is made between L-gas (80...90 % methane) and H-gas (>90 %) depending on the gas quality.

Natural gas can be stored both in liquid form at −162 °C as LNG (Liquefied Natural Gas) or in compressed form at pressures of up to 200 bar as CNG (Compressed Natural Gas). In view of the great expense involved in storing the gas in liquid form, natural gas is used in compressed form in virtually all applications.The low energy density of natural gas is a particular disadvantage, making large storage tanks necessary. Metal-hydride storage tanks represent a further storage option, although they are not used for reasons of cost.

Mixture formation

In most systems, gas is injected into the intake manifold as in conventional multi-point gasoline-injection systems. A low-pressure common rail supplies the injector valves that inject intermittently into the intake manifold. Mixture formation is simplified by the completely gaseous supply of fuel, as natural gas does not condense on the intake manifolds and does not form a film on the walls. This has a favourable effect on emissions, particularly during the warm-up phase.

The output of the natural-gas engine is approx. 10...15 % lower than that of the gasoline engine due to the lower fuel mass necessary for stoichiometric combustion (17.2:1 ratio) as well as a lower volumetric efficiency due to the injected natural gas. Higher compression can boost performance while simultaneously increasing efficiency. The extremely high antiknock quality of natural gas (120 RON) enables very high compressions of approx. 13:1 (8:1 for regular gasoline). As a result, the natural-gas engine is ideally suited for turbocharging. As piston displacement decreases, efficiency increases due to additional de-throttling and reduced friction.

A further improvement in efficiency can be achieved by lean-mixture operation up to $\lambda = 1.7$. A lean mixture reduces combustion temperatures while at the same time further de-throttling the engine.

Emissions

Natural-gas vehicles are characterized by low CO_2 emissions due to the favourable hydrogen/carbon ratio (H/C ratio) of almost 4:1 (gasoline: 2.3:1) and the resulting shift in the main combustion products CO_2 and H_2O. Apart from the virtually particle-free combustion, in conjunction with a three-way closed-loop catalytic converter only very low levels of the pollutants NO_X, CO and NMHC ("non-methane hydrocarbons": the sum of all hydrocarbons minus methane) are emitted. Methane is classified as nontoxic, and is therefore not considered to be a pollutant.

In lean mixture mode the NO_X emissions are higher than in $\lambda = 1$ mode with a three-way catalytic converter. In the same way as in gasoline operation, this disadvantage can be largely eliminated by using more expensive exhaust-gas treatment methods (e.g. NO_X catalytic converter).

Natural-gas-engine applications

In view of their limited range, natural-gas engines are used almost exclusively in local public transportation fleets (e.g. buses and taxis). Bivalent systems which can be easily changed over from natural gas to gasoline operation are used primarily in passenger cars.

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Operation on alcohol (spark-ignition engines)

The limited availability of fossil fuels has led to an increased effort to develop engines and injection systems capable of using alcohols such as ethanol and methanol as alternative fuels ("Alternative fuels", P. 246). Due to its non-availability, virtually the only place where ethanol is used is Brazil. In the US (and in California in particular), increasing attention is being focused on methanol, which generates lower emissions: reduced NO_X and CO_2 along with reduced ozone and smog formation.

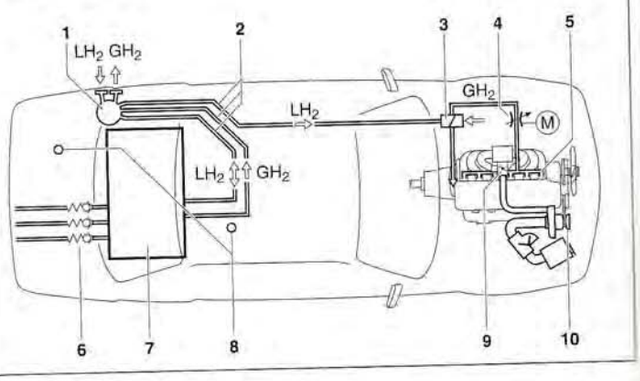
In the absence of comprehensive methanol-distribution networks to ensure universal availability, engines and engine-control systems must be designed for flexible dual-fuel operation (ranging from pure gasoline to max. 85% methanol). Alcohol places special, particularly critical demands upon engines and fuel-delivery components. Moisture, acids and gums contained in the fuel pose a hazard to metals, plastics and rubber. Because methanol has a high antiknock quality, engines designed to run exclusively on methanol have substantially higher compression ratios than gasoline engines, making them more efficient. On the other hand, methanol's low calorific value means that fuel consumption is almost doubled, necessitating higher fuel supply rates, greater tank volumes and special injectors.

Suitable Lambda (O_2) sensors can be employed for optimal emissions control with a catalytic converter. Special lubricants are able to maintain long-term stability in the face of this aggressive fuel and its combustion products.

Pilot control of the fuel mixture is facilitated by a fuel sensor which sends a signal to the ECU reflecting the proportion of methanol in the fuel.

Suitable programs implement the necessary mixture and ignition corrections applicable to a particular set of engine operating characteristics.

Hydrogen-powered passenger car with spark-ignition engine (BMW 735i)
LH_2 Liquid hydrogen, GH_2 Gaseous hydrogen. 1 Valve block for LH_2 fueling and GH_2 supply (vacuum-insulated), 2 Hydrogen lines, vacuum-insulated, 3 LH_2 Evaporator, 4 Metering valve for regulating power with electronic control, 5 Hydrogen injectors, 6 Overcurrent and safety valves, 7 Liquid-hydrogen tank with vacuum super-insulation, 8 Hydrogen sensors for automatic leak monitoring, 9 Throttle valve for gasoline operation with electronic control, 10 Variable-speed centrifugal supercharger.



Operation on hydrogen (spark-ignition engines)

Although the production of hydrogen, the required infrastructure and refueling all pose difficult problems, technically feasible solutions are on the horizon. Producing hydrogen by means of electrolysis necessitates sufficient quantities of electrical power in the form of solar energy or nuclear power.

Storing hydrogen in the vehicle

Gaseous storage in pressurized tanks
High pressures (300 bar) are required for storage in gaseous form. This results in high weight along with safety risks.

Liquid storage (cryogenic tank)
Liquid storage represents the best alternative with regard to both weight and energy density (present operating range approx. 300 km). The extremely low temperature required (–253 °C) places substantial demands on thermal insulation. Residual heat causes loss of hydrogen via the safety valves at a rate of about 2% per day when the vehicle is parked. An electric evaporator maintains the specified tank pressure during operation.

Metal-hydride tanks
Hydrides are produced as hydrogen is absorbed by a metallic powder. This is an exothermic process, i. e. heat must be dissipated during fueling. There are no storage losses.

The disadvantages associated with the low energy density (range: 120 km) and high materials costs are to a degree offset by uncomplicated safety technology.

Methylcyclohexanol storage
This type of storage employs a catalyst to dehydrate the hydrogenous methylcyclohexanol at 500 °C. The by-products are hydrogen and recyclable toluene.

Mixture formation

Regardless of storage mode, up to now all systems inject gaseous hydrogen into the intake manifold. Although a number of advantages could be gained by injecting extremely low-temperature hydrogen directly into the combustion chamber (improved charge for higher output, cool mixture for low NO_X emissions, no danger of backfiring), the short injector-valve service life means that this type of system is not likely to appear in production in the near future.

Current external mixture-formation concepts rely on a continuous-injection system in which a central electric metering valve and a hydrogen distributor conduct the vaporized hydrogen to the individual intake tracts.

Backfiring into the intake passage is prevented by lean mixtures or supplementary water injection. A supercharging device can be used to compensate for a portion of the power loss associated with lean operation.

One alternative, based on intermittent sequential injection of hydrogen into the intake manifold, is currently in the development stage.

This system's unlimited range of options for injection timing allows it to inhibit backfiring almost completely, even with rich mixtures.

Injector valve and electronic-control system must operate with extreme precision and short valve-opening times; the technical requirements are thus substantial.

Emissions

During combustion, pure hydrogen (H_2) oxidizes to form water (H_2O). No CO_2 is produced by the combustion process. Provided no fossil fuels are used in its production, H_2 is thus the only fuel which can be used to avoid all CO_2.

Electric drive is the only alternative which can make a similar claim. Future NO_X emission limits can be met by lean mixtures or a system for catalytic control of emissions (still to be developed).

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US PATENT NO. 6,557,540

Scott Andrews

(650) 279-0242 scott@cogenia.com Petaluma, CA

Summary

Creative, energetic, and innovative internationally recognized technical executive experienced in general management, systems engineering, advanced product development, advanced technology, business development, strategic planning, and program management

- Vehicle Electrical/Electronics Systems
- Vehicle Information Systems
- Communications Systems
- ITS and Related Industries
- Program and Project Management
- Enterprise Software
- Multimedia/Internet Computing
- Vehicle Safety and Control Systems
- Spacecraft Electronics
- Mobile Information Technology

Experience

12/2001-Present Cogenia Partners, LLC

Systems engineering, business development and technical strategy consulting supporting automotive and information technology.

Current Engagements:

- Technical consultant for connected vehicle security credential management system deployment; Sponsored by US DOT FHWA
- Expert witness for:
  - ZTE, related to cell phone navigation systems
  - Broadcom, related to vehicle infotainment systems
  - Club Car, related to golf cart navigation systems
  - Hyundai Motors, related to vehicle control systems
  - Delphi, related to automotive safety systems
  - LG, related to cell phone sensor systems
  - Wasica, related to tire pressure monitor systems

Prior Engagements/Projects:

- Subject matter expert and co-principle investigator on DSRC performance Measures development project for U.S.DOT NHTSA.
- Subject matter expert on communications data delivery system study to understand optimal roadside unit placements to support security credential management in connected vehicle systems ; Sponsored by U.S. DOT RITA
- Developed systems engineering methodology for vehicle E/E systems; Applied methodology on project for Yazaki to reverse engineer the E/E architecture for a 2004 BMW 5 series vehicle.
- Co-Principal investigator for Integrated Advanced Transportation System; A 30+ year future technical feasibility assessment and strategy for U.S. DOT Federal Highway Admin. (FHWA).
- Technical consultant to American Association of State Highway Transportation Officials (AASHTO) for connected vehicle deployment analysis and strategy.
- Chief System Architect for the Vehicle Infrastructure Integration (VIIC) program (BMW, Chrysler, Daimler Benz, Ford, GM, Honda, Nissan, Toyota, VW); A connected vehicle research program funded by U.S. DOT FHWA.
- Technical consultant to Michigan State DOT (Enterprise Pooled Fund) to develop

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a system architecture and deployment strategy for Rural ITS.

- Telematics delivery architecture development for a Fortune 100 service provider
- Technical consultant to the Vehicle Safety Consortium developing Dedicated Short Range Communications (DSRC) standards for safety systems;
- Designed novel super capacitor based high performance hybrid vehicle as part of an early stage startup company; Developed performance requirements, conceptual designs and patented integrated electrical system architecture concept.
- Toyota Motor Sales – 10 year technology survey;
- Connected Vehicle Trade Association- Transferred AMI-C specifications to ISO TC 22, TC 204 AND OSGi. Developed OSGi Vehicle Interface Specification;
- Expert witness for:
    - ATT vs. Vehicle IP relating to cell phone navigation systems
    - VW/Audi vs. Beacon, relating to traffic information systems
    - VW/Audi vs. Blitzsafe relating to mobile device integration and mobile audio systems
    - T-Mobile vs. TracBeam relating to wireless location technologies
    - VW/Audi vs. Joao relating to remote service architecturesApple Computer vs. Porto relating to cell phone navigation systems
    - Mercedes vs. Adaptive Headlamp Technologies relating to adaptive headlamps
    - Liberty Mutual, Geico and Hartford vs. Progressive Insurance relating to usage based insurance systems
    - Toyota vs. American Vehicular Sciences (AVS) relating to occupant sensing systems
    - Lenovo and Amazon vs. Pragmatus relating to device tracking
    - Ford in a patent vs. Eagle Harbor Holdings relating to Bluetooth systems and mobile device integration in the vehicle
    - Bentley vs. Cruise Control Technologies relating to adaptive cruise control
    - Google vs. Walker Digital relating to 3D navigation displays
    - Volkswagen/Sirius-XM vs. case relating to traffic information systems
    - Volkswagen, Ford and GM in patent cases vs. Affinity Labs, relating to the iPod interface
    - Honda vs. American Calcar, relating to telematics equipment and user interfaces
    - Alpine, Denso and Pioneer Corporation in an International Trade Commission patent case vs. Honeywell, related to navigation systems
    - BMW vs. American Calcar, relating to telematics equipment and user interfaces

4/2000 to 12/2001 Cogenia, Inc.
President and Chief Executive Officer, Founder
Founded company in 2000 to develop enterprise class data management software system. Responsibilities included development of business concept and plan, corporate administration including financial and legal management, leadership of executive team in product development, fundraising, business development, organizational development, and investor relations. Raised $2.2M between 8/00 and 5/01 from individuals and funds;

1996 to 4/2000 Toyota Motor Corporation, Japan
Project General Manager, R&D Management Division
Responsibilities included the conceptualization and development of multimedia and new

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technology products and services for Toyota's future generations of passenger vehicles in the United States and Europe, Heavy emphasis on strategy for information systems, and on development of technical concepts for computing and Internet oriented systems. Led automated vehicle Development program leading up to 1997 Automated Highway Systems (AHS) demonstration in Sand Diego, CA; Supported technology acquisition for hybrid vehicle control systems; Working under direction of Toyota board members, established the Automotive Multimedia Interface Collaboration (AMI-C), a partnership of the world's car makers to develop a uniform computing architecture for vehicle multimedia systems, and led all early technical, planning and legal work. Provided technical management of technical contracts with Carnegie Mellon University Robotics Lab (Image based collision warning systems), and the development of Toyota's position on the US Intelligent Vehicle Initiative.

1983 to 1996 TRW, Inc.
Held a series of increasingly responsible positions in program management, technology development and business development.

1993 to 1996 TRW Automotive Electronics Group
Director, Advanced Product Planning/Development
Specific responsibilities included leadership and overall management of advanced development programs such as Automotive Radar, Adaptive Cruise Control, Occupant Sensing, In Vehicle Information Systems, and other emerging transportation products; Managed remotely located advanced development laboratory performing approximately $6M in annual development projects.

1983 to 1993 TRW Space & Electronics Group
Manager, MMIC Products Organization
Developed TRW's commercial GaAs MMIC business. Responsibilities included development of business strategy and business plan, and overall management of customer and R&D programs. Developed extensive international business base and took operation from start-up to $5M sales per year in under two years. Developed the first single chip 94 GHz Radar (Used for automotive cruise control and anti collision systems).

1979-1983 Teledyne Microwave
Developed high reliability microwave components. Developed CAD tools.
1977-1979 Ford Aerospace, Advanced Development Operation
Designed, tested and delivered microwave radar receiver systems

Education

MSEE Stanford University, 1982
BSEE University of CA, Irvine 1977
TRW Senior Leadership Program 1992

Publications

1. Two Dimensional Vehicle Control for Obstacle Avoidance in Multi-Lane Traffic Environments; Published in the proceedings of the 1998 IEEE International Conference on Intelligent Vehicles.
2. Automotive Multimedia Interface Collaboration; Briefing Presented to the 9th VERTIS Symposium, April 1999, Tokyo Japan.

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3. Privacy and Authenticity in Telematics Systems; Published in the Proceedings of the Society of Automotive Engineers World Congress, 1999
4. Automated Highway Systems Acceptance and Liability; Briefing presented to the Automated Vehicle Guidance Demo 98 Conference, Rinjwoude, The Netherlands, June1998.
5. What is Telematics? Briefing presented at IIR Telematics Conference Scottsdale, AZ, December 2001
6. Advanced Telematics Services: A Hard Look at Reality; Briefing presented at IIR Telematics Conference Scottsdale, AZ, December 2001
7. Consumer Electronics and Telematics; Briefing presented at Eye For Auto Telematics Update Conference Las Vegas, NV, January 2003
8. The Automotive Multimedia Interface Collaboration Software and Network Architecture: Extending the Concept of Platform Independent Computing; Briefing Presented to the Future Generation Software Architectures in the Automotive Domain Conference, San Diego, CA, January 2004
9. Quality, Choice and Value: How New Architectures are Changing the Vehicle Lifecycle; Briefing presented at IEEE Convergence Conference, October 2004
10. Critical Standards for the Next Generation of Telematics Systems and Services; Briefing presented at the Telematics Update Conference, December 2004
11. VII System Overview; Briefing presented To Transportation Research Board, ITS and V-HA Committees 2007 Mid-Year Meeting; July 2007
12. Testing and Development of In-Vehicle Equipment and Private Applications (P08-1634); Briefing presented to the Transportation Research Board Annual Meeting, Washington, DC, January 2008
13. A Comparison of Communications Systems for VII; Presented at the ITS World Congress, New York, NY, October, 2008
14. Vehicle Infrastructure Integration Systems Overview; Presented at the ITS America Annual Meeting, June 1 2009, National Harbor, Maryland
15. Telematics Standards: Logical Next Steps; ITS International, August 2009
16. IntelliDrive^{SM} Overview; ITS International, May 2009
17. Time Synchronization and Positioning Accuracy in Cooperative IntelliDrive^{SM} Systems; Presented at the 2010 ITS America Annual Meeting, June 2010, Houston, Texas

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18. Systematic Development of Positioning Requirements for Vehicle Applications; Presented at the 18th World Congress on Intelligent Transportation Systems , November, 2011, Orlando, Florida
19. The Interpretation of GPS Positioning Accuracy and Measurement Integrity in a Dynamic Mobile Environment; Presented at the 18th World Congress on Intelligent Transportation Systems, November, 2011, Orlando, Florida
20. Connected Vehicle Positioning Requirements and Possible Solutions; Presented at the 22nd World Congress on Intelligent Transportation Systems, October, 2015, Bordeaux, France
21. Connected Vehicle Performance Requirements; Presented at the 22nd World Congress on Intelligent Transportation Systems, October, 2015, Bordeaux, France

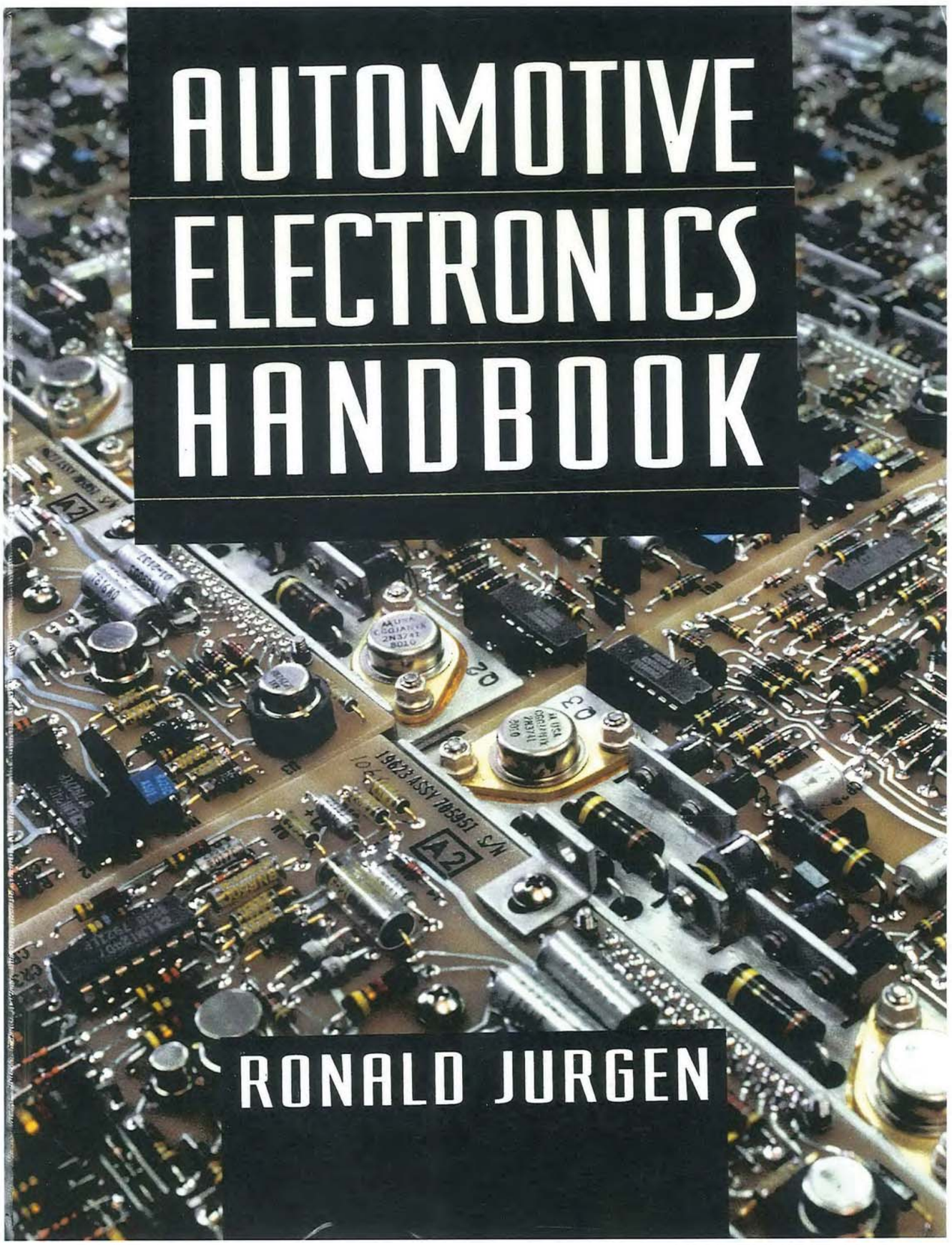
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1. Mobile Body Reporting Device And Its System; Patent Number: JP11118902; 4/30/1999
2. Multiformat Auto-Handoff Communications Handset; Patent Number: US5649308; 07/15/1997
3. A Communications Terminal Device, A Communications System, And A Storing Medium For Storing A Program To Control Data Processing By The Communications Terminal Device; Patent Number: EP0867850, A3; 09/30/1998
4. Communication System For Controlling Data Processing According To A State Of A Communication Terminal Device; Patent Number: US 6122682 3/23/1998
5. Method And Apparatus For Controlling An Adjustable Device; Patent Number: US5864105; 01/26/1999
6. Automatic Brake Device; Patent Number: JP2000108866; 4/18/2000
7. Visual Field Base Display System; Patent Number: JP2000029618; 01/28/2000
8. Intersection Warning System; Patent Number: US5926114; 07/20/1999
9. Security For Anonymous Vehicular Broadcast Messages; Patent Number: US 7742603 3/27/2006
10. Digital Certificate Pool; Patent Number: US7734050 3/27/2006
11. System, Method And Computer Program Product For Sharing Information In A Distributed Framework; Patent Number: US 7802263 12/15/2003

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12. System, Method And Computer Program Product For Sharing Information In A Distributed Framework; Patent Number: US 8566843 12/15/2003
13. System, Method And Computer Program Product For Sharing Information In A Distributed Framework; Patent Number: US 8209705 12/15/2003

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AUTOMOTIVE ELECTRONICS HANDBOOK

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Related McGraw-Hill Books of Interest

Handbooks

Avallone and Baumeister • MARK'S STANDARD HANDBOOK FOR MECHANICAL ENGINEERS
Benson • AUDIO ENGINEERING HANDBOOK
Brady • MATERIALS HANDBOOK
Chen • COMPUTER ENGINEERING HANDBOOK
Considine • PROCESS/INDUSTRIAL INSTRUMENTS AND CONTROL HANDBOOK
Coombs • PRINTED CIRCUITS HANDBOOK
Coombs • ELECTRONIC INSTRUMENT HANDBOOK
Di Giacomo • DIGITAL BUS HANDBOOK
Fink and Beaty • STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS
Fink and Christiansen • ELECTRONICS ENGINEERS' HANDBOOK
Ganic • MCGRAW-HILL HANDBOOK OF ESSENTIAL ENGINEERING INFORMATION
Harper • ELECTRONIC PACKAGING AND INTERCONNECTION HANDBOOK
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US PATENT NO. 6,557,540

AUTOMOTIVE ELECTRONICS HANDBOOK

Ronald K. Jurgen Editor in Chief

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This book is printed on acid-free paper.

This book is dedicated to Robert H. Lewis and to the memories of Douglas R. Jurgen and Marion Schappel.

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CONTRIBUTORS

Robert E. Bicking *Honeywell, Micro Switch Division* (CHAP. 4)
Tracy Blake *Arizona State University* (CHAP. 30)
David S. Boehmer *Intel Corporation* (CHAP. 11)
Werner Brehm *Robert Bosch GmbH* (CHAP. 13)
Wolfgang Bremer *Robert Bosch GmbH* (CHAP. 22)
Wolfgang Bullmer *Robert Bosch GmbH* (CHAP. 13)
Jerry L. Cage *Allied Signal, Inc.* (CHAP. 15)
Tom Chrapkiewicz *Philips Semiconductor* (CHAP. 25)
Armin Czinczel *Robert Bosch GmbH* (CHAP. 16)
Jeffrey N. Denenberg *Noise Cancellation Technologies, Inc.* (CHAP. 31)
William C. Dunn *Motorola Semiconductor Products* (CHAP. 7)
Randy Frank *Motorola Semiconductor Products* (CHAPS. 2, 5, 32)
Robert L. French *R. L. French & Associates* (CHAP. 29)
Frieder Heintz *Robert Bosch GmbH* (CHAP. 22)
Gary C. Hirschlieb *Robert Bosch GmbH* (CHAP. 12)
Raymond S. Hobbs *Arizona Public Service Company* (CHAP. 30)
Gerhard Hötzel *Robert Bosch GmbH* (CHAP. 6)
Robert Hugel *Robert Bosch GmbH* (CHAP. 22)
Ronald K. Jurgen *Editor* (CHAPS. 1, 20, 21)
George G. Karady *Arizona State Univeristy* (CHAP. 30)
Donald B. Karner *Electric Transportation Application* (CHAP. 30)
Shinichi Kato *Nissan Motor Co., Ltd.* (CHAP. 24)
Bernhard K. Mattes *Robert Bosch GmbH* (CHAP. 23)
Fred Miesterfeld *Chrysler Corporation* (CHAP. 26)
Salim Momin *Motorola Semiconductor Products* (CHAP. 32)
James P. Muccioli *JASTECH* (CHAPS. 27, 28)
Klaus Müller *Robert Bosch GmbH* (CHAP. 10)
Kurt Neuffer *Robert Bosch GmbH* (CHAP. 13)
Harald Neumann *Robert Bosch GmbH* (CHAP. 6)
Paul Nickson *Analog Devices, Inc.* (CHAP. 3)
Johann Riegel *Robert Bosch GmbH* (CHAP. 6)

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Makoto Sato *Honda R&D Co., Ltd.* (CHAP. 18)
Gottfried Schiller *Robert Bosch GmbH* (CHAP. 12)
Shari Stottler *Robert Bosch GmbH* (CHAP. 12)
Richard Valentine *Motorola Inc.* (CHAPS. 14, 19)
Helmut Weyl *Robert Bosch GmbH* (CHAP. 6)
Hans-Martin Wiedenmann *Robert Bosch GmbH* (CHAP. 6)
William G. Wolber *Cummins Electronics Co., Inc.* (CHAPS. 8, 9)
Akatsu Yohsuke *Nissan Motor Co., Ltd.* (CHAP. 17)

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PREFACE

Automotive electronics as we know it today encompasses a wide variety of devices and systems. Key to them all, and those yet to come, is the ability to sense and measure accurately automotive parameters. Equally important at the output is the ability to initiate control actions accurately in response to commands. In other words, sensors and actuators are the heart of any automotive electronics application. That is why they have been placed first in this handbook where they are described in technical depth. In other chapters, application-specific discussions of sensors and actuators can be found.

The importance of sensors and actuators cannot be overemphasized. The future growth of automotive electronics is arguably more dependent on sufficiently accurate and low-cost sensors and actuators than on computers, controls, displays, and other technologies. Yet it is those nonsensor, nonactuator technologies that are to many engineers the more "glamorous" and exciting areas of automotive electronics.

In the section on control systems, a key in-depth chapter deals with automotive microcontrollers. Without them, all of the controls described in the chapters that follow in that section—engine, transmission, cruise, braking, traction, suspension, steering, lighting, windshield wipers, air conditioner/heater—would not be possible. Those controls, of course, are key to car operation and they have made cars over the years more drivable, safe, and reliable.

Displays, trip computers, and on- and off-board diagnostics are described in another section, as are systems for passenger safety and convenience, antitheft, entertainment, and multiplex wiring. Displays and trip computers enable the driver to readily obtain valuable information about the car's operation and anticipated trip time. On- and off-board diagnostics have of necessity become highly sophisticated to keep up with highly sophisticated electronic controls. Passenger safety and convenience items and antitheft devices add much to the feeling of security and pleasure in owning an automobile. Entertainment products are what got automotive electronics started and they continue to be in high demand by car buyers. And multiplex wiring, off to a modest start in production cars, holds great promise for the future in reducing the cumbersome wiring harnesses presently used.

The section on electromagnetic interference and compatibility emphasizes that interference from a variety of sources, if not carefully taken into account early on, can raise havoc with what otherwise would be elegant automotive electronic designs. And automotive systems themselves, if not properly designed, can cause interference both inside and outside the automobile.

In the final section on emerging technologies, some key newer areas are presented:

- Navigation aids and intelligent vehicle-highway systems are of high interest worldwide since they hold promise to alleviate many of vehicle-caused problems and frustrations in our society.
- While it may be argued that electric vehicles are not an emerging technology, since they have been around for many years, it certainly is true that they have yet to come into their own in any really meaningful way.
- Electronic noise cancellation is getting increasing attention from automobile designers seeking an edge over their competitors.

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The final chapter on future vehicle electronics is an umbrella discussion that runs the gamut of trends in future automotive electronics hardware and software. It identifies potential technology developments and trends for future systems.

Nearly every chapter contains its own glossary of terms. This approach, rather than one overall unified glossary, has the advantage of allowing terms to be defined in a more application-specific manner—in the context of the subject of each chapter. It should also be noted that there has been no attempt in this handbook to cover, except peripherally, purely mechanical and electrical devices and systems. To do so would have restricted the number of pages available for automotive electronics discussions.

Finally, the editor would like to thank all contributors to the handbook and particularly two individuals: Otto Holzinger of Robert Bosch GmbH in Stuttgart, Germany and Randy Frank of Motorola Semiconductor Products in Phoenix, Arizona. Holzinger organized the many contributions to this handbook from his company. Frank, in addition to contributing two chapters himself and cocontributing a third, organized the other contributions from Motorola. Without their help, this handbook would not have been possible.

Ronald K. Jurgen

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P · A · R · T · 1

INTRODUCTION

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CHAPTER 1
INTRODUCTION

Ronald K. Jurgen
Editor

1.1 THE DAWN OF A NEW ERA

In today's world of sophisticated automotive electronics, it is easy to forget how far the technology has come in a relatively short time. In the early 1970s, other than radios and tape players, the only standard electronic components and systems on most automobiles were alternator diodes and voltage regulators.[1] By the fall of 1974, "there were twelve electronic systems available, none of which were across the board standard production items. . . . The twelve electronic systems or subsystems were: alternator diodes, voltage regulators, electronic fuel injection, electronic controlled ignition, intermittent windshield wipers, cruise control, wheel lock control, traction control, headlamp control, climate control, digital clocks, and air bag crash sensors."[1]

1.1.1 Car Makers and the Electronics Industry: Friendly Adversaries

In the early days of automotive electronics, the automotive industry and the electronics industry were often at odds. Carmakers needed inexpensive components and systems that would operate reliably in the extremely harsh automotive environment. The electronics industry, on the other hand, used to producing high-quality but expensive parts and systems for the military, was skeptical about its ability to produce the components the automobile industry wanted at the prices they demanded. But both industries realized that electronics could provide the capability to solve automotive problems that defied conventional mechanical or electromechanical approaches.

Some of the leading electronics engineers who worked in the automotive industry—as well as their counterparts in the electronics industry—realized that this existing friendly adversarial relationship had to be converted to a mutual effort to find cost-effective and reliable solutions to urgent automotive problems.

Thus it was in 1973 that Trevor Jones (then with General Motors), Joseph Ziomek (then with Ford), Ted Schaller (Allen Bradley), Jerry Rivard (then with Bendix), Oliver McCarter (General Motors), and William Saunders (Society of Automotive Engineers), proposed that a new conference be held in 1974.[1] Dubbed Convergence to signify the coming together of the two industries, the first conference was successful and, sponsored alternately by the Society of Automotive Engineers and the Institute of Electrical and Electronics Engineers, it has been held successfully every other year ever since.

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1.1.2 The United States Government Forces the Issue

One of the major problems facing the automotive industry at the time of the first Convergence conference was upcoming stricter government-mandated exhaust emissions controls. When the United States government first mandated emissions standards for all United States cars, car makers met the challenge through the use of catalytic converters for hydrocarbon and carbon monoxide emissions and exhaust gas recirculation techniques for nitrogen oxides emissions. But they knew that in 1981, when the standards would be tightened from the previous limit of 2.0 grams per mile to 1.0 gram per mile, those approaches would no longer in themselves be sufficient. A new approach was necessary and it involved use of a three-way catalyst for all three emissions together with a closed-loop, engine control system.[2]

Tighter emissions control solved one problem but created another—fuel economy. The two seemed to be mutually exclusive. Charles M. Heinen and Eldred W. Beckman, writing in *IEEE Spectrum* in 1977,[3] said, "The simple truth is that there is very direct interaction between emissions and fuel economy. Probably the clearest example of that interaction is the fact that automobiles equipped to meet California's tight emissions control regulations have consistently demonstrated about 10 percent poorer fuel economy than have comparable cars equipped to meet the less stringent Federal U.S. standards." As a result of this interdependence, emissions and fuel economy measures tended to be compromises. Greater fuel economies could be achieved if emissions levels were not a problem.

1.2 THE MICROCOMPUTER TAKES CENTER STAGE

The microcomputer, introduced in 1971, had yet to make major inroads in automobiles. But it became increasingly obvious that it was the key to meeting government exhaust emission and fuel economy demands while also providing car buyers with cars that performed well. Meeting these needs necessitated precise engine control in such areas as the air/fuel ratio and idle speed.

1.2.1 Early Applications of Microcomputers

One of the first microcomputer applications in cars was an advanced ignition system built by Delco-Remy for the 1977 Oldsmobile Toronado. Called the MISAR (microprocessed sensing and automatic regulation) system, it controlled spark timing precisely no matter what load and speed conditions prevailed while meeting emissions control requirements and providing good driveability. Input signals from sensors provided data on crankshaft position, manifold vacuum, coolant temperature, and reference timing.[4] The microprocessor used had a capacity of 10,240 bits.

Early applications such as the MISAR paved the ground for what would later become the prolific use of microcomputers in cars. Once reliable microcomputers met the cost restraints of carmakers, there was no end in sight to microcomputer applications in cars. In the late 1970s, total engine control with microcomputers became widespread and, as time went on, use of microcomputers spread to other controls for transmission, braking, traction, suspension, steering, lighting, air conditioning, and so forth.

1.2.2 The Bells and Whistles Period

There was also a time in the early 1980s when carmakers, heady with success with microcomputers in other areas, went through a period of electronic overkill. Notable in this regard were voice commands and warnings that tended to wear out their welcome quickly with car drivers

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and elaborate and flashy information displays that also turned off many car buyers. It was a period of doing things with microcomputers because they could be done rather than doing them because they were needed.

That overindulgent microcomputer period quickly waned as car buyers made their feelings known. Voice commands were all but totally abandoned and displays were made less garish. There was even a return to analog displays for speedometers, for example, albeit electronically based rather than the old mechanical or electromechanical system. Carmakers returned to using microcomputers in truly functional ways to answer real needs.

1.3 LOOKING TO THE FUTURE

The future for automotive electronics is bright. Electronic solutions have proven to be reliable over time and have enabled carmakers to solve problems otherwise unsolvable. But what does the future hold? Some predictions for the future have been discussed in the following pages by contributors.

1.3.1 Contributors' Predictions

Although there have been many significant automotive electronics advances over the years, the end is certainly not in sight. The final chapter in this handbook describes many upcoming advances in detail. Authors Frank and Momin, for example, state that a likely future scenario "will be a combination of centralization and distributed intelligence where the centralization would be based along the lines of body, chassis and safety, powertrain, and audio/entertainment and communications. Within these centralized systems would be distributed intelligence based on multiplex wiring with smart sensors, switch decoders, and smart actuators all controlled by a central intelligence."

Here are additional selected future developments cited by contributors in other chapters:

- Expansion of the air bag system to include side impact protection (Dunn, Chap. 7)
- Magnetic transistors and diodes that can be directly integrated with signal conditioning circuits (Dunn, Chap. 7)
- Electronic switched stop lamps involving a rate-of-closure detector system to determine if the vehicle's speed is safe for objects ahead of it. If the closure rate is unsafe, the stop lights could be activated to alert trailing drivers to a pending accident (Valentine, Chap. 14)
- The integration of watchdog and failsafe functions onto a microcontroller (Boehmer, Chap. 11)
- Microcontrollers that operate at frequencies of 24 MHz or 32 MHz to allow more code to be executed in the same amount of time (Boehmer, Chap. 11)
- In the mid-90s, cars will have twice the electronic content of today's cars but will be easier to manufacture because there will be half the number of modules due to feature content integration. The data network interconnecting the modules will reduce the size and number of cables and cut the number of circuits by 50 percent (Miesterfeld, Chap. 26)
- A move from switching units to stepped operation actuators and the substitution of continuous for discrete time control (Müller, Chap. 10)
- Electrorheological and magnetorheological fluid actuators (Müller, Chap. 10)
- Micromechanical valves as actuators for converting low control power as in regulating the flow of fluids in hydraulic or pneumatic systems (Müller, Chap. 10)

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P · A · R · T · 2

SENSORS AND ACTUATORS

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CHAPTER 2
PRESSURE SENSORS

Randy Frank
Technical Marketing Manager
Motorola Semiconductor Products

2.1 AUTOMOTIVE PRESSURE MEASUREMENTS

Various pressure measurements are required in both the development and usage of vehicles to optimize performance, determine safe operation, assure conformance to government regulations, and advise the driver. These sensors monitor vehicle functions, provide information to control systems, and measure parameters for indication to the driver. The sensors can also provide data log information for diagnostic purposes.

Depending on the parameter being measured, different units for indicating pressure will be used. Since pressure is force per unit area, basic units are pounds per square inch (psi) or kilograms per square centimeter. For example, tire pressure is usually indicated in psi. Manifold pressure is typically specified in kiloPascals (kPa). A Pascal, which is the international unit (SI or Systems Internationale) for pressure, is equal to 1 Newton per meter^2 or 1 kg $\cdot$ m^{-1} $\cdot$ s^{-2}. Other common units of pressure measurement include: inches, feet, or centimeters of water; millibars or bars, inches, or millimeters of mercury (Hg), and torr. The conversion constants as defined per international convention are indicated in Table 2.1.

Pressure can be measured by a number of devices that provide a predictable variation when pressure is applied. Sensors used on vehicles range from mechanical devices—with position movement when pressure is applied—to a rubber or elastomer diaphragm, to semiconductor-based silicon pressure sensors. Various pressure-sensing techniques are explained in Sec. 2.3.

The type of pressure measurement that is made can be divided into five basic areas which are independent of the technology used for the measurement: gage, absolute, differential, liquid level, and pressure switch.

2.1.1 Gage Pressure Measurements

The silicon pressure sensor technology explained in Sec. 2.3.5 is used to visualize the difference between gage, absolute, and differential pressure (refer to Fig. 2.1). For gage pressure measurements, the pressure is applied to the top of a (silicon) diaphragm (Fig. 2.1), creating a positive output. The opposite (back) side of the diaphragm is exposed to atmospheric pressure. Gage vacuum is a special case of gage pressure. For gage vacuum measurements, vacuum is applied to the back side of the diaphragm resulting in a positive output signal. Gage and gage vacuum are single-sided pressure measurements. Gage pressure is frequently indicated by psig.

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TABLE 2.1 Pressure Unit Conversion Constants
(Most commonly used per international conventions)

	psi*	In $H_2O^{\dagger}$	In $Hg^{\ddagger}$	K Pascal	Millibar	cm $H_2O^{\S}$	mm $Hg^{\P}$
psi*	1.000	27.680	2.036	6.8947	68.947	70.308	51.715
In $H_2O^{\dagger}$	3.6127×10^{-2}	1.000	7.3554×10^{-2}	0.2491	2.491	2.5400	1.8683
In $Hg^{\ddagger}$	0.4912	13.596	1.000	3.3864	33.864	34.532	25.400
K Pascal	0.14504	4.0147	0.2953	1.000	10.000	10.1973	7.5006
Millibar	0/01450	0.40147	0.02953	0.100	1.000	1.01973	0.75006
cm $H_2O^{\S}$	1.4223×10^{-2}	0.3937	2.8958×10^{-2}	0.09806	0.9806	1.000	0.7355
mm $Hg^{\P}$	1.9337×10^{-2}	0.53525	3.9370×10^{-2}	0.13332	1.3332	1.3595	1.000

* PSI = pounds per square inch
† At 39 °F
‡ At 32 °F
§ At 4 °C
¶ At 0 °C

2.1.2 Absolute Pressure Measurements

An absolute pressure measurement is made with respect to a fixed (usually a vacuum) reference sealed within the sensor (Fig. 2.1). For a 100-kPa-rated absolute unit, the diaphragm is fully deflected with standard atmospheric pressure. Application of a vacuum restores the diaphragm to its undeflected (flat) position. The result is a high-level output with no vacuum applied and a low-level signal at full vacuum unless the zero is established at the full-scale deflection of the diaphragm. Pressure can also be applied to absolute units with appropriately designed diaphragms to withstand the additional applied stress. Absolute pressure is frequently indicated by psia.

2.1.3 Differential Pressure Measurements

Differential or Delta-P measurements are also shown in Fig. 2.1. The higher pressure is applied to the top of the diaphragm and the lower pressure, possibly a reference pressure, is applied to the opposite side. The diaphragm's deflection is a result of the pressure difference.

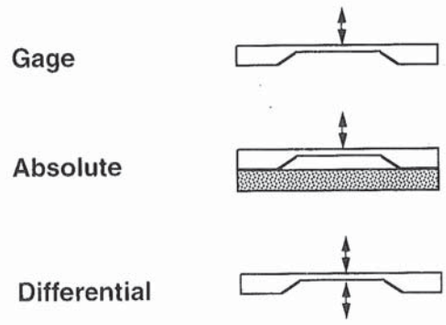


FIGURE 2.1 Types of pressure measurements: (*a*) gage, (*b*) absolute, and (*c*) differential.

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Typically, the pressure differential is only a small percentage of the total line pressure and a system fault can expose one side of the sensor to the full line pressure. This must be taken into account when choosing the sensor and determining the rated pressure range that will be required. Differential pressure is frequently indicated by psid.

2.1.4 Liquid Level Measurements

The height of a column of liquid can be measured by a pressure sensor. The term *head* is frequently used in hydraulics to denote pressure. Measurements of inches or feet of water and centimeters of mercury are direct indications of the effect of pressure on liquid level. Other liquid levels are dependent on their specific weight and can be calculated by $h = (P_L - P_H)/w$, where $(P_L - P_L)$ is the pressure differential caused by the height of the fluid column and w is the specific weight of the liquid. The vapor pressure in a sealed enclosure will have an effect on the measurement of liquid height. Returning the reference side of a differential pressure sensor to the top of the enclosure will compensate for vapor pressure.

2.1.5 Pressure Switch

A pressure switch is typically achieved by mounting an electric contact on a diaphragm (rubber or any elastic material). The application of sufficient pressure (or vacuum) on one side of the diaphragm causes the movable contact to meet a stationary contact and close the circuit.

A pressure switch can also be achieved by any of the previously described techniques merely by establishing a reference threshold voltage that is calibrated to indicate the point that the pressure changes from an acceptable to unacceptable (or low to high) level. Once the threshold voltage is achieved, additional electronic circuits can be used to produce an electronic switch that can control loads such as an indicator lamp.

2.2 AUTOMOTIVE APPLICATIONS FOR PRESSURE SENSORS

Automotive requirements for pressure measurements range from the basic—oil pressure—to the sophisticated—air pressure differential from one side of the vehicle to the other. This section elaborates on the various possibilities for pressure measurements that exist either in the development, laboratory, or pilot phases of the vehicle, to actual volume production. Table 2.2 lists a number of potential pressure measurements versus vehicle systems and provides an indication of the pressure range and type of measurement.

Automotive specification and testing guidelines have been developed and published by the Society of Automotive Engineers (SAE) specifically for manifold absolute pressure (MAP) sensors. These documents are intended to assist in establishing test methods and specifications for other sensors. Other SAE documents that may apply to sensors are summarized in Table 2.3.

The packaging and testing requirements for automotive sensors can represent 50 to 80 percent of the sensor cost and over 90 percent of the warranty and in-service problems. The pressure-sensing applications that are presented in the following sections will include packaging requirements that are of particular concern.

2.2.1 Existing Applications for Pressure Sensors

A late twentieth century production vehicle is likely to have a number of pressure sensors for measurements such as manifold pressure and engine oil pressure, and has the potential for

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TABLE 2.2 Pressure Sensing Requirements for Various Vehicle Systems

System	Parameter	Pressure range	Type
Engine control	Manifold absolute pressure	100 kPa	Absolute
	Turbo boost pressure	200 kPa	Absolute
	Barometric pressure (altitude)	100 kPa	Absolute
	EGR pressure	7.5 psi	Gage
	Fuel pressure	15 psi—450 kPa	Gage
	Fuel vapor pressure	15 in H_2O	Gage
	Mass air flow		Differential
	Combustion pressure	100 Bar, 16.7 Mpa	Differential
	Exhaust gas pressure	100 kPa	Gage
	Secondary air pressure	100 kPa	Gage
Elect transmission	Transmission oil pressure	80 psi	Gage
(continuously variable transmission)	Vacuum modulation	100 kPa	Absolute
Idle speed control	AC clutch sensor/switch	300–500 psi	Absolute*
	Power steering pressure	500 psi	Absolute*
Elect power steering	Hydraulic pressure	500 psi	Absolute*
(also elect assisted)			
Antiskid brakes/	Brake pressure	500 psi	Absolute*
traction control	Fluid level	12 in H_2O	Gage
Air bags	Bag pressure	7.5 psi	Gage
Suspension	Pneumatic spring pressure	1 MPa	Absolute*
Security/keyless entry	Passenger compartment pressure	100 kPa	Absolute
HVAC (climate control)	Air flow (PC) Compressor pressure	300–500 psi	Absolute*
Driver information	Oil pressure	80 psi	Gage
	Fuel level	15 in H_2O	Gage
	Oil level	15 in H_2O	Gage
	Coolant pressure	200 kPa	Gage
	Coolant level	24 in H_2O	Gage
	Windshield washer level	12 in H_2O	Gage
	Transmission oil level	12 in H_2O	Gage
	Tire pressure	50 psi	Gage/absolute
	Battery fluid level	1–2 in below	Optical
Memory seat	Lumbar pressure	7.5 psi	Gage
Multiplex/diagnostics	Multiple usage of sensors		

* Gage measurement but absolute sensors used for failsafe

TABLE 2.3 SAE Specifications That Effect Pressure Sensors

Recommended environmental practices for electronic equipment design	SAE J1211
Performance levels and methods of measurement of electromagnetic radiation from vehicles and devices	SAEJ551
Performance levels and methods of measurement of EMR from vehicles and devices (narrowband RF)	SAEJ1816
Electromagnetic susceptibility procedures for vehicle components (except aircraft)	SAE J1113
Vehicle electromagnetic radiated susceptibility testing using a large TEM cell	SAE J1407
Open-field whole-vehicle radiated susceptibility 10 kHz–18 GHz, electric field	SAE J1338
Class B data communication network interface	SAE J1850
Diagnostic acronyms, terms, and definitions for electrical/electronic components	SAE J1930
Failure mode severity classification	SAE J1812
Guide to manifold absolute pressure transducer representative test method	SAE J1346
Guide to manifold absolute pressure transducer representative specification	SAE J1347

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