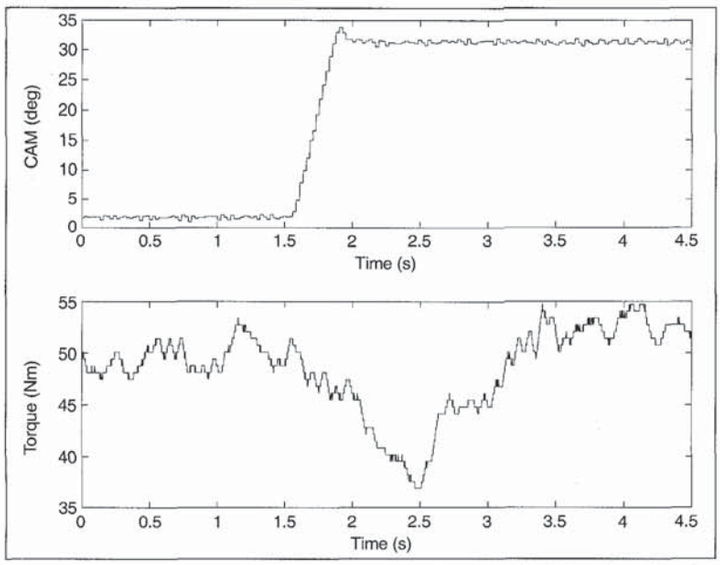


Fig. 3. Engine torque response to a change in cam phasing at fixed throttle and engine speed.

where $m_{cyl} \approx \phi_{cyl}\Delta T$, ($\Delta T$ is the duration of the intake event which depends on engine speed).

In spark ignited (gasoline) engines the air-fuel ratio is maintained at stoichiometry (14.3) in order to ensure that the catalytic converter operates at its peak efficiency. Thus, from the expressions (3) and (5) it is clear that the change in cam timing affects the torque through the change in cylinder mass air flow rate. In sonic flow, when $g_1(P_m) = c$ (c is a constant), the change in ζ_{cam} does not change the steady state value of the torque. This can be verified on the model by noting that, in steady state when $\dot{P}_m = 0$, $\phi_{cyl} = \phi_\theta = cg_2(\theta)$ independently of ζ_{cam}. However, cam transients do affect the torque as one can see in the dynamometer test data in Fig. 3 that show the response of engine torque to a change in ζ_{ref} with the other variables held constant. If the throttle flow is subsonic, cam changes also affect the steady state values of the cylinder mass air flow and torque.

The cam timing has to change depending on the operating conditions. For this reason, ζ_{ref} is scheduled on engine speed and throttle position. Typically, the schedule reaches maximal cam retards at part throttle which provides maximal internal EGR. While close to idle and at wide open throttle the cam phasing is at zero or slightly advanced. Scheduling cam timing on throttle causes it to change when the pedal is depressed or released. The torque variation caused by the cam transient leads to an undesirable engine response and drivability problems. This effect will be illustrated in subsequent sections.

Electronic Throttle Based Compensator

We design a compensator to remove or reduce the effect of the cam transients on the cylinder mass air flow which employs θ^* as a virtual actuator. We assume that the variables available for measurement are the manifold pressure P_m, engine speed N, and the cam position ζ_{cam}. Our design objective is to recover the drivability of the conventional engine.

The basic idea is to find a control law for θ^* such that the rate of change of ϕ_{cyl} coincides with that of the conventional engine. We start with the equations (1) and (3) which describe the manifold filling and engine pumping rates. By differentiating φ_{cyl} we obtain

$$\dot{\phi}_{cyl} = \frac{\partial F(N,P_m,\zeta_{cam})}{\partial N}\dot{N} + \frac{\partial F(N,P_m,\zeta_{cam})}{\partial P_m}\dot{P}_m + \frac{\partial F(N,P_m,\zeta_{cam})}{\partial \zeta_{cam}}\dot{\zeta}_{cam}.$$

To simplify our presentation we shall assume that the $\dot{N}$ term is approximately equal to the corresponding term in the conventional engine; that is, we assume that $\partial F(N,P_m,\zeta_{cam})/\partial N - \partial F(N,P_{m,0})/\partial N)\dot{N} \approx 0$. Hence, we suppress the $\dot{N}$-terms in our subsequent derivation. If this assumption does not hold we can redesign our compensator in a straightforward way to account for this additional disturbance term. By using the linear (in P_m) approximation of F and expanding $\dot{P}_m$ we obtain

$$\dot{\phi}_{cyl} = \alpha_1(N,\zeta_{cam})K_m(g_1(P_m)g_2(\theta_0+\theta^*)-\phi_{cyl}) + \left(\frac{\partial \alpha_1}{\partial \zeta_{cam}}P_m + \frac{\partial \alpha_2}{\partial \zeta_{cam}}\right)\dot{\zeta}_{cam}. \quad (6)$$

Now we can use θ^* to cancel the disturbance term proportional to $\dot{\zeta}_{cam}$. This, however, will not achieve complete disturbance rejection because α_1 and P_m depend on ζ_{cam}. To achieve our objective we have to choose θ^* in such a way that ϕ_{cyl} behaves as if it is a cylinder mass flow rate of the conventional engine:

$$\dot{\phi}_{cyl} = \alpha_1(N,0)K_m(g_1(\tilde{P}_m)g_2(\theta_0)-\phi_{cyl})), \quad (7)$$

where $\tilde{P}_m$ is a fictitious reference manifold pressure which should be equal to the manifold pressure of the conventional engine driven with the throttle θ_0 and engine speed N. This reference manifold pressure is generated by

$$\dot{\tilde{P}}_m = K_m(g_1(\tilde{P}_m)g_2(\theta_0)-\alpha_1(N,0)\tilde{P}_m-\alpha_2(N,0)). \quad (8)$$

The expression for θ^* is simplified if we substitute $\alpha_1(N,\zeta_{cam})$ instead of $\alpha_1(N,0)$ in (3). This is justified by the fact that between the maximal and the minimal values of ζ_{cam}, α_1 changes by approximately 20–25% and that α_1 affects mostly the speed of response of ϕ_{cyl}.

To achieve (3) with $\alpha_1(N,\zeta_{cam})$ instead of $\alpha_1(N,0)$, the following equality must be satisfied

$$\alpha_1(N,\zeta_{cam})K_m g_1(P_m)g_2(\theta_0+\theta^*) + \left(\frac{\partial \alpha_1}{\partial \zeta_{cam}}P_m + \frac{\partial \alpha_2}{\partial \zeta_{cam}}\right)\dot{\zeta}_{cam} = \alpha_1(N,\zeta_{cam})K_m g_1(P_m)g_2(\theta_0). \quad (9)$$

PAGE 4 of 9 HMC EXHIBIT 1005

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

Thus, the compensation θ^* should be chosen as

$$\theta^* = g_2^{-1}\left(\frac{\frac{\partial\alpha_1}{\partial\zeta_{cam}}P_m + \frac{\partial\alpha_2}{\partial\zeta_{cam}}}{K_m g_1(P_m)\alpha_1}\dot{\zeta}_{cam} + \frac{g_1(\tilde{P}_m)}{g_1(P_m)}g_2(\theta_0)\right) - \theta_0 . \tag{10}$$

Because the function g_1 changes little in the range of manifold pressures between 0.2 to 0.8 bar, another possible simplification is to use the steady state value $\tilde{P}_m^{ss}(\theta_{0,N})$ instead of the dynamically generated pressure $\tilde{P}_m$. In simulations, a slight degradation in performance is noticeable only at high reference manifold pressures.

Robust stability

The above compensation method uses the information of the engine speed, cam phasing, and manifold pressure to modify the throttle and achieve the drivability of the conventional engine. Even though it is designed as a feedforward compensator, because of its dependence on P_m, there is a feedback component which necessitates stability analysis.

If, for fixed N and θ_0, cam retard causes the steady state manifold pressure to rise into the subsonic region, the compensation will create a different set point at a higher value of manifold pressure. This new set point, denoted by P_m^0, may be sensitive to modeling uncertainties. Below, we propose a simple modification which makes the value of P_m^0 less sensitive to modeling uncertainties and guarantees that it is a stable equilibrium point.

If the functions g_1 and g_2 are known accurately, the implementation of the control law (3) leads to

$$\dot{P}_m = K_m\left(-\frac{\frac{\partial\alpha_1}{\partial\zeta_{cam}}P_m + \frac{\partial\alpha_2}{\partial\zeta_{cam}}}{K_m\alpha_1}\dot{\zeta}_{cam} + g_1(\tilde{P}_m)g_2(\theta_0) - F(N,P_m,\zeta_{cam})\right) \tag{11}$$

In steady state, when $\dot{P}_m$ and $\dot{\zeta}_{cam}$ are zero, $\phi_{cyl} = F(N^{ss},P_m,\zeta_{cam}^{ss}) = g_1(\tilde{P}_m^{ss})g_2(\theta_0)$, that is, in steady state, the cylinder mass air flow rate of the compensated VCT engine is exactly equal to that of the conventional engine.

To analyze the sensitivity of the compensation method we note that the functions g_1, g_2, α_1 and α_2 can be relatively accurately modeled from the static engine data. The only significant source of sensitivity arises because the function g_1, which is close to 0 at high manifold pressures, appears in the denominator in (10). So we only analyze the effect of modeling errors in g_1 on the steady state pressure P_m^0 and the stability of this equilibrium. To make it distinct from the "true" value g_1, we use $\hat{g}_1$ to denote the subsonic flow correction factor employed in the compensator (10).

The steady state pressure P_m^0 can be obtained by solving

$$0 = \frac{g_1(P_m)}{\hat{g}_1(P_m)}\hat{g}_1(\tilde{P}_m^{ss})g_2(\theta_0) - F(N^{ss},P_m,\zeta_{cam}^{ss}) . \tag{12}$$

At higher manifold pressures, the solution of (12) is very sensitive to changes in $\hat{g}_1$. We can reduce this sensitivity by intentionally skewing $\hat{g}_1$ so that $\hat{g}_1(P_m) > g_1(P_m)$ when P_m is high, say $P_m \geq 0.75$ bar. This guarantees the existence of a single solution of (12) and forces it to assume a lower value, in the direction of smaller sensitivity of (12). The resulting steady state error in the cylinder mass air flow rate does not affect the drivability.

To analyze the stability of the equilibrium at P_m^0, we define $x = P_m - P_m^0$. With $\dot{\zeta}_{cam} = 0$, the linearization of the manifold pressure dynamics around the equilibrium $P = P_m^0$ results in

$$\dot{x} = \left(\frac{1}{\hat{g}_1^2}\left(\frac{\partial g_1}{\partial P_m}\hat{g}_1 - \frac{\partial\hat{g}_1}{\partial P_m}g_1\right)\hat{g}_1(\tilde{P}_m^{ss})g_2(\theta_0) - \alpha_1\right)x .$$

By our choice of $\hat{g}_1$ we have assured not only that $\hat{g}_1 \geq g_1 \geq 0$, but also that $\left|\partial\hat{g}_1/\partial P_m\right| \leq \left|\partial g_1/\partial P_m\right|$. Since $\partial\hat{g}_1/\partial P_m$ and $\partial g_1/\partial P_m$ are both negative, this implies that $(\partial g_1/\partial P_m)\hat{g}_1 - (\partial\hat{g}_1/\partial P_m)g_1 \leq 0$. Because $\hat{g}_1$, g_2, and α_1 are always positive, the equilibrium $x = 0$ is asymptotically stable. Hence, our compensation creates a single equilibrium P_m^0 which is asymptotically stable.

Simulation results for ETC compensator

To demonstrate the effectiveness of the compensation (10) we have tested it on a model which differs from the one used in the controller design. We have used a simpler design model in order to keep the compensator simple. In addition, this provides some indication of the effects of modeling errors on the performance of the compensator.

To implement $\dot{\zeta}_{cam}$ we have chosen an approximate differentiation

$$\dot{\zeta}_{cam} \approx \frac{s}{\tau s+1}\zeta_{cam}, \quad \tau = 0.04s .$$

If the high frequency measurement noise present in the signal ζ_{cam} is excessive, one can use a model based approximation of ζ_{cam}. We shall discussed this issue in the final section.

The compensator, which has been developed in continuous time, has been discretized for simulations. The sampling rate is chosen to be 10ms.

Fig. 4 shows the reduction of the torque fluctuation during cam transients achieved by the compensation. For this simulation run we have varied the reference cam independently from the throttle and engine speed (which are held constant). In this and all other simulations the MBT spark is used, that is $\sigma = 0$. Clearly, the compensator achieves a substantial level of disturbance attenuation. The disturbance rejection is not perfect because of the differences between the design and simulation models, discretization, and filtering used for the derivative of ζ_{cam}. The performance of the compensator appears much better if we look at its effect on drivability. Fig. 5 shows the performance of the compensated VCT engine compared with the conventional engine and uncompensated VCT engine. The input is the throttle step with the engine speed held constant and the cam reference scheduled on throttle and engine speed. The uncompensated VCT engine response is not monotonically increasing, indicating a drivability problem. Our compensation θ^*, which can be seen in the top plot in Fig. 5 as the difference between the solid and dashed curves, brings the response of the VCT engine close to that of the conventional engine, effectively removing this problem. We emphasize that the difference between the steady state values of the conventional engine and the (uncompensated) VCT engine has little effect on drivability. Rather, it is the shape

PAGE 5 of 9 HMC EXHIBIT 1005

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

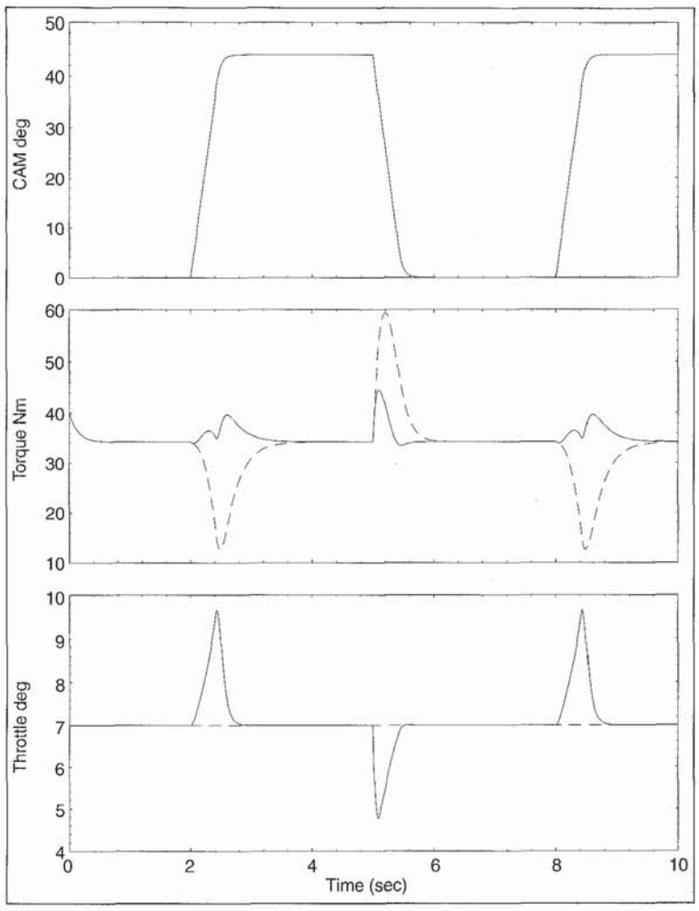


Fig. 4. Torque response of the VCT engine (dashed lines) to cam phase steps (0 to 44 deg.) at fixed engine speed (2000 RPM) and throttle angle (7 deg.); response with active compensation (full lines) shows substantial reduction in torque variation.

of the transient response which affects it the most. This observation will be used to modify our design objective in the next section, because low control authority of the air-bypass valve prevents us from recovering the torque response of the conventional engine.

Compensation with the Air-Bypass Valve

In the previous section we showed an effective way to modulate the electronic throttle to make a VCT engine respond like the conventional one. In most cases the engine will be equipped only with an air-bypass valve (ABV) which is used to control the idle speed by modifying the amount of air entering the intake manifold. We employ the ABV to affect the transients of the VCT engine and improve drivability.

Because an ABV has much smaller control authority than an ETC, we have to change our design objective: instead of trying to perfectly match the response of the conventional engine, we shall only try to modify the torque transient to have the same shape as that of a conventional engine. The steady state torque will be different, equal to that of the uncompensated VCT engine.

To explain this point, we refer to Fig. 6. The dashed and dotted curves show the static throttle-to-load (load is the normalized cylinder air charge) characteristics at a fixed engine speed for conventional ($\zeta_{cam} = 0°$) and fixed cam ($\zeta_{cam} = 35°$) engines. By scheduling the cam on the throttle and engine speed, we create a new static characteristic for the VCT engine shown by the solid curve in Fig. 6. Now our objective is to modify the transients of the VCT engine, using the ABV, so that the torque response is the same as that of a (fictitious) conventional engine which has a static throttle-to-load characteristic shown by the solid curve .

The new objective creates a problem for the design because now we do not have simple reference manifold pressure dynamics. In fact, as we change the throttle, the scheduled ζ_{ref} changes, and our reference manifold pressure model changes. We emphasize that it is not sufficient to introduce $F(N,P_m,\zeta_{ref})$ instead of $F(N,P_m,0)$ in the manifold pressure dynamics (8). The problem is that, at the step change in ζ_{ref}, not only must the dynamics for the reference pressure change, but also reference pressure value at that instant must change (jump). The generation of the desired reference manifold pressure can be done systematically at the expense of significant complexity. Instead, as a reference pressure we use the steady state value of the manifold pressure corresponding to the current values of N, θ_0, and ζ_{ref}. Simulation results have confirmed that the simplified algorithm performs very well.

With the air-bypass valve, the ideal gas law has to take into account the additional air coming through the ABV:

$$\dot{P}_m = K_m[g_1(P_m)(g_2(\theta_0)+g_3(\delta))-F(N,P_m,\zeta_{cam})], \tag{13}$$

where $\delta = \delta_0 + \delta^*$ is the opening of the air-bypass valve and g_3 is its static flow characteristic. We assign $\delta = 0$ to the completely closed and $\delta = 1$ to the completely open valve. Following the same steps as for the electronic throttle compensation, we obtain

$$\delta^* = g_3^{-1}\left(-\frac{\frac{\partial\alpha_1}{\partial\zeta_{cam}}P_m+\frac{\partial\alpha_2}{\partial\zeta_{cam}}}{K_m g_1(P_m)\alpha_1(N,\zeta_{cam})}\dot{\zeta}_{cam} + \frac{g_1(\overline{P}_m^{ss})}{g_1(P_m)}[g_2(\theta_0)+g_3(\delta_0)]\right)-\delta_0,$$

where, as we have said above, the reference pressure $\overline{P}_m^{ss} = \overline{P}_m^{ss}(N,\theta_0,\delta_0,\zeta_{ref})$ is the steady state value of the manifold pressure corresponding to the present values of the variables N, θ_0, δ_0, and ζ_{ref}. The evaluation of the reference pressure $\overline{P}_m^{ss}$ in real time can be done by evaluating two functions of two variables (two look-up tables).

The potential for instability for the compensation with the ABV is much smaller than with the ETC. The reasons are (i) at

PAGE 6 of 9 HMC EXHIBIT 1005

PETITIONER'S EXHIBIT 1002
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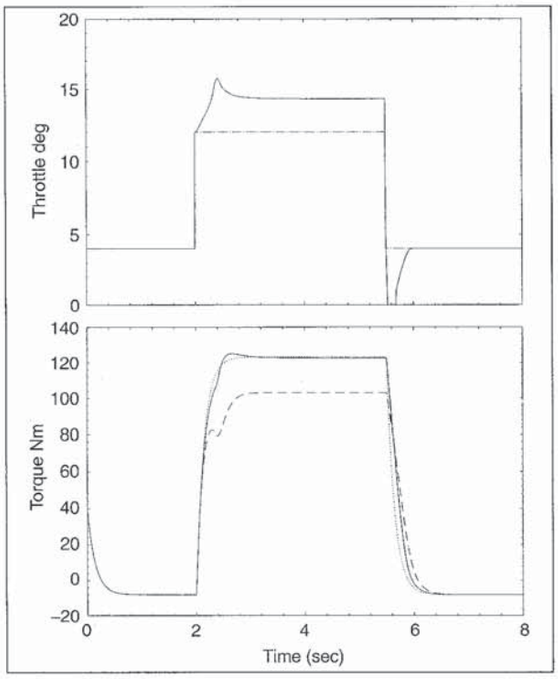


Fig. 5. Comparison of the throttle step torque response of the conventional engine (dotted lines), VCT engine without compensation (dashed lines), and VCT engine with compensation (full lines); engine speed is 2000 RPM, throttle is stepped from 4 to 12 and back to 4 deg.

the high end, $\overline{P}_m^{ss} < P_m^0$, and (ii) at the operating regimes with high manifold pressure, the ABV has little control authority. Nevertheless, we have used the skewed value $\hat{g}_1$ in the implementation.

The simulations are performed with the same simulation and design models as in the case of electronic throttle except that both models now include the air-bypass valve as an actuator. The air-flow characteristic of the valve is modeled as a sigmoidal function for the simulation model and as a straight line for the design model.

Plots in Fig. 7 show the air-bypass valve opening δ and the torque responses to throttle steps with the cam timing scheduled on throttle angle and engine speed. The torque of uncompensated VCT engine (dashed line) flares at both tip-ins and tip-outs indicating a drivability problem. Our compensation algorithm results in the torque response which closely resembles a scaled down response of the conventional engine (full line). The dynamics of the air-bypass valve have been neglected in the simulation model; the traces of δ for the uncompensated VCT engine show the dash-pot functionality of the air-bypass valve. The difference between the steady state values for two torques in Fig. 7 is due to the difference between the simulation and design models. It has no consequence on drivability and can be removed with a simple high-pass filter if desired.

The algorithm has shown very good performance in simulations The compensator has performed well over a variety of speed and load conditions. At high loads (high values of throttle) the air-bypass valve loses its control authority and the torque responses of the compensated and uncompensated engines are the same. However, this happens in the region where the VCT does not cause drivability problems.

Implementation of $\dot{\zeta}_{cam}$

Our compensation algorithms require that the derivative of ζ_{cam} be available. Two methods to obtain this derivative are explored. One method is to use the approximate differential of the available measurement as we have done for the simulations, the other one is a model based estimator. For the approximate differential, we use the a second order, low-pass Butterworth filter. The model based estimator uses ζ_{ref} and N as inputs to the model of the VCT mechanism (c.f. Fig. 2) which is itself a feedback loop consisting of the VCT actuator controlled by a PID regulator.

The VCT actuator system consists of a control valve and the actuator itself. This control oriented model captures the dominant behavior of the VCT actuator system. These dominant dynamics can be reduced to a single integrator. Adding higher frequency components does not add much to the accuracy of this model. The static control valve behavior is captured in the function $F(\cdot)$. It is purely a function of the control input. The gain of the VCT actuator depends heavily on the engine speed N and is described by the static function $K(N)$. A block diagram of the VCT mechanism model is shown in Fig. 8.

In Fig. 9, the estimated cam position and the cam position measured on the engine are the solid and dotted curve, respectively. The plot shows that the model captures the VCT mecha-

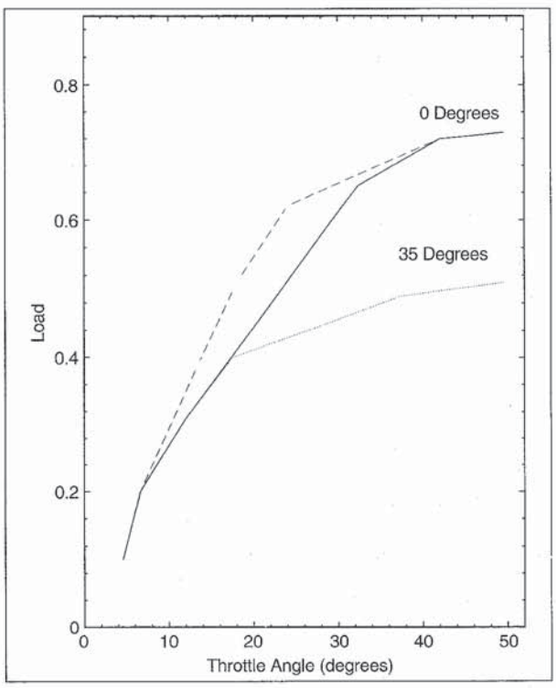


Fig. 6. Load vs throttle characteristic for the conventional engine (dashed line), an engine with cam fixed at 35° retard (dotted line), and the VCT engine with cam scheduled on throttle and engine speed (full line).

PAGE 7 of 9 HMC EXHIBIT 1005

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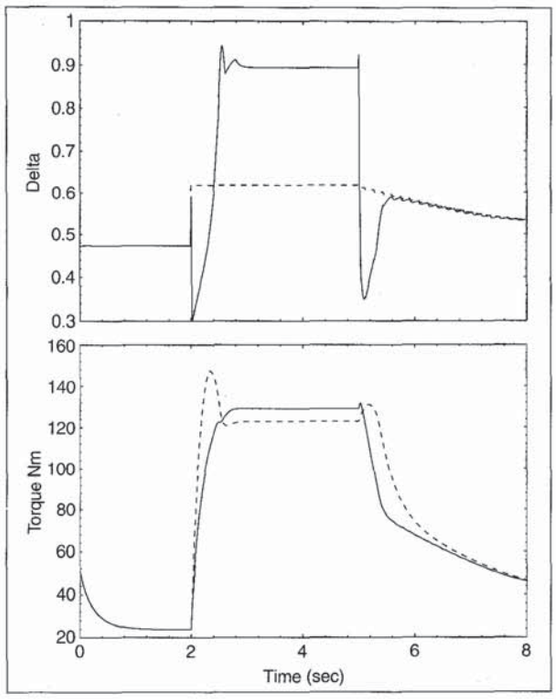


Fig. 7. Normalized air-bypass valve opening δ and torque response for the VCT engine without compensation (dashed lines) and with compensation (full lines); throttle steps 0 to 9 to 0 deg., engine speed 1250 RPM.

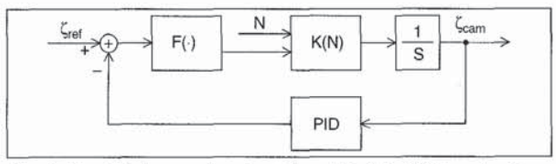


Fig. 8. Simplified controls-oriented model of the VCT mechanism.

nism dynamics very well. It also shows high frequency noise content in the measured signal which forces us to use a low bandwidth Butterworth filter for approximate differentiation.

The estimates of $\dot{\zeta}_{cam}$ obtained by two methods are shown in Fig. 10. The one obtained by differentiating the measured cam position lags the model-based one because of the low pass filtering and measurement delay. It appears that the model is sufficiently accurate to show a clear advantage over an approximate differentiation method. One must keep in mind, however, that this conclusion applies for the particular hardware implementation of the VCT sensor and actuator.

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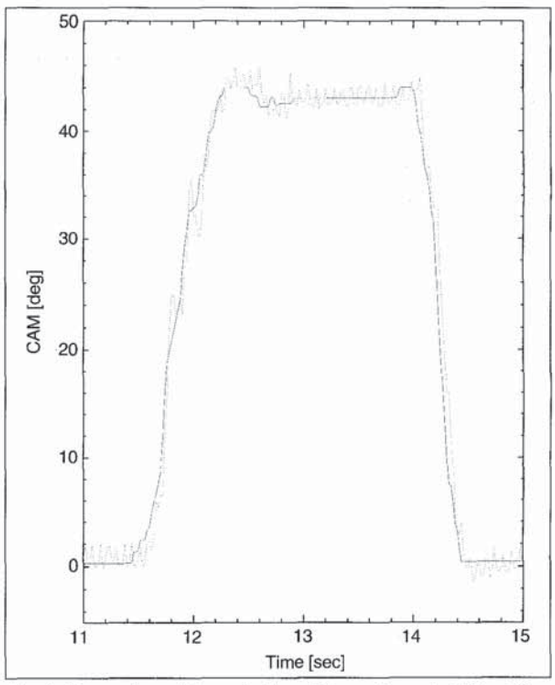


Fig. 9. Comparison of the model based ζ_{cam} estimate (solid) and ζ_{cam} measured (dotted).

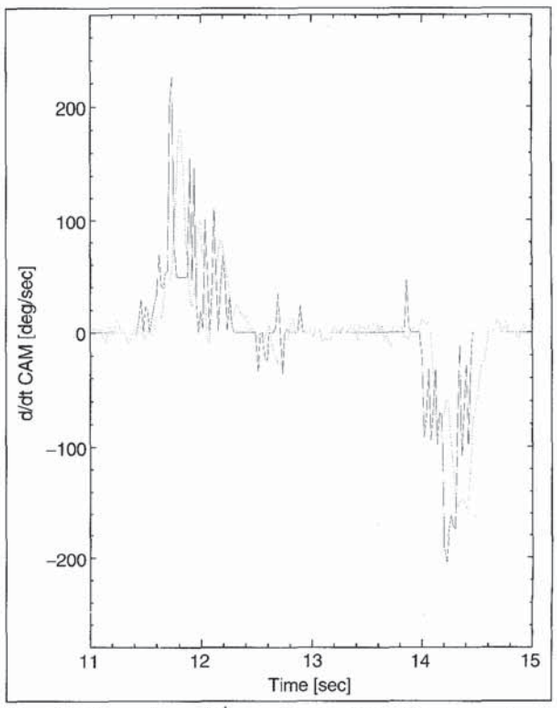


Fig. 10. Comparison of $\dot{\zeta}_{cam}$ estimate obtained by approximate differentiation (dotted) and the model based one (solid).

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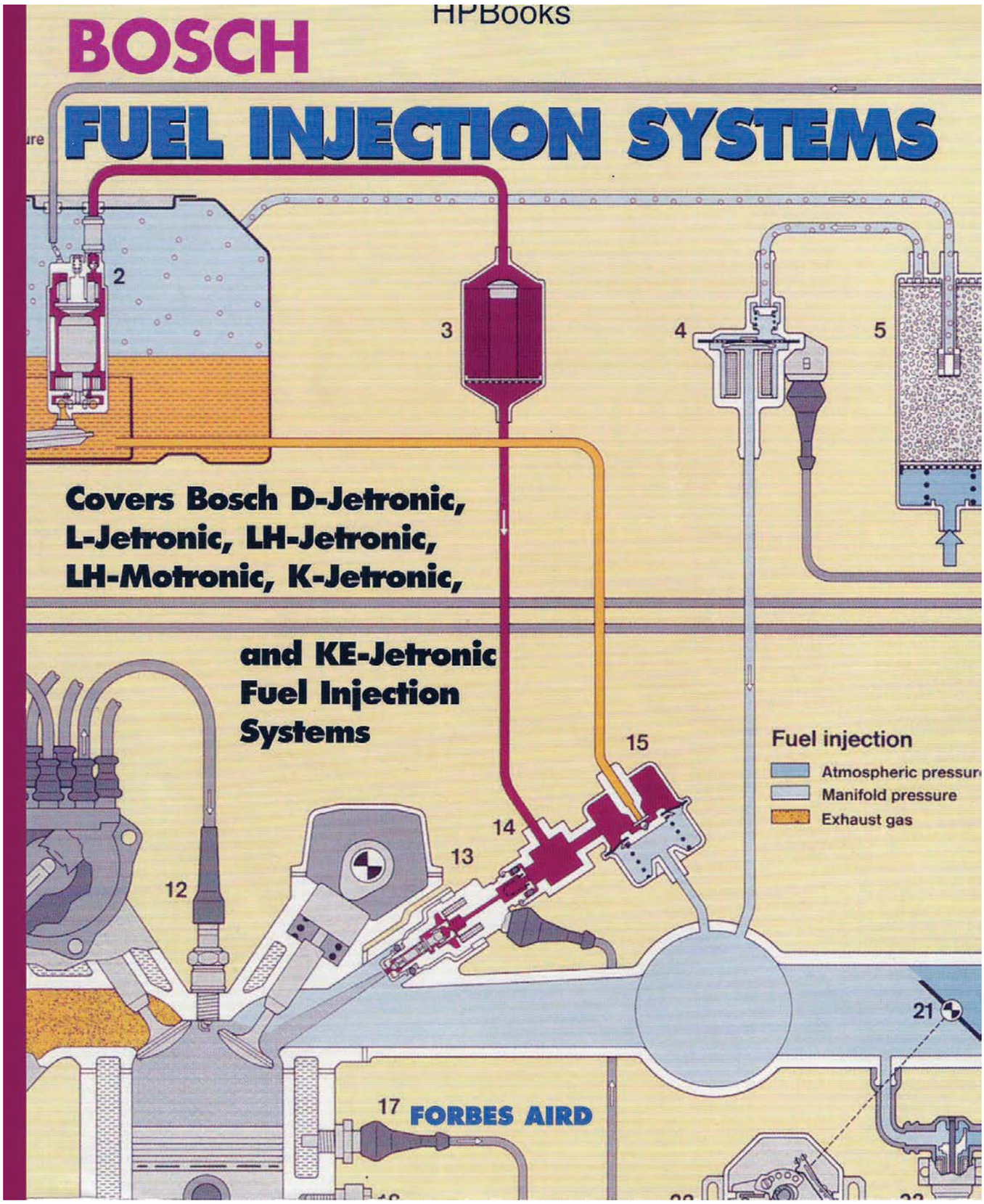
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INTRODUCTION

Although gasoline fuel injection (FI) has been around just about as long as the automobile itself, it has always been a mysterious technology. Until about 1970 it was both rare and expensive, restricted to some aircraft applications, and to a hand-full of exotic, high performance cars and racers. Production cars—even high performance sports cars—made do with carburetors.

Thirty-plus years later, and as a result of the "electronics revolution," that situation has been very nearly turned on its head. While cars in many racing classes wear carburetors, virtually every production car in the world has FI! Yet it remains a mystery to most.

This book is an attempt to de-mystify fuel injection. While it deals principally with the various electronic fuel injection systems produced by the Robert Bosch company, much of what is said in the following pages also applies to other systems.

No book of this size—indeed, likely no book of any size—could fully describe the minor variations in FI installations between one vehicle model and another. Still, it is hoped that sufficient detail is provided to be of benefit to mechanics both amateur and professional, while the general principles described will be useful for those attempting performance tuning, and informative for readers who simply seek to understand the mystery.

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CONTENTS

CHAPTER 1 **Food For Engines, Food For Thought**	**1**
CHAPTER 2 **Fuel Injection: Then and Now**	**19**
CHAPTER 3 **Bosch Intermittent Electronic FI**	**37**
CHAPTER 4 **Motronic Engine Management**	**59**
CHAPTER 5 **Troubleshooting Bosch Intermittent Electronic FI**	**75**
CHAPTER 6 **Bosch Continuous Injection**	**85**
CHAPTER 7 **Troubleshooting Bosch Continous Injection**	**109**
CHAPTER 8 **Performance Modifications**	**123**

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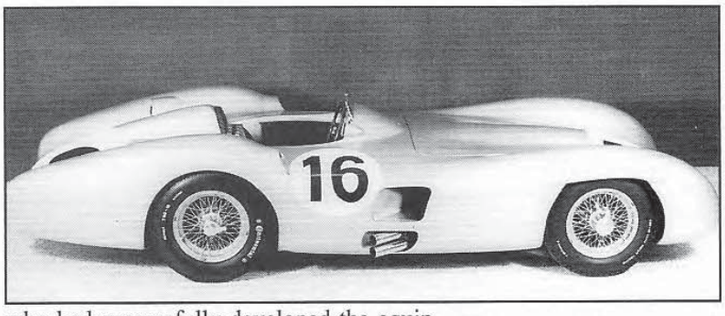
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2 FUEL INJECTION: THEN AND NOW

Despite the fact that there were a thousand and one other problems to be dealt with in the early days of the automobile, auto pioneers were quick to focus attention on the shortcomings of carburetors. The drawbacks included the possibility of ice forming within the venturi in cold, damp air, and a tendency to vapor lock in hot weather when volatile fuels were used. Conversely, carburetors were unsuitable for use with fuels that did not readily vaporize (remember, the automobile came first—gasoline followed, almost anything that would burn was used as a fuel at one time or another in the earliest days). Also, the venturi restricts airflow, and thus power. Because fuel delivery depends on the level in the float bowl, a carburetor is sensitive to the inclination of the car, such as when climbing hills. In addition, there was some dawning awareness of the problems of feeding multiple cylinders from a single "central mixer," as described in the previous chapter. Accordingly, some of the critics set about designing an alternative, specifically what we now call fuel injection.

Early Production FI Systems

Although there were even earlier experiments, perhaps the first production application of FI was by the German company, Deutz, who built about 300 fuel-injected stationary engines around the turn of the century. Hampered by a lack of precision manufacturing facilities, Deutz abandoned the scheme soon after. (Deutz is still in the business of manufacturing industrial and marine diesel engines.) Perhaps aware of Deutz's work, Robert Bosch began experiments with fuel injection in 1912. In 1927, Bosch bought the Acro company, and the patent rights of an Acro employee, Franz Lang, who had successfully developed the equipment needed for high-pressure fuel injection. Shortly afterward, Bosch began manufacturing diesel injection equipment of a pattern that has changed little in the 70-odd years since (see sidebar "The Real Jerk").



The straight eight engine of Mercedes Benz's first post-war Formula One race car—this streamlined W196—injected fuel directly into each cylinder, a system developed from Diesel injection principles. (Mercedes Benz).

The adaptation of this system to gasoline-fuelled engines began in the 1930s, initially for use in aircraft. In this application, three advantages of fuel injection over carburetors stand out: freedom from problems of vapor lock, no risk of icing, and a complete indifference to the attitude of the vehicle. Vapor lock is a significant problem at high altitudes, because the reduced atmospheric pressure there makes it so easy for the fuel to evaporate that it is inclined to boil, forming bubbles of vapor in all sorts of awkward places that can effectively prevent any fuel from getting to the engine. Carburetor icing, while merely an annoyance in an automobile, can be potentially fatal in an aircraft. And a fuel system that can keep the engine running no matter what the attitude of the aircraft becomes a matter of first importance during extreme maneuvers, such as inverted flight. Most, if not all, Daimler Benz engines fitted to German aircraft during World War II enjoyed this advantage over their Allied opponents.

Early Racing FI Systems

If we substitute severe cornering for

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THE REAL JERK

In a diesel, the cylinder at the end of the compression stroke is filled with nothing but air; combustion cannot begin until the fuel is injected. Thus, the moment of introduction of the fuel is equivalent to the ignition timing on a spark-ignition gasoline engine. For that reason, control is needed over not just the quantity of fuel injected, but also the timing of that injection.

Because the fuel has to be kept separate from the air until the correct instant for ignition, the fuel is injected directly into the combustion chamber—the injector nozzle lies inside the cylinder. As a result of that, the injector is exposed to full cylinder pressure during the power stroke. To prevent combustion pressure from blowing the fuel backward through the fuel lines, the injector is fitted with a very stiff spring-loaded check valve. This check valve also performs a number of other important functions. It prevents fuel from dribbling out of the injectors between timed squirts, and ensures that the start and end of each injection is clearly defined. Without this valve, the fuel spray would taper off gradually toward the end of each injection. The check valve, in conjunction with similar check valves at the pump outlets, also ensures that the fuel lines leading from the injection pump remain filled with fuel at full pressure, to ensure that the pressure pulse from the pump is transmitted immediately to the injector nozzle. To overcome the resistance of these check valves, the entire system has to operate at a very high pressure—as much as 3000psi!

The design of the classic diesel injection pump, and the gasoline injection pumps directly derived from that design, follows from the three requirements: to control the quantity of the fuel delivery, and its timing, and to provide a very high pressure output. In construction, it consists of an approximately rectangular body, bored with a number of small cylinders—one for each engine cylinder—each of which is lined with a cylindrical sleeve. The whole thing thus roughly resembles a miniature engine block, a similarity that extends to the "bottom end" of the pump, which has a shaft running lengthwise through it, analogous to an engine's crankshaft. Instead of crank throws, however, this shaft has a number of individual cams, one for each cylinder. Each cylinder in the pump contains a piston-like plunger that is driven up its sleeve by the corresponding cam lobe as the pump shaft rotates, driven by the engine at half crank speed, like an ordinary ignition distributor.

The mechanical drive thus provides the timing and the necessary pressure, leaving the problem of control of fuel quantity. To achieve this, each sleeve has a "spill" port drilled through its side, while the upper edge of each plunger has its side cut away to form a sort of spiral ramp. The sleeve fits in its bore with a very slight clearance, and so is free to rotate. Rotation of the sleeve in its bore thus covers or exposes the spill port, according to the angular position of the sleeve relative to the spiral cutaway on the plunger. With the sleeve rotated so that the spill port is covered even when the plunger is at the bottom of its stroke, the only route out of the cylinder is through a hole at the top, where the fuel lines to the injectors connect. A single stroke of the piston will thus expel the entire volume of fuel held in the cylinder; this represents the maximum capacity of the pump and thus corresponds to full power.

At anything less than wide-open throttle, a lesser amount of fuel per revolution is obviously needed, and this reduction is achieved by rotating the sleeve around, relative to the plunger, so that the spill port lies some distance above the plunger's spirally formed top edge. Upward movement of the plunger thus initially causes fuel to be discharged from this port, from where it is fed back to the tank, until the plunger rises far enough to close off the port, and injection commences.

The rotation of the sleeve(s) is accomplished by a toothed rack that meshes with gear teeth cut onto the outside of each sleeve. The rack is connected directly to the throttle linkage, so moving the pedal rotates the sleeves within the pump, thus controlling the quantity of fuel delivered with each stroke of the plunger.

Although such a mechanical injection pump is, in fact, quite a simple device, and contains few parts—just two per engine cylinder served, plus the camshaft and rack—the quantity of fuel delivered per stroke is very small, so all those parts have to be made with extreme precision, involving much hardening, grinding and precision gaug-

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ing. Accordingly, mechanical injection pumps—known widely and for fairly obvious reasons as "jerk" pumps—are mighty expensive. When adapted for use with gasoline, rather than the kerosene used in diesels, there is the additional problem that gasoline is a "dry" fuel, lacking the lubricating properties of diesel fuel, thus demanding the use of extremely hard, wear-resistant alloys, which further adds to the machining difficulty and expense.



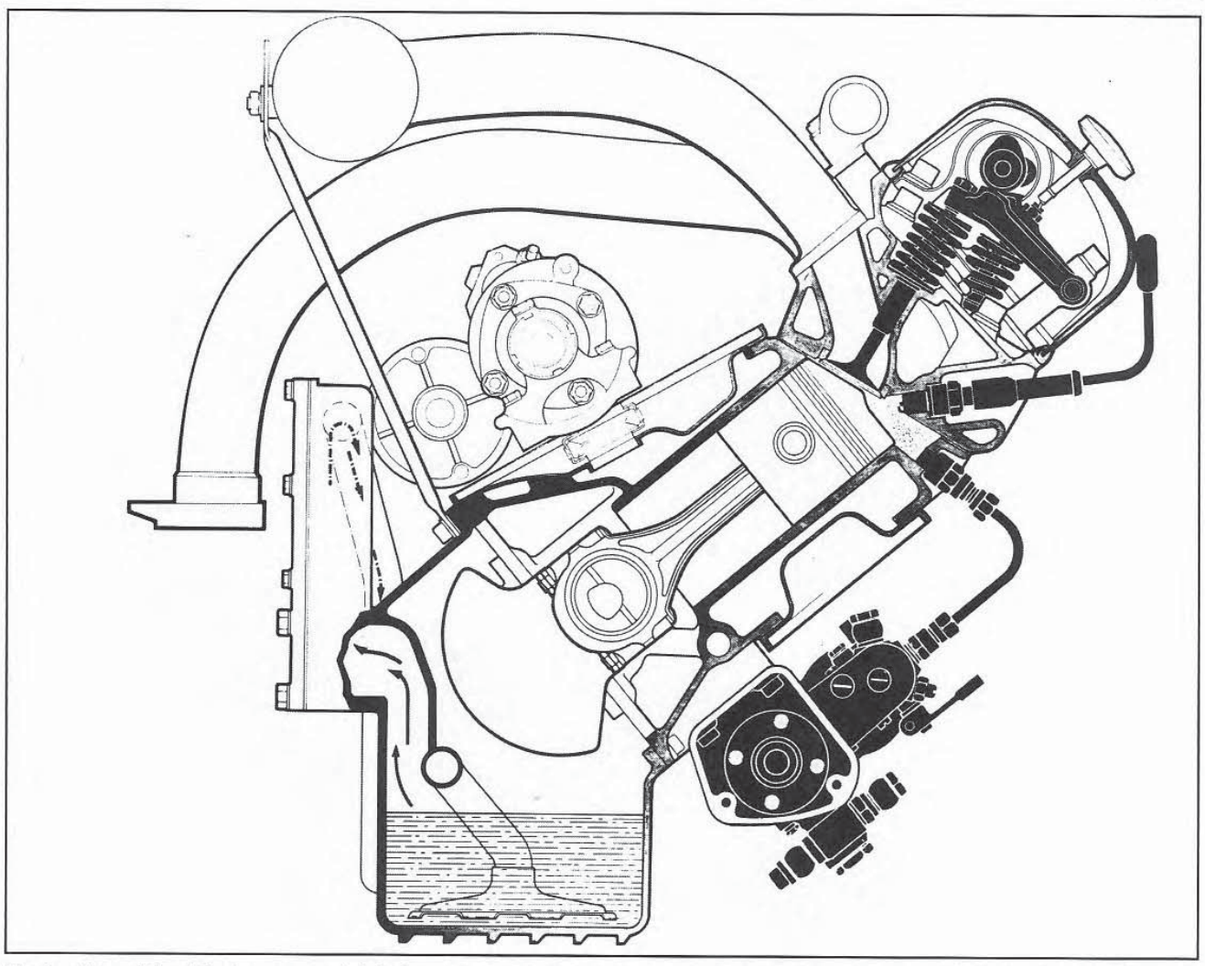
The famous Mercedes 300SL "gull-wing" coupe introduced fuel injection to the street. Like the W196, a system of direct injection was used. (Mercedes Benz).

inverted flight, most of the advantages listed are also highly applicable to race cars. Accordingly, by 1937 Mercedes Benz had tested a single cylinder mockup for a racing engine, using high-pressure injection of fuel directly into the combustion chamber. In the meantime, a handful of European makers of small, two-stroke engined passenger cars had introduced this "direct" fuel injection, in an attempt to tame the notorious thirst of two-strokes that results from something like one quarter of the air/fuel mixture whistling straight out the exhaust ports during the intake/exhaust event, when both inlet ("transfer") and exhaust ports are open together. Because these engines were two-strokes, the injection pump had to run at crank speed, rather than half-speed, as for a four-stroke. This provided Bosch with valuable lessons in running their injection equipment at high pump rpm. Mercedes's first post-war Formula One race engine made direct use of the experience so gained, both their own and that of Bosch.

In both the M196 Formula One engine that appeared in 1952 and in the engine for the famous 300SL "gull-wing" sports car, first exhibited in New York in 1954, Mercedes retained the direct (into the combustion chamber) injection scheme used in

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The location of the injector—screwed right into the cylinder head—is apparent in this cross-section of the 300SL engine. (Daimler-Chrysler Archive)

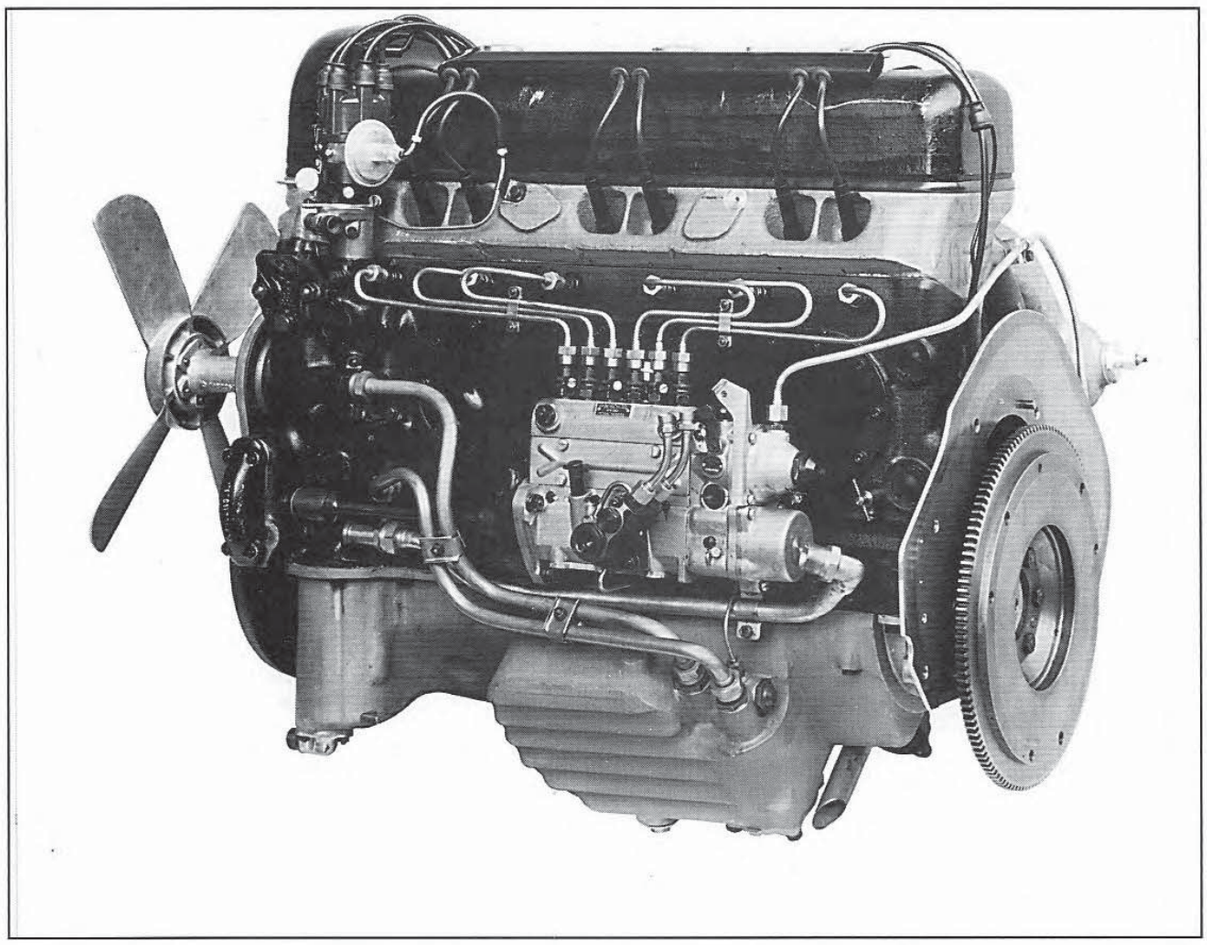
diesels and in the earlier experiments with gasoline fuel. Combined with suitable injection timing, this allowed radical valve timing and experiments with "tuned" intake pipes, without introducing the problem of poor fuel economy from portions of the intake charge being lost out the exhaust. Until injection occurred, after the exhaust valve had closed, the engine was inhaling only air.

Diesel Jerk Pump

Given the existence of an established technology for injecting fuel, it is hardly surprising that the diesel "jerk" pump was adapted in this way for gasoline injection. The adaptation, however, required hurdling a major difficulty—the problem of regulating the quantity of fuel delivered throughout the full range of engine operating speeds and loads.

Unlike gasoline engines where power is controlled by closing off ("throttling") the air supply, yet where a very narrow range of air/fuel ratios must be maintained, on a diesel there is no "throttle" as such. At any given speed, the engine inhales the same full load of fresh air no matter what the position of the gas pedal; varying the power is sim-

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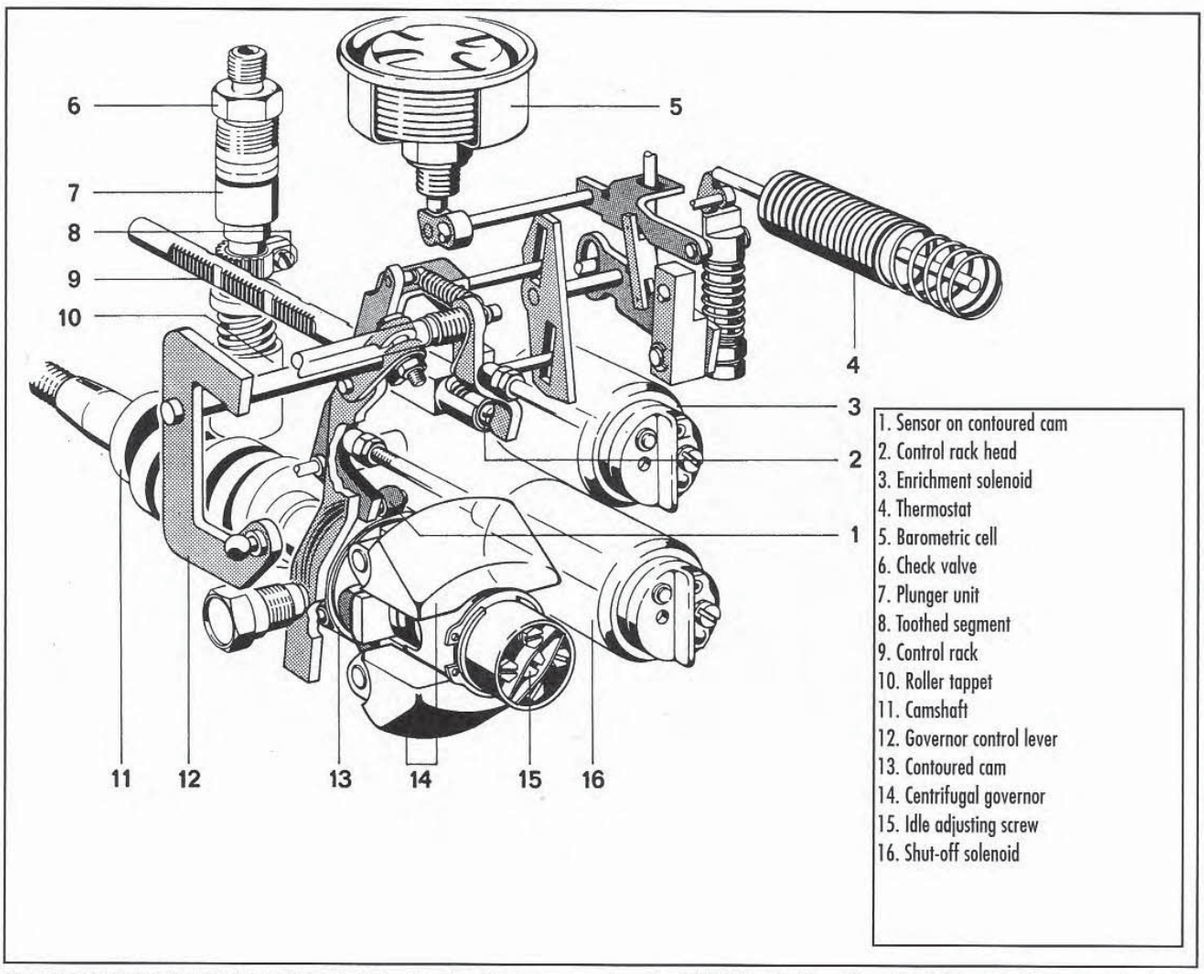


The resemblance to Diesel engine practice is clear in this exterior shot of the 300SL engine. Gasoline's lower lubricity, compared to diesel fuel, compelled the use of expensive, wear-resistant alloys in the injection pump. (Daimler-Chrysler Archive)

ply a mater of injecting more or less fuel. Power is regulated, in other words, by adjusting the mixture strength. In the simpler diesel systems, at least, this is directly controlled by the driver's right foot—the engine runs extremely lean at light throttle, and rich to the point that it visibly smokes when maximum power is demanded. In fact, it is the smoky exhaust that sets the limit for the rated power of a diesel engine; more power would be available simply by injecting yet more fuel—if we were prepared to put up with the smoke. (Even at full power, the amount of fuel injected falls short of a stoichiometric mixture—diesels are always running "lean," which is one reason they can never produce as much power as a gasoline engine of the same displacement.)

The inefficient breathing of any piston engine, gas or diesel, at speeds well away from the rpm at which torque peaks means that the mass of air inhaled per revolution, at any given throttle setting, will most definitely not be constant across the speed range. Because of the gasoline engine's finicky appetite, the amount of fuel mixed in with that air also has to be varied on the basis of the quantity of air inhaled, and not just

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The complexity of the mechanical controls for the Bosch system used on the 300SL is mind-boggling. Fuel delivery of the pump (only the camshaft is shown, 11) is controlled by the rack (9). The position of the rack is governed by engine speed, via the centrifugal weights (14) acting on a contoured cam (13), and by throttle position. Other factors are accounted for by a barometric capsule (5) and a temperature sensitive device (4). (Robert Bosch Corporation)

according to speed and throttle position.

Adapting to Gas Engines—To adapt a diesel jerk pump to gasoline operation, then, means that the rack (see sidebar, page 20) cannot simply be directly hooked up to the loud pedal; the relationship between the two has to be modulated by some other control(s). The usual way this is done is by adding a set of centrifugal weights, somewhat like those in a traditional ignition distributor, to provide a signal proportional to engine speed, plus a diaphragm that "reads" manifold vacuum, a fairly close approximation of engine load. These additional control devices are connected to the linkage controlling the rack via a system of cams and links, with the shape of the cams tailored according to the idiosyncrasies of the engine's breathing.

The monkey motion of these additional levels of control added even more to the substantial cost of the pump itself, demanded meticulous adjustment, and its complexity mocked the essential simplicity of the

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basic pump. Indeed, one observer at the time mused aloud that if all engines had worn fuel injection all along, then someone invented the carburetor, he would have been hailed as a genius.

Injector Location—Apart from the mechanical complexity of the "add-on" speed- and load-sensing mechanisms at the pump, another problem confronted this adaptation from diesel to gasoline—that of shielding the injector nozzles from the heat and fury of combustion. Surprising as it may seem, gasoline combustion chambers see higher peak temperatures than diesels. On their M196 Formula One engine, Mercedes dealt with this by fitting the injector into the side of the cylinder, where it was masked by the piston at TDC and thus shielded from the worst of the inferno.

Certainly, timed direct injection deals with the potential issue of fuel consumption, especially with radical valve timing, and the high pressure spray of these systems is favorable for atomization, but against these advantages were set the problems noted above, plus the issue of the power required to drive a pump that has enough grunt to blow open the stiff check valves in the injectors and at the pump outlets, used respectively to prevent combustion pressure from blowing back through the injection lines and to keep the lines fully charged. Nevertheless, the fact that engines operate quite happily on carburetors made it clear from the outset that there was no absolute need for precision timing of the fuel delivery in a spark-ignition engine.

Granted, a carbureted engine would probably make a little less power than a similar one with direct injection, but some part of this might be attributed to the fact that a separate injector for each cylinder eliminates the problems of a central mixer, rather than to the timing. Of course, the same thing can be achieved with carburetors if a separate carb is provided for each cylinder. That, however, would be heavier, probably more expensive and arguably even more complex, depending on the number of cylinders. Thus, while a handful of other Formula One teams and upmarket European sports car manufacturers also used Bosch gasoline injection, to the best of this writer's knowledge, all these others left the injector just outside the combustion chamber, aimed at, and spraying against, the head of the intake valve.

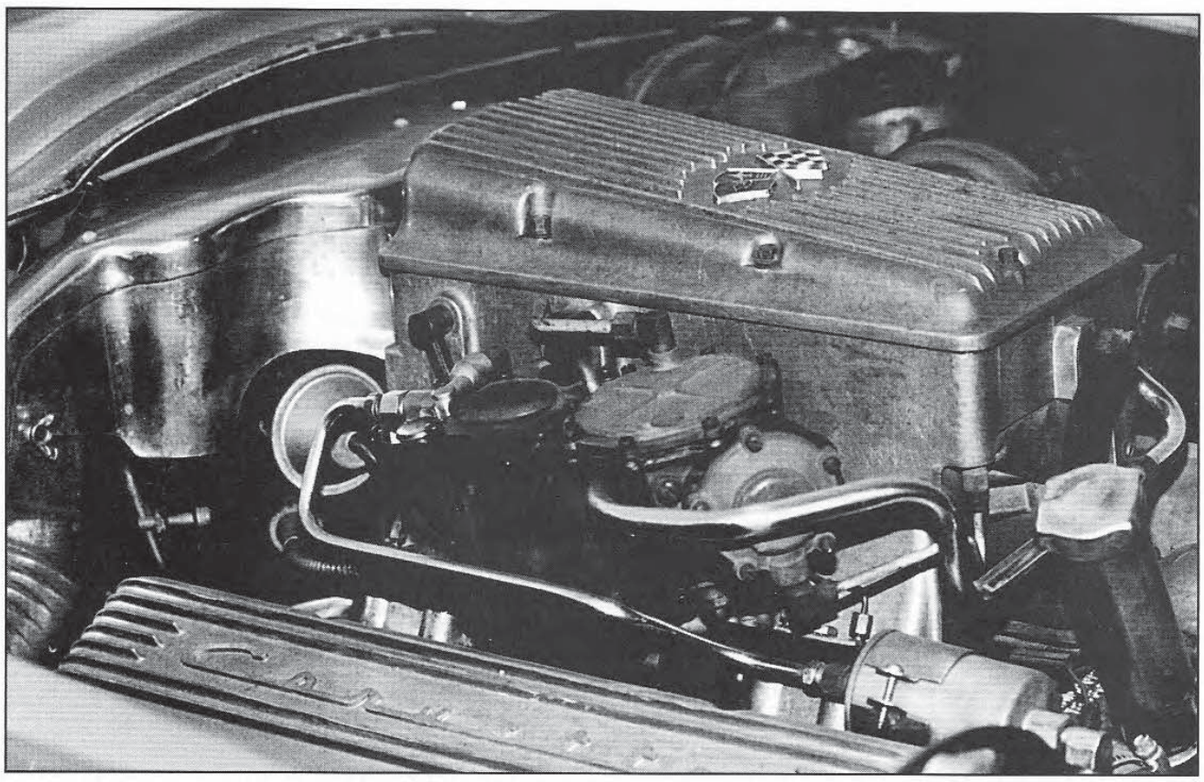
But if you decide to locate the injectors outside the combustion chamber, then you don't need to fight combustion pressure, so you don't need a very high pressure pump. Also, if the injector lies outside the cylinder, then you don't need to time the injection so it occurs with both valves closed. In that case, why bother to time it at all? And if the timing of discrete squirts is not crucial, then why does the fuel have to be delivered in individual pulses?

Early Continuous Injection Systems

These questions had occurred to a good many people, and an alternate form of fuel injection came into being. In these, fuel is injected continuously, rather than in pulses, and at very much lower pressure than a "jerk" pump provides, though still much higher than the small pressure difference that exists between a carburetor venturi and the atmosphere.

The Wright brothers used a primitive form of this continuous injection, as the arrangement is called, on the engine of their first successful aircraft. An engine-driven pump of the "positive displacement" type—one which supplies a fixed quantity of fuel at each revolution—was used, to continuously spray fuel directly into the engine air intake. It should be clear that while a satisfactory mixture strength might be arranged at full throttle—presumably after some tinkering with the size and/or drive ratio for the pump—with no means to reduce the pump output the mixture must have become hopelessly rich at anything less than full throttle.

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Although Stu Hilborn had proved, years earlier, that such a system could work on the track, Rochester were the first to demonstrate the practicality of the simpler, continuous flow fuel injection system, as on this early "fuelie" Corvette. (Dave Emanuel)

But then the Wrights' had no immediate interest in operation at part throttle!

Winfield's FI System—About the same time that Bosch and Mercedes were beginning their experiments with timed, high-pressure, direct gasoline injection in the mid-1930s, Ed Winfield developed a low pressure, continuous injection system, intended for Indy cars. Winfield's design had provision for varying the fuel flow with throttle position, but a lack of interest from potential customers forced him to eventually abandon the scheme, and he allowed his patents to lapse. It was not until fifty years after the Wrights that racers had access to a continuous injection system that dealt with the part-throttle problem.

Hilborn Injection—Stu Hilborn achieved this by incorporating a controllable spill valve, connected to the throttle linkage, that tapped off (and returned to the tank) some portion of the pump's output, according to how wide the throttle was opened.

On the face of it, this might appear to fill the bill, but the assumption built-in here is that an engine, at any given throttle setting, needs a fixed quantity of fuel per crank revolution, and we have already seen that this is mistaken, because of the way an engine's ability to take a full breath varies across its speed range. As a result, gasoline FI systems that use just engine speed and throttle position to determine fuel quantity can be arranged to provide a suitable mixture strength only under very limited circumstances, and must inevitably miss the mark by a large margin under others.

Still, schemes such as Hilborn's have a long and honorable history when used with methanol fuel. As discussed in more detail

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in Chapter 8, methanol will tolerate wide variations in mixture strength with little effect on power output, which helps mask the inherent shortcomings of such a simple system. In this case, rpm and throttle position alone provide a sufficiently accurate measure of fuel flow requirements, so it is not necessary to measure the rate of airflow at all. Since there is no need to measure it, there is no need for the restriction of a venturi or any other airflow sensor stuck in the airstream. This improves engine breathing and so promises more power just for that reason alone.

Rochester FI System

For a street engine running on gasoline, however, any purely mechanical system, whether injecting continuously or in a series of pulses, needs to somehow measure or compute the rate of airflow into the engine, and to use that information to modulate the delivery of fuel so as to keep the air/fuel ratio appropriate to the circumstances. We have discussed how this can be achieved with a jerk pump, but what about a continuous gasoline injection system?

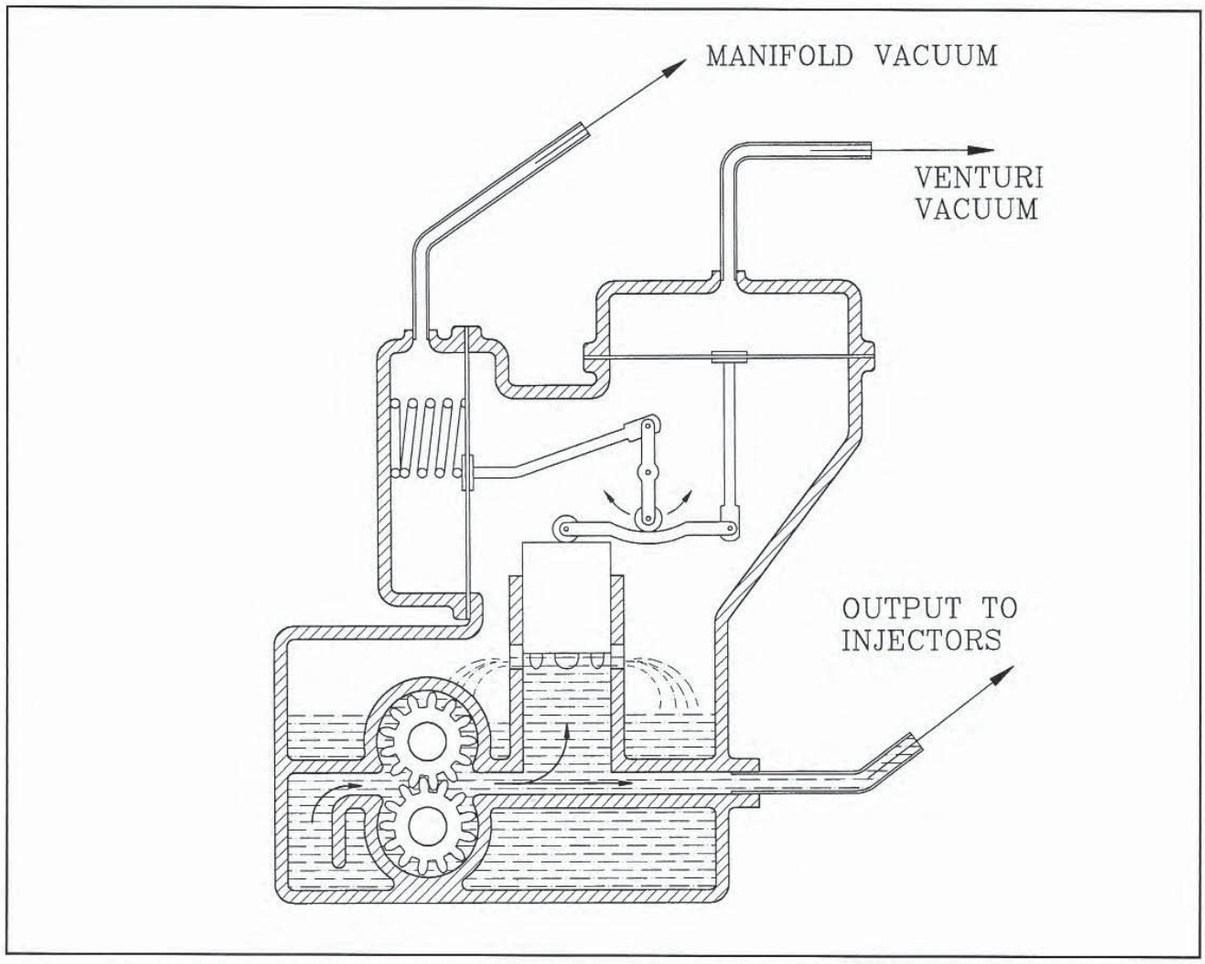
There have been many such systems throughout automotive history; one of the more recent and more widely used of these is the Bosch K-Jetronic system, described in Chapter 6. Nevertheless, the example most of us remember best is likely the Rochester system used on "fuelie" Corvettes from 1957 to 1965. The heart of the Rochester system is a spill valve that serves as a regulator of fuel quantity—indeed, it is the only mixture control element in the whole system. Fuel is fed to the spill valve by an engine-driven gear-type pump that simply serves as a source of fuel at medium-high pressure (200psi at maximum), with the pressure tending to rise with increasing rpm. The spill valve consists of a sleeve with a number of ports arranged radially in its side, plus a plunger that covers or exposes these ports, according to its position. The position of the plunger, in turn, depends on a balance between the fuel pressure and a force applied to the top of the plunger by a mixture control mechanism.

Increasing fuel pressure tends to raise the plunger, thus uncovering the sleeve ports and so bleeding off some of the pressure. The mixture control device, shown schematically in the following illustration, amounts to a simple mechanical computer that applies a spring force to the top of the plunger, modified by the forces acting on two diaphragms—one connected to the intake manifold, and one to a venturi through which all the air entering the engine has to pass. The eight individual port injectors downstream of the spill valve thus see a fuel pressure that depends on a balance between the supply pressure and the forces acting on the diaphragms, and their output varies accordingly.

The Rochester system is strikingly simple, especially when compared to a jerk pump having the controls needed for street use on gasoline, and none of its parts require exceptional precision or expensive materials for their manufacture. Although the injectors themselves had to be individually calibrated and installed as a matched set, given sufficiently large production numbers it seems likely that the system overall would have been little (if any) more expensive to make than a pair of four barrel carburetors. Nevertheless, it remained a somewhat rare and costly performance option, and justified its price premium by offering more power. Partly this was because the near-elimination of cylinder-to-cylinder variations in mixture strength permitted a higher compression ratio (CR) than was safe with carburetors, but an advantage still showed even when the CR was unchanged. We might attribute this to three sources: nearly identical air/fuel ratios at each cylinder, elimination of manifold heating, and a reduction in the breathing restriction imposed by the venturi, compared with a carburetor. Although a venturi

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The heart of the Rochester system's control unit was a spill valve that returned to the tank a certain fraction of the fuel delivered by the gear-type pump. The position of the piston in the spill valve was determined by two diaphragms—one hooked to a manifold vacuum, one to a single large metering venturi that fed the air box. A system of links and rollers linked movement of the diaphragms to the spill valve piston.

was needed to measure air quantity, the amount of pressure drop needed to provide a useful signal to the mixture control unit was much less than that required to lift gasoline out of a carburetor's discharge tube.

In its day, the Rochester FI was regarded by the auto industry and the public alike as very much a high-tech piece, and possibly the final word in fuel delivery. Ironically, at about the same time that GM was introducing this system, another completely different form of fuel injection was being unveiled, to much less public acclaim, yet this one would eventually sweep away not only the carburetor, but most other forms of fuel injection as well.

The First Use of Solenoid Valves

The basis of this little-hailed breakthrough was the use of an electrically operated solenoid valve as a fuel injector. Supplied with fuel at a modest constant pressure, it squirts at a constant rate as long as an electric current is applied to the solenoid windings, and stops when the current is turned off. Thus, the quantity of fuel injected depends simply

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on how long the juice is turned on. If one electrical pulse is delivered every second revolution of the crankshaft (for a four-stroke engine), then the air/fuel ratio of the mixture delivered to the engine can be controlled simply by varying the length of each pulse.

The idea of using a solenoid valve as a fuel injector is a surprisingly old one. Such a scheme had been developed by an engineer named Kennedy at the Atlas Imperial diesel Engine Co, in 1932, and an installation appeared on a marine engine exhibited at the New York Motor Boat Show in 1933, around the same time that Bosch and Mercedes in Germany, and Winfield in the U.S. were beginning their experiments. Given the primitive state of the electrical sciences back then, it is mildly astonishing that the thing worked at all, yet in 1934 a similar but smaller engine was installed in a truck and driven successfully from Los Angeles to New York and back.

The "Electrojector"—A quarter century later, A.H. Winkler and R.W. Sutton of the Eclipse Machine Division, Bendix Aviation Corporation, announced the fruits of four years' work at Bendix to develop anπ FI system for gasoline-fuelled automobiles using such a solenoid-controlled valve as an injector, in conjunction with an electronic control unit, or (as they termed it) "brain box." They described this combination of components as "electronic fuel injection"—surely the first time this phrase was ever used. The resulting "Bendix Electrojector" comprised a separate port injector for each cylinder, each supplied with fuel from a common rail at a regulated 20 psi. Sensors responsive to manifold pressure, engine speed, atmospheric pressure, and air and coolant temperature fed their various outputs to the "brain box"—the electronic control unit (ECU)—which then calculated the instantaneous fuel requirements of the engine. On the basis of that calculation, the ECU delivered a pulse of current to a rotary distributor which fed that current pulse to each solenoid valve in turn, causing each successively to open and supply fuel to the cylinder it served. The quantity of fuel delivered by each injection was simply a matter of the duration of the pulse—as long as it was "on," the injector would deliver fuel at a constant rate. At idle, the pulses were of very short duration; at maximum load, the injectors were open for as much as 150 crankshaft degrees.

At the beginning of the development of the Electrojector, about 1951 or 1952, the triggering signal for the ECU was provided by a mechanical commutator—a simple wiper making intermittent contact with a segmented brass ring, as the engine-driven ring swept past. That soon gave way to triggering by an extra set of contact points in a housing sandwiched under the ignition distributor. In at least the three earliest versions, the working bits in the ECU were . . . vacuum tubes! One such unit was installed on the V8 engine of a 1953 Buick, and used to demonstrate the system to the auto industry.

By 1957, when it became available to the public in very limited numbers, the electronics were, thankfully, all transistorized. This eliminated the need to wait for the tubes to warm up before the system became functional, shrank the size of the ECU and substantially reduced the electrical power required to run it, and doubtless greatly improved the system reliability—vacuum tubes do not take kindly to be rattled around! The Electrojector was listed by American Motors as an option for the 1957 Rambler Rebel, but very few cars so equipped were ever sold. A year later, Chrysler offered it on the 300D and DeSoto Adventurer, and several hundred with the option were manufactured in 1958 and 1959.

Despite occasional problems from external electrical fields causing the brain box to go haywire, and a degree of unreliability of the injectors themselves, on the whole the system worked satisfactorily and matched Bendix's claims of modest (5 percent)

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improvements in both fuel economy and power, compared to a similar engine fitted with a pair of four-barrel carburetors. The teething troubles were eventually worked out, and by 1965 Bendix had a fully developed production version ready to go.

At this point, rather than try to produce and market the Electrojector themselves, Bendix decided instead to enter into an agreement with the Robert Bosch Co., which gave Bosch access to the Bendix patents. From a business point of view, this made a good deal of sense. In view of their reputation in the auto industry as an established OEM supplier—one with wide experience both in fuel injection and in electrical and electronic equipment—Bosch was clearly in a better position to exploit the potential market. And fuel prices in Europe were many times what they were in the U.S. of the 1950s, justifying a much higher initial cost there, in exchange for the fuel economy benefits alone.

Bosch Jetronic FI

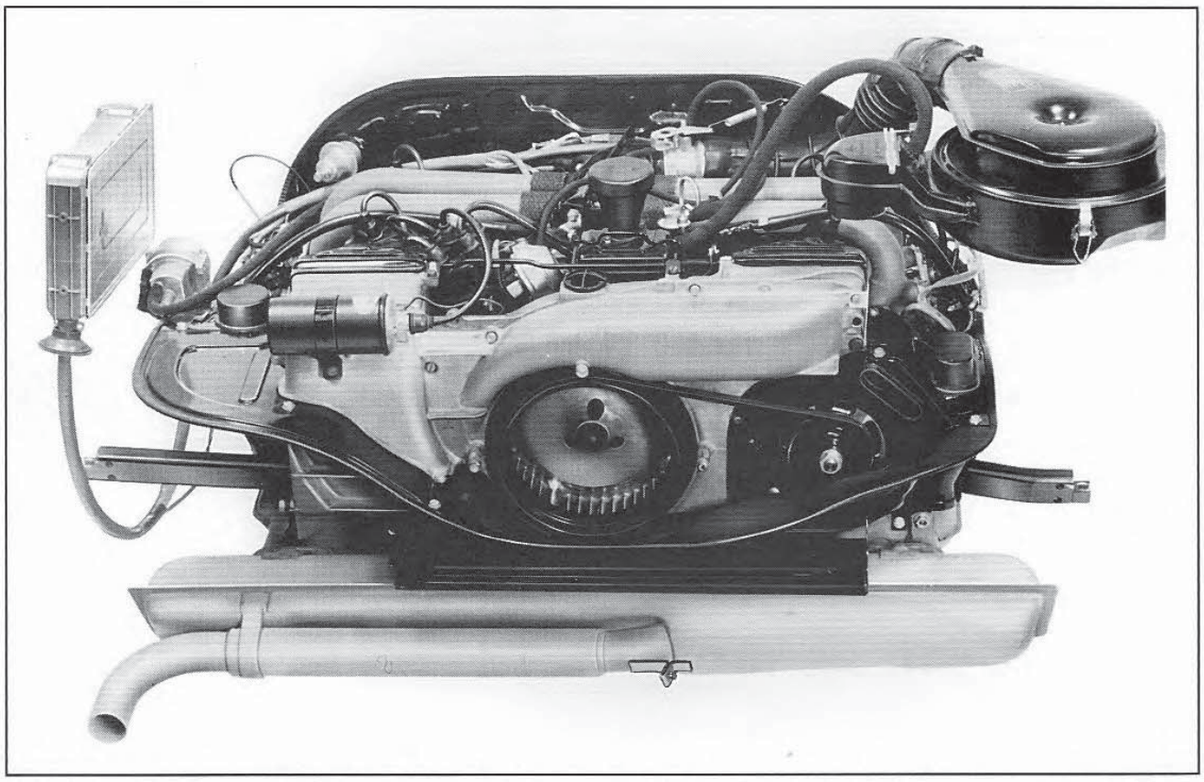
In most respects, the Bosch "Jetronic" FI that first appeared on the 1967 Volkswagen 1600, was functionally identical to the Electrojector system described by Winkler and Sutton ten years earlier. Apart from taking advantage of advances in electronics to produce a more compact ECU, this system—since identified as D-Jetronic, to distinguish it from later Jetronic versions—differed from the Bendix prototype in one respect. In the Electrojector, the housing that was piggybacked onto the ignition distributor and which contained the triggering contact points also contained a rotor, just like an ignition rotor; this distributed the timed pulse to each injector sequentially. In the D-Jetronic as applied to the four cylinder VW, there was no rotor, but there were two sets of triggering contacts, one for each pair of cylinders. Each set of contact points drove two injectors simultaneously, timed so that one cylinder received its injection while its intake valve was open; for the other cylinder, the injection occurred with valves closed. Fuel thus accumulated in the port, awaiting that cylinder's next intake stroke.

We have mentioned earlier that the mere fact that a carbureted engine will function in a satisfactory way should make it obvious that injection timing is, to say the least, not critical, and the power gains realized with a few continuous injection systems tended to confirm this view. The matter was pretty much clinched in 1959, when Mercedes successfully used a Bosch jerk pump with just two plungers, each feeding three engine cylinders, on its six cylinder 220SE. This must all have improved the comfort level of the Bosch and VW engineers who adopted the hop-skip timing used on the D-Jetronic, an arrangement that allowed eliminating the rotor used in the Electrojector.

The Electrojector-based, intermittent injection "Jetronic" systems from Bosch have undergone successive improvements and refinements over the years since the D-Jetronic's introduction. Apart from the electronic innards of the control unit gaining computing power while shrinking ever further in size and weight, and the use of all-electronic triggering (rather than contact points), the major differences between one variant and another have been in the way the quantity of air supplied to the engine is measured. These basic differences between systems are reflected in the nomenclature used: L-Jetronic, LH-Jetronic, etc. In addition, most later systems accept inputs from additional sensors, most notably an oxygen sensor, also called an O_2 sensor or lambda sensor. As mentioned in the previous chapter, this is a device fitted to the exhaust system that "sniffs" the exhaust gas to gauge its oxygen content, thereby providing a direct measure of what the air/fuel ratio actually is at any given moment, rather than obliging the system to depend totally on a set of pre-programmed "maps" or "look-up tables" that predict what the ratio should be for a

PAGE 18 of 28 HMC EXHIBIT 1006

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



With the rear-mounted "pancake" engine nestled under the apparent floor of the trunk, earlier carburetted versions of the VW 1500/1600 were notorious for vapor lock problems. This is the later 1600 engine with Bosch D-Jetronic injection. The ECU is visible at the far left. (VW Canada).

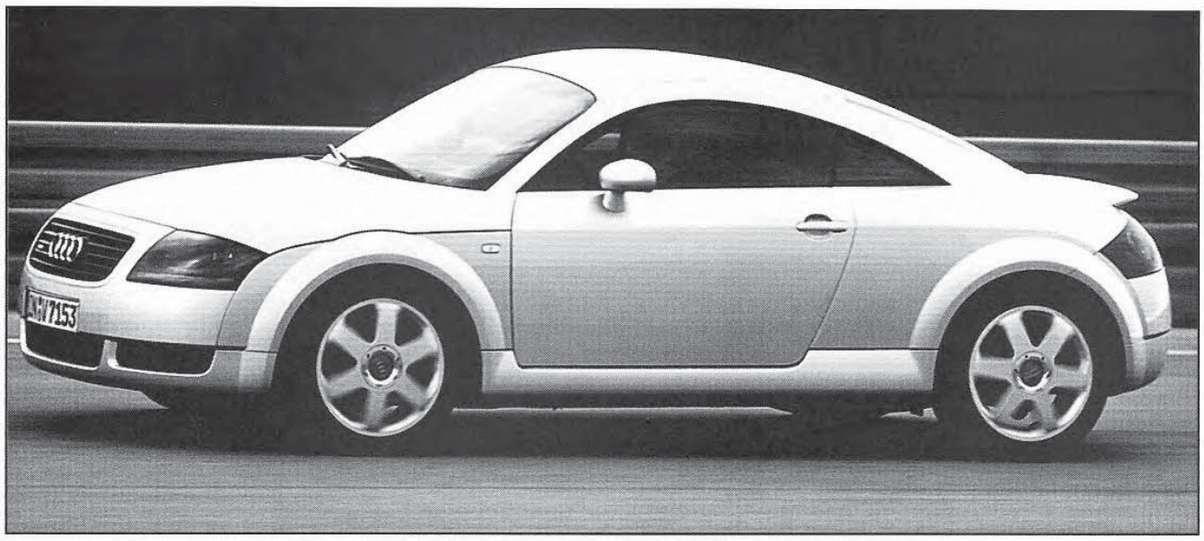
given set of operating conditions. (See also the sidebar "The Oxygen Battery.")

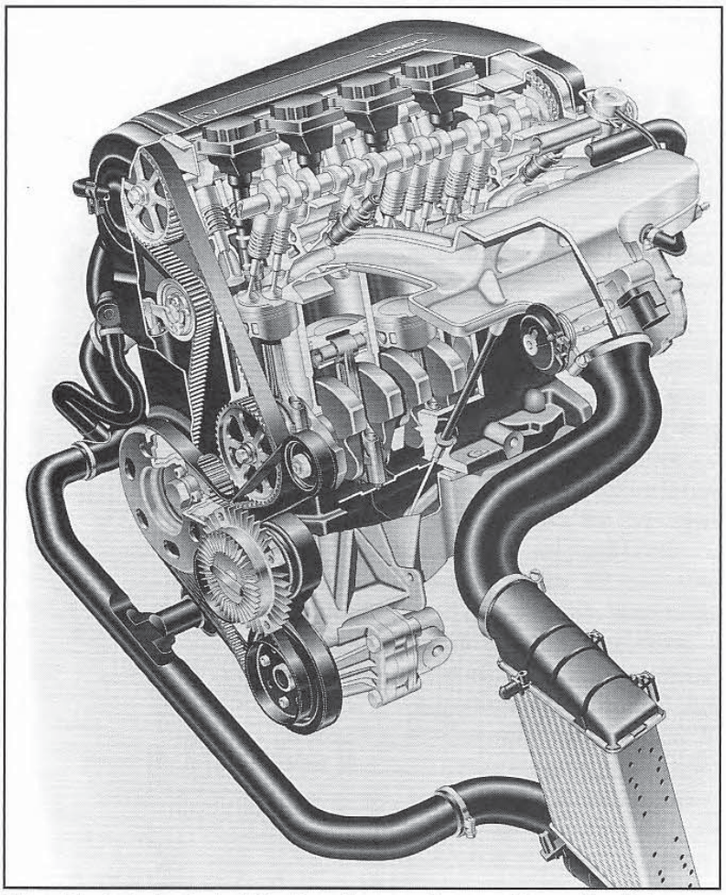
In many cases, control over ignition timing has been integrated into the ECU of these systems, in which case they are termed "Motronic," again with variants according to the method of air metering. Over time, an increasing number of functions have been combined into the Motronic system, including integrated control over automatic transmission shift points and torque converter lockup, the waste-gate on some turbocharger-equipped cars, selection among different length intake ports on some others, and authority over the variable valve lift and/or timing found on a few vehicles. We discuss these Motronic systems in some detail in Chapter 4.

K-Jetronic—At the start of the new millenium, the principle of intermittent injection using electronically controlled, electrically powered solenoid injectors is now universal on domestic passenger cars, and near-universal on models imported from Europe and Asia. Yet not everyone was an immediate convert to this plan. It seems ironic now that even after the pulsed (intermittent) Jetronic system was commonplace, Bosch felt obliged to introduce a continuous injection system, the K-Jetronic (The "K" stands for *kontinuierlich*, German for continuous). Early versions of this were purely mechanical; in response to ever-tightening emissions standards, later ones—such as KE-Jetronic and corresponding Motronic versions—added a degree of electronic control. In part this apparent preference for an all-mechanical system may have been due to a powerful conservative

PAGE 19 of 28 HMC EXHIBIT 1006

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





Intermittent electronic fuel injection allows modern cars to combine high power with driveability, economy, and low emissions. (VW Canada).

streak among some manufacturers and their engineers. In part, too, it may have been a matter of economics—the intermittent systems may have been more expensive at the OEM level. Although there were a few holdouts until the early 1990s, most of the various K-Jetronic systems were history by the mid 1980s. These now-superseded (not to say obsolete) systems are dealt with in Chapter 6.

We will not be dealing with a handful of sub-variants of Jetronic and Motronic FI that are used on vehicles not imported into North America.

To summarize, then, the essential difference between carburetors and fuel injection systems is that a carburetor uses the pressure drop within its venturi both to measure the airflow and as the means to propel the fuel into the intake air stream, whereas FI mechanically forces the fuel into the intake air in an amount usually determined by a separate airflow or manifold pressure sensor, acting on an electronic or mechanical system that actually controls the quantity of fuel injected.

Basic Types of Fuel Injection

All fuel injection systems can be divided up into two basic types: those that inject fuel

HMC EXHIBIT 1006

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

continuously and those that inject intermittently, in a series of pulses. Again, in either case control over how much fuel is injected can be achieved either mechanically or electronically. In the present context, only the old, diesel-type jerk pump uses mechanical control over intermittent injection; all Bosch intermittent systems use electronic control. Bosch K-Jetronic continuous injection systems—sometimes called CIS—may use purely mechanical control, as in the original K-Jetronic, or may include some degree of electronic fine-tuning on top of the basic mechanical computation.

Many FI applications, especially in newer cars and in older high-performance ones, use a separate injector for each cylinder. This greatly reduces the quantity of liquid fuel laying on the walls of the ports. If the injectors are located very close to the intake valves and the intermittent injections are sequential, the possibility of maldistribution of the mixture between one cylinder and another is essentially eliminated.

Many others, though, are of the "throttle body" type, in which the fuel is sprayed into and mixed with the air in one centralized location, then conducted to the cylinders through a thus "wet" manifold, just like that of a carbureted engine. This would seem to put it on the same footing as a single carb in terms of mixture distribution, but the fact that the fuel is injected under pressure means that it emerges from the injector nozzles as a very fine spray, with droplets so small that they have a much better chance of evaporating than is often the case with the lumpy soup coming from a carburetor. While a TBI system is thus likely to be better in this regard than a carb, an individual injector at each intake port can do even better.

One of the further advantages sometimes argued for FI is that it achieves the maximum possible engine power because it does away with the venturi. That is not quite true, because it is a basic principle of science that you cannot measure something without affecting the thing you are measuring. Certainly a venturi measures airflow, and in the process it also restricts that flow, but electronic fuel injection (EFI) systems that use a spring-loaded flap valve or a "hot wire" airflow sensor (the current needed to keep the wire at a constant temperature is used as the air-quantity signal) both offer at least some restriction to flow, too, although a hot wire (or hot film) sensor will impede airflow much less than any carburetor venturi.

The ultimate sophistication is to provide an oxygen sensor (O_2 sensor, lambda sensor) in the exhaust pipe and to correct the mixture strength from moment to moment, based on that information; an excess of O_2 calls for a richer mixture, and vice versa. For all these reasons, EFI with an injector for each cylinder is unarguably the state-of-the-art for fuel-air mixing and delivery.

PAGE 21 of 28 HMC EXHIBIT 1006

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

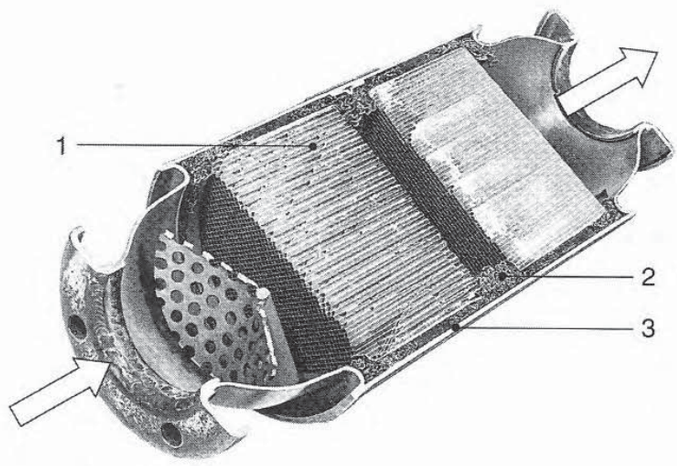
THE OXYGEN BATTERY

Rich mixtures, we explained in Chapter 1, mean that some of the hydrocarbon molecules in the fuel entering the engine pass out into the exhaust unreacted—there simply aren't enough oxygen molecules available for them to combine with. These unburned hydrocarbons are a source of air pollution, and legislation severely limits the quantity of them that is allowed to escape into the atmosphere. The shortage of oxygen also means that the reaction with the hydrocarbons that do burn is chemically incomplete—instead of the hydrocarbon-oxygen pairings forming CO_2 and H_2O, many of them wind up as CO—carbon monoxide. Emissions of carbon monoxide are also strictly controlled by law.

Lean mixtures would keep down the CO levels, and as long as they were just a little lean, the HC levels, too. Ironically, excessively lean mixtures actually raise HC levels above those found with a stoichiometric mixture, because as the mixture approaches the "lean limit"—the air/fuel ratio at which the mixture simply won't ignite—some cylinders misfire, so all of the HC in that particular cylinderful goes straight out the exhaust unburned.

But even mixtures just lean enough to minimize CO and HC create high combustion temperatures. Too-hot combustion encourages some of the nitrogen (N) in the air, normally thought of as inert, to combine with some of the excess oxygen, to form various oxides of nitrogen—NOx. NOx is also a pollutant—it is the principle source of photochemical "smog"—so the amount of it, too, is limited by law. (Damned if you do; damned if you don't!) A compromise setting won't work, either. Anything lean enough to meet HC and CO limits would bust the NOx limit, and anything rich enough to avoid excessive NOx would lead to illegal levels of HC and CO. (Damned even if you sit on the fence!)

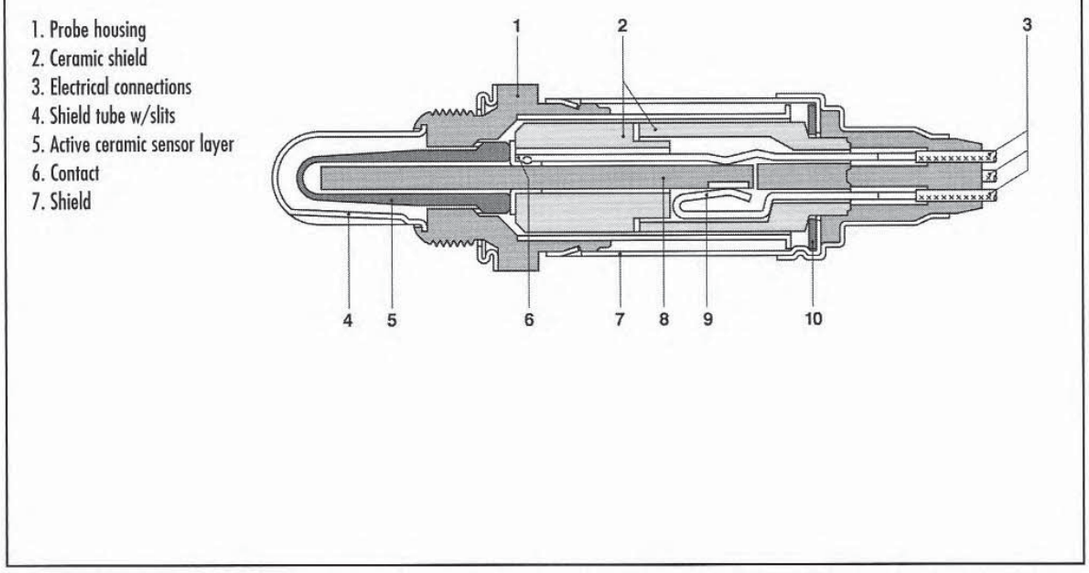
The solution arrived at by auto makers, beginning about 1975, has been the "three-way catalytic converter." In essence, this device splits the oxygen from the NOx and helps it combine with the CO to make CO_2, and with the HC to make H_2O, and more CO_2. This works well enough to satisfy the G-men . . . provided that the mixture was neither too rich nor too lean in the first place. And the three-way catalytic converter is mighty fussy indeed about just how close to the stoichiometric ideal the ingoing mixture has to be; mixtures that are less than one percent either



1. Ceramic material with catalytically active substances
2. Steel wool retainer
3. Housing

Construction of a three-way catalytic convertor. Convertors are essential to meet current emissions limits, but can only do their job if the air/fuel mixture fed to the engine is held very close to the chemically correct ratio. And to achieve that, a lambda (oxygen) sensor is essential. (Robert Bosch Corporation).

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



Lambda sensors have a voltage output that rises from near zero in the absence of oxygen in the engine exhaust to a bit less than one volt when small traces of it are present. This characteristic enables an electronic fuel injection system to control fuel delivery on the basis of the sensor's reading of the exhaust gas. The sensor only works when hot, however. To reduce the time between engine start-up from cold and the sensor reaching its operating temperature, some versions are electrically heated. (Robert Bosch Corporation).

side of the chemical ideal render the converter next to useless.

No fuel injection system yet developed (and certainly no carburetor!) can hope to control the mixture strength that closely, based simply on a set of values derived from the characteristics of some similar engine in a test lab. The device that enables EFI to "know" just what the mixture strength needs to be at any instant for any particular engine out in the real world is the "lambda sensor."

In construction, the lambda sensor consists of a hollow ceramic bulb, with both inner and outer surfaces covered with a microthin layer of platinum. For protection, the outer surface is surrounded by a shield. This bulb is inserted into the exhaust system so that its exterior surface is washed by the exhaust gas stream, while its hollow interior is exposed to the atmosphere. In operation, the lambda sensor acts like an oxygen-powered battery: a difference in the oxygen level of the gasses surrounding the two surfaces of the sensor causes it to generate a small voltage.

As you might expect, there is very little oxygen in the exhaust of an engine running on a stoichiometric mixture, yet there is some—about 0.5 percent. Surprisingly, even with a mixture that is about five percent rich, there is still about 0.2 percent oxygen. Equally surprising, a mixture that is five percent lean will only contain about one percent oxygen. A particularly useful feature of the lambda sensor is that its output voltage changes very dramatically right around the point of stoichiometry; very small changes (a few tenths of one percent) in oxygen content lead to large changes in the sensor output. While the sensor will put out about 900 millivolts (0.9v)

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

when the exhaust oxygen content corresponds to a lambda of about 1.2 (that is, the mixture is about twenty percent lean—an air/fuel ratio of a bit less than 12:1), and while its output drops to near zero at about lambda=0.8 (an air/fuel ratio of near 18:1), almost all of that voltage change occurs within one percent of stoichiometry. The voltage output of the sensor is fed back to the ECU, which slightly reduces or increases the duration of the on time for the injectors, according to whether the sensor reports the mixture is richer or leaner than stoichiometric. This "closed-loop" control maintains the air/fuel ratio within 0.1 percent of the chemical ideal, thus allowing the converter to do its job.

In practice, an output from the sensor of 450mv is used by the ECU as the threshold of the lean limit and 500mv as the rich limit. This means that the air/fuel ratio actually oscillates back and forth (though always within 0.1 percent of stoichiometry) as the ECU responds to the voltage signal from the sensor. The time required for the sensor output voltage to vary between these limits depends on its temperature. At idle, when the gas temperatures are low—say 300° C (about 570° F)—that time interval might be as much as a couple of seconds; under typical road loads, the exhaust temperature is more like 600° C (1100° F), and the "cycle time" is reduced to less than 50 milliseconds (1/20 second).

The sensor is essentially inoperative at temperatures below 300° C, so during engine startup and initial warm-up the ECU ignores the sensor voltage and falls back on a set of internal "maps," until such time as the signals it is getting from the sensor make sense. Accordingly, emissions are inevitably increased during this warm-up period, so to reduce the wait for the sensor to reach operating temperature, some sensors have an internal heating element to bring it on-line as quickly as possible.

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

Numbers" in Chapter 1), the test procedures for establishing the anti-knock properties of aviation gasolines vary not compression ratio, but inlet air pressure, in reflection of the fact that the tests were specifically developed for highly supercharged aircraft engines. The tests are also conducted at a higher rpm.

Two numbers fall out from this test: a lower number at a lean air/fuel ratio and a higher one established with a very rich mixture (a supercharged aircraft engine at take-off power setting is running as much as 60 percent richer than stoichiometric!). The two numbers are separated by a slash, e.g. 100/130.

The most humble grade of Avgas is labelled 80/87, and is colored red. In terms of octane rating—whether Research, Motor, or "pump" numbers—this would certainly rate lower than even pump regular unleaded. It is intended for the few remaining ancient aircraft engines of 6:1 or 7:1 compression ratio, and thus is extremely rare; it is entirely unsuitable for any automotive use, anyway.

By far the most common type of Avgas is designated 100LL—100 low-lead. This replaces 100/130, which had a high lead content and was colored green. Tested by the Motor and Research methods, 100LL (blue) Avgas rates at about 100 octane on both scales. Finally, and scarcely worth mentioning, is (or perhaps more correctly was) purple colored 115/145—it is essentially unavailable unless you happen to be the US Air Force.

Low-lead does not mean no lead, so 100LL Avgas cannot be used in a vehicle that depends on a catalytic converter. For race-only use, Avgas is a feasible alternative to purpose-specific racing gasoline. It is arguably easier on plastics and elastomers (synthetic rubbers and rubber-like materials) than racing gasolines containing a high proportion of aromatics, and being free of oxygenates, should require almost no change of overall air/fuel ratios compared to ordinary pump gas.

Methanol and Methanol/Gasoline Blends

The first racing use of methanol was in the 1920s, and it is still preferred by many racers for its cool-running, engine-friendly qualities, plus its ability to substantially increase power and torque. Methanol shows an octane rating of way over 100, which permits much higher compression ratios, and so more power.

Alcohol's cooling properties are also a source of increased power. Methanol takes much more heat to evaporate than gas (473 BTU/lb vs. 130–140 BTU/lb) and you can multiply that difference by two or more, since it takes twice as much alcohol as gas to make a chemically correct mixture with air, and it ignites even when it is 40% richer than that. All told, that makes for a sizeable refrigeration effect, and so a denser charge in the cylinder.

Unfortunately, methanol is somewhat corrosive to many metals, and severely degrades various plastics and elastomers. According to Bill Roth, who was involved in the development of the original D-Jetronic system, no Bosch system, indeed "no fuel injection system is resistant to methanol," over the long term, although he acknowledges that short term exposure is probably OK.

To take full advantage of the internal cooling properties of alky, methanol burners may consume nearly three times as much fuel as comparable gasoline-fuelled racers. This thirst can be a problem: the added weight of the alky may hinder performance and/or demand more time spent in the pits for refuelling. In some cases it may even be worth sacrificing some power to save on weight or pit-stops.

In the '30s, for instance, methanol/benzene/gasoline blends were popular for use in Offy engines racing at Indy. Likewise, until a gasoline-only rule was implemented in 1957, Formula One teams favored alcohol-

PAGE 25 of 28 HMC EXHIBIT 1006

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

based fuels, yet few if any of them ever ran methanol straight—all the blends used by the top teams also included a significant amount of gasoline.

There is reason to believe that the gas was not in there purely to reduce the fuel load. In some engines, a gasoline/methanol blend may provide more power than methanol alone. For example, on straight meth the 1954 Maserati Formula One motor delivered about 230 bhp, not bad for 154 unsupercharged cubic inches, nearly 50 years ago. But when the alcohol was cut with gasoline, benzol and acetone, the power rose to 242 bhp.

Problems With Blends

Given the problems of arranging to double or triple the fuel handling capacity of an EFI system, this notion of using a methanol/gasoline blend seems worth consideration. Mixtures of gasoline and methanol, however, are tougher on certain rubber and plastic fuel system components than either the gas or the alcohol alone. In certain proportions, a gasoline/methanol mix has a mighty appetite for magnesium, and the presence of other fuel components—even small amounts of lubricating oil or minor impurities in the methanol, and especially added aromatics—can have further serious solvent and corrosion effects.

There are other problems with blending gasoline and methanol. For one thing, while a little bit of water in straight methanol may actually help performance, even a small amount of water will cause a mixture of methanol and gas to separate into two parts, with the gas floating on top of the alky. Even if the alcohol is completely anhydrous (dry) when you buy it, it has the nasty habit of soaking up water from the atmosphere, so most people who run methanol or methanol/gas blends have learned to use tightly sealed containers, and to tape over tank vents whenever the race vehicle is not running. And because methanol does not have the slight lubricating properties of gasoline, don't forget to add a dash of alcohol-soluble oil to the race fuel, to keep the valve stems and cylinder walls happy.

Co-Solvents—There are certain blending agents that help prevent this tendency of gas/alky mixtures to separate. Among them are other alcohols like isopropanol (IPA) and tertiary butyl alcohol (TBA). IPA and TBA are readily available, and since they are both alcohols, they may be legal as blending agents under some racing rules. Unfortunately, they are only marginally effective as co-solvents for gas/alky mixtures.

Aromatics—Other, more effective co-solvents include the aromatic hydrocarbons like benzene, toluene, and xylene. Benzene is a pretty decent fuel itself, but it was a large part of the mix in some older fuel blends largely because of its effectiveness at co-dissolving methanol and gasoline when there is some water present. Benzene has since been found to cause cancer, so it is difficult to buy, especially in drum quantities.

The dangers of benzene and the relative ineffectiveness of IPA and TBA brings us back to toluene, xylene, and a few other aromatic hydrocarbons as gas/methanol/water blending agents. Toluene and xylene are also readily available, but these are powerful solvents—they will eat certain fuel system components.

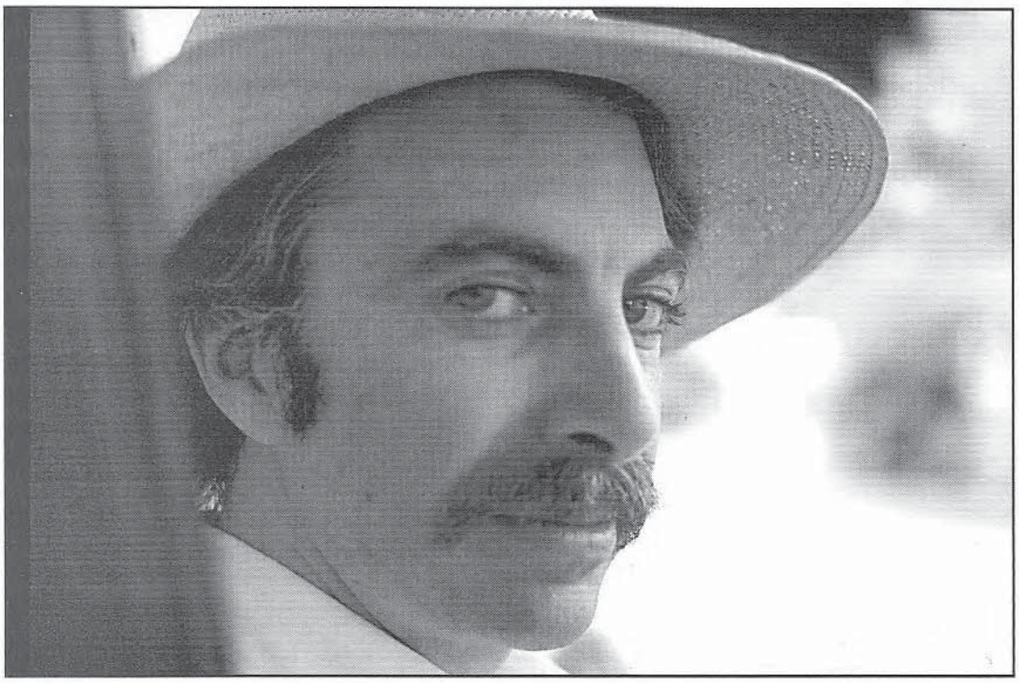
What can be said for certain here is that Bosch-based EFI systems have been used successfully to deliver methanol and gasoline/methanol blends, but that component life is shortened. Further, to achieve even modest survivability, the system has to be purged completely after each race weekend. After draining the tank, the engine is then run until it stalls from lack of fuel, then the system flushed through with straight gasoline, to remove all traces of the methanol.

PAGE 26 of 28 HMC EXHIBIT 1006

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US PATENT NO. 6,557,540

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About the Author



Born in Britain, Forbes Aird moved to Canada at the age of nine. He is gradually getting used to the climate. For several years, Forbes's career alternated between administrative/research work in various academic institutions, and self-employment—which included several years operating a small specialty reinforced plastics shop, and a financially doomed attempt to build a limited production sports car using RP stressed skin construction.

First published in 1965, he began writing full time in 1986. Despite strong evidence to the contrary, he retains the conviction that he can make a living in this way. Over 100 of his automotive, aeronautical, and science articles have appeared in more than a dozen different magazines in Canada and the U.S. In 1991 he received a Science Journalism Award from The Canadian Science Writers' Association; in 1992 the International Motor Press Association bestowed on him the prestigious Ken Purdy Award. Forbes is the author of eleven books, including HPBooks' *Fiberglass and Other Composite Materials*, *High Performance Hardware,* and *Aerodynamics for Racing and Performance Cars*.

Forbes works and lives in Toronto with his wife, Kate. When not slaving over a hot keyboard, he spends much of his time cooking Thai and Indian curries.

PAGE 28 of 28

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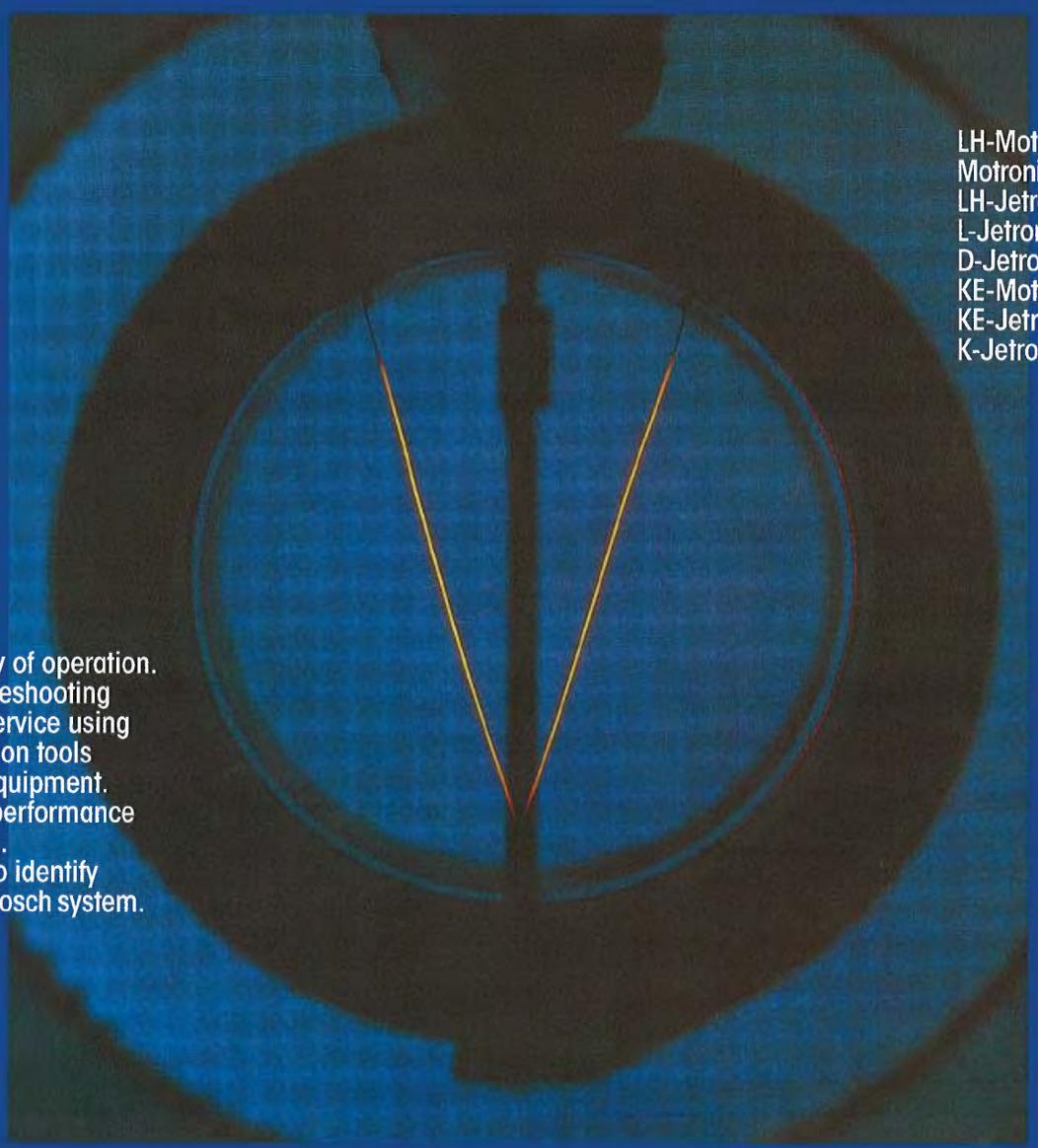
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By Charles O. Probst, SAE

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Motronic
LH-Jetronic
L-Jetronic
D-Jetronic
KE-Motronic
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Bosch Fuel Injection & Engine Management

Theory of operation
Troubleshooting and service using common tools and equipment
High performance tuning
How to identify your Bosch system

by Charles O. Probst, SAE

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Back Cover: clockwise from top: *Audi 90 Quattro* IMSA-GTO race cars at Road America. Courtesy Audi Motorsport. *Volvo 740 GL Wagon* in SCCA Escort Endurance showroom stock competition at Sears Point. Courtesy Volvo Cars of North America. *BMW M3* Group "A" competition engine. Courtesy BMW of North America, Inc. *Porsche 911 Cabriolet.* Courtesy Porsche Cars of North America. Photograph reprinted with permission of Dr. Ing. h.c.F. Porsche AG. Porsche, the Porsche Crest, Carrera and Targa are registered trademarks of Dr. Ing. h.c.F. Porsche AG. *Volkswagen Golf GL.* Courtesy Volkswagen United States. Inc.

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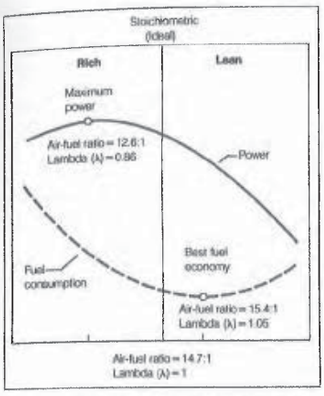
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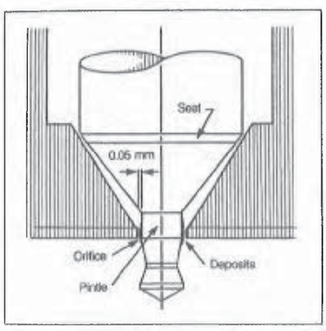
Bosch Fuel Injection & Engine Management

How to Understand, Service, and Modify

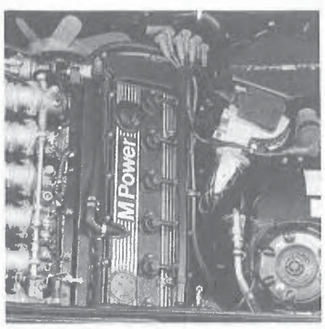
Table of Contents



Understanding the stoichiometric "ideal" air-fuel ratio—Chapter 2



Checking and servicing pulse system injectors—Chapter 4



When to modify fuel injection, and when to leave it alone—Chapter 7

1 Bosch Fuel Injection—An Overview 1

Introduction to fuel Injection and engine management • Air-fuel mixtures • Fuel delivery • Carburetors vs. fuel Injection • Types of Bosch fuel injection • What is engine management? • The Bosch Jetronic family • Listing of cars equipped with Bosch systems covered in this book

2 Engine Management Fundamentals 2

Basic factors: Air-fuel mixture, stoichiometric ratio, Lambda • Operating conditions and driveability: Warm and cold start-up, warm-up, cruising and accelerating • Effects of altitude and other external factors • Emission controls: EGR, AIR, catalytic converters • Control systems

3 Pulsed Injection—Theory 3

Pulsed injection identification and applications • L-Jetronic: Design and operation, componentry, circuitry • LH-Jetronic: Design and operation, system signals, stabilization and adjustment • Motronic: Data mapping, "Drive-by-wire" electronic throttle • D-Jetronic • Digifant II

4 Pulsed Injection—Troubleshooting & Service 4

Troubleshooting the system • Checking the fuel delivery system from tank to injector tip • Testing during starting and warm-up • Air-flow measurement: Air-flow sensor, air-mass sensor, throttle switches • Idle speed testing and adjustment • Idle mixture (CO) and Lambda control • Motronic timing and dwell

5 Continuous Injection—Theory 5

CIS identification and applications • Air-flow system: Control plunger; backfire protection • Fuel system: Accumulation and distribution, regulating system pressure • Fuel metering: governing differential pressure • Control systems: pressure drop • Functions and compensations • KE3-Jetronic and KE-Motronic

6 Continuous Injection—Troubleshooting & Service 6

Troubleshooting the system • Air-flow measurement • Checking the fuel delivery system • K-basic, K-Lambda and KE-Jetronic control systems: Checking fuel, system, lower-chamber and residual pressure, pressure-actuator current • Reading fault codes • Idle RPM and mixture (CO)

7 Tuning for Performance and Economy 7

Legal issues • High performance with driveability • Injection system improvements and tricks • Street and track performance systems

8 Appendix 8

SAE and Bosch terminology • Pressure conversion table

9 Glossary 9

Clear and concise definitions of terms used in this book

10 Index 10

Comprehensive alphabetical guide to this book

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About the Author



Charles O. Probst received his BSE (ME—Automotive) from the University of Michigan. His career specialty was technical communication, primarily in automotive subjects. He worked as an instructional-system designer, writer and filmmaker, and was responsible for numerous video and film productions, manuals, job guides, and other systems for improving human performance.

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He was active in the SAE as Chairman of the Technician Training Task Force, which is responsible for SAE Recommended Practices for technician-training systems.

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Charles O. Probst died in September 2000 at the age of 82.

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Please read these warnings and cautions before proceeding with maintenance and repair work.

WARNING—

- Some repairs may be beyond your capability. If you lack the skills, tools and equipment, or a suitable workplace for any procedure described in this manual, we suggest you leave such repairs to an authorized dealer service department, or other qualified shop.
- Manufacturers are constantly improving their cars. Sometimes these changes, both in parts and specifications, are made applicable to earlier models. Therefore, before starting any major jobs or repairs to components on which passenger safety may depend, consult your authorized dealer about Technical Bulletins that may have been issued since the editorial closing of this book.
- Do not re-use any fasteners that are worn or deformed in normal use. Many fasteners are designed to be used only once and become unreliable and may fail when used a second time. This includes, but is not limited to, nuts, bolts, washers, self-locking nuts or bolts, circlips and cotter pins. Always replace these fasteners with new parts.
- Never work under a lifted car unless it is solidly supported on stands designed for the purpose. Do not support a car on cinder blocks, hollow tiles or other props that may crumble under continuous load. Never work under a car that is supported solely by a jack. Never work under the car while the engine is running.
- If you are going to work under a car on the ground, make sure that the ground is level. Block the wheels to keep the car from rolling. Disconnect the battery negative (–) terminal (ground strap) to prevent others from starting the car while you are under it.
- Never run the engine unless the work area is well ventilated. Carbon monoxide kills.
- Finger rings, bracelets and other jewelry should be removed so that they cannot cause electrical shorts, get caught in running machinery, or be crushed by heavy parts.
- Tie long hair behind your head. Do not wear a necktie, a scarf, loose clothing, or a necklace when you work near machine tools or running engines. If your hair, clothing, or jewelry were to get caught in the machinery, severe injury could result.
- Do not attempt to work on your car if you do not feel well. You increase the danger of injury to yourself and others if you are tired, upset or have taken medication or any other substance that may keep you from being fully alert.
- Illuminate your work area adequately but safely. Use a portable safety light for working inside or under the car. Make sure the bulb is enclosed by a wire cage. The hot filament of an accidentally broken bulb can ignite spilled fuel or oil.
- Catch draining fuel, oil, or brake fluid in suitable containers. Do not use food or beverage containers that might mislead someone into drinking from them. Store flammable fluids away from fire hazards. Wipe up spills at once, but do not store the oily rags, which can ignite and burn spontaneously.
- Always observe good workshop practices. Wear goggles when you operate machine tools or work with battery acid. Gloves or other protective clothing should be worn whenever the job requires working with harmful substances.
- Disconnect the battery negative (–) terminal (ground strap) whenever you work on the fuel system or the electrical system. Do not smoke or work near heaters or other fire hazards. Keep an approved fire extinguisher handy.
- Batteries give off explosive hydrogen gas during charging. Keep sparks, lighted matches and open flame away from the top of the battery. If hydrogen gas escaping from the cap vents is ignited, it will ignite gas trapped in the cells and cause the battery to explode.
- Connect and disconnect battery cables, jumper cables or a battery charger only with the ignition switched off, to prevent sparks. Do not disconnect the battery while the engine is running.
- Do not quick-charge the battery (for boost starting) for longer than one minute. Wait at least one minute before boosting the battery a second time.
- Do not allow battery charging voltage to exceed 16.5 volts. If the battery begins producing gas or boiling violently, reduce the charging rate. Boosting a sulfated battery at a high charging rate can cause an explosion.
- Some cars covered by this book may be equipped with a supplemental restraint system (SRS) that automatically deploys an airbag in the event of a frontal impact. The airbag is inflated by an explosive device. Handled improperly or without adequate safeguards, it can be accidently activated and cause serious injury.
- Greases, lubricants and other automotive chemicals contain toxic substances, many of which are absorbed directly through the skin. Read manufacturer's instructions and warnings carefully. Use hand and eye protection. Avoid direct skin contact.

CAUTION—

- If you lack the skills, tools and equipment, or a suitable workshop for any procedure described in this manual, we suggest you leave such repairs to an authorized dealer or other qualified shop.
- Manufacturers offer extensive warranties, especially on components of fuel delivery and emission control systems. Therefore, before deciding to repair a car that may still be covered wholly or in part by any warranties issued by the manufacturers, consult your authorized dealer. You may find that he can make the repair for free, or at minimal cost.
- Part numbers listed in this manual are for identification purposes only, not for ordering. Always check with your authorized dealer to verify part numbers and availability before beginning service work that may require new parts.
- Before starting a job, make certain that you have all the necessary tools and parts on hand. Read all the instructions thoroughly, do not attempt shortcuts. Use tools appropriate to the work and use only replacement parts meeting manufacturer specifications. Makeshift tools, parts and procedures will not make good repairs.
- Use pneumatic and electric tools only to loosen threaded parts and fasteners. Never use these tools to tighten fasteners, especially on light alloy parts. Always use a torque wrench to tighten fasteners to the tightening torque specification listed.
- Be mindful of the environment and ecology. Before you drain the crankcase, find out the proper way to dispose of the oil. Do not pour oil onto the ground, down a drain, or into a stream, pond or lake. Consult local ordinances that govern the disposal of wastes.
- On cars equipped with anti-theft radios, make sure you know the correct radio activation code before disconnecting the battery or removing the radio. If the wrong code is entered into the radio when power is restored, that radio may lock up and be rendered inoperable, even if the correct code is then entered.
- Connect and disconnect a battery charger only with the battery charger switched off.
- Do not quick-charge the battery (for boost starting) for longer than one minute. Wait at least one minute before boosting the battery a second time.
- Sealed or "maintenance free" batteries should be slow-charged only, at an amperage rate that is approximately 10% of the battery's ampere-hour (Ah) rating.
- Do not allow battery charging voltage to exceed 16.5 volts. If the battery begins producing gas or boiling violently, reduce the charging rate. Boosting a sulfated battery at a high charging rate can cause an explosion.

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Chapter 2

Engine Management Fundamentals

2

Contents

1. Introduction 3

2. Basic Factors 3
   - 2.1 Air-Fuel Ratios 3
     - The Basic Combustible Mixture 3
     - Rich and Lean Mixtures 4
     - Stoichiometric Ratio 4
     - The Excess Air Factor—Lambda 5
   - 2.2 Driveability and Emission Control 5
     - Fuel Economy - CAFE 6
   - 2.3 Air Flow, Fuel Delivery, and Engine Load 6
   - 2.4 Fuel Pressure 7
   - 2.5 Pressure Measurement 7
     - Gauge Pressure vs. Absolute Pressure vs. Vacuum 8

3. Operating Conditions and Driveability 9
   - 3.1 Normal (Warm) Cruise 10
   - 3.2 Starting 10
     - Cold Start 10
     - Warm Start 11
     - Hot Start 11
     - Ignition Timing and Starting 11
   - 3.3 Post-Start and Warm-Up 12
   - 3.4 Idle 12
     - Cold and Warm-up Idle 12
     - Warm Idle 13
   - 3.5 Acceleration 13
   - 3.6 Deceleration and Coasting 13
   - 3.7 Altitude 14
   - 3.8 Engine Shut-Off 14
   - 3.9 RPM Limitation 14
   - 3.10 Ignition Timing 14

4. Emission Control 15
   - 4.1 Combustion By-Products 15
   - 4.2 Effects of Air-Fuel Ratios on Pollutants 16
   - 4.3 Exhaust Gas Recirculation (EGR) 17
   - 4.4 Exhaust Gas Aftertreatment 17
     - AIR, Air Injection Reaction 17
     - Catalytic Converters 17
     - Three-way Catalytic Converters 17

5. Control Systems 18
   - 5.1 Closed-loop Control Systems 18
     - Lambda Sensor 18
     - Changing Engine Conditions 19

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1. INTRODUCTION

What sets fuel-injection and engine-management systems apart from other fuel delivery systems is their ability to precisely control fuel metering and adjust it in response to changing operating conditions. The key elements in the success of Bosch fuel-injection and engine-management systems are (a) a comprehensive understanding of the engine's varying fuel delivery requirements over a broad range of operating conditions, (b) extensive research into how the factors which influence the engine's fuel needs can be measured and interpreted by control systems and, (c) highly developed methods for controlling fuel metering to optimize overall performance.

In this chapter, I'll review the basic factors governing air-fuel mixture and fuel delivery, I'll describe why various engine operating conditions demand different air-fuel mixtures, and I'll explain how the air-fuel ratio can be manipulated to improve driveability and control exhaust emissions with little sacrifice of power. In chapter 3 and chapter 5, you'll see how Bosch applies these principles to the design and operation of their fuel-injection systems.

2. BASIC FACTORS

First, the basics. We'll take a closer look at air-fuel ratios and the engine's basic demands for a combustible mixture. I'll describe additional factors affecting fuel delivery which are imposed by the demands of the car-buying public, and we'll examine pressure and pressure measurement—a subject that is fundamental to understanding how Bosch fuel-injection systems work.

2.1 Air-Fuel Ratios

An engine's throttle controls the amount of air the engine takes in. The main function of any fuel delivery system is to mix fuel with that incoming air in the proper ratio. Small variations in air-fuel ratio can have dramatic effects on power output, fuel consumption, and exhaust emissions.

The Basic Combustible Mixture

Laws of physics tell us that combustion of any substance requires a sufficient ratio of surface area to mass (small enough particles), and the correct amount of oxygen (in proportion to the amount of fuel). In internal combustion engines these conditions are met by atomizing the fuel into tiny droplets, and by metering fuel in correct proportion to the intake air. In round numbers, approximately 14 parts of air are required to support complete combustion of 1 part of fuel—in other words, an air-fuel ratio of about 14:1.

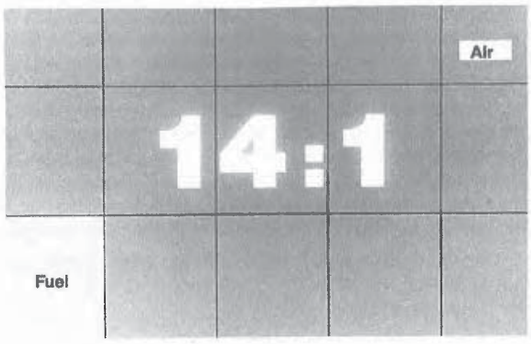


Fig. 2-1. By mass, it takes about 14 parts of air to support complete combustion of 1 part of fuel. Before today's concerns over fuel economy and emissions, an air-fuel ratio somewhere close to 14:1 was good enough.

2

Throughout this book, I'll follow generally accepted practice and discuss air-fuel ratios primarily in terms of mass. This is the simplest and best way to help you understand the basic factors governing fuel delivery and combustion. Many of the Bosch systems, however, measure air flow by volume. It is interesting to see that, by volume, the proportion of air to fuel is approximately 11,500:1.

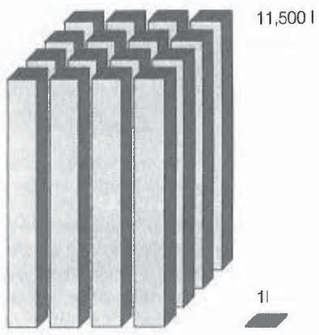


Fig. 2-2. By volume, it takes approximately 11,500 parts of air to support complete combustion of 1 part of fuel.

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Notice that I am talking about combustion that is complete—combustion that makes the best, most thorough use of fuel. Air-fuel ratios which are higher or lower than approximately 14:1 will still burn, but such combustion produces unwanted by-products and other side effects. As you read further into this chapter, you'll see what those are, and why precise control of the air-fuel ratio has become so important.

Rich and Lean Mixtures

The terms "rich" and "lean" are used to describe mixtures which deviate from the theoretically perfect air-fuel ratio and burn less efficiently.

A rich mixture is one with a lower air-fuel ratio; there is insufficient air (oxygen) to support complete combustion of the fuel. Rich mixtures increase fuel consumption and emissions of hydrocarbons (HC) and carbon monoxide (CO)—the products of incompletely burned gasoline. They tend to reduce power, increase carbon deposits and, in the extreme case, foul spark plugs and dilute the engine's lubricating oil.

"Enrichment" is the process of metering more fuel for a given amount of air to produce a richer mixture.



Fig. 2-3. Rich mixtures contain more fuel than can be completely burned in the given amount of air.

A lean mixture is one with a higher air-fuel ratio; there is more air than necessary for complete combustion of the fuel. The fuel will burn completely, but more slowly and at a higher combustion temperature. Lean mixtures reduce power, elevate engine temperature, and increase emissions of oxides of nitrogen (NO_x)—a product of combustion at excessively high temperature. They also tend to cause driveability problems. In the extreme case, the high temperatures resulting from lean combustion will cause pre-ignition—violent, untimed combustion of the mixture which has the potential to cause serious engine damage.



Fig. 2-4. Lean mixtures contain more air than is necessary for combustion of the fuel. Inferior combustion reduces power and can cause engine damage.

Stoichiometric Ratio

When "gas was cheap and the air was dirty," carburetors were usually set up to deliver mixtures richer than 14:1, perhaps with an air-fuel ratio as low as 12:1. As the car aged and a little excess air leaked in around the gaskets of the carburetor or the intake manifold, the engine still got a good combustible mixture. Then, too, the carburetor was farther from the end cylinders than from the middle ones. A richer mixture was some compensation for unequal fuel distribution.

There was another reason for setting up carbureted engines to run a little rich. Air-fuel mixture was less precise, and some variations were to be expected. As shown in Fig. 2-5, variations in a rich mixture have only a small effect on power, while variations in a lean mixture affect power dramatically.

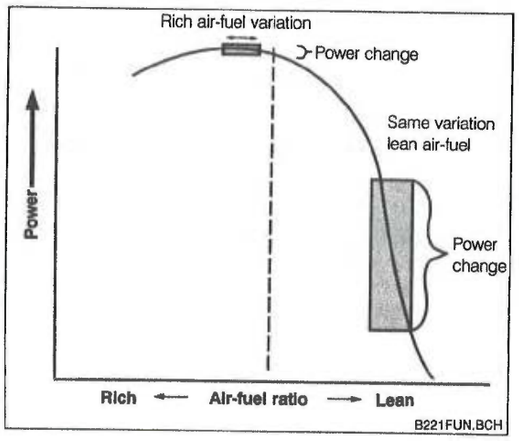


Fig. 2-5. Variation in a rich air-fuel ratio makes much less difference in power than the same variation in a lean air-fuel ratio.

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For today's engines, with the increased emphasis on fuel economy and reduced emissions, the air-fuel ratio has to be controlled much more carefully. The "ideal" air-fuel ratio—the one which yields the most complete combustion and the best compromise between lean and rich mixtures—is 14.7:1. This is called the "stoichiometric" ratio. The mixture is neither rich nor lean.

The Excess Air Factor—Lambda

The stoichiometric ratio can also be described in terms of the air requirements of the engine. Bosch calls this the "excess air factor" and represents it using the Greek letter λ (lambda). At the stoichiometric ratio—when the amount of air equals the amount required for complete combustion of the fuel and there is no excess air—lambda (λ) = 1.

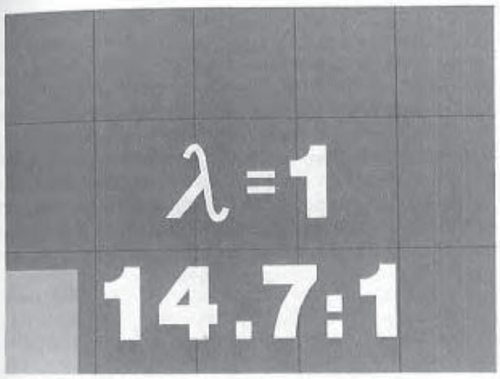


Fig. 2-6. The ideal or "stoichiometric" air-fuel ratio—when there is just enough air to burn all the fuel—is 14.7:1. This is also described as λ (lambda) = 1.

When there is excess air (air-fuel ratio leaner than stoichiometric), lambda is greater than one. When there is a shortage of air (air-fuel ratio richer than stoichiometric), lambda is less than one.

The concept of lambda (the excess air factor) was created specifically to support thinking about fuel delivery in terms of the air requirements of the engine. As you'll see later on, this concept plays a big part in controlling exhaust emissions.

2.2 Driveability and Emission Control

I've described the engine's basic requirement for a combustible mixture of air and fuel, how variations in mixture influence performance, and how older carburetor systems tended to run richer than the ideal air-fuel ratio in the interest of delivering smooth, reliable power.

While power is always a requirement, modern fuel delivery systems face additional demands. Increasing concern over the cost and availability of gasoline has resulted in greater demand for fuel economy. Environmental concerns and resulting legislation demand rigid control of harmful exhaust emissions. And, the car-buying public increasingly demands good driveability—quick-starting and smooth, trouble-free performance under any and all operating conditions. Each of these factors places different demands on the fuel delivery system, and there are trade-offs.

Adjusting the system for maximum power also means increasing fuel consumption. Minimizing fuel consumption means sacrificing power and driveability. Choosing either maximum power or minimum fuel consumption means increased exhaust emissions. The modern fuel delivery system must be able to maintain strict control of air-fuel ratio in order to achieve the best compromise and meet these conflicting demands in the most acceptable way. In general, this means slight sacrifices of power and fuel economy in exchange for optimum emissions control.

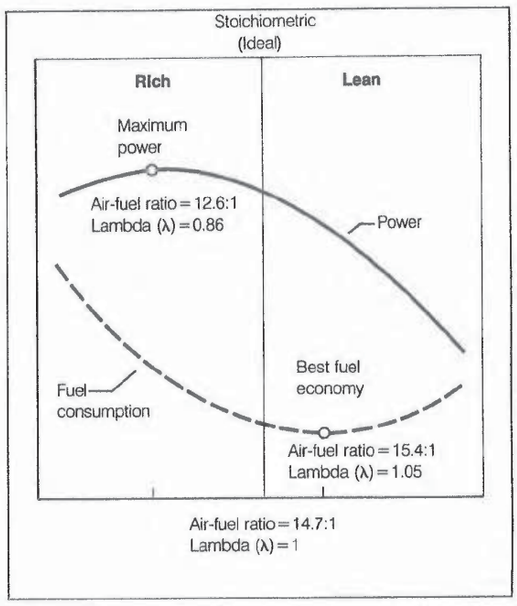


Fig. 2-7. The air-fuel ratio which delivers maximum power is slightly richer than stoichiometric; the one which delivers minimum fuel consumption is slightly more lean than stoichiometric. The stoichiometric ratio is a compromise which sacrifices very little of either.

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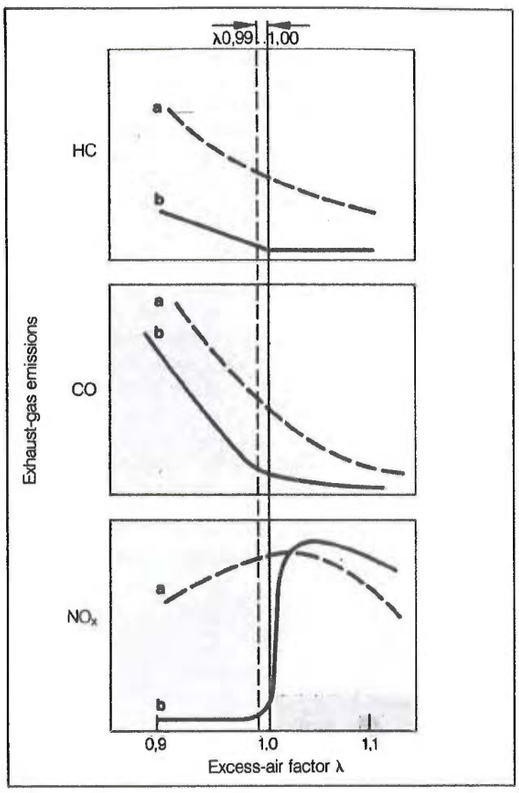


Fig. 2-8. Stoichiometric air-fuel ratio (λ = 1) yields the best compromise for control of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions, before the catalytic converter (a) or after it (b).

It is fuel injection's ability to maintain the air-fuel ratio within close tolerances that makes it superior to carburetor systems. For the manufacturer, fuel-injection means better emission control and better fuel economy, both important in meeting increasingly stringent government regulation. For the owner, fuel-injection means achieving fuel economy and emission control while preserving driveability and maximum power.

Fuel Economy - CAFE

Along with the general demand for fuel economy, each manufacturer must consider another factor: mandated federal standards for rated fuel economy—the Corporate Average Fuel Economy (CAFE) standards. The industry trend in rated miles-per-gallon (mpg) turned upward beginning in 1975, as catalytic converters replaced engine de-tuning as a means of emission control. In addition, government legislation established an average mpg standard to apply to the total fleet of cars each manufacturer delivers each year. Further, the target mpg standard rose each year, starting at 18 mpg in 1978, and rising to 27.5 mpg in 1985, but cut in 1986 to 26 mpg. By 1990 it was back up to 27.5 mpg. Fuel injection's precise control of fuel delivery minimizes fuel consumption while still providing good driveability.

2.3 Air Flow, Fuel Delivery, and Engine Load

You know that air is drawn into the engine with each intake stroke of each piston. The piston moving down on its intake stroke increases cylinder volume and lowers pressure in the cylinder. With the intake valve open, air at higher pressure rushes in from the intake manifold to fill the cylinder. The amount of fuel necessary to create a stoichiometric mixture depends on how much air rushes in.

In simplest terms, intake air flow occurs because normal atmospheric pressure is higher than the pressure in the cylinders. Air rushes in during the intake stroke, trying to equalize the pressure. In gasoline engines, the throttle valve restricts intake air flow. As you open the throttle, the opening to atmospheric pressure raises manifold pressure. So, in practice, the amount of air that rushes into the cylinder on the intake stroke depends on the difference between the pressure in the intake manifold and the lower pressure in the cylinder. Pressure in the intake manifold depends on throttle opening.

The greatest intake air flow occurs when the throttle valve is fully open. The throttle valve causes almost no restriction, and full atmospheric pressure is admitted to the intake manifold. This creates the greatest possible difference between manifold pressure and cylinder pressure, and the greatest intake air flow.

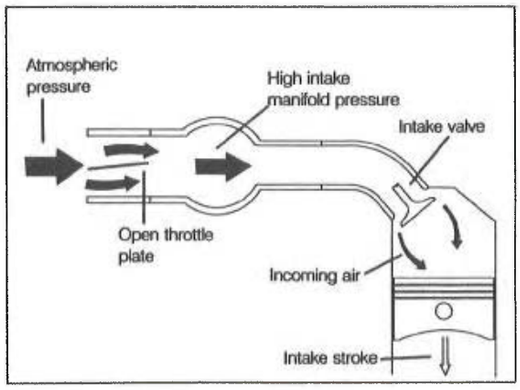


Fig. 2-9. At full throttle, nearly unrestricted atmospheric pressure raises manifold pressure. Large pressure differential between manifold and cylinders increases air flow.

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The least intake air flow occurs when the throttle is nearly closed. The restriction of the throttle valve limits the effect of atmospheric pressure. There is little difference between manifold pressure and the low pressure in the cylinders, and air flow is low.

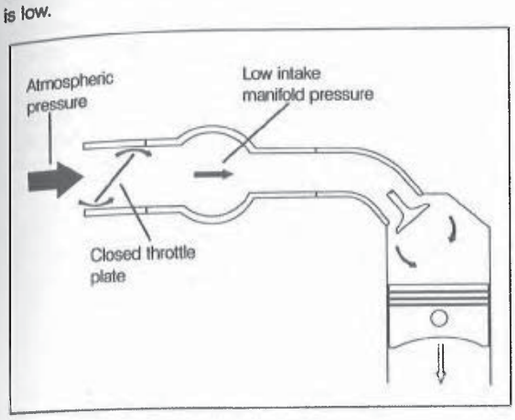


Fig. 2-10. With the throttle closed, atmospheric pressure has little effect on manifold pressure. Low pressure differential between manifold and cylinders results in little air flow.

Fuel delivery requirements depend more than anything else on how much work you are asking the engine to do—on how much of a "load" you are placing on it. To accelerate, you step down harder on the accelerator. This opens the throttle valve, increasing manifold pressure. The greater pressure difference between the manifold and the cylinders increases intake air flow, and therefore fuel flow, to increase power and accelerate the car.

Driving down a level road, you can cruise along comfortably and maintain a desired speed with a relatively small throttle opening. When you come to a hill, it is necessary to press farther down on the accelerator to maintain the same speed, even though engine rpm is unchanged. The hill has demanded more work from the engine—created a higher load—and the engine has demanded more air and fuel to match that load.

Regardless of engine speed, the air flow and fuel delivery demands of the engine depend on the load being placed upon it. That load, and the resulting throttle opening, directly affect manifold pressure. Manifold pressure in turn affects air flow and thus fuel requirements.

2.4 Fuel Pressure

Both carburetors and fuel-injection systems rely on pressure or pressure differential to dispense fuel into the intake air stream. The atomized fuel vaporizes and mixes with the air to produce a combustible mixture.

In a carburetor system, the fuel system supplies fuel to the carburetor float bowl. The bowl is vented, and the fuel in the bowl is at atmospheric pressure. Intake air passing through the carburetor's venturi creates low pressure in the venturi—lower than atmospheric pressure. This pressure differential—between atmospheric pressure in the carburetor bowl and reduced pressure in the venturi chamber—causes fuel to flow from the bowl through the discharge nozzle, and into the intake air stream.

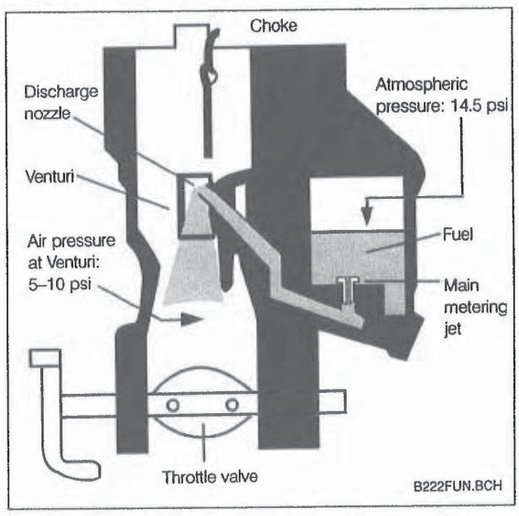


Fig. 2-11. The fuel-metering part of a carburetor operates with small differences in pressure: fuel in the bowl at atmospheric pressure vs. reduced pressure at the discharge nozzle in the venturi.

The pressure differential in the fuel-metering system of a carburetor is usually pretty small—only a few pounds-per-square-inch (psi). In contrast, fuel-injection systems introduce the fuel at higher pressures, anywhere from 30 to 90 psi depending on the system and specific operating conditions. Fuel delivery at these higher pressures ensures that the fuel is better atomized, and it is vaporized more completely in the airstream. Higher fuel pressure also makes possible more precise control of fuel delivery.

2.5 Pressure Measurement

As I get into the specific functional details of each of the various fuel-injection systems, you'll see that many functions and relationships are defined in terms of pressure. They may be fuel pressure values in the fuel system, manifold pressure in the air intake system, or atmospheric pressure. I may be talking about a differential pressure—the difference between two opposing pressure values somewhere in the system.

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In any case, pressure values are always expressed in one or more of the following units or terms. All are correct. With the appropriate conversion factors, all are interchangeable. Fortunately, the math required to convert between the different units is simple.

- **Pounds-per-Square Inch (psi).** The English system unit of pressure defined as force (pounds) divided by area (square inches). Atmospheric pressure at sea level is approximately 14.5 psi.
- **Bar.** A metric term derived from barometer or barometric pressure—atmospheric pressure. One bar is approximately equal to standard atmospheric pressure at sea level, so 1 bar = 14.5 psi. Typical fuel pressure in a pulsed-injection system might be 2.5 bar, or about 36 psi. European manufacturers' specifications and pressure gauges usually refer to pressures in bar.
- **kiloPascal (kPa).** The proper metric unit for pressure. 1 bar = 100 kPa, so atmospheric pressure at sea level is 100kPa. Used mainly in the U.S.
- **Inches of Mercury (in. Hg).** Originally refers to measurement of pressure using a mercury manometer. (Hg is the chemical symbol for mercury). This is a term used to specify manifold vacuum; 29.92 in. Hg is the difference between standard atmospheric pressure at sea level and absolute vacuum.

Table a lists the various units of pressure and appropriate conversion factors.

Table a. Units of Pressure Conversion

Unit	Atmospheric pressure (sea level)	to convert to:			
		psi	bar	kPa	in.Hg
		multiply by:			
psi	14.5	—	0.069	6.9	2.06
bar	1	14.5	—	100	29.92
kPa	100	0.145	0.01	—	0.299
in.Hg	29.92	0.485	0.033	3.34	—

If you watch the local TV weatherperson, you'll see how barometric pressure readings (in. Hg) are used to describe atmospheric pressure changes. Listen to the references to "highs" and "lows". Changing atmospheric pressure changes the density of the air. Denser intake air can slightly alter the air-fuel ratio and may affect how your engine operates. Some Bosch fuel-injection and engine-management systems have features which allow the system to compensate for variations in air density.

Gauge Pressure vs. Absolute Pressure vs. Vacuum

I've described engine intake air flow and load in terms of manifold pressure, and I've discussed the units of measure used to describe pressure. Now it is important that you understand exactly what you are measuring.

For many years, people have traditionally thought about engine air flow and load in terms of vacuum—the "vacuum" created in the intake manifold by the pistons' intake strokes. Using atmospheric pressure as a baseline, as zero, the lower manifold pressure is expressed as a negative value—vacuum.

By the 1980s, the automotive industry had moved away from thinking in terms of vacuum. Widespread use of fuel injection began to demand more accurate measurement of manifold "vacuum", and turbocharging—where manifold pressure may exceed atmospheric pressure—began to blur the distinction between vacuum and pressure. A simpler and more useful approach is to think in terms of manifold absolute pressure (MAP). MAP refers to the pressure in the intake manifold which is positive compared to zero absolute pressure, rather than negative compared to atmospheric pressure.

If that seems hard to understand, think of atmospheric pressure at sea level. We tend to think of this as zero pressure and, in fact, an open fuel-pressure gauge will read 0 at sea level. But remember, atmospheric pressure at sea level is actually 1 bar (14.5 psi). Almost all pressure gauges use atmospheric pressure as their reference. Any measurement made with the gauge reads pressure only with respect to atmospheric pressure. As indicated by Fig. 2-12, a gauge which reads 0 pressure at sea level (atmospheric pressure) is actually measuring 1 bar on the absolute pressure scale.

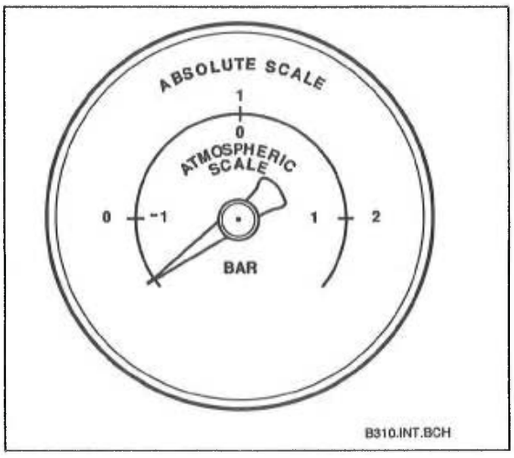


Fig. 2-12. Calibration of pressure gauge influences how you interpret pressure readings.

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Using absolute pressure as the reference point, the piston on its intake stroke is creating a very low pressure in the cylinder—approaching zero absolute pressure. The pressure in the intake manifold—manifold absolute pressure (MAP)—is higher and always a positive number. Higher still is atmospheric pressure outside the engine, its influence on manifold pressure controlled by the throttle. Boost from a turbocharger or supercharger is pressure above atmospheric pressure. Many European boost gauges read MAP. They are calibrated from zero absolute pressure so, with the engine off, the gauge reads 1 bar—normal atmospheric pressure.

I've been driving with a "vacuum" gauge connected to the intake manifold of each of my last 9 cars. The gauge comes calibrated in terms of vacuum, so at wide open throttle (WOT) it reads close to zero. I have also marked my gauges to read MAP, positive manifold pressure relative to absolute pressure at or near sea level. That means that at WOT (near zero vacuum), my gauge reads about 9 on the homemade MAP scale, as shown in Fig. 2-13. I can read it two ways: multiply by 10 to read pressure in kPa (90 kPa), or divide by 10 to read pressure in bar (0.9 bar). The important point is that the numbers increase as the load and power increase. Fig. 2-14 shows approximate range of gauge values for various driving conditions and throttle positions. By coincidence, 65 mph cruise reads about 65 kPa or 0.65 bar.

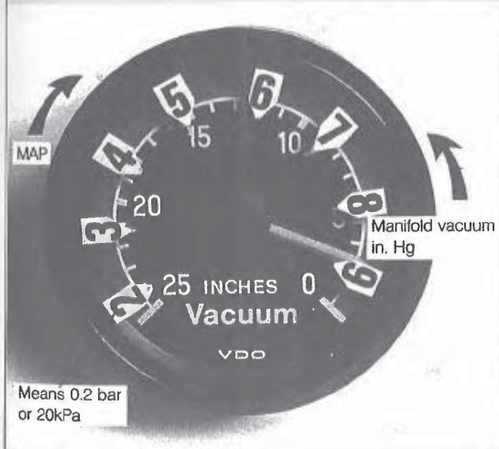


Fig. 2-13. Manifold vacuum gauge calibrated to read vacuum (in. Hg) can also be calibrated to read manifold absolute pressure (MAP). With fuel-injection or forced-induction systems, MAP makes it easier to relate engine load and throttle opening to manifold pressure.

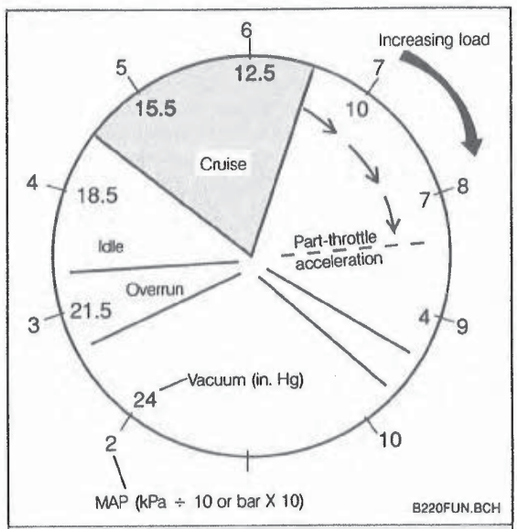


Fig. 2-14. Gauge schematic shows how vacuum and MAP indications relate to throttle opening.

On a turbocharged car, boost will read above 10 (100 kPa) on the MAP scale. MAP changes continuously from about 20kPa during overrun (coasting with closed throttle) to perhaps 160kPa at maximum boost. When we discuss the importance of manifold pressure to fuel injection, you will find it an advantage to think in terms of the positive MAP values (from absolute zero) rather than vacuum.

3. Operating Conditions and Driveability

If I were talking about the requirements of a stationary industrial engine, I'd expect it to operate under basically fixed conditions: constant rpm, constant load, nearly constant temperature, limited stops and starts, no acceleration, and no heavy-footed driver. Such an engine would operate quite nicely at a fixed air-fuel ratio. It could be easily tuned to maximize fuel economy, and would require only the simplest of fuel systems.

Cars, however, are a different story. We expect them to perform under the widest possible variety of operating conditions. And we have given "performance" a new definition it is not only impressive horsepower and torque, but also maximum fuel economy, and controlled exhaust emissions. As if these performance demands were not enough, we also expect the car to meet these demands effortlessly, at any time, under any conditions, and at the turn of a key. We expect what has come to be called "driveability"—the ability of the car to provide smooth, trouble-free performance under virtually any conditions while delivering power, fuel economy, and controlled emissions.

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Driveability is a term which evolved out of the early days of strict emission control and the '70s energy-crisis concerns over fuel economy. The less-developed technology of the time dictated an approach to both problems which often resulted in the engine running too lean. Running too lean robbed power and contributed to rough idle, poor throttle response, stumbling and stalling, and overall poor running. Fuel injection and more complex engine-management systems offer the precise control and flexibility necessary to meet modern performance requirements.

To meet these demands under different operating conditions, the engine has different air-fuel requirements. I'll discuss these operating conditions, the effect they have on basic air-fuel requirements, and how the capabilities of fuel-injection and engine-management systems are used to meet these requirements. I'm describing what these systems in general can do, not necessarily what a basic Jetronic fuel-injection system will do, particularly those systems on cars manufactured before 1982.

3.1 Normal (Warm) Cruise

Normal cruising at light load with the engine fully warmed up is the baseline operating condition. The basic fuel system is designed to meet the engine's need for the proper air-fuel ratio under these simple cruising conditions. The design must be flexible enough to handle fuel delivery at different speeds and loads, but this basic fuel metering is the fuel system's simplest task. Though the driver may add power on a hill or to pass another car, or cut back power to slow down, fuel management is still relatively simple. All other parts of the fuel system which compensate for different operating conditions do so by making adjustments to this main fuel-metering function.

When you are cruising down the interstate, if the road is level the engine is operating under relatively constant normal conditions. The fuel quality may vary from one tank fill to the next; weather and outside temperature may change; it may be dry or it may be damp. The ideal air-fuel ratio will be different for each of these conditions. A fuel-injection system can adjust to these changing conditions with little challenge, maintaining air-fuel delivery near the ideal (stoichiometric) ratio of 14.7:1 to satisfy the most important considerations of fuel economy and low exhaust emissions.

3.2 Starting

As an owner, you expect the engine to start instantly; whether it's at sub-zero temperatures or parked in the desert, too hot to touch; whether it's been sitting for five minutes at the store or for five weeks in the garage.

As far as fuel system requirements are concerned, starting makes different demands depending on temperature. I'll discuss cold start, warm start, and hot start.

Cold Start

This means the engine is cold; that is, it probably hasn't run for at least 12 hours. In most cases, the temperature needle is at the low end of the gauge. The engine might be as cold as −20°F (−30°C), sometimes called cold-cold; or as hot as 115°F (45°C), sometimes called warm-cold. In either case, the engine is still cold compared to its normal operating temperature of about 195°F (90°C).



Fig. 3-1. Engine-cold temperature varies according to outside temperature. Cold start means the engine has not run for several hours.

To understand the distinctions I've made in cold-start temperature, consider the Environmental Protection Agency (EPA) definition of cold start. For EPA testing, cold is room temperature, about 68°F (20°C); all cars are tested on dynamometers inside the lab. The engine must cold-soak at 68°F in the lab next to the dynamometer for 12 hours before the test. Cars are pushed onto the dynamometer for the cold-start test. As it happens, 68°F is close to actual cold start temperatures in Southern California and much of southern U.S. Engine temperature affects the driveability of your engine, which may be much colder than an EPA cold engine. For scientific comparison testing, and for the regulatory aspects of EPA testing for emissions and fuel economy, uniformity is the most important factor.

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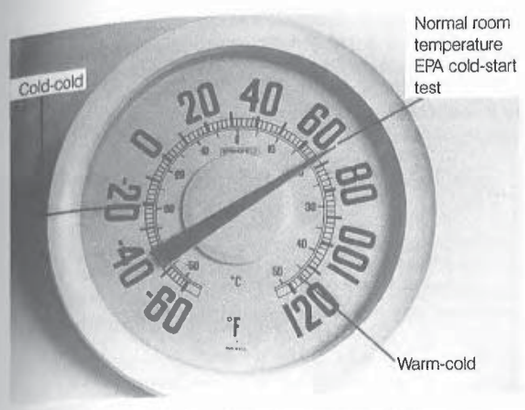


Fig. 3-2. Fuel requirement for engine starting varies according to outside air temperature: cold-cold or warm-cold. These temperatures are both cold compared to normal engine operating temperatures.

In most parts of the country, you will at times be faced with cold-cold starting conditions; the most challenging of all. Gasoline is less likely to vaporize when it is cold. Even if it is adequately vaporized, some fuel condenses on the cold parts of the engine before it can be burned. The engine requires extra fuel for starting so that, in spite of vaporization and condensation problems, the engine still receives a combustible air-fuel mixture.

What constitutes a combustible mixture depends on air temperature, the volatility of the gasoline, altitude, barometric pressure and humidity. While a carburetor relies on a relatively crude choke mechanism to increase fuel delivery for cold starting, fuel injection compensates for many of these factors. Temperature is the most important.

Cold-start enrichment quickly becomes a problem if the engine does not start right away; due to a marginal battery, ignition components in poor condition, or whatever. Enrichment during cranking must be cut back in a matter of seconds; if it goes on too long, the air-fuel mixture will be too rich to ignite. The spark plugs may become fuel-fouled, particularly when they are cold, and the engine will not start.

Cold starting also needs help in terms of intake air flow. A closed throttle and slow cranking speeds do not allow enough air for starting. Drivers of carbureted cars develop intricate starting procedures: depress the accelerator to the floor, release, then hold the throttle about ⅓ open (for example). The first depression is necessary to set the carburetor choke and fast-idle cams; the second is to open the throttle and make sure the engine is getting enough air. Fuel-injection systems can control the air by bypassing the closed throttle, admitting more air when cold without any effort or attention from the driver.

Warm Start

Warm starting is very much like warm running. The air-fuel demands are simple. A warm engine helps promote fuel vaporization, and fuel is much less likely to condense out of the air stream onto warm engine parts

Depending on the temperature, the engine may benefit from some small portion of the usual cold-start compensations. A carbureted car may benefit from a light push on the throttle, using the accelerator pump to deliver a little extra fuel. A fuel-injection system sensing temperature only a little below normal may just slightly enrich the mixture and slightly increase intake air to improve warm starting.

Hot Start

This means the engine is hot; perhaps after being driven for some time on a hot day, and then allowed to sit for a short time, unable to significantly cool. Under these conditions, sometimes called "hot soak" under-hood temperatures may exceed 250°F (120°C).

The most important aspect of hot soak and subsequent hot starting is the possibility of overheating the fuel. For a carbureted engine this may mean boiling the fuel in the fuel bowl and losing it as fuel vapor into the atmosphere. Hot starting becomes more difficult, since it takes time for the fuel system to refill the bowl so that fuel can reach the discharge nozzle.

In any engine, the excess heat may raise fuel temperatures and cause "vapor lock" – vaporized fuel in the lines. Unlike fuel, the resulting vapor in the lines is compressible, so the fuel pump cannot necessarily overcome the problem and deliver fresh fuel. In fuel-injection systems, the number of fuel lines to individual injectors and the routing of lines near the engine makes heat-soak a more acute problem. To ensure quick hot restart, the system must maintain pressure in the fuel lines and the injectors while the engine cools to prevent vapor lock.

Some fuel-injection systems combat the fuel vaporization problem by adding small doses of extra fuel, similar to cold start enrichment. The extra fuel while cranking slowly helps the engine start; then the increased air flow and fuel demands of the running engine can overcome the vapor lock.

Ignition Timing and Starting

For the more sophisticated engine-management systems, adjusting the ignition timing can help start a cold engine. If the engine is turning over a little slowly because of thick, cold oil in the crankcase, or reduced battery voltage at low temperatures, the best ignition timing is near Top Dead Center (TDC). More advanced timing, even as little as 10 degrees before TDC, allows the slow-turning engine to fire while the piston is still rising; the reverse torque may damage the starter.

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On a warm day, ignition timing of a cold engine can be advanced because the engine spins a little faster. But if the temperature were high (hot start), retarded ignition timing can prevent reverse torque and starter damage caused by igniting the air-fuel mixture before the piston reaches TDC. Also, the engine may knock during starting if intake air temperature is too high. In short, it is desirable to retard ignition timing for conditions of low cranking speed, and on the basis of high intake-air temperature. More advanced ignition timing is permissible under less challenging, warm starting conditions.

3.3 Post-Start and Warm-Up

Post-start refers to the period immediately after the engine fires. The engine requires less enrichment than for starting, but it is still cold. Some enrichment is required to compensate for poor fuel vaporization and for condensation; and to improve torque and throttle response, even though acceleration at this point might not be good driving practice. Engine torque must be sufficient to carry the load of a cold automatic transmission shifted from Neutral to Drive; many cold engines have a tendency to stall when so shifted.

The amount of post-start enrichment required depends on temperature and time; a colder engine requires more enrichment for a longer period of time. On the other hand, exhaust emission control demands that enrichment be cut back properly. An engine can fail its EPA emission test in the first thirty seconds after "cold" start if the post-start enrichment causes excessive exhaust emissions.

Post-start ignition timing can be advanced to improve the engine running and incidentally to reduce the requirement for enrichment during this period. Post-start can end in a few seconds or may last as long as fifteen or twenty seconds if the temperature is extremely cold. But, strangely, ignition retard can be used to heat the exhaust, and therefore the lambda sensor and catalytic converter, which work as intended only at high temperatures. That means emission control can be effective quickly after a start.

Warm-up refers to that period when the engine is in transition from its cold, post-start temperature, to its normal operating temperature. As the engine begins to warm up, it begins to require less and less enrichment. Since warm-up is a smooth, gradual process, the reduction of enrichment needs to be gradual too. If the engine is really cold, warm-up can last for several minutes. Since the car is probably being driven during the warm-up period, enrichment which is appropriate for the conditions at any given time is essential to ensure driveability.

On a carbureted engine, the choke mechanism is sensitive to temperature. As the engine warms the choke warms, gradually reducing warm-up enrichment. Fuel-injection and engine-management systems also use temperature as the main input for control of warm-up enrichment. Engine coolant temperature is the most common input. Some systems also respond to changes in intake air temperature.

For systems that have the capability to control ignition timing, advancing the timing during warm-up under part-throttle load can aid driveability. Retarding timing during warm-up under closed-throttle deceleration will reduce hydrocarbon (HC) emissions which risk being excessive anyway due to the warm-up enrichment.

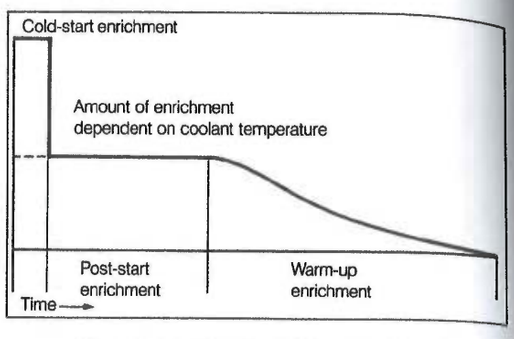


Fig. 3-3. Until the engine is fully warm, various degrees of enrichment are required. Starting requires maximum enrichment, depending on engine temperature. Post-start enrichment keeps the engine running for the first 30 seconds or so. Warm-up enrichment slowly drops off as the engine warms to normal operating temperature.

3.4 Idle

Our cars spend a lot of time idling, so a smooth idle and good off-idle throttle response are important aspects of driveability. First, there are some unique requirements for idle control during post-start and warm-up. Once the engine is warm, there are other factors which influence idle speed, and fuel injection's capabilities make possible improved idle characteristics.

Cold and Warm-up Idle

As I've already suggested under **3.2 Starting**, a cold engine has different air-fuel requirements than a warm engine. At idle, more air and more fuel are needed just to overcome the higher running friction of a cold-engine. A slightly higher idle speed is necessary to keep the cold engine from stalling, and to support good off-idle throttle response.

Fuel-injection systems, using both temperature inputs and direct rpm input, can precisely control idle speed by controlling intake air flow. With this precise control, cold idle is higher, but driveability is maintained. One of the joys of driving cars with fuel-injected engines is the freedom from a too-fast idle that can jar the car when an automatic transmission is shifted into Drive or Reverse.

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Warm Idle

The main requirements of a warm engine running at idle speed are smoothness, and smooth response once the throttle is opened. Some engines require a richer mixture at idle for smooth running, and to ensure good off-idle response. With ignition timing control capability, it is also possible to operate with a leaner mixture and achieve a smooth idle by changing ignition timing.

In general, the engine should idle at the lowest speed at which the engine will still run smoothly enough to satisfy the driver. Reducing idle speed to a minimum reduces noise and fuel consumption.

The biggest obstacle to low idle speeds is the variation in load on the engine at idle. At idle, small changes have big consequences. Friction loads change with temperature; the power required to operate the charging system varies with electrical load (headlights, for example); air conditioning compressors switch on and off; on cars with automatic transmissions, shifting into Drive or Reverse at idle increases the load.

Fuel injection's capabilities include idle stabilization (also called idle-speed control). By monitoring and constantly correcting idle speed, it is not necessary to maintain a higher-than-minimum idle to handle variations in engine performance, changing of loads, and similar causes of stalling from idle.

Advanced idle-speed stabilization systems satisfy some sophisticated requirements, particularly on cars with air conditioning (A/C) and automatic transmission:

1. In Neutral, A/C off: maintains the minimum idle speed that is required for engine smoothness

2. In Neutral, A/C on:
   - for small compressors, increases idle speed to run the compressor faster (increase A/C performance)
   - for large compressors, maintains idle speed by compensating for added compressor load
   - through A/C relay, delays compressor-clutch engagement for ½ second to prevent temporary rpm drop

3. In Drive:
   - for smooth-idling engines, reduces idle speed to minimize stoplight creep
   - for rough-idling engines, increases idle speed to minimize idle/load-induced vibration

4. In Drive, when A/C switches on: controls idle speed increase to avoid inadvertent surge when driver does not expect it

3.5 Acceleration

Any time you press the accelerator, opening the throttle increases manifold pressure which in turn increases intake air flow. The fuel system, responding to this increase in air flow, meters additional fuel to maintain the correct air-fuel mixture.

Accelerating—opening the throttle very quickly—places additional demands on the system. The sudden transition from closed throttle to open throttle produces sudden spikes in manifold pressure. The fuel system responds quickly to these changes, but not instantly. Some additional fuel delivery capability is required to compensate for these changes in manifold pressure—to prevent stalling and produce the quick throttle response we have come to expect and demand.

For quick, smooth throttle response under acceleration, the basic system of air flow sensing and fuel metering is too slow. The fuel system must be able to instantly compensate for rapid increases in manifold pressure with additional fuel. In many carburetors, additional fuel is supplied by the accelerator pump. It mechanically squirts additional fuel into the intake air stream whenever the throttle is opened suddenly. As you will see in later chapters, fuel-injection systems employ various methods of acceleration enrichment.

In **2. Basic Factors** I explained that fuel injection systems are designed to maintain the air-fuel ratio in the narrow range around stoichiometric, but that maximum power output is achieved with an air-fuel ratio that is slightly richer. In addition, the engine may need a richer mixture to reduce the tendency to knock. Many fuel-injection systems recognize full-throttle acceleration as a special case, and provide additional acceleration enrichment keyed to the full-open throttle position.

During acceleration, systems which can control ignition timing can deliver the best balance between advanced timing for maximum torque, and retarded timing for knock control.

3.6 Deceleration and Coasting

In the quest for minimum fuel consumption, engineers are quick to take advantage of opportunities to reduce fuel waste. One such opportunity is coasting cut-off, also known as overrun or deceleration cut-off.

The basic idea of deceleration fuel cut-off is this: the engine takes in some air and the fuel system delivers some fuel even when the throttle is completely closed (at idle, for example). On the road, when the car is decelerating or coasting with the throttle closed, this fuel is wasted. It is passing through the engine and being expended, but doing no useful work. Cutting off fuel during these conditions can save fuel, even in city driving. It also reduces exhaust emissions. To prevent stalling, fuel flow must be re-established at some programmed engine speed (above idle).

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Fuel cut-off behavior may be less satisfactory when the engine is cold, so normally the rpm limits for cut-off and for re-establishing fuel injection are higher for a cold engine. Coasting cut-off must also be restricted so it will not operate during shifting of manual transmissions, and so it will not interfere with cruise control.

Engine-management systems which can control ignition timing can retard the timing during the transition to smooth the response to the cut-off and resumption of fuel injection.

> Deceleration fuel cut-off was a feature of the early D-Jetronic systems supplied on some Volkswagens, but the air-cooled engine cooled irregularly during the cut-off so emissions were actually increased; the feature was discontinued.
>
> Water-cooled engines equipped with Jetronic systems have greater temperature stability, and can use deceleration cut-off successfully to save fuel and reduce emissions. Fuel cut-off is less successful in carbureted engines and those with throttle-body injection because the fuel is delivered so far from the cylinders. As fuel flow is resumed, the lag between restoring fuel delivery and resuming combustion spoils driveability with jerky response.

3.7 Altitude

At altitudes above sea level, the air is less dense; for a given volume of air, there is less oxygen to support combustion of fuel. In carburetors, and in fuel-injection systems which measure intake air by volume, less dense air changes the effective air-fuel ratio; at higher altitude, the mixture is richer.

Some fuel-injection systems can measure and respond to changes in air density, changing the air-fuel ratio as required to maintain the ideal (stoichiometric) ratio.

3.8 Engine Shut-Off

Engine shut-off is another chance to prevent wasting fuel. Carburetors dispense fuel into the intake air stream as long as the engine is turning over, whether or not the ignition is on. In contrast, turning off the ignition of a fuel-injected car also cuts power to the electric fuel pump. Fuel flow is immediately cut-off to prevent dieseling, or run-on.

3.9 RPM Limitation

Precise control of fuel delivery allows the fuel system to be used to limit engine rpm and prevent damage from over-revving. Before the days of catalytic converters, rpm was limited by simply cutting out the ignition when the rpm got too high. Cutting the ignition, however, still allows unburned fuel into the catalytic converter and causes it to overheat; sometimes dangerously. Since the mid-1970s and the advent of catalytic converters, rpm limitation has been accomplished by the fuel-injection system cutting back on fuel delivery. The goal is to keep the engine running at its limitation without dumping unburned fuel into the catalytic converter.

3.10 Ignition Timing

For some of the specific operating conditions described above, I've described how ignition timing adjustments can be used to enhance performance and satisfy driveability requirements.

In terms of all four major aspects of performance—power, fuel economy, emission control, and driveability—ignition timing is a significant factor; perhaps as significant as air-fuel mixture. Combustion in the cylinders takes a certain amount of time. In terms of how we usually think about time, combustion is very rapid, but it is not instantaneous.

As the piston is compressing the mixture on the compression stroke, the exact point at which the spark plug fires to ignite the mixture—ignition timing—has profound effects on the quality of combustion and the amount of power that is produced. Because of its influence on the combustion process, ignition timing also affects combustion temperature which can also significantly affect exhaust emissions.

Modern fuel-injection systems have evolved into engine-management systems—systems which manage much more than fuel delivery. Chief among the extra capabilities of an engine-management system is simultaneous control of ignition timing and fuel delivery. Controlling both factors opens up new possibilities for power and driveability improvements while maintaining tight control of exhaust emissions and fuel economy.

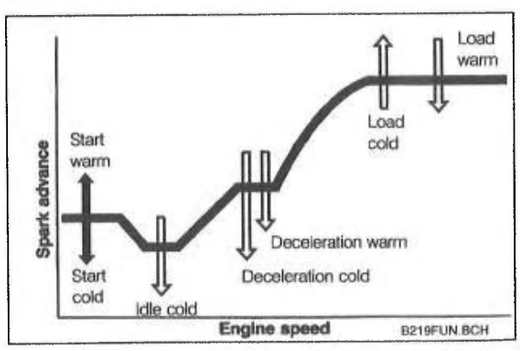


Fig. 3-4. Typical ignition timing advance curve can be modified for best performance, from starting to acceleration.

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4. Emission Control

It is practically impossible to separate the development of today's fuel-injection and engine-management systems from the increasing demand for control of harmful exhaust emissions. Exhaust emission control could not have been accomplished as successfully without fuel injection and, likewise, fuel injection may not have been so successful and widely used were it not for the challenges of meeting emission control regulations.

With changing legislation and tougher regulatory standards, fuel-injection systems have undergone significant changes so that engines can meet the emission standards while providing the driveability demanded by owners. The superiority of these systems is also demonstrated by the fact that, even as U.S. fuel economy standards have tightened, fuel injection has added both economy and power to smaller engines.

It is interesting to note that many fuel-injected cars are able to eliminate some types of emission control that interfere with driveability on carbureted cars, including exhaust gas recirculation (EGR) and air pumps. If you know something about emissions and the limits placed on them by legislation, you'll understand more about how fuel-injection and engine-management systems work.

4.1 Combustion By-Products

Combustion of the air-fuel mixture in the engine cylinders creates gaseous by-products which make up the exhaust. Some of these are harmless, and some are known to be harmful. Three gases: hydrocarbons (HC); carbon monoxide (CO); and oxides of nitrogen (NO_x) are the most harmful ones. Emission of these gases in vehicle exhaust is regulated by the Federal Clean Air Act. The same gases are often subjected to tighter limits by state regulation in California.

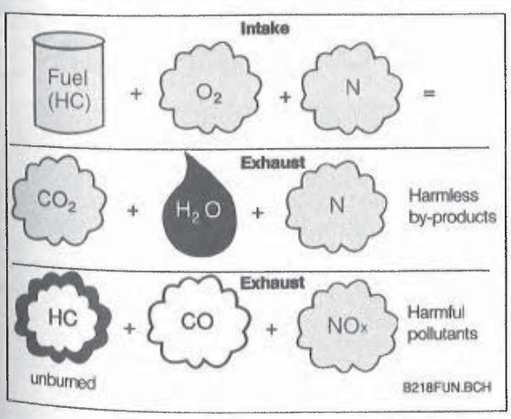


Fig. 4-1. The emission equation: Engine takes in fuel, oxygen, and nitrogen (top). Combustion produces harmless by-products: carbon dioxide, water, and nitrogen (middle); and harmful pollutants: unburned hydrocarbons, carbon monoxide, and oxides of nitrogen (bottom).

Hydrocarbons (HC). Gasoline is a compound composed of hydrogen and carbon; in the combustion process, these elements combine with oxygen to form the by-products water (H_2O) and carbon dioxide (CO_2); HC in the exhaust is unburned gasoline, the result of incomplete combustion.

Carbon Monoxide (CO). CO, a poisonous gas, is another result of incomplete combustion; when gasoline burns completely, the result is CO_2.

Oxides of Nitrogen (NO_x). (NO_x) refers to several kinds of nitrogen oxide which result from nitrogen and oxygen during combustion. Nitrogen and oxygen are normal parts of air, but they exist in air as separate elements. And, as long as the combustion temperature stays below about 2000°F (1100°C), the nitrogen and oxygen do not combine. The nitrogen passes out the exhaust pipe just as it came in, separate and harmless. Combustion temperatures only slightly higher, however, cause these two elements to combine chemically into various forms of nitrogen oxide (NO_x), a key element of smog.

Remember, these exhaust gases are normally colorless and invisible. A clear tailpipe is not the sure sign of a clean-burning engine; it may be pumping out invisible pollutants.

> Until recently, carbon dioxide (CO_2) was considered a harmless emission. But now we must consider the "greenhouse" effect. Recen studies show that CO_2 is accumulating in the upper atmosphere, trapping global heat much as glass traps heat in a greenhouse. The probable results are rises in global temperatures, successive heat waves, and iceberg melting, which could raise ocean levels to flood seaside properties worldwide.
>
> Any burning of fossil fuels such as oil, gasoline, and coal produces CO_2. Automobiles are a significant source. What can we do in driving to reduce CO_2? Avoid unnecessary idling, for one thing. This hichlights the need to adjust traffic patterns to reduce traffic jams. What else could the "greenhouse" efect mean to car owners? Smaller engines, because CO_2 increases with displacement. Also, it could mean restrictions on driving, and increased pressure from Congress for higher CAFE (more rated mpg) from every maker. As I write this, in recognition of the "greenhouse" effect, some carmakers are scrapping plans for new large engines. But the alternative is not very attractive, either.

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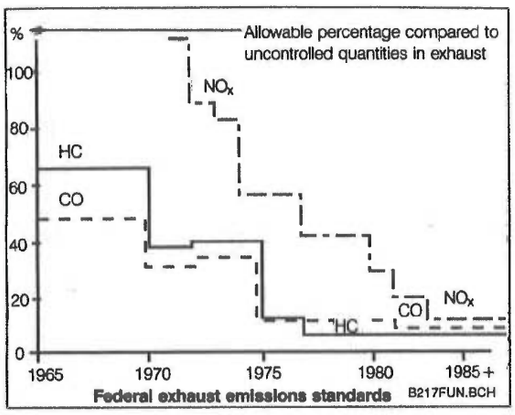


Fig. 4-2. Evolution of U.S. government-mandated emission control standards. Jetronic fuel injection came in to meet the early exhaust emission standards. As limits tightened after 1980, virtually all European cars sold in the U.S. were equipped with Bosch fuel injection.

4.2 Effects of Air-Fuel Ratios on Pollutants

Although exhaust pollutants are not normally visible, some visual clues are a tip-off to poor air-fuel mixture control. Black smoke coming from the exhaust pipe is usually a sign of unburned gasoline; a rich mixture. But look around you on the street; black smoke is something rarely seen on fuel-injected cars.

Just as variations in the air-fuel ratio affect power output and fuel consumption, they also affect exhaust emissions. As I described in **2. Basic Factors**, the air-fuel ratio is a key to complete combustion of the fuel. It also affects combustion temperature which in turn affects the formation of pollutants. Too rich (too little air), and the fuel will not be completely burned. The unburned fuel will enter the atmosphere as CO and HC. Too lean (too much air), and elevated combustion temperature increases NO_x. Fig. 4-3 shows how relative levels of each of the three major pollutants in the engine exhaust are affected by variations in the air-fuel ratio.

While Fig. 4-3 illustrates the effects of air-fuel ratio on the formation of harmful emissions, it also illustrates the fundamental problem in the control of these three pollutants: adjusting air-fuel ratio to ensure complete combustion and minimize the production of HC and CO has the undesirable side-effect of increasing NO_x. Likewise, richening the mixture to minimize combustion temperature and the formation of NO_x brings unacceptable increases in HC and CO.

It becomes clear then that manipulation of the air-fuel ratio is simply not enough to adequately control all three of the most harmful pollutants, especially in the face of increasingly tough emission control regulations. Control of air-fuel ratio to optimize emissions is a first step, to be followed by treatment of the exhaust after it leaves the engine. Maintaining precise control of the air-fuel ratio by electronic control of fuel metering is important not only to the composition of the combustion by-products but also, as you'll see, to the operation of three-way catalytic converters.

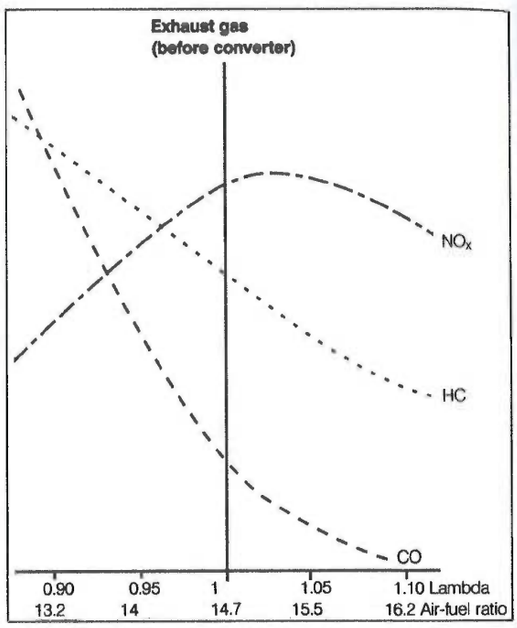


Fig. 4-3. Pollutant levels in engine exhaust change drastically as air-fuel ratio changes. Notice the trade-off between control of HC and CO, and control of NO_x.

When I flew piston-engine aircraft, I adjusted for a rich air-fuel mixture during high-power climbs to keep the engine cool. Then, during cruise, I leaned the mixture. If the needle on the temperature gauge started to rise above the green arc, I knew I had leaned the mixture too much. If you install an exhaust gas temperature (EGT) gauge on your car engine, you can make similar observations (though the mixture is not cockpit-adjustable). I added an EGT gauge when I installed an aftermarket turbocharger.

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4.3 Exhaust Gas Recirculation (EGR)

Exhaust Gas Recirculation (EGR) is a technique for reducing the formation of oxides of nitrogen (NO_x). A small amount of exhaust gas is rerouted back into the combustion chambers, diluting the combustible mixture and lowering combustion temperature. You'll remember that excessive combustion temperature is the cause of NO_x formation.

EGR is necessary to properly control emissions in almost all carbureted engines; fuel-injected engines can often do away with EGR by maintaining proper control of the air-fuel ratio and treating the exhaust with a three-way catalyst.

4.4 Exhaust Gas Aftertreatment

As I discussed above under **3.2 Effects of Air-Fuel Ratios on Pollutants**, precise control of the air-fuel ratio alone is not enough to provide adequate reduction and control of engine exhaust pollutants. While this precise control is essential, the necessary reductions require additional treatment of the exhaust after it leaves the engine—aftertreatment.

A variety of methods of exhaust gas aftertreatment have been employed as the allowable levels of pollutants have been forced lower. All rely to some degree on particular exhaust characteristics to function properly, so the success of all depends on precise control of the air-fuel ratio.

AIR, Air Injection Reaction

One of the early approaches to reduce emissions was air injection. An air-pump, commonly referred to as a "smog pump", delivers air into the exhaust manifold. Adding air tends to burn HC and CO as they exhaust from the cylinders, reducing emissions but increasing underhood heat. You'll find air injection on most carbureted engines and even on many U.S. fuel-injected engines. But Bosch fuel injection controls fuel delivery with enough precision that air injection is seldom necessary; it is used only on the largest Bosch-equipped engines.

Catalytic Converters

Catalytic converters are installed as part of the exhaust system, located between the exhaust manifold and the tailpipe. The interior surfaces of a catalytic converter are coated with special materials—catalysts—that promote additional chemical reactions with the pollutants in the exhaust gas and convert them into less harmful substances.

Oxidation catalysts make use of excess air supplied by an air pump to oxidize CO and HC—add oxygen—and convert them to CO_2 and H_2O. Reduction catalysts work without the addition of excess air to reduce NO_x. The combination of an oxidation catalyst and a reduction catalyst in one housing—a dual-bed catalyst—produces a complex series of chemical reactions which reduce all three pollutants. A disadvantage of dual-bed catalysts is that they rely on a slightly rich air-fuel ratio which increases fuel consumption.

To work most efficiently, the converter must be as hot as possible. For this reason, the best placement is in the exhaust system as near to the engine as possible. In addition to operating at high temperature, the reactions themselves produce heat. Most catalytic converters require heat shields to prevent combustion of something under the car. Even so, drivers are cautioned to avoid parking a hot car near anything combustible, such as tall grass or dry leaves.

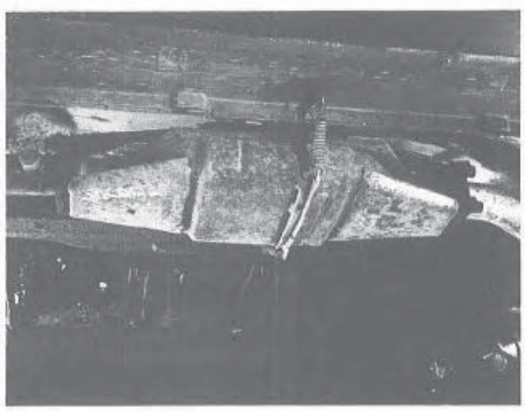


Fig. 4-4. Catalytic converter treatment of exhaust generates heat, so converter has heat shield to protect car and anything combustible under the car.

Three-way Catalytic Converters

The most advanced—and by now the most widely used—catalyst is the three-way catalyst, so-called because its chemical reactions operate to lower all three controlled pollutants to levels which could not be achieved previously.

Remember that, in complete combustion, $HC + O_2 + N = CO_2 + H_2O + N$; incomplete combustion produces CO instead of CO_2; and high temperature combustion, as from a lean mixture, combines $N + O_2$ to form NO_x.

In the three-way catalytic converter, we want to (1) add oxygen to oxidize the HC and CO to make H_2O and CO_2 and, (2) take away oxygen to reduce NO_x, separate it into N and O_2.

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You might think it's as simple as taking the oxygen away from the NO_x and giving it to the CO. Stated simply, that is what happens in some three-way catalytic converters.

The catalytic material in the converter helps these chemical reactions take place. In order for reduction (taking away oxygen from NO_x) to match oxidation (adding oxygen to CO and HC), the proportion of the gases in the engine exhaust must be controlled very closely; that means the intake air-fuel ratio must always be in the narrow range near stoichiometric – lambda (λ) = 1, or an air-fuel ratio of 14.7 parts of air to one part of fuel. In some three-way converters, oxygen is pumped in after the reduction to further enhance oxidation.

Fig. 4-5 illustrates the degree of emission control afforded by a three-way catalyst on an engine running very near the stoichiometric ratio. You can see that if the air-fuel strays from λ = 1, the proportion of exhaust gases (HC, CO, & NO_x) exiting the converter changes. As the air-fuel ratio becomes leaner, hotter combustion temperature causes increased production of NO_x. A rich mixture will produce an excess of HC and CO.

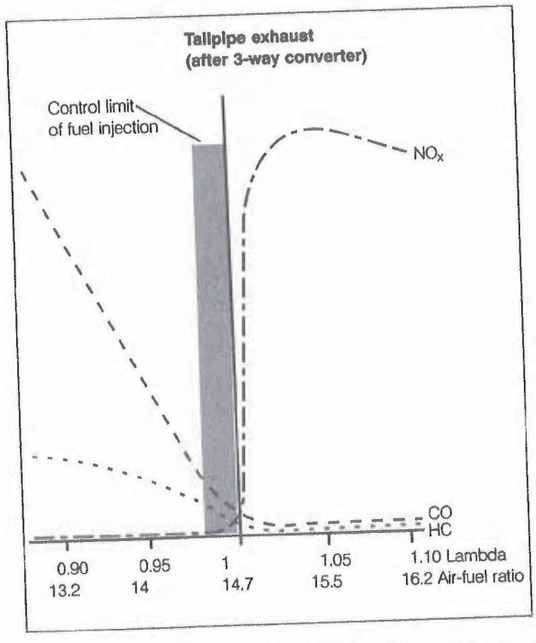


Fig. 4-5. Three-way catalytic converter treats three exhaust gases. HC and CO are oxidized, NO_x is reduced so tailpipe gases meet emission limits. Engine can be tuned to stoichiometric air-fuel ratio for better driveability and economy. Compare with untreated exhaust (Fig. 4-3 above).

When the air-fuel ratio is maintained at λ = 1, the ideal air-fuel ratio, the emission of all three pollutants is reduced to very low levels. Precise control, however, is very important to the successful operation of three-way converters. Any significant deviation from λ = 1 upsets the balance of the chemical reactions in the converter and the level of one or more pollutants increases dramatically. Development of three-way catalytic converters has been accompanied by development of more sophisticated systems for the fine control of air-fuel ratio.

5. Control Systems

By now, you are aware that control plays an overwhelmingly important part in maintaining the acceptable balance of power, fuel economy, emission control, and driveability. The modern fuel-injection system, by responding to measured inputs and precisely metering the appropriate amount of fuel for the conditions, offers unparalleled control.

Fuel injection's basic control systems are one-way or "open-loop" controls. They take the information about operating conditions received from various sensors, and then use that information to determine – either by mechanical means or using pre-programmed electronics – exactly how much fuel it should dispense to achieve the desired air-fuel mixture. Accuracy of the fuel metering and the resultant air-fuel mixture depends entirely on how well the system – whatever type it may be – can predict the engine's needs based on its "knowledge" of operating conditions.

A major advance in fuel-injection control systems has been the advent of "closed-loop" controls – systems which not only try to predict the engine's needs based on operating conditions, but also measure the results of their fuel metering, using that information as an input to achieve ever more precise control.

5.1 Closed-loop Control Systems

In a closed-loop or feedback control system, information about whatever is being controlled is continuously fed back to the system as an input. The operation of a thermostat in an automatic heating system is an example of closed-loop control. As the temperature falls, the thermostat senses lower temperature and signals the furnace to add heat. As soon as the temperature rises above the setting, the thermostat senses the results of its own control action – heat produced by the furnace – and signals the furnace to cut back the heat.

An open-loop system may, for example, sense low temperature and simply turn on the heat for a predetermined amount of time; however, the closed-loop control is automatic, temperature stays relatively constant, and energy consumption is probably reduced. All in all, the result is better, more precise control.

Lambda Sensor

As you saw above in Fig. 4-5, the three-way catalytic converter operates best when the air-fuel ratio is near stoichiometric, when lambda (the excess air factor) is within a very narrow range around λ = 1. Fuel-injection systems, while very good at controlling the air-fuel ratio, cannot hold the air-fuel mixture within the required range. The necessary precision requires the additional feedback available from a closed-loop control system.

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The source of this feedback is a lambda sensor (also called an exhaust-gas sensor, or oxygen sensor), installed in the exhaust system. The sensor generates a low-voltage signal; the signal's strength is based on the amount of unused oxygen remaining in the exhaust stream—an indirect measurement of the air-fuel ratio. The lambda sensor signal provides feedback to the fuel-injection ECU, indicating by actual results whether the air-fuel ratio needs to be corrected. The system can then adjust its fuel metering so that $\lambda = 1$, and the exhaust remains as clean as possible.

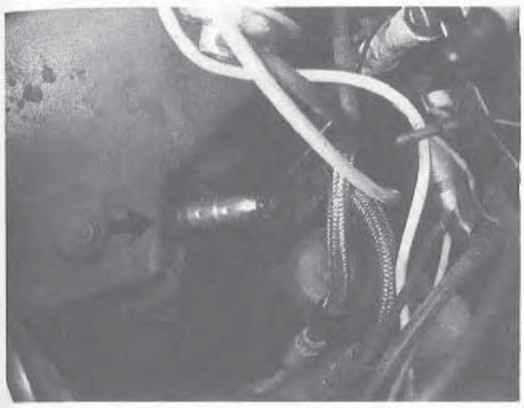


Fig. 5-1. Lambda sensor, usually installed in exhaust manifold, is about the size of a spark plug. Mounting location near engine is required to maintain proper sensor temperature.

Because of tightening exhaust emissions regulations and the need for three-way catalysts, you'll find a lambda sensor on virtually every car made since 1981, domestic or import, fuel-injected or carbureted. For more information on the lambda sensor and its closed-loop control, see chapter 3.

Changing Engine Conditions

You can see that closed-loop lambda sensor system provides automatic control of air-fuel ratio, continuously adjusting the amount of fuel injected in response to the amount of oxygen in the exhaust. The lambda sensor system can also adjust fuel metering to compensate for changing engine conditions over time. If general wear or a leaking valve causes a change in combustion, the feedback system can compensate within its limits and still provide the best possible air-fuel mixture. It has been described as the equivalent of having a skilled technician riding under the hood, continually tuning the mixture for the best operation under the current conditions.

The ability to finely adjust fuel metering to match conditions is what makes lambda control so important, but lambda-sensor closed-loop control is limited to small adjustments within its range of operation. It is often referred to as fine-tuning; in fact, as you'll see in chapters 4 and 6, one of the measures of properly set mixture control is consistent output of CO—the same whether the lambda sensor is working closed-loop, or whether its circuit is disconnected and running open-loop. This means that the basic mixture adjustment is correct and the lambda sensor is operating in the center of its range of adjustment, giving it maximum possible correction range.

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Chapter 3

Pulsed Injection—Theory

Contents

1 **General Description** ... 3
1.1 Pulsed Injection Systems ... 3
1.2 Applications ... 4

2. **L-Jetronic** ... 4
Identifying Features ... 4
Basic Flow Rate ... 6
2.1 Air-Flow System ... 6
Air-Flow Sensor ... 6
Air-Flow Sensor Design and Operation ... 6
Advantages of Sensor Design ... 7
Limitations of Sensor Design ... 7
2.2 Fuel System ... 7
Fuel Pump ... 7
Fuel Filter ... 8
Fuel Rail ... 8
Pressure Regulator ... 9
Relative Fuel Pressure and Fuel Delivery ... 9
Fuel Injectors ... 10
Fuel Metering and Pulse Time ... 10
2.3 Control Unit ... 11
Control Unit Inputs and Outputs ... 12
Analog/Digital ... 14
Control-Unit Connectors ... 14
2.4 Electrical Circuits ... 15
Control Relay ... 15
Fuel-Pump Safety Circuit ... 15
2.5 Operating Conditions ... 15
Starting ... 16
Post-Start and Warm-Up ... 19
Acceleration ... 19
Idle and Drive-Off ... 20
Coasting Cut-Off ... 21
Anti-Search Circuitry ... 21
RPM Limitation ... 21
Pulse-Period Limitation ... 21
Lambda Control ... 21
2.6 LU-Jetronic ... 23

3. **LH-Jetronic** ... 23
3.1 Air-Mass Sensor ... 23
Air-Mass Sensor Design and Operation ... 24
3.2 Idle-Speed Stabilizer ... 25
Dwell Signals ... 26
RPM Stabilization ... 26
Adaptive Control ... 27
Idle Speed Adjustments ... 27

4. **Motronic Systems** ... 27
Applications—Identifying Features ... 28
4.1 Ignition Timing Control ... 29
Timing Data "Maps" ... 29
Distributor ... 30
Dwell-Angle Control ... 30
4.2 Air and Fuel Systems ... 31
Pulsation Damper ... 31
4.3 Control Unit ... 31
Data "Maps" ... 31
Timing Signals: RPM, TDC ... 32
Injector Pulse Patterns ... 33
Adaptive Circuitry ... 33
Sequential Injection ... 34
4.4 Idle Speed Control ... 34

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US PATENT NO. 6,557,540

2 PULSED INJECTION—THEORY

Ignition Timing 34
4.5 Operating Conditions 35
Starting 35
Post-Start 35
Warm-Up 35
Closed-Loop Operation 36
Part-Throttle Acceleration 36
Full-Load Acceleration 36
Knock Control 37
RPM Limitation 38
Coasting Cut-Off 38
Electronic Throttle—Drive-By-Wire 39
Diagnostics 39

5. D-Jetronic 39
Manifold Pressure Sensing 40
Trigger Contacts 40
Acceleration 40
Pressure Regulator 41

6. Digifant II 41

TABLES

a. Bosch Pulsed Fuel Injection Systems 4
b. Fuel-Injection Wiring Harness Terminal Identification .. 15

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1. General Description

You'll find a number of different Bosch fuel-injection systems which are all based on electronically-timed, pulsed injection. See **Table a** on the next page. These systems are sometimes referred to by the term EFI (Electronic Fuel Injection), or AFC (Air-Flow Controlled) injection. The pulsed systems I'll discuss in this chapter include:

- L-Jetronic
- LU-Jetronic
- LH-Jetronic
- Motronic
- LH-Motronic
- D-Jetronic
- Digifant II

I use the term "pulsed" instead of "electronic" to describe this branch of the Bosch family tree because, since 1980 the other branch, the continuous injection systems, also use some electronic controls to adjust fuel metering.

This chapter begins with a general description of the main components and operating principles of all Bosch pulsed injection systems. It then describes pulsed systems in detail, starting with L-Jetronic. For more basic information on fuel injection, see chapter 1 and chapter 2. To determine what system is installed on your car, see **1.2 Applications**, and the detailed applications table at the end of chapter 1.

1.1 Pulsed Injection Systems

All of the systems in this chapter are pulsed injection systems. They meter fuel to the engine by electronically controlling the amount of time that the fuel injectors are open. In contrast to the continuous systems where the injectors are open and flow fuel from the moment the engine starts, pulsed injectors open and close in time with the engine to deliver the fuel. The main components of pulsed systems are the air-flow meter, the electronic control unit, and the fuel injectors. See Fig. 1-1.

In pulsed injection, all air entering the engine first flows through an air-flow meter. The air-flow meter measures this air, which indicates engine load, and converts that measurement into an electrical signal to the control unit. The control unit uses the air flow and engine rpm inputs to compute the amount of fuel necessary to give a good air-fuel mixture, and then electrically opens the injectors at each cylinder intake port to inject the appropriate amount of fuel into the intake air stream. The control unit times the injections to the rotation of the crankshaft. The main fuel pump supplies fuel under pressure to the injectors.



Fig. 1-2. Motronic pulsed injection system on Porsche 944. Note air-flow sensor (**1**) and fuel injectors (**2**). Components may differ depending on system.

Bosch pulsed systems also use many additional sensors that monitor engine operating conditions. The control unit monitors the signals from these sensors and increases or decreases injector opening time—increasing or decreasing the amount of fuel delivered—to give the best air-fuel mixture for the various conditions.

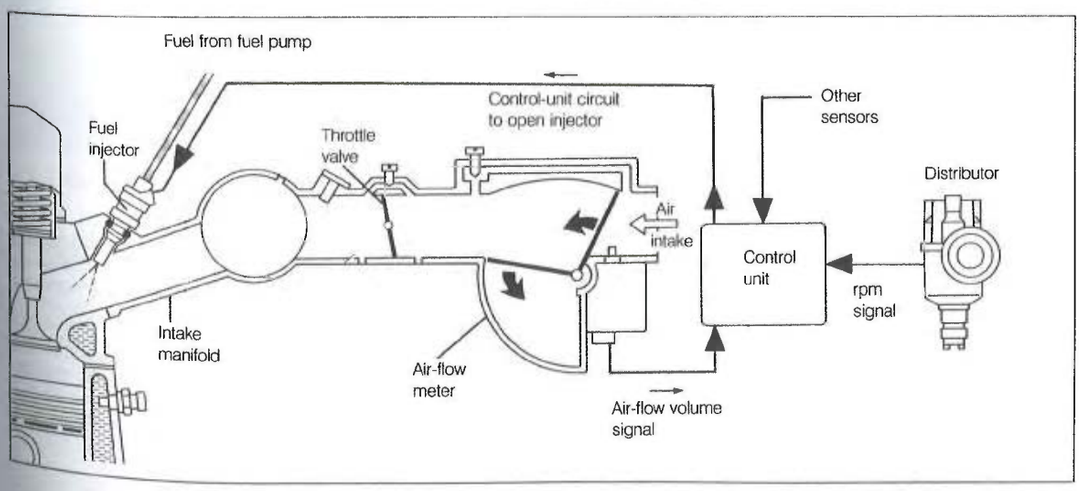


Fig. 1-1. Schematic of pulsed injection operation. Air-flow meter measures air entering engine. Control unit computes proportional amount of fuel required and opens injectors.

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US PATENT NO. 6,557,540

Table a. Bosch Pulsed Fuel Injection Systems

Name	First used	Measure load	Fuel pressure	Computer /no. of pins	Lambda
D-Jet	1967 VW 311	manifold pressure	pressure 2.0 bar (29 psi)	analog/25	no
L 1-Jet	1974 Porsche 914	air flow	2.5–3.0 bar (36–43.5 psi)	analog/35	some
LH 1-Jet	1982 Volvo	air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all
Motr.ML.1	1982 BMW 528e	air flow	2.5–3.0 bar (36–43.5 psi)	digital/35	all
LU-Jet	1982 BMW 318i	air flow	2.5–3.0 bar (36–43.5 psi)	analog/25	all
LH 2-Jet	1984 Volvo	air mass	2.5–3.0 bar (36–43.5 psi)	digital/25	all
Motr.ML.3	1984 BMW/Porsche	air flow or air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all
LH-Motr.	1988 BMW	air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all

1.2 Applications

Bosch L-Jetronic systems are installed in many makes of cars sold in the U.S., beginning in 1974. Considering licensed versions, L-Jetronic has the largest world-wide installed base of any port-type injection system. The Bosch pulsed systems are developments of L-Jetronic, except D-Jetronic. That leads to an interesting name confusion. To contrast with the original D-Jetronic, a pressure-controlled system, L-Jetronic was described as AFC for Air Flow Control. As it turns out, all Jetronic systems that followed D-Jetronic are air-flow or air-mass controlled, including the continuous systems.

The term "Motronic" originally (in 1979) meant a single control unit controlling L-Jetronic fuel injection and ignition timing. Nowadays, there is more than one type of Bosch Motronic system controlling fuel injection and ignition timing (LH-Motronic, KE-Motronic), so following Bosch nomenclature, I'll use Motronic to mean the original definition: L-Jetronic fuel injection and ignition-timing control. Why do I tell you all this? To help steer you through the various names that auto manufacturers and service people have attached to Bosch systems for 20+ years.

2. L-JETRONIC

In the broad terms I've discussed, L-Jetronic is a fuel-injection system, not an engine-management system. While most L-Jetronic cars have electronic ignition, they do not have electronic management of ignition timing. In most cases, the control unit will affect only the injection pulse-time. Ignition timing will be controlled traditionally—advanced or retarded by fly weights and vacuum diaphragms at the distributor.

Identifying Features

A quick way to recognize L-Jetronic systems is by the curved housing of the air-flow sensor as shown in Fig. 2-1. Note that's also found on most Motronic systems.

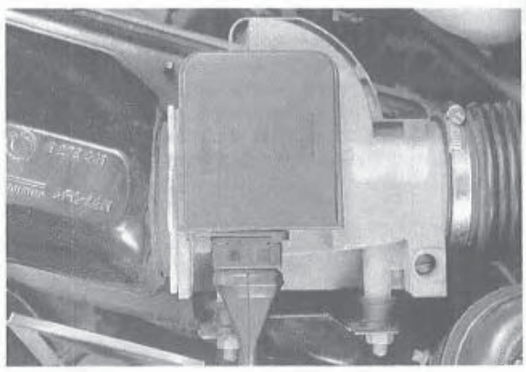


Fig. 2-1. Curved housing of air-flow sensor identifies L-Jetronic, also most Motronic.

Depending on its mounting in the engine compartment, you may also see the waffle grid of the curved housing. That design saves weight while maintaining a rigid flat surface inside for vane contact.

L-Jetronic systems seem to require more parts than the familiar carbureted fuel systems, yet several of these are also required by modern feedback-carburetor systems. See Fig. 2-3 for a diagram of the system components.

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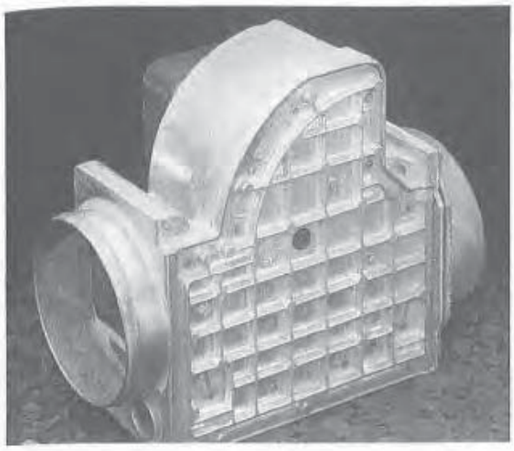


Fig. 2-2. Waffle grid of air-flow sensor maintains a rigid inside surface.

Pulsed systems are completely electronically controlled. Sensors supply information to the central control unit which then operates the port injectors. In the simplest terms, the air-flow system measures the air intake; the fuel system delivers clean, pressurized fuel to the injectors; the control system adjusts the amount of fuel needed for the various operating conditions and electrically opens the fuel injectors to deliver the fuel corresponding to air intake. In addition, somewhat separate from the control system, is the electrical system. Beginning about 1980 (earlier in California), Lambda control was added to the system. To see how they work together, I'll look at how these parts and systems meet the engine needs discussed in chapters 1 and 2.

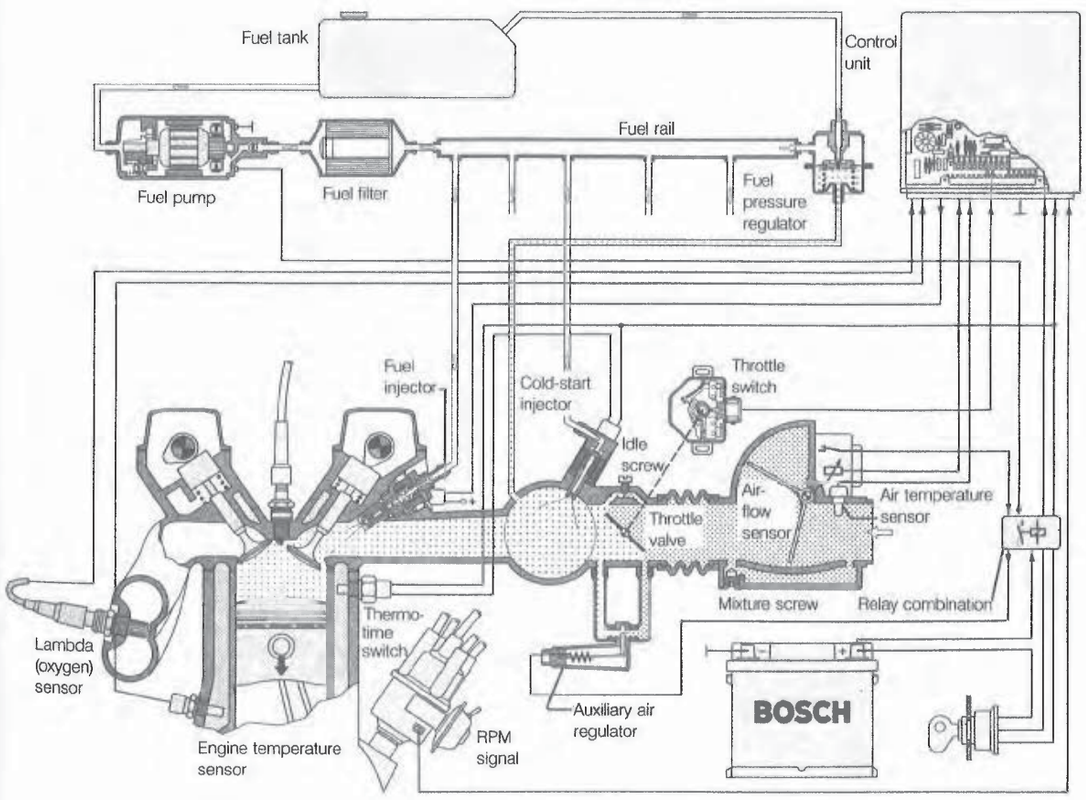


Fig. 2-3. L-Jetronic system diagram. LH-Jetronic is similar, except it has air-mass sensor instead of air-flow sensor.

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L-Jetronic

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Basic Flow Rate

The design of pulsed fuel injection is based on achieving the ideal air-fuel ratio for normal cruise at part throttle, with a warm engine. The pulse time of the injectors that satisfies the fuel requirements for this condition is known as the Basic Flow Rate. Two engine conditions determine the basic flow rate: load and speed. In measuring the volume of the air passing through the intake manifold into the engine, the air-flow sensor provides a measure of engine load. Engine speed is measured as in a tachometer, by counting the ignition pulses in the primary circuit. From the basic flow rate, compensation times can be added or subtracted for other operating conditions.

2.1 Air-Flow System

The air-flow system measures the amount of air being drawn into the engine (engine load), and sends a voltage signal to the control unit based on that measurement. The air-flow system also regulates idle speed and idle mixture.

Air-Flow Sensor

The L-Jetronic air-flow sensor is a vane-type, so called because its internal vane deflects, or moves, as air is drawn into the engine. The sensor measures the air flow controlled by the regular throttle valve; the sensor does not regulate the air flow. The air vane (also called an air flap) is lightly spring-loaded, and pivots by the force of the air flow as the throttle opens to admit more air. See Fig. 2-4.

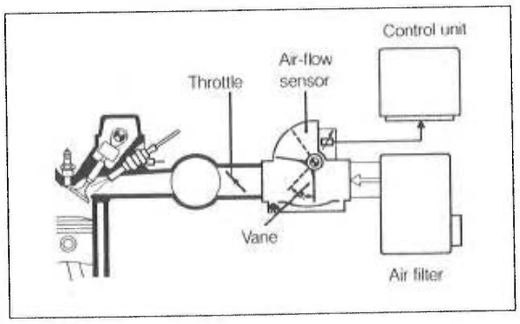


Fig. 2-4. Air-flow sensor air flap measures intake air; throttle controls intake air.

Air-Flow Sensor Design and Operation

If you could remove the waffle-grid cover of the air-flow sensor, you would see the air vane and the damper flap. See Fig. 2-5. The air vane is pushed by the incoming air. In the curved portion of the housing, and mounted on the same shaft as the air vane, the damper flap operates to dampen, or cushion the movement of the air vane by pressing against the air in the chamber. It reduces flutter caused by manifold pressure variations from the opening and closing of the intake valves.

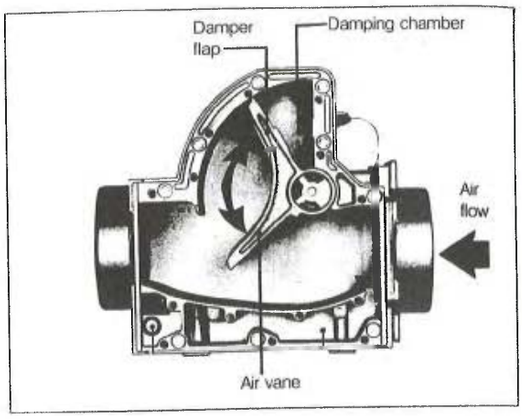


Fig. 2-5. Backfires and pulsations cancel out as opposite forces on the air vane.

Notice the damper flap is the same area as the air-flow vane, and is at right angles to it. This is a clever design: any pulse of increased pressure that rotates the air vane also rotates the damper flap the other way, cancelling the effect of the pressure change. During sudden throttle openings, the air-vane assembly will rotate clockwise rapidly, but its final movement will be cushioned by the damper flap as it squeezes the air in the damping chamber. Bosch tests show the air pressure drop at the sensor is only 0.12 kPa (0.017 psi). That's a fraction of a percent of the atmospheric pressure that forces air into the air system.

The shape of the housing surface opposite the end of the air vane is calculated so the relation between the air passing through and the angle of the flap is logarithmic. That is, a doubling of the air vane angle indicates that air flow has increased 10 times. That means that the most sensitive measurements are at low air flows; at low speeds, measurements are more critical. Maximum air flow is 30 times the minimum.

A moving electrical contact called a wiper is mounted on the same shaft as the air vane. As the vane rotates, the wiper also rotates, crossing a series of resistors and conductor straps on a ceramic base, increasing resistance. See Fig. 2-6. On L-Jetronic air-flow sensors, the resistors oppose current flow from a fixed-voltage input from the control unit. As a result, the more air passing through, the less the voltage signal to the control unit. The control unit is designed to interpret such inverse signals, so the more air there is, the longer the injection pulses are.

In addition to the measured air signalled by the air vane, additional unmeasured air is admitted through a bypass channel to change the idle air-fuel ratio (mixture), as shown in Fig. 2-7. When you turn the bypass screw clockwise, that decreases the amount of unmeasured air. Because the amount of fuel injected is unchanged, decreased air passing into the manifold (for a given vane position) enriches the mixture. Turn the screw counterclockwise to lean the mixture.

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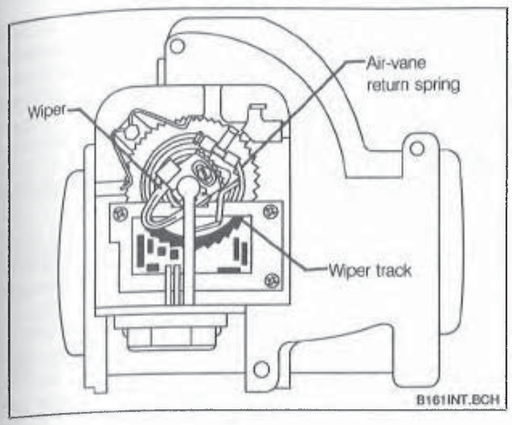


Fig. 2-6. Under the air-flow sensor cover, you can see how the wiper is rotated on the wiper track.

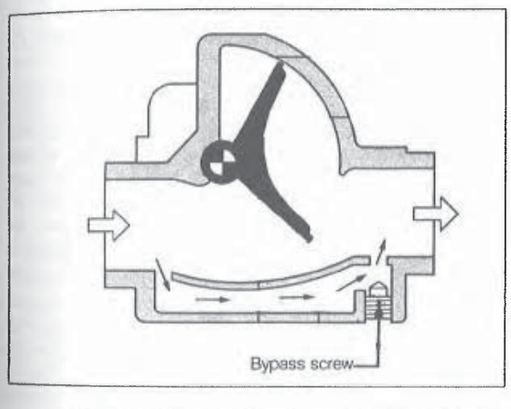


Fig. 2-7. Idle-mixture (bypass) adjusting screw changes bypass of unmeasured air.

Advantages of Sensor Design

What are the advantages of such an air-flow sensor? It provides a direct measurement of the air intake by the engine. By measuring air flow, it tends to compensate for changes to the engine during its service life, such as changes caused by wear, combustion chamber deposits, or valve settings. It permits Exhaust Gas Recirculation (EGR) for emission control without disturbing the measurement of fresh air and the related fuel to be burned with it. In addition, aging of components and varying temperatures have no effect on accuracy because of the resistors in the measurement circuit.

Limitations of Sensor Design

What are its limitations? First, vacuum leaks can be caused by any loose clamp or gasket, or by any slit in the flexible intake boot or vacuum hoses. The air-flow sensor is usually mounted some distance from the intake valves rather than directly on the engine manifold. Any air that enters the intake system between the sensor and the valves is unmeasured air, so-called "false air". Therefore the engine gets no fuel to match that air. The result can be lean mixtures that can cause hard starting, rough idle, low CO, and stumbling; it adds up to poor driveability. Later, in chapter 4, you'll see how to check Jetronics for false air.

Second, the sensor vane measures volume of air intake, but the engine burns weight, or mass of air. Colder air is heavier and requires more fuel than the same volume of warm air. The air temperature sensor corrects for this problem to some degree, as you'll see in **2.3 Control Unit**.

Third, in most cars (those without an anti-backfire valve in the air vane) the vane can be damaged by backfires. The best advice to help prevent this damage when starting the engine is to keep your foot off the accelerator.

Fourth, the air-flow sensor costs more than the pressure sensor, also widely used, particularly in U.S. fuel injection as a measure of engine load. Bosch discarded the pressure sensor in 1974. For more information see **5. D-Jetronic**.

2.2 Fuel System

The fuel system, shown in Fig. 2-8, delivers clean, pressurized fuel to the injectors—usually about one gallon every 2 minutes. As in most newer cars, it is a re-circulating system; the electric pump delivers more fuel than is needed even at maximum consumption, so most of the fuel is returned to the tank. The fuel tank itself is usually pressurized at 7–14 kPa (1–2 psi), controlled by a relief valve in the filler cap. Vapor lock is virtually eliminated because:

- the fuel is cooled by constant recirculation
- the fuel is pressurized, usually at about 2.5 bar (36 psi)

Fuel Pump

The fuel pump, shown in Fig. 2-9, is electrically-driven. Fuel enters at tank pressure through the inlet and is pressurized by the roller cells as shown in Fig. 2-10. The pressure limiter opens and directs fuel back to the tank if fuel pressure in the lines goes over a limit. High-pressure fuel is delivered through a check valve, which closes when the fuel pump stops to hold pressure in the lines. Constantly-pressured fuel lines ensure quicker restarts, and also help prevent vapor lock.

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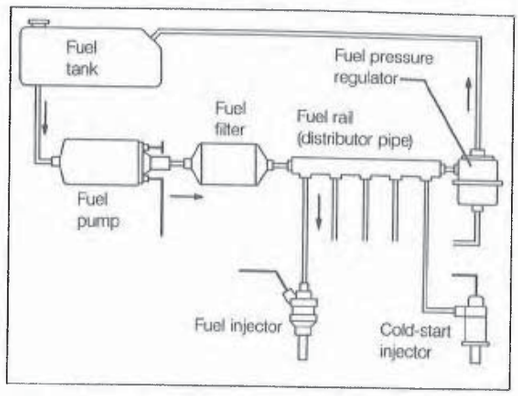


Fig. 2-8. Fuel circulates as pressure regulator at end of fuel rail returns unused fuel to tank.

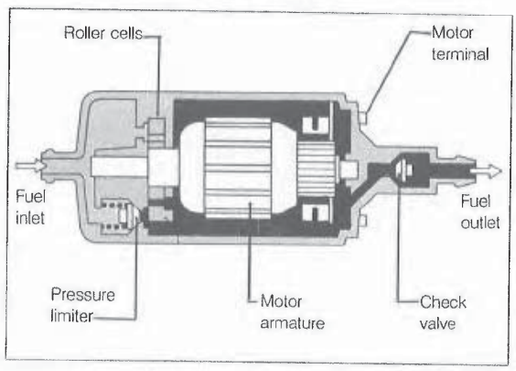


Fig. 2-9. Fuel pump and its electric motor operate surrounded by fuel that cools motor.

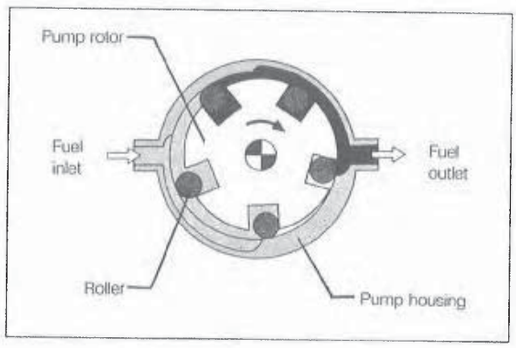


Fig. 2-10. Operation of roller-cell pump. Rotor disc is mounted eccentrically in pump housing. When rotor turns, the rollers are pressed outwards by centrifugal force, and act as a circulating seal. Fuel pressure builds as rollers and disc move fuel through narrowing passages to outlet.

The electric motor actually operates in the fuel in the pump housing. The thought of an electric motor running in gasoline may seem dangerous, but it is safe because the housing never contains an ignitable mixture. There are those who, fearing a burnable mixture, say "never run out of gas with a fuel-injected car," but thirty years of electric pump experience shows they just don't catch fire that way. On the contrary, the gasoline is important—it cools the pump. So if you do run out of gas, just don't crank a long time or you may ruin the pump.

Bosch systems locate the fuel pump next to the fuel tank. This pressurizes the maximum length of the fuel lines to reduce vapor lock. Some cars place the pump inside the tank, or provide a low-pressure electric supply pump in the tank to deliver pressurized fuel to the main electric pump. Electric fuel pumps require relays and safety circuits to ensure that the pumps stop when the engine stops. For more information see **2.4 Electrical Circuits.**

Fuel Filter

In most fuel-injected cars, the fuel filter is located next to the fuel pump. It is much larger than the usual carburetor fuel filter because clean fuel is so important to fuel-injection systems. It is also finer. The paper filter, shown in Fig. 2-11, has a medium pore size of 10 micrometers. It is backed by a strainer that catches any loose particles, and is supported by a plate. The filter is replaced as a complete unit, not as an insert. Vehicle specifications usually call for 30,000–80,000 km (20,000–50,000 mi). When you replace it, observe the direction-of-flow arrows on the filter housing. Some late-model cars use fuel filters that need no replacement unless contaminated.

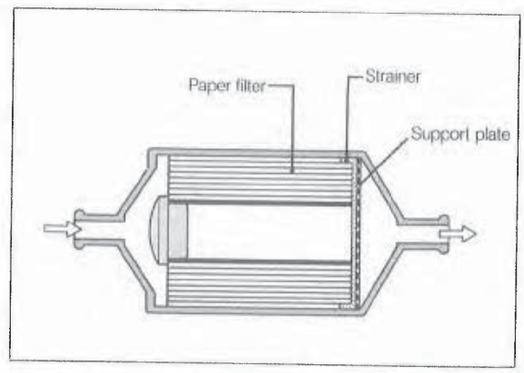


Fig. 2-11. Cut-away of typical fuel filter. Filter is large and fine pore size of 10 micrometers.

Fuel Rail

The fuel rail (also known as the distributor pipe) serves two purposes. The first is to deliver fuel to the injectors. The second is to stabilize fuel pressure at the injectors. You can imagine

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how the pressures change rapidly in the fuel rail as the injectors pop open and closed. This can affect the amount of fuel injected. But the larger the pipe, the more fuel it stores and the steadier the pressure at the injectors.

On later engines, the fuel rail is larger, a square box, as shown in Fig. 2-12. In the large rail, fuel pressure is more stable at the injectors. On earlier engines, the distributor pipe looks like a typical fuel line, a round pipe leading to all the injectors. In the smaller pipes, with small volume, pressure tends to fluctuate each time the injectors open.

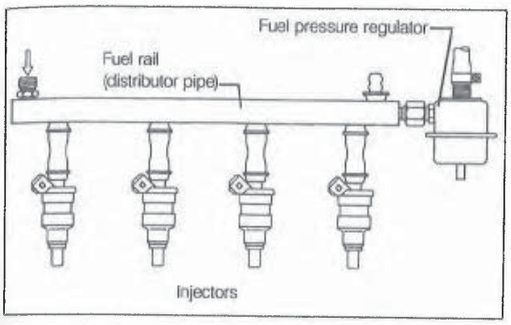


Fig. 2-12. Large fuel rail reduces pulsations as injectors open and close.

Pressure Regulator

Relative fuel pressure in the fuel system is held constant by the pressure regulator, usually mounted on the fuel rail. As shown in Fig. 2-13, spring pressure normally keeps the regulator valve closed. When the fuel pump turns on, fuel pressure presses on the diaphragm to compress the spring and open the valve, returning excess fuel to the tank. The higher the pressure, the more the diaphragm moves away from the return pipe, increasing the volume of the chamber, maintaining the desired pressure. Most systems operate on 2.5 bar (36 psi) gauge pressure, but some higher-powered engines use 3 bar (44 psi) for greater fuel delivery per millisecond.

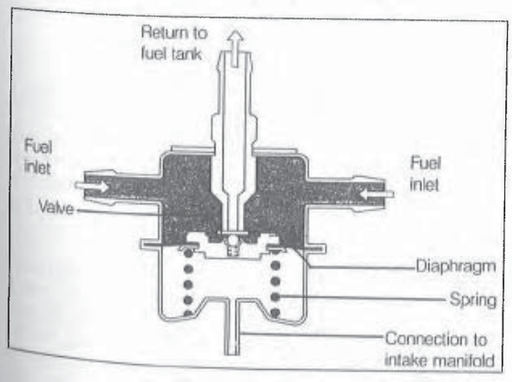


Fig. 2-13. Pressure regulator controls system pressure, usually 2.5 bar (36 psi) above manifold pressure.

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Relative Fuel Pressure and Fuel Delivery

For each millisecond of injector pulse time, the amount of fuel delivered through the injector tip depends on the size of the injector opening; that's a fixed factor. But fuel delivery also depends on the relative pressure—the difference between fuel pressure pushing the fuel out into the manifold, and manifold absolute pressure pushing back, as shown in Fig. 2-14.

As you know, manifold pressure changes with throttle opening. If the fuel pressure were constant for all manifold pressures, then at low engine loads, with the throttle partly closed, reduced manifold absolute pressure would increase fuel delivery. To keep that relative pressure constant as the throttle is opened and closed, the fuel-pressure regulator is connected to the intake manifold by a vacuum hose. Manifold pressure acts on the diaphragm to hold the relative pressure constant.

> When thinking about fuel pressure, remember that the ordinary fuel-pressure gauge measures relative pressure—the amount that fuel pressure is greater than barometric pressure (14.5 psi). But barometric pressure is measured from an absolute zero pressure, so 2.5 bar (36 psi) gauge pressure actually means 2.5 bar greater than 1 bar of barometric pressure, or 3.5 bar (51 psi) absolute, measured from an absolute zero. When the gauge is not connected, it reads zero: zero here means the difference between the open connection and barometric pressure.

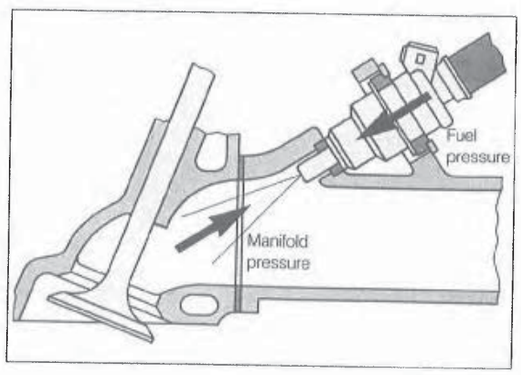


Fig. 2-14. Precise delivery depends on constant relative pressure, that is, difference between fuel pressure and manifold pressure.

For example, with the engine off, manifold pressure is the same as barometric pressure. If you measure fuel pressure with the pump running and the engine off, the regulator controls fuel pressure balancing the forces: fuel pressure on one side of the diaphragm balanced against spring force plus the force of barometric pressure in the manifold. The gauge then reads 2.5 bar, 2.5 bar (36 psi) more than atmospheric. At wide-open throttle (WOT), manifold pressure is close to barometric, so again, the fuel-pressure gauge reads about 2.5 bar.

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At idle, absolute pressure in the manifold is about 0.3 bar (0.7 bar less than barometric)—old-timers would say "20 inches vacuum". Now the manifold absolute-pressure pushing the pressure-regulator diaphragm is only 0.3 bar instead of 1 bar. The reduced manifold pressure on the diaphragm allows it to move away from the opening, returning more fuel to the tank, and dropping the gauge fuel pressure in the distributor pipe to about 1.8 bar (2.8 absolute). The relative pressure at the injector tip is still 2.5 bar (2.8 minus 0.3 absolute). That's why fuel delivery per injection is not affected by changes in the manifold absolute pressure. When you understand this principle of fuel delivery, you'll understand the checking of fuel pressures. You'll also understand how greater delivery for off-road and performance operation may be increased by increasing fuel pressures.

Fuel Injectors

The port injectors (located at the intake ports next to the intake valve) are solenoid valves. Each injector is opened by an electrical signal from the control unit, and closed by spring force when that signal stops. See Fig. 2-15. When current is sent through the connection to the winding, electromagnetic force lifts the solenoid, and fuel is delivered. The lift is about 0.15 mm (0.006 in), and takes about 1 millisecond. When the needle valve is closed by the spring, no fuel flows. The pintle on the tip of the needle valve helps to atomize and distribute the fuel.

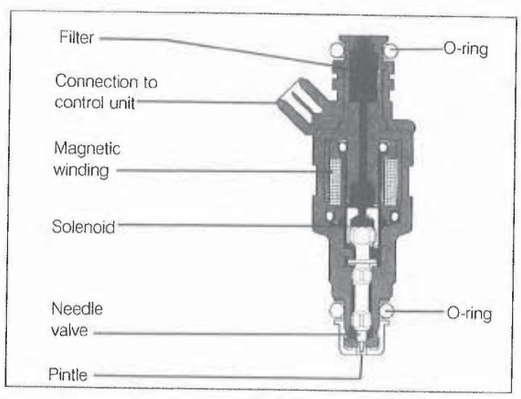


Fig. 2-15. Injectors seal to fuel rail and to manifold by O-rings.

Interestingly, the injectors are electrically-hot all the time the key is ON and the relay combination is closed. For fuel delivery, they are grounded in the final stage of the control unit. In early L-Jetronics (until about 1978) each injector circuit includes a resistor to limit the current flow. In these circuits, the initial current-flow must be great enough to rapidly open the solenoid/needle valve, and then flatten out when only a holding current is needed. Since about 1979, L-Jetronics regulate the current in the control-unit final stage, and so do not need separate series resistors. The resistance is built into the injector itself, using a solenoid winding of brass (higher resistance than the previously-used copper winding). This also requires less power than the series-resistor type.

L-Jetronic

The injectors are held in the intake manifold with O-rings that tend to insulate the injectors from engine heat and vibration. If the O-rings crack, false air enters, leans the mixture and increases idle rpm. In most engines, the injectors are connected directly to the fuel rail with safety clips. In other engines, they are connected to the rail with fuel lines.

Fuel Metering and Pulse Time

In pulsed injection, the metering of fuel takes place at the tip of the injector as the fuel flows past the pintle. The lift of the needle valve from its seat is always the same distance, so assuming that fuel pressure is regulated as described above, the amount of fuel injected into the engine depends solely on the amount of time the control unit applies voltage to open the injector.

This injector opening time is known as the Pulse Time, and it can vary anywhere from 2 milliseconds to as much as 15 milliseconds or more. The injector takes about 1 millisecond to open, which is counted in the injection time. The closing time is not counted, but it averages out; pulse time is the effective injector open/delivery time.

If, when the control unit grounds the circuit, you measured voltage at the injectors on an oscilloscope, it would look something like Fig. 2-16. Remember that the injectors are always hot, and are grounded in the control unit. Note that when reading pulse time on a scope, it can be referred to as pulse width—the actual width of the pulse-time voltage on the screen.

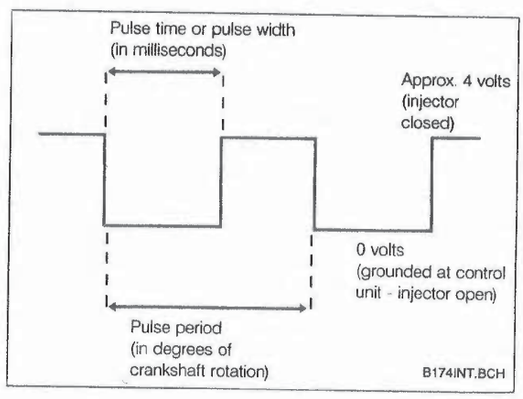


Fig. 2-16. Fuel-injector voltage over time, showing difference between pulse time and pulse period. Voltage supply at injectors is always approximately 4 volts. Oscilloscope shows change in circuit as it is grounded in control unit.

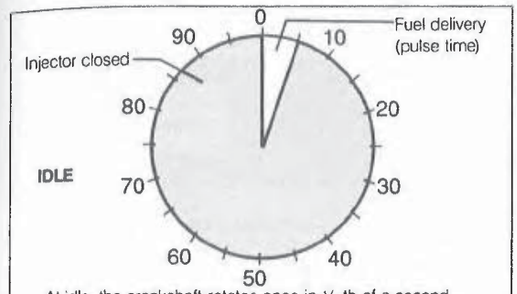
Various operating factors determine pulse time as you'll see below, but there is one other basic factor—called Pulse Period. This is the total time from one opening of an injector to the next opening of the same injector. Normal pulse period for the pulsed systems covered by this book is twice per 4-stroke cycle, or once per crankshaft revolution. Half of the total amount of fuel needed for one firing of a cylinder is injected in each injection. If the pulse period were once per 4-stroke cycle,

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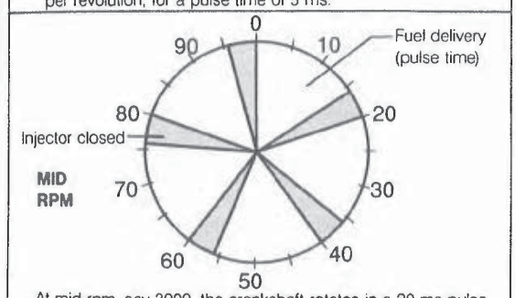
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then pulse time would increase so that all of the fuel was injected at once.

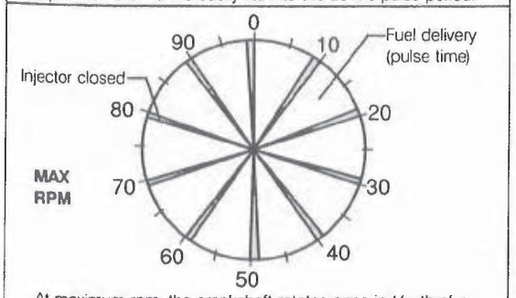
To see the relationship between pulse period and pulse time, let's take a typical engine that idles at 600 rpm and has a maximum rpm limit of 6000 rpm. Dividing each of those revs/minute by 60 seconds, we can say the engine idles at 10 revs/second, and runs max at 100 revs/second. Fig. 2-17 shows pulse period and pulse time for this engine. Each circle represents 100 milliseconds (ms) of time.



At idle, the crankshaft rotates once in 1/10th of a second, or 100 ms. That's the pulse period. The injectors open once per revolution, for a pulse time of 5 ms.



At mid-rpm, say 3000, the crankshaft rotates in a 20 ms pulse period. Full-load delivery for maximum torque at wide-open throttle requires longer injection times than at maximum rpm since at mid-rpm the engine takes in more air per stroke. But a pulse time of 15 ms easily fits into the 20 ms pulse period.



At maximum rpm, the crankshaft rotates once in 1/100th of a second. Pulse period is now 10 ms; in 100 ms the crankshaft rotates 10 times, and the injectors open ten times. If the pulse time is 8 ms, the injectors barely have time to close before they open again.

Fig. 2-17. Relation between pulse period and pulse time. Each circle represents 100 milliseconds (1/10 sec.).

It's important to remember the inputs that control the basic injection pulse time: air-flow volume and rpm. Fig. 2-18 shows that full-throttle injection time varies from about 6 milliseconds to 9 milliseconds, and that injection time follows the torque curve.

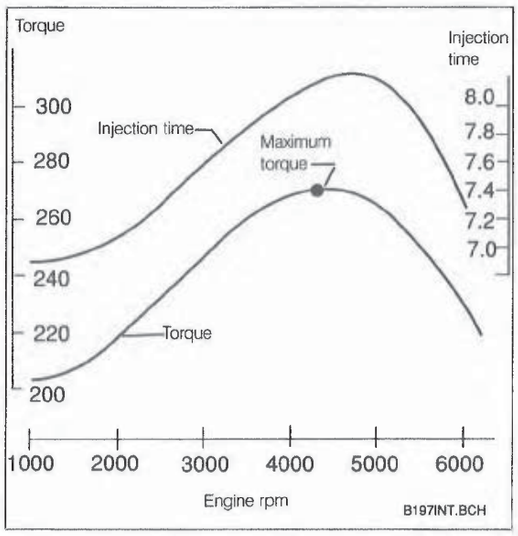


Fig. 2-18. Typical pulse time in milliseconds for full-load matches torque curve.

2.3 Control Unit

The control unit is sometimes called the "brain" of the control system. It receives input of signals from various sensors, processes those signals, computes the pulse-time for the injectors, and completes the circuits in a series of pulses to deliver the required fuel.

The control unit is a complicated piece of electronic equipment. If you open it—and that is not recommended—you'll find it full of transistors, integrated circuits, and printed circuit boards, as shown in Fig. 2-19. The heart of the control unit is a microprocessor chip, about the size of a thumbnail as shown in Fig. 2-20.

In most cases, the control unit is sensitive to heat and vibration, so it is usually located in the passenger compartment away from the engine. A common location is the kick panel to the right of the passenger's feet. You may also find it behind the glove box, under the passenger seat, or in the fresh air compartment under the hood.

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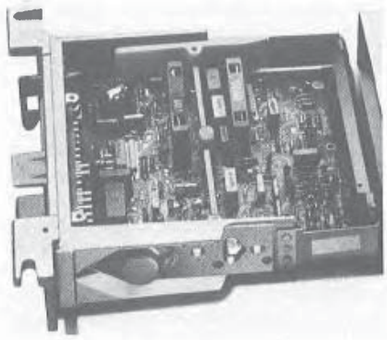


Fig. 2-19. Control unit does the data processing for fuel-injection management.

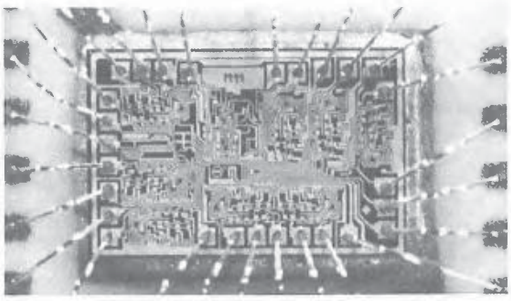


Fig. 2-20. The chip is the heart of the control unit. This integrated circuit is about the size of a thumbnail.

Modern control units are protected from EMI (Electro-Magnetic Interference)—stray radio frequency signals that can scramble the control-unit brain. I've heard a story about early pulsed systems, before proper shielding was provided: A driver in a Volkswagen Beetle, running on the freeway beside an 18-wheeler, called the truck on his CB radio. When the 18-wheeler answered, using CB power boosted way over the legal limits, the CB signal shut down the VW engine. Story, remember.



Fig. 2-21. Jetronic car is tested under transmitter antenna to check EMI shielding.

L-Jetronic

Control Unit Inputs and Outputs

Fig. 2-22 is a block diagram showing the basic processing functions of the control unit for the inputs it receives. The rpm signal from the ignition circuit enters the control unit through a shaper and a divider. As shown in Fig. 2-23, from each ignition pulse, the pulse shaper generates a rectangular pulse (voltage on/voltage off), 4 per each 4-stroke cycle. This is divided by two to provide one injection pulse per crankshaft revolution; for a 6-cylinder engine, it is divided by 3.

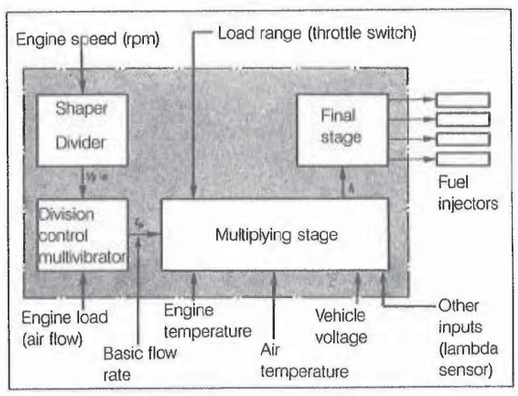


Fig. 2-22. In control unit, basic flow rate is compensated for variables including engine temperature, air temperature, vehicle voltage.

In the division-control multivibrator, the output of the shaper (rpm divided by two) is combined with the load-signal input from the air-flow sensor, resulting in a basic-pulse time. This corresponds to the basic-flow rate, the quantity of fuel to be injected for each injector opening.

The multiplying stage processes the compensation inputs, such as those from the two temperature sensors, engine temperature and air temperature; from the throttle-switch, closed or full-open signals. In later cars, generally those since 1980, it also processes inputs from the lambda sensor. The control unit calculates compensation factors, applying them to the basic pulse-time. In most cases, this will enrich the mixture: when the engine is cold, the injection pulse-time may be two to three times the basic-pulse time.

Compensation for battery voltage is also necessary. This is because battery voltage may vary from 14 volts while the alternator is charging, to 10 volts or less during cold cranking. The lower the battery voltage, the less power to the injector solenoids, and the less fuel injected, perhaps during a cold start when the engine needs it most.

In a 4-cylinder system, the final stage grounds 4 injectors at the same time. Control units for 6-cylinder engines may have two final stages, but they operate together, firing all injectors simultaneously. With two injections per four-stroke cycle, each delivery is half of the total required.

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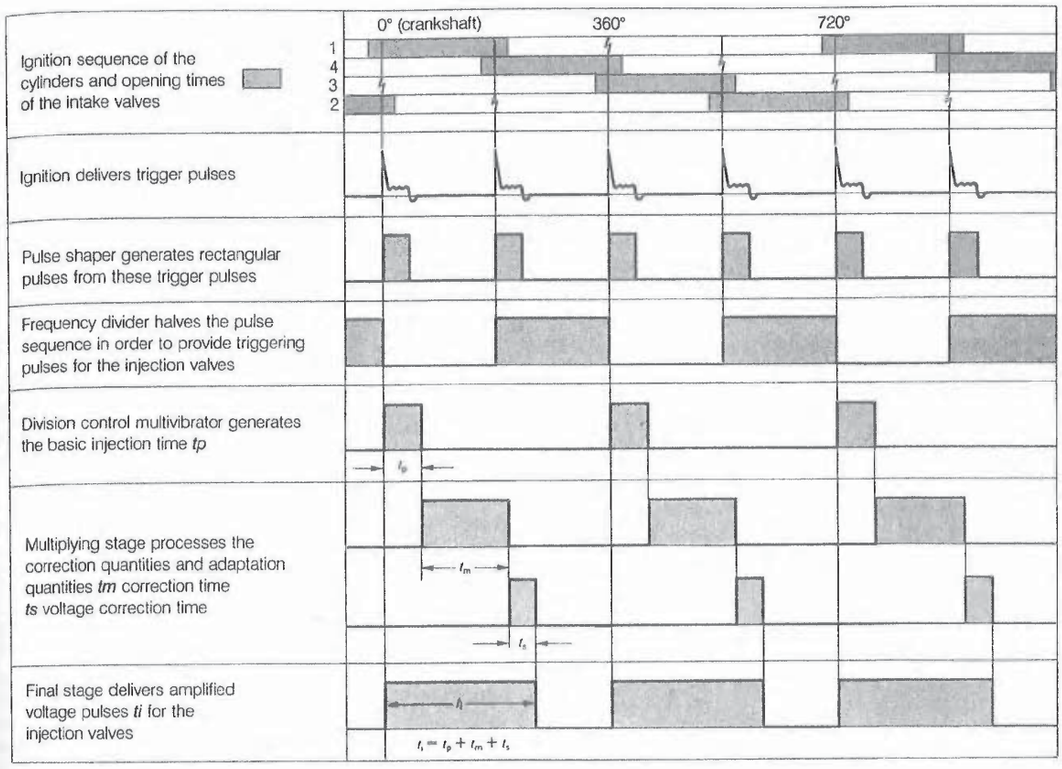


Fig. 2-23. Each basic injection pulse-time is compensated and corrected.

Although it may seem as if the control unit passively receives inputs from the sensors, in some cases its role is an active one, as shown in Fig. 2-24. For example: voltage output from the control unit (terminal 5) is fed to the engine temperature sensor. The sensor reduces the flow of current back to the control unit (terminal 13) which the control unit measures. The colder the engine, the more resistance, and the less current back to the control unit. In the same manner, a voltage signal is sent to the air-flow wiper track, and the return signal is measured. Note that the cold-start injector, thermo-time switch, and auxiliary-air device operate independently of the control unit.

RPM Signal. Engine rpm, to help determine the basic flow rate, is one of the most important inputs to the control unit. Bosch pulsed systems are synchronized, that is, injector pulses are synchronized with crankshaft rotation. All L-Jetronic injectors fire twice per 4-stroke cycle, or once per crankshaft revolution. As you saw earlier, the total amount of fuel delivered depends on how many injections there are per minute, and how long the injectors are open for each injection.

In the control unit, air measurements alone could determine the amount of fuel required for the ideal air-fuel ratio. But, as you'll see, injector opening-times are computed for many conditions and air-fuel ratios, some of which depend on engine rpm. So engine rpm is one factor in determining the basic flow rate.

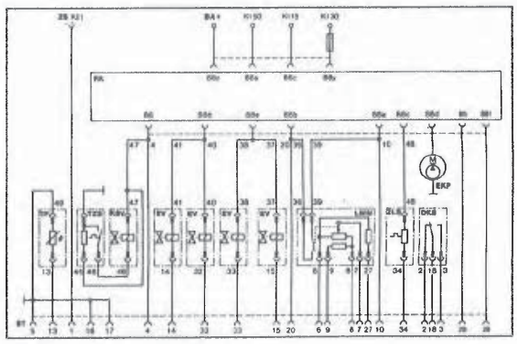


Fig. 2-24. Example of control-unit connections for L-Jetronic system with regulated final stage and no resistors. For component identification, see **Table b** below.

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The L-Jetronic rpm signal comes from the primary ignition pulse, the current that turns the coil on and off. For most cars, that is a signal from the negative terminal of the ignition coil.

The ignition circuit sends four signals for each 720° of crankshaft revolution (each 4-stroke cycle). In a 4-cylinder engine, this means that the ignition circuit closes every 180° of crankshaft revolution (once for each distributor revolution). If you look at Fig. 2-23, above, you'll see the ignition pulses for the firing order at the top of the diagram, and the opening time of the intake valves.

Analog/Digital

Early control units were analog-type; later are digital. You are bound to run into these terms when troubleshooting, so it's important to know the difference. Analog measures continuously; an analog display changes in direct proportion to the input, such as an ordinary odometer. If you've gone two-thirds of a mile since it measured an even mile, the tenths digit will read about two-thirds. On the other hand, digital measures in steps. The digital clock shows exact steps, nothing in between as shown in fig. 2-25. Each step can be extremely accurate, and does not change with wear or aging factors.



Fig. 2-25. Analog measures continuously; digital measures in steps, and each step is exact.

The important point is: steps versus continuous change. See Fig. 2-26. Analog accuracy is limited, as indicated by the curved line measuring the signal of the straight line. But analog measurement can be more accurate than digital measurement that uses large steps. By increasing the number of steps, digital accuracy is usually greater than analog.

Some inputs are analog; for example, consider the changing current flow from the resistor of the engine-temperature sensor. That analog signal must be changed in the control unit by an analog-to-digital (A/D) converter. Some inputs are digital, for example the rpm pulses from the ignition primary.

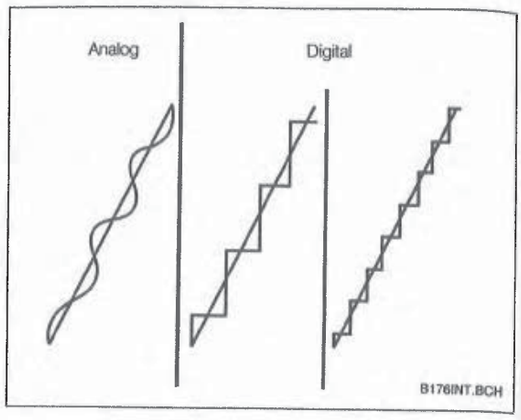


Fig. 2-26. Analog accuracy is limited by many variables; digital limited by number of steps.

Some outputs are digital, as you'll see later. These are a series of pulses sometimes described as percent dwell. Analog outputs from digital control units are handled by digital-to-analog (D/A) converters.

Control-Unit Connectors

Inputs and outputs of the control unit are generally handled by a multiple-connector plug, as shown in Fig. 2-27. Some control units provide 35 pins for the connectors, while others, with simplified circuitry, operate with 25-pin connectors. When reading circuit diagrams or making tests at the control-unit connector you'll need to understand the German abbreviations that often identify the connector terminals. **Table b** lists the common abbreviations and their English equivalents.

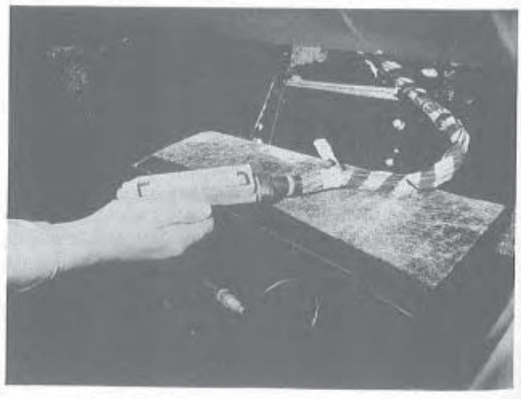


Fig. 2-27. Multiple-pin connector handles all inputs and outputs to control unit pins.

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Table b. Fuel-Injection Wiring Harness Terminal Identification

Abbr.	German Word	English Equivalent
TF	TEMPERATURFUHLER	Engine-temperature sensor, NTC II
TZS	THERMOZEITSCHALTER	Thermotime switch
KSV	KALTSTARTVENTIL	Start valve
EV	EINSPRITZVENTIL	Injector
LMM	LUFTMENGENMESSER	Air-flow sensor
ZLS	ZUZATZLUFTSCHREIBER	Auxiliary-air device
DKS	DROSSELKLAPPENSCHALTER	Throttle-valve switch
EKP	ELECTRISCHE KRAFTSTOFFPUMPE	Electric fuel pump
RK	RELAISKOMBINATION	Relay combination
ZS	ZUNDUNG, SPULEN	Ignition coil
BA	BATTERIE	Battery
ST	MEHRFACH-STECKER	Multiple-plug to control unit

2.4 Electrical Circuits

In addition to the electronics of the control system, L-Jetronic requires simple electrical circuits to power the control unit, fuel pump, and other components.

Control Relay

When the ignition is on, current flows from the battery through the ignition switch to a relay or combination-relay. This relay then closes to power the control unit. It also feeds the cold-start injector and the auxiliary-air valve. Thus, do not replace a control unit to "fix" these parts. See Fig. 2-28.

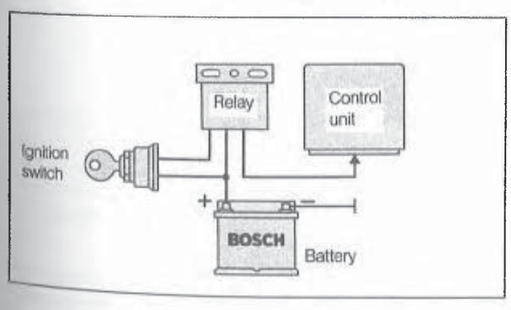


Fig. 2-28. System power flows through relay powered by ignition switch.

Fuel-Pump Safety Circuit

The relay also controls the fuel-pump safety circuit. The START position of the key starts the fuel pump during cranking. But the pump will stop running in 1–2 seconds unless it receives a signal that the engine is turning. This helps prevent flooding, or a fire in the event of an accident. See Fig. 2-29. In most L-Jetronics, the relay receives the rpm signal from the ignition circuit and shuts down the pump if the engine is not turning fast enough: 4-cylinder engines, faster than 225 rpm; 6-cylinder engines, faster than 150 rpm. Early L-Jetronics (before 1978) do not use the rpm signal; instead, a safety switch in the air-flow sensor closes when the air vane begins to open.

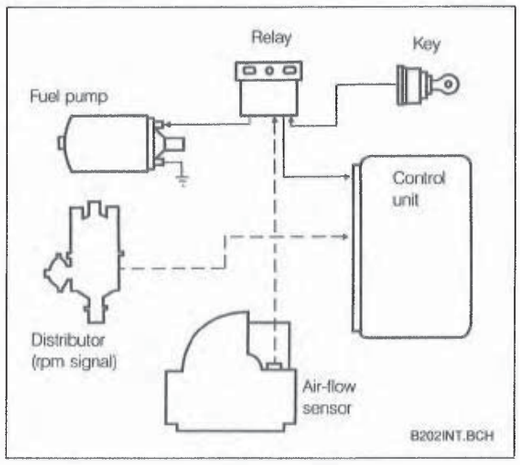


Fig. 2-29. Pump safety circuit is usually controlled by rpm signal from primary ignition circuit; in early L-Jetronics, control is by air-flow sensor switch.

Service technicians can bypass the safety circuit to run the fuel pump without running the engine: on early cars by reaching in to move the air vane with the ignition on; on later cars by jumping the rpm safety circuit either at the relay set or at the air-flow sensor. For more information see chapter 5.

2.5 Operating Conditions

For all of the conditions under which the engine operates, the control system computes the following:

- Main variables: engine load and speed for the basic flow rate. Each basic flow rate can be modified, or compensated based on inputs from sensors that signal changes in operating conditions.
- Compensation variables: such as starting, cold operation, and special load conditions, and
- Precision compensation: tweaking the other compensations for overrun or coasting, and mixture (lambda) control for emission-reduction.

All compensations are added to, or subtracted from the basic flow rate. So let's look at each of the conditions and see what sensors and signals affect L-Jetronic through the control unit. We'll also see some auxiliaries that operate independently of the control unit.

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Starting

As we've seen, depending on the temperatures, the engine may need additional fuel, and also additional bypass air around the closed throttle. How does L-Jetronic compensate for all the different starting conditions? How does the system operate without any setup by the driver; how can you simply turn the key to start it?

These systems have no choke or fast idle cam to set. As the car sits, the engine changes temperature due to changing weather, or cooling after running. Its sensors signal the control unit about engine temperature and other conditions that could affect starting. Other components inject additional fuel or allow additional air.

Engine Temperature Sensor. The most important sensor is the engine temperature sensor, shown in Fig. 2-30. It is a semi-conductor resistor, also known as a thermistor. You may find service instructions referring to it as NTC II. NTC stands for Negative Temperature Coefficient, meaning the sensor's resistance goes down as the temperature goes up. This is the opposite of most resistors; hence the term "negative." See Fig. 2-31.

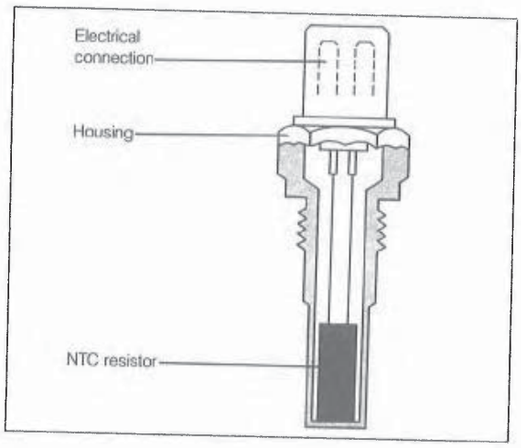


Fig. 2-30. Engine temperature sensor is a solid-state resistor, sometimes called a thermistor. NTC means Negative Temperature Coefficient.

Suppose the engine is in the shop and has not run recently, say for several hours. In round numbers, the resistance at ordinary indoor temperatures is about 3Kohms (3,000 ohms). If the engine has run recently, long enough to fully warm up, resistance is only about 400 ohms. If the control unit applies a fixed voltage to the NTC resistor, it will receive a smaller signal back as input from a cold resistor with higher resistance than from a warm one. From a cold input signal, the control unit will compensate by adding to the basic pulse time as shown in Fig. 2-32.

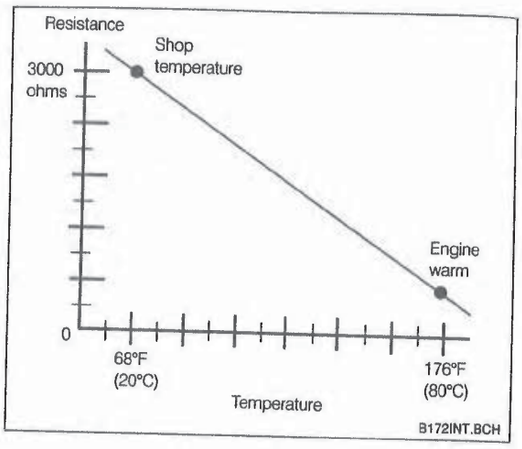


Fig. 2-31. NTC resistance is lower when engine is warm.

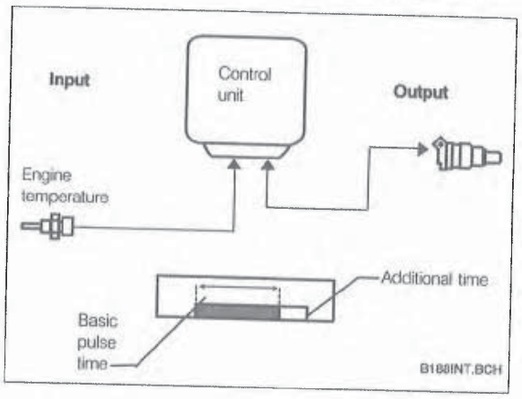


Fig. 2-32. Cold engine temperature sensor causes increased pulse time.

On water-cooled engines, look for the engine temperature sensor, sometimes called NTC II, to be mounted in the cooling system, usually in a fitting near the block, or in the thermostat housing. See Fig. 2-33. Be careful not to confuse the engine temperature sensor with the thermo-time switch or the coolant temperature sender for the instrument-panel temperature gauge.

The NTC sensor is quite simple: an electrical connector on a housing, enclosing the thermistor. The first L-Jetronic came on an air-cooled engine, so on those, you'll find NTC II in a cylinder barrel or a head.

Air Temperature Sensor. With the air cleaner removed, you can see the Intake Air Temperature Sensor in the air-flow sensor as shown in Fig. 2-34. Known as NTC I, this sensor also has a negative-temperature coefficient. Remember, the control unit sends a signal which is changed by the air temperature sensor.Cold air, weighing more, needs more fuel, so a cold-air

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signal also adds fuel to the basic-pulse time. The air-fuel ratio relates weight of air to weight of fuel. The combination input signals of volume (from the air-flow sensor), corrected for temperature, are the same as inputs of weight or mass of air passing into the engine.



Fig. 2-33. Engine temperature sensor (also called Temp II or NTC II) is often mounted in thermostat housing. In this BMW, temperature sensor (**2**) is mounted with thermo-time switch (**1**) and engine temperature sender (**3**).

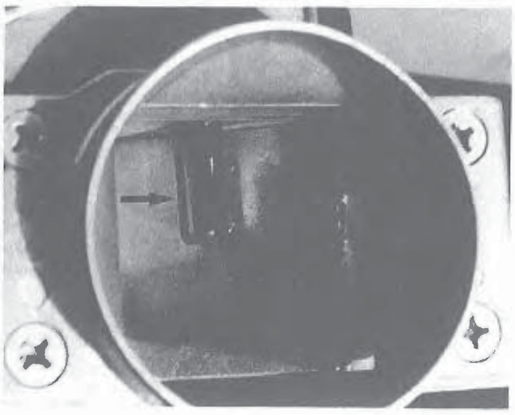


Fig. 2-34. This air-temperature sensor (**arrow**) (also called Temp I or NTC I) signals intake air temperature.

Cold Starting Enrichment. There are two ways that additional fuel can get to the engine during cold starting. The first is an auxiliary or cold-start injector which is controlled by the thermo-time switch. The second method is the Start Control System in the control unit which adjusts the pulse time of the fuel injectors as needed. Most L-Jetronics use the cold-start injector. Some combine that with start control; and a few use only start control.

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> One system missing from most fuel-injection engines is the Intake Air Heater, or Heated Air Cleaner. For emission control and driveability, carbureted and throttle-body-injected engines heat the intake air to about 100°F (40°C). Warmed air tends to prevent condensation of the air-fuel mixture on the intake walls, which causes stumbling and increased emissions from the lean mixture. Because L-Jetronic delivers fuel at the intake ports, it can compensate fuel flow as necessary, enriching for cooler air without wall wetting. Without the Intake Air Heater, L-Jetronic delivers cool air, with greater density, producing more power in cold conditions.

The cold-start injector (also called the cold-start valve) is energized during cold starting. When the key is turned to start, a relay delivers power to the start injector. A thermo-time switch grounds that circuit, causing fuel delivery based on switch temperature. This auxiliary injector does not operate through the control unit, and is not usually affected by the engine temperature sensor.

If installed the cold-start injector is easy to find, mounted on the intake manifold downstream of the throttle, as shown in Fig. 2-35. It has an electrical connector and a fuel line. Whenever the system is pressurized, the start injector is pressurized; that means it is under pressure whenever the engine is running, and for some time afterward. Why is that important? If this injector leaks, the engine runs rich.

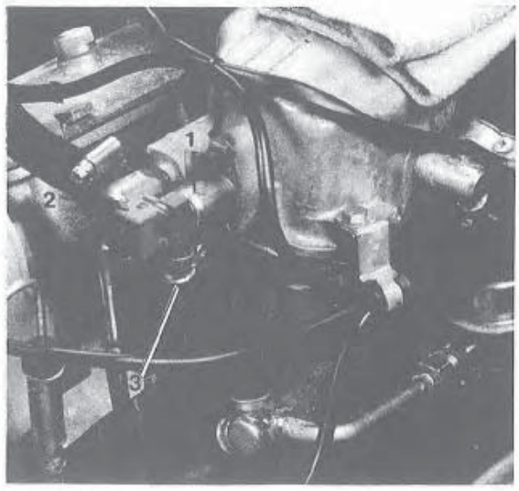


Fig. 2-35. Cold-start injector (**1**) delivers fuel into intake manifold to enrich mixture for all cylinders. Electrical connection is at **2**, fuel connection at **3**.

The cold-start injector is solenoid-operated, something like the port injectors, but it holds open for seconds rather than milliseconds. At system pressure, fuel enters through the fuel

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fitting; when current flows through the electrical connections, the solenoid lifts the armature from the valve seat. Fuel flows to the nozzle where it is swirled. That swirl action provides a fine vaporized mist that fills the manifold between the closed throttle and the intake valves.

The injector receives voltage whenever the key is in START position, but it only operates when it is grounded by the thermo-time switch. Think of this as a switch, not a resistor. It limits the open-time of the start injector to prevent flooding during cranking. See Fig. 2-36. Inside the housing is a bimetal switch arm surrounded by a heater winding. When the bimetal is cold, it closes the switch contact. The bimetal is a strip of two different metals bonded together; as it gets hot, it bends to open the contact.

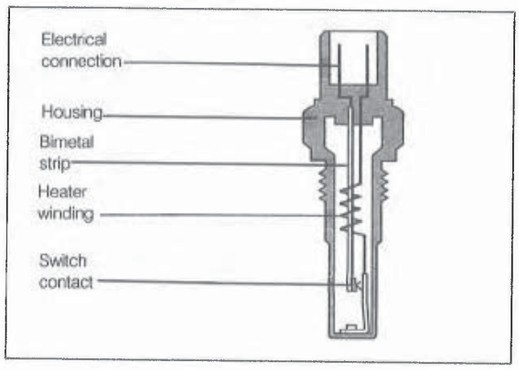


Fig. 2-36. Thermo-time switch bimetal opens start-injector circuit when coolant is warm, preventing flooding.

When you turn the key to START, that powers the start injector, and also powers the heater. If the engine is cold-cold, the closed switch grounds the circuit and the start injector delivers fuel. But as the heater winding warms the bimetal, it bends away and opens the grounding circuit, ending the start injection. Even at the coldest temperatures, the delivery time will be less than 10 seconds. Of course, delivery stops when you release the key from START. If the engine does not start for some reason, the already-heated bimetal will stay open, preventing excess fuel delivery. If the engine is warm-cold when you crank it, the bimetal is already bent to open the circuit as a result of coolant temperature. The result, no fuel delivery from the start injector.

Consider this auxiliary fuel injector in two terms: it must operate when the engine is cold, or the engine won't start. It must remain closed without spray or drip when the engine is warm, or the mixture will be rich. A leaking cold-start valve will cause hot-starting problems as fuel leaks into the manifold.

In the start control system, the control unit lengthens the injector pulses to the port injectors when the key is turned to START, based on the input from the engine temperature sensor. The colder the engine, the longer the pulses. To prevent flooding from repeated attempts to start, the control unit includes a recovery-time factor. This determines how many seconds must elapse before ⅔ of initial start-fuel quantity can be delivered.

In some cars, the start-control impulse is also influenced by the rpm during cranking, as shown in Fig. 2-37. The start-control impulse (t2) is superimposed on the basic pulse-time (t1). When the engine is cold-cold, cranking rpm is likely to be low. If so, the reduced-rpm signal causes the system to double the pulses, two per crankshaft revolution, and to add large compensation to the basic pulse-time. If the engine is warm, but cranking rpm is low, perhaps because of low battery voltage, less compensation is added, still 2 pulses per revolution. When the engine is warm, usually above 140°F (60°C), there is only 1 pulse per revolution.

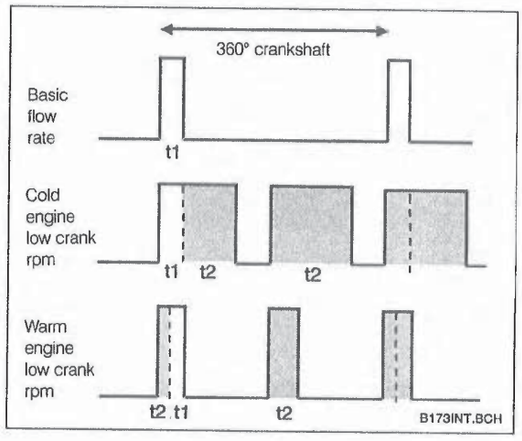


Fig. 2-37. On some systems, pulse time increases if engine is cold and turning slowly; pulse time decreases if engine is warm and turning slowly.

Auxiliary Air Valve. The auxiliary air valve helps the engine overcome the mechanical drag of a cold engine by adding additional air flow as shown in Fig. 2-38. It does this without racing the engine, as is common on engines with a fast-idle cam. Usually located on top of the cylinder head or valve cover, the auxiliary air valve can also be on the block because it is influenced by engine temperature. Look for it to bypass the throttle body with an auxiliary passage of air at barometric (atmospheric) pressure to the intake manifold at reduced manifold pressure. It is this pressure difference that causes the air flow when the valve is open.

The air bypassing the throttle through the auxiliary air valve is measured air; it has been measured by the air-flow sensor, so the required fuel is being delivered for injection. With the cold engine receiving extra air-fuel mixture, the extra friction resistance is overcome. Cold-idle rpm is increased, but will vary according to the engine manufacturer's calibration, as well as oil viscosity, engine condition and other variables. It is not rpm-controlled, as we'll see in later systems with idle-speed stabilization.

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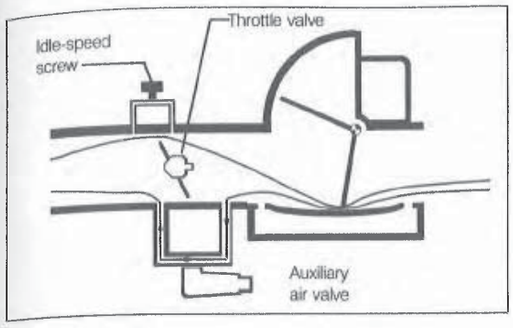


Fig. 2-38. Auxiliary air valve bypasses closed throttle when cold.

Two types of auxiliary air valves are used. Most are electrically heated, while a few early types are coolant heated. When the valve is cold, the blocking plate pivots to allow bypass air through the opening. When it is warm, the plate closes the opening.

Operation of the electrical type depends on the position of a bimetal arm, wrapped with an electric heating element, as shown in Fig. 2-39. When cold, the bimetal arm moves the blocking plate for maximum bypass air. When warm, the bimetal closes the opening. See Fig. 2-40. By shaping the hole in the plate, the designer can control the amount of bypass air for each engine temperature so idle rpms are close to the desired speeds.

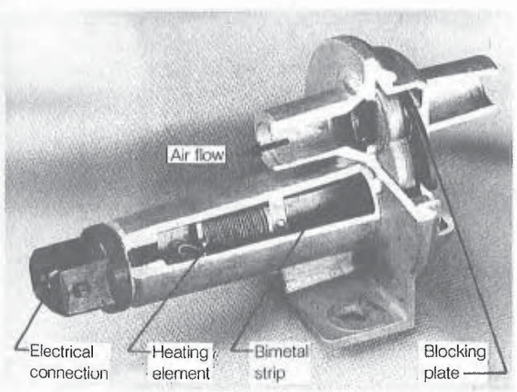


Fig. 2-39. Electric heating element closes auxiliary-air bypass in a maximum of 8 minutes from freezing.

The position of the bimetal depends on engine temperature and the length of time current flows through the heating element. When the engine is warm, the bimetal is influenced primarily by the block temperature. When the engine is cold and the plate is open, the heating element is the main influence on the bimetal. Where the delivery of auxiliary fuel for starting is generally timed in seconds, the delivery of auxiliary air is timed in minutes. From the coldest, the heater will close the bypass in about 8 minutes, faster than block warm-up would close it.

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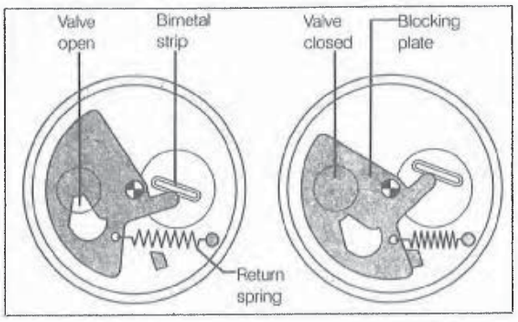


Fig. 2-40. Bypass opening closes when bimetal strip bends and spring pulls rotary valve.

Proper operation of the auxiliary air valve is important to driveability:

- for cold starts, and post-start, this valve must be open
- when the engine is warm, it must be closed to prevent fast-idle

In chapter 4, you will see two ways to check if the auxiliary air valve is functioning properly.

Post-Start and Warm-Up

You've already seen how the cold-engine idle rpm is affected by the auxiliary-air bypass. For post-start and warm-up fuel enrichment, pulse time of the port injectors is increased, but much less than during start control.

Bosch considers post-start, sometimes called after-start, as the first several seconds after the cold engine fires. The engine is running, but it needs a hefty enrichment factor. When the key is released from START to RUN, that ends the enrichment from the injectors, as much as 250%. For a start from ordinary temperatures, 70°F (20°C), the engine might need an enrichment factor of 150%, decreasing rapidly with time. This compensates for poor mixture formation and fuel coating of the manifold walls. The richer mixture increases torque, and therefore driveability.

After 20–30 seconds, the engine is considered into the warm-up phase, and the enrichment factor tapers off. Remember, driveability must be balanced with emission control; some engines can fail the EPA cold run test in the first 30 seconds. Warm-up driveability improves with more enrichment (or slower reduction of enrichment), but at the cost of high emissions.

Acceleration

How do L-Jetronics supply the acceleration enrichment ordinarily delivered by the accelerator pump of a carburetor?

Part-throttle. For part-throttle acceleration, the mixture is enriched by over-swing of the air vane. When you open the throttle quickly, the vane swings beyond the required position. This over-swing adds compensation pulse-time for a second or so until the vane stabilizes for the new air flow. During warm-up, the engine temperature sensor operates through the control unit to add additional enrichment compensation to the over-swing.

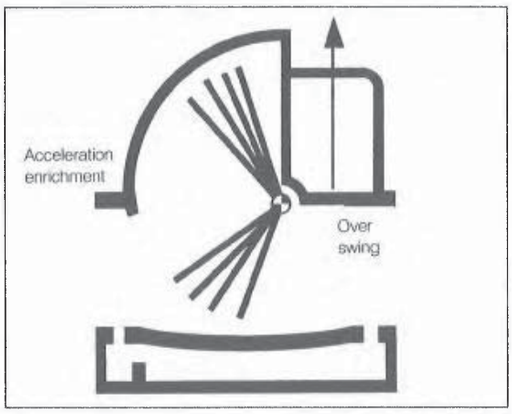


Fig. 2-41. Acceleration enrichment momentarily increases pulse time by over-swing with sudden throttle opening.

In some engines, over-swing enrichment is enhanced with electronic acceleration enrichment. The control unit evaluates how fast the air-flow sensor signal is changing. In effect, it looks at the velocity of vane movement. Above a certain voltage jump, acceleration enrichment begins, adding to the pulse-time. Electronic acceleration enrichment is modified or cancelled:

1. when the engine is warm
2. during starting
3. during manual shifting
4. at higher air flows

Full-throttle. Full-throttle acceleration enrichment is handled differently. When you floor the throttle, over-swing enrichment is delivered. But more importantly, a full-throttle signal is sent by the switch mounted on the throttle shaft. See Fig. 2-42. Sometimes you'll find microswitches out in the open; usually they are enclosed in a single unit as shown in Fig. 2-43. The full-load contact is closed by the cam on the throttle shaft, signalling the control unit to add enrichment. Full-throttle acceleration requires a rich mixture, so the control unit switches the system from closed-loop operation to open-loop, with the mixture determined by factory-programmed air-fuel ratios.

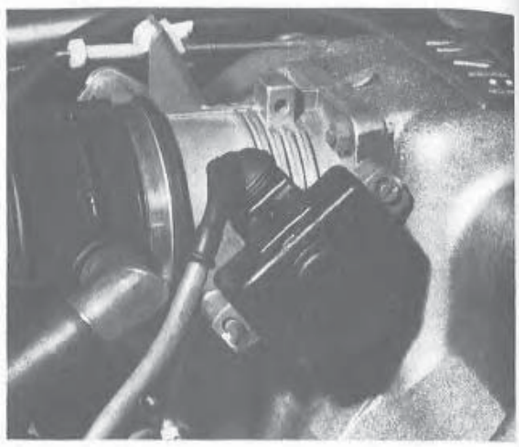


Fig. 2-42. Throttle switch is usually mounted directly on throttle shaft.

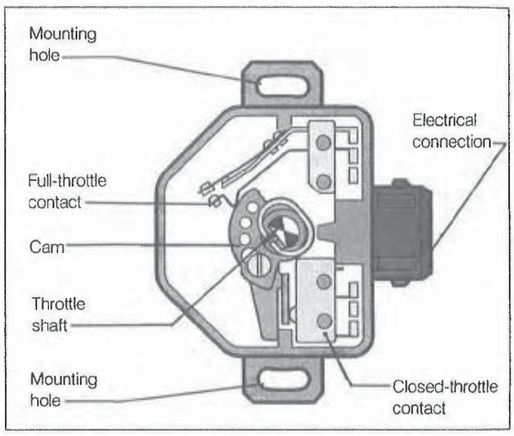


Fig. 2-43. Throttle switch signals full-throttle and fully closed throttle.

Idle and Drive-Off

Idle enrichment is usually signalled by the closed-throttle switch, shown above in Fig. 2-43. This switch was originally called the idle-switch, but in recent cars it signals closed throttle during coasting, and that's not idle, hence the name change. The switch is also closed by the cam on the throttle shaft, when the throttle is fully closed. When the computer receives an input that the throttle is closed, it adds compensation pulse-time to the basic flow rate, enriching the idle mixture. In chapter 4, you will see how simple it is to check the throttle switches for continuity.

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Increased fuel for drive-off from idle can improve driveability, particularly when the engine is cold, something like an accelerator pump improves drive-off of cold carbureted engines. In some cars, to improve driveability, when the closed-throttle contact circuit opens as the throttle is opened from idle, a special circuit adds compensation fuel, usually temperature-compensated.

Coasting Cut-Off

In later systems, fuel is cut off during coasting, or deceleration, when closed-throttle is signalled. This improves emission control and also fuel economy. In the control unit, the closed-throttle input is combined with inputs from engine temperature and rpm to determine the beginning of cut off and the end of it. Remember, as rpm drops toward idle, the closed-throttle switch may first signal for zero fuel, then at idle will signal for enrichment.

Anti-Search Circuitry

In some systems, transition from one mode to another is smoothed by anti-search circuitry. This part of the control unit looks for sudden changes in rpm, either deceleration or acceleration. It keeps the engine from searching for the proper flow during the transition, improving driveability.

RPM Limitation

When some engines approach red line, the computer compares engine rpm to a programmed limit-rpm. As soon as engine rpm rises above the limit, the injectors receive pulse-time signals once per every two crankshaft revolutions, cutting fuel flow in half. As soon as rpm drops, every-revolution signals resume. You'll feel as if the the car is first decelerating, but if you hold the throttle open, you'll feel the engine surge as rpm cycles around the limit. See Fig. 2-44. In some cars, drivers report rpm limitation differs slightly from the tachometer red line. During a quick run-up through the gears, good drivers shift before the rpm-limitation cut-off.

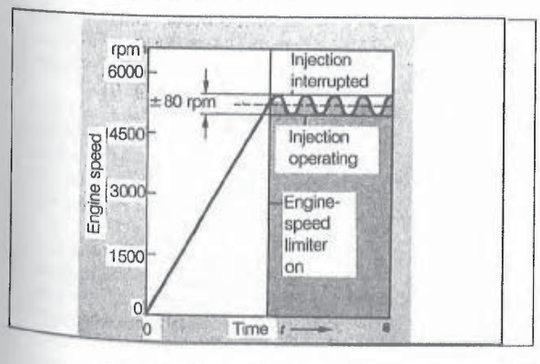


Fig. 2-44. Engine-speed limiter holds rpm at maximum allowed ±80 rpm, only one injection per 4-stroke cycle.

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Pulse-Period Limitation

Recall the earlier discussion of pulse period, the time available for injector-open pulse time. Pulse-period limitation circuitry operates under two conditions to limit pulse time:

1. Lower limit: at high revs, in overrun or coasting, minimum pulse time must be limited to prevent excess Hydro Carbons from too-lean mixtures;

2. Upper limit: at low revs, during full acceleration, maximum pulse time must be limited to prevent too-rich mixtures, causing stumbling, depending on temperature.

Lambda Control

You'll remember from chapter 2 the discussion of the ideal air-fuel ratio (lambda) and its relation to emissions. On most systems, the air-fuel ratio for best emission control is achieved by sensing the oxygen content of the exhaust gas with a lambda sensor, shown in Fig. 2-45. The lambda sensor's signal is monitored by the control unit, which then adjusts pulse time to maintain the ideal air-fuel ratio. The system operates closed-loop.

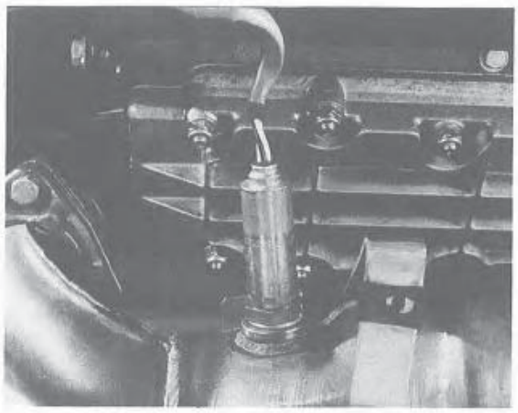


Fig. 2-45. Lambda sensor looks something like a spark plug installed in exhaust pipe or exhaust manifold to sense oxygen content of exhaust gas. The closer to the exhaust valves, the faster it heats up.

Lambda Sensor Design and Operation. The lambda sensor is essentially a small battery that generates a voltage signal based on the differential between the oxygen content of the exhaust gas, and the oxygen content of the ambient air.

A cutaway view of the lambda sensor is shown in Fig. 2-46. The tip of the sensor that protrudes into the exhaust gas is hollow, so that the interior of the tip can be exposed to the ambient air. Both sides of the ceramic tip of the sensor are covered with metal electrodes that react to create a voltage only if the ambient air has a higher oxygen content than the exhaust and the ceramic material is hotter than 575°F (300°C)

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When these conditions are met, voltage is generated between the two sides of the tip. The voltage is usually about 1 volt. But if the engine is running lean, the exhaust gas has about the same amount of oxygen as the ambient air, so the lambda sensor will generate little or no voltage; if the engine is running rich, the oxygen content of the exhaust will be much lower than the ambient air and the sensor voltage will be larger. See Fig. 2-47.

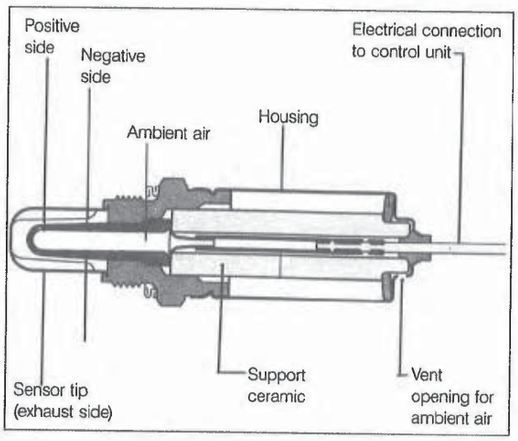


Fig. 2-46. Cutaway view of lambda sensor.

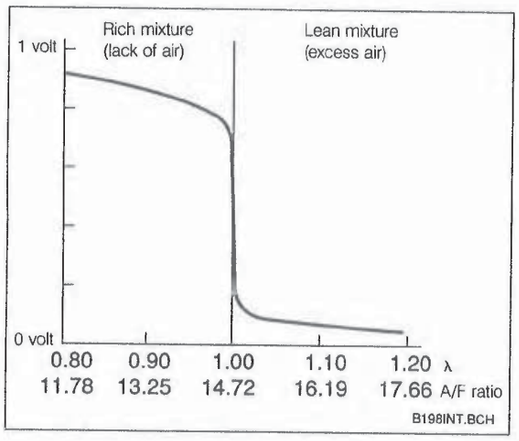


Fig. 2-47. Rich mixture and low content of oxygen in exhaust causes voltage output from oxygen sensor. Remember, rich = voltage.

Some cars have a lambda sensor that has a heating element built-in to speed warming of the sensor to improve the driveability and reduce the emissions of a cold engine. On a cold engine, it may take 90 to 120 seconds for an unheated lambda sensor to get warm enough to start generating voltage, while a heated sensor may be warm enough after 10 to 15 seconds.

Lambda Closed-Loop Control. Recall the discussion of open-loop/closed-loop systems in chapter 2. The lambda sensor and the control unit form a closed-loop system that continually adjusts the air-fuel ratio by means of the fuel-injector pulse time. For example, the sensor generates a high voltage because the mixture is rich, so the control unit reduces pulse time to lean the mixture. Sensor voltage falls, so the control unit increases pulse time to enrich the mixture. Sensor voltage increases, etc....

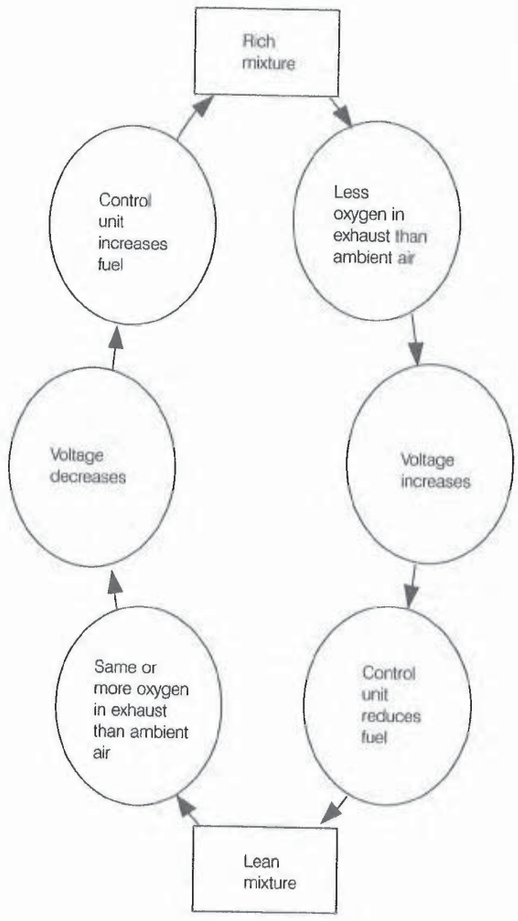


Fig. 2-48. Since about 1980, fuel-injected engines operate closed-loop most of the time.

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The lambda sensor voltage is always fluctuating as shown in Fig. 2-49, so it is hard to maintain the exact point at which the air-fuel ratio is ideal. Instead, the ratio tends to oscillate to either side of the ideal ratio, but the oscillation is so fine (about 0.1% change in the air-fuel ratio) that it is not noticeable in engine performance. The rate of the air-fuel ratio oscillation is related to the quantity of exhaust passing the sensor. At idle, the cycle from lean to rich and back again may take 1 to 2 seconds. At cruising speed, the cycle may happen several times a second.

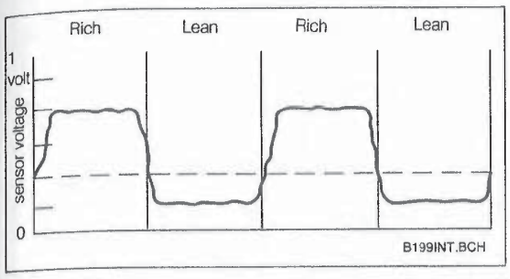


Fig. 2-49. Closed-loop lambda sensor voltage cycles back and forth from slightly rich to slightly lean. In chapter 4, you'll measure the effects of this cycling.

This closed-loop system can compensate to some degree for changes in the engine over time. For example, if a valve is leaking slightly, or if there is an intake air leak, the lambda sensor senses the change in combustion and brings the system back within its design limits. This has been described as having a skilled technician under the hood, continuously tuning the mixture for best operation under all conditions. Changes beyond the system's range, though, can still lead to driveability problems.

When the oxygen sensor is cold and not generating a voltage signal, the control unit is programmed to operate open-loop at a programmed injection rate. The same thing happens if you disconnect or cut the lambda sensor wire, or if the sensor is fouled by leaded gasoline. This becomes important when you are trying to make closed-loop adjustments at idle, but the sensor cools off because not enough exhaust is passing it. Many service procedures depend on closed-loop operation, so remember that the sensor has to be warm enough.

As you'll see in the service chapters, the lambda control system is properly adjusted when engine-out CO is the same whether the system is closed-loop or open-loop. This adjustment point allows the system its full range of compensation for operating conditions.

L-Jetronics have been used since 1974. Engines adapt easily to L-Jetronic. In 1980, when tighter U.S. emission limits were mandated, virtually every European car imported to the U.S. which had used carburetors in 1979 switched to L-Jetronic. Those that did not, switched to K-Jetronic.

2.6 LU-Jetronic

LU-Jetronic is a refinement of L-Jetronic, used in few cars in the U.S. In fact, the U stands for U.S.; it is a lambda-control version of a refined Jetronic used in Europe: LE-Jetronic. Its main features are optimized circuitry in the control unit, and a start control system. The control unit is analog. You'll find it in:

- a few BMW 3 series, used before switching to Motronic
- 1983–84 California AMC Alliances when the Bendix central fuel-injection system system could not meet California emission limits
- a few late-model Renault Fuego and 18i

3. LH-JETRONIC

LH-Jetronic is a further refinement of L-Jetronic. The main difference between the two systems is the method of measuring air flow on LH-Jetronic. Instead of an air-flow sensor, LH systems use something called an air-mass sensor, which you'll learn more about later. All LH-Jetronics use lambda control, and the control unit is digital, not analog.

Volvo was the first user of LH-Jetronic systems on the 1982 Volvo GL with the 2.3 liter 4-cylinder engine. By 1987 all Volvo engines, including the 2.6 liter V6, were using LH-Jetronic. The first Volvo system is identified as LH 1. In addition to the differences mentioned above, it uses a vacuum switch to signal inlet pressure (instead of a throttle switch), and uses an auxiliary air valve, the same as on L-Jetronic.

Since 1984, LH systems are identified as LH 2. Instead of the auxiliary air valve, LH 2 has an idle-speed stabilizer for automatic idle speed control. The LH 1 vacuum switch is replaced by the throttle switch. Since 1988, LH-Motronic combines the air-mass sensor with control of ignition timing as well as adaptive control and diagnostics. See **4. Motronic Systems**.

3.1 Air-Mass Sensor

The air-mass sensor is completely electronic. It depends on the measurement of current flowing through heated wires to measure air flow. It is also known as the hot-wire sensor because of its heated-wire design, hence the "H" in LH. It has several advantages over the vane-type air-flow sensors of L-Jetronic.

1. It measures air mass, or weight, so it requires no correction for changes in density due to temperature or altitude. The air-fuel mixture ratio depends on mass: so much weight of fuel mixed with so much weight of air. Measuring mass eliminates the need for compensation sensors: air temperature, and altitude. It also reduces correcting computations in the control unit.

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2. It has no moving parts. That means mechanical simplification. It responds even faster than the moving vane of the air-flow sensor. Measurements follow changes in air-mass in 1–3 milliseconds.

3. It offers insignificant resistance to the passage of air. Even at maximum air flow, drag force on the wire is measured in milligrams.

Air-mass measurement by hot-wire improves driveability, stability, and reliability. It is used in racing. In my opinion, air-mass sensing will probably supplant the measurement of air flow by vane-type sensors.

Air-Mass Sensor Design and Operation

Underhood, between the air cleaner and the manifold, you'll see a simple black plastic cylinder with an electronic box, as shown in Fig. 3-1. If you remove it and look inside the protective screens, you may be able to see the small platinum resistance, or hot wires, that are suspended inside the cylinder so that the intake air can flow over them. See Fig. 3-2. How fine are these wires? The diameter is 70 micrometers—that's less than 1/10 millimeter, finer than a human hair. By careful design of the sensor and its mounting, the fine wires survive automobile vibration. In the unlikely event a wire should break, the warm engine runs, though without fuel compensation, in a limp-home mode. You can simulate limp-home mode by driving the car after pulling the air-mass sensor connector of a warm engine.

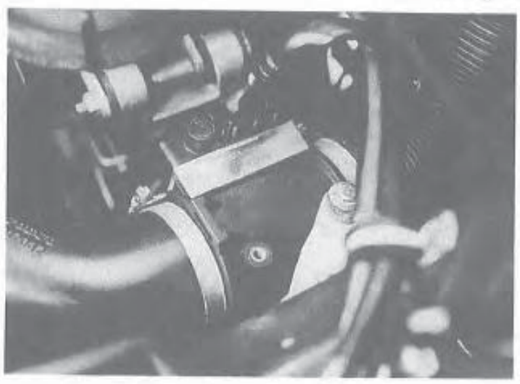


Fig. 3-1. Look for air-mass sensor between air cleaner and intake manifold.

The hot-wire system depends on measurement of the cooling effect of the intake air moving across the heated wires. Suppose you had a fan blowing across an electric heater. With a small movement of air past the heated wires, the cooling effect is small. With more air moving past the heated wires, the cooling effect is greater.

LH control circuits use this effect to measure how much air passes the LH hot wire. The hot wire is heated to a specific temperature differential 180°F (100°C) above the incoming air when the ignition is turned on. As soon as air flows over the wire, the wire is cooled. The control circuits then apply more voltage to keep the wire at the original temperature differential. This creates a voltage signal which the control unit monitors; the greater the air flow (and wire cooling) the greater the signal.

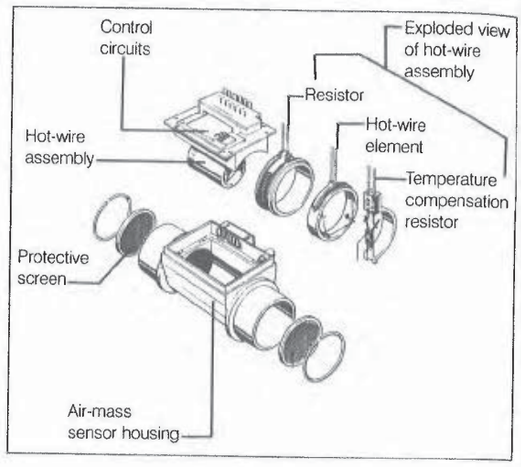


Fig. 3-2. Air-mass sensor includes hot-wire assembly and control circuits.

Control Circuits. The LH control circuits use a Wheatstone bridge, as shown in Fig. 3-3. The hot wire is one leg of a bridge circuit whose output voltage is held to zero by regulating the heating current. The hot wire, known as Rh, changes resistance with temperature. Incoming air passes over the hot-wire, Rh, and also over another resistance wire, Rk. The same voltage is applied to both wires. In series with Rk are two fixed resistances, R1 and R2; in series with our hot wire, Rh, is fixed resistance R3.

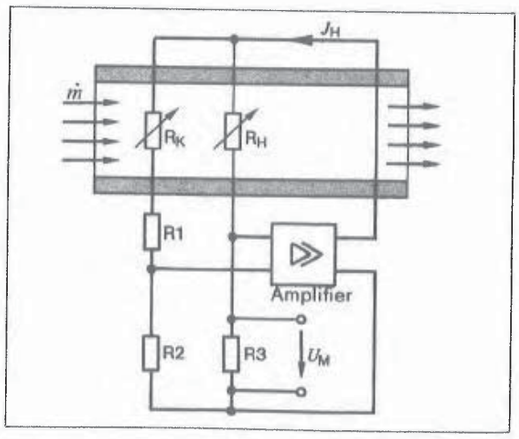


Fig. 3-3. Wheatstone bridge principle explains maintenance of hot-wire temperature.

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The Rh wire is controlled to be 180°F (100°C) hotter than the intake air flowing through. For example, if the air is at freezing, 32°F (0°C), the wire will be heated to 212°F (100°C). On a hot day, if the air is at 86°F (30°C), the control circuits heat the wire to the same 180°F (100°C) difference, to 266°F (130°C).

The air mass changes when the driver changes the throttle opening:

1. more air passes over both resistance wires in the air-mass meter;
2. both Rh and Rk are cooled by the increased air mass;
3. Rh decreases its resistance, because of its Positive Temperature Coefficient;
4. current flowing through Rh increases more than the current through Rk;
5. that unbalances the bridge circuit;
6. comparator increases its output;
7. amplifier increases current (Jh) to bring Rh back to its original resistance, and thus its original temperature back to 180°F (100°C) above ambient temperature of the intake air;
8. the heating current is measured as a voltage drop (Um) across the fixed resistance R3;
9. this voltage drop is a measure the air mass and is used as the output signal to the control unit.

All this happens is 1–3 milliseconds.

The air mass can also change because air temperature or altitude changed its density.

Control Unit Inputs and Outputs. LH-Jetronic control of injection pulse time is the same as in L-Jetronic. Low engine speeds mean a smaller air flow. As the air mass increases, the air-mass sensor control circuits provide an output voltage signal to the control unit, and pulse time is adjusted accordingly. Note that in contrast to L-Jetronic, the LH-Jetronic air-mass signal increases with air flow.

For limp-home operation, pulse time is fixed. Each pulse is delivered to the injectors with no compensation. For any rpm above idle, the control unit is programmed to deliver fixed pulses, typically 7.5 milliseconds. Of course, the faster the engine turns, the more pulses are delivered and the more fuel is injected. When the closed-throttle switch completes its circuit, each fixed pulse is a little shorter, typically about 5 milliseconds to keep the idling engine from running too rich.

Shut-Off, Hot-Wire Cleaning. With the air-mass sensor connected for normal operation, the hot wire does not glow. It does not look hot, any more than the heated wires in a rear-window defroster do.

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But shortly after you shut off the engine, the control system will heat the wire red hot for about one second, hot enough to burn off any dirt. See Fig. 3-4. Because of the hot-wire cleaning, LH is ready to start every time with a clean wire.

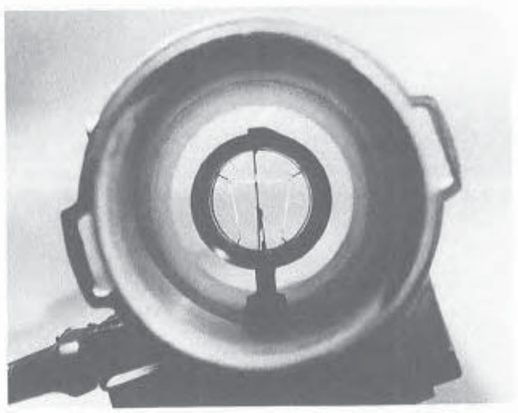


Fig. 3-4. LH hot wire glows at 1800°F (1000°C) during burn-off at engine shut-down.

How's this for attention to detail: There's no burn-off unless the engine has run above 3000 rpm; that usually happens normally each time the car is driven. That way, restart won't normally happen with an 1800°F (1000°C) hot wire. Further, there's no burn-off if the engine stops running at less than 200 rpm; the engine would not be running at such a low rpm, so it has stalled. This prevents the hot wire from glowing after an accident.

In normal operation, don't suspect the wire is inoperative if it fails to glow. The wire is so fine you may not even see it unless the light is right, so don't suspect it is broken if you can't see it right away. You can measure the output signal, as described in chapter 4.

Mixture Adjustment. You'll find the idle-mixture adjustment screw on the side of the air-mass sensor, under a seal. Electronic circuits inside this sensor are not serviceable. When you adjust idle mixture, you adjust the voltage signal from the air-mass sensor by turning a potentiometer, a variable resistor. Because it is an electrical adjustment, it feels different; it turns more turns than the mechanical adjustment of L-Jetronic airflow sensor.

3.2 Idle-Speed Stabilizer

On most LH-Jetronics (LH 2 and later) the idle-speed stabilizer replaces the auxiliary-air valve. See Fig. 3-5. Idle-speed stabilizers can have different shapes, but they all work the same. They change the amount of air that bypasses the closed throttle. You'll remember this is measured air so it changes the amount of air and fuel to the engine, which changes idle speed, not mixture.

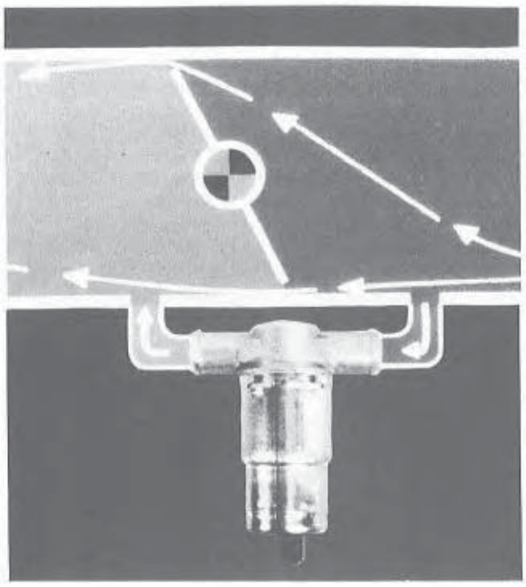


Fig. 3-5. Idle-speed stabilizer allows measured air to bypass closed throttle.

In a cutaway in Fig. 3-6, you can see the rotary valve that turns slightly to change the opening for the bypass air. The stabilizer may look like a motor, but it's not. Signals from the control unit drive the valve toward open.

Bosch also calls the idle-speed stabilizer an actuator. On other cars, a similar device could be called an idle-air control, idle-speed compensator, or idle-speed control. The distinction is whether it actually controls rpm by measuring rpm—a closed-loop system—or on some preprogrammed basis—an open-loop system.

Experts can be fooled by other terminology. Some call idle-speed stabilization CIS—Constant Idle Speed. For our purposes, CIS means Continuous Injection System.

Dwell Signals

The opening of the idle-speed stabilizer depends on the percent dwell—the on-off ratio—of the digital control signals from the control unit. Note that digital signals are on-off, nothing in between. Measuring the on-off ratio tells you the percentage of time that current is on, something like a dwell meter measures ignition-points closing time. The greater the on-off ratio, the further open the stabilizer and the more air will bypass the throttle. For a normal warm engine at idle, the stabilizer is open part-way with a typical dwell of 32%. You can use a dwell meter to measure the on-off ratio, as discussed in chapter 4.

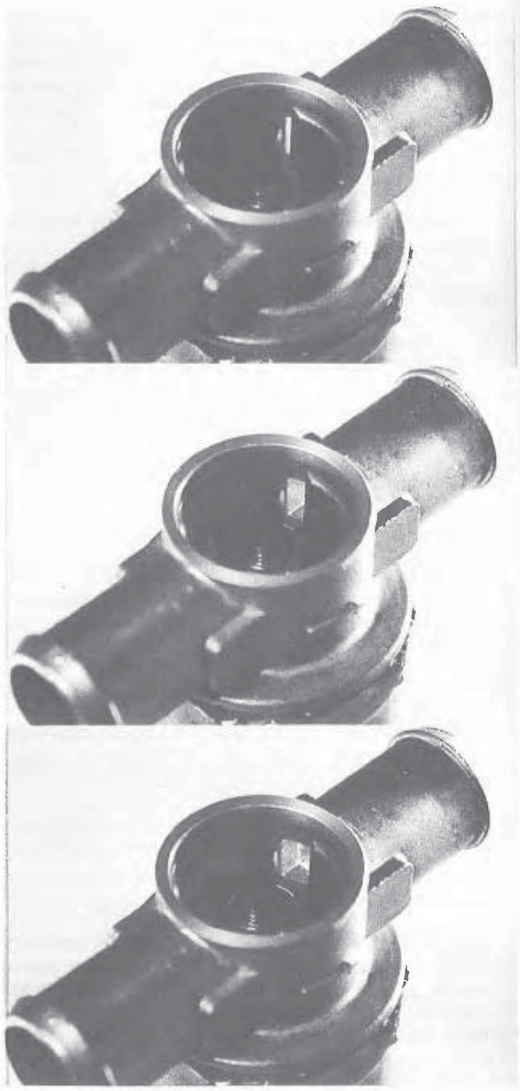


Fig. 3-6. Idle-speed stabilizer valve controls rpm. Smaller opening (top) reduces idle rpm. Medium opening (middle), normal rpm. Larger opening increases idle rpm.

RPM Stabilization

The idle-speed stabilizer is a closed-loop governor that holds a steady rpm. If load is added to the engine—such as when the lights are turned on, increasing alternator drag—the control unit increases the on-off ratio; that keeps the engine speed steady at normal idle. It can keep engine rpm steady for other loads too, such as power steering, or shifting the automatic transmission from Neutral to Drive.

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On some cars with automatic transmission (A/T), the idle-speed stabilizer operates to reduce creep at stoplights. While the transmission is in Neutral, engine idle rpm might be governed at 1000 rpm at a temperature of −4°F (−20°C). When the engine is warm, Neutral idle rpm might be 750. But while the A/T is in Drive, the stabilizer may cut back the idle rpm to 670. This luxury touch pleases some drivers, and is possible if the engine does not exhibit roughness at the lower revs.

On the other hand, the stabilizer can work to increase rpm. Turning on the air conditioner (A/C) usually requires higher idle speeds to insure adequate A/C cooling. The input signal to the control unit may be one or more switches:

- driver's actuation of the A/C switch
- closing of the circuit for the A/C magnetic clutch
- pressure increase in the high-pressure side of the compressor

Idle-speed stabilization can also avoid an rpm drop when switching on the A/C. The engine control unit talks to the A/C control, and delays energizing the A/C compressor for about ⅓ second after the A/C is switched on at idle. This gives the stabilizer time to hold or increase idle rpm as necessary for the load of the A/C compressor. On the other hand, while in Drive, A/C operation will not raise the rpm, which could cause creep of a stopped car idling in Drive.

When you service the engine, it can be important to know the difference between:

- closed-loop idle-speed stabilizer
- open-loop systems, such as:
  - Bosch auxiliary-air valve
  - fast-idle cam
  - fixed-position throttle positioner

While open-loop systems increase the air flow into the engine, with most of those, rpm will vary according to engine temperature, engine condition, weight of oil in the crankcase, whether the transmission is in Drive or Neutral, and many other variables. Unless rpm is sensed, fast-idle rpm must usually be set higher to handle unforeseen variations, higher rpm than would be necessary on an engine with an idle-speed stabilizer.

Because the idle-speed stabilizer usually operates closed-loop on the basis of engine rpm, it needs to increase rpm less for cold conditions. This saves stop-light fuel and reduces emissions. In closed-loop, it will maintain idle rpm with small-load changes. As rpm drops, the stabilizer receives control unit dwell signals to bypass extra air to keep the engine from stalling.

Cranking the engine will cause an open-loop signal to increase the air flow as needed. Cold engine temperatures will increase idle rpm, usually only a few hundred rpm from the normal warm idle speed.

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When the car coasts, the stabilizer will receive a brief open-loop increase-bypass signal, based on how rapidly the air-flow signal drops toward zero. Functioning in a manner similar to a throttle dashpot, this provides a gradual drop in manifold pressure, helping to reduce the emission of Hydro Carbons.

Because the idle-speed stabilizer automatically controls engine rpm, you must be alert when making an rpm drop test for the injectors or ignition. The fact is, with the idle-speed stabilizer working, you probably won't get any rpm drop; that can be confusing if you don't realize what the stabilizer does. For example, suppose you disconnect one injector. When the stabilizer is working, the engine does not slow down the way you'd expect it to. As soon as the rpm starts to drop off, the stabilizer opens, to increase rpm back to normal.

Adaptive Control

Beginning with some 1984 systems, idle-speed stabilization can be adaptive. That means that, during the lifetime of the engine, it will adapt the idle rpm setting to compensate for changes in internal friction. Adaptation takes place as the engine idles for a few minutes. This dwell value is stored in the control unit non-volatile memory which then becomes the center point for increase/decrease rpm signals.

Idle Speed Adjustments

Although idle speed is automatically controlled, in some cars you may still need to set the basic idle speed (lower than curb idle) with a knob, changing the amount of bypass air. You have to ground the idle-speed stabilizer as mentioned above, so it is fixed. When you remove the grounding, the engine will seem to take a gulp of air as the stabilizer rapidly opens; then rpm steadies at normal idle.

On the newest systems, idle-speed stabilization has become so well controlled by adaptive circuits in the control unit that no adjustment is provided for idle mixture or idle rpm. For more on adaptive circuits, see **4. Motronic Systems**.

4. Motronic Systems

In simple terms, Motronic is an engine-management system with a single control unit for control of ignition timing as well as fuel-injection. Many of the sensors important for fuel injection are also needed for ignition-system control, as shown in Fig. 4-1, so the integration of the two systems can accomplish many things that L-Jetronic and LH-Jetronic can't:

- Integrated control of fuel injection and ignition can manage the engine better than control of either one alone. That is, timing is sometimes dependent on the air-fuel ratio, and vice versa; also, emissions can be reduced by coordinated control

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- Engine control can be based on actual needs of each engine model based on large amounts of engine-test data during different operating conditions stored in the Motronic Read Only Memory (ROM)
- Many additional operating functions can be provided. Important from the standpoint of service are the adaptive functions, and the self-diagnostics for troubleshooting
- Motronic advantages are better driveability and fuel efficiency, and reduced emissions. More specific benefits:

1. fuel savings achieved from best combination of mixture and timing
2. dependable starting, cold or hot
3. stable idling at reduced rpm
4. relative freedom from maintenance
5. good torque characteristics, allowing longer gear ratios

Applications—Identifying Features

Motronic systems use the same pulsed fuel injection principle as the L-Jetronic systems described earlier, so many of the functions and components are the same. This section covers those Motronic functions and components which are additional to basic L-Jetronic fuel injection.

Underhood, how do you tell a pulsed Motronic system? Most "L" Motronic systems use the vane-type air-flow sensor as in L-Jetronic. Some Motronic systems also operate with the air-mass sensor of the LH-Jetronic, as in BMW 750i V12 (known as LH-Motronic). So checking these components won't immediately identify a pulsed Motronic system.

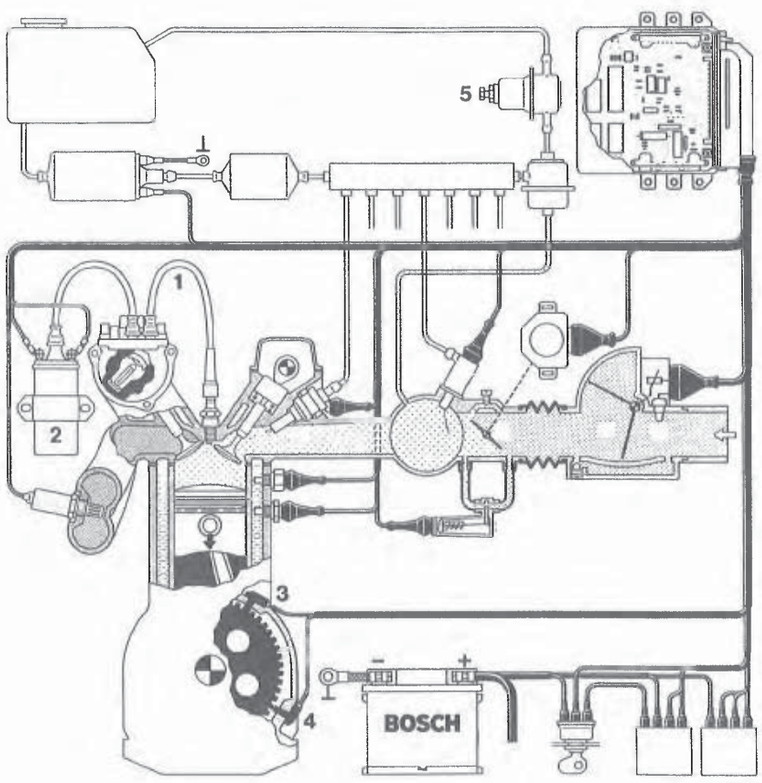


Fig. 4-1. Motronic schematic shows ignition system (**1, 2**), crankshaft signalling (**3, 4**), and pulsation damper (**5**) added to L-Jetronic.

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Try looking at the distributor as shown in Fig. 4-2; a Motronic distributor will not have vacuum hoses—or centrifugal weights inside. But even this can be confusing. Some 6-cylinder Porsche 911 engines use centrifugal weights to advance the rotor during high rpm for better contact between the rotor and the cap contacts, but not to affect ignition timing. Several cars, such as Porsche 928 and Peugeot 505STX have separate electronic ignition controls, no vacuum hoses or weights, and are not considered Motronic systems. Don't be confused by systems that control distribution of ignition-firing pulses, so-called distributorless ignition.

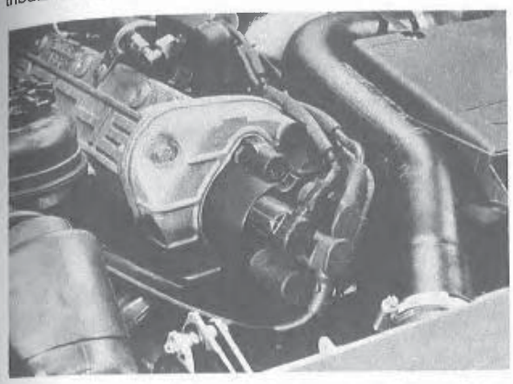


Fig. 4-2. Most Motronic distributors are simple; no vacuum hoses, no centrifugal weights. With distributorless ignition, the control unit times and distributes power to multiple coils.

The best way to identify Motronic is to check your vehicle specs. With modern, complex engines, you cannot guess about engine management systems; you must have the vehicle shop manual.

4.1 Ignition Timing Control

I'm talking here about more than electronic ignition—the systems that have replaced the points and condensers of yesterday. I'm talking about microcomputer control of ignition-advance angle for every plug firing, or at most, every two plug firings. The millisecond response time of electronic ignition-advance control is far faster than the traditional mechanical flyweight/vacuum advance systems.

In a mechanical system (and that includes electronic ignition), as rpm increases, centrifugal weights advance timing. Changing load (manifold pressure) can further change timing advance with a vacuum diaphragm. As rpm increases, there is less dwell time for the coil to charge when perhaps the engine needs more spark energy.

Traditional curves for distributor timing show the limited control of timing advance possible. A timing point that is proper for one combination of rpm and load is probably wrong for other combinations of centrifugal weight position and vacuum diaphragm action. Once the vacuum control or the centrifugal weights reach their limits, advance control is fixed. Mechanical timing has been patched with more vacuum hoses, temperature and delay valves, and other servicing headaches; it's still a compromise. Even at its best, this control falls far short of the precise and rapid timing needed by today's cars.

In Motronic systems, however, the control unit processes a number of inputs as shown in Fig. 4-3, and then adjusts timing for all conditions based on its internal data map.

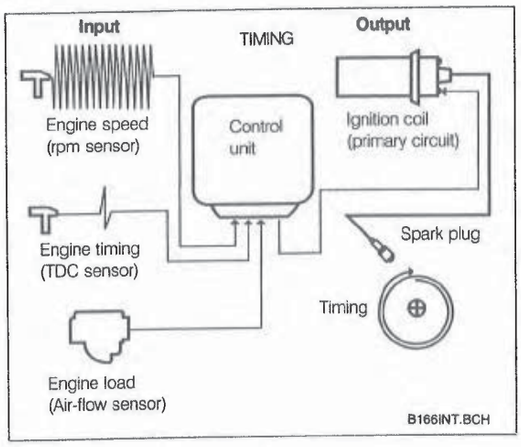


Fig. 4-3. Timing is controlled by the control unit by inputs of rpm, TDC, and load. Control unit controls charging of coil.

Timing Data "Maps"

To determine precise timing-advance requirements, each family of engines is tested to learn the best timing for each condition of speed, load, and other variables in heat and cold, on the dynamometer and in the mountains. The goal is to find the timing for best power, for best economy, all the while meeting emission limits.

The result of these tests is a series of data "maps", as shown in Fig. 4-4. Literally thousands of data points from these tests are stored in the computer memory of the Motronic control unit ROM (Read Only Memory) for readout during engine operation. As you may know, a ROM cannot be changed. For any combination of engine load and rpm, the control unit can supply the best ignition timing. For example, for an rpm-input signal of 2000 rpm, at a load signalled by the air-flow sensor, the computer would look up the timing advance angle, let's say it should be 22 degrees BTDC.

But control is even more precise. Suppose the rpm were 2050, and the memory contained only data points for 2000 and 2100; then the computer would look up both 2000=22 degrees BTDC, and 2100=24 degrees BTDC, and interpolate. It would calculate an advance for the 50 rpm difference between

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2000 and 2050, and would output timing of 23 degrees BTDC. In the control unit, timing is computed so fast that Motronic can adjust timing for every firing of each spark plug!

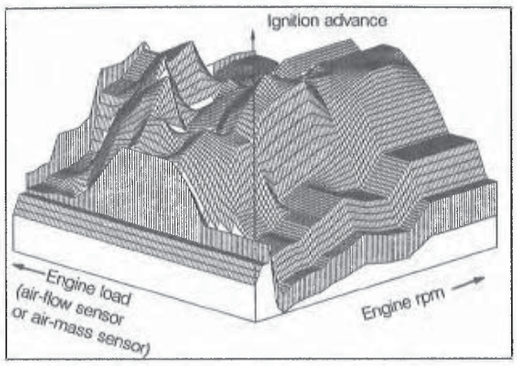


Fig. 4-4. Ignition advance map shows electronic timing control according to engine load and speed. Maps are symbolic of thousands of data points stored in control unit memory. Don't confuse these maps with term MAP, commonly applied to Manifold Absolute Pressure.

Distributor

Because it does not control timing or signal rpm, the Motronic distributor's only job is to distribute the secondary, that is to send the control-unit-timed spark to the proper cylinder.

While timing and dwell were formerly dependent on each other, Motronic memory provides separate dwell-angle data, based on battery voltage and rpm. Later, we'll see how timing and dwell control improve starting and other variations, but here are the principles.

Dwell-Angle Control

As engine rpm increases on mechanical advance systems, there is less dwell time for the coil to charge between firings, resulting in a fall-off of coil voltage. In Motronic systems, dwell angle is electronically controlled so the coil receives the proper current at the time of plug firing. The more battery voltage, the less dwell angle needed. On the other hand, as rpm increases, more dwell angle is needed for the time to charge the coil. By controlling dwell angle, the coil is charged properly for each ignition firing, no more, no less. The objective is to provide the required secondary power at the plug at the moment of firing with minimum losses in the ignition output transistor and the coil.

To reach the nominal value of primary current at the moment of firing, the dwell angle is changed according to the battery voltage as shown in Fig. 4-6. When battery voltage is less, dwell time is increased. In effect, the dwell control answers the question: "When should the primary circuit be closed for the optimum time for the coil primary current to rise to proper value at moment of opening primary circuit?" In addition, the control-unit output stage limits current so that if, due to rapid engine speed changes as in acceleration, current reaches the nominal value before the ignition point, current is held constant.

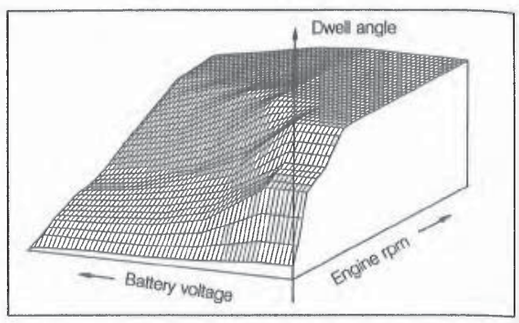


Fig. 4-5. Dwell angle is controlled for battery voltage and engine speed, according to memory map in control unit.

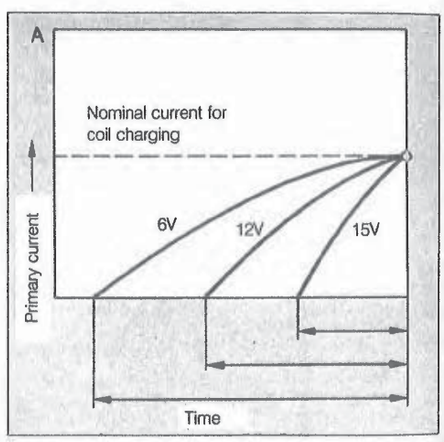


Fig. 4-6. The lower the battery voltage, the longer it takes to charge the primary in the coil.

So engine rpm, and battery voltage are inputs to the control unit. From dwell-angle data in the ROM, control unit output is the dwell, or charge-time control, that conserves energy and prevents overheating the coil. Also, if the rpm signal indicates less than 30 rpm, as when the engine stops or the key is left on with the engine stopped, primary cut-off prevents coil overheating.

Now that you understand the basics of Motronic ignition control, let's look at the rest of the Motronic system and draw similarities and differences from the Jetronic systems described earlier.

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4.2 Air and Fuel Systems

The basic flow rate is still determined by the air-flow signal and by the rpm signal. But in Motronic systems, the rpm signal comes from the flywheel rpm sensor instead of from the distributor. Also, the pulsed Motronic air-flow sensor signal increases with increasing air flow, a direct relationship. Remember, in the L-Jetronic air-flow sensor, the signal decreases with increasing air flow.

Pulsation Damper

The Motronic fuel system is quite similar; see the L-Jetronic section for details of the pump, distributor pipe, pressure regulator, and injectors. Some Motronic cars add a pulsation damper on the fuel rail, to reduce pressure fluctuations and noise in the system. It looks similar to the pressure regulator as shown in Fig. 4-7, so learn to tell them apart. Although each has a hose connection on its base, the pulsation damper hose does not have a pressure function; it provides for a possible rupture in the diaphragm, dumping the fuel into the manifold instead of spilling it on the engine. How else do you tell the difference? The pressure regulator is on the high pressure side; the damper is on the low pressure, or return side.

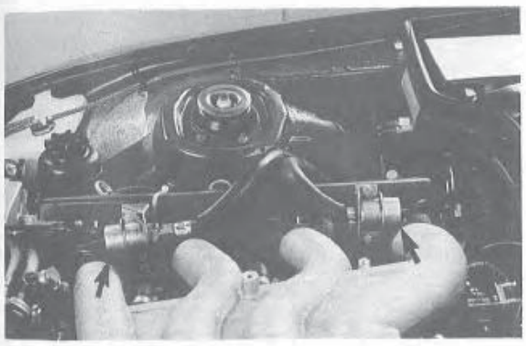


Fig. 4-7. Fuel pressure regulator (right) and fuel pulsation damper (left) look similar, so be careful when servicing them.

4.3 Control Unit

Motronic systems make extensive use of other data maps stored in ROM for many of the control unit functions, including:

1. fuel injection
2. lambda closed-loop control
3. warm-up
4. acceleration
5. ignition timing
6. dwell angle
7. EGR
8. idle-speed control

Data "Maps"

The main map in the control unit is a set of lambda memory-points used to determine the desired air-fuel ratio for the fuel injection pulses. The lambda memory map, shown in Fig. 4-8, is derived from lab and road tests, and modified for the requirements of the vehicle and the country where it will operate:

- at part load, maximum economy and minimum emissions
- at wide-open throttle, maximum torque while avoiding knocking
- at idle, maximum smoothness
- during throttle opening, maximum driveability

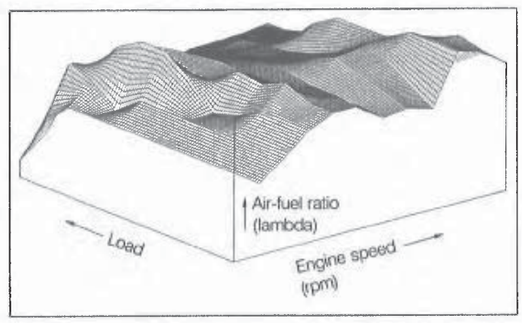


Fig. 4-8. Lambda "map" establishes lambda, or air-fuel ratio for each load/speed point.

Air quantity and the requirements for control of injected fuel can vary due to many factors such as manifold-pressure variations resulting from individual piston pumping, and intake-valve opening/closing. As shown in Fig. 4-9, idling manifold absolute pressure can vary by 5 kPa from an average 42, over more than 10% plus or minus. For this and other variations, the lambda map insures the best possible adjustment of the air-fuel ratio as corrected by inputs that control fuel injection, and without affecting other operating points.

Air flow and rpm set up basic pulse time. Other inputs can change that basic pulse time, and compensate for other variations. Later, you'll see how each of these works for each driving condition.

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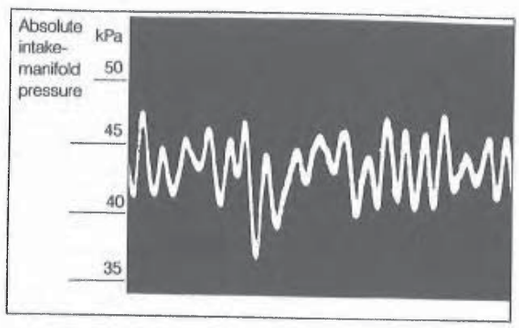


Fig. 4-9. Manifold pressure fluctuates rapidly (as much as 10%) as a result of intake valves opening and closing. This can cause changes in fuel-injection requirements.

Timing Signals: RPM, TDC

For the most accurate measure of engine timing and speed, Motronic systems read the position of the crankshaft directly, instead of from the ignition system as in L-Jetronic. Special sensors, shown in Fig. 4-10, pick up signals from the flywheel teeth. Taking RPM and TDC timing signals from the crankshaft avoids inaccuracies from gear-lash or belt-drive such as when rpm and timing are determined in a camshaft-driven distributor, causing "spark scatter".

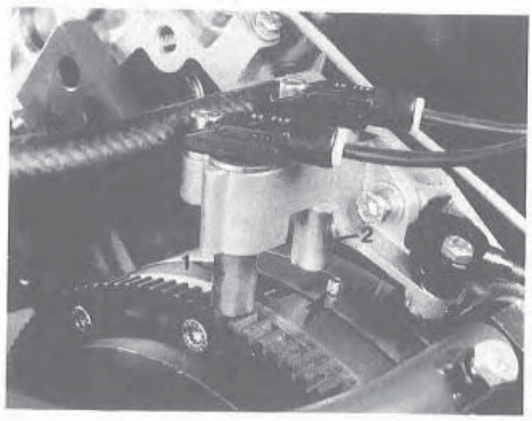


Fig. 4-10. RPM sensor (1) sends engine-speed signals from flywheel teeth; TDC sensor (2) sends one pulse per passing of set screw (arrow) each crankshaft revolution.

The rpm sensor (also called the engine-speed sensor) is an inductive-pulse sender that picks up pulses from a toothed wheel, usually the flywheel. The rpm signal can be displayed on a scope just as it is sent to the control unit, one blip or spike for each tooth as shown in Fig. 4-11. It is so accurate it can sense an rpm change while the crankshaft turns only a few degrees.

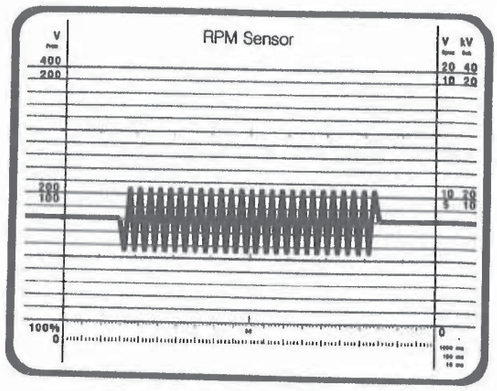


Fig. 4-11. RPM sensor scope pattern shows one pulse per flywheel tooth.

The TDC, or reference-mark sensor (reference from cylinder #1 TDC), is triggered by a set screw on the flywheel. Each time the screw passes the TDC sensor, the sensor signals one blip for each crankshaft revolution as shown in Fig. 4-12. Both sensors are magnetic, with a soft iron core that stores the magnetic field. When a tooth in the flywheel or the reference pin moves through the magnetic field, the change induces an electrical voltage in the winding. This voltage is the input signal to the control unit. The sensor is known as a passive diffusion-field sensor because it does not require a current supply.

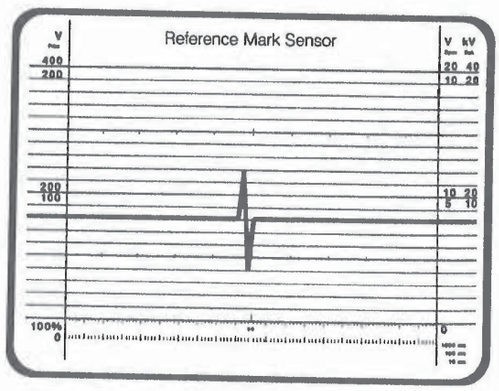


Fig. 4-12. TDC sensor scope pattern shows one pulse per crankshaft revolution.

One of these flywheel sensors provides input of rpm to the control unit. The other sensor provides input of TDC reference. The air-flow sensor provides input of engine load. From the control unit ROM, an output signal to the coil primary sets timing advance and dwell for the next spark firing.

Some engines operate with only one sensor that combines both functions, using a toothed timing-wheel instead of the flywheel. Two missing teeth signal TDC, as shown in Fig. 4-13.

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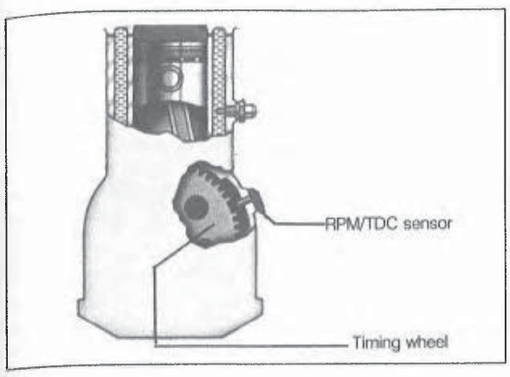


Fig. 4-13. In some Motronics, special timing wheel replaces starter gear ring or is mounted on front of crankshaft. Single sensor picks up rpm from teeth, and picks up TDC from gap in teeth.

Injector Pulse Patterns

On the scope, Motronic injector patterns look different from other Jetronic injector patterns because the digital control signals are different. See Fig. 4-14. The small blip on the left is the TDC reference signal. The injector is opened by the first negative, or grounding pulse, and held open by a series of smaller pulses. When the injection signal ends, a sharp counter voltage shows as a plus spike.

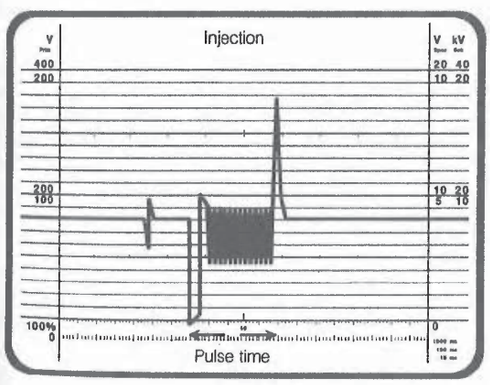


Fig. 4-14. Injection pulse on scope shows large pull-in signal and pulse time. Notice signal drops to 0 (ground) to open injector.

Adaptive Circuitry

Some Motronic control units (those identified as ML.3) include adaptive circuitry so your engine is controlled based on its individual operating conditions, and on how you drive it. It adapts or learns what is best for you and this engine, which may be different from the engine tested to develop the basic data for the memory maps.

If the concept seems hard to handle, think of it in this way: Remember from earlier discussion that closed-loop control depends on the oxygen sensor signal that fine tunes the air-fuel ratio, and that the air-fuel mixture is properly adjusted when the output of CO is the same whether the system is open-loop or closed-loop. In effect, the adaptive circuits do the same thing. The control unit looks at the base pulse-time signals during closed-loop, then adapts the open-loop base pulse-time signals to match. The result is less worry about intake air leaks, as the system adapts to such variations. It also adapts to the thinner air at higher altitudes, reducing the need for an altitude sensor.

The adapted values are stored in the control unit's volatile memory—that means that if the battery cable is disconnected for any reason, even something as remote as installing the anti-theft alarm, that adapted value will be lost. If the value is lost, you may find the car drives differently when it's first restarted. Driving it for about 10 minutes should give it time to re-adapt. Adaptive time is carefully considered: anything shorter than 10 minutes would cause the control unit to be adapting to every little change. Anything longer than 10 minutes would cause concern to the driver: "What did they do to my car when they put in that alarm system?" It pays to know when someone disconnects your battery.

> Drivers who drive their adaptive-engine GNX or other hot cars to the dragstrip often find they've lost a few tenths of a second in strip times as the engine adapted to the street. Their times picked up when they ran the strip a few times to re-adapt.

Canister Purge Control. You may know that the evaporative fuel control system stores fuel vapors in a charcoal canister to be drawn into the running engine upstream of the throttle, as shown in Fig. 4-15. Motronic ML.3 considers the adaptive function in the canister-purge control in the control unit. The air-fuel mixture is controlled to lambda 1 by the lambda sensor system as the control unit slowly operates the canister-purge valve. During any purge of the evaporative canister, the adaptive value is forced to neutral by a so-called "forget" function, and the adaptive circuits are turned off. Adaptive control is allowed only when no canister flow is feeding fuel vapors into the manifold. All this adds up to proper emptying of the evaporative fuel vapors without interfering with driveability.

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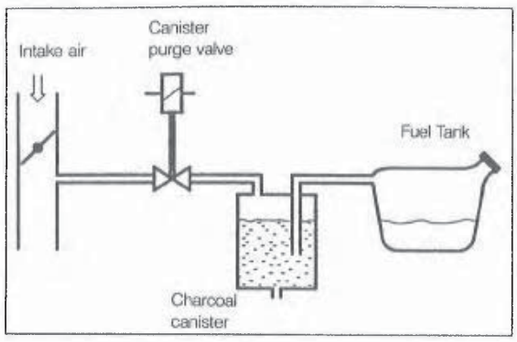


Fig. 4-15. Motronic ML.3 controls canister-purge valve to admit fuel vapors to the intake manifold without affecting adaptive system.

Sequential Injection

Sequential injection means delivering fuel separately from each injector in sequence—in firing order. With an increase in computing power, and an increased demand for idle smoothness and reduced emissions, Bosch Motronic ML.3 can provide sequential injection. Each injector is timed to cut off just before the intake valve opens. During acceleration, the ECU can deliver additional enriching pulses, cylinder by cylinder for the rapidly changing conditions.

In spite of its increased cost, you'll see more pulsed Motronic sequential injection because:

- each individual injector pulse can be much longer than simultaneous injection, as long as 720° crankshaft rotation less intake valve opening, permitting lower idle speeds
- less variation between cylinders in air-fuel ratio for smoother idle and reduced emissions
- injector fuel-rail pressure is more constant because only one injector opens at a time, meaning smoother operation
- improved acceleration enrichment because it can be applied to the "next cylinder"
- soft rpm limitation by reducing fuel flow cylinder by cylinder

Some people think "sequential" means injecting the fuel just as the intake valve opens, but it is not that simple. Depending on the engine, the injection may be timed before the valve opens. It is all based on the desired stratification in the manifold, swirl effects in the cylinder, emissions, and other considerations.

4.4 Idle Speed Control

Most Motronics control idle rpm by a combination of the idle-speed stabilizer and ignition timing. The stabilizer is described in the section on LH-Jetronic. Inputs include rpm, closed-throttle signal, and engine temperature. The control unit sends on-off, or digital signals to the idle-speed stabilizer. Early Motronics use the auxiliary air valve to increase air flow during warm-up, also described in the L-Jetronic section. In these, cold-engine idle rpm is increased according to temperature; it is an open-loop system.

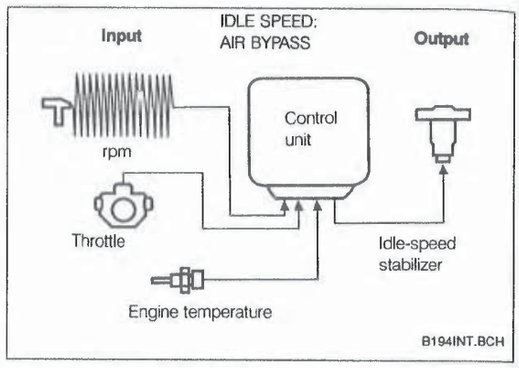


Fig. 4-16. Idle-speed control by idle air bypass. Idle-speed stabilizer handles coarse rpm corrections.

Ignition Timing

Even before the idle-stabilizer acts on air flow, Motronic idle rpm is first stabilized by changing ignition timing. If idle rpm falls, the control unit advances ignition timing to increase rpm. On the other hand, if rpm rises, it retards timing to cut back rpm. Ignition timing handles small rpm changes, handles them in milliseconds. The idle-speed stabilizer handles larger changes, and takes a bit longer.

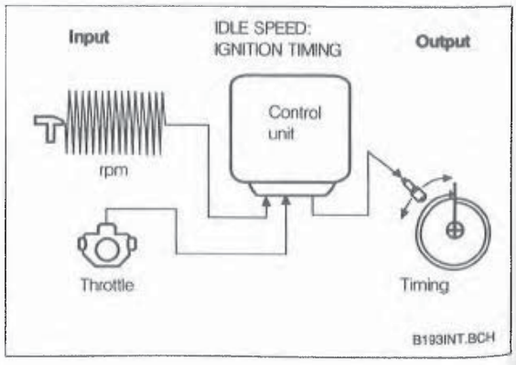


Fig. 4-17. Idle-speed control by ignition timing responds in milliseconds.

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4.5 Operating Conditions

In this section, let's look at operating conditions to see how Motronic controls injection and ignition as well as idle-speed bypass air for good engine management.

Starting

Start Control, Fuel. In most Motronics, start enrichment is provided by the port injectors rather than the separate start injector/thermo-time switch. For start control, the important inputs are rpm and engine temperature. The control unit monitors cranking rpm, and also the number of revolutions since the time cranking began. The injection pulses may be longer than normal, once per crankshaft revolution, as you've seen in L-Jetronic.

But at low engine temperatures, the control unit may deliver instead several shorter injection pulses per revolution to improve starting. Remember, these are 10 millisecond pulses in a pulse period, or crankshaft-revolution time of 200ms. To prevent flooding, fuel quantity will cut back after a measured number of revolutions, or after the engine has reached a cranking rpm that is temperature related, for example 200–300 rpm.

Start Control, Ignition Timing. With a cold engine at low cranking speeds, timing will be controlled near TDC. For normal cranking rpm, a large advance in timing might fire too early, damaging the starter. Further, starting would be difficult if not impossible. With a cold engine at higher cranking rpm, however, timing will be advanced for better starting.

For hot starts, or high intake air temperatures, timing will be retarded because a hot cylinder can fire easier while the piston is rising at cranking rpm. Retarded timing prevents knocking that can occur in high-compression engines, and may be masked by the starter sound.

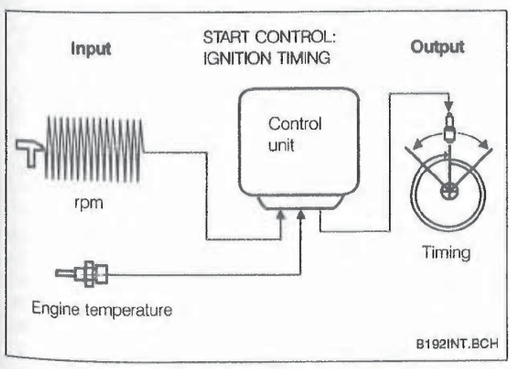


Fig. 4-18. Start control sets ignition timing based on rpm and engine temperature.

Start Control, Air. As in L-Jetronic, the idle-speed stabilizer is normally driven open more by increased dwell signals to provide extra bypass air for cold starting.

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Post-Start

Post-start—the 5–30 seconds when you want the engine to keep running after you release the key from CRANK—is affected by engine temperature as well as a timer in the control unit. Colder engines get more fuel injected. Also, colder engines get more timing advance. Based on the start-up temperature, and the time since start, post-start enrichment is gradually reduced. The idle-speed stabilizer maintains rpm.

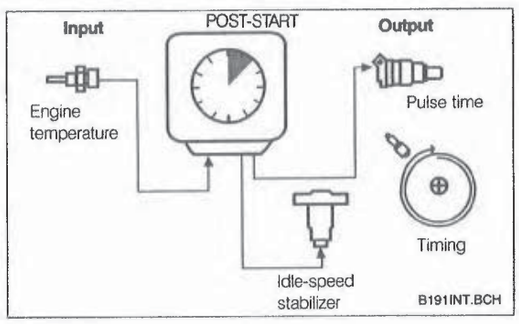


Fig. 4-19. Post-start temperature and time determine injection pulse time, ignition timing, and idle-speed stabilizer bypass opening.

Warm-Up

During warm up, the most important input, besides engine load and rpm for basic pulse time, is engine temperature. The control unit includes a ROM map of warm-up characteristics to apply a correction factor based on load and engine speed, greater at low loads and rpm than at high loads and rpms. See Fig. 4-20. Control unit outputs include injection pulses for the proper mixture, ignition timing for driveability (advance under part-load acceleration, retard on deceleration to reduce HC emissions), and idle stabilization to help keep the engine running at idle.

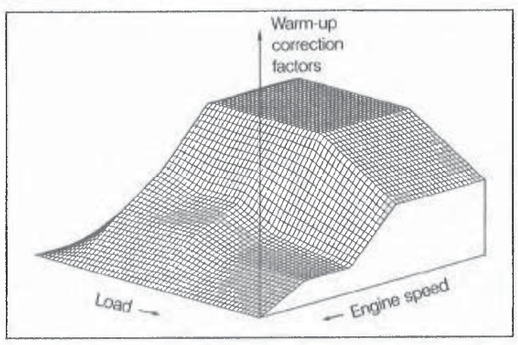


Fig. 4-20. Warm-up correction is greatest at low speeds and low loads, represented by the back of this "map." At the front, correction is least for high loads and high rpm.

Remember, during warm-up, the temperature of the lambda sensor is important. Unheated lambda sensors can be heated faster by changing ignition timing. Motronic retards timing to cause a hotter exhaust. That heats the oxygen sensor much quicker and also heats the catalytic converter faster for more efficiency.

Closed-Loop Operation

Based on the inputs of a warm engine, and oxygen-sensor voltage when hot, the system normally operates closed-loop. The oxygen sensor fine-tunes the fuel-injection delivery for proper air-fuel ratios.

For every combination of inputs, the control unit looks in its memory for the best timing, the best dwell angle, the best lambda, or air-fuel ratio. On the basis of engine temperature, Motronic controls ignition timing with independent calibrations for starting, idling, deceleration, and acceleration, both part-load and full-load or WOT (Wide Open Throttle). For example, control of timing advance at idle reduces the need for idle fuel enrichment.

Part-Throttle Acceleration

Just as in L-Jetronic, the overswing signal of the air-flow sensor increases fuel delivery, compensated by temperature. For air-mass sensors, the rate of increase of the voltage signals acceleration. As shown in Fig. 4-21, during part-throttle acceleration, the normal pulse for steady cruise increases for just about one second while you open the throttle. Then the pulse cuts back even as the engine picks up speed; this saves fuel and reduces emissions.

In addition, ignition timing can be retarded to avoid the brief acceleration knock that could occur for the first few cycles of engine acceleration. Ignition timing control also reduces the formation of NOx, which is normal with acceleration.

Rate of ignition timing change is also controlled;

- to avoid knocking, the control unit allows fast change
- to reduce jerk during transition, the control unit normally changes ignition advance gradually

Full-Load Acceleration

Full-load enrichment is signalled by the throttle switch. As long as the throttle is full-open, longer injection pulses will be delivered for enrichment. Rich mixtures reduce the tendency to knock. This enrichment is based solely on rpm, and programmed from engine tests. The air-flow signal is ignored.

At the same time as rpm and throttle position control full-load injection enrichment, air temperature and engine temperature supply inputs to control the advance of ignition timing for best acceleration without approaching knock. For engines without knock sensors, timing advance is based on engine test data stored in the timing map. The engine can operate close to the ignition-advance limit, developing maximum torque over the entire rpm range with least chance of knocking based on three factors:

1. the timing curve can be programmed specifically for each engine operating point
2. the system operates with narrow tolerances and freedom from mechanical wear
3. timing is compensated according to engine temperature and intake-air temperature

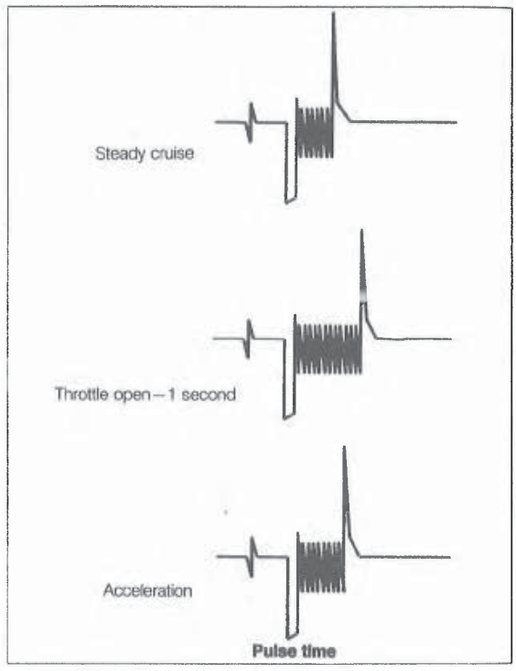


Fig. 4-21. Part-throttle acceleration enrichment is limited to the time the throttle is opening, usually about one second.

In some turbocharged cars, a second air-temperature sensor is mounted in the manifold downstream of the turbo or the intercooler to sense the temperature of the air entering the engine. This is a special fast-response sensor overriding the first air-temperature sensor to handle the quick changes in temperature that can occur during full-throttle acceleration.

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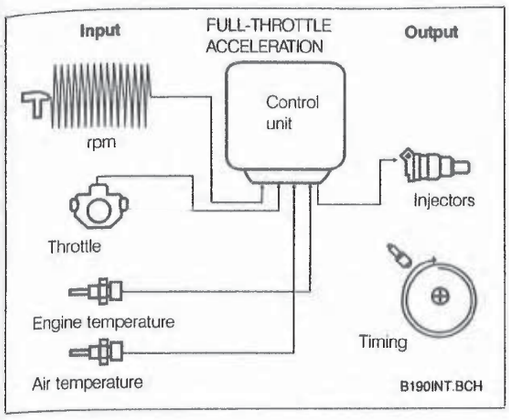


Fig. 4-22. Full-throttle acceleration controls injection and ignition timing, based on inputs of rpm, throttle switch, air temperature, and engine temperature.

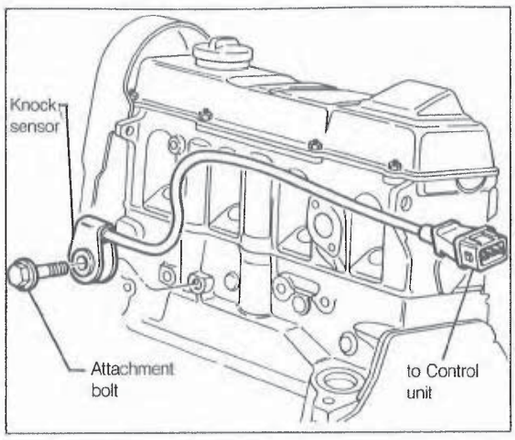


Fig. 4-23. Knock sensor is fastened to selected part of block or head. It is coated with plastic to reduce the effect of changes due to engine temperature.

Knock Control

Programmed timing accuracy, even with compensations, can be improved by a knock-sensor system that causes timing to advance to just before the point where knock could damage the engine. With a knock sensor controlling timing advance in a separate closed-loop system, power output can be maximized without endangering the engine.

Some engines, particularly turbocharged engines, include knock sensors to pick up vibrations from the engine at the first signs of knock. See Fig. 4-23. Some systems use two control units, mounted inside the passenger compartment, one for Motronic, and a related knock control regulator, called KLR. Knock-sensing inputs help both control units to work together. The first and fastest output changes the timing. If the engine is turbocharged, the second output controls the boost. See Fig. 4-24. In the Motronic known as ML.3, knock sensing and engine management are combined in one control unit.

When the engine knocks, it vibrates with characteristic frequencies of 5–10 kilohertz together with corresponding harmonics. These vibrations must be sorted from other engine vibrations in a recognition circuit in the control unit. The Motronic control unit has accurate information on crankshaft position and firing order so it is possible to determine which cylinder is knocking (one cylinder usually knocks before the others). Further, circuits operate with such speed that ignition timing can be retarded only for the knocking cylinder, and advanced for the firing of the next cylinder. Each knock signal can modify timing in milliseconds. When ignition retard eliminates the knock, timing is advanced slowly in steps to the original value or until knocking again occurs.

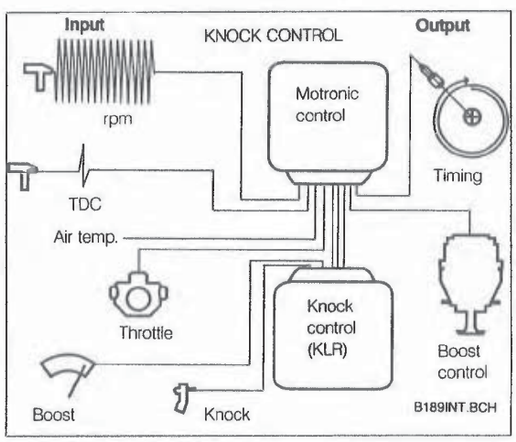


Fig. 4-24. Knock control uses several inputs to control ignition timing and boost, sometimes with a separate knock control computer, known as KLR.

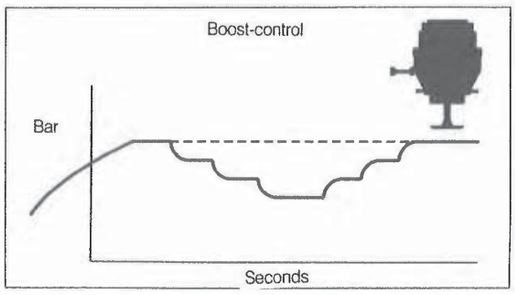


Fig. 4-25. Boost control cuts back pressure in steps until knocking stops, then gradually restores boost.

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On turbocharged engines, if knock continues for seconds, boost control reduces manifold pressure. Knock control permits more boost, and higher compression ratios for greater power. Automatically, it tends to adjust for the octane-rating of the fuel being burned.

With precise control of ignition timing and turbo boost, engines can be designed with higher compression ratios for greater power output. On all engines, the knocking limits depend on many factors:

- intake air temperature
- engine temperature
- engine deposits
- combustion-chamber form
- mixture composition—A/F ratio, and stratification
- fuel quality
- air density

For years, drivers have known that using higher-octane fuel did not add to engine power unless ignition timing was adjusted at the distributor to take advantage of the improved anti-knock index. Now, with knock sensors and closed-loop ignition-advance control, power output can depend on the anti-knock index of the fuel being burned. It is not unusual to see engine power specifications include the anti-knock index of the fuel to be used.

RPM Limitation

If the rpm signal is greater than max-allowable rpm stored in the computer memory, the control-unit signals a cutback of the fuel-injection quantity. A scope set to read four pulses for simultaneous injection for four cylinders shows the limitation cutback of every other pulse, one pulse every other crankshaft revolution. See Fig. 4-26. If you press the engine into the rpm-limitation range, you will feel a surge as the limitation of fuel injection cuts in and out.

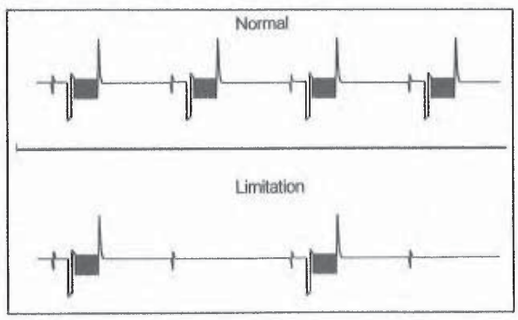


Fig. 4-26. Normal 4 pulses per two crankshaft revolutions, or two 4-stroke cycles. RPM limitation cuts every other injection pulse.

Coasting Cut-Off

Signals of rpm, closed throttle, and engine temperature control coasting cut-off of injection. On the scope during coast-down, the single-injection pattern looks blank except for the TDC pulse. See Fig. 4-27. No fuel is being injected. As rpm approaches idle speed, the normal pulse will show again. If the engine is colder, normal fuel injection returns at some higher rpm, to prevent stalling. See Fig. 4-28. Motronic adds one refinement: as fuel-delivery resumes, perhaps as the driver resumes speed, ignition timing is gradually advanced to smooth the transition from fuel cut-off to cruise or acceleration.

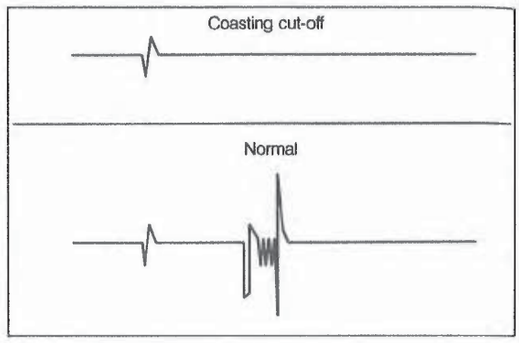


Fig. 4-27. Scope pattern for coasting cut-off shows only TDC pulse until injection resumes to prevent stalling.

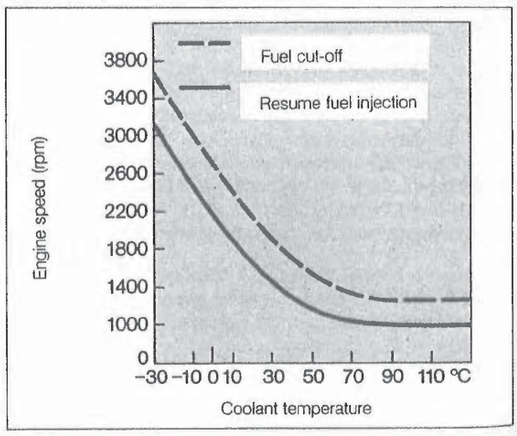


Fig. 4-28. Warm engine cuts off and resumes fuel at lower rpm than cold engine. RPM difference between cut-off and resume fuel prevents hunting.

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Electronic Throttle — Drive-By-Wire

Some of the newest Motronic systems have an electronic throttle (also known as a drive-by-wire system). The electronic throttle has no mechanical link between the accelerator pedal and the throttle valve. Instead, as shown in Fig. 4-29, an accelerator sensor picks up your movement or position of the accelerator pedal. It signals the control unit about pedal movement, and the control unit signals the servomotor on the throttle shaft to open. The electronic throttle (Bosch calls it EGAS) may sound like something none of us needs, but it has many benefits.

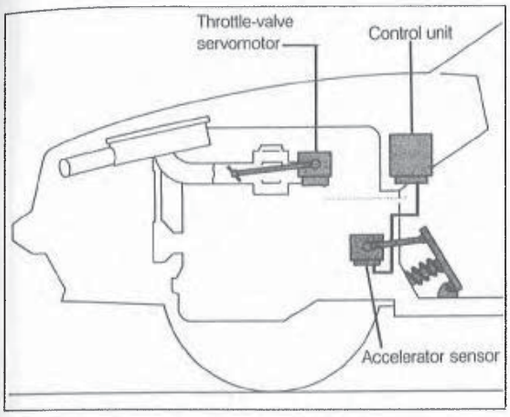


Fig. 4-29. Electronic throttle sends accelerator signal to Motronic control unit. DC motor moves throttle valve, modified by engine temperature, idle rpm, and maximum rpm.

The throttle opening signal may be modified according to engine rpm and engine temperature. It can provide simplified cruise control. It can also control minimum rpm, replacing the idle-speed stabilizer, and control maximum rpm, replacing the alternate-injector cut-out.

But there's more. For traction control, the electronic throttle links with the ABS (Anti-lock Braking System). The same wheel-speed sensors of ABS also feed the ASR (Anti-Slip Regulator). When any driving wheel starts to slip, a slight brake application prevents that wheel from slipping so much that the differential delivers no power to the other driving wheel. If both driving wheels show signs of slipping, the electronic throttle cuts back power for maximum traction. Traction control gives the car the max acceleration the tires can deliver to the road. If laying down tire smoke is your thing, avoid ASR. But for making the fastest takeoff, you cannot beat it.

Can you trust the electronic throttle? Will it provide unintended acceleration? The system checks its safety circuits before start-off, and reports defects to the driver. If a defect is found, a limp-home circuit may disable some of the functions, but it will allow you to get to the house or the shop. It may well be more reliable than some cable actuated throttles.

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Diagnostics

Beginning with Motronic ML.3, diagnostic systems in the control unit provide troubleshooting information. Each time you turn the key ON, the computer checks itself. Then it checks the sensors. Any defects are stored in the fault memory for later readout by a diagnostic device. During servicing or troubleshooting, the actuators can be driven by short pulses so the technician can hear or feel the actuation to pinpoint the problem. See Fig. 4-30. You'll see more about diagnostics in chapters 4 and 6.

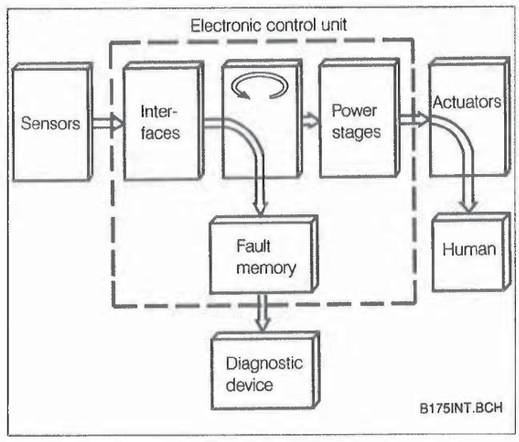


Fig. 4-30. Diagnostics store trouble codes in fault memory for readout by diagnostic device.

The more you study the manuals for different applications, the more you'll realize how well engines can be managed by Motronic injection and ignition control, and idle-speed stabilization.

5. D-JETRONIC

D-Jetronic was the first of the Bosch pulsed injection systems. I write about it at the end because the most recent cars with Bosch D-Jetronic were the 1975 Volvo 164E and the 1975 Mercedes 450. In 1976, both changed to K-Jetronic. It's most interesting to see how L-Jetronic evolved from D-Jetronic. At the 1967 introduction, Bosch called it ECGI, Electronically Controlled Gasoline Injection, contrasting this new electronic system with a long background of mechanically-driven injection pumps.

Based on a cross-licensing of the Bendix Electrojector system, which was briefly used in the U.S., D-Jetronic depends on sensing manifold pressure as an indication of engine load.

You can refer to the L-Jetronic section for details concerning most of D-Jetronic. The major differences are:

- manifold-pressure sensor senses engine load

- trigger-contacts in the distributor synchronize injection pulses

- Injectors are operated in two groups
  - 4-cylinder, 2 groups of 2: VW, Porsche, Saab, Volvo
  - 6-cylinder, 2 groups of 3: Mercedes, Volvo
  - 8-cylinder, 2 groups of 4: Mercedes

Bosch now regards manifold-pressure sensing as a less accurate measure of load than measuring air flow, as in L-Jetronic, and in K-Jetronic, or measuring air mass, as in LH-Jetronic. For certain Bosch racing applications, however, manifold-pressure sensing is sometimes used. Manifold-pressure sensing is widely used by GM, Ford, Chrysler, AMC, and some Toyotas, but the trend in passenger cars is away from manifold-pressure sensing.

Manifold Pressure Sensing

As shown in Fig. 5-1, the pressure sensor is connected to the intake manifold between the throttle and the intake valves. The air-temperature sensor signals for correction for colder, denser air.

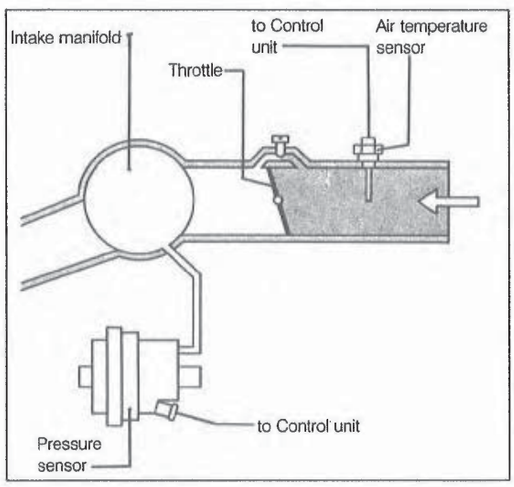


Fig. 5-1. Pressure sensor signals manifold absolute pressure (MAP) downstream of throttle.

As shown in Fig. 5-2, the pressure sensor contains two pressure diaphragm cells that expand and compress according to pressure. The inside of one is vented to the atmosphere; the outside of both is connected to the intake manifold pressure. When manifold pressure increases, the cells compress and pull an iron core armature into a coil, changing the electrical signal to the control unit. Increasing manifold-pressure signals increasing load so the control unit increases the pulse-time of the injectors. This is a succession of analog actions, requiring no digital computation. D-Jetronic control units are analog. When manifold pressure is low, as at idling, the diaphragm cells expand, pushing the core into the coil; the electrical signal to the control unit reduces the pulse-time, reducing the fuel injected per stroke.

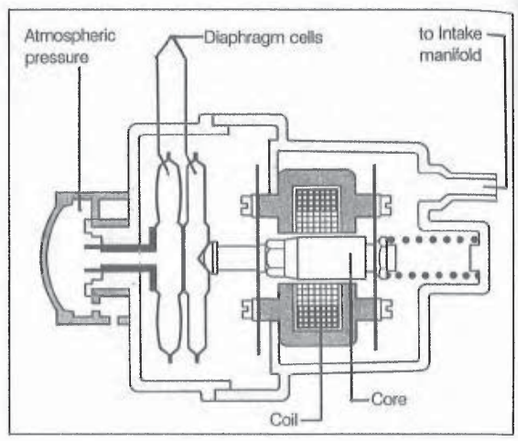


Fig. 5-2. Cutaway view of manifold pressure sensor.

Altitude, or density compensation is provided by the venting of one cell to the atmosphere. In the part-load range, both manifold pressure and atmospheric pressure are reduced with altitude, so the fuel-injection signal is tailored to the thinner air.

Trigger Contacts

Injection timing is determined by a set of trigger contact points in the distributor. See Fig. 5-3. These contacts are mounted below the centrifugal weights of the ignition advance mechanism. They are operated by a special cam on the distributor shaft. Bosch makes the distributor, too. The trigger contacts provide a signal of crankshaft position for timing, and of crankshaft rotation for rpm input. Because they are mounted below the centrifugal weights, the trigger contacts are not affected by distributor ignition timing action.

D-Jetronic injectors are triggered in two groups. Each 4-stroke cycle, D-Jetronic fires each group once instead of firing all twice as in L, LH, and Motronic systems.

Acceleration

Acceleration is compensated at the throttle switch. See Fig. 5-4. This switch contains the full-load contact and the closed-throttle contact as in L-Jetronic. But in D-Jetronic, it also contains a contact path for acceleration enrichment. As the throttle is opened during acceleration, the signal enriches the mixture by increasing the pulse time, and also by increasing the number of injection pulses.

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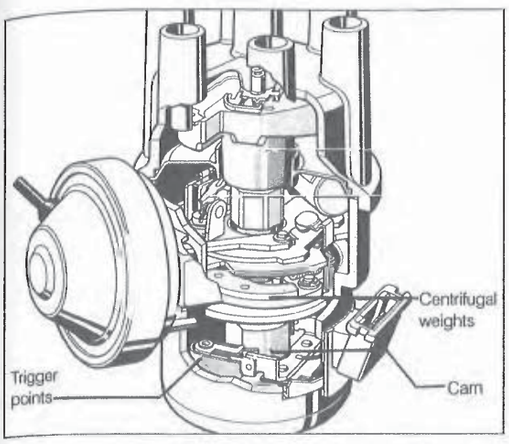


Fig. 5-3. D-Jetronic trigger contacts are built into the distributor.

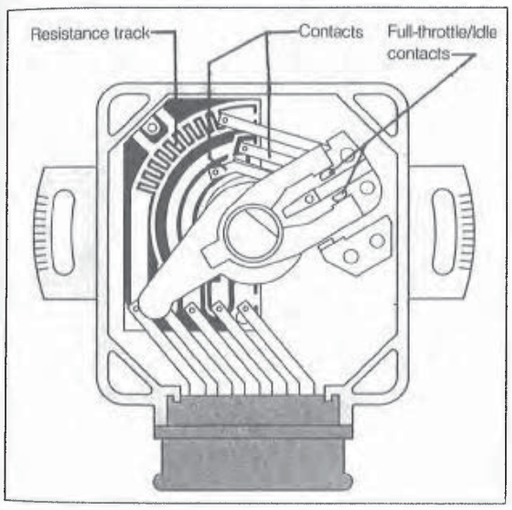


Fig. 5-4. D-Jetronic throttle-position sensor compensates for part-throttle acceleration.

Pressure Regulator

The final difference in D-Jetronic is the fuel pressure regulator shown in Fig. 5-5. It maintains constant pressure at 2 bar, less than the 2.5 or 3 bar of L-Jetronics. Unlike L-Jetronic, fuel pressure can be adjusted by the nut on the bottom of the regulator to control pressure on the spring. Increasing the fuel pressure will enrich the mixture and increase power, but not equally in all rpm ranges. Also unlike L-Jetronic, fuel pressure does not need to be related to manifold pressure because the system is already controlling pulse-time, and therefore mixture, according to manifold pressure.

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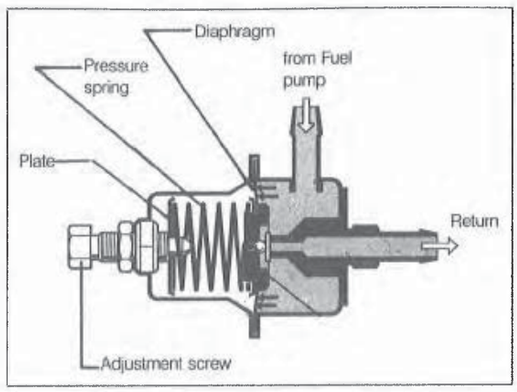


Fig. 5-5. D-Jetronic fuel pressure can be adjusted at regulator.

6. DIGIFANT II

Digifant II is a Volkswagen cousin to Bosch Motronic, controlling pulsed fuel injection, electronic ignition, and idle speed from the same control unit. It includes a knock sensor for ignition-timing control. First use is on 1988 8-valve engines in Golf and Jetta, replacing Bosch K-Jetronic (CIS).

Similarities to Motronic:

- vane-type air-flow sensor on un-supercharged engines (VW Corrado uses pressure sensor)
  - A/F mixture is adjusted by bypass of unmeasured air
  - intake air temperature sensor
- electrically-opened pulsed injectors
- ignition timing controlled by control unit
- coolant-temperature sensor
- switches on throttle shaft
  - closed throttle (idle)
  - WOT

Similarities to K-Jetronic:

- idle-speed stabilizer valve with throttle bypass adjusting screw
- fuel system: pump, relay, filter; no accumulator

Digifant II differences from K-Jetronic or Motronic are few:

- system pressure is specified with engine idle: 2.5 bar (36 psi) instead of engine off. Actually, engine-off pressure (comparable to Bosch specs) is 3.0 bar, 0.5 bar higher than many pulsed systems

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- service port for fuel-pressure testing
- idle-speed stabilizer circuit delivers fixed (higher) idle rpm when coolant temperature sensor is disconnected
  - measuring current flow to stabilizer at idle shows fluctuation 400–460mA, closed loop, causing 790–850 rpm. Disconnecting sensor shows fixed 430mA, causing 930 rpm, open-loop
- ignition timing is set with coolant sensor disconnected for fixed idle rpm
- control unit increases idle rpm for hot start

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US PATENT NO. 6,557,540

Chapter 5

Continuous Injection – Theory

Contents

1. **General Description** 3
   - 1.1 Continuous Injection System (CIS) 3
     - Mixture-Control Unit 3
     - Air Flow Measurement and Fuel Metering 3
   - 1.2 Applications - Identifying Features 5
     - K-Jetronic and K-Jetronic with Lambda Control (K-Basic and K-Lambda) 5
     - KE-Jetronic, KE3-Jetronic, and KE-Motronic (KE Systems) 6

2. **Air-Flow System** 6
   - 2.1 Air-Flow Sensor 7
     - Sensor Plate and Control Plunger 7
     - Funnel Angles 7
     - Control-Plunger Counterforce 8
     - Backfire Protection 9
     - KE Sensor-Plate Positions 9
     - Mixture (CO) 10
   - 2.2 Throttle Valve 11
     - Idle Speed 11

3. **Fuel System** 11
   - 3.1 Fuel Accumulator 11
   - 3.2 Fuel Distributor 12
   - 3.3 System-Pressure Regulator 13
     - K-Basic, K-Lambda 13
     - KE Systems 14
   - 3.4 Fuel Injectors 14
     - Air-Shrouded Injectors 14

4. **Fuel Metering** 15
   - 4.1 Basic Fuel Metering 15
     - Control Plunger Movement and Slit Size 15
     - Fuel Metering and Pressure Drop 16
     - Differential-Pressure Valves and Pressure Drop 16
     - Comparison of Differential-Pressure Valves 17
     - Summary of Basic Fuel Metering 17

5. **Control Systems** 18
   - Changing Slit Size 18
   - Changing Pressure Drop 18
   - 5.1 K-Basic – Changing Slit Size 18
     - Control-Pressure 18
     - Control-Pressure Regulator 18
     - Control Pressure and Mixture Adjustment 20
     - Additional Control-Pressure Compensations 21
   - 5.2 K-Lambda – Changing Slit Size and Pressure Drop 22
     - K-Lambda Differential-Pressure Valves and Mixture Adjustment 22
     - Lambda Control System 22
     - Lambda Control and Changing Pressure Drop 23
     - Lambda Closed-Loop Control 23
     - Lambda Thermoswitch 23
   - 5.3 KE Systems – Changing Pressure Drop 24
     - KE Differential-Pressure Valves and Separate Fuel Flows 24
     - KE Differential Pressure and Pressure Drop 25
     - Pressure Actuator 25
     - Pressure Actuator and Mixture Adjustment 26
     - Control Unit and Sensors 26

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US PATENT NO. 6,557,540

2 CONTINUOUS INJECTION—THEORY

Actuator Current, Pressures, and Air-Fuel Ratios ... 27
Limp-Home Mode ... 29
Logic Circuits ... 29
5.4 Summary of Control Systems: K-Basic, K-Lambda, KE ... 29
K-Basic ... 29
K-Lambda ... 30
KE Systems ... 30

6. Functions and Compensations ... 31
6.1 Starting ... 31
Cold Starting ... 31
Hot-Start Pulse Relay ... 31
6.2 Post-Start/Warm-Up ... 31
6.3 Acceleration ... 31
Part-Throttle Acceleration ... 32
Full-Throttle Acceleration ... 32
6.4 Lambda Control ... 33
6.5 Cut-off (KE only) ... 33
6.6 Altitude ... 33

7. KE3-Jetronic and KE-Motronic ... 33
Actuator Current ... 35
KE-Motronic Adaptive Control ... 35
Fault Memory (Diagnostic Codes) ... 35

TABLES

a. Bosch Continuous Fuel Injection Systems ... 5
b. CIS Upper-Chamber and Lower-Chamber Pressures ... 29

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1. General Description

This chapter covers the operating theory of Bosch continuous fuel-injection systems. Continuous Injection System (CIS) is the term widely used to refer to this branch of the Bosch fuel injection family. Do not confuse this with the Volvo term CIS (Constant Idle Stabilization), which is their term for the Idle-Speed Stabilizer, an unfortunate overlap of terminology. The continuous systems I'll discuss in this chapter include:

- K-Jetronic (I'll call it K-basic)
- K-Jetronic with lambda control (I'll call it K-lambda)
- KE-Jetronic and its variations: KE3-Jetronic, and KE-Motronic (I'll call them KE systems)

I'll begin this chapter with a general description of how Bosch continuous systems meter fuel to match a given air flow. I'll then examine in detail how the different subsystems of CIS—air flow measurement and fuel delivery—interact mechanically to create this basic fuel metering function. Finally, I'll explain how K-basic, K-lambda, and KE control systems fine-tune this basic fuel metering to compensate for different operating conditions.

For more information on the general principles of fuel-injection, see chapter 1 and chapter 2. To determine which Bosch system is installed on your car, see **1.2 Applications - Identifying Features**, or the detailed applications table at the end of chapter 1.

1.1 Continuous Injection System (CIS)

As I described in chapter 1 and chapter 2, the aim of the fuel-injection system is to measure the amount of air the engine is taking in and to meter a precise amount of pressurized fuel to match that air and create the correct air-fuel mixture. All Bosch continuous systems provide this basic air-measuring and fuel-metering function in the same way: in the mixture-control unit.

Mixture-Control Unit

The mixture-control unit is the heart of continuous injection. As Fig. 1-1 shows, it is where the air-flow measurement system and the fuel delivery system interact. The mixture-control unit measures the engine's intake air, and then meters fuel in proportion to that air flow.

The mixture-control unit is actually the combination of two separate components: the air-flow sensor, and the fuel distributor. See Fig. 1-2. The air-flow sensor measures the air entering the engine. The fuel distributor, in turn, delivers a proportional amount of pressurized fuel to the injectors.

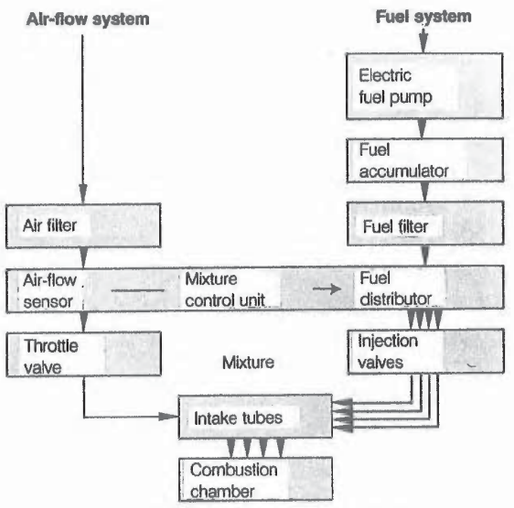


Fig. 1-1. Air-flow measurement system and fuel delivery system interact in mixture control unit to deliver the basic air-fuel mixture.

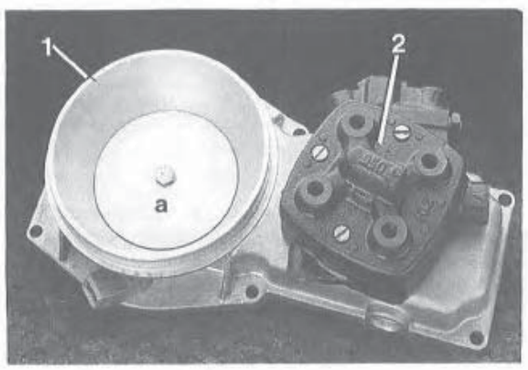


Fig. 1-2. The mixture-control unit is the combination of the air-flow sensor (**1**) and the fuel distributor (**2**). Circular sensor plate (**a**) is lifted by flow of engine intake air.

Air Flow Measurement and Fuel Metering

Fig. 1-3 is a schematic view of the operation of the mixture-control unit. The circular air-flow sensor plate is positioned in the intake tract so that all air entering the engine flows past it. The plate is attached to a lever which pivots, allowing the plate to move up and down. Intake air flowing through the housing raises the sensor plate. The movement of the sensor plate and lever is in direct proportion to the volume of the incoming air.

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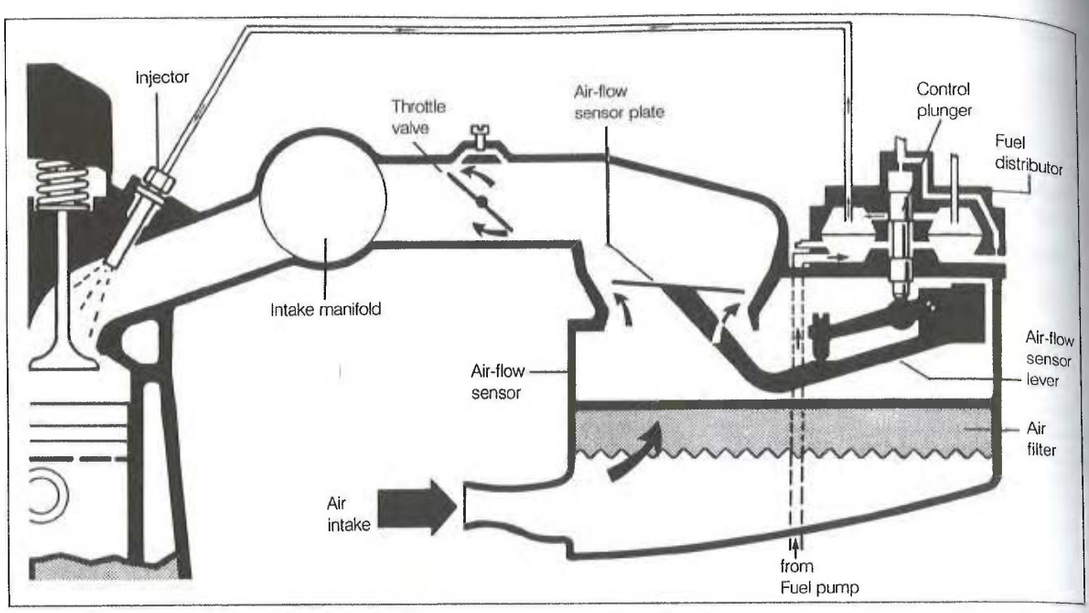


Fig. 1-3. Schematic of continuous injection air-flow measurement and fuel metering. Air entering intake manifold raises air-flow sensor plate. Rise of sensor plate mechanically raises control plunger. This basic fuel metering function applies to all systems in this chapter.

This air measurement is turned into an injection quantity by the control plunger in the fuel distributor. The plunger rests on the air-flow sensor lever, and it rises and falls at the same rate as the sensor plate. The position of the plunger controls fuel flow to the injectors. When air flow into the engine increases and raises the air-flow sensor and plunger, the rise of the plunger increases fuel flow proportionally. This maintains the correct air-fuel ratio. See Fig. 1-4. This mechanical lift of the control plunger by the air-flow sensor is how all continuous injection systems perform basic fuel metering.

In continuous injection all fuel metering takes place in the fuel distributor. The fuel injectors flow fuel continuously while the engine is running; their only function is atomization of the fuel. This is in contrast to the pulsed systems described in previous chapters, where fuel metering is controlled by opening and closing of the injectors.

Now you can see why continuous systems are often referred to as "mechanical" fuel injection, because basic fuel metering is controlled by the mechanical relationship between the air-flow sensor and the control plunger in the fuel distributor. As you'll see later in this chapter, continuous systems are also referred to as "hydraulic" fuel injection. This is because their control systems alter this basic air-fuel mixture for different operating conditions by changing fuel pressures in various parts of the system.

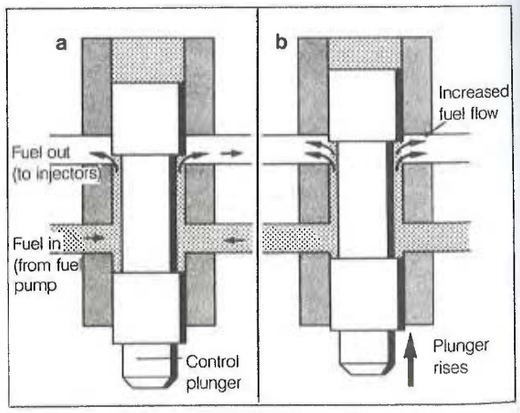


Fig. 1-4. Fuel metering by control plunger in the fuel distributor: At low air flow (**a**), rise of air-flow sensor and control plunger is low so less fuel flows to injectors. At increased air flow (**b**), when air-flow sensor rises higher, control plunger in turn rises, so more fuel flows to injectors.

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General Description

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1.2 Applications - Identifying Features

Bosch continuous injection systems are installed only by European car manufacturers. As of 1989, no Japanese or U.S. manufacturer is installing K-Jetronic fuel injection or its derivatives. With a large installed base on Volkswagen models, several million continuous systems are on the road in the U.S. Other makers using Bosch continuous systems include: Audi, BMW, Ferrari, Lotus, Mercedes-Benz, Peugeot, Porsche, Rolls-Royce, Saab, and Volvo. The 12-cylinder Ferrari Testarossa and Mercedes-Benz engines both use twin KE-Jetronic mixture control units, one for each 6 cylinders. Clearly, Bosch continuous systems are capable of performing well in many different applications.

To identify continuous systems, look for the separate mixture-control unit. It is usually mounted on a fender panel with flexible air duct leading to the throttle body and intake manifold. Also, continuous systems have separate injector fuel lines delivering fuel to each injector, instead of the common fuel rail found on pulsed systems. The fuel lines are usually flexible lines enclosed in protective metal braiding. See Fig. 1-5.



Fig. 1-5. Separate continuous mixture-control unit (**1**) between air cleaner and intake manifold. Each injector gets fuel through separate fuel line (**2**). No fuel rail, as in pulsed injection.

There are exceptions: On Mercedes cars, and on Peugeot, Renault, and Volvo cars using the PRV V-6 engine, the mixture-control unit is mounted directly on the intake manifold, as shown in Fig. 1-6. It usually delivers fuel through rigid metal lines to the injectors. The large air cleaner covers most of this so it may look like a carbureted engine at first glance.

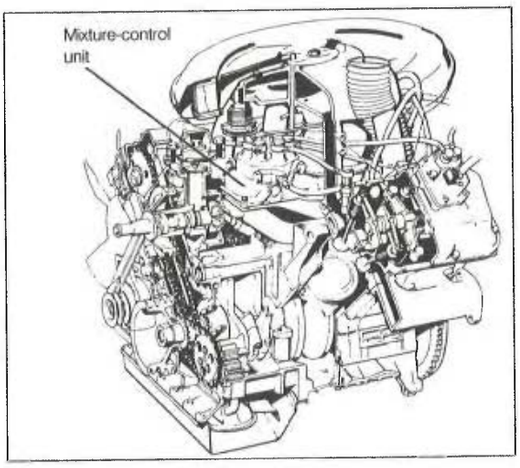


Fig. 1-6. On the PRV V-6 engine used by Peugeot, Renault, Volvo, the mixture-control unit hides under air cleaner. Location on Mercedes 4-cyl., 6-cyl. and 8-cyl. engines is similar.

How can you tell the systems apart? You can distinguish between each by component and function.

K-Jetronic and K-Jetronic with Lambda Control
(K-Basic and K-Lambda)

K-basic and K-lambda fuel distributors are made of cast iron and usually painted black. K-lambda systems are further distinguished from K-basic by the solenoid-type lambda valve next to the fuel distributor; it has an electrical connector and looks almost like a pulsed injector. See Fig. 1-7.

Table a. Bosch Continuous Fuel Injection Systems

Name	First use	Fuel pressure	Computer/pins	Lambda control
K-basic	1974 Porsche 911T	4.8–5.2 bar (70–75 psi)	no	no
K-lambda	1980 almost all mfrs.	4.8 bar (70 psi)	analog/25	yes
KE-Jet 2	1984 Mercedes 190E	5.4 bar (78 psi)	digital/25	yes
KE-Jet 3	1986 Mercedes 300/560	5.4–5.8 bar (78–84 psi)	digital/25	yes
KE-Motronic	1988 Audi 4-cylinder	6.2 bar (90 psi)	digital/35	yes

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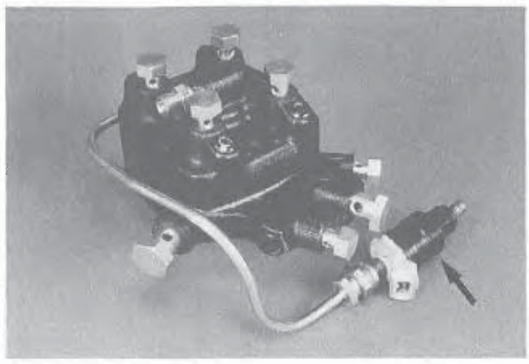


Fig. 1-7. You can tell both K-basic and K-lambda by the black color of the fuel distributor. Only K-lambda has the lambda control valve (**arrow**), which looks something like a pulsed injector.

KE-Jetronic, KE3-Jetronic, and KE-Motronic

(KE Systems)

All KE systems have a pressure actuator fastened to the fuel distributor as shown in Fig. 1-8. Also, KE fuel distributors are usually unpainted aluminum. Further differences which distinguish the three different KE systems are mostly in the electronics; not immediately apparent. For example, KE-Motronic systems lack vacuum lines to the distributor, but some KE-Jetronics also lack such vacuum lines (1988 Audis with separate electronic ignition-timing control, for example). Check your manual to identify which KE system you have.

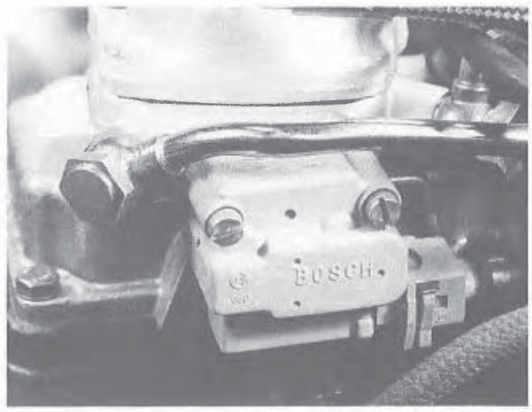


Fig. 1-8. You can identify KE systems by the attached pressure actuator. Some are gray, some are black; all have electrical connector for control-unit wiring connection.

2. AIR-FLOW SYSTEM

The most basic function of a fuel-injection system is to measure the amount of air drawn in by the engine and to meter a proportional amount of fuel. The air-flow system performs this air measurement function. The air flow system also includes the throttle valve which controls engine speed by regulating engine air intake. See Fig. 2-1.

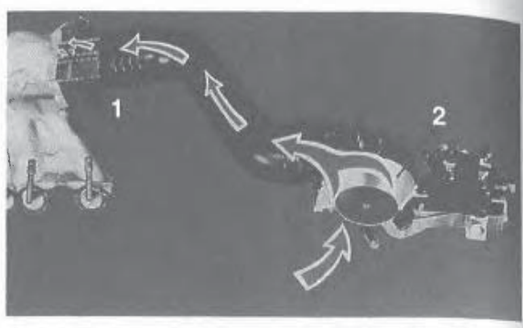


Fig. 2-1. Continuous injection air-flow system. Throttle valve (1) regulates air flow into intake manifold and engine. Air-flow sensor (2) measures volume of intake air.

The air-flow system includes the air-flow sensor (part of the mixture-control unit), the ducting to the throttle body, the throttle valve, and the intake manifold. The throttle valve controls the amount of air entering the engine. The air-flow sensor is deflected by that air, measuring its volume. The movement of the sensor in turn controls the basic fuel metering in the fuel distributor. The air-flow system also provides adjustment for engine idle speed.

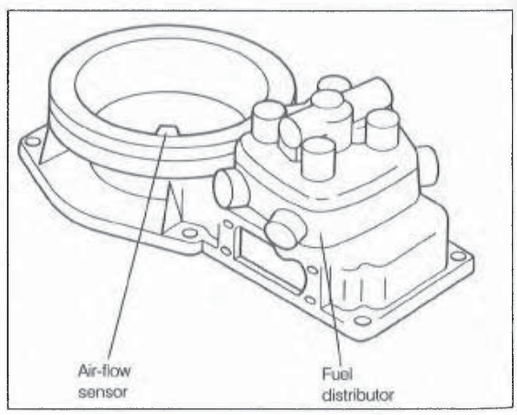


Fig. 2-2. The air-flow system measures engine air intake at the air-flow sensor, and turns that measurement into a proportional amount of fuel in the fuel distributor. Together, the fuel distributor and air-flow sensor are known as the mixture-control unit.

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2.1 Air-Flow Sensor

The key to air-flow sensor operation is a circular sensor plate that is deflected by engine intake air moving through the sensor plate housing. The movement of the plate in turn lifts the control plunger in the fuel distributor.

Sensor Plate and Control Plunger

When the engine is off, the sensor plate rests on a spring support, as shown in Fig. 2-3. This is known as the Zero Position. The plate is carried by a pivoting main lever. This allows the sensor plate to move in the intake air flow. The fuel distributor's control plunger rests directly on the same lever that carries the sensor plate.

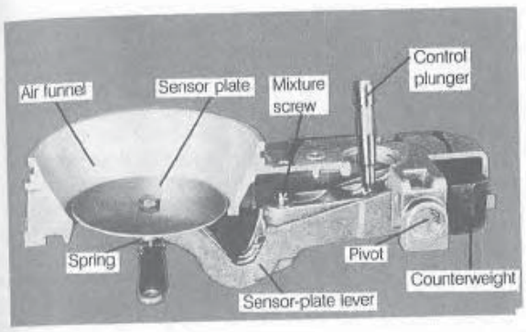


Fig. 2-3. Cut-away view of air-flow sensor shows sensor plate carried by a lever on a pivot, balanced by a counterweight. Shown with fuel distributor removed.

As the engine takes in air, the sensor plate rises as shown in Fig. 2-4. The more air flow, the more the plate and lever rise. The control plunger, because of its position on the lever, rises at the same rate as the sensor plate. This is a linear relationship: a doubling of air flow doubles sensor-plate lift, which in turn doubles the lift of the control plunger. The height of the plunger determines fuel flow to the injectors, so the higher it rises the greater the fuel flow. It is this mechanical relationship between the air flow sensor and the control plunger in the fuel distributor that determines basic fuel metering.

There are actually two types of air-flow sensors that are used in continuous injection, updraft and downdraft. In updraft sensors, as you've just seen, intake air flows from below and lifts the sensor plate **up**. In downdraft sensors, air flows from above and pushes the sensor plate **down**. Although the direction of air flow through the two sensors is different, the operating principles are identical: as the sensor plate is deflected by the intake air, the control plunger **rises**, increasing fuel flow. See Fig. 2-5.

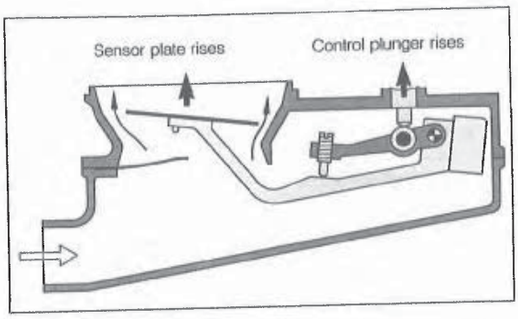


Fig. 2-4. As air is drawn into the engine, the sensor plate lifts, floating on the column of air. The movement of the sensor plate also lifts the control plunger.

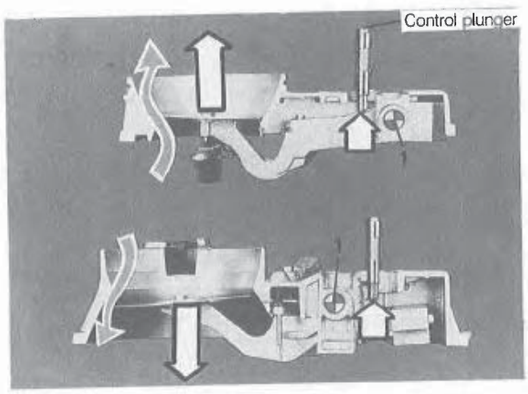


Fig. 2-5. When an updraft sensor plate rises, it lifts the plunger—on the same side of the pivot (1). When a downdraft sensor plate is forced down, it also lifts the plunger—on the opposite side of the pivot.

In both types of air-flow sensors, the weight of the sensor plate and lever is balanced by a counterweight. This means that the plate acts as though it were weightless in the intake air stream. The force of the air flow easily lifts the sensor plate, so much so that a counter-acting force is necessary to stabilize the movement of the plate. As you'll see later, fuel pressure force is used, applied to the top of the control plunger.

In later continuous systems, the counterweight is replaced by a balance spring; the spring has less inertia than the weight. This permits the sensor plate to adjust more quickly to changing air flow, so fuel metering and throttle response are faster.

Funnel Angles

The operation of the air-flow sensor is based on something called the "floating body principle." This principle states that under the right conditions a column of pressurized air will support and move an object, and that the movement of this object will be in direct proportion to the volume of air flowing past.

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In the air-flow sensor, all intake air flows through the sensor air funnel to create a column of air. Because the counterweighted sensor plate is positioned in the middle of the air funnel, it floats on the column of air. As the engine uses more air, the flow through the funnel is greater and the sensor plate rises in the column of air.

The shape of the sides of the funnel is tailored so that for a given air flow, the strength of the column of air is greater or less, and the lift of the sensor plate will be greater or less. See Fig. 2-6. The funnel is designed for each system on which it is installed, according to the power characteristics of the particular engine design.

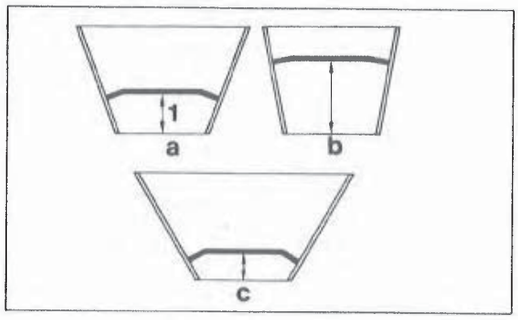


Fig. 2-6. Air-flow sensor funnel shape affects lift of sensor plate. For a medium cone angle (**a**), the sensor plate lifts to height **1** for a given air flow around the sensor plate. If the funnel walls are steep (**b**), the plate would have to lift much higher to pass the same amount of air. If the funnel wall angle is shallow (**c**), the same amount of air pushes with much less lift.

If you remember that sensor-plate lift affects control-plunger lift and basic fuel metering, you can see that funnel angles can be changed to affect the air-fuel ratio for a given air flow.

For example, in K-basic systems, the funnel is usually shaped with different angles according to engine needs for different operating conditions, as shown in Fig. 2-7. A steeper wall section near the top of the funnel causes more sensor-plate and plunger lift for the air flow, giving a richer mixture for full load. A shallower wall section in the middle causes less lift for a leaner mixture at part-load. At the bottom of the funnel, another steeper wall section gives more lift and a richer mixture for idle/off-idle conditions. In K-lambda and KE systems, the funnel shape is usually conical, so the proportion of the basic fuel metering is constant for the entire range of sensor plate lift.

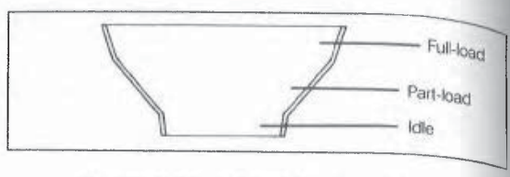


Fig. 2-7. In K-basic, funnel shape is designed to fit specific engines for enrichment at different air flows. Funnel shape is matched to each engine and model; do not interchange funnels.

Control-Plunger Counterforce

Some additional force is needed to balance the air-flow force that raises the sensor plate and control plunger. Otherwise, the movement of the plate would be too quick, and when the engine is started the plunger would rise to the top of its travel and stay there.

Fuel pressure supplies this counterforce, applied to the top of the control plunger in the fuel distributor. This pushes down against the upward force of the air flow sensor and the upward movement of the control plunger, regulating their movement and allowing the sensor plate to float in the air stream. The counterforce pushes the plunger back down for less fuel flow when there is less air flow, and returns the control plunger to its rest position when the engine stops running.

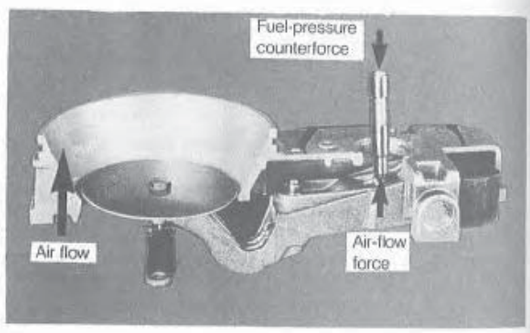


Fig. 2-8. Air-flow force lifts sensor plate and control plunger. Fuel-pressure counterforce presses down on the plunger. Balance of these two forces determines amount of plunger lift for a given air flow.

As you'll see later, this fuel-pressure counterforce can be varied to affect control-plunger lift for a given air flow, changing the proportion of fuel injected, and therefore changing the basic air-fuel ratio. In K-basic and K-lambda, the counterforce is known as the control pressure. I'll explain control pressure in **5. Control Systems**.

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Beginning with 1983 models, a return spring atop the control plunger ensures that the plunger follows the movement of the air-flow sensor during starting and engine deceleration. This improves starting and reduces hydrocarbon emissions during coasting. See Fig. 2-9.

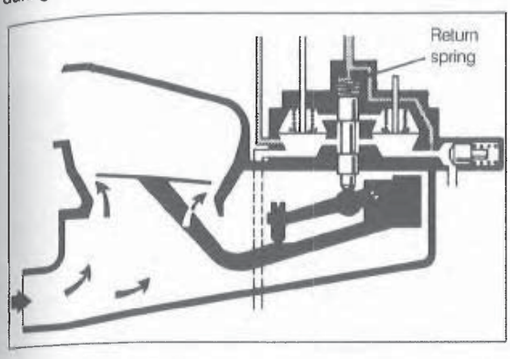


Fig. 2-9. Beginning in 1983, a small spring presses down to ensure control plunger follows sensor lever more closely.

Backfire Protection

The clearance between the edge of the sensor plate and the small part of the air-flow sensor funnel is very small, only about .10 mm. Because the plate effectively blocks the intake tract, any backfire in the intake manifold could build up reverse pressure and blow the ductwork, bend the sensor plate, or damage vacuum-operated systems.

To prevent damage in the event of a backfire, the air-flow sensor is designed with a secondary relief area in the funnel. See Fig. 2-10. Any backfire explosion in the manifold drives the sensor plate against its spring support and rubber bumper so that the pressure is vented around the edge of the plate. The sensor plate is driven past the zero position, down against its stop. (In downdraft sensors the plate is driven up against its stop).

KE Sensor-Plate Positions

Up until now, I've been talking about principles that apply to all continuous air-flow sensors. KE sensors operate in the same basic way as K-basic and K-lambda sensors: intake air lifts the air-flow sensor plate, which lifts the control plunger to meter fuel. But in KE, you'll find a big difference in the rest position of the control plunger due to some design changes. Because this difference affects restarting, it's important to know for chapter 6 when you'll be making checks of the air-flow sensor.

In K-basic and K-lambda, the control plunger rests on the lever when the engine is off (zero position); the sensor plate's rest position is determined by its stop. In contrast, KE is designed so that, at zero position, the plunger rests on an O-ring seal in the fuel distributor; there is a small amount of clearance between the plunger and the lever so the plunger seats firmly on the O-ring. See Fig. 2-11. This seals off fuel pressure more completely when the engine is off, and helps prevent vapor lock in the fuel lines.

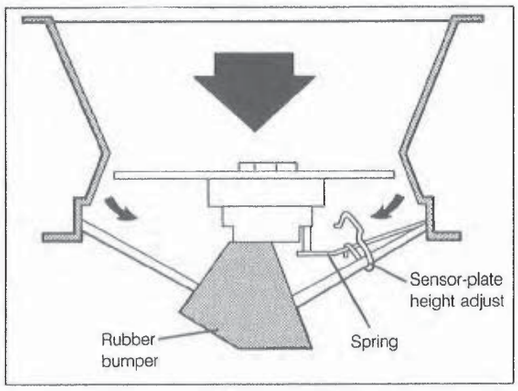


Fig. 2-10. In case of backfire, plate is pressed into second part of funnel relieving pressure in manifold.

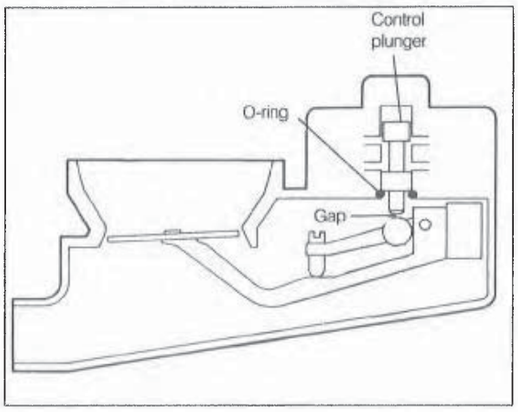


Fig. 2-11. KE control plunger rests on O-ring that seals in fuel pressure at base of plunger.

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This difference in KE means that there are actually two important KE sensor-plate positions. The first is the zero position as described above, where a wire-clip supports the sensor plate when the engine is off and there is clearance between the control plunger and the lever. The second is the basic position (and that's only in KE), the position of the plate in the air funnel when it is lifted so the lever just touches the control plunger. See Fig. 2-12.

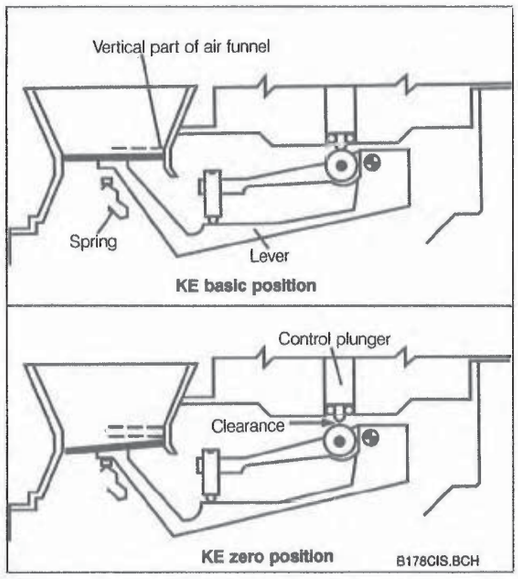


Fig. 2-12. In updraft KE basic position (**top**), sensor plate is at top of vertical part of air funnel (**dotted line**) and lever just touches control plunger. In zero position (**bottom**), plate rests on spring, and there is a gap between plunger and lever. You should be able to see all of the vertical part of funnel (**dotted lines**) around the sensor plate.

Incorrect clearance between the sensor lever and the control plunger will cause problems. If there is no clearance, the plunger will not seal against the O-ring, and residual fuel may dribble down into the mixture-control unit when the engine is off. This can cause flooding-type restart problems and, in a worst case, a potential fire hazard.

In contrast, if there is too much clearance between the sensor plate lever and the plunger you may experience a different start problem. During cranking, the air flow must lift the sensor plate a certain amount before the lever contacts the plunger to lift it and increase fuel flow. If there is excess clearance the lever will not lift the plunger soon enough for the air flow, upsetting the basic air-flow and fuel-metering function.

In chapter 6 you'll see how to check these important KE sensor plate positions. Also, remember the distinction between how updraft sensors and downdraft sensors operate: In updraft KE air-flow sensors, the sensor plate is lifted up from the zero position to the basic position; in downdraft air-flow sensors, the plate is pushed down from the zero position to the basic position.

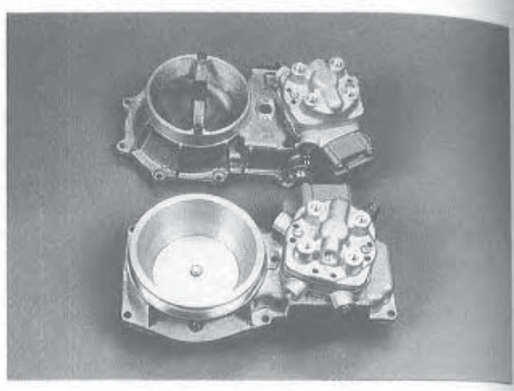


Fig. 2-13. KE-Jetronic air-flow sensors; downdraft (top) and updraft (bottom). Note that on downdraft sensors, sensor plate is angled.

Mixture (CO)

To ensure that the basic air-fuel mixture is in the best range for emission control, all continuous systems have a provision for mixture adjustment. Although this adjustment is made at idle, it affects the basic sensor-plate and control-plunger relationship over the entire range of operating conditions. For a given lift of the sensor plate, the lift of the control plunger is adjusted to change the amount of injected fuel, and therefore the air-fuel mixture. This adjustment is also known as the CO adjustment because the change in the air-fuel mixture changes the amount of CO (carbon monoxide) in the exhaust. The accuracy of the mixture adjustment is commonly checked by measuring exhaust CO.

You adjust mixture with the mixture-control screw, which is shown in Fig. 2-14. You can see that the air-flow sensor lever is actually two parts, and that turning the mixture screw in or out moves the mixture lever only. This moves the control plunger without changing the position of the sensor-plate lever or sensor plate.

For example, for a constant air flow at idle, turning the mixture screw clockwise pushes the mixture lever up. This lifts the control plunger further and more fuel is injected for the same air flow, enriching the mixture. If the screw is turned counterclockwise, the control plunger is lowered and the mixture is leaned. As you'll see in chapter 6, because the mixture screw is located in the air-flow sensor you'll need a special tool to reach it.

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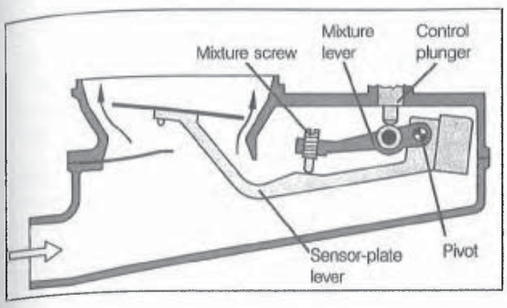


Fig. 2-14. Schematic view of air-flow sensor showing location of mixture-control screw.

2.2 Throttle Valve

The throttle valve regulates air flow into the engine. The more it is open, the greater the air flow into the engine. The throttle valve is downstream of the mixture-control unit, usually mounted on the intake manifold, and is controlled by the accelerator cable. The throttle valve does not control idle speed. This is done by a separate idle screw as described below.

Idle Speed

You adjust idle speed on continuous systems not by fine adjustment of the throttle valve, but by controlling a small amount of air that is allowed to bypass the throttle. This is more reliable since it's independent of accelerator-cable stretch or wear in the throttle valve mechanism.

The idle air bypass is regulated by the idle screw, as shown schematically in Fig. 2-15. The screw is usually on the throttle-valve housing. Turning the screw in or out changes the amount of bypass air. The screw is downstream of the air-flow sensor. Any change in bypass air results in a corresponding change in the amount of fuel injected, so idle speed adjustments do not affect the mixture adjustment.

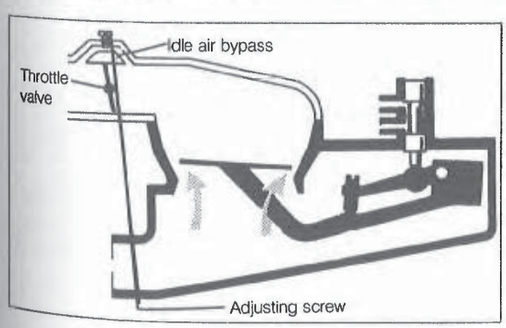


Fig. 2-15. Schematic view of air-flow sensor and throttle valve shows idle air bypass and adjusting screw.

3. Fuel System

In continuous systems control of fuel pressure is extremely important, even more so than in pulsed systems. As you'll see, fuel pressure opens the fuel injectors, and the control systems manipulate fuel pressure to alter the basic air-fuel mixture when compensating for different operating conditions. It's vital that the fuel system not only supply adequate fuel for the amount of air the engine is using, but also that the fuel be under pressure, maintained and controlled within a narrow range.

The fuel system includes the fuel tank to store the fuel, the electric fuel pump to pressurize the fuel, the fuel accumulator to damp pressure surges in the system, the filter, the fuel distributor to meter and distribute the fuel, the pressure regulator to maintain primary system pressure, and the fuel injectors to atomize the fuel. See Fig. 3-1. The electric pump and the filter operate similarly to those used in pulsed systems. For a discussion of how they operate see chapter 3. Some cars have an additional electric low-pressure in-tank pump, called the pre-supply or transfer pump. It ensures delivery to the main pump without vapor lock.

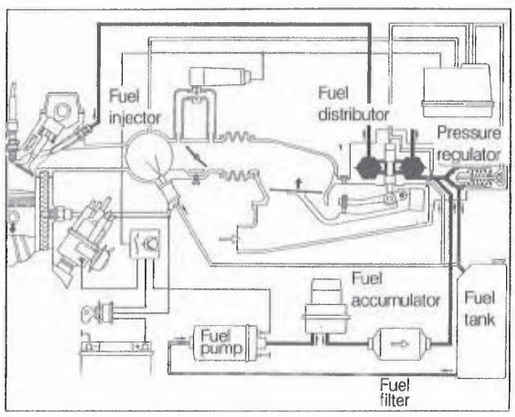


Fig. 3-1. Continuous injection fuel system. Supply components (fuel pump, filter) are generally similar to those of pulsed systems, with addition of accumulator. K-basic shown, K-lambda and KE systems similar.

3.1 Fuel Accumulator

Most continuous systems include a fuel accumulator, shown in Fig. 3-2, which damps fuel-pressure surges and holds residual pressure in the system when the engine is shut off. The accumulator's damping action protects the fuel distributor from the rapid build-up of fuel-pressure during startup, and reduces fuel pump noise when the engine is running. When the engine stops, the accumulator holds fuel pressure to help prevent vapor lock and improve hot restarts.

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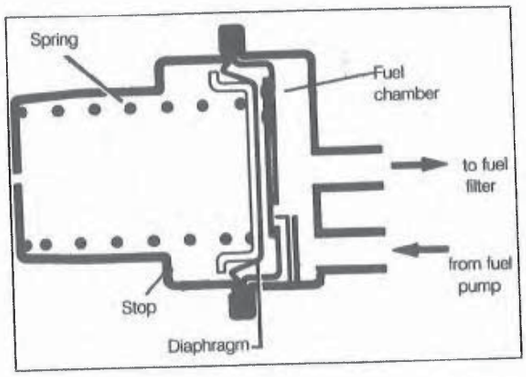


Fig. 3-2. Fuel accumulator. When engine starts, fuel chamber fills with fuel. Pump noise is dampened by the diaphragm. With engine off, accumulator spring maintains pressure in lines to help hot starts.

The main components of the accumulator are a spring and a diaphragm that separates a spring chamber and a fuel chamber. When the pump begins running, pressure builds in about 1 second as fuel fills the fuel chamber and presses the diaphragm against the stop. At pump shut-off, the pressure drops rapidly to about 2 bar (30 psi). See Fig. 3-3. This residual pressure is maintained by the force of the spring pressing against the diaphragm and the fuel in the fuel chamber. The accumulator holds pressure for a half hour or more to prevent vapor lock caused by fuel vaporization in the fuel lines of a hot engine.

3.2 Fuel Distributor

The fuel distributor is the part of the mixture-control unit that meters the fuel and then distributes it to the individual injectors. See Fig. 3-4. All fuel metering takes place in the center of the fuel distributor at the control plunger as it rises and falls. Secondary mixture control by the control systems to fine-tune the basic air-fuel mixture takes place through the manipulation of fuel pressures in the fuel distributor. The fuel distributor's role in fuel metering is discussed in **4. Fuel Metering**; the action of the control systems to further manipulate fuel pressures is discussed in **5. Control Systems.**

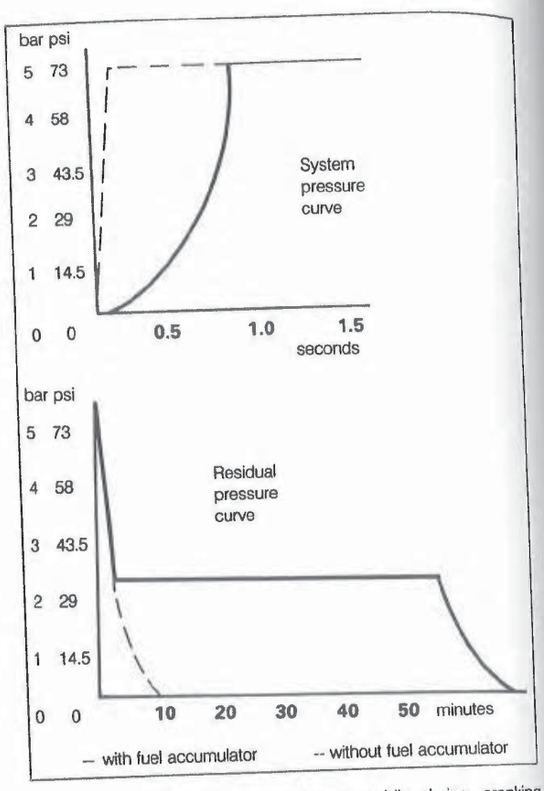


Fig. 3-3. Fuel pressure builds rapidly during cranking, damped by accumulator (**top**). After shut-off, pressure falls rapidly to close injectors, preventing fuel dribble at injector tips (**bottom**). Then accumulator maintains pressure in lines to aid hot starts. As engine cools over time, pressure falls—rate depends on minor leaks in lines and injectors.

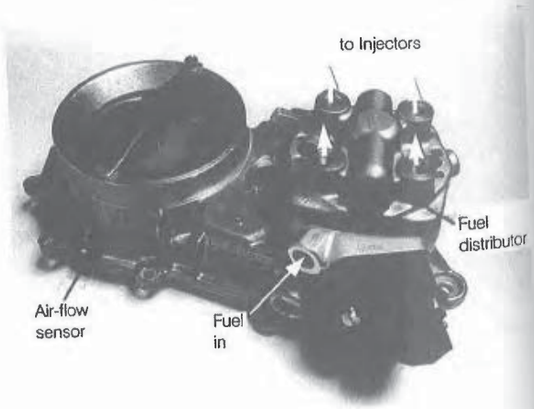


Fig. 3-4. Fuel distributor is part of mixture control unit, bolted to air-flow sensor. It meters and distributes fuel to the injectors. Downdraft air-flow sensor shown.

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3.3 System-Pressure Regulator

Continuous injection depends on fuel pressure to manipulate the air-fuel mixture, so that pressure must be closely regulated. The system-pressure regulator maintains system pressure (sometimes called primary pressure) in the fuel system at the specified level. There are two different types of pressure regulators, depending on the system. K-basic and K-lambda use a pressure relief valve located in the fuel distributor housing; KE systems use a separate diaphragm pressure regulator. Both regulate pressure by recirculating excess fuel back to the fuel tank.

K-Basic, K-Lambda

In K-basic and K-lambda, the system-pressure regulator is built into the fuel distributor. System pressure is set by spring force against the regulator relief valve. When the pump is turned on, fuel pressure builds until it overcomes spring pressure and opens the relief valve, returning excess fuel to the tank. See Fig. 3-5.

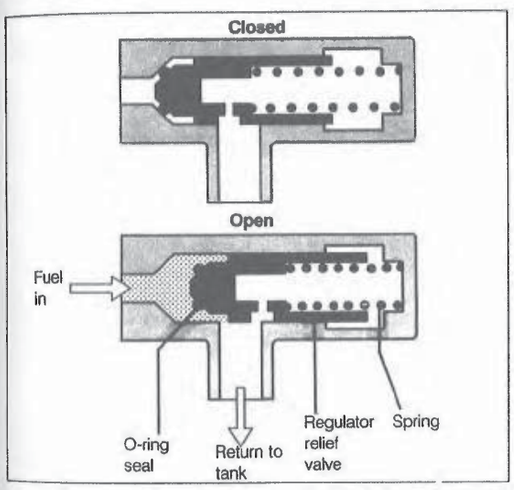


Fig. 3-5. Basic operation of K-basic and K-lambda system-pressure regulator. Fuel-pressure force overcomes spring force and opens regulating valve at specified pressure, returning excess fuel to the fuel tank.

There are actually two variations of the K-basic and K-lambda system-pressure regulator, depending on when the system was manufactured. The first one, shown above, was used until about 1978 and controls only system-pressure. Beginning about 1978, a new type of system-pressure regulator performs a second pressure-control function. See Fig. 3-6.

This slightly larger type includes what is known as a push valve. In the push-valve regulator, the opening of the relief valve also opens the push valve. The push valve controls the return of fuel from something called the control-pressure regulator. You'll see more about the control-pressure regulator in **5. Control Systems**. For now, all you need to know is that the push valve O-ring shuts off fuel return from the control-pressure regulator to better maintain residual system pressure. The difference between the two regulators will affect how you measure fuel pressure in chapter 6. You can tell the two apart by the shape of the system-pressure regulator on the fuel distributor. See Fig. 3-7.

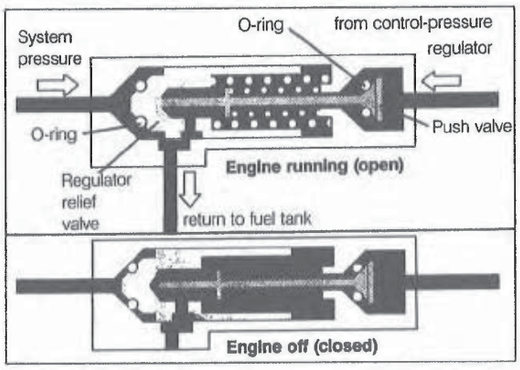


Fig. 3-6. Post-1978 K-basic and K-lambda system-pressure regulator with push valve. When engine is running, relief-valve plunger opens push valve. With engine off, larger spring closes relief plunger and smaller spring closes push valve, sealing control pressure in the system.

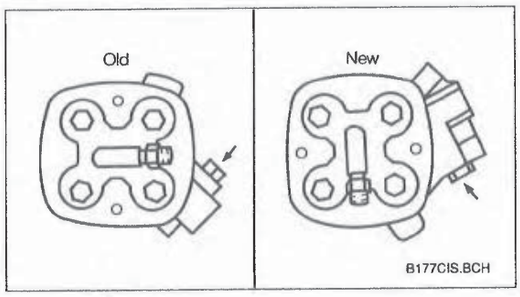


Fig. 3-7. K-basic and K-lambda system-pressure regulator (arrows) is built into the fuel distributor casting. Learn the difference between old (used before 1978) without push valve, and new with push valve.

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KE Systems

The KE system-pressure regulator is mounted outside the fuel distributor as shown in Fig. 3-8. System pressure is set by fuel-pressure deflecting a diaphragm. See Fig. 3-9. When the fuel pump is running, fuel pressure builds until it overcomes spring pressure in the regulator and moves the diaphragm. This opens the regulating valve to return excess fuel to the tank and maintain pressure at the specified level. The thinner return line carries fuel from the fuel distributor to the regulator; the thicker line supplies fuel from the pump.

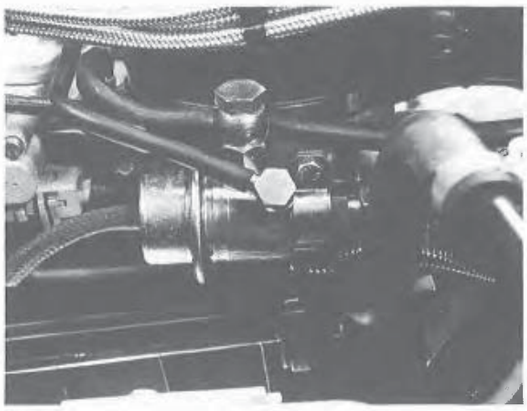


Fig. 3-8. KE pressure regulator looks like that of pulsed systems. It controls system pressure, and also controls return flow from the fuel distributor.

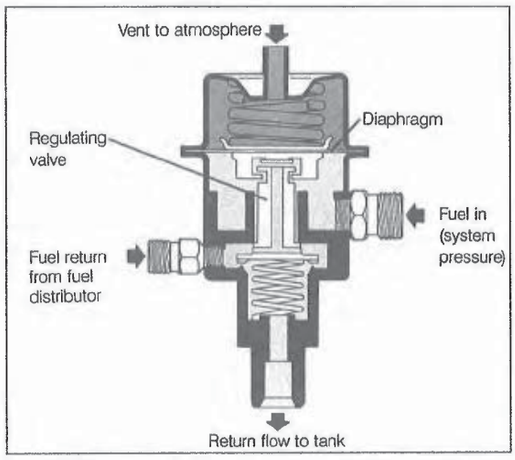


Fig. 3-9. KE fuel pressure regulator in open position.

3.4 Fuel Injectors

The fuel injectors used on continuous systems are mechanical. See Fig. 3-10. Pressure of the fuel delivered from the mixture-control unit overcomes spring pressure and opens the injector. Injector opening pressure is determined by the spring in each injector. There are no electric signals, and the injectors do not meter the fuel; they just continually inject fuel and atomize it. When an injector is working, you can hear a chatter as fuel pressure vibrates the open valve pins to atomize the fuel. Delivery stops when fuel pressure drops; the injector closes to keep fuel in the injector lines.

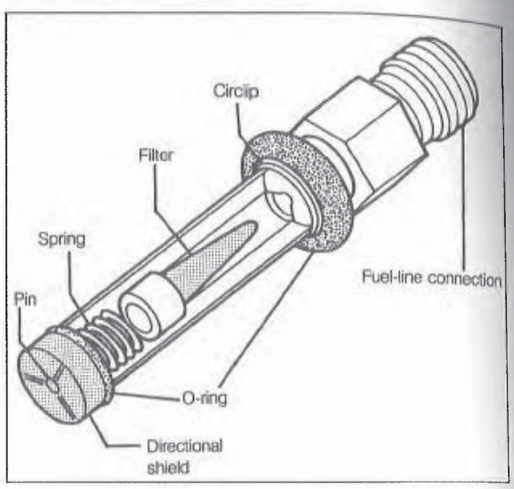


Fig. 3-10. Mechanical injectors are simple, no electrical connections. K-basic, K-lambda, and KE are all similar.

Air-Shrouded Injectors

Beginning in 1984, some KE systems have air-shrouded injectors to improve fuel atomization. Better fuel atomization means more efficient combustion. This saves fuel and reduces exhaust emissions. The injectors are mounted in a special air shroud in the intake manifold as shown in Fig. 3-11. At idle, lower manifold pressure at the injector tips induces air flow from upstream of the throttle to flow around the injected fuel stream.

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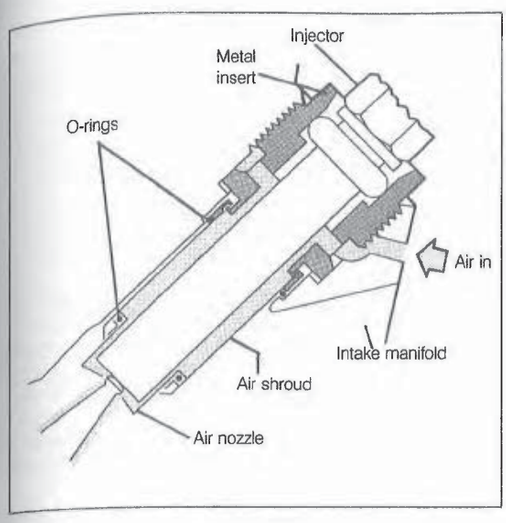


Fig. 3-11. Most KE injectors are air-shrouded to improve fuel atomization for smoother idle, better fuel economy and reduced emissions.

4. Fuel Metering

In continuous systems, all fuel metering takes place in the fuel distributor. This section describes basic fuel metering for all systems: matching a proportional amount of fuel to the air entering the engine to create the correct air-fuel mixture. This basic air-fuel mixture is then fine-tuned by the control system to compensate for different operating conditions. The control systems for each system are different; I'll describe them in detail in the next section, **5. Control Systems.**

4.1 Basic Fuel Metering

Basic fuel metering occurs when air entering the engine lifts the sensor plate, which in turn lifts the control plunger in the fuel distributor, allowing fuel to flow to the injectors. See Fig. 4-1. You've already seen how the air-flow sensor measures air flow and lifts the plunger, now I'll show you just how the control plunger and fuel distributor turn that air-flow measurement into a proportional fuel quantity.

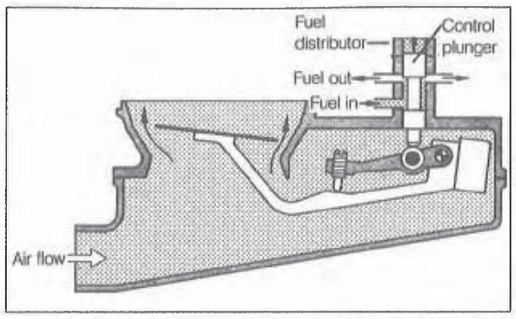


Fig. 4-1. Schematic view of mixture-control unit. Basic fuel metering begins when air-flow sensor lifts control plunger in fuel distributor, allowing fuel to flow to injectors.

Control Plunger Movement and Slit Size

The control plunger is mounted in the center of the fuel distributor, in a precision housing called the "barrel". See Fig. 4-2. The fuel pump supplies fuel at system pressure to the lower portion of the barrel. As the plunger is lifted, the fuel flows though upper slits to the injectors. See Fig. 4-3. There is one slit for each injector.

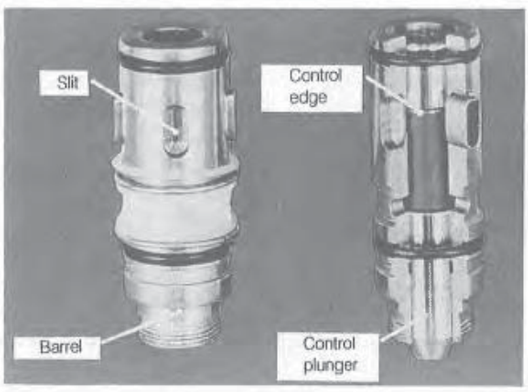


Fig. 4-2. The control-plunger and its barrel. Metering of fuel takes place at precision slit, one for each cylinder. Same for K-basic, K-lambda, KE.

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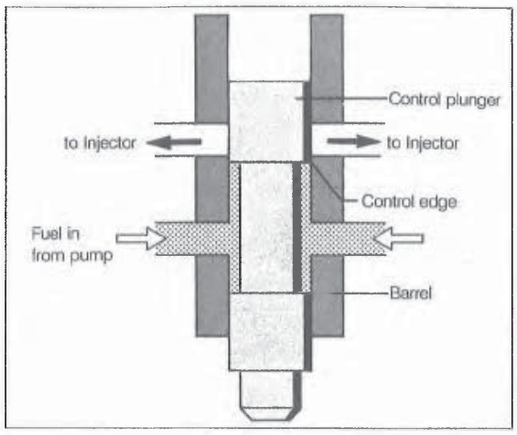


Fig. 4-3. Fuel flow through control-plunger barrel. As the plunger control edge rises, it uncovers the slits. Precisely sized slits are very narrow: approximately 0.2 mm (.008 in.).

The key to control-plunger fuel metering is the control edge of the plunger. This controls the amount that the upper slits are open, and therefore the amount of fuel that flows through the slits to the injectors. See Fig. 4-4. As the plunger is lifted in the barrel, the control edge of the plunger exposes more of each slit. Low air flow into the engine causes a small lift of the sensor plate and plunger; a small amount of each slit is exposed, delivering a small quantity of fuel through each slit. Increased air flow increases sensor-plate and plunger lift; more of each slit is exposed and fuel flow increases.

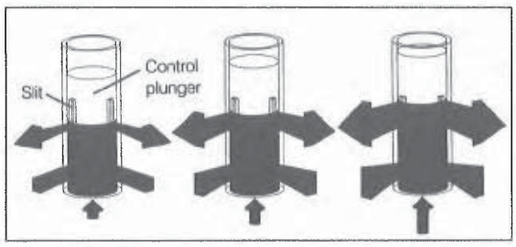


Fig. 4-4. The more the control plunger rises, the greater the flow of fuel through each slit.

Fuel Metering and Pressure Drop

Fuel flow to the injectors is influenced not only by the size of the exposed slit, but also by the pressure drop at the slit. Think of it this way: the pressure drop at the metering slits is the pressure differential between system pressure inside the slit pushing fuel out, and the lower pressure outside the slit in the fuel distributor. If the pressure drop changes for a given air flow and plunger lift, fuel flow through the slit also changes. For example, increased pressure drop forces more fuel to flow through the slit; fuel delivery increases.

Changing pressure drop at the slits causes problems with the linear relationship between air flow and fuel flow. When the control plunger rises, a more open slit changes the pressure drop and upsets the basic proportional relationship between air flow and fuel flow. So while increased air flow produces a linear increase in plunger lift, it does not necessarily provide a linear increase in fuel flow. At a certain point the change in pressure will cause the air-fuel mixture to be incorrect.

To hold constant pressure drop at the slits for the entire range of plunger lift, all continuous systems have something called Differential-Pressure Valves in the fuel distributor.

Differential-Pressure Valves and Pressure Drop

The differential-pressure valves maintain a constant pressure drop at the metering slits of the control plunger by reacting to the increased fuel flow that comes with a larger slit opening. There is one differential-pressure valve for each injector. They are mounted in chambers in the fuel distributor, and have a flexible metal diaphragm that separates the upper and lower halves of the chamber. See Fig. 4-5.

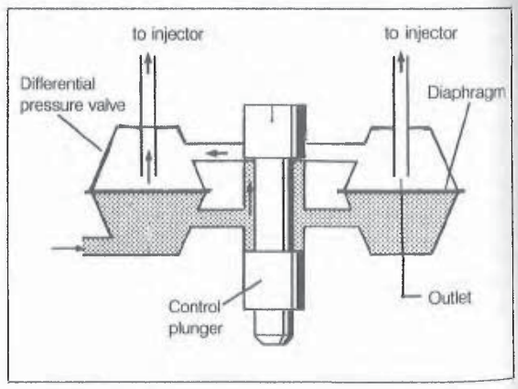


Fig. 4-5. Schematic view of fuel distributor shows location of differential-pressure valves. There is one valve for each fuel injector. Arrows indicate fuel flow through the control plunger and differential-pressure valves.

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As the control plunger rises, and fuel flow into the differential-pressure valve increases, the fuel pressure deflects the diaphragm. This causes a proportional increase in the area of the fuel outlet to the injector and maintains the same pressure drop at the control-plunger slit. Even though there is more fuel flow through a more open slit, the differential between pressure inside the slit and pressure outside the slit is constant.

It may seem, because the deflection of the diaphragm enlarges the outlet to the fuel injectors, that fuel metering is a function of how close the diaphragm is to the outlet. But this is not the case. All fuel metering takes place at the control-plunger slits. The movement of the diaphragm acts only to maintain constant pressure drop—to eliminate pressure drop as a variable and maintain accurate metering to each injector, regardless of changing fuel flow rates.

As you'll see in **5. Control Systems**, the differential-pressure valves play an important part in how the control systems fine-tune the basic air-fuel mixture. The control systems manipulate fuel pressure in the differential-pressure valves to change the pressure drop at the slits for a given plunger lift.

Comparison of Differential-Pressure Valves

In each differential-pressure valve the diaphragm separates the flow of injector fuel through the upper chambers from the fuel in the lower chambers. The upper chambers are separate so that the pressure-drop regulating function is independent for each injector and its line.

In K-basic and K-lambda, there is a spring which pushes down on the diaphragm to reduce the pressure in the upper chamber by 0.1 bar (1.5 psi). See Fig. 4-6. It is this pressure drop which causes fuel to flow out through the slits to the upper chambers and from there to the injectors.

In K-basic, the lower chambers are always at system pressure so the job of each diaphragm is to flex up and down to maintain the constant 0.1 bar pressure drop regardless of flow in the upper chamber.

In K-lambda systems, the electronic control systems operate to change the lower-chamber pressure. The flexible diaphragms still move up and down to equalize the pressures in between the upper and lower chambers, except as modified by the spring in each differential-pressure valve and by the change in lower-chamber pressure.

In KE systems, the control systems also change the lower chamber pressure, but the valves are different from K-lambda. The spring presses up from the bottom as shown in Fig. 4-7. The reasons for this difference are explained in detail in **5. Control Systems.**

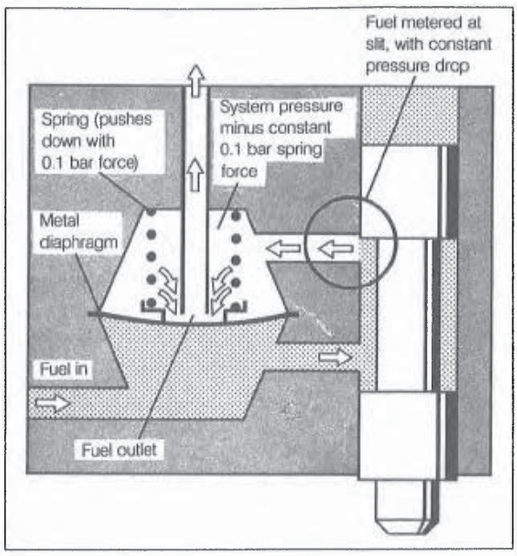


Fig. 4-6. Cross-section of K-basic differential-pressure valve in fuel distributor shows deflection of diaphragm from fuel flow. Accuracy of fuel metering is precise, based on constant pressure drop for each cylinder slit regardless of changing fuel flow rates.

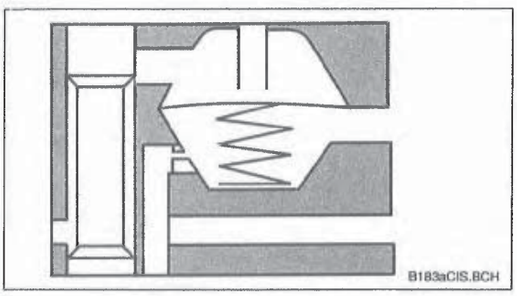


Fig. 4-7. In KE systems, spring in differential-pressure valve presses up against diaphragm. Flexible metal diaphragm still deflects with fuel flow, as modified by lower-chamber pressure.

Summary of Basic Fuel Metering

To briefly summarize basic fuel metering of continuous systems: Air flow entering the engine lifts the sensor plate and, in turn, the control plunger in the fuel distributor. Fuel-pressure counterforce applied to the top of the plunger balances the force of the air entering the engine and stabilizes plunger and sensor-plate movement. As the control plunger rises, its control edge uncovers the metering slits in the plunger barrel. As the slits open, fuel flows through the differential-pressure valves and out to the injectors. Fuel pressure opens the injectors, and the injectors atomize the fuel.

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The differential-pressure valves operate to equalize pressures between each upper chamber and its lower chamber. As a result, even as the delivery quantity changes to meet changing engine operating conditions, the pressure drop at each slit remains consistent with the spring pressure in the chamber and the lower chamber pressure. That insures equal delivery to each cylinder for increased engine smoothness.

5. CONTROL SYSTEMS

In **4. Fuel Metering**, I've described the basic fuel metering function of the air-flow sensor and the fuel distributor—the basic matching of fuel and intake air in the proper proportions. As I've described in chapter 2, modern fuel injection systems must make even finer adjustments to the mixture to maintain the stoichiometric air-fuel ratio and to compensate for the demands of different operating conditions.

This section describes how control systems manipulate fuel pressures in the system to fine-tune the basic air-fuel mixture. For any given air flow the basic fuel metering system creates the basic air-fuel mixture, and the control systems enrich or lean the basic mixture for more precise control of fuel metering.

There are two methods that the control systems use to adjust the basic mixture—changing slit size, and changing pressure drop at the slits. Later, you'll see how the control systems of each of the three continuous systems, K-Basic, K-Lambda and KE, apply these methods in different ways.

Changing Slit Size

The first method of adjusting fuel metering is to change the position of the control plunger for a given air flow by changing the counterforce on the plunger. You've seen how the fuel pressure counterforce is used to oppose the lift of the control plunger (against the air-flow force). Reducing the counterforce allows the sensor plate to lift the plunger higher for the same air flow, exposing more of the slits and allowing more fuel to flow for a richer mixture. Increasing the counterforce reduces plunger lift for a given air flow, exposing less of the slits and resulting in less fuel flow for a leaner mixture. This control is a fine adjustment to the basic movement of the plunger by the air-flow sensor; I'll refer to it as "changing slit size."

Changing Pressure Drop

The second method the control systems use for mixture adjustment is the manipulation of pressures on either side of the differential-pressure valves. This changes the deflection of the diaphragm and, in turn, changes the pressure drop at the slit. Remember, pressure drop here is the difference between pressure inside the slit and pressure outside the slit. For any given air flow and plunger lift, a change in the pressure drop changes the amount of fuel flowing through the slit, enriching or leaning the mixture. This control is in addition to the normal action of the differential-pressure valves; I'll refer to it as "changing pressure drop."

5.1 K-Basic—Changing Slit Size

K-basic systems use fuel under pressure as a hydraulic control fluid to maintain counterforce on the control plunger. This is called control pressure. To fine-tune the basic fuel metering, K-basic systems vary control pressure to change the counterforce on the control plunger. This changes the lift of the plunger and the size of the metering slit for a given air flow. The K-basic control system does not affect the differential-pressure valves. They deflect in a normal way to keep the pressure drop at the control-plunger metering slits constant.

Control-Pressure

As shown in Fig. 5-2, control pressure is applied through passageways in the fuel distributor. A flow restrictor admits fuel pressure from the system-pressure side to the control-pressure side without delivering full system pressure to the top of the plunger. A damping restrictor admits control-pressure force to the top of the plunger in order to balance the air-flow force of the air-flow sensor plate. The damping restrictor is large enough to permit transfer of pressure, but small enough to dampen any possible oscillation of the sensor plate and plunger which could result from pulsating air flow.

Control-Pressure Regulator

The control-pressure regulator adjusts control pressure by returning excess fuel from the control pressure circuit to the fuel tank. See Fig. 5-3. If more fuel is bled off to the tank, control pressure is reduced. If less fuel is bled off, control pressure is increased.

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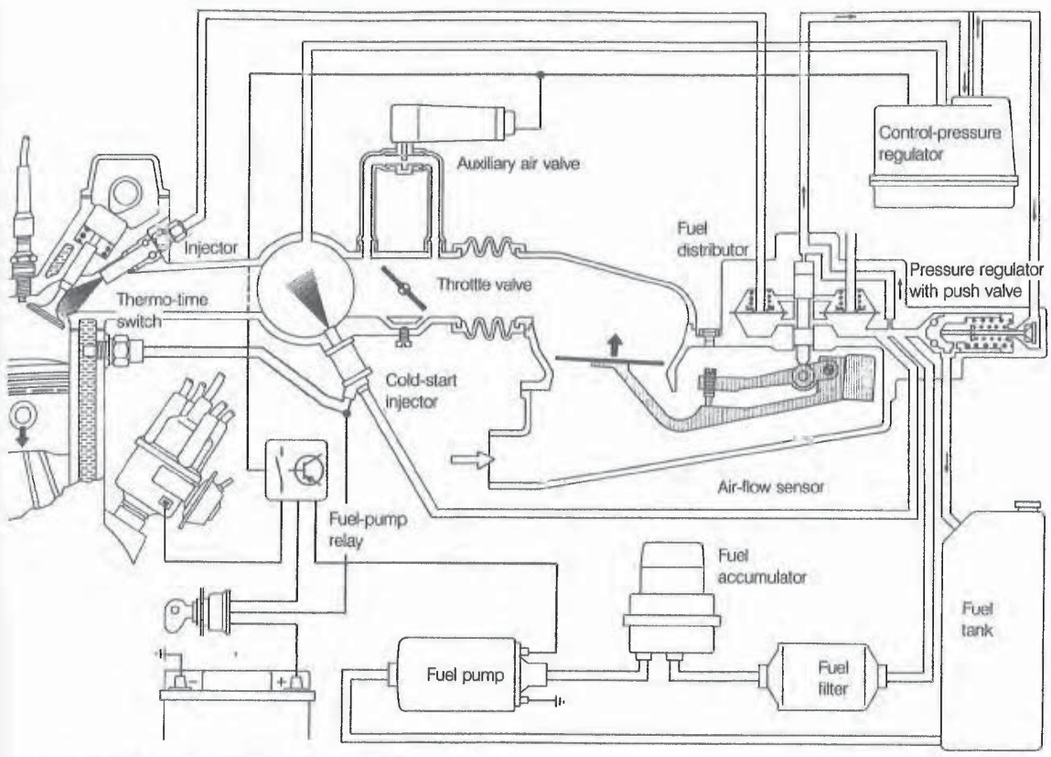


Fig. 5-1. Schematic of K-basic system shows all of the components. Control-pressure regulator and its compensation of the basic air-fuel mixture is described in this section.

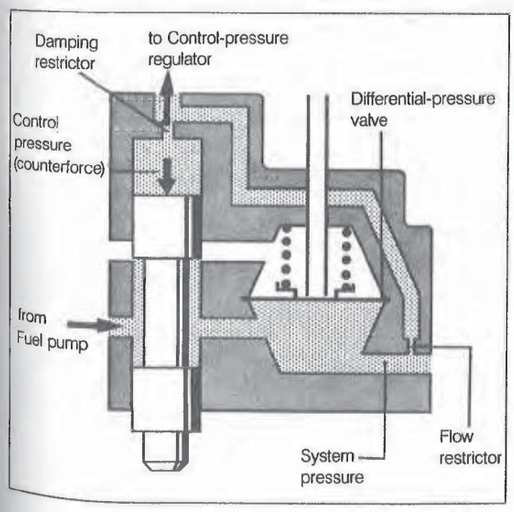


Fig. 5-2. Relationship of control pressure and system pressure in K-basic. System pressure is constant, control pressure varies.

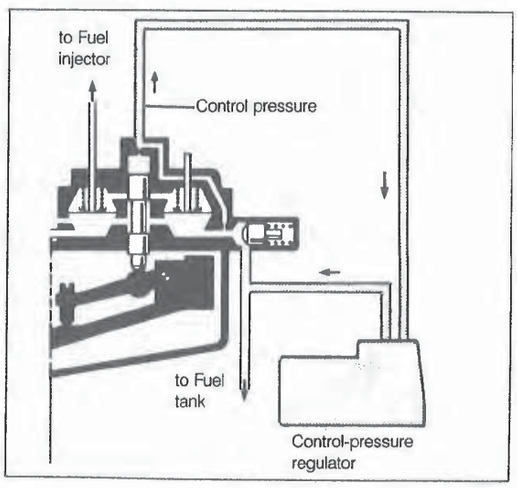


Fig. 5-3. Control pressure regulator adjusts control-pressure counterforce on the plunger by bleeding off fuel to the fuel tank.

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As shown in Fig. 5-4, the control-pressure regulator consists of a valve mounted on a bimetal arm. The arm is made up of two different metals of different expansion rates. It bends one way when it is cold and the other way when it is warm, changing control pressure in response to temperature.

When cold, the natural shape of the bimetal arm pulls the diaphragm away from the valve. As a result, the valve:

- increases fuel return to the tank, and
- reduces control pressure

As the regulator warms, the bimetal arm bends the other way. The spring closes the valve, which:

- decreases fuel return to tank, and
- increases control pressure

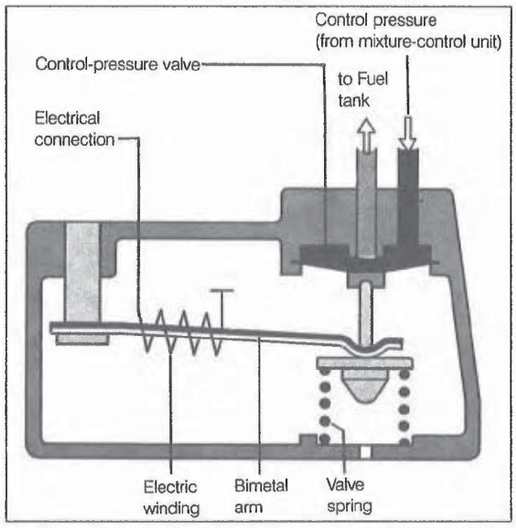


Fig. 5-4. K-basic control-pressure regulator. When cold, bimetal arm bends down. This increases fuel return and lowers control pressure, reducing counterforce on the control plunger. When warm, spring lifts diaphragm to increase control pressure and counterforce on the plunger.

Control Pressure and Mixture Adjustment

Remember that the basic action of the fuel-pressure counterforce on the plunger is to balance the force of the air flow entering the engine, so that the movement of the sensor plate and plunger is opposed. If this counterforce is changed, but the air flow stays the same, the amount that the sensor plate and plunger lift will also change.

The primary action of the control-pressure regulator is to enrich the basic mixture for cold operating conditions by reducing the control-pressure counterforce on the control plunger. As you saw above, when the control-pressure regulator is cold, control-pressure counterforce on the plunger is low. The plunger is able to rise higher for a given air-flow force, uncovering more of the metering slits so more fuel flows for the same amount of air. This enriches the mixture, improving cold driveability.

As the control-pressure regulator and its bimetal arm warm up, control-pressure increases. This increases counterforce on the plunger and it is forced lower for a given air-flow force. This reduces the size of the slits and leans the mixture. The regulator eventually warms to the point where it no longer compensates the mixture for cold conditions; only the basic sensor-plate lift of the control plunger determines the mixture.

A typical control pressure at freezing temperatures might be 1 bar (14.5 psi), and warm control pressure 3.5 bar (51 psi). As you'll see in chapter 6, measuring control pressure is the best way to check the operation of the regulator as pressures change with temperature.

The control-pressure regulator is usually located on the engine block, as shown in Fig. 5-5, so that engine-block temperature can affect the position of the bimetal arm. The regulator is often buried and hard to find. Look for two fuel lines to the fuel distributor: one is the control-pressure line to the regulator, and one returns fuel to the tank. In pre-1978 systems, return fuel flows uncontrolled through a "tee" into the return line from the system-pressure regulator. In 1978 and later, return fuel flow is controlled by the push valve, through the system-pressure regulator and back to the tank. See earlier Fig. 3-7.

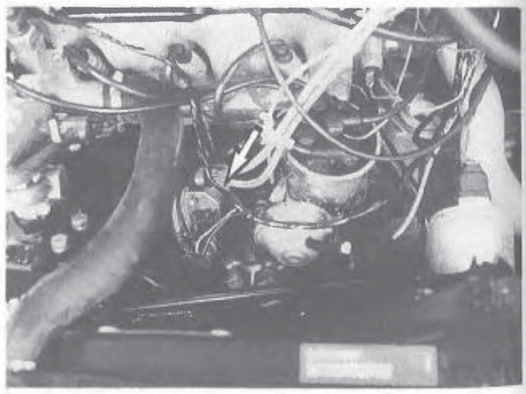


Fig. 5-5. Control-pressure regulator (arrow) is often buried, located on the block to react to engine temperature. Look for two lines from the mixture-control unit.

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After a cold start, fuel enrichment needs to be cut back in one or two minutes, but the engine block might take 10 minutes to warm up to the point where it affects the bimetal arm in the control-pressure regulator. To insure that the mixture is not enriched for too long, an electric heating coil warms the arm when the ignition is turned on. Warm-up needs are different for each car model, so do not interchange regulators.

Additional Control-Pressure Compensations

The control-pressure regulator was originally called the warm-up regulator (WUR), because in its early applications, warm-up compensation was its only job. In some cars, control-pressure changes are also used for other reasons; to enrich the mixture during full-load operation or when under boost from a turbocharger, or to lean the mixture for altitude compensation.

For load compensation, the special control-pressure regulator has a second diaphragm which responds to engine load by sensing intake manifold pressure. See Fig. 5-6. High manifold pressure from an open throttle or from turbocharger boost influences the diaphragm and lowers control pressure. Lower control pressure allows greater plunger lift, more open slits, and greater fuel flow for a richer mixture. You can recognize these special control-pressure regulators by the vacuum-hose connection to the intake manifold, and by the extra chamber along the bottom of the regulator.

At part-throttle, when little enrichment is needed, manifold pressure is less than atmospheric pressure in the lower chamber of the diaphragm. This raises the diaphragm to add its spring pressure to the control-pressure valve. Control pressure is high, and there is little additional lift of the control plunger to enrich the mixture.

Altitude compensation is provided by an aneroid chamber at the bottom of the regulator. This chamber expands as the air gets thinner at higher altitudes; this in turn acts on the control-pressure valve to increase control pressure and lean the mixture.

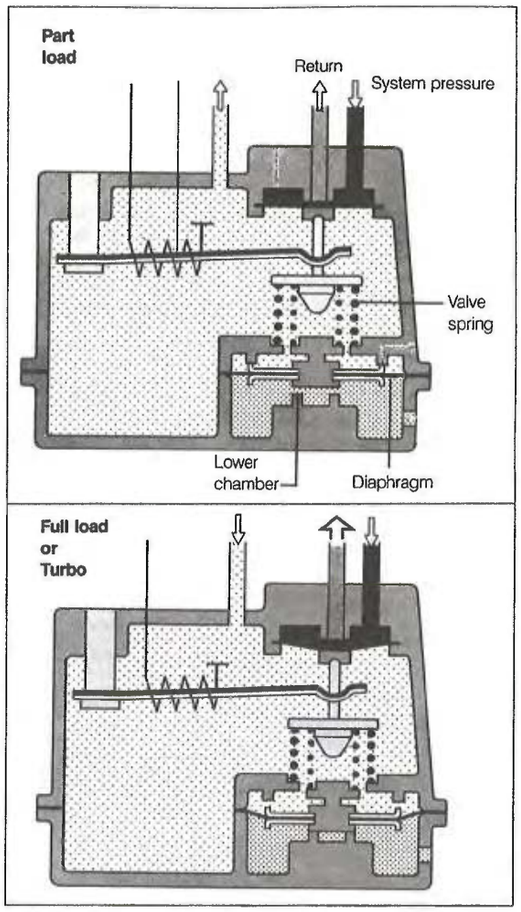


Fig. 5-6. Full-load control-pressure regulator on some K-basic and K-lambda systems has vacuum connection to intake manifold so control pressure is modified according to manifold pressure. Full-load or turbocharger-boosted manifold pressure (**bottom**) presses down on lower diaphragm to reduce control pressure and enrich mixture.

5

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5.2 K-Lambda—Changing Slit Size and Pressure Drop

K-lambda control systems adjust the basic air-fuel mixture by a combination of two ways. The first is by changing slit size for a given air flow. This is done just as in K-basic, by the control-pressure regulator, primarily for cold running.

The second method of adjusting the basic air-fuel mixture is by changing the pressure drop at the control-plunger slit so that fuel flow changes for a given plunger lift. This is done by manipulating pressures in the differential-pressure valves' lower chambers is controlled by the Lambda Control System, in response to the signals from a lambda sensor in the exhaust system.

K-Lambda Differential-Pressure Valves and Mixture Adjustment

As you saw earlier, the K-basic differential-pressure valves hold the pressure drop constant at the metering slits of the control plunger. The deflection of the valve diaphragm increases with fuel flow for this pressure-drop function. If air flow and plunger lift stay the same but the deflection of the diaphragm is changed for some other reason, the pressure drop, and therefore the amount of fuel flowing through the slits, will also change.

For example, with a given plunger lift and fuel flow through the slits the pressure drop at the slits is a constant. But if the lower-chamber pressure of the differential-pressure valves is lowered, the diaphragm will deflect further. This extra deflection of the diaphragm decreases pressure in the upper chamber and increases the pressure drop at the slits; more fuel flows for the same plunger lift, enriching the mixture.

K-lambda control systems use this method to adjust air-fuel mixture. The lower-chamber pressure of the differential-pressure valves is not system pressure, as in K-basic. The pressure in the lower chambers, and therefore the pressure drop at the slits, is controlled by a separate pressure circuit which is in turn controlled by the lambda control system. Fuel is admitted to the lower chambers through a restrictor, and flows back to the tank through the lambda valve and the fuel return lines. In that way, the pressure of all lower chambers is controlled by the lambda valve.

Lambda Control System

The lambda control system includes a lambda sensor, a lambda electronic control unit, and a lambda control valve. See Fig. 5-7. The lambda valve (sometimes called a frequency valve, or timing valve) looks similar to a pulsed fuel injector, as shown earlier in Fig. 1-5. It opens and closes in a similar manner, but its opening and closing does not meter fuel. Rather, the amount of time the valve is open controls the pressure in the lower-chambers of the differential pressure valves. This in turn changes upper-chamber pressure to change the pressure drop and change enrichment.

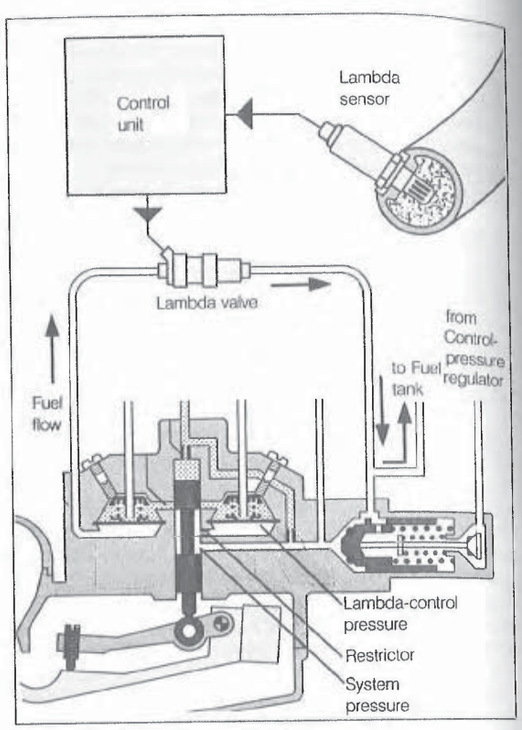


Fig. 5-7. In addition to K-basic control-pressure regulator, K-lambda control adds lambda sensor (or oxygen sensor), control unit, and lambda valve. Note additional fuel connection to pressure regulator.

The opening of the lambda valve is controlled by the electronic control unit, which monitors the signal from the lambda sensor (also known as the oxygen sensor.) The lambda sensor sends a signal to the control unit which is based on the oxygen content in the exhaust. The control unit then operates the lambda valve to control lower-chamber pressure.

The lambda valve is a solenoid valve which is either open or closed. The control unit sends on-off voltage pulses to the lambda valve. The frequency of these pulses determines the amount of time the valve is open and, therefore, the amount of fuel that is returned to the fuel tank. The on-off cycle of these pulses is known as the duty cycle. Duty cycle is measured on a scale of 0 to 100%. When the duty cycle is 50%, that means the lambda valve is open 50% of the time and closed the rest of the time.

Duty cycle can also be measured using a dwell meter scale of 0 to 90°. If you read a 50% duty cycle on a dwell meter set to the 4-cylinder scale, it would read 45° (50% of 90°).

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