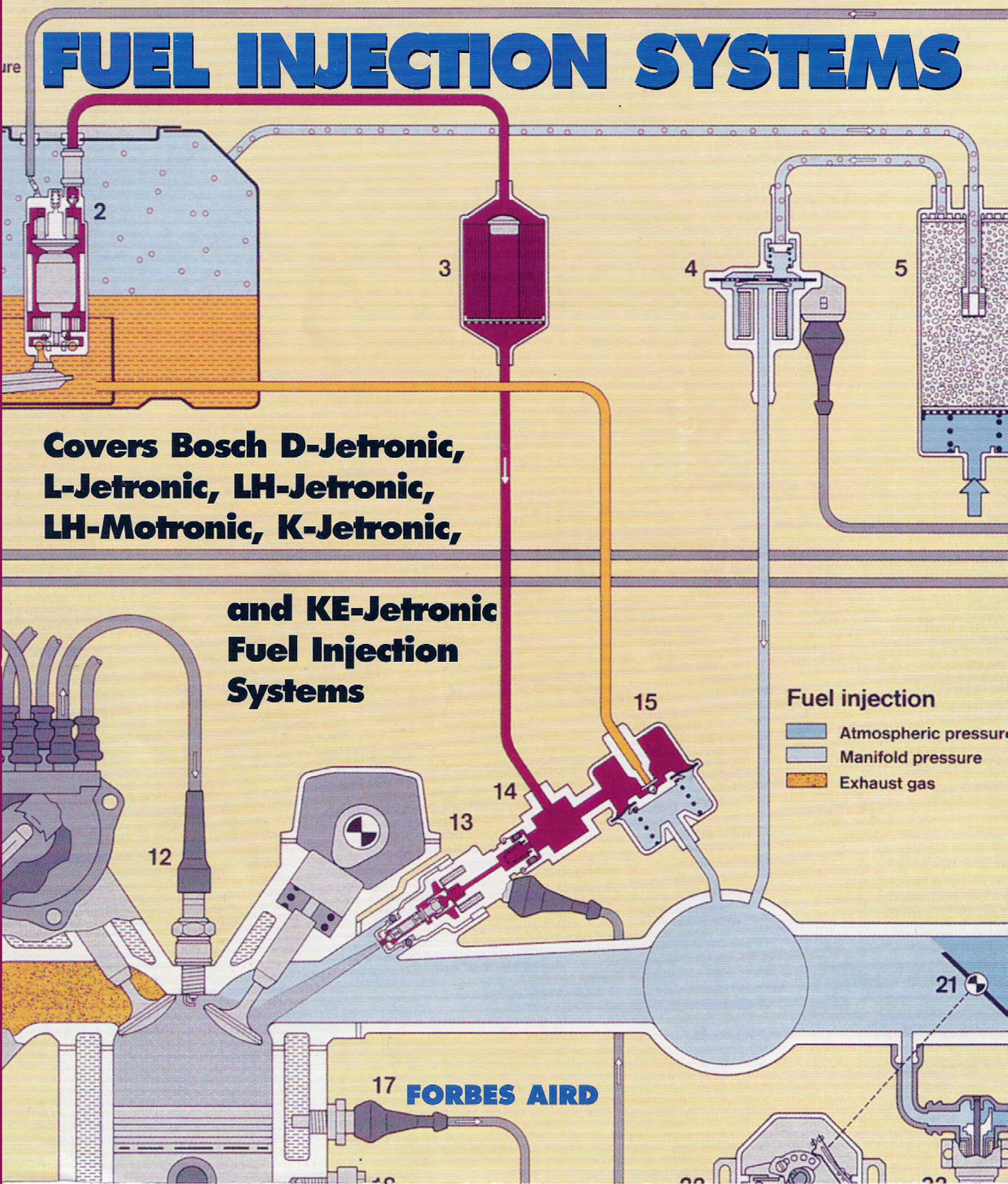
HPBooks

BOSCH FUEL INJECTION SYSTEMS

Covers Bosch D-Jetronic, L-Jetronic, LH-Jetronic, LH-Motronic, K-Jetronic, and KE-Jetronic Fuel Injection Systems



FORBES AIRD

BOSCH FUEL INJECTION SYSTEMS

Forbes Aird

HPBooks

HPBooks
are published by
The Berkley Publishing Group
A division of Penguin Putnam Inc.
375 Hudson Street
New York, New York 10014

First edition: July 2001
ISBN: 1-55788-365-3

10 9 8 7 6 5 4 3 2 1

This book has been catalogued with the Library of Congress

Book design and production by Michael Lutfy
Cover design by Bird Studios
Interior illustrations courtesy of Bosch, Inc. and the author as noted

ACKNOWLEDGMENTS

I am grateful to Robert Bosch GmbH in the persons of Gerhard Kopany, for permission to reproduce copyright photos and illustrations, and of Wolfgang Boerkel, for answers to some technical questions. Thanks are also due to Wolfgang Hustadt of Bosch North America and to Bill Roth, for further technical information.

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.

CONTENTS

1 FOOD FOR ENGINES, FOOD FOR THOUGHT

If a certain fixed quantity of air—or any other gas—is confined in a closed container and then heated, the pressure inside the container will rise. If one of the walls of the container is moveable, the internal pressure will push that wall outward with a certain amount of force, according to how much heat was put into the trapped gas.

That, in a nutshell, is the working principle of all internal combustion engines: Each cylinder is a closed container, and each piston represents a moveable wall of that container; the heat is supplied by the burning of a fuel, usually gasoline, and the trapped gas is whatever mixture of gaseous compounds left over after the burning.

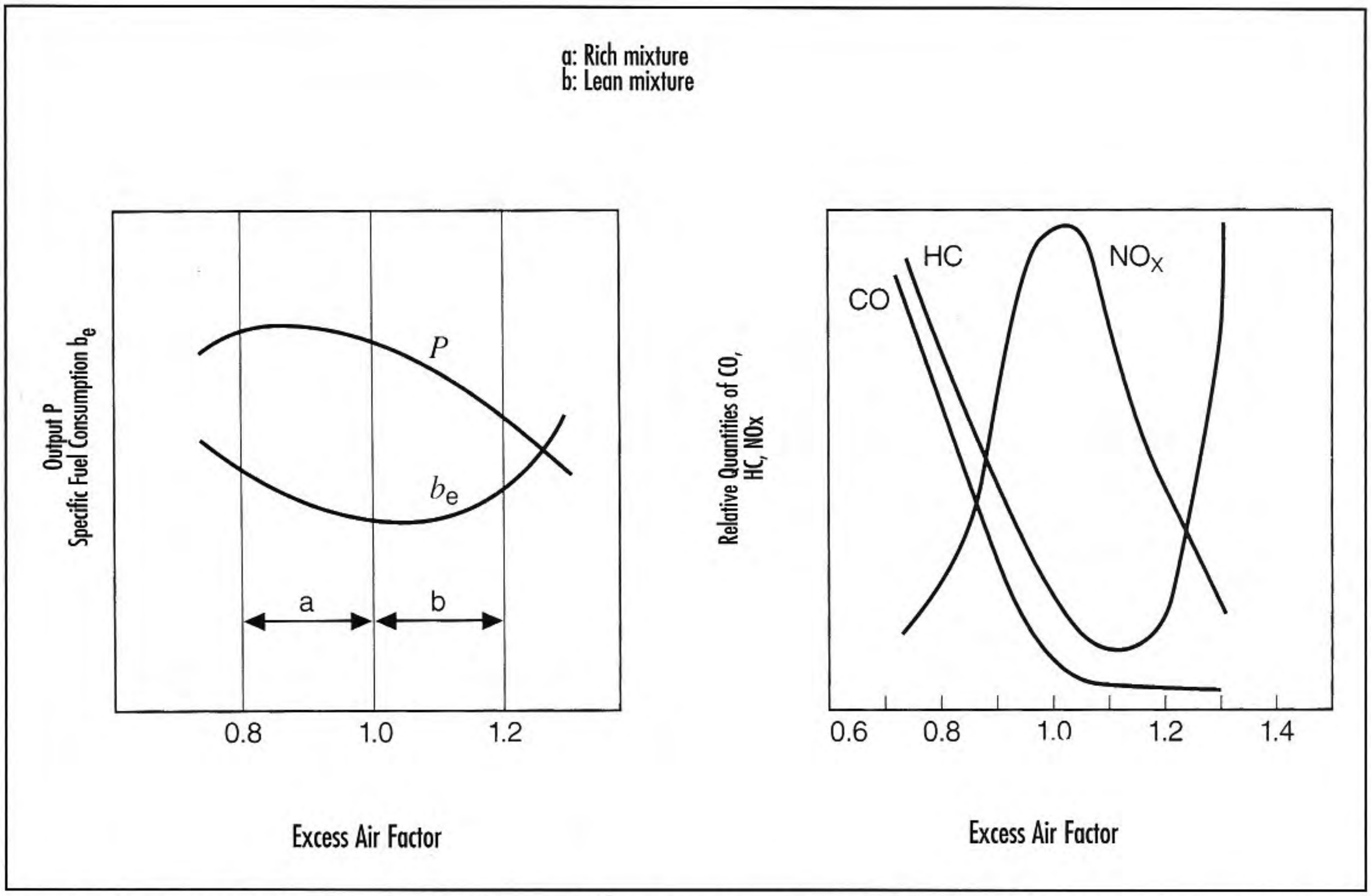
Meanwhile, the other moving parts of an engine are there for one or the other of just two supporting functions. The "bottom end" converts the movement of the pistons into rotary motion and, by returning them to the top of their strokes, restores the closed containers to their original size; the valve gear and everything else at the "top end" are there simply to provide for the emptying out of the spent gasses and the refilling of the cylinders with a fresh charge of burnable mixture.

This may all seem very obvious to anyone with even the most basic understanding of how engines work, but lurking within the simple facts outlined above is a wealth of detail. Consider the fuel, for example. Some fuels contain more chemical energy per pound than others, and so can produce more heat when burned. Even limiting the discussion to gasoline, the fact is that ordinary pump gasoline is a mixture of hundreds of different flammable compounds, and each of those compounds has a different potential ability to generate heat when burned. The exact nature of the mixture of these compounds varies from one pump to another and from one season to the next, so a pound of gasoline from one pump on one day might release somewhat more or less heat when burned than would a pound from another pump, or from the same pump on some other day.

While each is unique, all the hundreds of compounds that make up gasoline have one thing in common—they are all hydrocarbons. That is, they are all made of just two kinds of atoms, hydrogen (H) and carbon (C). The difference between one of these hydrocarbons and another lies in either the number of hydrogen and carbon atoms, or in the way in which these two component elements are arranged, or both.

Now, burning is a process of oxidation—a combining with oxygen (O)—so, reduced to its basics, when a hydrocarbon fuel like gasoline burns, individual hydrocarbon molecules from the gasoline combine with individual molecules of oxygen from the air. The hydrogen (H) in the hydrocarbon combines with some of the oxygen (O) in the air to produce water (H_2O), while the carbon (C) in the hydrocarbon combines with the rest of the oxygen to form carbon dioxide (CO_2). In this process, a large amount of energy gets released, in the form of heat. This chemical dance amounts basically to a reversal of the processes that went into creating the hydrocarbons in the first place. See the box, "Sunlight by the Gallon."

Air, too, is a mixture of substances, although all of them are gasses at room temperature. About 78 percent of our atmosphere is nitrogen (N); only about 21 percent



Burning fuel with insufficient air results in carbon monoxide (CO) being formed, instead of carbon dioxide (CO_2). Excess fuel also leaves unburned hydrocarbons (HC) in the exhaust. Paradoxically, a too-lean mixture causes misfires, which also lets unburned fuel escape. Oxides of nitrogen (NOx) are produced in greatest abundance when the mixture strength is just a bit lean, when combustion is hottest. (Robert Bosch Corporation)

of it is oxygen. The remaining one percent or so is made up of several rare gasses, like neon and argon, plus CO_2 and water vapor. The chemical reaction of burning gasoline—especially inside the cylinders of an operating gasoline engine—is further complicated by the presence of these other elements, and particularly the nitrogen.

Nitrogen is a comparatively inert substance—it does not readily react with anything much, so in a simplified description of the burning of gasoline in air, the nitrogen is ignored, on the assumption that it passes right through the whole operation unchanged. In fact, that is not quite true. Exposed to the enormous temperatures and pressures in the combustion chamber of an engine, a little of the nitrogen does end up combining with some of the oxygen, forming various oxides of nitrogen—NO_2, NO_3 and so on—known collectively as NOx. While for most purposes the minor involvement of the nitrogen does not make much difference, these nitrogen oxides are air pollutants. Thus, while the idea of "burning" a fuel seems a simple business, here is just one factor that begins to reveal that it is somewhat more subtle and complex than it at first appears.

Stoichiometric Mixture

Within narrow limits, a fixed quantity (that is, weight) of air contains a certain specific number of oxygen molecules, and any given weight of any specific gasoline likewise contains some definite number of

SUNLIGHT BY THE GALLON

Vegetables are a lot smarter than you might think. Millions of years ago, they managed to harness the energy of sunlight in order to manufacture themselves from the simple raw materials available to them, specifically water (H_2O) from the ground and carbon dioxide (CO_2) from the atmosphere. A plant—a tree, for instance—grows by using solar energy to split the CO_2 into separate atoms of carbon (C) and oxygen (O), and then to combine the carbon with the water to make molecules of cellulose ($C_6H_{10}O_5$). In effect, a tree uses water and carbon to make more tree.

From the tree's point of view, the oxygen remaining after the carbon is split from the CO_2 is incidental, and so is cast aside, into the air. From our point of view, this aspect of the process is vital—it is the reason we have a breathable atmosphere. (And you thought those tree-huggers were as dumb as vegetables!)

Usually, once a plant dies, the cellulose breaks down, but the process is not exactly a reversal of the original chemistry. In fact, some of the carbon and hydrogen the tree has spent so much of its sun-energy input combining remain hooked together as molecules having a certain number (say, "x") of carbon atoms and some number (say, "y") of hydrogen atoms, (CxHy), of which there are many hundreds of different ones. If exposed and left to rot, the major product is likely to be a gas—methane (CH_4), otherwise known as "swamp gas," or "fire damp." Under certain conditions, however, entire forests can get buried and, over the course of countless millions of years, subject to enormous pressure from the weight above, the carbon and hydrogen atoms get re-shuffled into more tightly clustered hydrocarbon molecules, many of which are liquids. All of the world's oil (hydrocarbon) deposits are the age-old remains of this process of decay and chemical rearrangement of vegetation.

When we subsequently extract, refine and burn some of this liquid sunshine, we are recombining the hydrogen and carbon with oxygen. When we do so, the swapping of chemical partners that occurs liberates all of the considerable solar energy that, over years, went into the original separation processes. And it is that energy, in the form of heat, that makes the wheels go 'round.

hydrocarbon molecules. Because the burning process amounts to individual atoms combining with each other, it follows that there is only one particular ratio of gasoline-to-air that can ensure that all of the oxygen molecules mate up with all of the hydrocarbon molecules. This theoretical ideal is called a stoichiometric mixture.

If there is an excess of oxygen molecules, some of them will fail to find partners. In terms of the number of oxygen-hydrocarbon pairings, and thus the amount of energy released, the effect is as if we had started with a smaller quantity of air. At the same time, if there are too many hydrocarbon molecules in relation to the amount of air, then some of the hydrocarbons will emerge from the combustion process unburned.

Some of the gasoline is simply wasted. Not only that, but a shortage of oxygen means that there is a likelihood of some of the carbon atoms in the hydrocarbon fuel to combine with just one oxygen atom, rather than two, yielding carbon monoxide (CO) rather than carbon dioxide (CO_2). While CO_2 is one of the "greenhouse gasses" that are partly responsible for global warming, at least it is only immediately harmful to animal life when its concentration grows so large that it displaces much of the oxygen we need to breathe. CO, on the other hand, is toxic even in small doses.

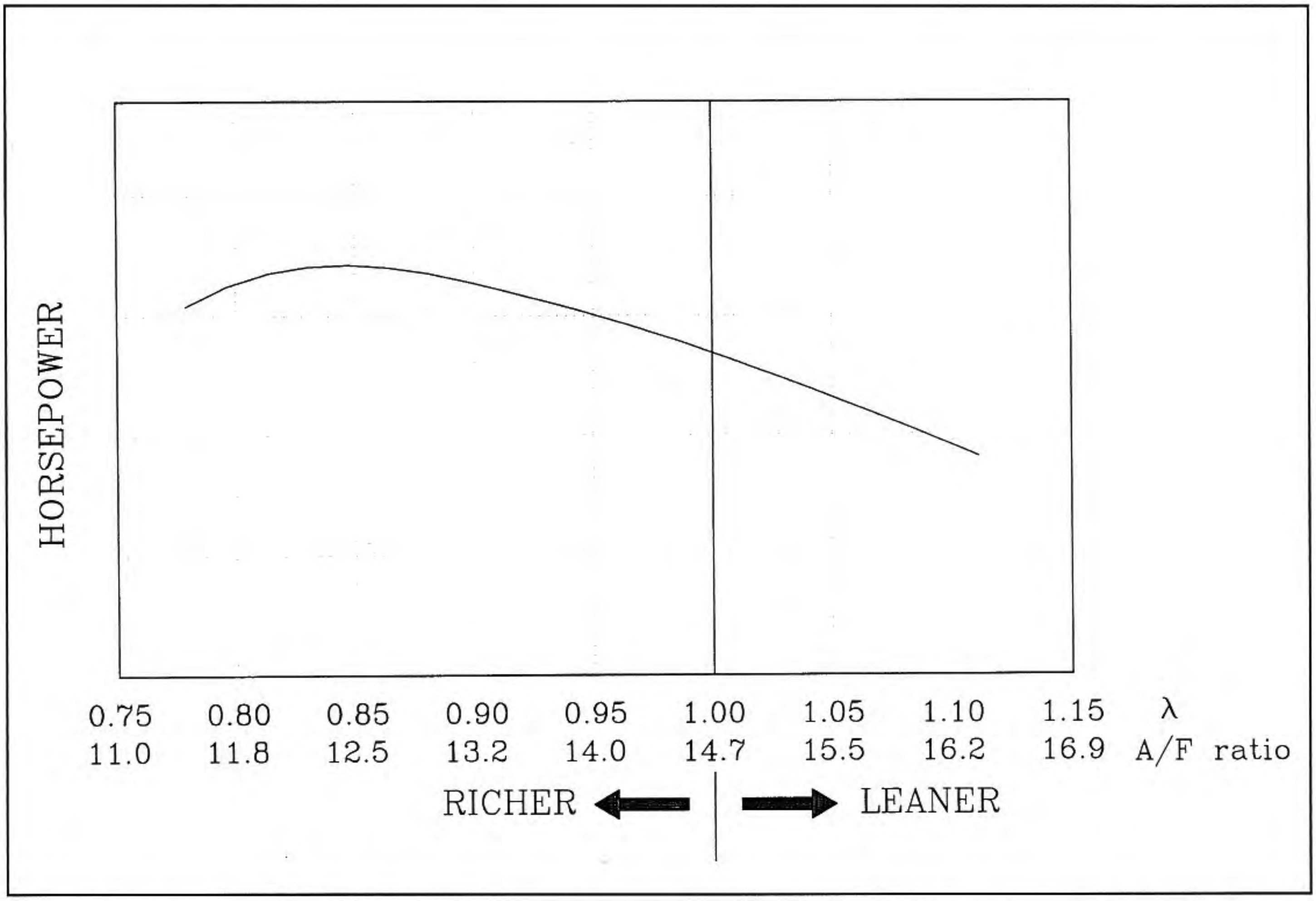
It turns out that about 14.7 lbs. of air contains the correct number of oxygen molecules to pair up with the number of hydrocarbon molecules in 1 lb. of gasoline. The ratio of air to gasoline to achieve a stoichiometric mixture, in other words, is approximately 14.7:1, by weight. Note we say approximately—there is no single number that correctly identifies the stoichiometric mixture for all gasolines. To explain, recall that gasoline is a mixture of hydrocarbons. Each has its own stoichiometric mixture strength, ranging from less than 13:1 to more than 15:1, so the stoichiometric ratio for the entire blend depends on the proportions of the differing hydrocarbons that make it up. Apart from incidental variations, the major oil companies deliberately modify the blend of hydrocarbons in pump gasoline from season to season and from place to place, so the stoichiometric mixture may correspondingly vary slightly, according to where and when you buy the fuel. (See also the sidebar "The Oxygen Battery," page 34.)

As we have said, gasoline, strictly defined, contains only hydrocarbons, but oil companies have also begun, fairly recently, to include certain additives in gasoline that further affect the chemically correct mixture. Among the additives commonly found in both pump and racing gasolines are ethyl alcohol (ethanol) and methyl tertiary butyl ether (MTBE). Both these substances are examples of what are called oxygenates—like the hydrocarbons we have been speaking of they contain hydrogen and carbon, but unlike the hydrocarbons they also contain oxygen. A fuel carrying its own oxygen adds to the amount inhaled by the engine, so the presence of oxygenates means that a little extra fuel is needed in relation to the quantity of air the engine is breathing in, to take account of the additional oxygen being carried within the fuel—the stoichiometric ratio becomes a little (numerically) smaller. This is yet another reason why it is not possible to specify one exact stoichiometric mixture strength for any and all gasolines.

Note, too, that the stoichiometric mixture strength is expressed as a ratio of weights—or more correctly, masses—not volumes. (The mass of something is, in effect, a "count" of the number of molecules in it.) A certain mass of air—that is, a certain number of molecules—will occupy more or less volume, according to its temperature. A cubic foot of hot air contains fewer gas molecules, including oxygen molecules, than a cubic foot of cold air. Other factors, like barometric pressure and altitude also affect the density of air—the weight of a certain volume, in other words. For that matter, the density of gasoline also varies with temperature, though not nearly as much.

While the ideal of stoichiometry expresses the chemically correct air-to-fuel ratio for any particular gasoline blend, gasoline will, in fact, burn in air over a spread of ratios from about 6:1 to more than 24:1. Mixtures that contain more fuel than the theoretical optimum are said to be "rich," while those with an excess of air are termed "lean." For maximum power production, there is something to be said for mixtures that are somewhat richer than stoichiometric.

To begin to explain, consider a four-cycle engine turning 6000 rpm. At that speed, each power stroke lasts just 1/400 of a second. To get an idea of just how short a time that is, sight through the shutter of an unloaded



Maximum power is produced with a mixture just a bit richer than the chemically "correct" ratio. Power tapers off sharply with increasing richness beyond that point, and more slowly as the mixture is leaned-out.

camera set to that speed, and push the button. Even though the combustion event involves extreme turbulence that violently stirs and mixes the different molecules, it is extremely unlikely that each and every oxygen molecule will be able to find a hydrocarbon molecule to react with in such a brief flicker of time. Yet for maximum power we want maximum heat, and the heat comes from the combining of the hydrocarbon molecules in the fuel with the oxygen molecules from the air.

An engine's cylinders are of a fixed size, however, so the maximum quantity of air, and so the number of oxygen molecules, that each cylinder can inhale is limited. For maximum power, we want to make sure that all the oxygen molecules available in the fixed amount of air inside the cylinder react with a hydrocarbon, and the way to do that is to provide some extra hydrocarbon molecules. And the way to do that, in turn, is to provide a mixture that has a little excess fuel—a slightly rich mixture. As noted, however, that extra gasoline is wasted; it also adds to air pollution. Unburned hydrocarbons, or "HC," are another of the exhaust pollutants that environmental laws seek to control.

On the other hand, if we are prepared to sacrifice a little power, we can make maximum use of the quantity of fuel burned by providing a slightly lean mixture. In the same way that a little surplus fuel ensures that all the oxygen gets used, a little extra air helps ensure that every hydrocarbon molecule finds an oxygen molecule to mate with.

This can reduce, if not eliminate, HC emissions. Within limits, it also leads to lower fuel consumption for a given power output.

Most fuel injection (FI) systems—and most carburetors, for that matter—take these considerations into account in their design and operation. During light load operation, such as occurs when cruising at a constant modest speed with a comparatively small throttle opening, the system leans the mixture out a bit, to enhance fuel economy and minimize HC pollution. When the driver opens the throttle wide, demanding full power, the system provides a richer mixture, at some cost to fuel economy and HC levels in the exhaust.

There are other aspects to the rich-mixtures-equal-maximum-power issue. First, when gasoline evaporates, it soaks up a lot of heat in the process, as you probably know from spilling gas on your hands in cold weather. The internal cooling effect of a slightly rich mixture reduces internal temperatures somewhat, especially in critical areas like the piston crowns and the edges of exhaust valves. While modern street engines are boringly reliable, the internal cooling provided by a surplus of fuel can make a considerable difference to the survival of a race engine that is running on the ragged edge of thermal self-destruction.

Also, the heat soaked up in the process of boiling that excess liquid gasoline into vapor can reduce the temperature of the air/fuel mixture entering the engine. As we have pointed out, cooler air is more dense than hotter, so a cylinder full of an intake mixture cooled in this way will weigh more (and thus contain more oxygen molecules) than otherwise. This accounts for some slight potential gain in power output.

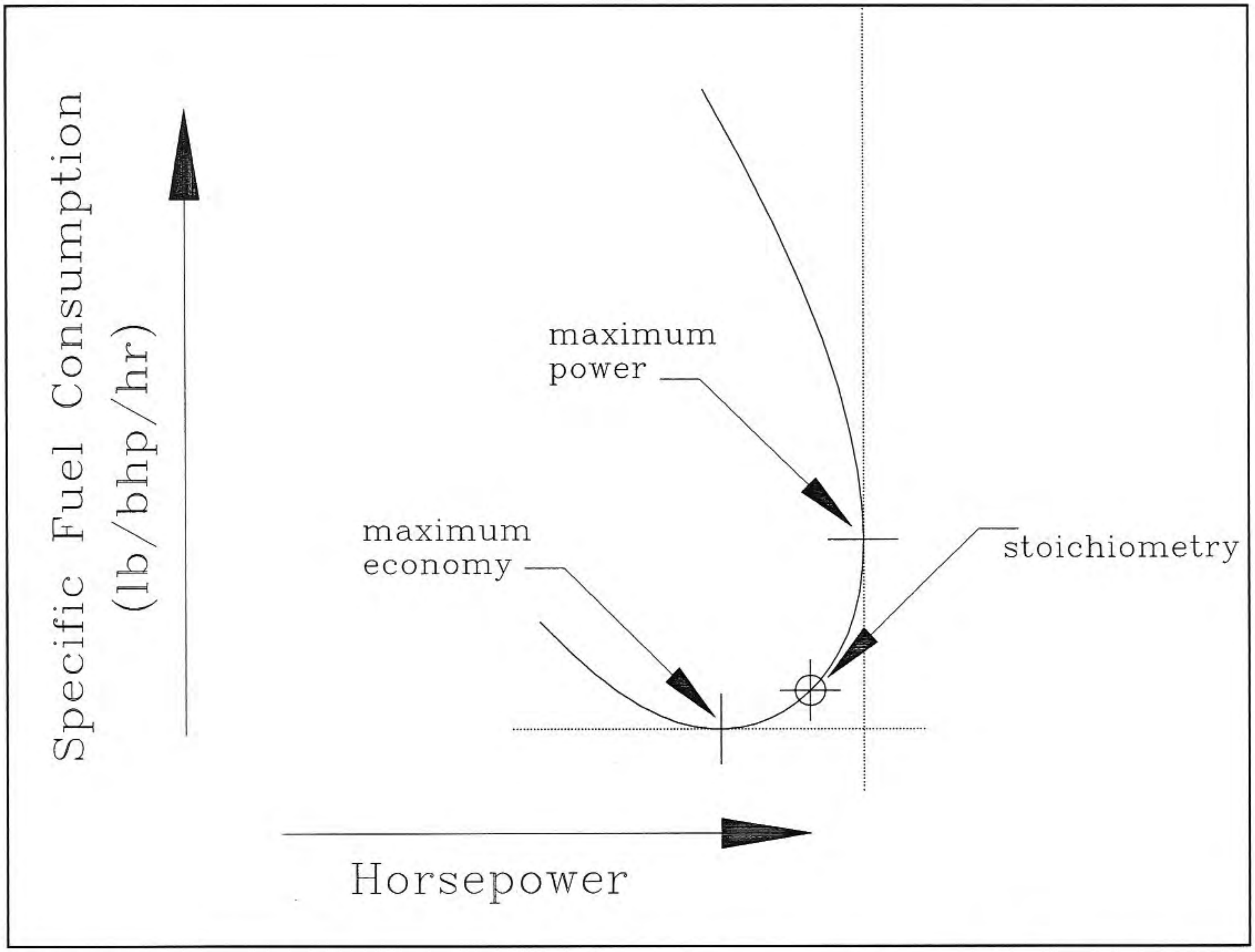
Detonation

Another consideration relating to the connection between mixture strength and power is the issue of the tendency of a gasoline/air mixture to detonate. To explain, the burning of fuel inside an engine cylinder is often characterized as an explosion, but although the combustion event is extremely rapid, it is not, technically, an explosion. Once initiated by the spark, the burning begins as a small bubble of flame around the plug electrodes. Under normal conditions, the burning process then spreads rapidly but smoothly throughout the rest of the mixture as an expanding ball of fire.

In some circumstances, however, the combustion may start off smoothly enough, but as the flame-front expands through the combustion chamber, the rapidly rising temperature and pressure ahead of it causes complex chemical changes in the unburned mixture furthest away, called the end-gas. Squeezed and heated by the approaching fireball, it changes from a predictable, slow burning mix into something far more unstable. As a result, the overheated end-gas ignites spontaneously almost all at once, the pressure inside the cylinder rises so fast it is more like an explosion than a controlled burn, and the resulting shock wave rings through the motor. That is detonation, or "knocking."

The sharp pressure spike that results when this violent secondary event meets up with the original flame front can punch holes in pistons. Even if it does not, the turbulence created by detonation scours against the surfaces of the combustion chamber, allowing heat to flow out of the swirling gasses and into the surrounding metal much faster than normal. As a consequence, the gasses lose heat, their pressure accordingly falls, and power drops off immediately. (Although the peak pressure during detonation is much higher than during normal combustion, the average pressure is way down, because of this heat loss.)

Because the changes preceding detonation are chemical, the ability of a particular blend of gasoline to resist detonation depends on the chemistry of the blend, and thus in turn on the various hydrocarbons that make it up. Overall, the knock-resistance of any sample



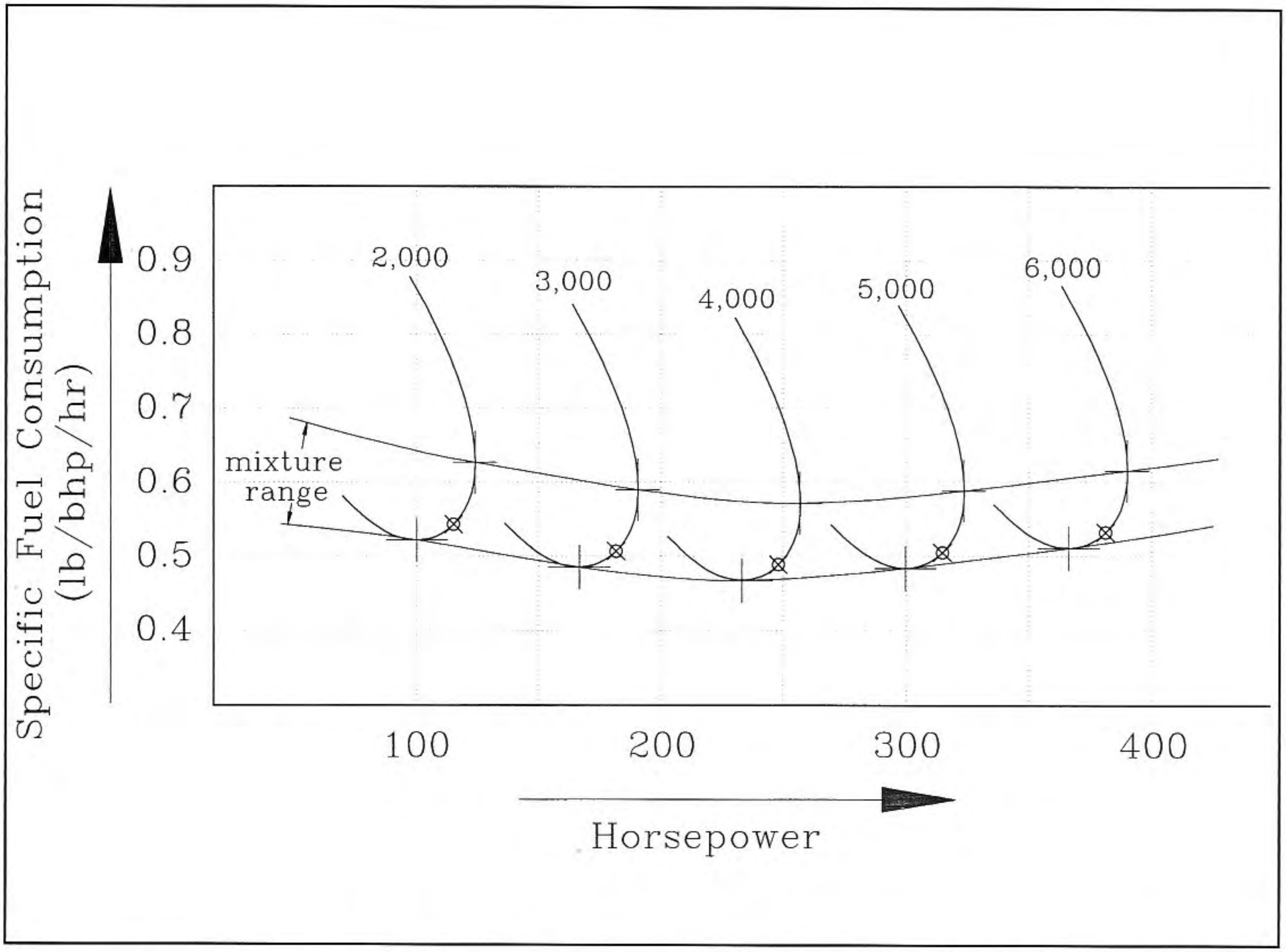
A mixture "fish hook," showing the points of maximum power and of maximum economy. Fuel flow is expressed in terms of the quantity used per hour per horsepower produced.

of gasoline is expressed by its octane rating (see the sidebar "Doing Octane Numbers"), but the number so obtained also depends to some extent on the mixture strength. Some gasoline components knock worst when run rich; some others increase substantially in knock-resistance with wholesale enrichment. Predictably, these latter are found in abundance in race gas.

For typical pump gasoline in a typical engine, the mixture ratio for peak power is likely to be in the area of 12:1. Depending on the particular blend of gasoline, anything richer than that may exaggerate detonation problems, and the cooling effect of the surplus fuel, if carried to extremes, may sap some of the heat that we would rather have working to raise the gas pressure. For better mileage and lowest HC emissions, something closer to 16:1 is wanted. Indeed, at comparatively high engine speeds under very light load, mixtures as lean as 18:1 may offer even better fuel economy. Such lean mixtures burn hot, however, and that extra heat, together with all those extra oxygen molecules, makes it more likely that the supposedly inert nitrogen will combine with some oxygen, worsening the NOx emissions.

Optimizing an Engine's Diet

While the generalizations above are broadly applicable to all engines, establishing the correct air:fuel diet for any particular engine over a full range of speeds and loads can only be achieved by a long and tedious



A series of fish hooks established at various engine speeds produce, when linked together, a curved band that represents the practical range of mixture strengths for any given engine. The line forming the upper boundary of this band represents the mixture curve for maximum power; the lower one for maximum economy.

process that involves dyno testing. The engine is run at some fixed throttle opening, and the load is adjusted to keep the rpm constant. Starting with a very rich air:fuel ratio, the mixture is adjusted leaner in small steps, and the fuel flow is measured at each setting in, say, pounds per hour. As the mixture is gradually leaned out, power initially increases until some maximum is reached. Further leaning results in a reduction in power but, initially at least, the quantity of fuel burned for each horsepower produced actually grows smaller.

This relationship between fuel consumption and power production is described by the expression brake specific fuel consumption, or BSFC. The first word, "brake," simply refers to the fact that the engine is being run under load on a dynamometer, or "brake." (The original dynamometer was simply a friction brake; modern hydraulic and electric dynos differ in construction, but the principle of using a retarding device to produce an artificial load remains the same.) "Fuel consumption" is pretty obvious; it is simply the number of pounds per hour (lb/hr) of fuel being consumed at some particular throttle opening and speed. "Specific" is actually a contraction of "power-specific," meaning that the fuel consumption at any given setting is divided by the horsepower produced at that setting. The results are expressed in units of pounds of fuel burned per horsepower per hour—lb/hp/hr. As a rough rule of thumb, we can figure that an unsupercharged engine burning gasoline will have a BSFC of about 0.5 lbs/hp/hr at peak power. That is, an engine making 300 hp will need to burn about 150 lbs. of fuel per hour to do it.

At some mixture strength, the engine will produce a maximum value of BSFC—a maximum amount of power from each pound of fuel, but this will not actually give the maximum possible power. At some richer setting, the power will likely be somewhat higher, but disproportionately more fuel will have to be burned to achieve that slightly higher peak power. As the mixture is leaned out past the point of peak BSFC, the power falls off markedly, as you might expect. What is particularly interesting is that the amount of fuel burned, in relation to the power (the BSFC, in other words) actually increases—although engines can be made to run on such extremely lean mixtures, it is actually wasteful of fuel to do so. The results of such a test are then plotted on a graph, with BSFC on the vertical axis and power output on the horizontal axis. The resulting curves resemble, and are called, "fish hooks."

Once one such test has been completed, the whole thing is repeated all over again at some other engine speed, until the entire operating speed range has been covered in, say, 500rpm steps. Then the entire set of tests is repeated at different throttle openings. As we said, the operation is tedious.

Special Diets

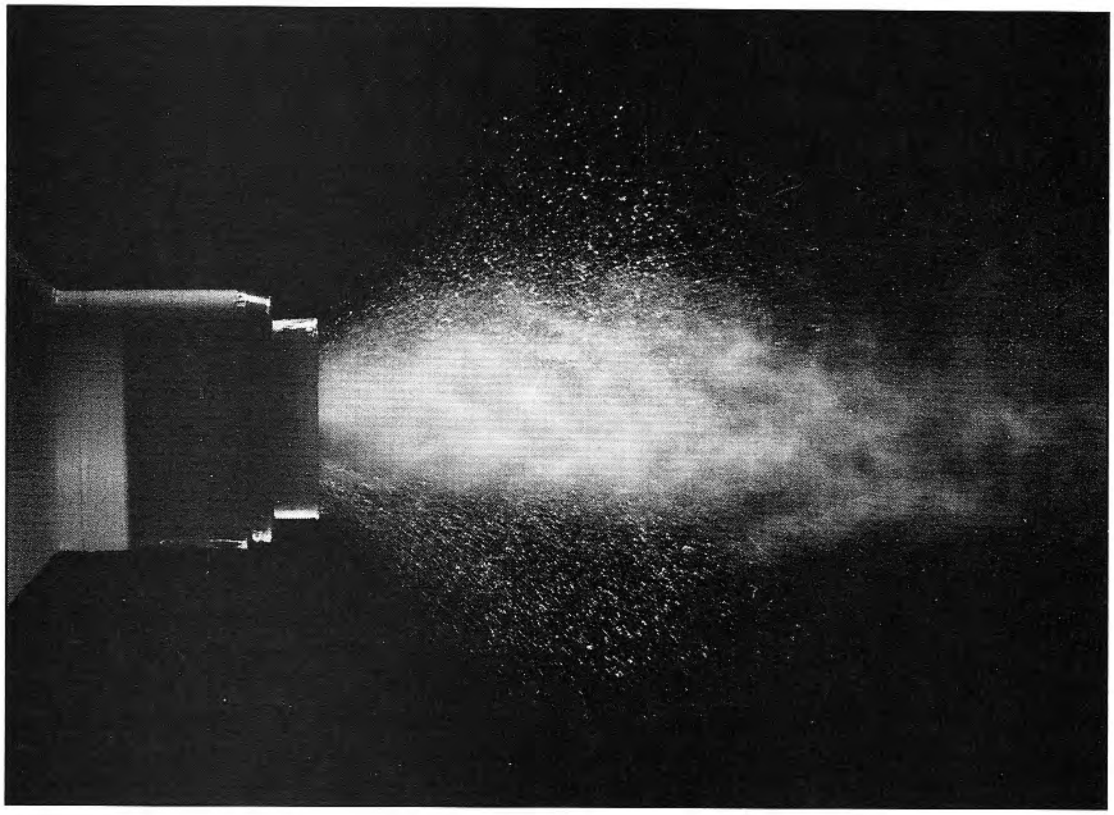
One special circumstance that requires a much richer than stoichiometric mixture is cold starting. It may come as no surprise to learn that the various hydrocarbons that make up gasoline have widely different boiling points and so evaporate at differing rates. At very low temperatures, some of them may not evaporate at all, so the only way to ensure there is enough of the ones that do vaporize to make a burnable mixture in air is to provide a lot of gasoline overall. Typical cold start fuel-to-air ratios are between 2-to-1 and 1-to-1.

Historically, there are two other situations that are (or were) thought to demand a rich mixture—idling and acceleration. Certainly idle enrichment is needed on typical carbureted engines, and to a lesser extent on those with throttle body injection (TBI) systems, but this is mainly a matter of the problems that arise from trying to distribute from a central point all the air:fuel mixture needed by a multi-cylinder engine. Proof that very little enrichment at idle is necessary in principle comes from current emissions-certified production engines, which get by with idle mixtures very close to stoichiometric.

The other situation conventionally thought to demand significant enrichment is acceleration. Every successful carburetor ever made had either an accelerator pump that shot in an extra squirt of fuel every time the throttle was opened, or (more rarely) some other means to temporarily richen the mixture under sudden throttle opening. It seems that much (although not all) of this "need," too, turns out to be due to secondary factors—in this case the nature of carburetors—rather than a characteristic of the needs of engines themselves. In view of that, this seems as good a time as any to veer off from our consideration of the kinds of food that engines prefer and to look at the various methods for bringing that food to the table.

The Drawbacks of Central Distribution

For satisfactory engine operation, whatever mixes the fuel and air has to closely match, in terms of air:fuel ratios, the various feeding requirements of the engine under differing conditions, and must be able to move smoothly and continuously between



Ideally, all fuel ingested by the engine would be in the form of vapor. In practice, some droplets remain. Squirting the fuel through a small orifice under considerable pressure improves atomization, which is one reason why fuel injection is superior to carburetors. (Robert Bosch Corporation).

them as the situation requires. There is more to it, however, than just keeping the proportions right. Large blobs of fuel haphazardly distributed throughout the air just will not do, even if the overall proportions are correct.

To begin to understand the reasons for this, imagine setting fire to a tablespoon measure full of gasoline. Yes, it will burn off fairly fast, but consider that an engine making 225hp goes through about that much gas every second. Allowing for the fact that each power stroke occupies at most half of a complete revolution of the crankshaft, and that it takes two full revolutions for a complete engine cycle, the combustion event in the engine obviously occupies, at most, one quarter of that time. You cannot burn a tablespoon full of gasoline in one quarter of a second.

Vaporization—If you were to divide the same amount of fuel into, say, three teaspoon measures and set them all alight simultaneously, then the gas will burn more quickly. If you further divide it into large droplets, it will burn quicker still. The more finely you divide the fuel, the more surface area each particle has in contact with the oxygen in the air, in relation to the volume of fuel within the droplet, so the faster the energy gets released. The ideal would be to divide the fuel into the smallest possible units—individual molecules. In that case we will not see any liquid fuel at all; it will all exist as a true vapor. In fact, we cannot usually get quite that close to perfection, so the intake charge will consist of a mixture of air, gasoline vapor and fine droplets. One of the inherent advantages of fuel injection over carburetors is that the fuel is introduced into the intake air under comparatively high pressure. In the same way that a shower head produces a fine spray when the taps are cranked all the way open, but gives forth large drops when the taps are nearly closed, the pressurized mist issuing from a fuel injector helps this process of vaporization.

Intake Port Airflow—But there is more to it than that. Consider one cylinder of a 320 cubic inch (ci) V-8, turning 6000 rpm. That individual cylinder displaces 40 ci and so inhales that much air every second engine revolution (again, assuming it is a four-cycle engine), for a total of 120,000 ci of air per minute. That air flows through the intake ports in the cylinder head and intake manifold which may have a cross-sectional area of somewhere around 3 square inches (sq in). The average rate of flow through that hole is simply the volume divided by the area of the hole it flows through, so the speed of flow is:

120,000/3 = 40,000 inches per second, or about 37.8 mph.

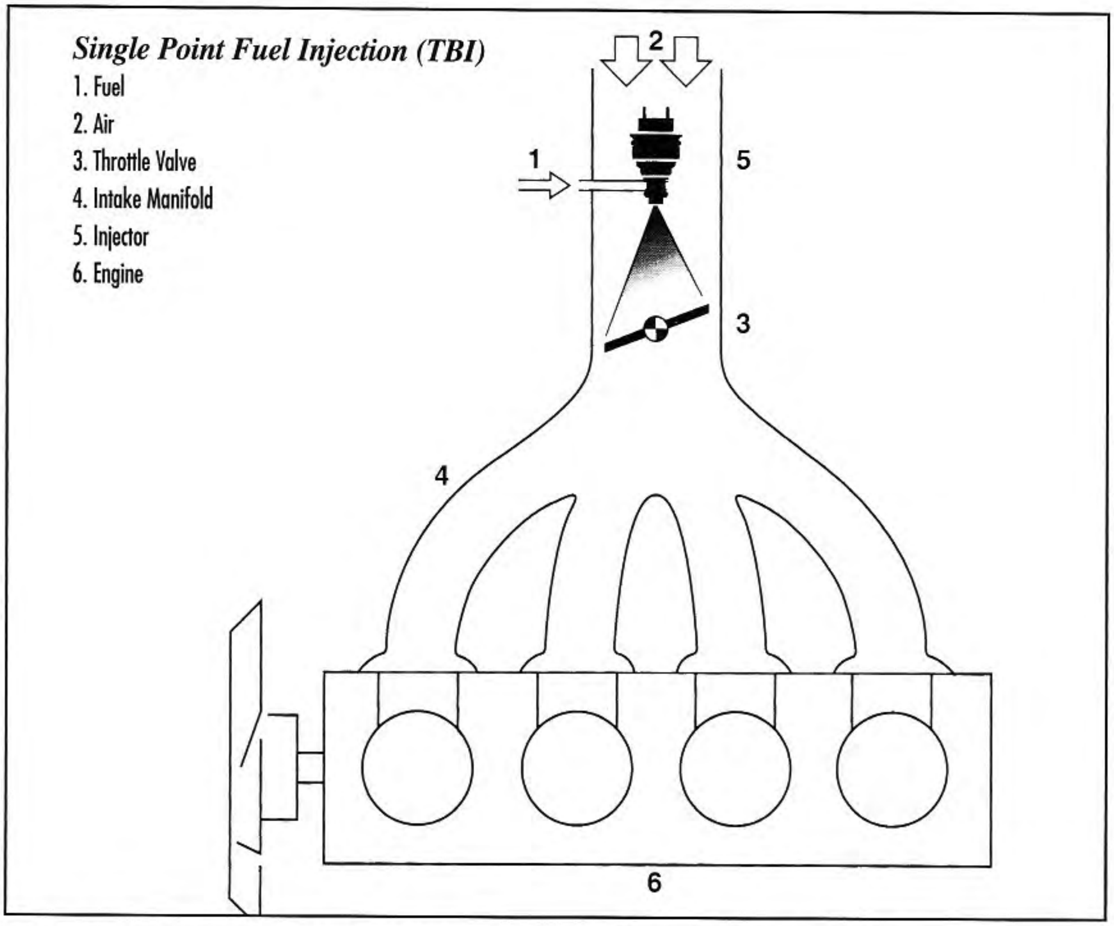
Now 38 mph doesn't sound like a particularly high speed, but the air on its way to the cylinder usually has to negotiate some turns, and those turns can be mighty sharp—maybe something like 3" radius. If you bother to do the arithmetic, you will discover that the airflow negotiating a turn with a radius of 3" experiences an acceleration equivalent to 382 times the force of gravity (382 g).

Now, if all that is flowing through the intake ports is air and fuel in vapor form, those 382 g turns won't bother the gasses at all. But with any arrangement that mixes the fuel and air at a central location, those sharp, high-speed turns really disturb the movement of any fuel droplets that are mixed in with those gasses. What will happen, in fact, is that they will get centrifuged to the outside of the bend and form puddles of liquid on the inside surfaces of the ports.

At first it may seem that this does not matter much; the fuel will get carried along by the air rushing past and will eventually make its way into the cylinder and the correct fuel-to-air ratio will be maintained, at least on average. But "on average" is not good enough; the mixture strength in the cylinder will vary from moment-to-moment, according to the whims of the puddles. Of course, if there is only one cylinder, there is less need for bends in the intake plumbing, but things turn really ugly when we are dealing with more than one cylinder eating from the same trough, so to speak.

When multiple cylinders are fed from one common source, as is the case with TBI and carburetor induction systems, there must inevitably be bends, and probably lots of them. Unavoidably, this fuel-drop-out effect will favor some cylinders and short-change others. In the days before concern about emissions (which means in the days of carburetors), a variation of four numbers in mixture strength between cylinders in the same engine was not uncommon—some cylinders might be working on 16:1, others on 12:1. To keep the engine lit at idle, it was necessary to provide a surplus of fuel overall in order to ensure that the leanest running cylinder got a burnable mixture. With painstaking development of the manifold design, it is possible to reduce this cylinder-to-cylinder variation, and modern manifold designs for engines fitted with carburetors or TBI systems do much better than in the bad old days. Still, the desirability of ensuring as nearly complete vaporization as possible should be obvious.

At idle speeds, the speed of the flow of gasses through the ports is obviously vastly reduced, so the tendency of droplets to separate out from the gas flow because of centrifugal forces will be dramatically decreased. At the same time, the high vacuum condition existing in the intake manifold of an idling engine encourages fuel droplets to vaporize. In the same way that water boils at a lower temperature (that is, evaporates more readily) on a mountaintop than it does at sea level, gasoline evaporates more readily in thin air than when it is more dense. Ironically, the problem of incomplete atomization remains—at least for carbureted engines—simply because the lower rate of



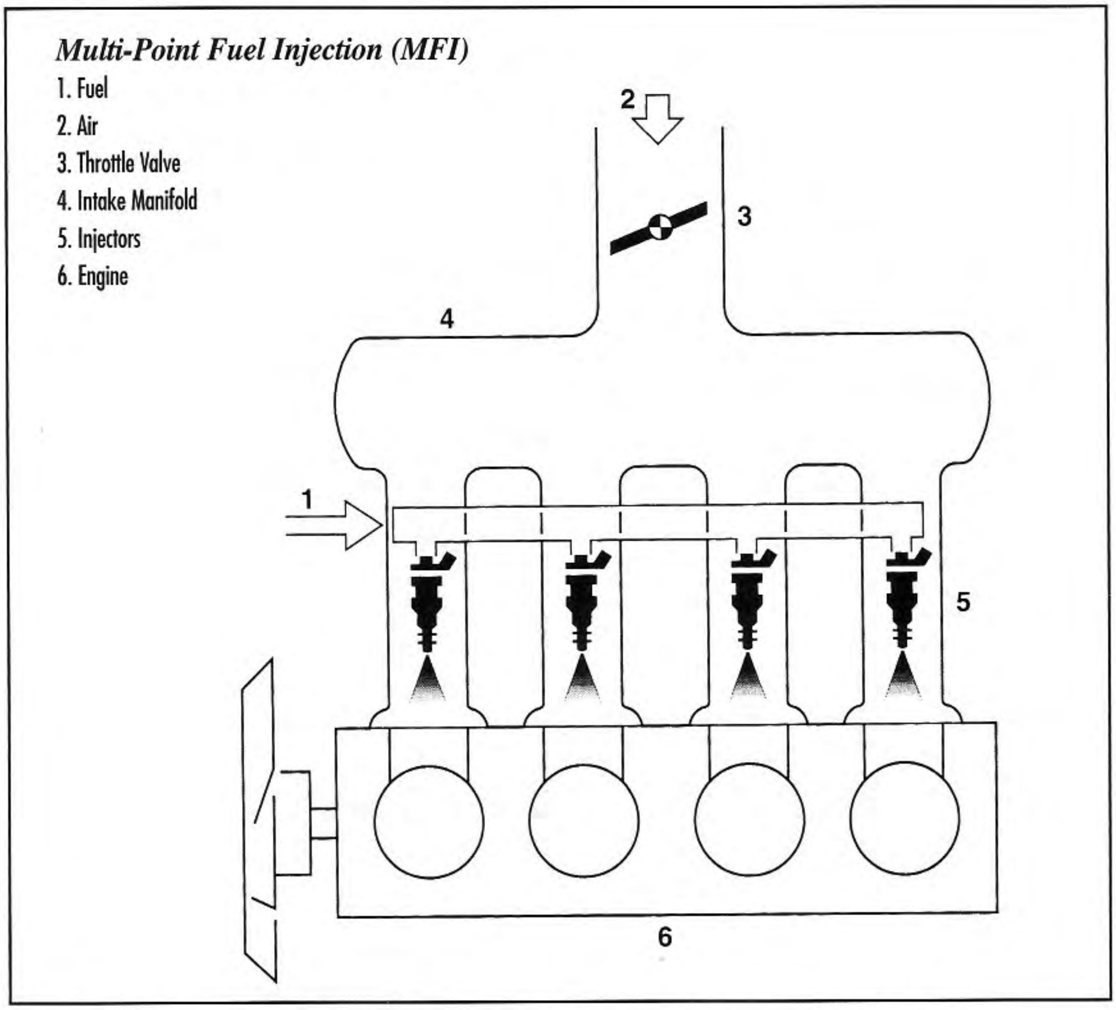
Introducing fuel at a single point—whether from a carburetor or a throttle body injector—"wets" a large area of manifold surface, and gives unevaporated droplets many chances to drop out, forming puddles of fuel. (Robert Bosch Corporation)

flow means reduced turbulence which might otherwise break large droplets up into smaller ones.

Quite apart from the matter of the rate of flow, there are other factors at work that oblige engines with a "central mixer"—and especially those fitted with a carburetor—to operate with rich air:fuel ratios at idle. Two of these are charge dilution and reversion, terms we shall soon define.

Valve Overlap—To explain, in the kind of idealized engine that appears in beginner-level explanations of how piston engines work, the intake valve opens at top dead center (TDC) of the intake stroke and closes at bottom dead center (BDC). Following the compression and power strokes, the exhaust valve opens at BDC, and closes again at TDC. Yet surely anyone reading this book knows that on all real world engines the cam timing is arranged to open the valves earlier and close them later than this.

The reason for this is the inertia of the intake and exhaust gasses. Although gasses are very light, they are not weightless—a cubic foot of air, for example, weighs about 0.08 lbs. Thus, as the valves open and close, and the columns of gas passing through the ports on their way to and from the combustion chamber start and stop, the inertia of those gas columns makes them lag behind piston movement. To give sufficient time for emptying and filling the cylinder, especially at high engine speeds, the intake valve opens before TDC and closes after BDC, while the exhaust valve opens before BDC of the power stroke and does not close until after TDC on the exhaust stroke. As a result, there is a period toward the end of the exhaust stroke when the intake and exhaust



Multi-point injection ensures equal mixture strength at each cylinder. (Robert Bosch Corporation)

valves are both open together.

This valve overlap helps an engine to produce useful power at high speeds, as the "lead" in the valve timing gets to be in synch with the "lag" in the movement of the gasses. But it also leads to problems at very low speeds, because there is then obviously an opportunity both for some of the fresh intake charge to zip right out the exhaust and/or for some of the exhaust gasses to make their way backward, upstream, into the intake manifold.

Charge Dilution—This intermingling of exhaust gasses with the fresh intake mixture that occurs at idle because of valve overlap is termed charge dilution, and for years it was argued that this demanded a rich idle mixture, because the dilution tends to keep the hydrocarbon and oxygen molecules separate. A hydrocarbon molecule at one side of the combustion chamber, it was argued, might be desperately seeking an oxygen molecule at the other side but they would be unable to meet, because of the crowd of exhaust gas molecules in between.

While the above argument appears plausible, it is apparently at least partly wrong, as confirmed by the near stoichiometric idle mixtures of modern fuel injected engines. The difference between these motors and the typical rich-idle engines of a few years ago seems mainly to be the difference between the degree of variation in mixture strength between one cylinder and another that exist when the mixture for all an engine's cylinders is delivered at one central point, such as in a carbureted or TBI engine, compared to one with multi-point fuel injection, in which each injector is located near the one individual cylinder that it serves.

TBI engines, at least, are not afflicted by another complication that affects carbureted engines at idle, that of charge reversion. The violent pulsations that occur in the intake ports and manifold of an engine at idle speed means that a portion of the flow on its way to the cylinders sometimes actually reverses direction—some of the intake air, already mixed with fuel, actually pops back outside briefly! This can sometimes be seen as a pulsating cloud of air:fuel mist hovering over the intake. Apart from being a potential fire hazard, a consequence of this in-out-in-again motion is that some air passes through the carburetor three times. Because a carburetor adds fuel to gas flowing through it, and neither knows nor cares which direction the flow is going, fuel gets added on every trip. On the face of it, it should be possible to adjust the basic idle mixture setting to take account of this triple-dosing. Indeed, a correctly adjusted carburetor will do so, but the reversion phenomenon is unpredictable, so the mixture has to be set somewhat rich to take account of the instants when it is ineffective.

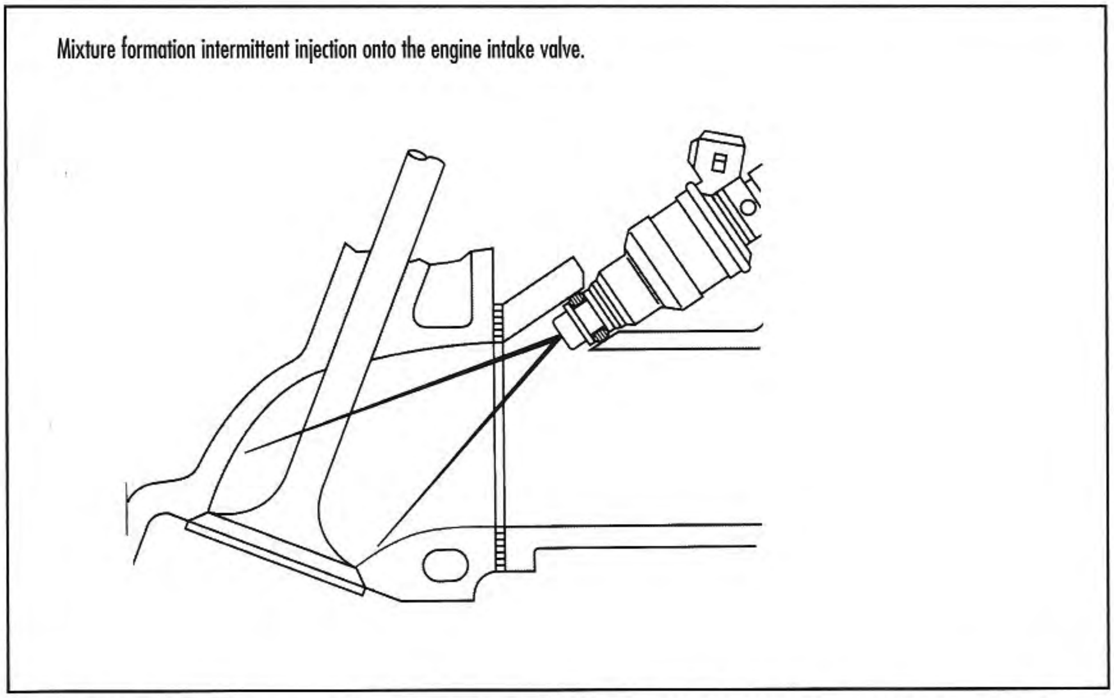
Another area where fuel injection—at least multi-point FI, with each injector located very near the intake valve it serves—has an inherent advantage over carburetors is the ability of FI systems to cope with sudden increases in engine speed and load. There is certainly a need to shift from the leaner-than-stoichiometric, best-BSFC air:fuel ratio, to the richer-than-stoichiometric best-power ratio if the throttle is suddenly opened while cruising along at light load, but why should the actual fact of acceleration itself—that the engine speed is increasing—introduce any greater need for enrichment at any instant during the acceleration than does any other situation demanding that same power output at the same rpm?

The answer to this is that, as previously noted, some of the mixture supplied by any "central mixer" will wind up as liquid on the walls and floors of the ports and manifold. This fuel will eventually flow to the cylinders, but note that the density and viscosity of this liquid fuel is much greater than that of the air, gasoline vapor, and very tiny droplets that make up the remainder of the mixture, so its motion is much slower than those gaseous and near gaseous components.

Under steady state conditions, this "pool" of fuel is being consumed and replaced more or less equally all the time, so under those conditions there will always be some more-or-less constant quantity of liquid in the manifold at any moment. That quantity, however, will vary according to just what steady state conditions prevail. Under large throttle opening/high load conditions, the density of the air in the manifold and ports is higher than otherwise and, as noted above, gasoline evaporates less readily in air that is dense than when it is thinner.

An engine operating under a large load will thus require a larger quantity of liquid fuel in the manifold in order to maintain equilibrium between what gets consumed and what gets supplied. On sudden throttle opening, additional fuel thus has to be supplied to rapidly build this pool up to the larger size of "store" needed to maintain equilibrium under the new, higher load conditions.

It is noteworthy, too, that to encourage vaporization under these and other conditions, carbureted engines for street use are almost always provided with some means to heat the mixture in the manifold, whether by the heat of the exhaust gasses (the familiar "heat-riser") or of the engine coolant. While this reduces the problems of having comparatively large amounts of liquid fuel washing about in the manifold, the heating of the entire intake charge lowers its density. As we have already seen, hot air is less dense than cooler air, so a cylinder full of such a warm mixture will contain fewer oxygen



Multi-point injection also provides the opportunity to locate each injector very near the valve it serves. This reduces port "wetting," and so reduces the amount of enrichment needed for acceleration. (Robert Bosch Corporation)

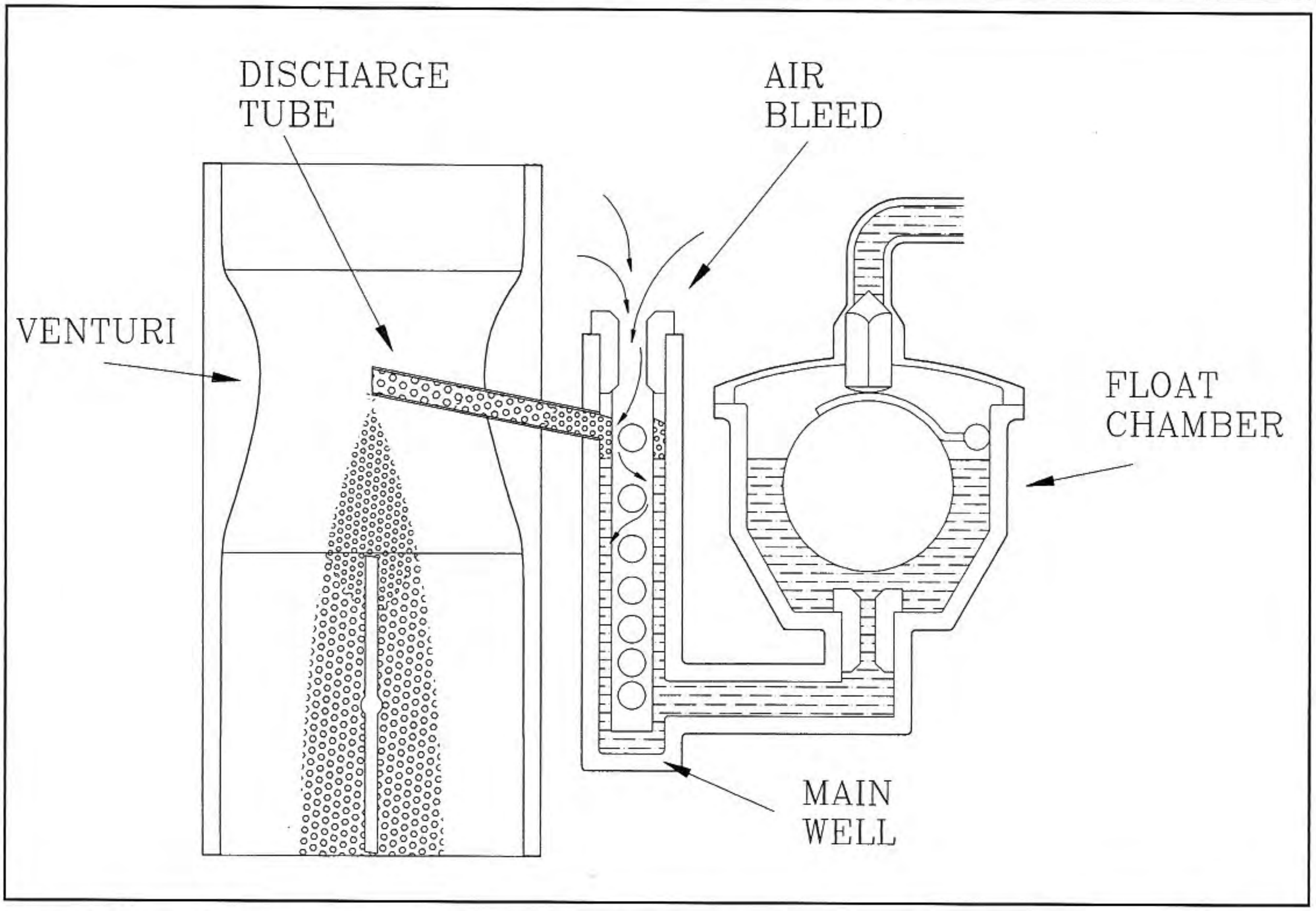
molecules—and thus can make less power—than the same cylinder filled with a cool mixture. The vaporization problem is most severe when the engine is cold, so many engines provided with such a "hot-spot" have some means to turn down the heat once the engine is fully warmed up. Usually, however, the heat does not get completely turned off.

To some extent, this problem of wetting of manifold and port walls also affects multipoint fuel injection systems, to a degree that depends on where the injector is located, relative to the intake valve. On some engines, the injector is as close to the back of the intake valve as possible. Here, clearly, the length of port that is wetted by fuel is extremely short, so the additional amount of fuel needed to fatten up the "store" is minimal. However, on other engines—perhaps for reasons of packaging, or access for servicing—the manufacturer decides to locate the injectors a considerable distance from the valves. The more remote the injectors, and so the greater the length of the wetted port and manifold, the more the additional fuel requirements on acceleration resemble those of a central mixer arrangement, such as a carburetor.

Carburetors have an accelerator pump to tide them over this transition, but the amount of additional fuel supplied by the accelerator pump of a carburetor considerably exceeds the amount that should be needed to maintain the "pool." To see why this is so, and to better understand some of the other shortcomings of carburetors, we should end this chapter by taking a brief look at their nature, before moving on to consider the fuel injection systems that have now almost completely displaced them.

The Carburetor

The earliest attempts to feed a gasoline engine hinged on wacky arrangements like a drip-feed of fuel into the air intake pipe, or an arrangement of cotton wicks with their bottom ends immersed in a pool of fuel and their upper ends exposed in the intake pipe. These hit-and-miss methods at controlling mixture strength came to an end soon after the invention of a basic carburetor, in 1863,



A rudimentary carburetor. The essential features are a "pool" of gasoline maintained at a constant height by a float-operated valve; a restriction (the main jet) to regulate the flow; a venturi, with a discharge tube connecting the low pressure area in the venturi to the fuel supply; and a throttle plate, to control the total amount of mixture flowing through. There is also a calibrated air bleed, that meters extra air into the fuel before the discharge tube, usually through a perforated "emulsion tube," that helps to atomize the fuel.

attributed to a Frenchman by the name of Lenoir. By 1894, the German engineer Wilhelm Maybach had advanced the development of this device by including the now-familiar float-and-needle-valve arrangement, to maintain a reliable supply of fuel at a constant height. Arguably, no small part of the success of Karl Benz's "Patentwagen" of 1897 was attributable to its wearing one of Maybach's float-equipped carburetors.

The adjacent illustration shows the essential workings of a simple carburetor. Fuel is supplied by a pump to the float chamber (or bowl), where a float and needle-valve assembly maintains the contents at a fixed level, very much like the float and valve arrangement in your toilet tank. The float chamber connects to a smaller reservoir—the main well—so the fuel level in the well will be at the same height as in the float chamber. A pipe, usually termed the discharge tube, leads slightly uphill from the well to the carburetor's throat—the main air passage through it. With the engine stopped, at least, the level of the fuel will reach part way up the discharge tube, close to—but not quite—spilling out the end. At the point where the discharge tube enters it, the carburetor throat is fitted with a narrowing piece, called the *venturi.* Note, too, that both the well and the float chamber are open to the atmosphere at the top.

As the engine draws air through the carb throat, the restriction created by the venturi obliges the air to speed up. It is no coincidence that the venturi is named after an Italian physicist of that name; it was he, G.B. Venturi, who established, a couple of hundred years ago, that when a fluid passing through a pipe or channel is forced to speed up, its pressure drops. As a result of this phenomenon, the pressure within the venturi is

DOING OCTANE NUMBERS

"Octane" is a measure of a fuel's detonation resistance, compared to two reference fuels, both of them components found in pump gasoline. One, a particular hydrocarbon called iso-octane, strongly resists knocking. It defines one end of the scale—100 octane. The other reference hydrocarbon, n-heptane, detonates like crazy, so it defines the zero end of the scale. Mix the two together and you get a tendency to knock that varies from zero to 100 according to the proportions of the mix. A fuel under test that behaves like a 90:10 mix of iso-octane and n-heptane, then, would be rated at 90 octane.

The actual measurement is performed using a standardized single cylinder test engine which is specially designed to allow its compression ratio to be varied while the engine is running. During the test, the compression is raised until the engine just starts to knock. From knowing exactly what blend of iso-octane and n-heptane would also just barely knock at that CR, it is possible to establish the octane number.

Just to keep things baffling, though, there are two octane numbers, "Research" and "Motor," established under different test conditions. From the chart below it appears that the Motor method provides a more severe test. In fact, the Research method tallies closer to real world experience in ordinary cars on the road. To add to the confusion, the number printed on a gas pump is the average of the Research and Motor numbers.

TEST CONDITIONS FOR RESEARCH AND MOTOR METHOD OCTANE RATINGS

	Research Method (RON)	**Motor Method** (MON)
Inlet air temp.1	25.6	300.2
Coolant temp.	212	212
Engine speed	600 rpm	900 rpm
Spark advance	13 degrees BTC	19–26 degrees BTC (varies with CR)
Air/fuel ratio	Adjusted for maximum knock	Adjusted for maximum knock

lower than that of the surrounding atmosphere, which thus pushes the fuel out of the discharge tube and into the carb throat.

The rush of air past the end of the discharge tube tends to tear the fuel into droplets, thus going some way to achieving atomization. An air bleed at the top of the main well allows a certain amount of air to leak into the flow of fuel, via a perforated sleeve called the emulsion tube, before the fuel reaches the discharge tube, thus assisting atomization. This is, in fact, almost a secondary function of the air bleed. Its primary reason for existence is to deal with an odd phenomenon that would otherwise cause the mixture to become ever richer as the rate of airflow through the venturi speeds up, as it does with any increase of engine speed.

Because the pressure drop within the venturi is a function of the rate of flow through it, it might seem that the fuel flow would increase in proportion, maintaining a constant air/fuel ratio over a wide range of flow rates. In fact, the ever-increasing pressure drop at the venturi as the airflow increases means that the air within it becomes increasingly rarified. Meanwhile, the fuel flow, propelled by the pressure difference between the venturi and the atmosphere, increases as the volume of air increases, but the density of the air is dropping at the same time. The result is that the mixture grows ever richer. A carburetor venturi, it turns out, is a volume measuring device, rather than one that measures mass flow. The air bleed provides a corresponding "leak" of air that compensates for that phenomenon (indeed, it is sometimes called a compensating circuit.)

A carburetor as simple as the one just described would in fact work, and would supply the engine to which it was fitted with a reasonably constant mixture strength over a reasonable range of speeds and loads, but only if those speeds are constant and moderately high. Under two sets of conditions, it would fall flat on its face.

At very low flow rates, such as at idle, the pressure drop through the venturi is so low that the fuel cannot make it out of the end of the discharge tube. In these circumstances the carburetor cannot function at all. To deal with this, most real world carburetors have a separate idle circuit, in fact a miniature carburetor-within-a-carburetor, that completely bypasses the main throat and venturi. But we needn't bother ourselves with the details of these.

The other situation that hobbles our simple carburetor is changing from one speed to another. (Actually, slowing down probably would not present much of a problem; speeding up, however, would.) We have explained that air weighs about 0.08 lbs. per cubic foot. While not weightless, this is vastly less dense than gasoline, at about 43 lbs. per cubic foot. Thus, if an engine should suddenly begin to draw much more air through the venturi, the airflow will speed up almost instantly, but the fuel, because of its greater inertia, will lag behind. As a result, the mixture will lean out, to the point where the engine will, in all probability, quit.

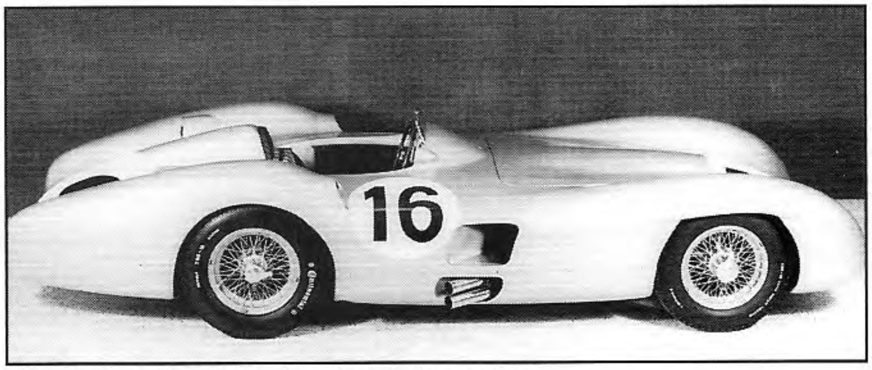
To deal with this, most carburetors are equipped with an accelerator pump, that mechanically squirts an extra shot of fuel into the venturi whenever the throttle is suddenly opened. Note, again, that this tendency to run lean on sudden throttle opening is a peculiarity of carburetors. The accelerator pump exists as much to make up for this deficiency as it does to build up the larger quantity of liquid fuel "store" in the manifold, as described above.

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

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.

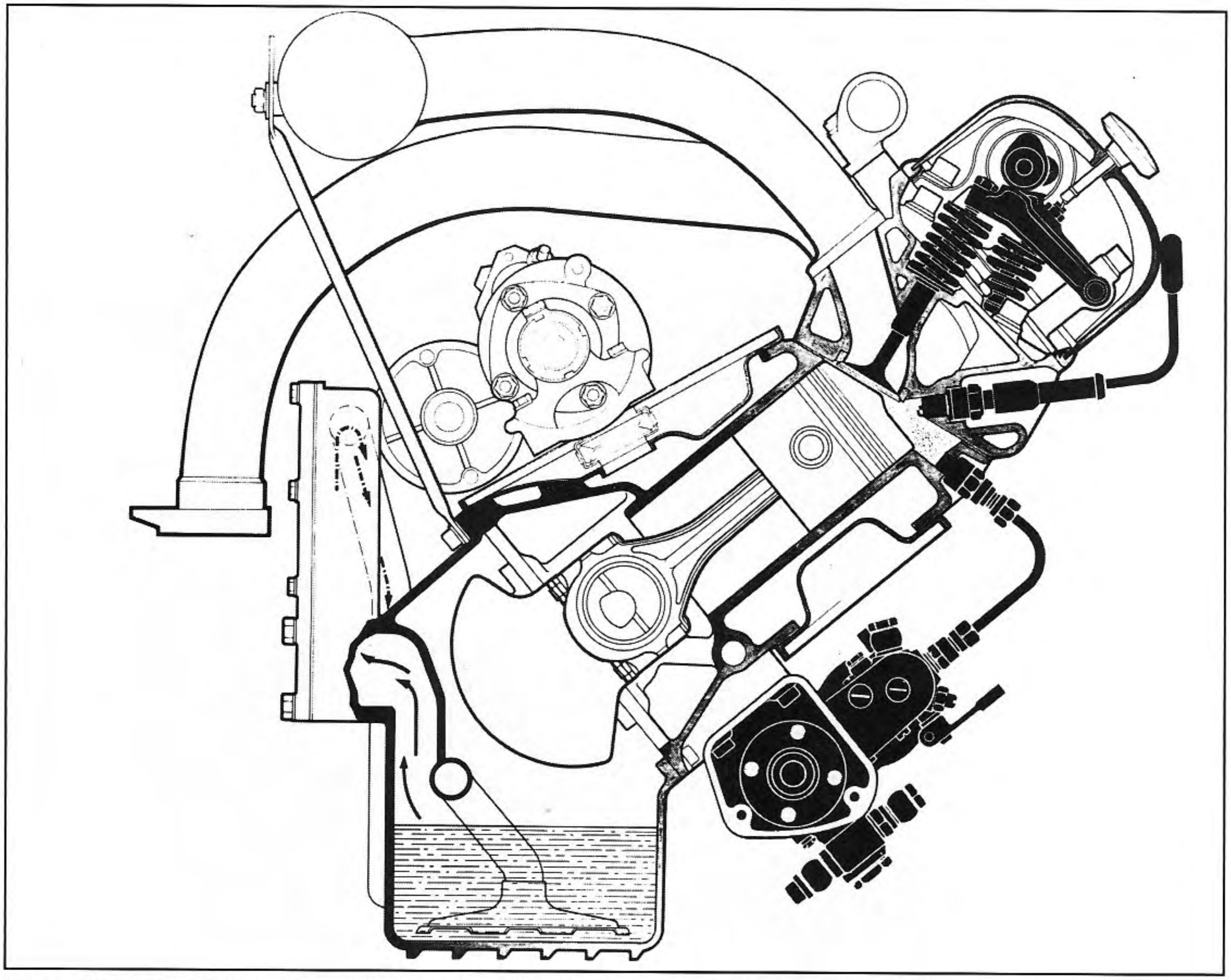
The rotation of the sleeve(s) is accomplished by a toothed rack that meshes with gear teeth cut onto the outside of each sleeve. The rack is connected directly to the throttle linkage, so moving the pedal rotates the sleeves within the pump, thus controlling the quantity of fuel delivered with each stroke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



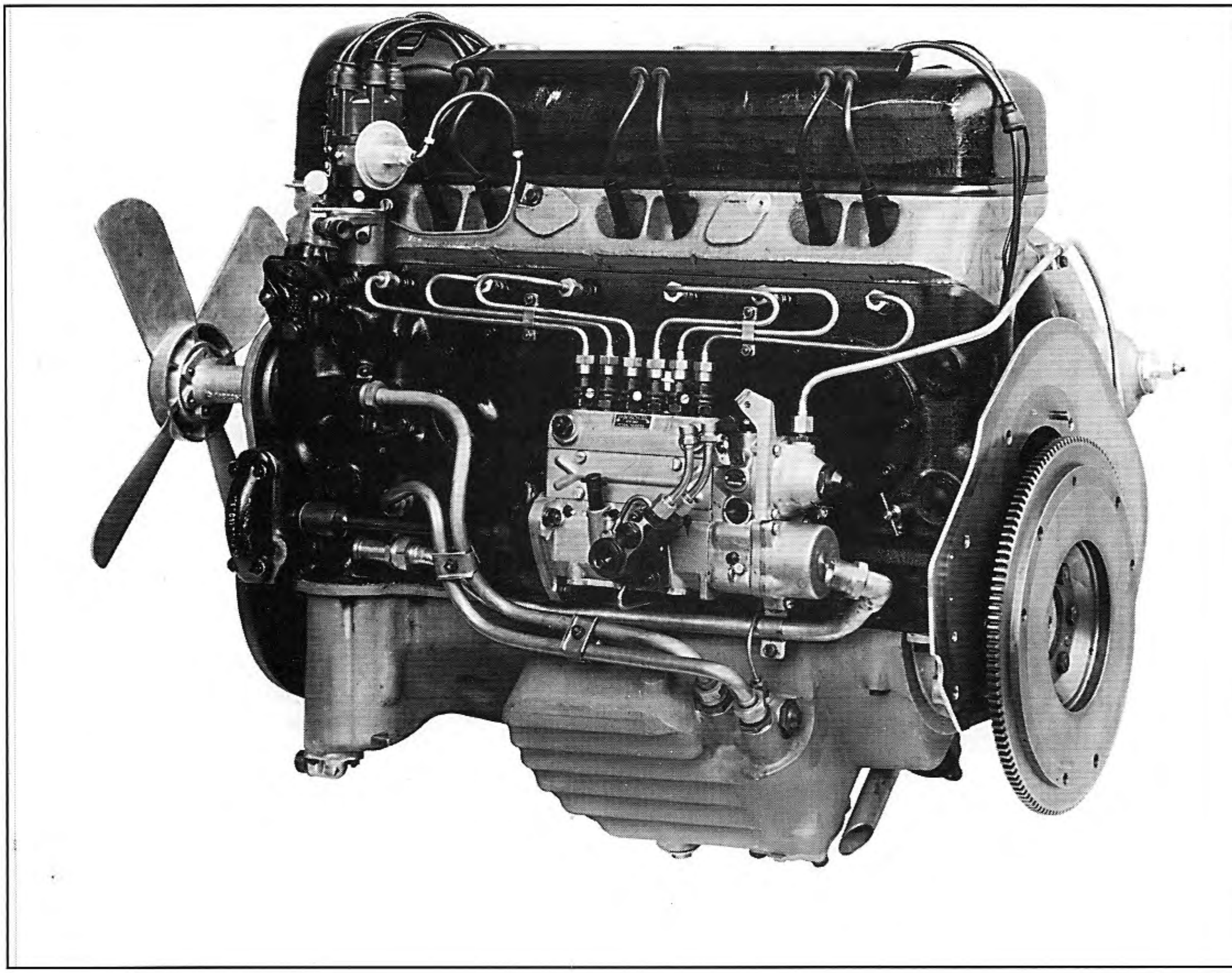
The location of the injector—screwed right into the cylinder head—is apparent in this cross-section of the 300SL engine. (Daimler-Chrysler Archive)

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.

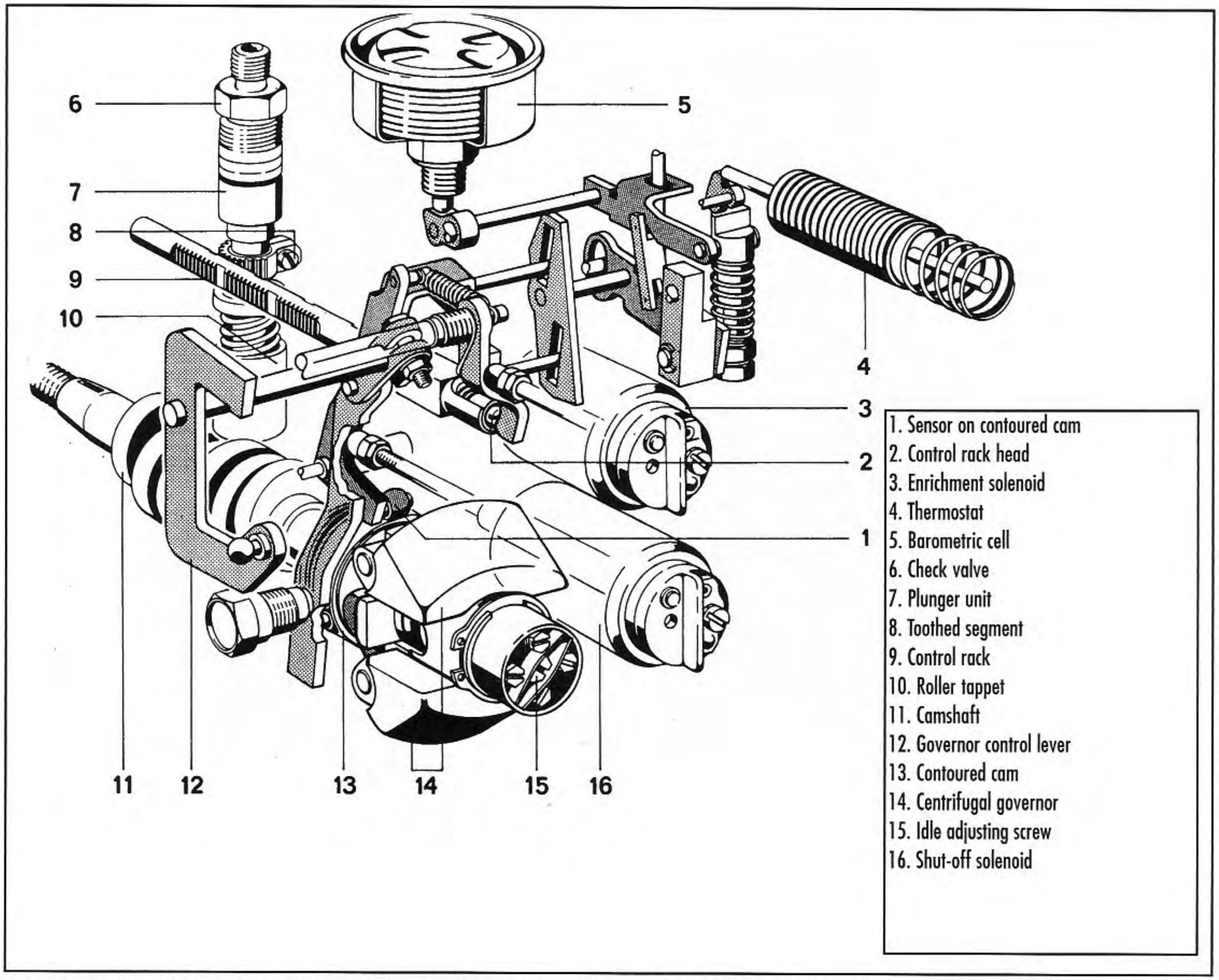
Unlike gasoline engines where power is controlled by closing off ("throttling") the air supply, yet where a very narrow range of air/fuel ratios must be maintained, on a diesel there is no "throttle" as such. At any given speed, the engine inhales the same full load of fresh air no matter what the position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



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



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 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.

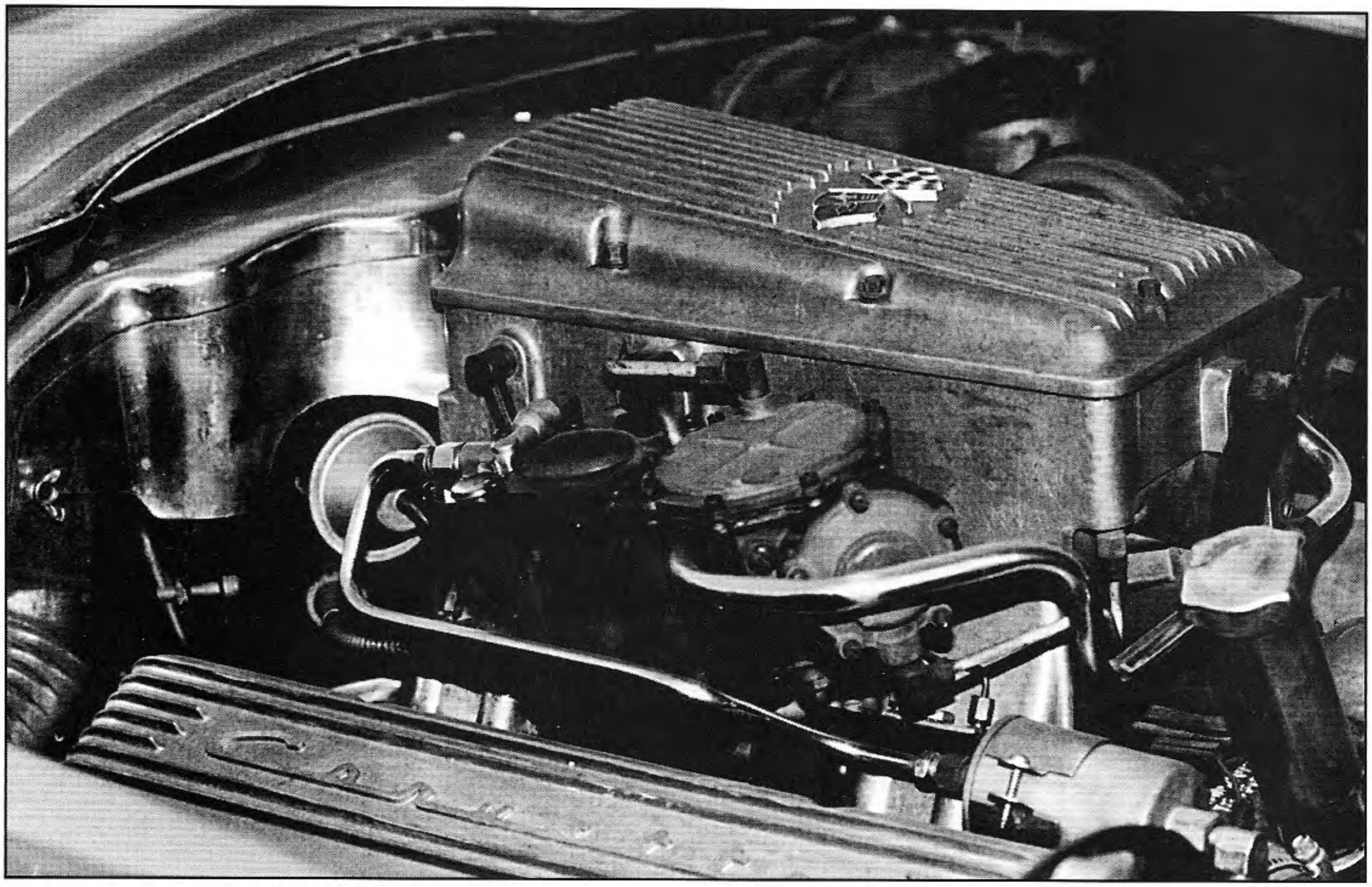
Granted, a carbureted engine would probably make a little less power than a similar one with direct injection, but some part of this might be attributed to the fact that a separate injector for each cylinder eliminates the problems of a central mixer, rather than to the timing. Of course, the same thing 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.



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 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.

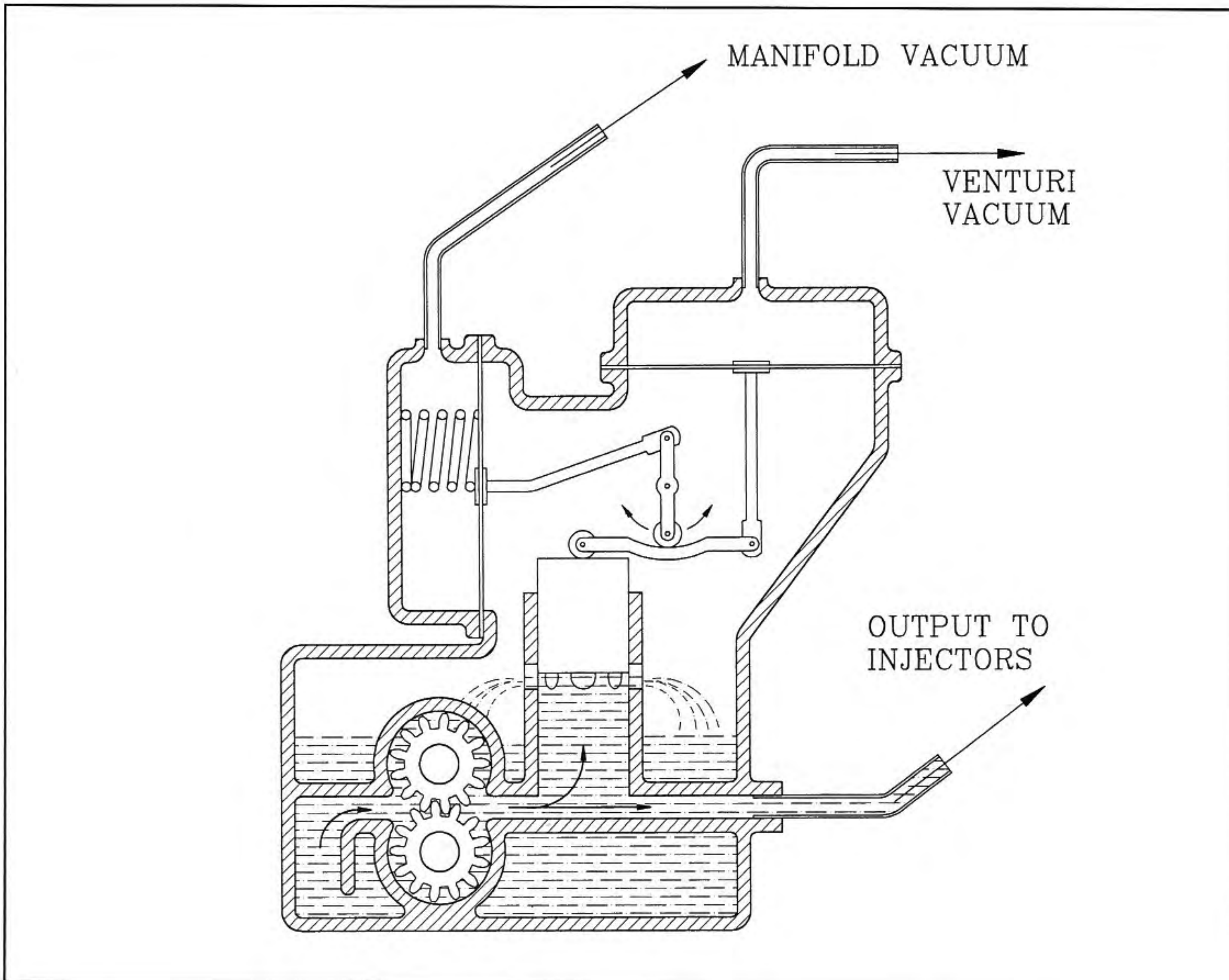
Rochester FI System

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



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 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) 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.

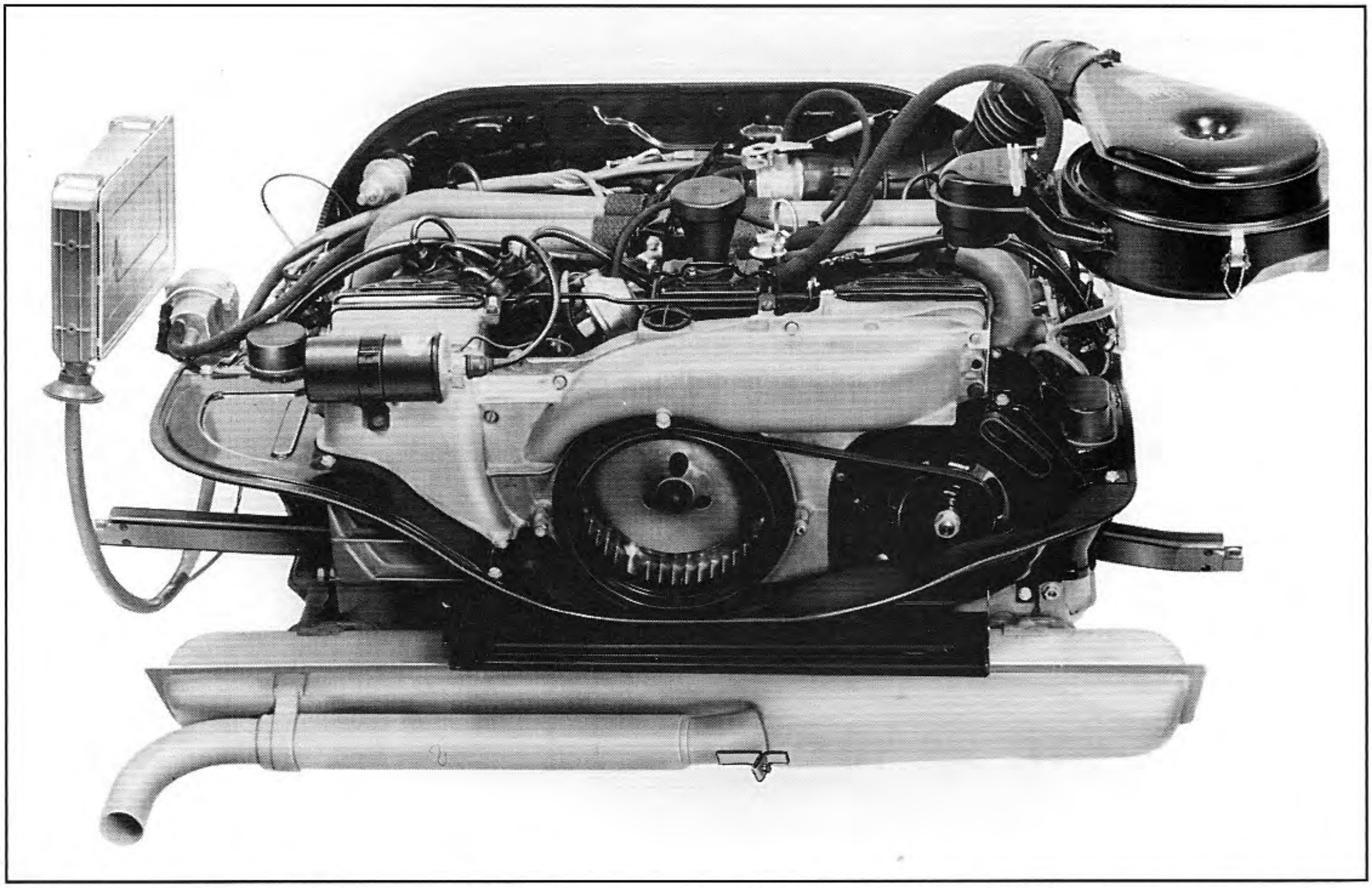
At this point, rather than try to produce and market the Electrojector themselves, Bendix decided instead to enter into an agreement with the Robert Bosch Co., which gave Bosch access to the Bendix patents. From a business point of view, this made a good deal of sense. In view of their reputation in 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

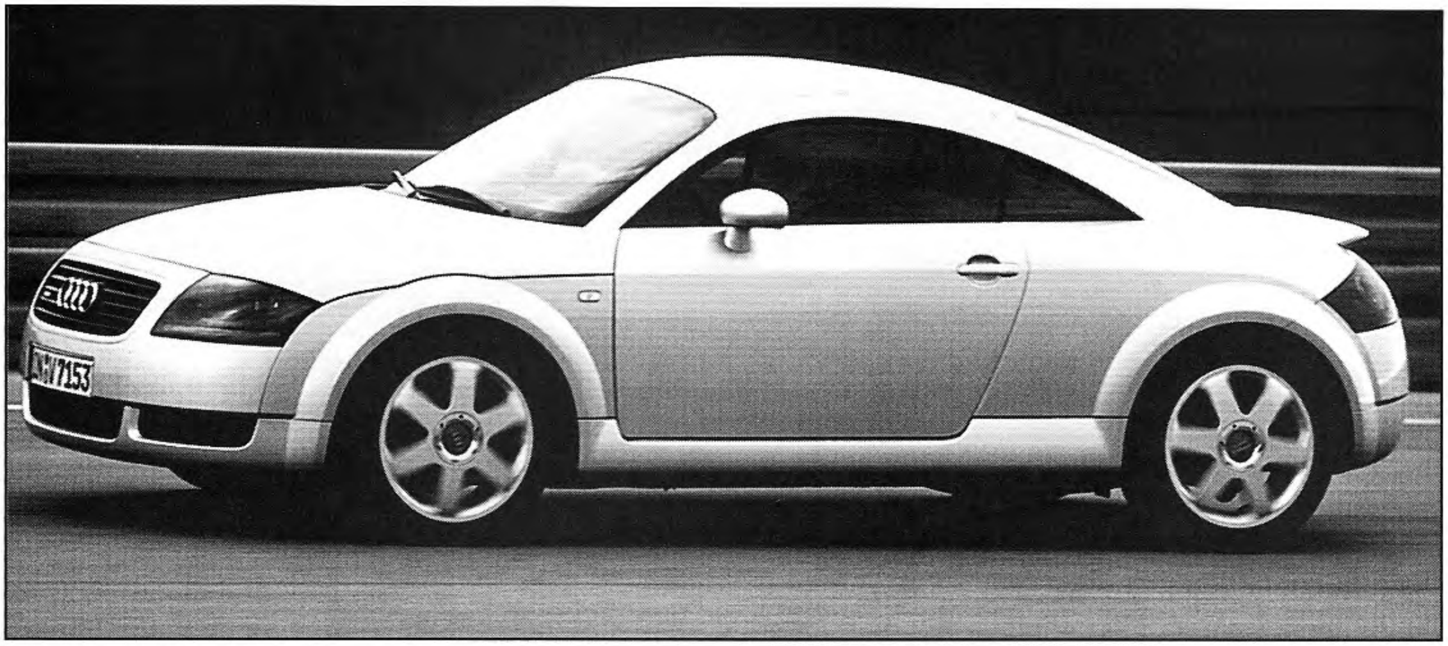


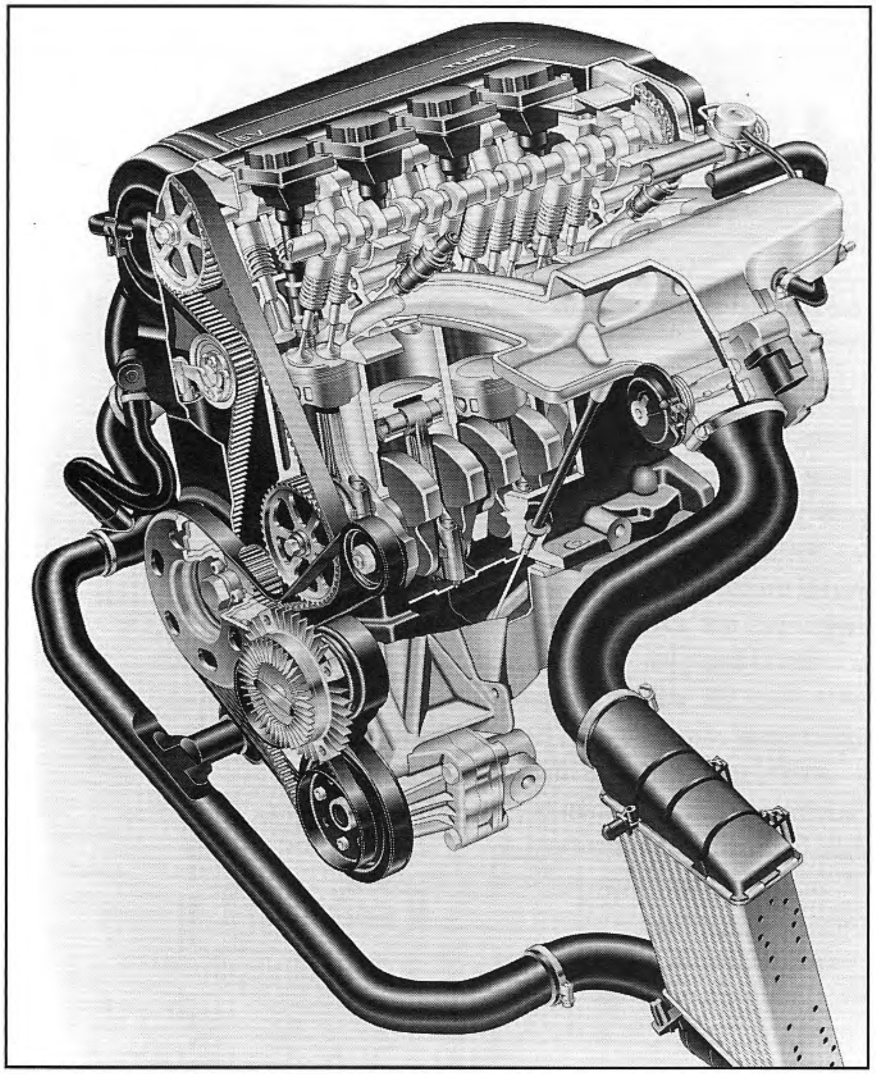
With the rear-mounted "pancake" engine nestled under the apparent floor of the trunk, earlier carburetted versions of the VW 1500/1600 were notorious for vapor lock problems. This is the later 1600 engine with Bosch D-Jetronic injection. The ECU is visible at the far left. (VW Canada).

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





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 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.

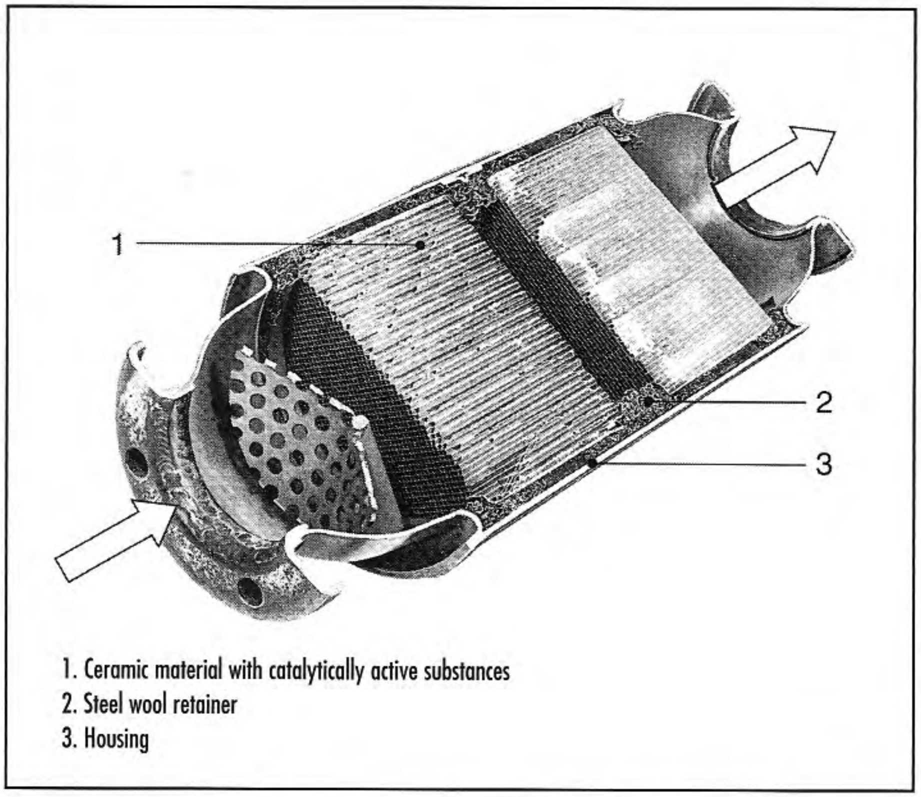
THE OXYGEN BATTERY

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.

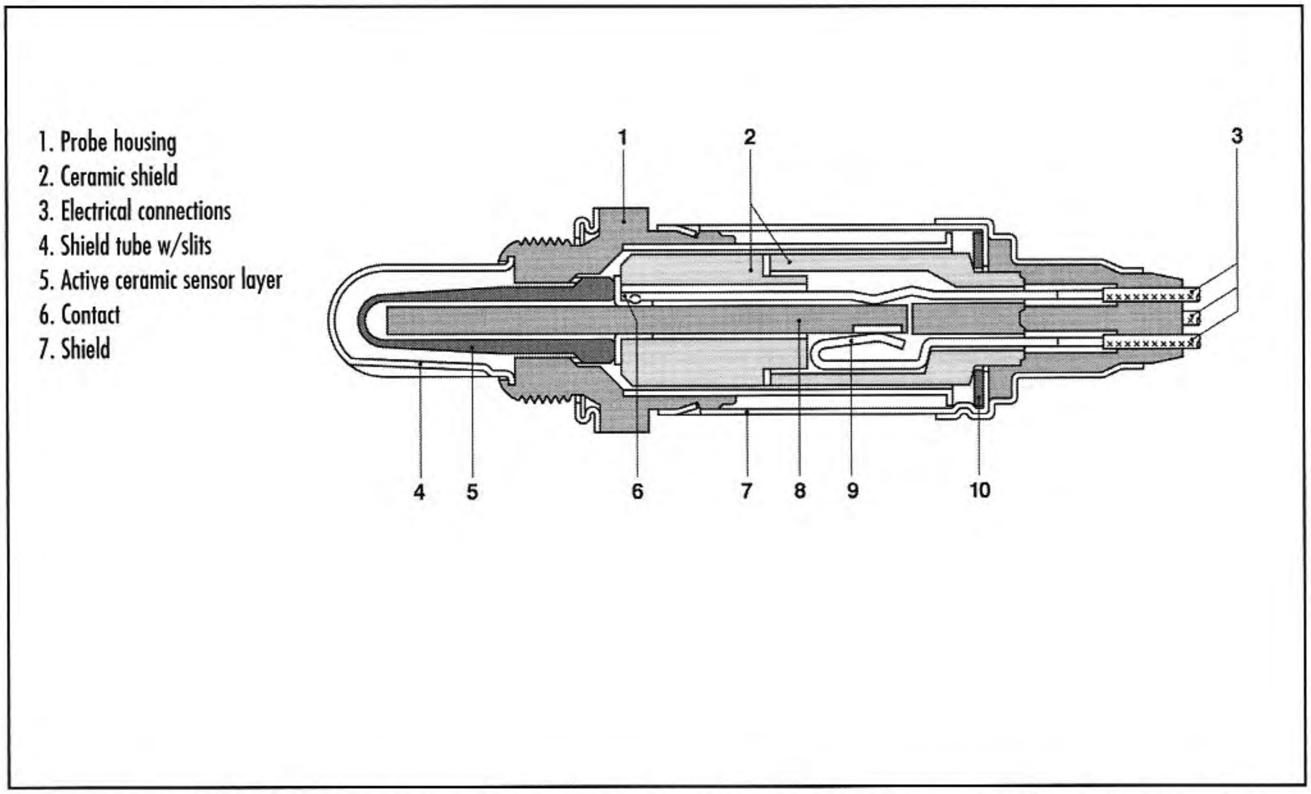
Lean mixtures would keep down the CO levels, and as long as they were just a little lean, the HC levels, too. Ironically, excessively lean mixtures actually raise HC levels above those found with a stoichiometric mixture, because as the mixture approaches the "lean limit"—the air/fuel ratio at which 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



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).



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) 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.

3 BOSCH INTERMITTENT ELECTRONIC FI

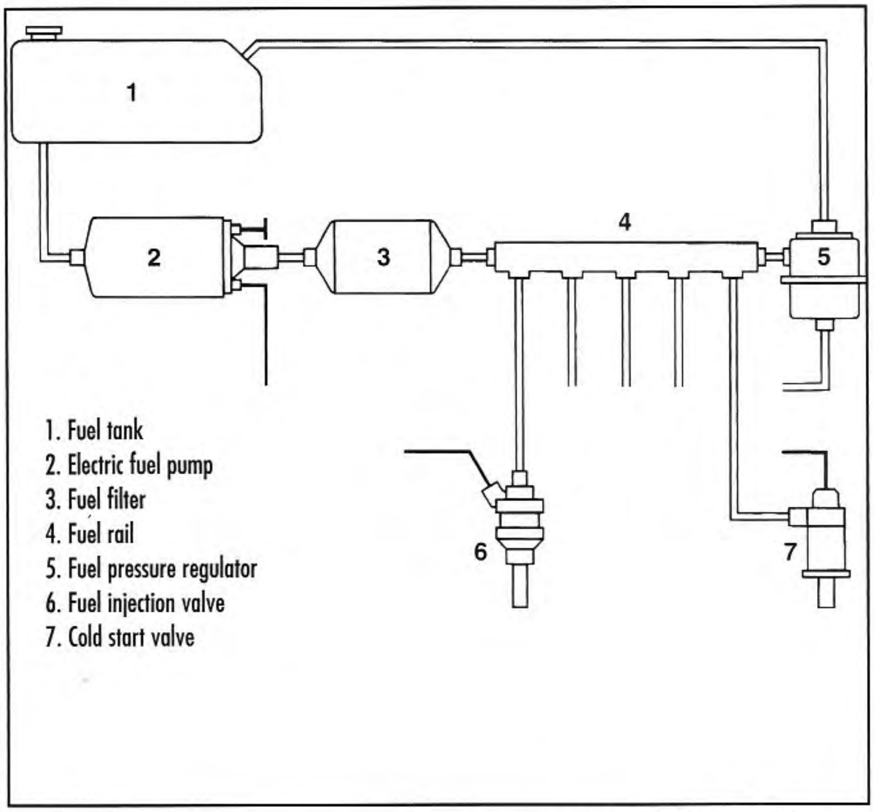
As noted in the previous chapter, the first production application of Bosch electronic fuel injection was the version installed on the Volkswagen type 3 1600, in 1967, for the 1968 fastback and Variant (station wagon) models. Although the prototype for this system—the Bendix Electrojector—was introduced a decade earlier, it was a very rarely encountered option, on just a couple of uncommon and expensive models. By contrast, that first Bosch/VW system was standard equipment on a low-priced, mass production car, and as such is rightly regarded as something of a milestone in automotive history.

D-Jetronic

At the time of its introduction, this system was simply identified by Bosch as "ECGI"—Electronically Controlled Gasoline Injection; it was soon relabeled "Jetronic." To distinguish it from subsequent versions, it has since become known as the "D-Jetronic." Here, the "D" stands for *druck*—German for pressure—because the calculation of the quantity of fuel to be injected was based on manifold pressure. After the 1968 VW, the D-Jetronic was also used on the Porsche 914, and a number of Mercedes, Volvo and Saab models, in some cases until 1975. The last cars to be fitted with this system were the 1975 Mercedes 450 and the Volvo 164E of the same year. Doubtless many thousands remain in use today.

Mechanical Components

The mechanical parts of the system include the fuel pump, filter, pressure regulator, fuel lines and injectors. An electrically driven roller-type rotary pump draws fuel, through a filter, from the fuel tank and delivers it to a "common rail" fuel line supplying the injectors. Pressure in the fuel rail is maintained at a constant 28–32psi by a regulator which functions by bleeding off excess fuel and allowing it to flow back to the tank via an essentially unpressurized return line. The regulator is thus located, schematically at least, at the opposite end of the fuel rail from the pump.



Schematic layout of the fuel supply components of a typical Bosch intermittent injection system. (Robert Bosch Corporation)

The need for tight control of fuel pressure should be apparent from the system description in the previous chapter: The system controls fuel quantity by varying the "on-time," or "pulse time" of the injectors, but the rate of fuel flow through an injector that is "on" is a direct function of the supply pressure. For the on-time to be the controlling variable, the supply pressure must be fixed within narrow limits.

Each injector is installed near the intake valve it serves. While all D-Jetronic installations thus employ a number of injectors equal to the number of engine cylinders, the injectors do not "fire" individually, but rather in groups of two, as mentioned in the previous chapter. Thus, on four-cylinder engines there are two groups of two, on sixes two groups of three, and on eights there are two groups of four.

Each electromagnetic injector consists of a valve assembly with a needle valve that opens a single orifice nozzle. The opposite end of the needle valve is attached to the core of the solenoid. When no current is supplied, the needle is pressed onto its seat by a spring. When current is supplied, the needle is pulled inward very slightly (about 0.006 inch), and fuel flows out through the calibrated nozzle opening, past a protruding tip at the point of the needle that aids atomization of the fuel. The action is very much like that of an ordinary paint spray gun.

Electrical Components

The electronic components of the system include a pair of contact points, a manifold pressure sensor, an air temperature sensor and an engine temperature sensor. There is also a "throttle position sensor," although in early versions this consists simply of two microswitches that detect just full throttle and closed (idle) throttle. All these components feed signals to the electronic control unit (ECU), which contains a couple of hundred discreet transistors, diodes, and capacitors (condensors) mounted on a circuit board, and all contained in a metal box about the size of a large book.

The heart of the ECU is a device known in electronics as a multivibrator. This is not actually a single component, but rather a circuit comprising a number of components, and having the characteristic that, once triggered, it will turn on an electric current for a certain length of time. (There is one of these in your windshield wiper "intermittent" control). The actual duration of that time interval depends on the value of the components in the circuit. Thus by arranging for the electrical characteristics of one or more components to be variable, the on-time following each triggering can be altered. (We will postpone describing the internal logic of the ECU until we deal with the L-Jetronic system, below.)

It seems that the very earliest versions of D-Jetronic achieved the mixture enrichment needed for cold starting simply by providing, in response to information from the engine temperature sensor, a longer duration pulse for the injectors. Although the history has been somewhat difficult to reconstruct, it also appears that this proved inadequate for some areas in North America, shortly after cars fitted with this early equipment starting arriving on these shores in 1969. What is certain is that a factory "cold start kit" was made available, to be retrofitted to these early units. The heart of this kit was an extra injector, fitted onto and feeding into the intake manifold, that opened and stayed open continuously while the engine was being cranked. This so-called "fifth injector" (the name stuck, even when there were six or eight injectors, for equally numerous engine cylinders) subsequently became an integral part of the system.

Drawbacks

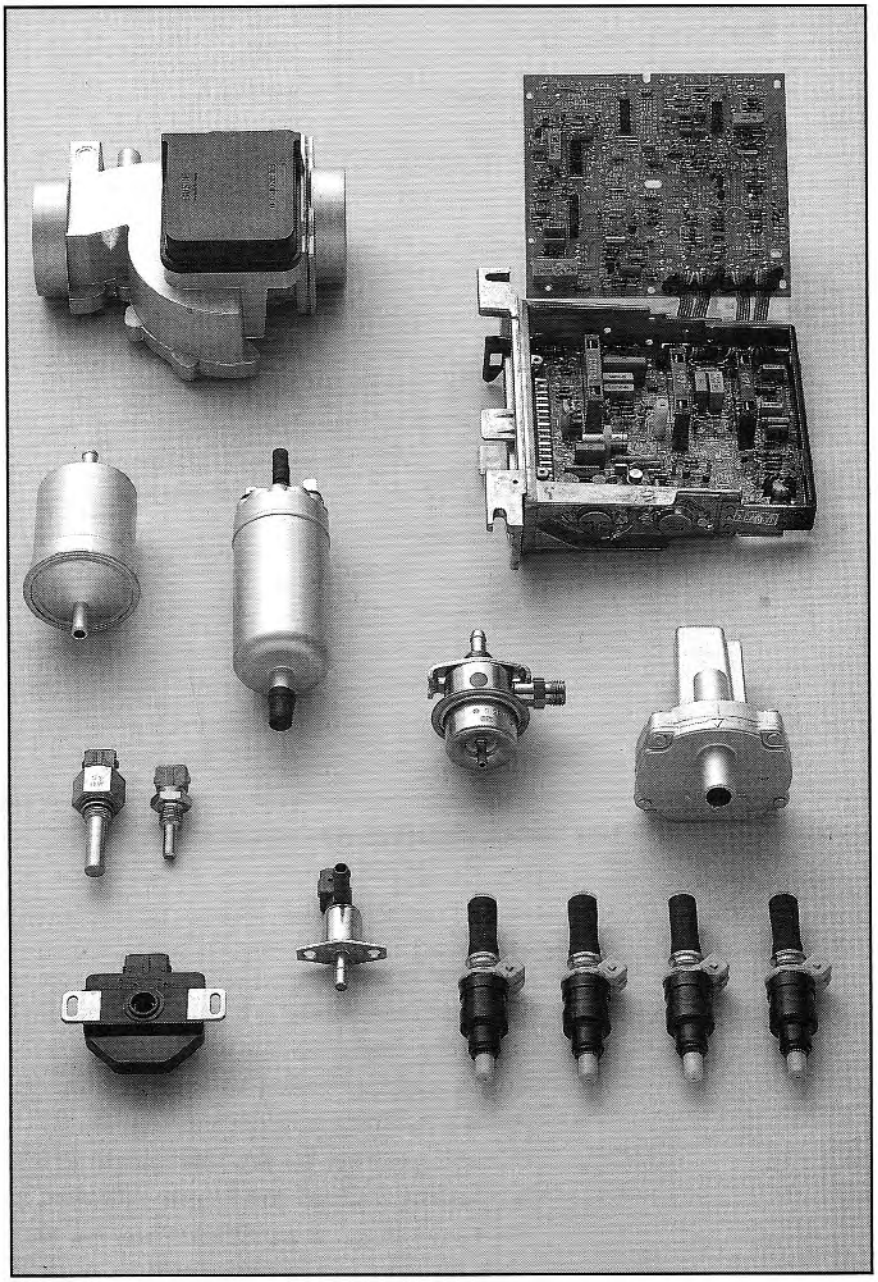
While it was in general an effective and reliable system, the D-Jetronic was not without its shortcomings. One of these was the mechanical triggering contacts. Now, a mechanical device operating in conjunction with any electronic device often proves to be a weak spot, but because the triggering contacts for the FI only carried a tiny current, arcing of these points was not the problem it is for a traditional ignition distributor. There nevertheless remained the problem of wear of the rubbing block on the moveable contact. While these contact points were considered good for 100,000 miles—essentially the life of the vehicle—they were an occasional source of grief.

Early versions of D-Jetronic exhibited another occasional source of complaint (more an annoyance than a serious defect): a very brief hesitation on sudden throttle opening at low rpm. We can speculate that this resulted from the absence of any direct provision for acceleration enrichment. Later versions had a more elaborate throttle position sensor that enabled the ECU to detect sudden throttle opening and to adjust the pulse time appropriately.

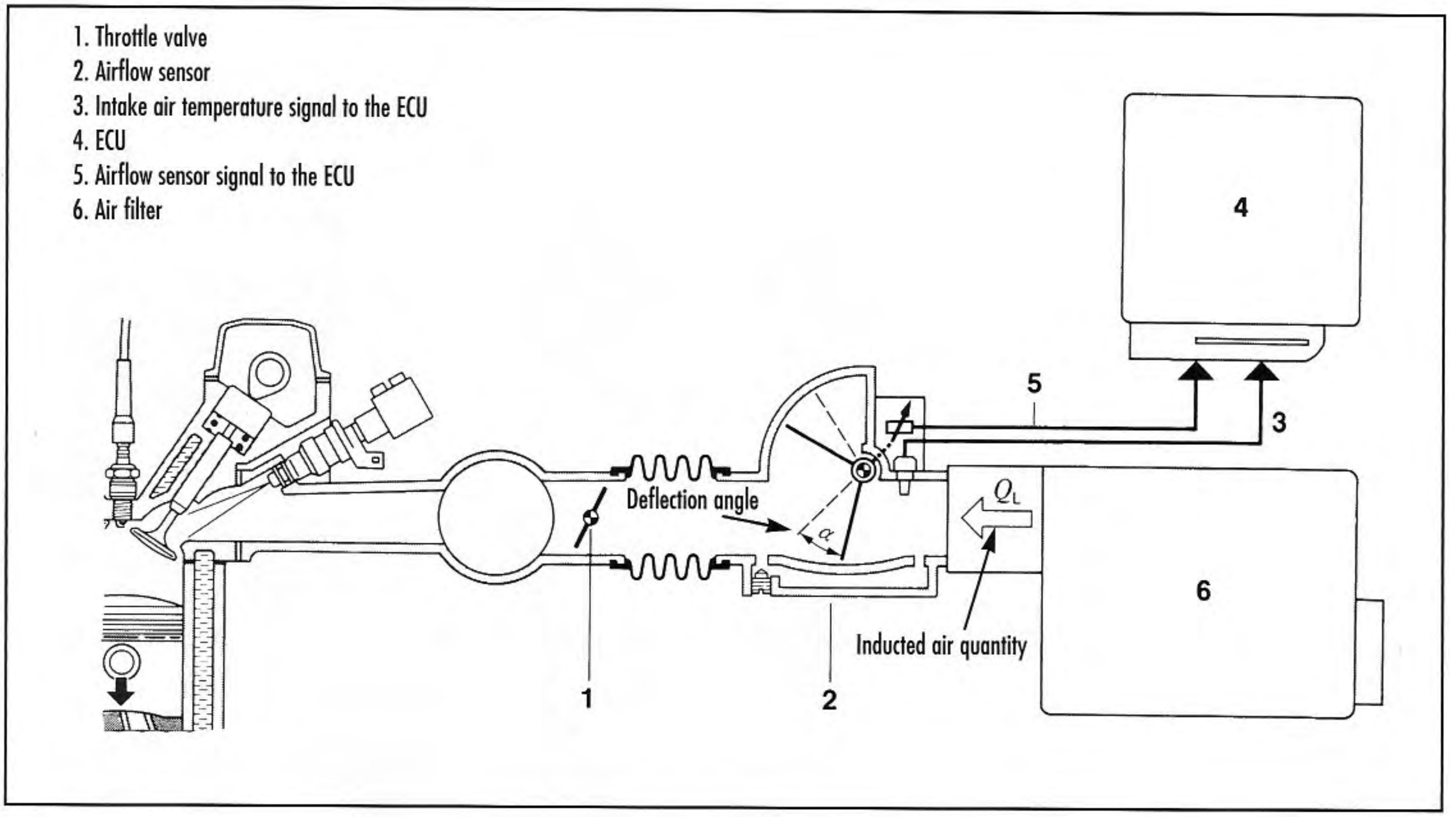
Somewhat surprisingly, the manifold pressure sensing principle itself was also eventually regarded by Bosch as a shortcoming. On the face of it, manifold absolute pressure (MAP) appears to be a valid measure of engine load, and thus of fuel quantity requirements, and one having inherent correction for variations in air temperature and atmospheric pressure. There are a couple of points about which we might speculate. First, to measure manifold absolute pressure obviously requires that there be a manifold! Manufacturers wishing to make full use of acoustic ramming (see Chapter 8) might prefer to have the intake pipe for each cylinder as completely separate as possible from all the others. And when multiple intake pipes are joined together in a common manifold, the pressure fluctuations within those individual pipes are likely to cause oscillations in the manifold pressure, especially on four cylinder engines. Apart from these design considerations, time revealed that the D-Jetronic was very sensitive to engine condition. An aging engine with poorly sealing valves could confound the calculations of the ECU.

L-Jetronic

Many of the shortcomings of the D-Jetronic system were answered in the L-Jetronic, introduced in 1974, and first appearing on the Porsche 914 of that model year. Although there have been numerous subsequent versions of EFI manufactured by Bosch under the "Jetronic" label, the L-Jetronic established the principle of calculating the fuel quantity required—and thus the pulse time of the injectors—on the basis of airflow, rather than manifold pressure as on the D-Jetronic. This fundamental difference is reflected in the designation—the "L" stands for *luft*, the German word for air.



Components of the L-Jetronic system. (Robert Bosch Corporation)



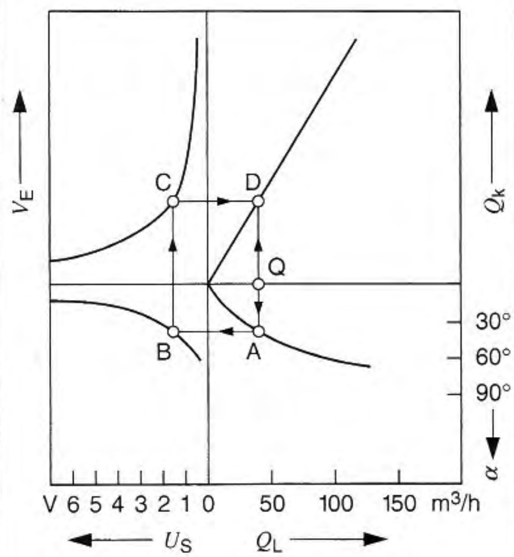
Airflow sensor in the intake system. (Robert Bosch Corporation)

Airflow Sensor

The airflow sensor is a box through which all of the intake air has to pass. Within the box is a spring-loaded vane or flap, hinged at the top, which is deflected from the down (closed) position by the momentum of the air passing through the sensor. Attached to the vane's hinge is a potentiometer—a variable resistor, like a radio volume control. Movement of the vane causes an electrical contact in the potentiometer to wipe around a ring-shaped surface that is wound with a resistance wire, so that the total resistance of the potentiometer depends on the position of the wiper, and thus of the vane. By measuring this resistance value, the ECU is thus able to "know" the position of the vane and thus the rate of airflow through the meter.

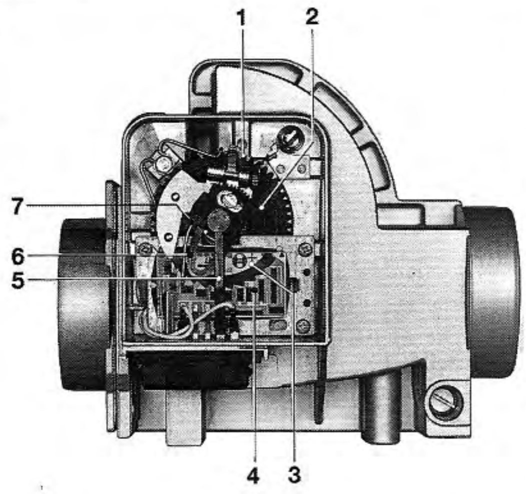
The internal "floor" of the box is shaped so that, in combination with the weight of the vane and the calibration of its return spring, the angle of the vane is proportional to the logarithm of the airflow rate. That is, a doubling of the flap angle corresponds to a tenfold increase in airflow. The sensitivity of the airflow meter is thus greatest at small values of airflow, when the greatest metering precision is needed.

As mentioned in Chapter 1, the opening and closing of an engine's valves causes pressure fluctuations in the intake air stream. To reduce the tendency of these fluctuations to cause the vane to oscillate or flutter, a second flap is arranged at ninety degrees to the first. Pressure pulsations act on both vanes at the same time; a pulse of pressure that would swivel one of the vanes in one direction has the opposite effect on the other vane, so the two forces tend to be self-cancelling. This second balance (or damping) vane also has another function. As the measuring vane opens, the balance vane moves into a closely surrounding space, so the tendency of the measuring vane to slam open—and perhaps bounce—is damped by the balance vane run-

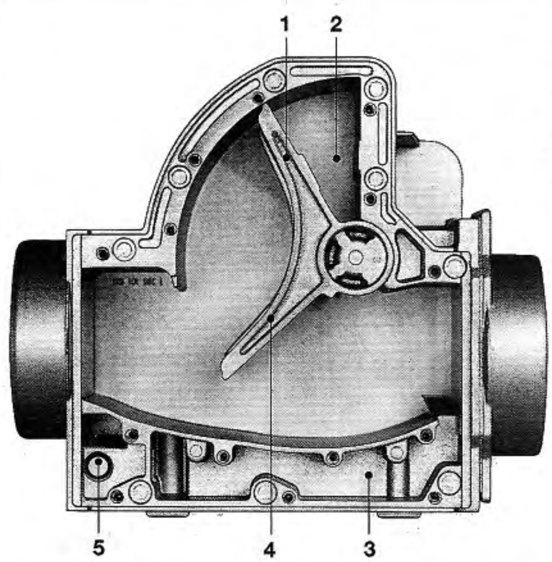


Interrelationships between intake air quantity, sensor-flap angle, voltage at the potentiometer and injected fuel quantity. (Robert Bosch Corporation)

1. Ring gear for spring preloading
2. Return spring
3. Wiper track
4. Ceramic substrate with resistors and conductor straps
5. Wiper tap
6. Wiper
7. Pump contact



The vane-type air meter of an L-Jetronic system, viewed from the electrical connection side. (Robert Bosch Corporation)



1. Compensation flap
2. Damping volume
3. Bypass
4. Sensor flap
5. Idle mixture adjusting screw (bypass)

The vane-type air meter of an L-Jetronic system, viewed from the other side. Note the compensating flap which serves both as a counterweight and as a pulsation damper. (Robert Bosch Corporation)

ning into this dead-end air pocket.

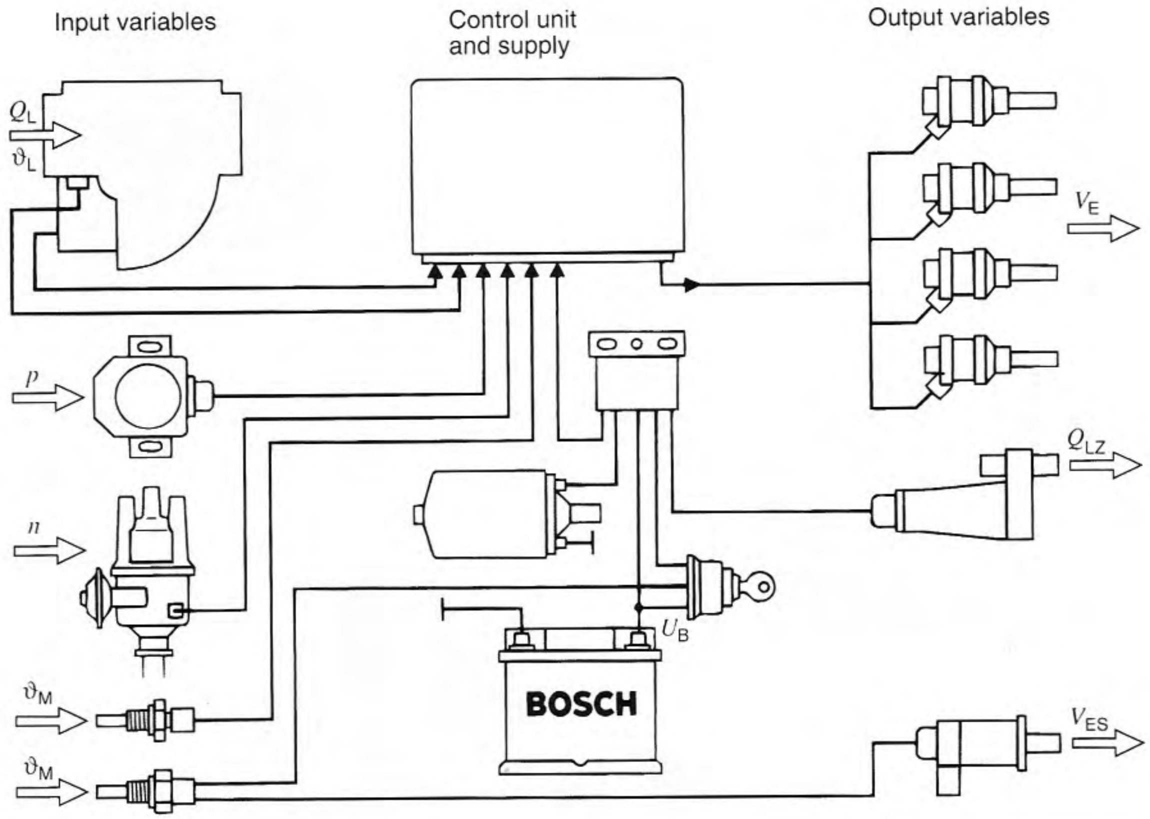
Now, the force that pushes on the measuring vane is a result of the momentum of the passing air, and momentum is simply the product (multiple) of mass and velocity. At first thought, then, it might seem that this sensor apparatus directly measures mass flow—the weight of air passing per minute, which is what matters. In fact, the only way that the vane could measure the total momentum of the passing air would be to bring it all to a complete halt—no air would flow! Obviously, the vane must obstruct the airflow as little as possible (the pressure drop caused by the vane is just 0.017 psi), so it only measures a small fraction of the total momentum, and we have no direct way of knowing what that fraction is. As a result, the meter is actually measuring volume flow. The relationship between the volume of a certain quantity of air and its mass is a function of its temperature—cold air is denser than hot air. Consequently, an air temperature sensor is provided, to allow the ECU to correct the volume flow information from the airflow sensor on the basis of the air's temperature.

Idle Air Bypass

To permit a degree of manual adjustment of idle mixture strength (mainly to allow adjustment of idle speed), a small amount of

Signals and controlled variables at the ECU

Q_L Intake air quantity, ϑ_L Air temperature, n Engine speed, P Engine load range,
ϑ_M Engine temperature, V_E Injection quantity, Q_{LZ} Auxiliary air, V_{ES} Excess fuel for starting,
U_B Vehicle-system voltage.



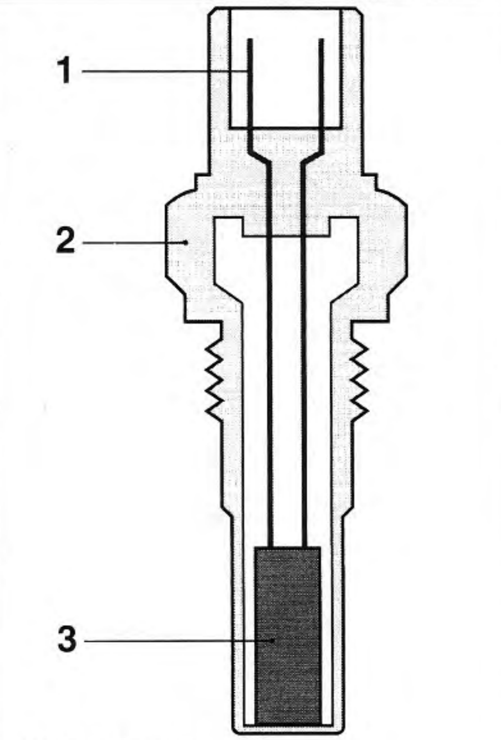
Signals and controlled variables at the ECU. (Robert Bosch Corporation)

air is allowed to bypass around the measuring section of the airflow meter through a separate small passageway. This extra idle air is thus unmetered; the ECU is "unaware" of it. The amount of air that is bypassed in this way can be adjusted by a small needle valve arranged at the end of the bypass passage nearest the engine. Turning this screw in makes the opening smaller, reducing bypass airflow and so richening the mixture.

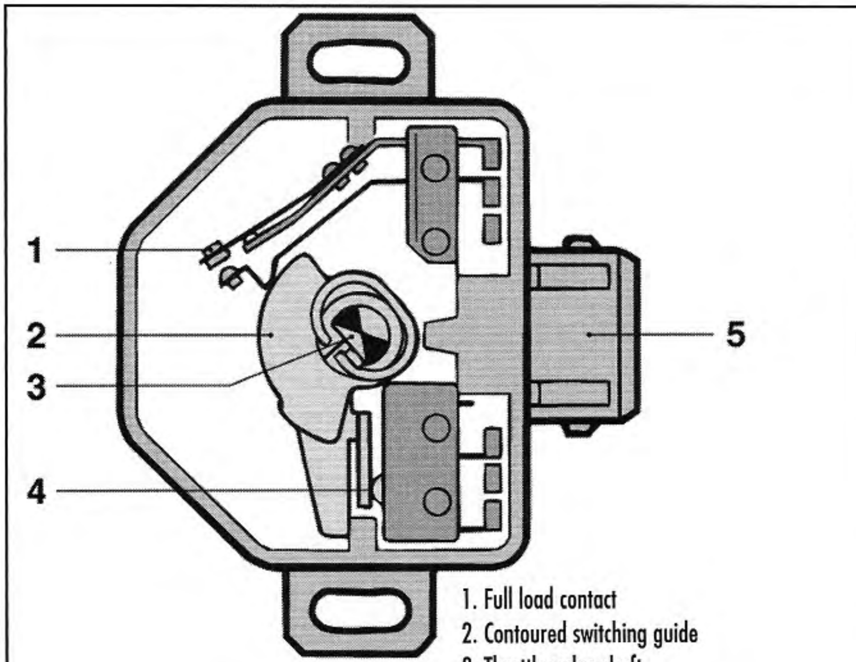
Other Sensors

Apart from the main air quantity signal from the airflow sensor and the density correction signal from the air temperature sensor, there are additional sensors continuously providing information to the ECU. Like the D-Jetronic, there is an engine temperature sensor, the output of which is used by the ECU to enrich the mixture during cold starts and during warm-up. Also like the early D-Jetronic, there is a throttle position sensor that reports just closed (idle) throttle and full throttle. This information is used by the ECU to provide mixture strength corrections for those two operating conditions.

Even though some domestic auto makers retain manifold absolute pressure as the principle load signal for their EFI systems, Bosch regards the L-Jetronic's airflow metering as an improvement over the manifold pressure metering used on the D-Jetronic. Certainly it makes the system less sensitive to changes in engine condition with age, such as deterioration of valve and piston ring sealing, carbon build-up, etc.,



Engine temperature sensor. (Robert Bosch Corporation)



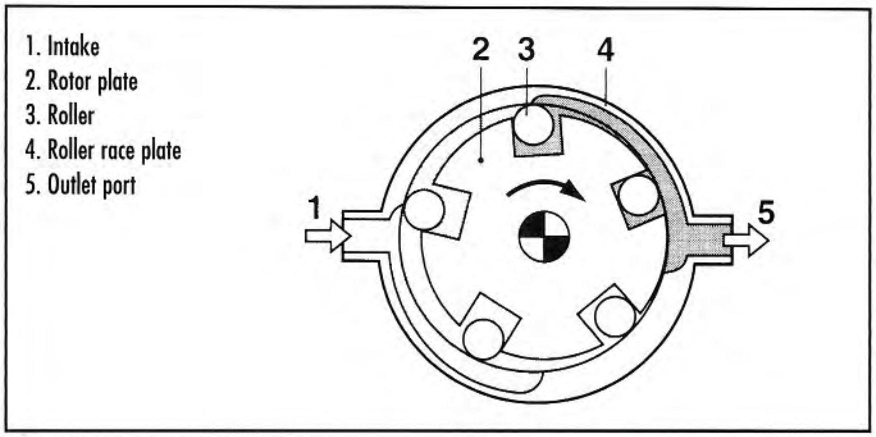
Throttle valve switch. (Robert Bosch Corporation)

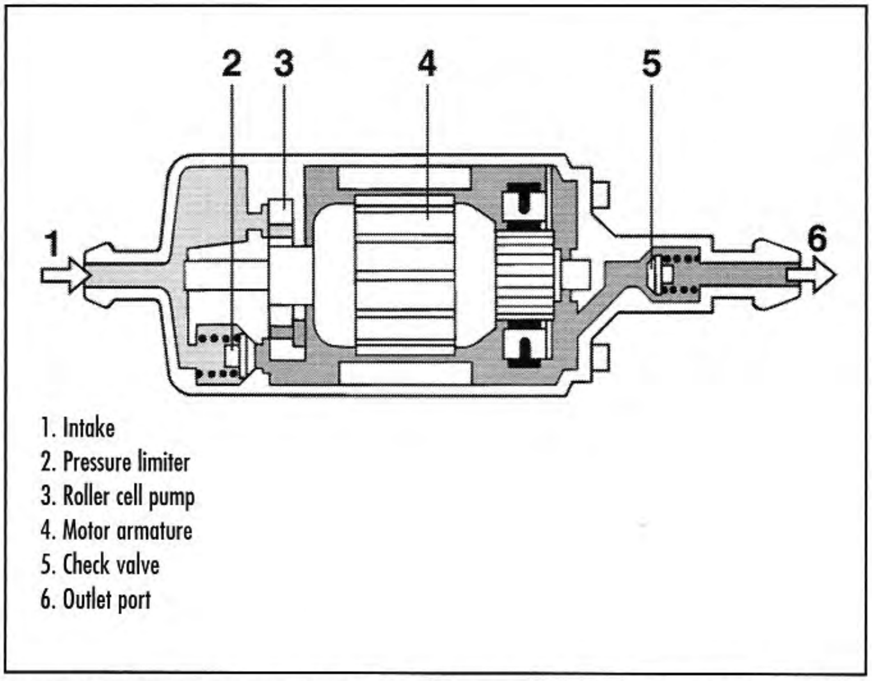
but it has some potential faults of its own. For one thing, early versions could be destroyed by a backfire, although later ones incorporate an "anti-backfire valve" that opens when exposed to a high pressure on the engine side of the vane. And like the D-Jetronic, any air leaks downstream of the meter allow unmetered air (sometimes called "false air") into the engine, causing the mixture to become lean. The airflow meter is also more expensive to manufacture than the simple aneroid bellows of the D-Jetronic's pressure measuring apparatus.

Mechanical Components

The mechanical components of the L-Jetronic are similar to those of the D-Jetronic. As there, an electrically driven roller-type rotary pump draws fuel from the tank. The L-Jetronic's pump is equipped with a check valve that keeps the fuel lines full and pressurized even when the engine is stopped. This permits quicker restarts, and helps to prevent vapor lock. The pump also has a relief valve at its intake end, which returns fuel to the tank if the internal pressure rises too high.

Because roller-cell pumps are much better at pushing than at pulling, the pump is located low down, near the tank; indeed, in some cars it is actually inside the tank, immersed in fuel! Even in those cases where the pump is located outside the tank, its internal electrics are totally submerged in the fuel carried within the pump; this helps to cool the pump motor. Although this sounds dangerous, it is a practice that has been used in aircraft for years, and three decades of uneventful experience with Bosch systems using this scheme should dispel any anxiety. (Although the pump can be damaged by





The roller cell fuel pump. The rollers fit loosely in their lands; centrifugal force pushes them against the contoured interior of the pump body. (Robert Bosch Corporation)

overheating if it is run dry for long; bear this in mind if you ever run completely out of fuel.) A paper element filter is provided, but unlike the D-Jetronic this is located after the pump rather than before it.

As with the D-Jetronic, the regulator is schematically at the far end of the fuel rail, maintaining pressure within the rail for the injectors, and bleeding excess fuel back to the tank. (A notable side benefit of this constant circulation of fuel is that it helps keep the fuel cool, thus further reducing the risk of vapor lock.) The L-Jetronic's regulator maintains either 36psi or 44psi fuel pressure, according to the vehicle model, somewhat higher than the D-Jetronic's 28–32psi. Generally, the higher pressure (about 44psi) is used with more powerful engines; higher pressure means a greater fuel flow for a given injector pulse time. Of course, the rate of flow at a given fuel pressure depends on the local pressure where the fuel is being injected. Because manifold pressure varies according to engine load, the pressure against which the fuel is working has to be taken into account. Accordingly, the spring-loaded diaphragm in the L-Jetronic's regulator has a connection from its back surface to the manifold. As manifold pressure varies, the load against the diaphragm changes, so the regulator maintains a constant pressure difference between the fuel in the rail and the air in the manifold. The D-Jetronic did not need this feature because the ECU took the manifold pressure into account in the calculation of the injector pulse time.

Although all later L-Jetronic systems used digital electronics, the first version was analog (see the sidebar "Much or Many?"). Nevertheless, the principles of operation that were established with the first L-Jetronic system have enough in common with all subsequent versions that it is now worthwhile to look at the way the inputs from the various sensors are dealt with by the internal logic of the ECU.

Inside the ECU

In contrast to the mechanical contact points used in the D-Jetronic, L-Jetronic systems use the firing of the ignition system as a trigger signal. In a four-cylinder, four-stroke engine, there will be a spark plug firing twice per engine revolution. Thus, the ECU (electronic control unit) receives two triggering pulses per revolution. If you have ever seen an oscilloscope trace of an operating ignition system, you will understand that these pulses, as received by the ECU, are "ragged"—the electrical oscillations in the coil windings produce a voltage trace with a succession of "wiggles" that rapidly damp out.

The first operation within the ECU is to turn these ragged, spikey voltage pulses into a simple square pulse of fixed duration—upon triggering by the ignition "spike," the voltage at the output of these stages rises nearly instantaneously from zero to some small positive value, dwells there for a brief time, then drops back to zero. (In electronics, this "pulse-shaping" circuitry, known as a "Schmidt trigger," is commonplace. They are used, for example, to eliminate the effects of the bouncing that occurs with ordinary mechanical switch contacts, etc.) Thus, there are now two square-wave pulses departing from the pulse-shaping circuit with each revolution of the crankshaft. These pulses then pass to a frequency divider, which, in effect, ignores every other one and passes on just one of them. The next stage in the internal electronics thus receives just one pulse per revolution.

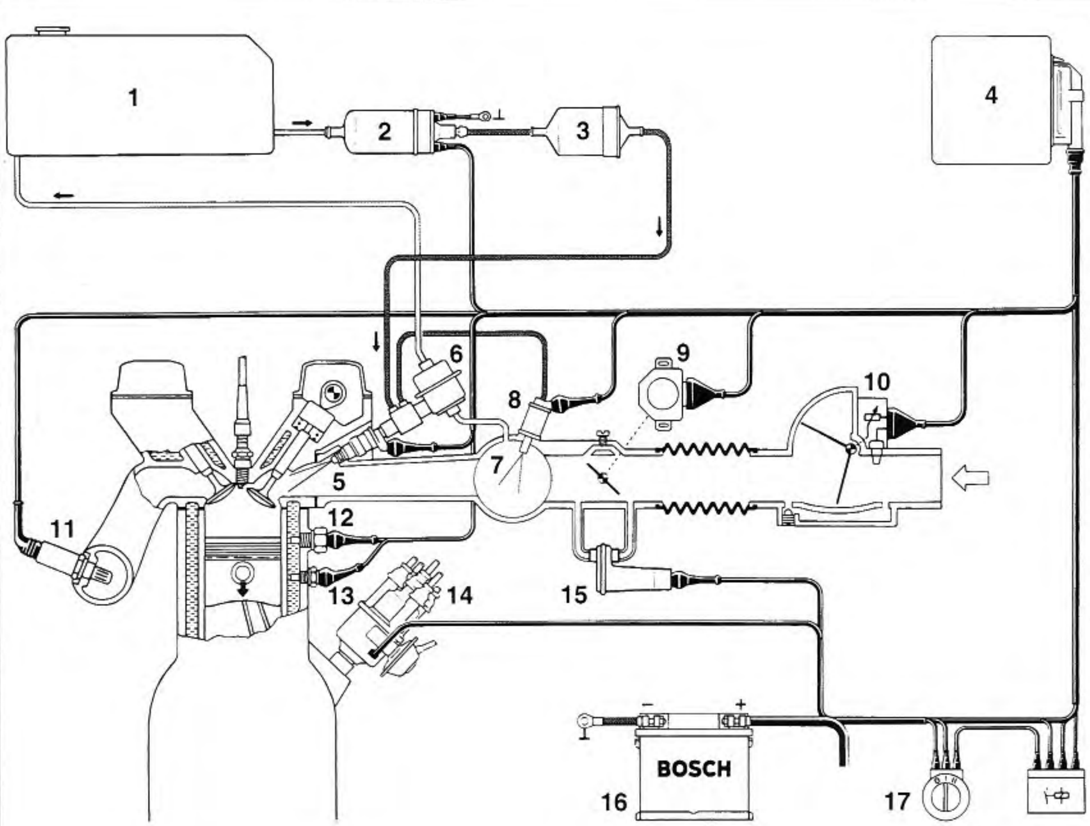
Pulse Time—That next stage is termed by Bosch the "division control multivibrator." Here a basic pulse time is generated, on the basis of engine speed and air mass flow. The rpm is known from the frequency of the pulses arriving from the frequency divider; the air mass flow is known from the position of the vane in the airflow meter, plus a correction introduced on the basis of information from the air temperature sensor. If all operating conditions are "normal"—engine fully warmed up, running at a moderate speed and load, and battery voltage near nominal value—that pulse time would give an appropriate injector pulse time. These pulses of "basic" duration are then passed on to the next batch of circuitry—the "multiplier stage."

Multiplier Stage—When circumstances vary from the optimum that calls for a pulse of "basic" duration, further internal calculations are performed by the multiplier stage. Low battery voltage, for example, will slow down the opening of the injector valves. The basic pulse time is calibrated on the assumption that the injector spends a mere one millisecond opening, stays open for the duration of the pulse, then closes almost instantly when the pulse ceases. Of course, almost instantly means that there is some small amount of fuel injected after the pulse ceases, while the spring within the injector returns the needle valve fully onto its seat. As long as the one millisecond delay in opening can be counted on, this "incidental" fuel on closing is offset by the opening delay, so the basic pulse time will deliver an appropriate amount of fuel. Low voltage does not affect the closing spring, so the incidental delivery remains pretty much constant, but low voltage does extend the opening delay, so less fuel will be delivered under these conditions. A connection to the battery "hot" terminal provides the multiplier stage of the ECU with information about battery voltage, allowing the calculation of an extension to the basic pulse time, to make up for the short-changing of fuel that results from the slow injector opening accompanying a low system voltage, such as occurs after an extended period of cranking. This voltage connection is usually made as direct as possible (no fuse, for example) to reduce the risk that corrosion at terminals may give the ECU a false reading of battery voltage.

Inputs from the air temperature and engine temperature sensors are used by the multiplier stage to add more time to the basic pulse duration to account for cold starting and warm-up phases. Similarly, the pair of microswitches that signal idle and full throttle also feed information to the multiplier stage, which adds the appropriate amount of pulse duration to provide further enrichment under these two conditions.

Acceleration Enrichment

Apart from the microswitch that signals full throttle, there appears to be no provision for acceleration enrichment on many versions of L-Jetronic. In fact, this is handled



1. Fuel tank
2. Electric fuel pump
3. Fuel filter
4. ECU
5. Fuel injector
6. Fuel rail and fuel pressure regulator
7. Intake manifold
8. Cold-start valve
9. Throttle valve switch
10. Airflow sensor
11. Lambda sensor
12. Thermo-time switch
13. Engine temperature sensor
14. Ignition distributor
15. Auxiliary air device
16. Battery
17. Ignition and starting switch

Schematic diagram of an L-Jetronic system with lambda (oxygen sensor) control. (Robert Bosch Corporation)

mechanically, rather than through the electronics. When the throttle is opened suddenly, the rapid increase in airflow through the sensor causes the vane to overshoot momentarily. Because the ECU is using the vane position as a measure of airflow, this exaggerated movement of the vane influences the ECU to briefly increase the pulse time, thereby providing the enrichment needed to avoid a "lean stumble" when the throttle is banged open.

Some versions of L-Jetronic have a further refinement in this regard, in addition to the enrichment from vane "overshoot." The same signal from the vane position sensor that provides the ECU with its basic information about air quantity is also analyzed for the rate-of-change of the vane's position, so a rapidly moving vane will prompt the ECU to provide more enrichment than would a more slowly opening one. In either case, the ECU will add acceleration enrichment whenever the microswitch that signals full throttle is closed.

On cars with a lambda sensor—generally, those built after 1980—the output from that sensor are also fed to the ECU. The multiplier stage processes information from the lambda sensor, increasing the pulse time (that is, richening the mixture) when the oxygen level detected by the sensor is high, reducing the pulse time (leaning the mixture out) when the oxygen level drops. This coupling between the lambda sensor and the ECU is called "closed-loop" control—information from the sensor induces the ECU to make changes, which are detected by the sensor which then provides a different signal to the ECU, which adapts again . . . and so on. (See also the sidebar "The Oxygen Battery" in Chapter 2.) Whenever the full throttle microswitch is closed, the ECU reverts to "open-loop" control—it ignores data from the lambda sensor, and depends on its internal "maps."

After all these calculations, the pulse that emerges from the multiplier stage has the "basic" on time span, plus some added duration for enrichment, according to inputs from all the various sensors. That pulse, however, is extremely weak; the internal electronics all operate on just tiny amounts of voltage and current. Heftier electronic components are needed to deal with the 12 volts and comparatively large currents that actuate the injectors. That task is handled in the final "amplifier stage" of the ECU.

There are two points to note here. First, the pulses are coming once per crank revolution—on a four-cylinder, four-stroke engine that means two pulses per cycle—and all the injectors fire at once. Second, while the above description of pulses leaving the ECU to drive the injectors is a fair schematic representation of what is going on, the injectors are actually hot all the time—the ECU in fact grounds the injectors for the duration of each pulse.

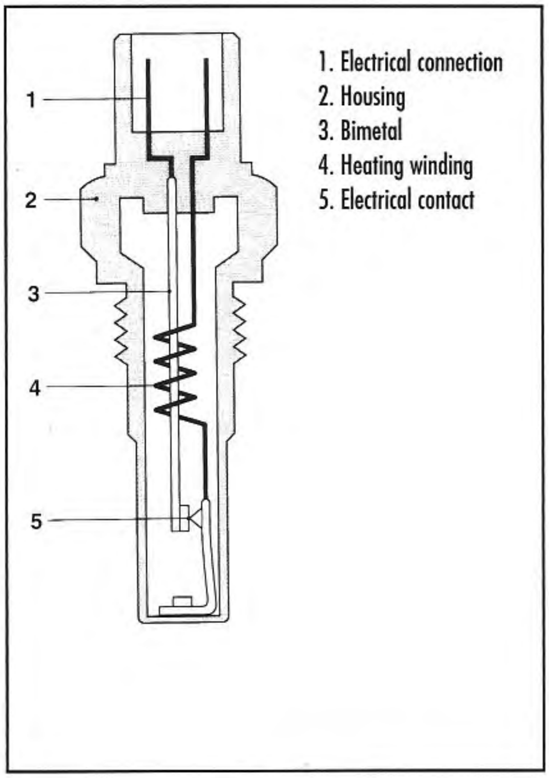
Cold Starting

As might be expected, cold starting is a special case that may lie outside the normal range of calculation of the multiplier stage, and the total fuel requirement may exceed the capacity of the injectors, even when they are "on" almost all the time. Different versions of L-Jetronics adopt different strategies for cold starting. A few get by simply by vast increases (a doubling or tripling) of pulse time; most use a separate "cold start" injector, just like the mature version of the D-Jetronic; a few others use both approaches.

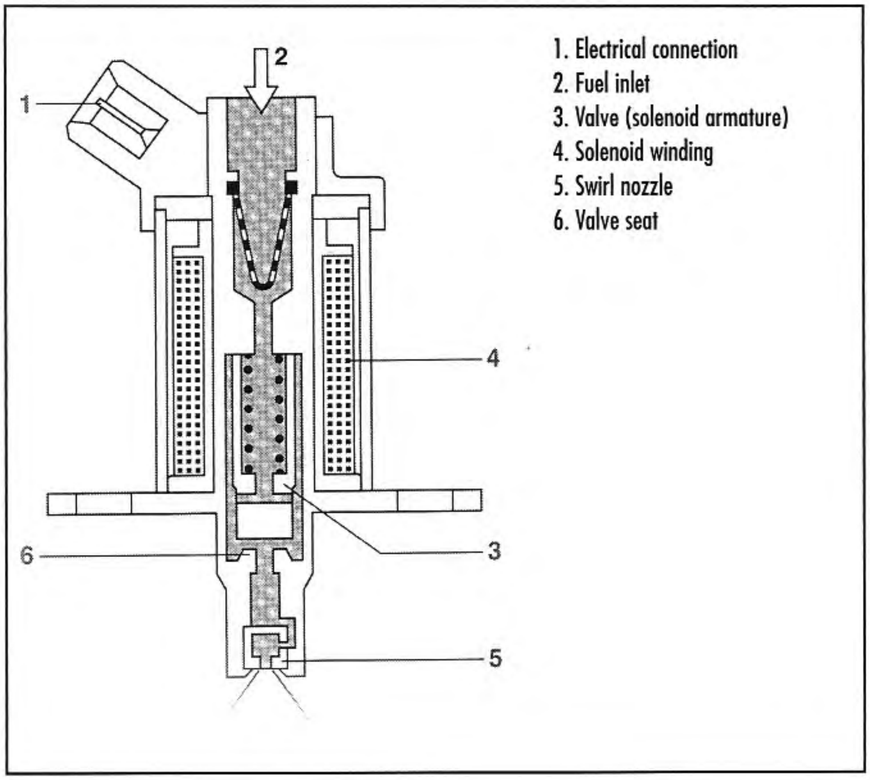
The two temperature sensors on L-Jetronic systems—one for intake air, the other for engine temperature—are both based on what is called a "negative temperature coefficient" (NTC) resistor. This refers to the fact that, unlike many resistors whose resistance value increases positively with temperature, the NTC has the opposite characteristic; when the NTC is cold, it has a high resistance, when hot the resistance falls. NTC I (or Temp I), in Bosch's terminology, is the air temperature sensor; NTC II senses engine temperature. So, while information from NTC I is used all the time by the ECU to correct the airflow information from the airflow sensor vane, in effect to calculate air mass flow, NTC II is the key component in achieving the wholesale enrichment needed for cold start. On water-cooled engines, NTC II will be found in the same sort of places—such as the thermostat housing—where you would expect to find an ordinary "temperature sender" for the dash temperature gauge . . . and may be confused with it! On air cooled engines, NTC II will be screwed into a cylinder head.

In the comparatively new L-Jetronics that use just an increased fuel delivery through the standard injectors for cold starting, a high resistance value (say 3000 Ohms or more) detected at NTC II will simply influence the ECU to increase the pulse time. In these systems, the required fuel flow for a "cold-cold" start (engine temperatures much less than room temperature) may require the ECU to "double-up" the firing of the injectors as long as the starter is cranking, to provide two injection cycles per crank revolution, instead of the usual one cycle. The ECU makes this decision based on both the temperature reported by NTC II and by the cranking rpm. The ECU also keeps track of the time elapsed during cold cranking, and will reduce the quantity of fuel injected under circumstances that seem likely to lead to flooding.

However, many L-Jetronics (and certainly most early ones) use a "cold start valve," in



The thermo-time switch. The contacts are closed when the switch is cold, and open when it is hot, either from a warm engine or because the electric heating element has had time to warm it. (Robert Bosch Corporation)



A cold start injector (cold start valve), shown in the "on" state. (Robert Bosch Corporation)

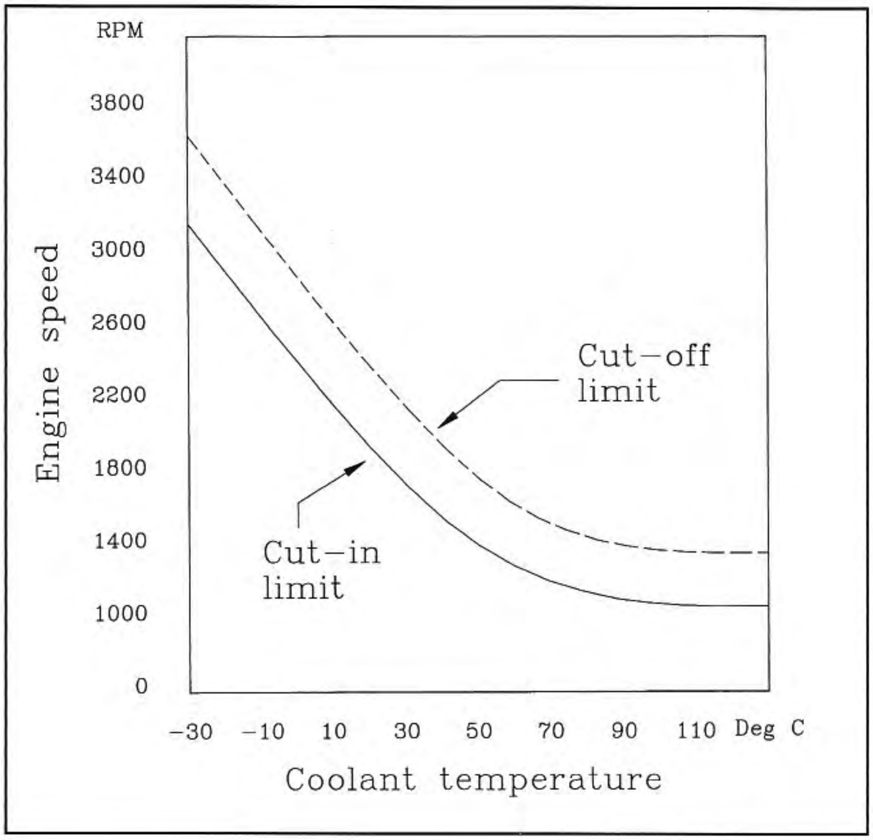
conjunction with a "thermo-time switch." This cold-cold start circuit, which operates only as long as the starter is cranking, is quite independent of the ECU. Power is fed to the cold start injector (which Bosch terms a "cold start valve") via the starter terminal on the ignition switch, but whether or not the injector is actually energized depends on whether or not it is grounded. And that depends on the thermo-time switch.

The thermo-time switch comprises a pair of electrical contacts, one fixed and one at the end of a bimetallic strip, which consists of two layers of different metals bonded together. The two metals chosen have widely different thermal expansion characteristics, with the result that the strip bends to a greater or lesser extent, according to its temperature. When "cold" (less than about 95° F), the strip is nominally straight, and the contact on its end touches the fixed contact, closing the switch so current will flow. The cold start injector is wired in series with this switch, so when the starter is energized with the thermo-time switch closed, current flows through the windings of the cold start injector, so it opens and passes fuel into the intake manifold.

To prevent engine flooding, an electrical heating element surrounds the bimetallic strip. This heater is fed by the same current that is passing through the contacts, so after a brief time (never more than about ten seconds, even in the coldest weather) the strip will heat up, bend, and so open the switch, cutting off juice to the cold start injector. Because its working end is immersed in engine coolant, or at least attached to the engine block, the thermo-time switch will remain open if the engine is much above room temperature.

Auxiliary Air Bypass

Because Bosch EFI systems have no mechanism corresponding to the fast-idle cam on a carburetor equipped with an auto-



To improve economy and reduce emissions, the fuel is shut off when the throttle is closed, as signalled by the throttle switch. To prevent "hunting," the cut-off and cut-in limits are separated by a few hundred rpm. The rpm at which cut-off occurs is lowered proportionally as the engine warms up, to prevent stalling with a cold engine. (Robert Bosch Corporation)

matic choke, the extra internal friction of a cold engine could pull the idle speed down so low that the engine may not continue to run. To provide the equivalent of a slight throttle opening so as to maintain a reasonable idle speed, an "auxiliary air bypass" is provided. This bypass amounts to a small rotary disc valve; depending on the position of the disc, more or less air (or none) is allowed to bleed around the nearly closed throttle. The position of the disc, in turn, is governed by a bimetallic coil. When the coil is warm, the valve is completely closed; when very cold, it is fully open; at intermediate temperatures, it adopts a position somewhere in between. A smooth and gradual transition from open to closed as the engine warms up is assured by the profiling of the valve disc and the calibration of the bi-metallic coil and of a return spring that pulls the valve to the closed position. A few early versions of this valve are heated by engine coolant; most recent ones are electrically heated, just like the thermo-time switch.

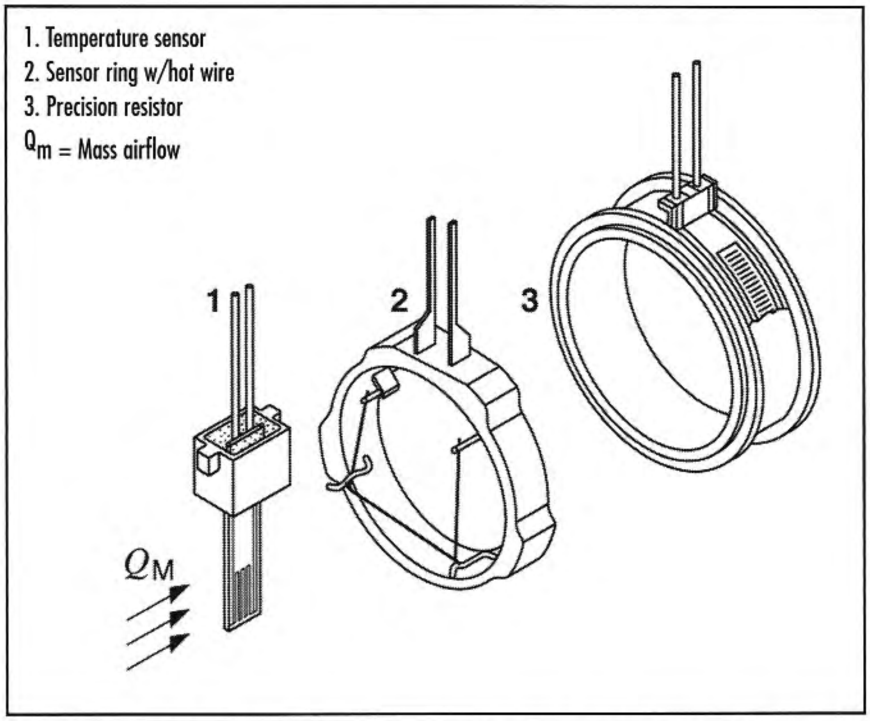
Note that unlike the idle air bypass, the auxiliary air valve merely skirts around the throttle plate; all the air passing through the auxiliary air valve has already passed through the airflow meter, and so is "counted" by the ECU. Note too that, unlike the functioning of the thermo-time switch/cold start injector which is never in operation for more than a few seconds, in very cold weather the auxiliary air bypass valve can take several minutes (though never more than eight or ten) to move from fully open to fully closed.

Warm-Up

The first 30 seconds after a cold start represent perhaps the toughest challenge to auto emissions engineers. On the one hand, considerable enrichment is needed to keep a cold engine running and to have good "driveability;" on the other hand, all the fuel in excess of stoichiometry just flushes out the exhaust, adding to HC emissions. Once a cold engine has fired, the ECU immediately cuts back on the wholesale enrichment that has been provided for starting. A much richer than nominally stoichiometric mixture is still needed, however, until the engine is fully warmed up, so instead of two to three times normal pulse time (plus whatever has been added through the cold start valve), the enrichment drops to, say, 1-1/2 times the "basic" pulse time. The ECU gradually tapers off the "post-start" and warm-up enrichment, on the basis of both time elapsed and the information from NTC II. The initial rate of this progressive leaning of the mixture toward a stoichiometric value is quite rapid, and is determined mostly on the basis of time; after about 30 seconds, the continuing reduction of fuel quantity is essentially determined by engine temperature. Even in the coldest weather, the engine will have warmed up enough for the mixture to be dialled back to near nominal values within a couple or three minutes.

Idle/Coasting "Cutoff" Switch

We have mentioned that the microswitch that signals closed (idle) throttle signals the ECU to provide a slight enrichment for idle. There are a couple of other functions for this switch on some vehicles equipped with L-Jetronic. To avoid a "stumble" during the off-idle transition, the opening of this switch—indicating that the throttle has just been opened—is used to trigger a brief additional enrichment. Also, on later vehicles, the closing of this switch when engine speed is well above an idle causes the fuel flow to be shut off entirely, to eliminate emissions (and fuel consumption) during this "overrun" situation. To prevent the engine from stalling, the fuel is turned back on again as the idle speed is approached, at an rpm that depends on engine temperature.

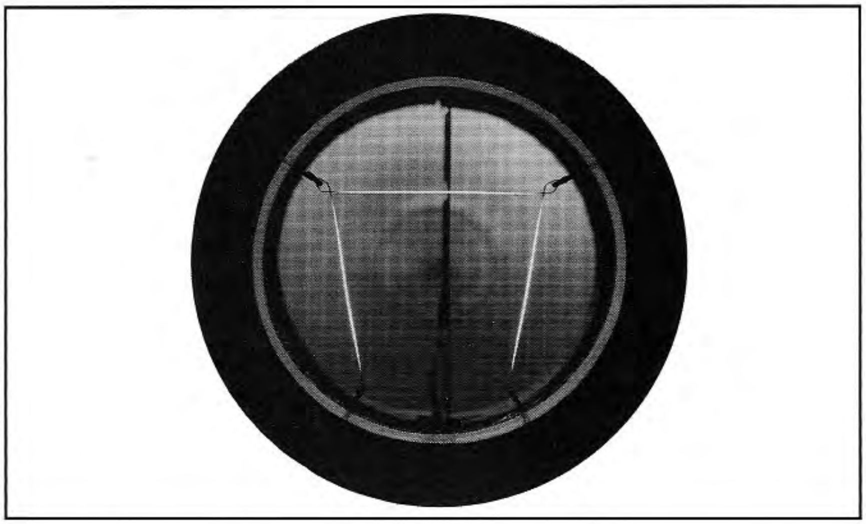


Components of the hot-wire air mass meter. (Robert Bosch Corporation)

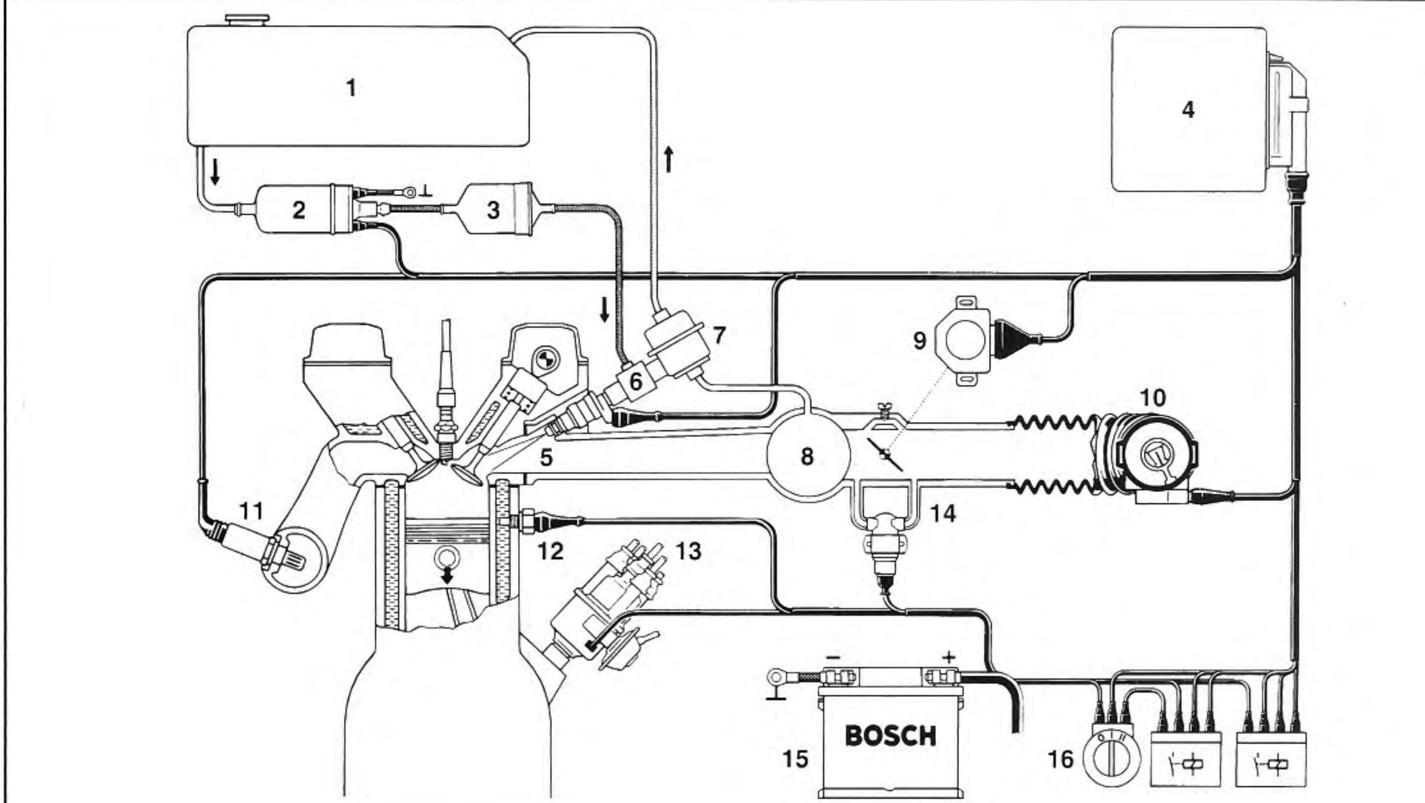
LH-Jetronic

For all that it was an advance on D-Jetronic, the L-Jetronic system was not without its own shortcomings. One of these was the need to make combined use of two separate signals—one from the airflow meter and one from NTC I—in order to compute the air mass flow. The design of the airflow meter itself might also be regarded as imperfect, depending as it does on a combination of electronic and mechanical components. While modern electronics are about as reliable as man-made systems get to be, anytime a mechanical device is interconnected with an electronic one, the mechanical bits are the most likely source of future problems. Apart from reliability issues, certain types of road disturbances can potentially "jostle" the metering vane, leading to momentarily inaccurate information coming from it. The vane-type airflow meter is also a somewhat expensive device to make.

To produce a light, compact, simple, all-electronic sensor with no moving parts that directly measures air mass, with no need for calculations relating volume flow, temperature, and density, Bosch embraced a device long used in fluid-flow laboratory work—the hot-wire sensor. Other advantages of this form of airflow sensor are its more rapid response (measured in milliseconds), and an even further reduction of the already near-trivial resistance to airflow of the vane type sensor. The adoption of the hot-wire sensor gave rise to a next-generation form of intermittent EFI called LH-Jetronic, first introduced in 1982 and used on the Volvo 2.3 liter GL model of that year. The "H" stands



Hot-wire air mass meter. The wire is so fine (less than 0.003 inch) it may only be visible when it glows red hot during its "burn-off" cycle. (Robert Bosch Corporation)



1. Fuel tank
2. Electric fuel pump
3. Fuel filter
4. ECU
5. Fuel injector
6. Fuel rail
7. Fuel pressure regulator
8. Intake manifold
9. Throttle valve switch
10. Hot-wire air mass sensor
11. Lambda sensor
12. Engine temperature sensor
13. Ignition distributor
14. Rotary idle actuator
15. Battery
16. Ignition and starting switch

Schematic diagram of an LH-system. The "H" stands for heiss—the German word for hot. Apart from the air meter itself, this is almost identical to the L-Jetronic. (Robert Bosch Corporation)

for *heiss*, the German word for hot.

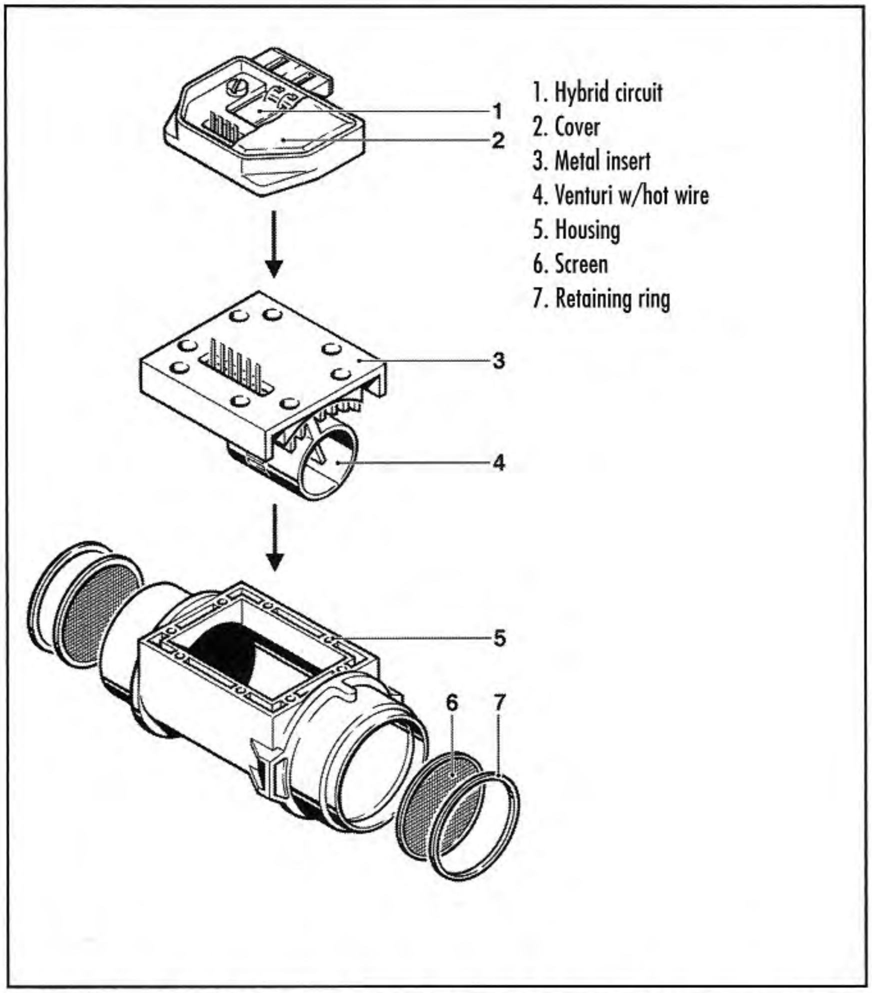
Other than the nature of the sensor itself, many of the operating principles (and a few of the components) of L-Jetronic and LH-Jetronic are held in common. The mechanical components—fuel pump, regulator and injectors—differ only in detail, if at all, and the computation underlying the fuel quantity/pulse time calculation is logically identical to that of the L-Jetronic. Note, however, that while early versions of L-Jetronic use analog electronics, all LH-Jetronic systems are purely digital. Further, all LH-Jetronic systems include lambda feedback control.

Hot-Wire Sensor

The sensing element is a very fine wire of platinum alloy, just 0.7 millimeters (less than 0.003 inches) in diameter, strung across the interior of a housing through which all the incoming air stream has to pass. The wire is heated by an electric current, but cooled by the passing air stream. An electrical circuit adjusts the current passing through the wire so as to maintain it at a temperature that is consistently 180° F above that of the entering air. Thus, if the air temperature is 80° F, the wire will be running at 260° F; if the air is at 30° F, the wire temperature will be at 210°. The current required to maintain this equilibrium is a measure of the mass of air passing the wire, and is used as the principal signal to the ECU as to air quantity.

You many wonder how the electronics "know" that the wire is 180° hotter than the incoming air. The electrical circuit referred to above is a "Wheatstone bridge," an elegantly simple form of electrical circuit, and while we will not delve into the actual electronics, the principles are not particularly hard to understand, even for the "electronically challenged." First, note that the electrical resistance of platinum varies very strongly with its temperature (it is sometimes used as a temperature detecting/controlling device, just for this reason). Second, note that, like the L-Jetronic, the LH is equipped with an intake air temperature sensor, which is itself a temperature-sensitive resistor—a thermistor—but one whose resistance varies much less with temperature than the platinum wire.

If an electrical path is divided into two parallel branches, and each branch contains a resistor, the voltage difference between the two branches, measured after the resistors, will depend on the relative values of the two resistors. Because one of those resistors—the wire—has a resistance that varies strongly with temperature, the voltage difference between the two branches will similarly depend strongly on the temperature of the wire. If the current through both resistors is changed, the wire will either heat up or cool down. At some level of current—that is, at some temperature of the wire—the two resistors will have equal values, so the voltage between them will be zero. So, by introducing a detector and amplifier that constantly adjusts the current so as to maintain the voltage between the two branches of the circuit at zero, we can be sure that the wire is some fixed temperature (in this case 180 degrees) higher than the temperature at the

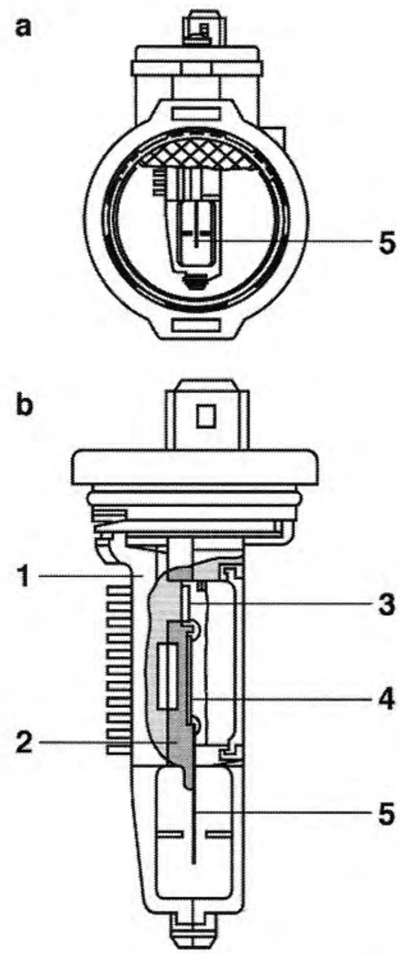


Another view of the hot-wire air mass meter, with integrated electronics. (Robert Bosch Corporation)

other resistor—the air temperature sensor. In this case, the current flowing through the circuit will be in direct proportion to the heat lost by the hot wire, which is proportional to the mass flow of air. The ECU, which supplies the current, thus "knows" what mass of air per minute is passing through the air mass sensor.

Like the L-Jetronic, early LH systems had provision for adjustment of the idle mixture strength. Unlike the L-Jetronic, however, in which the adjuster actually varies the size of the air "leak" around the flow meter, the adjustment on the LH-Jetronic is electrical in nature. The small adjuster (located under a sealed cover on the meter) is actually a potentiometer that modifies the current signal received by the ECU. Later LH-Jetronics

a. Housing
b. Hot film sensor (fitted in middle of housing)
1. Heat sink
2. Intermediate module
3. Power module
4. Hybrid circuit
5. Sensor element



The hot-film air mass meter, as used on most later versions of LH-Jetronic. This is less prone to damage than the fine wire in the earlier meter. (Robert Bosch Corporation)

omitted this adjustment.

Drawbacks

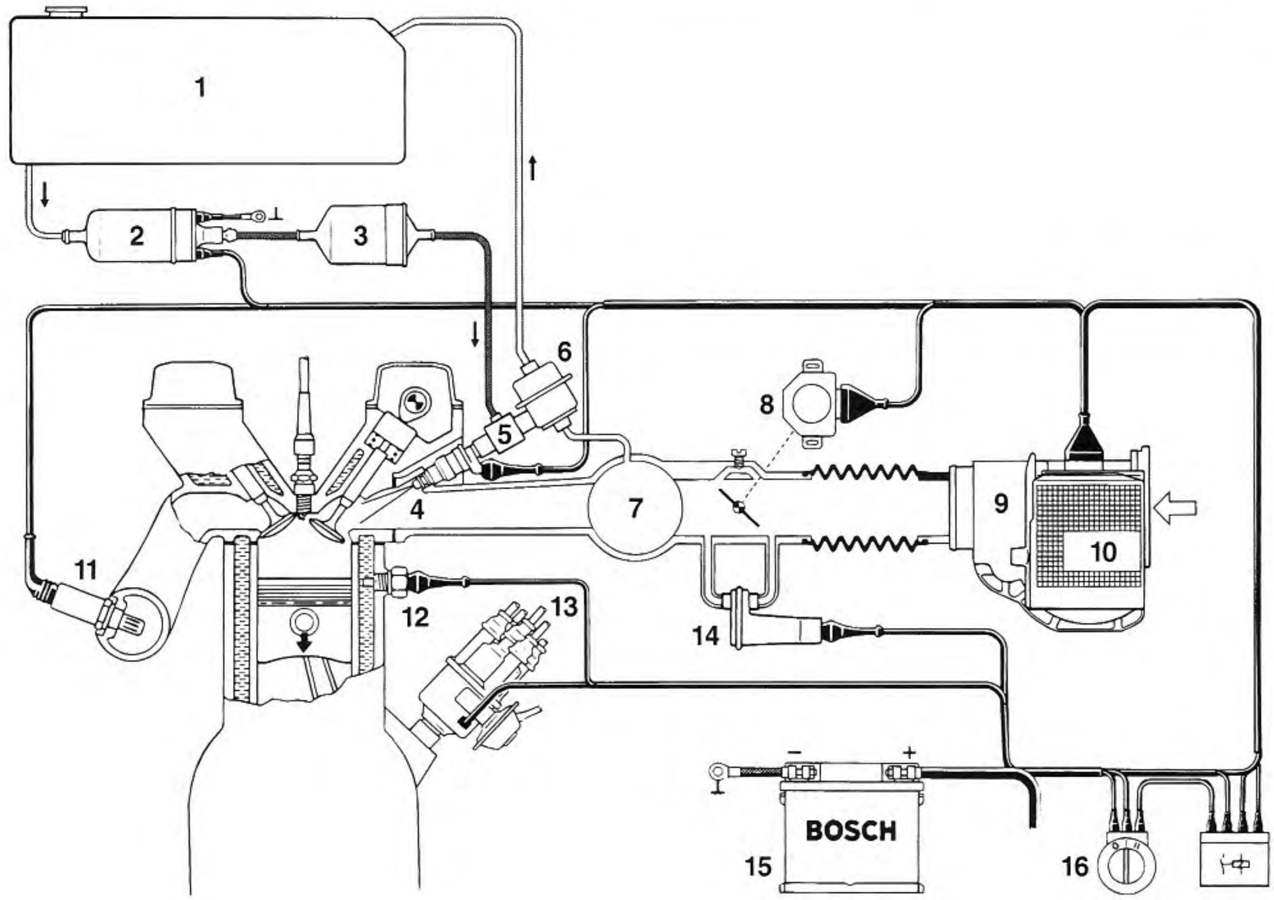
One potential problem with a hot wire as a metering element is that if its surface becomes contaminated, the rate of heat flow out of it will be reduced, in which case it would send the ECU a false signal, underestimating the amount of air passing. To deal with this, the ECU's program includes a "burn-off" cycle that feeds a much larger than normal current to the wire for about one second immediately after the engine shuts off. This brief, large surge of current heats the wire to about 1800° F, which turns it red-hot and vaporizes any dirt deposits on the wire. (The whole concept is a bit like a self-cleaning oven!)

Safety Issues—Of course, there are a couple of safety issues here—anything red-hot in close proximity to a device that meters gasoline is a potential hazard. Accordingly, Bosch provides a couple of safeguards. First, if the last reported rpm before the ignition was turned off was less than 200 rpm, then the engine was not idling, it stopped dead for some reason—and that reason might be an accident. In that case, the burn-off cycle is suppressed. Second, if the engine has not exceeded 3000 rpm since the last time the ignition was shut off, then maybe the driver just started the engine, then changed his mind . . .and maybe he will change it back again and refire the engine. Again, you don't want any chance of the engine turning over with the wire red-hot, so again the burn-off is cancelled.

In more recent versions of LH-Jetronic (and LH-Motronic—see next chapter), the hot-wire is replaced by a hot-film air mass sensor. Apart from the rearrangement of the material that forms the heated surface, the operating principle is identical to that of the hot-wire sensor. The hot-film sensor is used on most modern Audis and Mercedes, as well as some VW and BMW models.

Idle Speed Stabilization

While early versions of the LH system used the same auxiliary air valve as the L-Jetronic to help maintain a constant idle speed, irrespective of engine temperature, most LH systems use a different device for the same purpose. Like the auxiliary air valve on the L-Jetronic, this "idle speed stabilizer valve" functions by bypassing a certain amount of air around the closed (idle) throttle. (Again note that this air has passed through the hot-wire air sensor, so it is "measured" air—the functioning of the idle speed stabilizer does not affect the mixture strength. Functionally, this is exactly the



1. Fuel tank
2. Electric fuel pump
3. Fuel filter
4. Fuel injector
5. Fuel rail
6. Fuel pressure regulator
7. Intake manifold
8. Throttle valve switch
9. Airflow sensor
10. ECU
11. Lambda sensor
12. Engine temperature sensor
13. Ignition distributor
14. Auxiliary air device
15. Battery
16. Ignition and starting switch

Schematic diagram of an L3-Jetronic, having the additional control of a lambda (oxygen) sensor. (Robert Bosch Corporation)

same thing as cracking the throttle open slightly.)

While the L-Jetronic's auxiliary air valve is a free-standing piece of equipment, with no connection to the ECU, that determines for itself the amount of air that should be allowed to pass based on its own temperature, the idle speed stabilizer of the later LH systems is connected to the ECU, and the amount of air that is bypassed through it is determined by the ECU.

Instead of the auxiliary air valve's bimetal strip and electric heating element, the LH system's idle speed stabilizer is opened and closed by a rotary actuator whose position is a function of the "on time" to "off time" of a series of digital pulses coming from the ECU. The greater the on/off ratio, the further the valve opens, passing proportionally more air. The ECU, of course, "knows" the engine rpm from the frequency of the ignition triggering pulses it receives. If idle rpm drops—say, because the driver turned on something that produces a heavy electrical load, such as a rear window defroster—the ECU increases the on/off ratio of the pulses it is sending out to the idle speed stabilizer so as to bleed more air past the closed throttle to maintain an appropriate idle speed.

As with the connection with the lambda sensor, this coupling of the actions of the ECU and the idle speed stabilizer produces a closed-loop control. Because this provides direct, feedback-driven control over idle speed, the idle rpm can be set lower than when the amount of air bypassed is based on a fixed, "best guess" program. During cold starting, the ECU breaks the feedback loop, and directs the idle speed stabilizer to open a preprogrammed amount, according to temperature.

An ingenious additional feature of the idle speed stabilizer is found on some LH installations. Arguably the largest load change that an idling engine experiences is the engagement of the air conditioner compressor. This load is sufficiently large, and can commence with such suddenness, that there is a risk of the engine stalling before the stabilizer has a chance to respond. To conquer this tendency, the air conditioner controls are fed through the ECU, and when the a/c thermostat "tells" the compressor to cut in, the ECU briefly delays the actual clutching-in of the compressor, to give the idle speed stabilizer a chance to anticipate the additional load. Clever!

MUCH, OR MANY? ANALOG VS. DIGITAL

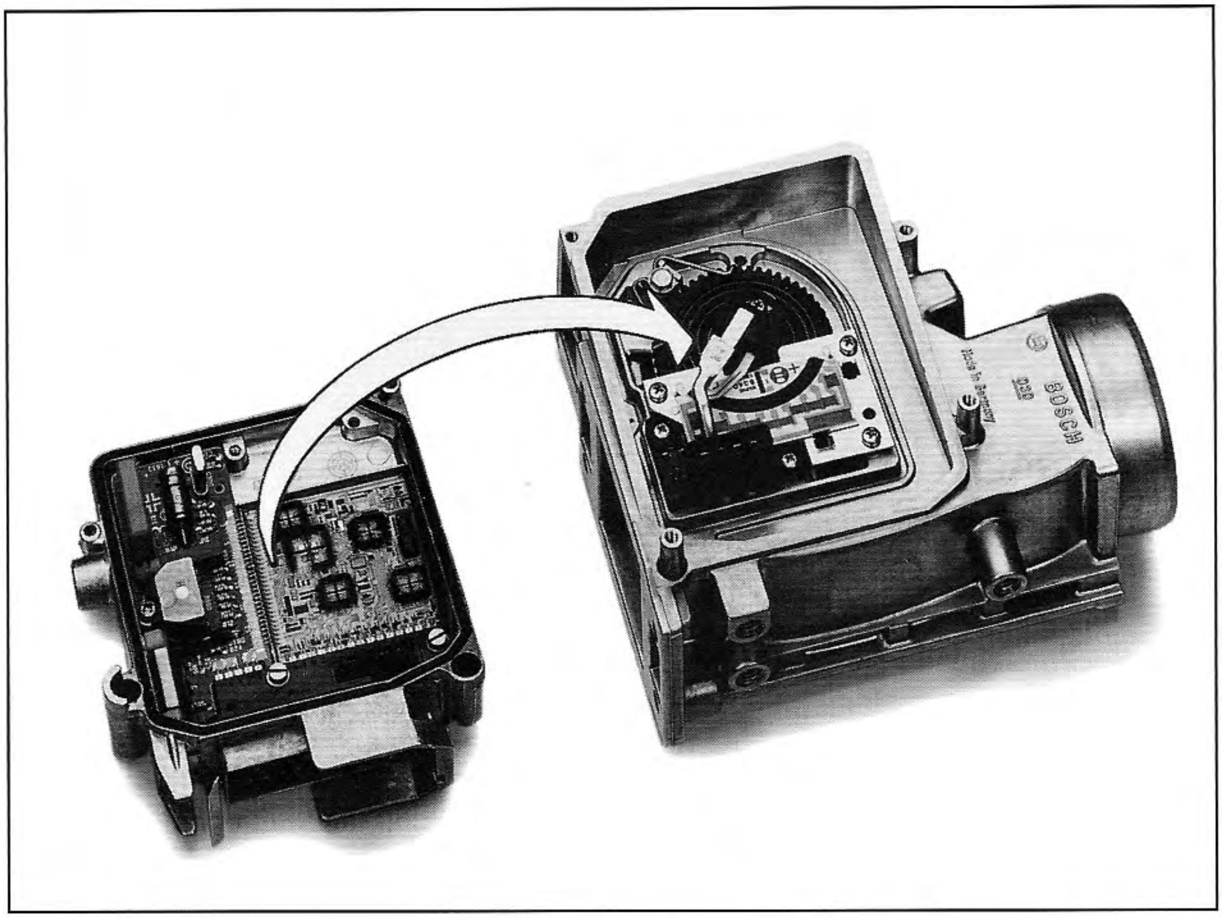
A dozen eggs, a quart of milk; a hundred bricks, a bag of cement. We gauge the quantity of some things by counting, but others we measure by weight or volume. The difference is subtle but basic—the first case involves a digital operation, the second is an analog process. Now, while one major aspect of the electronic revolution was the invention of the transistor, the shift from electronic devices that operated on an analog basis to ones that work digitally is at least equally significant.

At its simplest, a transistor can be thought of as an electronic control valve. There are three wires attached; two "in" and one "out." You feed a fixed, comparatively large amount of power to one of the inputs, and a much smaller, variable amount of juice to the second. What comes out of the third wire may vary from zero up to the full supply voltage, depending on the size of the signal (the voltage) coming in on wire number two. The special-purpose computers that comprised the "brain box" of early electronic fuel injection systems used transistors in this way—as proportional devices. A sensor—say for engine coolant temperature—was hooked (in principle, at least) to the input of a transistor. Variations in engine temperature would thus directly alter the output, which in turn controlled the "on time" (pulse time) for the injector(s), adjusting the mixture strength according to whether the engine was cold, cool, warm, or hot.

But if you fix the "signal" voltage at some comparatively high value, then a transistor will operate more like a solenoid relay—if the input at the signal terminal is "on," the transistor puts out; if the signal voltage is "off," so is the output. That makes the transistor function as a digital device. On the face of it, it seems a shame to waste the ability of a transistor to work proportionally, but this digital way of doing things has the enormous advantage that now you can use transistors to create an electronic memory. String a few of them—say sixteen—together, and by having some of them "on" and others "off," you have 256 (16 x 16) possible arrangements. Each arrangement might then correspond to one of 256 different values along the cold-hot continuum.

Part of the attraction of operating digitally is the unambiguous result you get when you count things. One plus one always equals exactly two, but when you add "some" and "some," you surely get "more," but you cannot be sure you have twice as much. Even slight variations in components—whether from production tolerances, or from aging, or heaven knows what—would mean corresponding variations in the electrical outputs. Air/fuel ratios controlled by those electronics would then be slightly (or perhaps wildly) in error. Doing things digitally means that a given sensor input (coolant temperature equals 86° F, say) would correspond to "coolant temperature value #47," for example, and "#47" stored in the digital memory would correspond to an injector pulse lasting so many milliseconds.

The opportunity to make use of a memory also means that many more combinations of factors can be taken into account in the process of determining the pulse time of the injectors, and thus mixture strength. Thus, the appropriate amount of fuel for a certain engine speed and load when the coolant is at 86 degrees and the air temperature is 75° F is likely to be different from the same situation but with an air temperature of minus 10° F. And when ignition control gets added in—as with the Motronic systems—the complication becomes unmanageable without a digital memory.



The air meter of an L3-Jetronic. Use of digital electronics and advances in component miniaturization permit integrating the ECU into the body of the air meter itself. (Robert Bosch Corporation)

4 MOTRONIC ENGINE MANAGEMENT

In many of the very earliest internal combustion engines ignition was by means of a "hot tube" igniter. The tube, usually made of porcelain, was located immediately outside the combustion chamber, and was continuously heated by a small gas flame that made it glow red hot. As the piston approached top center on the compression stroke, a timing valve opened, exposing the contents of the combustion chamber to the hot tube, which lit (sometimes) the combustible mixture in the cylinder. Motoring accounts written around the turn of the century make frequent reference to stoppages resulting from the flame blowing out!

By the early 1900s the days of hot tube ignition were over, and the automotive world embraced ignition by an electric spark. As is common with emerging technologies, there was a bewildering proliferation of designs at first, but there were really only two general categories: magnetos of various types, and systems based on an induction coil. Magnetos eliminated the need for a battery—in those days a fragile device, and even heavier than today's batteries—and so became almost universal on race cars, motorcycles, and aircraft. Induction coil systems offered the advantage over magnetos of improved ignition at low speeds, but required an on-board source of low voltage—a battery. As electric lighting (and, later, electric starting) became widespread, the battery was seen as less of a liability, and design rapidly converged toward the coil and breaker system designed in 1911 by Charles Kettering. This "Delco" system—named after the Dayton Electric Company, founded by Kettering—rapidly became almost universal after its introduction on GM cars in 1922, and remained so for more than half a century, through the early 1970s.

Coil and Breaker Ignition

An induction coil consists of a central core of soft iron surrounded by two separate windings of copper wire. One of the windings, called the "primary," consists of a small number of turns (typically a couple of hundred) of comparatively thick wire; the other, called the "secondary," consists of a much larger number of turns of much finer wire. At one end, the primary winding is connected to the "hot" lead of the electrical source, while the other end is grounded, at least most of the time. The secondary winding shares the primary's connection to the "hot" lead of the battery; the other end is connected to the spark plug's center electrode, via the distributor cap and rotor.

When current flows through the primary winding, a magnetic field is created in the core—the coil is said to be saturated—and this field is maintained as long as current is flowing. But if this flow then suddenly stops for any reason, the magnetic field in the core collapses, and the stored magnetic energy "induces" a burst of electricity in the secondary winding, hence the name "induction coil." The interruption of the current flow is accomplished by the breaker points. While the primary circuit nominally operates at just twelve volts, the induced secondary voltage is a thousand or more times higher than that—sufficient to jump the gap in the spark plug. Notably, the collapse of the core's field also induces a high voltage in the primary windings, which thus momentarily experience a surge of perhaps a couple of hundred volts.

Transistorized Ignition

For passenger cars, the "Kettering" system worked adequately well—though only just. (At the very least, it was an advance on hot bulb ignition!) The major catch was the need for regular maintenance, but there were other drawbacks as well.

One limitation of the coil and breaker system is the current-switching capacity of the points—a primary current of more than 5 or 6 amps will tend to cause burning and arcing at the points, shortening their life. This, in turn, places a restriction on the strength of the magnetic field that can be stored in the coil, which limits the amount of power available to fire the plug.

Dwell

Another problem is the business of *dwell.* With the traditional cam and breaker arrangement, the primary has current flowing through it for a certain fixed number of degrees of crank rotation, but the corresponding length of time that the current is flowing thus varies with engine speed. This leads to a dilemma: If you keep the dwell angle small, the coil will have insufficient time to become fully saturated at high engine speeds, leading to misfiring at high rpm; but if you arrange for a longer dwell time, say by using a distributor cam with a different lobe shape, so the points spend more time closed and less time open, then at low speeds the primary becomes saturated early in the cycle, but then the current keeps flowing because the points are still closed, and the coil will tend to overheat.

Finally, the fiber rubbing block on the moveable half of the point set slowly wears down, which causes it to contact the cam ever closer to the peak of the lobe, so the points open progressively later, and the ignition timing gets more and more retarded. We will soon discuss the importance of this issue of spark timing.

These first began to emerge as serious problems during the 1960s, when manufacturers were heavily engaged in a horsepower race. Compression ratios over 12:1, combined with engine speeds over 6000 rpm, tested the upper limits of coil and breaker ignition, and it became clear that the days of the classic Kettering/Delco system were numbered. Ironically, what finally ensured the emergence and universal adoption of modern electronic ignition was not street hemi's and other monster motors, but rather the introduction of emissions legislation, in the 1970s. Though compression ratios tumbled and revs dwindled, the need to fire very lean mixtures, and to do so reliably throughout the life of the car, became the new factors that finally eliminated contact points. When you are scraping to meet standards for the emission of hydrocarbons you cannot afford even one misfire in ten thousand, and when you have to certify the engine's emissions for 50,000 miles without a tune-up, you need a system that does not depend on breaker points, and one that can still fire a spark plug when its gap has eroded open to 50 thou or more.

The solution that was eventually adopted retained the familiar induction coil, but eliminated the problems of contact points by eliminating the points themselves. Instead of a mechanical switch to turn on and off the current flow in the primary windings of the coil, the switching is done electronically. The distributor cam is replaced by a rotating magnet, having a number of teeth or "poles" corresponding to the number of cylinders. As each pole passes a fixed pickup head, a small pulse of electricity is produced. That pulse is then used to trigger a transistor—an electronic relay—that briefly interrupts, then quickly restores, the current in the primary winding of the coil.

Compared to a conventional Kettering system, there are two major advantages to this scheme. First, the constant wear on the rubbing block is eliminated, so timing remains accurate and no adjustment or replacement is ever needed. Second, when you remove the concern over the amount of juice you can put through the points, the current in the primary circuit can be dramatically increased, so the coil can be redesigned to provide a greater secondary voltage output that can fire a plug with a gap that is larger, whether by design or as a result of wear, without the risk of frying the points. As long as there is enough juice to jump the gap, a wider plug gap provides a bigger spark that is more likely to light the mixture in the cylinder. (The belief that "the mixture doesn't care if it's lit by a match or by a blowtorch" is mistaken; the amount of energy in the spark does matter.) The same increase in potential output from the coil also means you can fire a plug that has some additional insulation, beyond the air gap, between its electrodes, such as one that is fouled. The potentially higher energy output of a modern electronically switched coil will light the fire in such an engine when a points type system would not.

The "brains" of an electronic ignition system makes this possible without risking overheating of the coil because it can, in effect, vary the dwell angle. At low engine speeds, a timing circuit in the electronics delays restoring the primary current until it judges there is just enough time remaining to saturate the core. At higher speeds, it tries to keep the dwell time nearly constant, allowing primary current to flow during a larger number of crank degrees. This feature, together with freedom from the current limitations of breaker points, is what permits the redesign of the coil to give potentially more secondary output, without cooking it through an excessive primary current. But beyond the potential for greater spark energy, and near bulletproof reliability, electronic triggering of ignition also makes it possible to use electronic control for the timing of the spark.

Ignition Timing

We explained in Chapter 1 that the combustion event, while extremely fast, is not an instantaneous explosion that takes place the moment the plug fires; rather, it is an occurrence that takes some time. Indeed, as a very rough first approximation, we can say that at any given load, the time taken by the combustion event is pretty much constant, over a considerable range of engine speeds. What that means, however, is that the combustion event occurs over a variable range of crank angle, the variation depending on the rpm.

Now, if the spark was arranged to occur exactly at TDC, then the engine might run satisfactorily at very low speeds, but as the rpm's increase, the combustion would lag farther and farther behind the piston movement, reaching the point where the fire was just barely getting started at the moment the exhaust valve opened, so most of the energy would just get flushed down the pipe. This, clearly, is no good for power output, fuel economy or emissions. Thus, real world engines incorporate a degree of ignition advance—the spark occurs before the piston reaches TDC. And because of the fixed-combustion-time/variable-engine-speed relationship, that advance is usually arranged to be variable—less advance at low speeds; more at high speeds.

Limits and Complications

Of course, there are limits, and there are complications. As to limits, if the spark occurs too soon, the pressure will have risen so high by the time the piston reaches TDC that the pressure opposing the rising piston negates much of the power delivered later, when the piston is on its way back down on the power stroke. Also, an advanced spark means that the pressure of the early stages of combustion add to the pressure rise caused as the ascending piston squeezes the combustion chamber contents ever smaller, and we saw in Chapter 1 that the uncontrolled combustion called detonation is initiated by excessively high temperatures and pressures during these early phases of combustion. Thus, excessive spark advance leads to detonation. Finally, the assumption that combustion takes a fixed length of time, even at constant load, is only valid at moderate engine speeds. In fact, at high speeds the increased degree of turbulence in the combustion chamber, both before ignition and during the early stages of combustion, increases the speed of combustion and so the requirement for an ever increasing advance with rising rpm levels out at some point, beyond which the appropriate amount of "spark lead," as it is called, is more or less fixed.

As to complications, all of this discussion refers to an engine at constant load, and real engines don't work under those simplified conditions. A larger load at a given speed means the throttle is open wider, so a greater mass of air/fuel mixture will be inhaled, so the pressure in the cylinder near the end of the compression stroke will be higher. Thus to avoid detonation, increased load calls for less ignition advance.

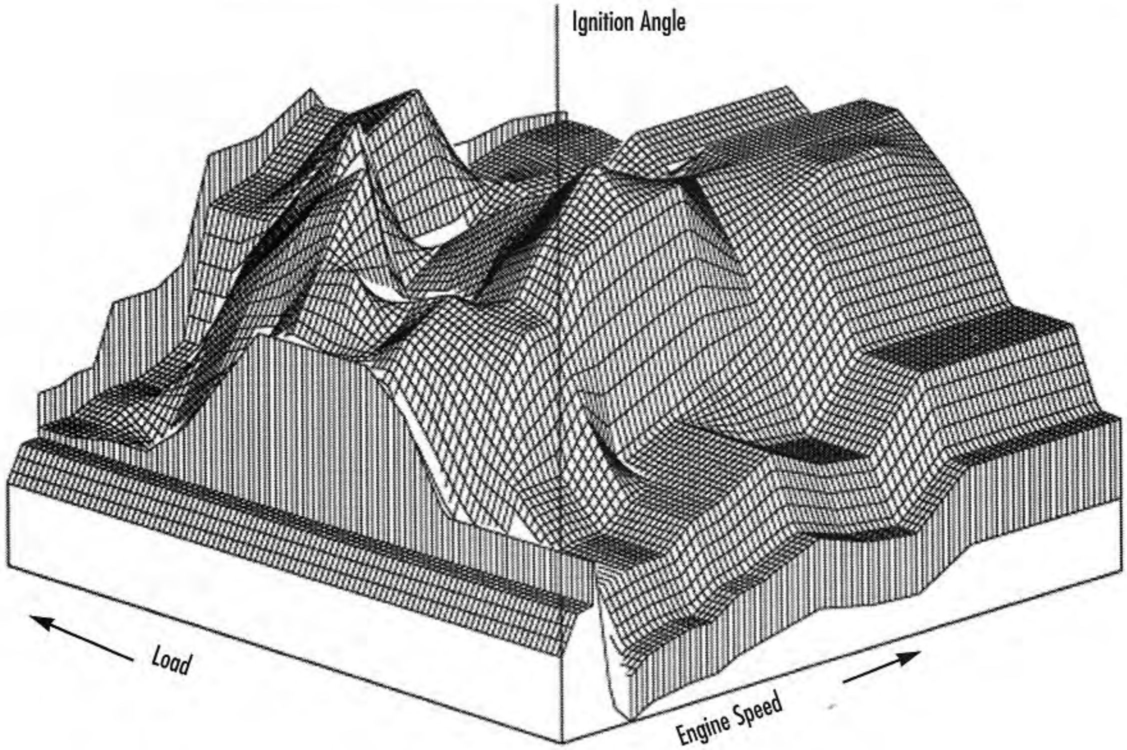
In the old days of "flintlock" ignitions, the variation of advance with rpm was handled by a centrifugal advance mechanism. This comprised a set of weights spinning within the distributor body that were flung further outward as speed increased and so, through a system of links, rotated the plate on which the points were mounted, relative to the position of the cam that opened them.

Vacuum Advance Mechanism

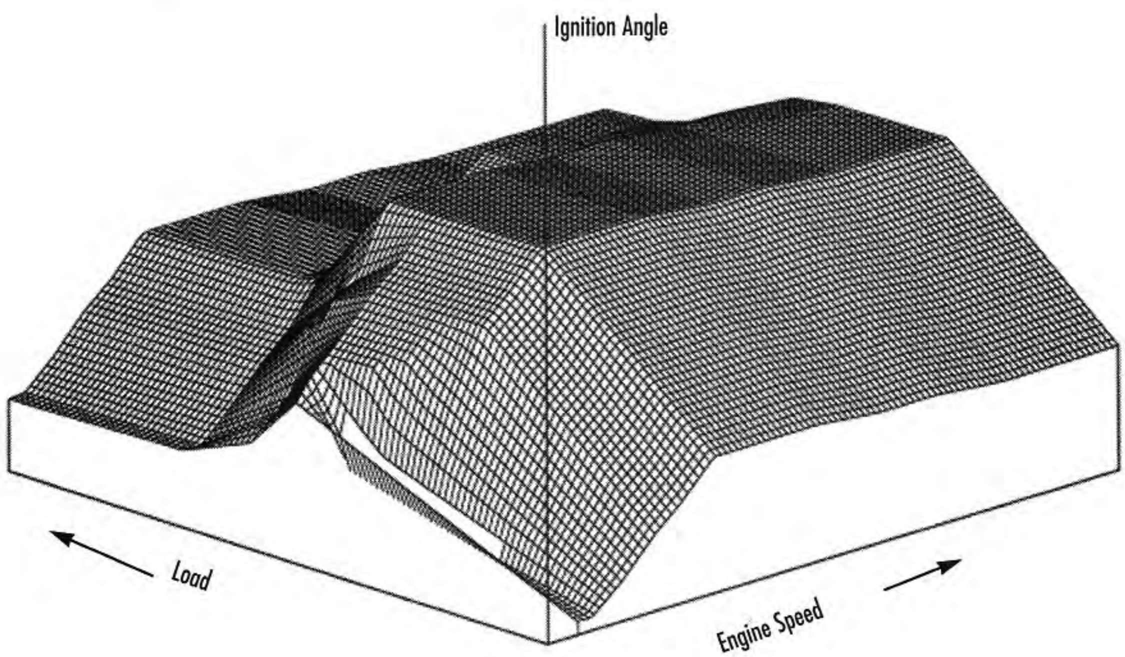
The reduction in advance called for by an increase in load was provided by a vacuum advance mechanism. (The name is potentially confusing; while it did in fact increase advance in response to high manifold vacuum, its function was really to retard the spark when vacuum was low, indicating a high load.) The vacuum advance generally took the form of a chamber containing a diaphragm that had one side exposed to manifold vacuum and a link connected to the other surface that, like the centrifugal weights, swiveled the distributor plate (although this motion opposed that caused by the weights).

Asking mechanical devices like these to balance all the variables that determine optimum spark advance is, of course, asking too much. Accordingly, soon after the introduction of electronically triggered ignition—generally called transistorized ignition—the task of timing the spark was sometimes also entrusted to the "black box." Because the centrifugal and vacuum advance mechanisms were eliminated from the distributor, leaving simply the rotor and cap to direct the spark to the appropriate plug, the distributors on engines equipped with such electronic ignition have a stumpy, squat appearance. We are terming this as electronic ignition, to distinguish it from transistorized ignition, described above. Note that this is not quite the same thing as distributorless ignition, in which the rotor and cap are eliminated and a separate coil provided for each plug, individually triggered by the ignition "black box." Bosch introduced a true distributorless system like this in 1990, with the Motronic M3.1. BMW was the first to use this on its in-line, 4 valve per cylinder in-line six, and on 2.0 and 2.5 liter four cylinder engines, as used in both 3- and 5-series cars.

Apart from eliminating the potentially troublesome mechanical components, and beyond the fact that electronics also respond much faster than the old fly-weights and vacuum diaphragm arrangement, electronic control over spark timing meant that these ignition systems could (at least potentially) calculate the appropriate amount of spark advance based on many more factors than simply rpm and manifold vacuum. These additional factors include the rate of change of load and/or speed, coolant temperature, battery voltage, and speed of starter cranking, among others. Some sophisticated dis-



Motronic ignition advance (top) compared with map of a conventional mechanical system (bottom). Electronic control over ignition timing, based on numerous inputs, permits finer and much more detailed control over spark advance, maximizing performance without risking detonation. (Robert Bosch Corporation).



1. Additional program memory

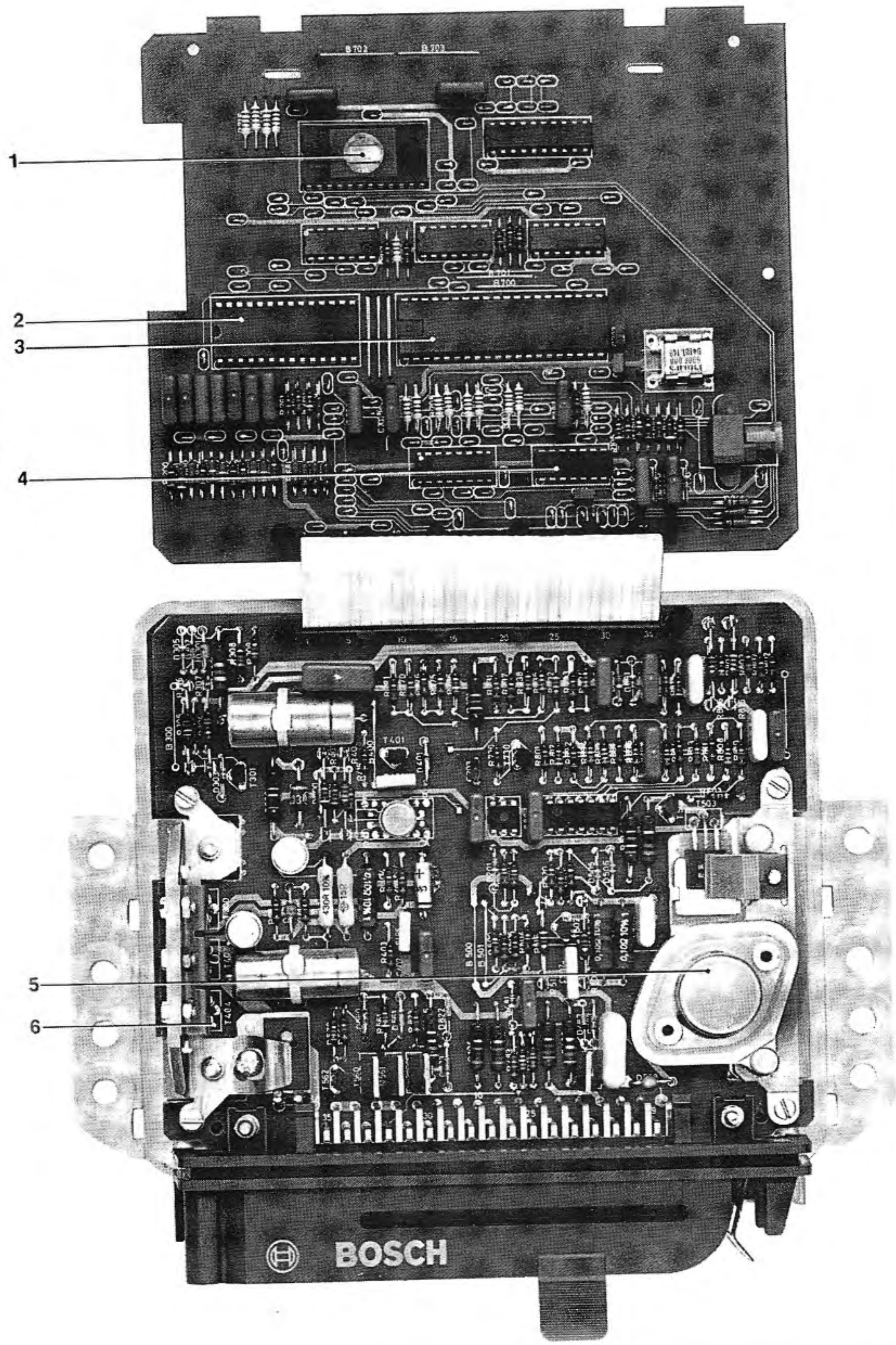
2. Analog digital converter

3. Microcomputer for standard program and data

4. Integrated circuit for engine speed and reference-mark signal processing

5. Ignition output stage

6. Fuel injection output stage



Because the ideal ignition advance depends on mixture strength, and vice versa, optimum results can only be achieved with integrated control over both ignition timing and fuel injection. This is what the inside of the "black-box" that does it looks like. (Robert Bosch Corporation)

tributorless ignitions do, in fact, use these inputs to tailor the spark advance, and further accept signals from a knock sensor, to retard the spark when detonation is detected—see the sidebar "Knock, Knock?."

Motronic Engine Management

It may already have occurred to you that most or all of these sensors already form parts of the D/L/LH-Jetronic EFI systems. By integrating the ignition and fuel injection "black boxes," we should expect, at the very least, to wind up with a lighter, simpler and more compact arrangement than if each system were to operate completely independently. Merged systems like this are the basis of Bosch "Motronic" engine management. The expected packaging advantages are realized, but there is much more to it than that, because the ideal amount of spark advance also depends on the air/fuel mixture strength, and vice versa. Only when the ignition and EFI electronics are enabled to talk to each other can both spark timing and mixture strength be optimized together to achieve the best compromise amongst torque, driveability, economy, and emissions under all engine operating conditions.

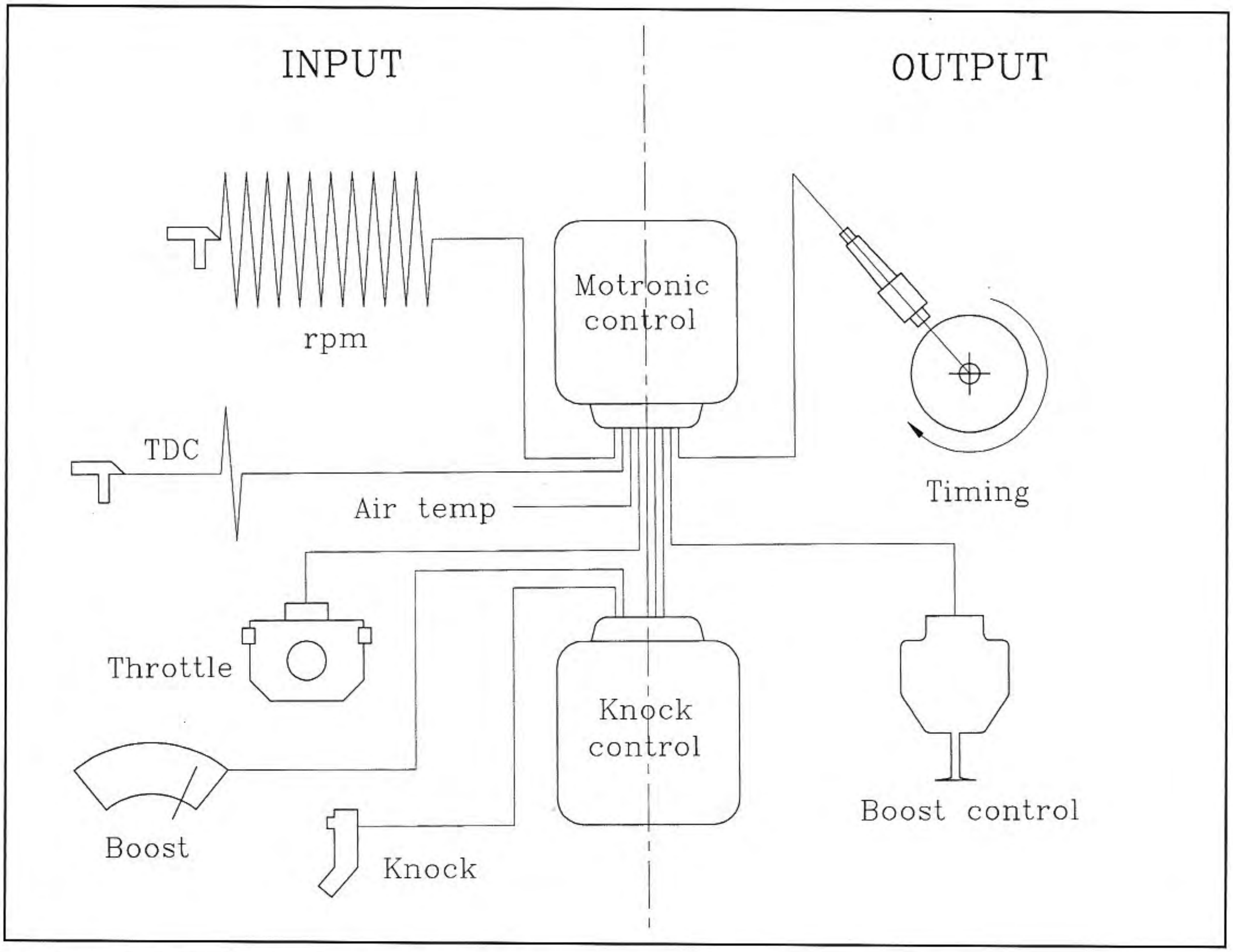
Engines operating at light loads and high speeds can tolerate a lot of ignition advance without detonating; indeed they work most efficiently that way, as the existence of the vacuum advance unit on traditional distributors confirms. The reason for this is that the rate of pressure rise in the combustion chamber after ignition depends, among many other things, on the density of the air/fuel charge. With the small throttle openings that correspond to light load, the mass of mixture trapped in the cylinder is small—its density is low. If, at that same high engine speed, the throttle is opened wider, the manifold pressure will rise (that is, the vacuum will drop), the density of the charge in the cylinder will increase, the flame will spread more rapidly once ignited, so less advance is called for.

Experiments have shown that the rate of the chemical reaction during the very earliest stages of combustion is fastest when the air/fuel mixture is near stoichiometric, and that it slows down quite distinctly with either leaner or richer mixtures. Because detonation is very much a time-sensitive phenomenon, optimum spark advance thus also depends strongly on mixture strength. With most pump gasolines, a mixture slightly richer than stoichiometric (around the air/fuel ratio that gives maximum power) will generally increase the tendency to detonate, and so would call for less timing advance. Paradoxically, the same engine is likely to tolerate more advance without detonation if run either very rich or with mixtures leaner than stoichiometric.

When a three-way catalytic converter is used, however, the mixture must be kept stoichiometric within very close limits for proper functioning of the converter, and this tight control is provided by an oxygen sensor (lambda sensor) feeding information back to the EFI computer in closed-loop control. All Motronic systems have a lambda sensor, so if this ensures that the mixture is always stoichiometric within a few tenths of a percent, there might seem to be no point in taking mixture strength into account in calculating spark timing. This would be true if the system were always operating in closed-loop mode, but note that both L-Jetronic and LH-Jetronic revert to open loop operation during cold starts, warm-up, full throttle operation and sometimes, transiently, during acceleration.

Cold Start and Warm-Up Ignition Timing

While the optimum ignition timing for an idling engine might be several degrees advanced from TDC, in a stone-cold engine being cranked at very low rpm, any advance at all may cause the piston to be driven backward, possibly damaging the starter drive, and certainly preventing the engine from



In early versions of Motronic, the knock sensor/control function was physically separated from the main ignition/injection ECU. The principal remains the same.

starting. The very bottom end of the engine's speed range—cranking and idling—thus presented an insoluble dilemma to engine designers in the days of mechanical distributors, because the speed was so low that the centrifugal advance mechanism could not respond to the comparatively slight difference in rpm between cranking speed and idle speed.

Faced with these same conditions, Motronic will retard the spark to approximately TDC during slow cranking, then immediately dial in a few degrees of advance as soon as the engine fires (which the ECU "knows" because the rpm rapidly builds, and the starter becomes disconnected). As with L- and LH-Jetronics, a much richer than normal mixture will be supplied to a just-fired-from-stone-cold engine; the Motronic system goes further and provides more spark advance, which will raise the otherwise too-low idle speed of a cold, rich-running engine. On the other hand, an engine being started at a higher temperature will be given a small amount of initial advance during cranking, as this helps starting. Motronic makes this "judgement" based on both temperature and cranking rpm.

Idle Speed Adjustments

Although all Motronics are equipped with some form of idle speed stabilization, whether the thermostatically controlled auxiliary air bypass of the L-Jetronic or the ECU controlled idle speed stabilizer valve of the LH-Jetronic, these devices are somewhat slow in response. The Motronic system continuously and almost instantly "fine tunes" variations in idle speed away from the ideal by slight adjustments in spark advance—a little more advance will speed up the idle; a little less will slow it down. This ability to tightly control spark advance at idle reduces the amount of mixture richness needed.

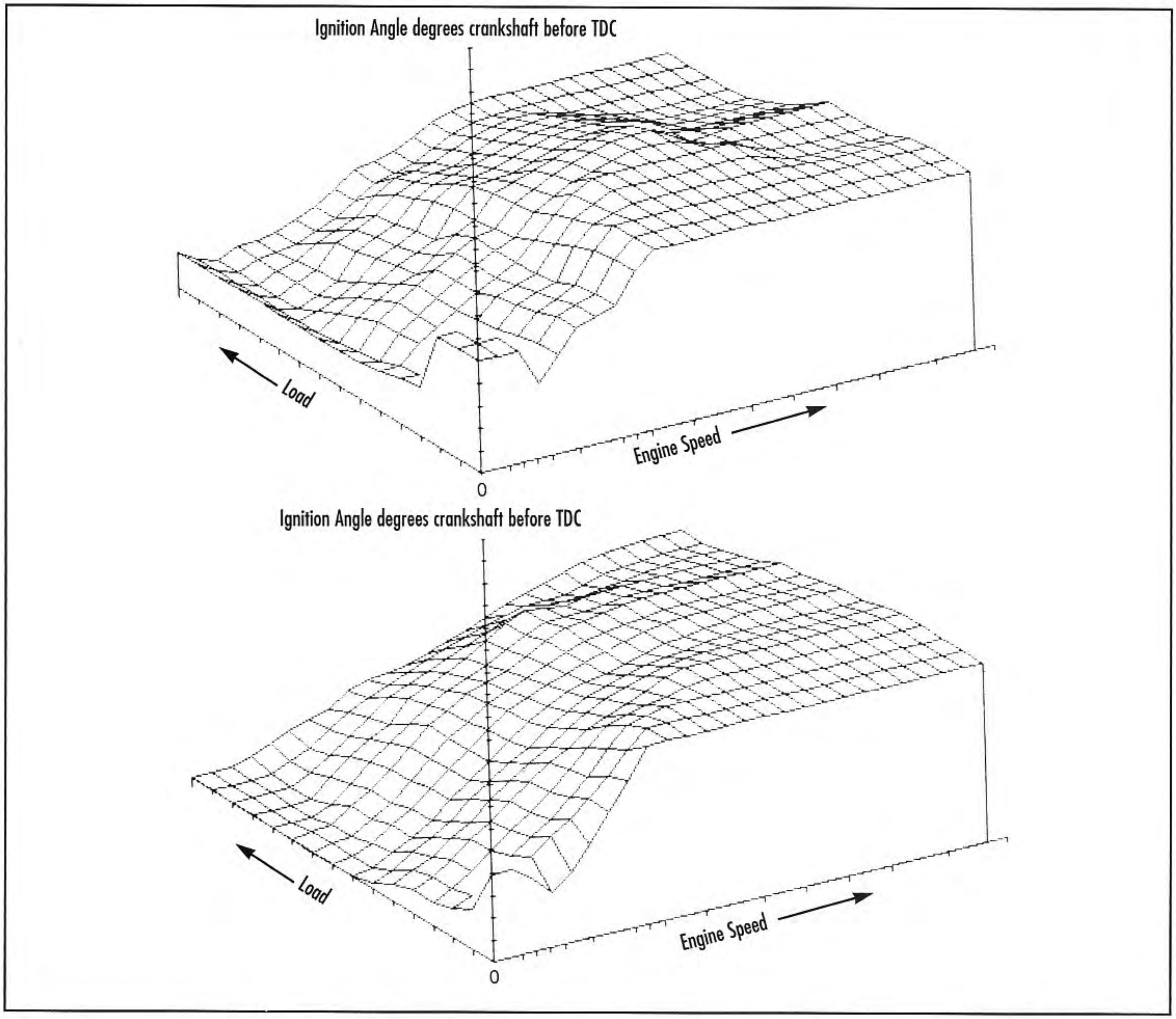
After startup and during the initial warm-up phase, until the lambda sensor becomes hot enough to provide meaningful signals to the ECU, the system will operate open loop for a certain length of time, according to the temperature and time elapsed since starting. During this time, the spark advance and fuel injector pulse time will be gradually adjusted toward the "nominal" values stored in the ECU's memory, but always with each taking account of the other. An added subtlety here is that the ECU will retard the spark, relative to the nominal value for the circumstances, in order to raise the temperature of the exhaust gasses and so aid a rapid warm-up of both the lambda sensor and the catalytic converter.

Once fully warmed up, mixture strength for most driving is thereafter maintained at stoichiometry by the ECU, in concert with the lambda sensor. Ignition advance will be constantly adjusted according to airflow (and thus load), rpm, injected fuel quantity, coolant temperature, air temperature, the output of the lambda sensor, and, on engines so equipped, signals from a knock sensor. The ECU also takes into account how quickly load and speed are changing. When the rpm and airflow signals from the flow meter indicate part throttle acceleration, for example, the spark will be retarded slightly, to avoid the knocking that would otherwise occur during this transient phase if the timing advance is just below the detonation limit for the immediately previous (and immediately following) steady-state conditions. But note that sudden changes in engine operating conditions might call for equally rapid changes in ignition timing, and the ECU is quite capable of that. Such abrupt changes in spark advance, however, would sometimes lead to a jerky response by the engine, so the ECU, in fact, smoothes the transition by spreading the adjustment over a few engine cycles. At the same time, ignition dwell—the length of time that primary current flows in the coil—is also continuously optimized.

The way all this is achieved gives some idea of the blinding speed at which all these electronic calculations are carried out within the ECU. Based on the firing of the immediately previous cylinder and the rpm, the time available until the next cylinder reaches TDC is calculated, and the appropriate amount of spark advance for the prevailing conditions is looked up in the internally stored maps. A suitable time interval for coil saturation is computed next (with a correction for the battery voltage—low voltage will start the process earlier), and the current to the primary side of the coil is turned on at a moment that anticipates its interruption an instant later, when the ECU will open the primary circuit, causing the spark. It is worth bearing in mind, here, that in an eight cylinder engine turning 6000rpm, the interval between two consecutive sparks will be just 0.025 seconds! As an added feature to prevent overheating the coil, the primary current is shut off if the engine is stopped with the ignition on.

Knock Sensor Functioning

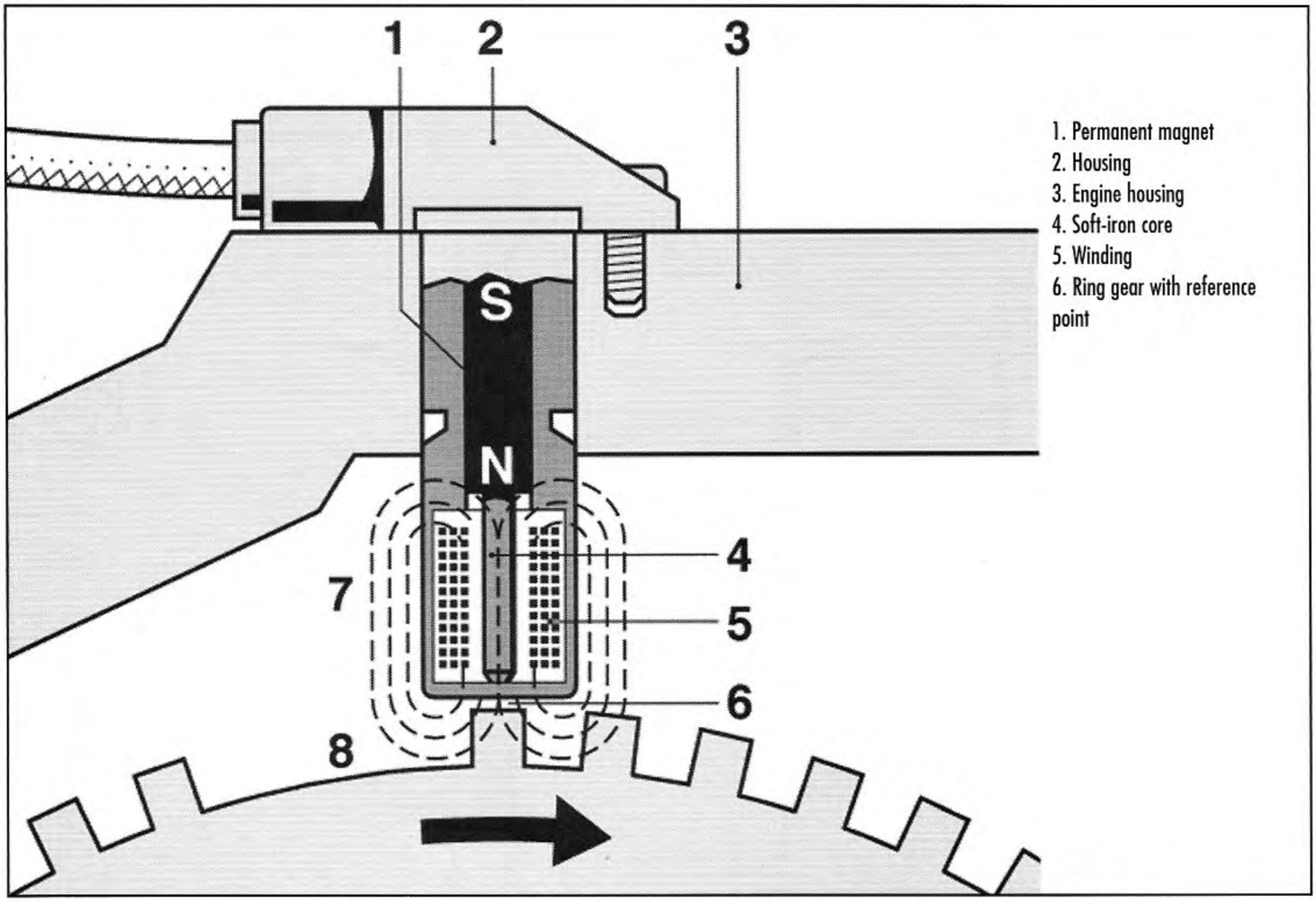
Use of knock sensing allows the basic, open-loop spark advance map in the ECU to be biased toward a bit too much advance.



Some Motronic systems have two sets of ignition timing "maps." A typical one for premium fuel is at the top; below is one for regular fuel. If the knock sensor still reports detonation even though the ignition is retarded as far as "premium" map says it should be, then the system switches to the map for "regular" fuel. Only performance suffers, not the engine. (Robert Bosch Corporation)

When knock is detected, the spark is retarded a little while the circuitry "listens" again. If knock is still detected, the timing is retarded a little further. If not, the advance is cranked up a little, until knock is again heard. Thus, the engine is always operating on the brink of detonation, but the knocking is always held at a point where it is just detectable to the electronics, but inaudible to the human ear, and perfectly safe for the engine.

In some cases, two sets of internal map are provided. One is programmed for regular fuel, the other for premium. If the ECU determines that the reduction of advance needed lies well off the premium fuel map, it switches to the other one. Thus, the owner of a car that calls for premium fuel can buy a tankful of the nastiest, cheapest sort of regular and suffer nothing worse than a reduc-



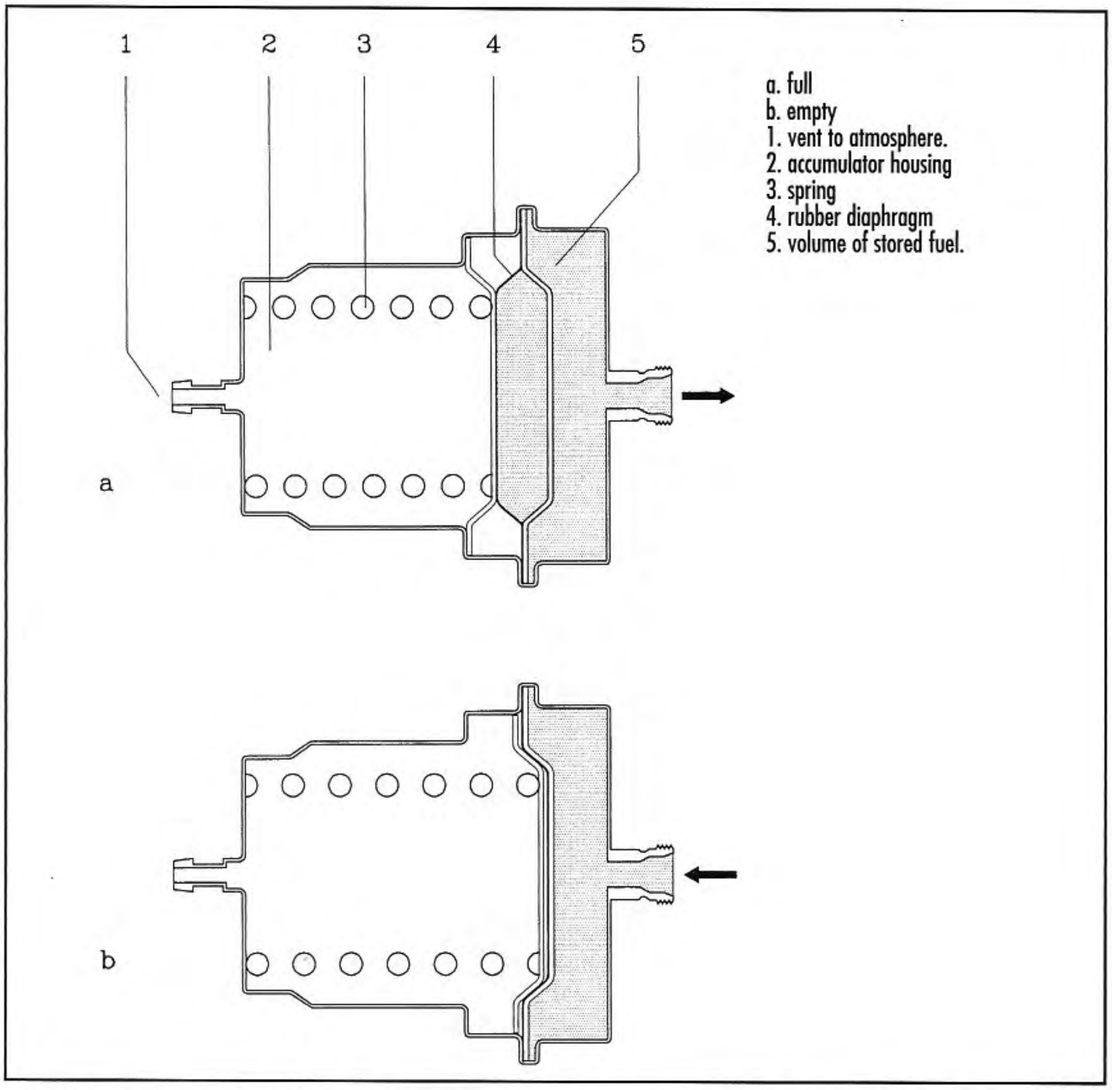
Engine speed sensor—essential for the kind of precision control offered by Motronic systems. (Robert Bosch Corporation)

tion in performance, resulting from the knock sensor/ECU backing off the advance to keep the engine from making buckets-of-bolts noises.

Again, the speed with which all this adjustment of spark lead happens is mind-boggling. There is always one cylinder that knocks first, but because the ECU "knows" the crank angle at any instant, it "knows" which one it is, and can retard the spark for that cylinder alone, while dialing up more advance for the next one! And note that even though many other changes in spark timing are phased in comparatively gradually by the ECU, the onset of knocking will be acted on instantly.

Triggering

High precision control of ignition timing, as just described, demands at least equal precision in detecting the crank angle. For that reason, Motronic systems detect crankshaft angle directly at the crank, rather than from a camshaft or other half speed shaft, such as the distributor drive, where gear (or chain or belt) "backlash" can introduce errors, both fixed and variable. In many cases, it is the movement of the flywheel itself that is gauged, with a magnetic sensor that "reads" the ring gear teeth going past. This provides a finely detailed rpm signal—there are a lot of teeth, and each one provides a little "blip"—so detailed, in fact, that the ECU is able to detect a change in speed after just a few degrees of crank rotation.



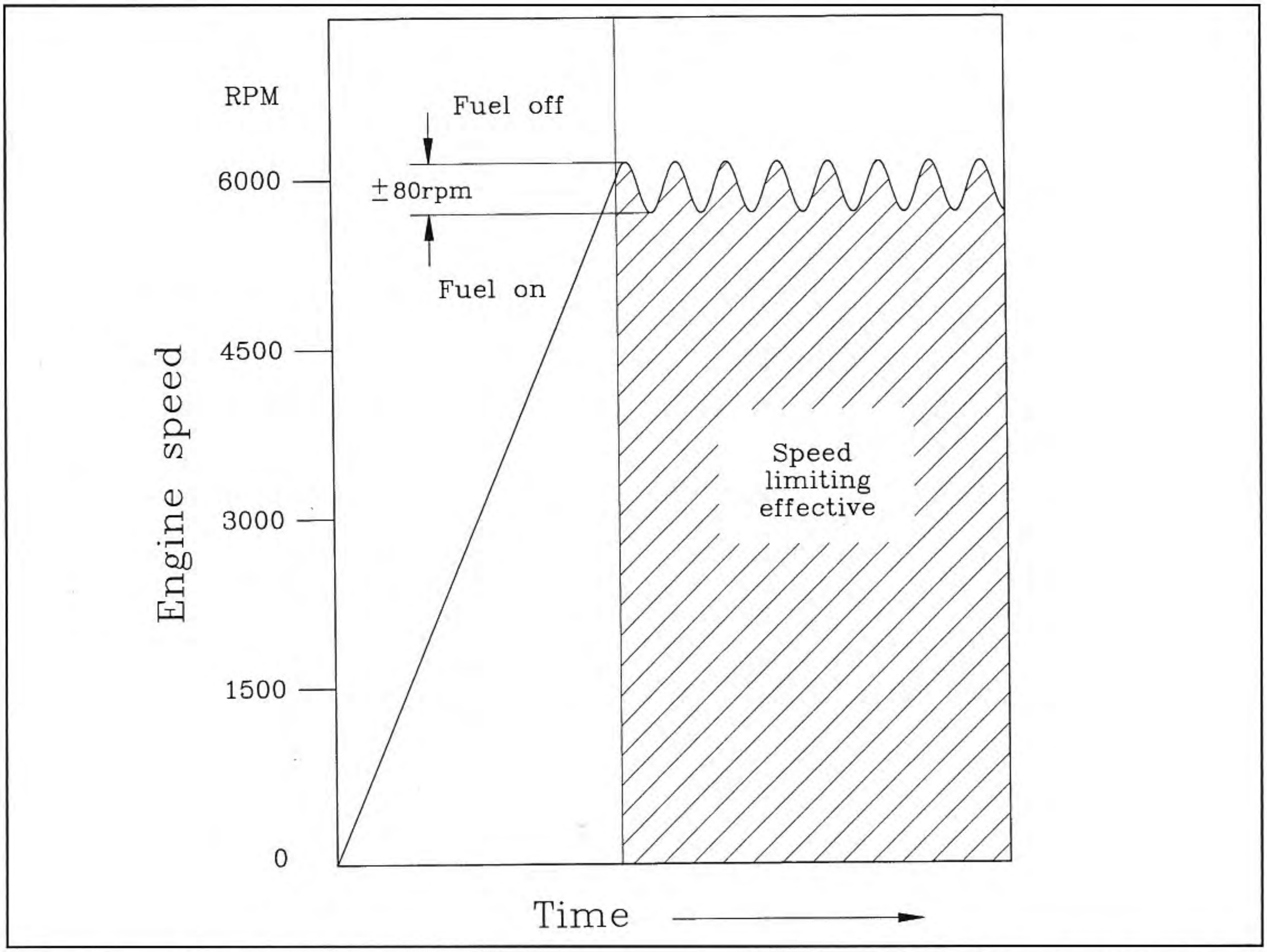
The fuel accumulator that helps damp out system pressure fluctuations and maintains some residual pressure when the engine is stopped to ease warm restarts.

To establish TDC on the number 1 cylinder, a separate magnetic sensor is used which produces just a single pulse per engine rotation by reading, for example, a single bolt head on the flywheel perimeter. On installations where this location is impractical, a separate toothed wheel is provided, often at the nose of the crank. In these cases, a single sensor is used for both rpm and #1 TDC, the TDC signal being provided by a missing tooth on the rotating wheel.

In either case, it is of course necessary to distinguish between TDC on the compression stroke and TDC at the end of the exhaust stroke. This is achieved with a third sensor that reads a timing mark on the camshaft. Since the cam rotates at half crank speed, this simply establishes which stroke the engine is on; the precision timing is left to the crank sensor.

Fuel Sub-System

It is the integration of ignition and EFI "black boxes" that characterizes Bosch's Motronic systems. Since we earlier explained that the fuel delivery aspect of these systems is essentially either L-Jetronic or LH-Jetronic, our attention so far has been focussed on the ignition aspects. Nevertheless, there are some points of inter-



Another feature of Motronic systems is a built-in rev limiter. Although engine rev limiting can be achieved by interrupting the ignition, this can cause rough running and backfires and be hard on the machinery. Cutting off fuel is smoother, and reduces emissions, too. Once the preset rpm limit is reached, the cut-off rapidly oscillates between "fuel on" and "fuel off," with about +/- 80 rpm between the two states.

est in the fuel side of things, too.

For one thing, many later versions of Motronic inject sequentially, rather than using the "ganged" firing of the injectors in D-, L- and LH-Jetronics. Rather than injectors firing in pairs or all together, each cylinder receives its dose of fuel at exactly the same point in the intake stroke. The exact phasing of the start of injection, however, varies from one family of engines to another—the injection does not necessarily take place only while the intake valve is open.

While it requires more, (and more rapid) computations, and thus demands a more complex ECU, this approach has some potential advantages. For one thing, the problem of port wetting, discussed in earlier chapters, can be minimized or even eliminated. That reduces the amount of acceleration enrichment needed, and so improves both economy and emissions. For another thing, the ganged firing of earlier systems causes both a brief, transient drop in fuel pressure, and a large momentary electrical load. Even though the fuel rail on D-, L- and LH-Jetronics has an internal volume equal to many times the volume of fuel of one injection, and so the fuel pressure pulsation does not drive the mixture strength out of whack—it could be accommodated in the internal "maps," anyway—it can cause disagreeable noise. (Motronic systems that do inject on the "ganged" basis fit a surge suppressor—a kind of hydraulic accumulator—at the upstream end of the fuel rail, to dampen these pulsations.) Reducing the size of the electrical load "spike" reduces the peak electrical consumption of the system and allows some components to be made smaller and lighter. Further, the system's response to changes in engine speed and load can be made more rapid—acceleration enrichment, for example, can begin with the next cylinder, rather than having to wait for a full two revolutions of the crank before fattening up the mixture. Finally, each injector can remain open for much longer than if all were fired together. Because ganged injectors open only every other revolution of the crank, the maximum number of crank degrees they are open is something less than 360 degrees. Individual, sequential injectors can stay open for a bit less than 720 degrees. That permits injectors with a smaller flow rate to be used which, in turn, simplifies the problem of metering very small amounts of fuel at idle.

Injector Pulse

The nature of the pulse that opens the injectors is also different from that in the "fuel-only" systems. Rather than a single "on" pulse that persists for the duration of the injection, the injectors in LH-Motronic systems are driven by a "stream-of-blips." The injector valve is first opened by a comparatively large voltage "spike" from the ECU, then held open by a sequence of further on-off blips that cycle rapidly. The injector never gets a chance to close, however—it is held open continuously. The voltage doesn't drop below 8V, and it will stay open if the voltage is above 6V. While it has been suggested that this is merely an approach that makes the design of the electronics more convenient, another reason may be that it reduces the total electrical power consumed by an injector during a cycle. Apart from a miniscule savings in fuel—the engine doesn't have to work as hard turning the alternator—this may also permit smaller and lighter windings in the injector solenoids, without the risk of overheating them, in the same way that dwell control avoids overheating the ignition coil. Note that this issue of having to limit the "duty cycle" (the ratio of on-time to off-time) is intensified if sequential firing is used and long periods of time are spent with the engine at high power and thus demanding that the injectors remain open for long periods.

Adaptive Control

A final refinement is "adaptive" control, in which the ECU "learns" changes in the engine's condition and responds appropriately. Recall that in closed loop mode, the ECU is continually adjusting the mixture strength on the basis of signals received from the lambda sensor. Thus, the tendency of an aging engine with numerous air leaks admitting unmetered air to run lean will be corrected by the ECU detecting this on the basis of the signals from the lambda sensor, and make appropriate corrections for it. In open-loop mode, however, such as during cold starts, cold engine idling and full throttle acceleration, the ECU reverts to its internal maps. If these maps were fixed for all time, the engine would consistently run lean whenever it operated in open loop. Given a sufficiently large and subtle memory, the ECU can "remember" that the engine always needs a richer mixture than its maps call for. With adaptive control, the ECU adjusts the values in the maps, for use in open loop mode, on the basis of the amount of enrichment beyond the map values when running closed loop. So much for regular tune-ups!

KNOCK, KNOCK?

In broad terms, an engine running on a stoichiometric mixture will produce the most power for the least fuel when the spark is advanced to a point just short of where detonation or "knocking" occurs. Working at that optimum value of spark advance, however, is fraught with dangers.

When combustion goes haywire and the entire contents of the cylinder "go off with a bang," power is lost and fuel wasted because the violent turbulence that accompanies detonation scrubs the hot gasses against the interior surfaces of the combustion chamber, so much of the heat energy winds up in the exhaust or cooling system. Far worse, the rapid "spike" in cylinder pressure from this explosive combustion is potentially crippling to an engine. If knocking persists for long, piston crowns can—quite literally—have holes punched through them, spark plugs can have their side electrodes knocked clean off the shell and/or have their porcelain bodies cracked, rod and main bearings can be damaged, head gaskets can be eroded away.

In the days of mechanical distributors, the static setting of ignition timing had to be chosen conservatively, because the additional advance arrived at by the combination of mechanical and vacuum advance controls was approximate at best, and changed with wear of the mechanical parts. (Ever installed a new set of points in an older vehicle, had it tend to knock slightly, but then marveled that it seemed to "heal up" after a time? That's because the rubbing block on the moveable half of the points wore down enough to retard the timing a few degrees.)

The higher precision of electronic triggering allowed engineers to work closer to the danger mark, but variability in climate, fuel quality, driving habits, and engine condition still meant that a safety margin had to be held in hand. What was needed was some device that could detect the incipient onset of detonation—plus, of course, the ability to continuously and rapidly adjust the timing so that it was always at the ragged edge. The device is the knock sensor.

While the internal working principle of knock sensors can have a variety of possible forms, the one used by Bosch (and many other manufacturers) depends on the piezoelectric principle. Some materials—in this case a special ceramic—produce an electrical voltage when they are strained, or deformed. Such devices have been used for microphones and in inexpensive cartridges for LP record players. As applied to the knock sensor, a rigid, massive housing contains a lump of the piezoelectric ceramic, one face of which is attached to the housing, while the other face is attached to a smaller weight. When the housing is shaken, the "free weight" tries to dance around and so strains the ceramic, which accordingly produces a small electrical signal. We can arrange to shake the housing by attaching it to the engine block.

Shaking of the outer housing, of course, occurs all the time the engine is running—not just because the engine is moving around on its mountings (that movement is too slow to excite any measurable signal, anyway), but because the engine block is vibrating from the fury going on within it. The nature of the shake, however, changes significantly when knocking occurs, so the electrical signal put out by the sensor changes too. If that signal is fed to a device that can recognize the characteristic "sound" of knocking, then we have captured the information we need to control ignition timing so as to avoid the knock. (While Bosch categorizes its knock sensor as an accelerometer, it is helpful, and not completely wrongful, to think of it as a microphone.)

The device that does the recognizing may be a separate electronic "black box," as on some early Motronics, or can be integrated into the ECU, as on models ML3 and later. The characteristic frequencies the electronics are looking for are in the range of 10,000–15,000 cycles per second—exactly the range of frequencies of the sounds we hear as engine knock.

5 TROUBLESHOOTING BOSCH INTERMITTENT ELECTRONIC FI

Preventative Maintenance

Before attributing some operating fault to the fuel injection system, be sure the remainder of the engine is in sound order. It is quite pointless to start to troubleshoot the injection system if the spark plugs are years old, the rubber intake ducting is cracked, or an exhaust valve is burned.

Spark Plugs

As in the days of carburetors and point-and-breaker ignition systems, the first diagnostic test should be to remove the plugs and examine them—the removed plugs can reveal a great deal about engine condition. The insulator should be a light gray-to-tan color. An insulator that is bone-white—or worse, blistered—indicates excessive leanness, or perhaps a plug of the wrong heat range; a blackened insulator may be the result of a too-cold plug, or excessively rich running, or may be a product of oil fouling, because of worn rings or valve stems, a plugged PCV valve, or even simply an overfilled oil pan. To distinguish between carbon (fuel) fouling and oil fouling, rub the plug against the heel of your hand—oil fouling will leave a greasy smudge; carbon fouling will not.

Any mechanical damage to the plug—a cracked insulator, a broken side electrode—implies detonation, which may have damaged much more than the plug. A plug that is truly wet with gasoline implies a non-firing cylinder that has continued to receive fuel.

Check Gap**—**Also, check the gap on removed plugs. If the plugs have seen any substantial amount of service, the gap is sure to be larger than on a new, correctly gapped one. This widening of the gap results from erosion by the hot gasses within the cylinder. An excessive plug gap can make unsustainable demands on the ignition system—the voltage required to jump the exaggerated gap may cause the secondary (high-tension) voltage to rise so high that the spark seeks another path to ground, perhaps punching a microscopic hole right through the insulation on the plug or coil wires, leaving a leak path to ground that remains even after the plugs are replaced.

Replacing Plugs**—**The replacement interval for spark plugs suggested by the factory is likely to be highly optimistic; except for platinum tipped plugs, they should be replaced annually, as should the air and fuel filters. Check the gap on new plugs before installing them even if they come pre-gapped, and take care when replacing the fuel filter that the act of removal and replacement does not allow dirt to enter the system. High-tension wires should be replaced every couple of years, likewise the distributor cap and rotor, if applicable.

Routine Checks

Other routine service inspections that should be taken care of before going further are checking ignition timing and, on engines without hydraulic lifters, the valve clearances. Inspect all rubber air trunking for cracks and other sources of air leaks.

Assuming all is in order so far, the next step is a compression check. This will reveal worn rings or leaking valves. Compression that is uniformly down by even as much as 20–30psi relative to the factory figure is not much to worry about, but variations between cylinders of that much is cause for concern.

Gas Pains

Many fuel injection troubles can be avoided, or at least long postponed, simply by paying attention to the quality of fuel used, and where and when it is bought. While the owner's manual may make clear that regular gas of about 87 pump octane is suitable, and while the engine may not be able to take advantage of the higher octane (about 92) of premium fuel, the premium fuel from most national gasoline brands contains a more aggressive detergent additive package than does their regular fuel. Clogged injectors are one of the more common causes of grief with fuel injection systems—all systems, not just Bosch. Higher detergency of the fuel helps prevent these faults. Even supplementing a standard diet of regular with a tankful of premium every few weeks helps. Aftermarket detergent additives may also be effective.

Running out of gas is a pain, argument enough for following the advice implicit in the old saw that "it costs no more to drive around with a full tank than a near empty one," but running most of the time with the gauge showing 1/4 tank or less is especially poor practice with fuel injection systems. The larger the air space above the fuel in the tank, the greater the amount of water that condenses out of the air, and the greater the susceptibility of steel and iron components in the system to rusting. Apart from the direct consequences of this corrosion, tiny flakes of rust can play havoc if they get into the system.

Note, too, that it is a good idea to keep an eye on when your habitual gas station gets its deliveries. The replenishment of the station's underground storage tanks stirs up rust and sediment in their tanks that may wind up in yours. Better to fill up the day before or the day after.

"No User Serviceable Parts Inside"

No matter what the results of the diagnostic tests described below, bear in mind that in most cases the only remedy for something out of spec is component replacement. Parts that cannot be repaired or adjusted include, where applicable: pressure regulator; accumulator; injectors; cold start injector; auxiliary air bypass (idle speed stabilizer); fuel pump (except for the check valve, which is replaceable); and all sensors.

Bear in mind, too, that without the highly specialized equipment to which service technicians in dealerships have access, there is absolutely nothing you can do with any electronic control modules; you cannot even test them. All you can do if an electronic controller is suspect is to systematically eliminate all other components as potential culprits and, as a final resort, replace the controller.

Troubleshooting Tests

Despite the dismayingly long list of things that cannot be done, there are nevertheless some troubleshooting procedures that can be helpful. These should be carried out in a logical way, and with an understanding of how the system is supposed to work and what different components do in various circumstances. For example, if an engine starts readily from cold and runs well while first starting to warm up, but then runs progressively richer as it reaches operating temperature, guzzling gas and spewing black smoke, one plausible culprit is a cold start injector stuck open. In the same way, if the idle speed is way too high when warm, or too low when cold, one of the first places to look might be the idle speed stabilizer/auxiliary air bypass. In general, if only one part of the engine's operating regime is affected,

WARNING!

Gasoline is highly flammable and potentially explosive. It can be ignited by an electrical spark or by contact with hot engine parts. Use extreme care when working on any engine's fuel system. Work only in a well ventilated area, ban smoking or any open flame from the work area, and ensure a fully charged large capacity fire extinguisher is close to hand. Many fuel injection system circuits remain under pressure even when the engine is stopped and the fuel pump is deactivated; before loosening any fuel fitting, wrap a rag around it.

look first at components whose function is directly related to operation in that regime.

Air Meter (vane type)

As noted, the airflow meter is not serviceable; all you can do is check for smooth mechanical action and test the electrical output of its potentiometer. Test for free, smooth movement simply by moving the vane with your finger. After unplugging the electrical connector, apply one probe of an Ohmmeter (or multimeter set to "Ohms" or "resistance" scale) to a clean chassis ground and contact each terminal on the meter in turn with the other probe. In every case, the meter should read an open circuit (infinite Ohms).

The "voltage-in" and "voltage-out" pins differ from one model to another; the manual for your vehicle may identify them. In every case, however, there will be one pair of pins that show a varying resistance as the vane is moved. The exact numbers don't matter much; what is important is that the resistance should vary smoothly as the vane is slowly deflected by hand.

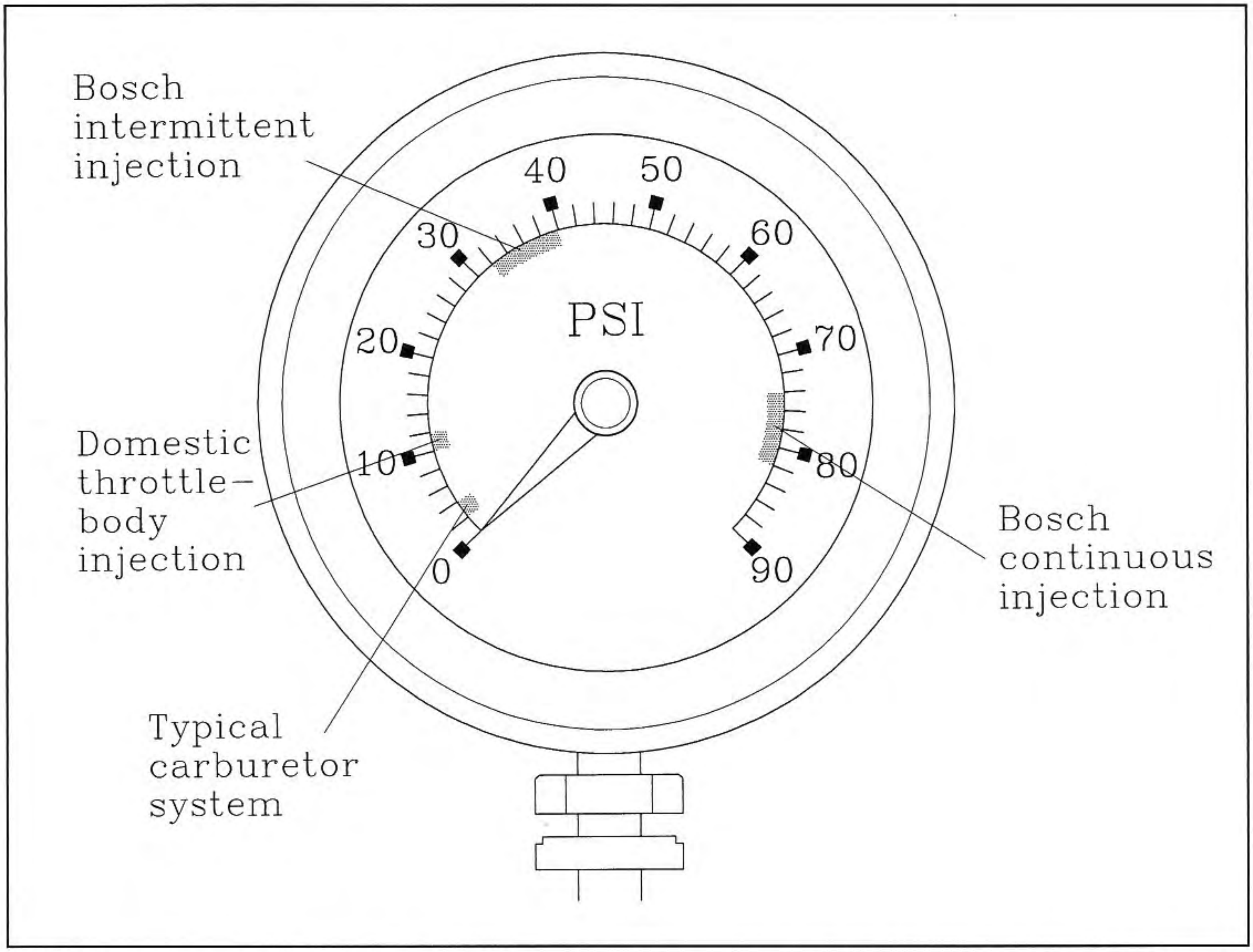
Air Meter (Hot-Wire Type)

There is nothing serviceable or adjustable in the hot-wire air mass sensor; all you can do is confirm its functioning. If it doesn't work, it must be replaced.

The wire in the sensor is so fine that, without ideal lighting, it is easy to mistakenly suppose that it is broken or missing. Recall that a "burn-off" cycle is provided, that feeds a large amount of current to the wire to vaporize any dirt deposits on it. The wire glows red hot during this brief (about one second) cycle, which makes it plainly visible.

With the engine running and the meter oriented so it is possible to sight through it with its wire harness and trunking to the throttle body still connected (it is OK to detach the housing and move it around, as long as you don't damage the trunking or wiring), rev the engine to at least 3000 rpm and shut it off. (For safety reasons, the burn-off cycle is cancelled if the engine has not exceeded 3000 rpm since the last time the ignition was shut off). After three or four seconds, the wire will glow for about one second. While this doesn't confirm that the meter is working correctly, it does prove the wire is OK.

There are five wires connected to the hot-wire sensor. One is a ground; one is voltage-in, one is voltage-out, and the other two are involved only in the burn-off cycle. Which is which depends on the specific model, and should be specified in each vehicle's manual. Failing that, the above test (you may have to repeat it several times, working this way) should identify those last two by placing the probes of a high-impedance digital voltmeter/multimeter on pairs of terminals (peel back the insulating boot on the connector) until you find the pair that are "live" and "ground" during the burn-off. DO NOT USE AN ORDINARY ANALOG (NEEDLE-AND-DIAL) VOLTMETER; there is severe risk of damage to the ECU.



One of the minor reasons why fuel injection is superior to carburetors is because forcing the fuel through small orifices at high pressure does a better job of vaporizing it than sucking it through small orifices with a small pressure difference. A potential downside for servicing is an increased fire risk. Many circuits contain fuel under residual pressure, even when the engine is stopped.

With one voltmeter probe grounded, the voltage-in terminal will show battery voltage (nominally 12 volts) when the ignition is switched on. WITH THE IGNITION OFF, the ground will show zero Ohms (no resistance) to ground. (Never apply an Ohmmeter to a powered circuit.) By elimination, the remaining terminal must be voltage-out.

The voltage between ground and the voltage-out terminal will typically vary from a bit more than 2 volts with the engine idling to a bit less than 3 volts at about 3000-4000rpm. Again, the factory specs may be in the manual for your vehicle, but the exact numbers are less important than seeing a smooth voltage increase pretty much in proportion to engine speed.

Fuel Pressure Checks

Unless the engine has been stopped for a very long time (hours), there is likely to be residual pressure in the system. Before breaking into the fuel plumbing to attach a pressure gauge, this residual pressure must be relieved. The simplest way to do this is to pull the fuel pump fuse, thereby disabling it, then run the engine until it stalls for lack of fuel. For pressure tests, a pressure gauge with a capacity of at least 50psi is needed, together with hoses and fittings to connect it.

Some engines have an extra port for convenient connection of a pressure gauge. Failing that, the fuel line to the cold-start injector can be pulled and the connection made there. A specific figure for fuel system pressure will be listed in the manual for your particular vehicle, usually about 35psi, although some high powered engines may run at about 44psi. Note, however, that this "factory" figure is measured with the engine stopped.

An alternative test procedure that permits checking the functioning of both the fuel pressure regulator and the pump is to gauge the pressure with the engine idling. In that case, the pressure should be somewhere in the neighborhood of 30psi, or a bit less. Again, this applies to most engines; high horsepower ones that call for, say, 44psi with the engine stopped will usually show a bit less than 40psi when checked idling.

Recall from the previous chapter that the fuel pressure regulator has a vacuum hose running to the intake manifold, so manifold vacuum can act on the diaphragm within the regulator. This allows the regulator to maintain fuel pressure in the rail at some constant amount higher than the pressure in the intake manifold, no matter how manifold vacuum may vary. If the vacuum hose is disconnected at the regulator (and plugged), then with the engine idling the gauged pressure should have risen to the "factory" figure.

High Pressure—If the system pressure is too high, the problem is either a defective pressure regulator or a restricted return line from the regulator to the tank. This last can be checked by disconnecting the return line at the regulator and attaching a test line leading to a suitable container. If the pressure returns to normal, the original line is obstructed; if not, then the regulator is defective. The pressure regulator on intermittent systems—except for now somewhat rare D-Jetronic—is not adjustable.

Low Pressure—If the pressure is too low, on the other hand, there are numerous possibilities. First there are the obvious things: Is there fuel in the tank? Are there any visible external leaks? Is any part of the supply line from the tank to the fuel rail dented partly shut? Less obviously, the tank vent may be obstructed, forcing the pump to attempt to "implode" the tank. This can be checked by removing the gas cap. The fuel filter may be clogged, as may the (usually fitted) in-tank strainer—a kind of wire mesh "sock" that filters out rust flakes and other large pieces of debris.

Other possible causes for low pressure are low/no voltage at the pump and a defective pressure regulator. Confirm that the pump is running. In a reasonably quiet environment, you should be able to hear it. If the pump is not running, check the electrical supply to the pump, starting with its fuse. If the fuse is OK, check for electrical power at the pump. A voltmeter with one probe applied to one of the fuel pump terminals and the other to a good chassis ground should show battery voltage (near 12 volts) at one pump terminal, and zero at the other. (You will have to fold the rubber boot around the connector out of the way to gain access to the electrical terminals.) Low voltage at the pump is likely the result of corroded terminals or a bad ground. Check the pump ground.

Pump Does Not Run—If there is adequate power to the pump but it does not run, the pump is defective and will have to be replaced. If the pump seems to be in order, pinch shut the return line from the pressure regulator to the tank. If the pressure rises to standard values, the regulator is defective; if not, and the alternative faults listed above are excluded, it is likely the pump after all.

Residual Pressure—Recall from the system description in Chapter 3 that the pump on intermittent systems is equipped with a check valve that keeps the fuel lines full and pressurized even when the engine is stopped. This permits quicker restarts, and helps to prevent vapor lock. With the pressure gauge connected as described above, run the engine briefly, then shut it off (or energize the fuel pump with the engine stopped). The pressure should not drop below about 14 psi for at least 20 minutes after shut-down. A loss of residual pressure may be caused by an external leak, one or more leaking injectors, a defective pressure regulator, or the fuel pump check valve.

To check both these last two, repressurize the system and, immediately after shutting down the engine (or disabling the pump), pinch shut the supply line from the pump to the regulator. If the residual pressure now holds, the regulator is defective; if not, the pump check valve is leaking.

If all this fails to stem the drop in residual pressure, about the only remaining candidates are one or more defective injectors, and the cold start valve.

Injector Leakage, Flow, Pattern

With system pressure relieved, remove the cold start injector (cold start valve), but leave its fuel supply connected. Place the injector in a suitable container and repressurize the system; the injector should not seep or drip fuel. If it does, it is defective.

Remove the injectors and temporarily plug the holes they came out of. Set each injector into the mouth of a graduated vessel. A reasonable degree of accuracy is needed here, so graduated cylinders (available at any laboratory supply outfit, or ask your druggist) are preferable to domestic measuring cups, etc. It should be pretty obvious that plastic vessels are preferable to glass ones!

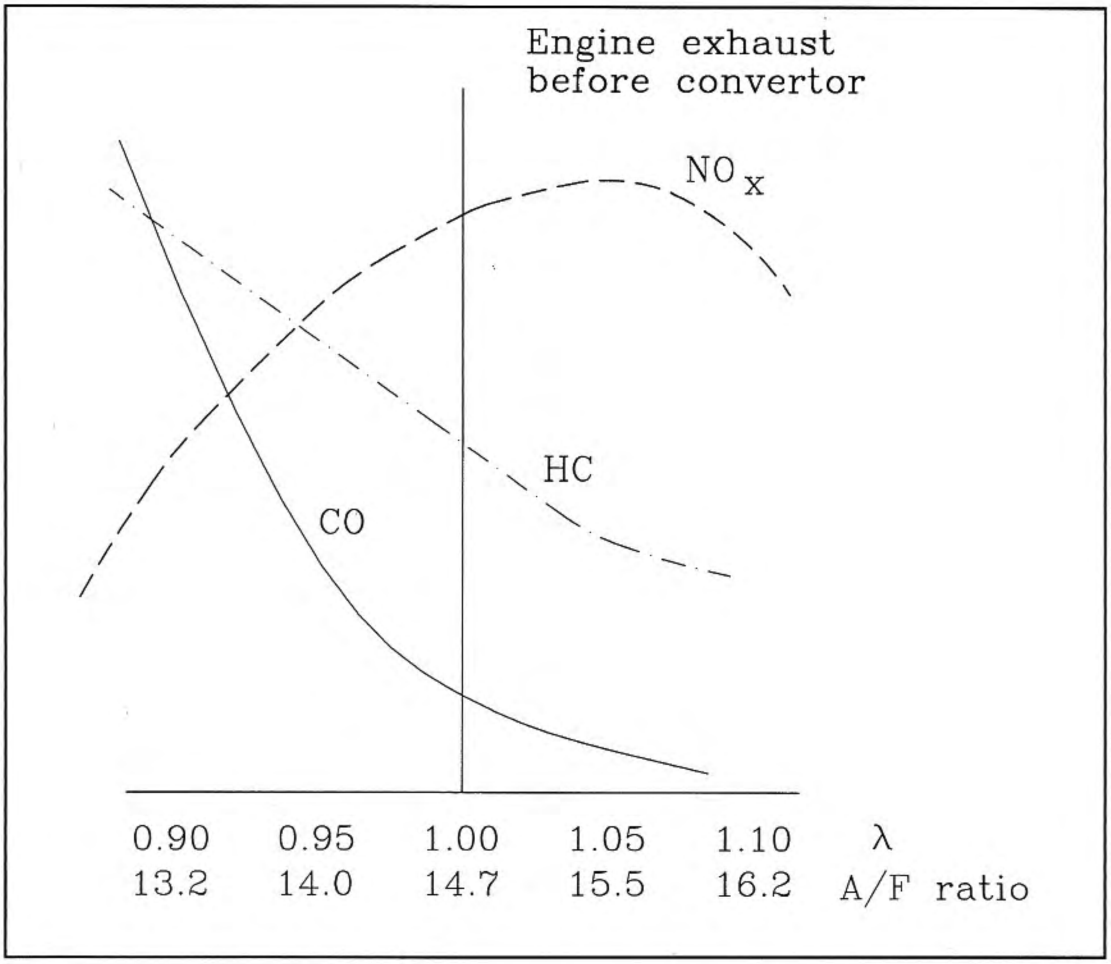
For safety's sake, disable the primary ignition circuit by disconnecting the connection from the battery to the coil. Now run the pump; no fuel should flow from the injectors. Look also for seepage around the seams in the injector bodies.

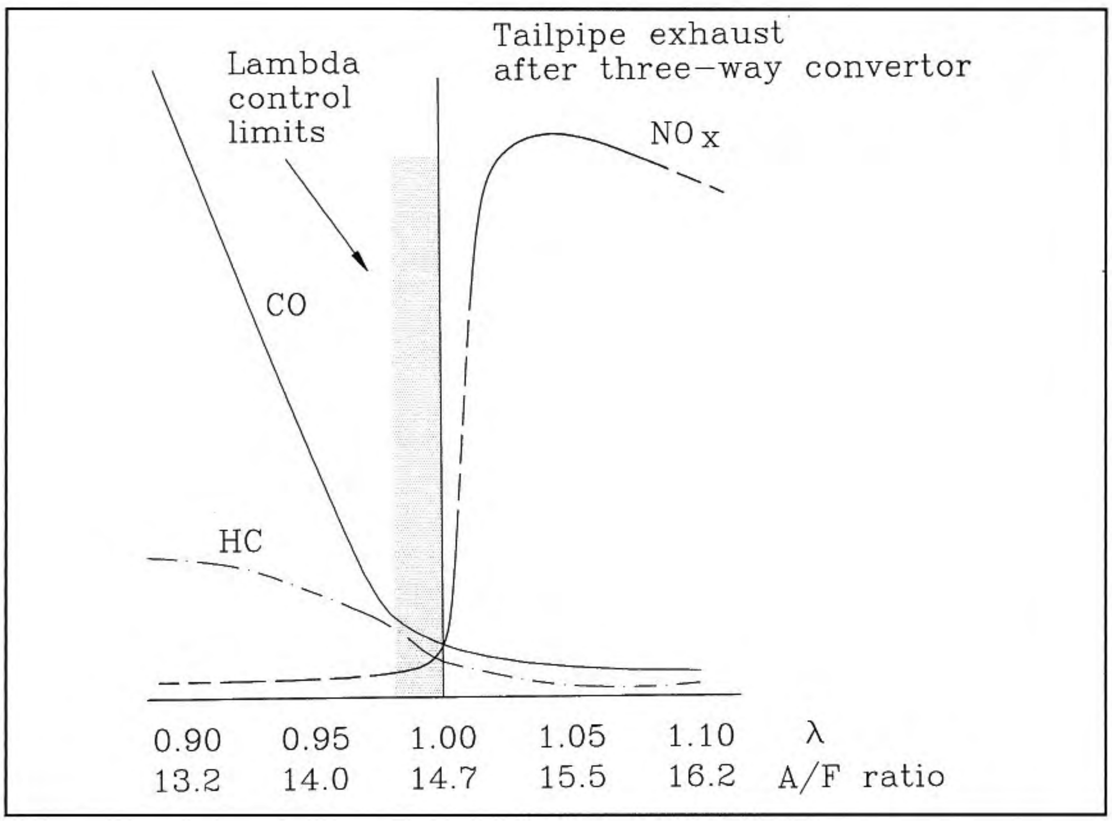
Next, remove the spark plugs and crank the engine for about one minute, allowing the injectors to discharge into the graduated cylinders. The amount of fuel discharged by each injector should be the same, within 10 percent or less. Also, observe the spray pattern from each. It should be cone shaped and symmetrical. Partial clogging may result in a spray pattern that is lopsided, or a discharge that is hardly atomized at all—more like a stream than a spray—or may simply reduce the rate of delivery. A slight degree of asymmetry in the spray pattern is acceptable, as long as the delivery volumes match, but pronounced lopsidedness or a stream rather than a spray requires that the defective injector(s) be replaced.

Basic Mixture Strength/CO Adjustment

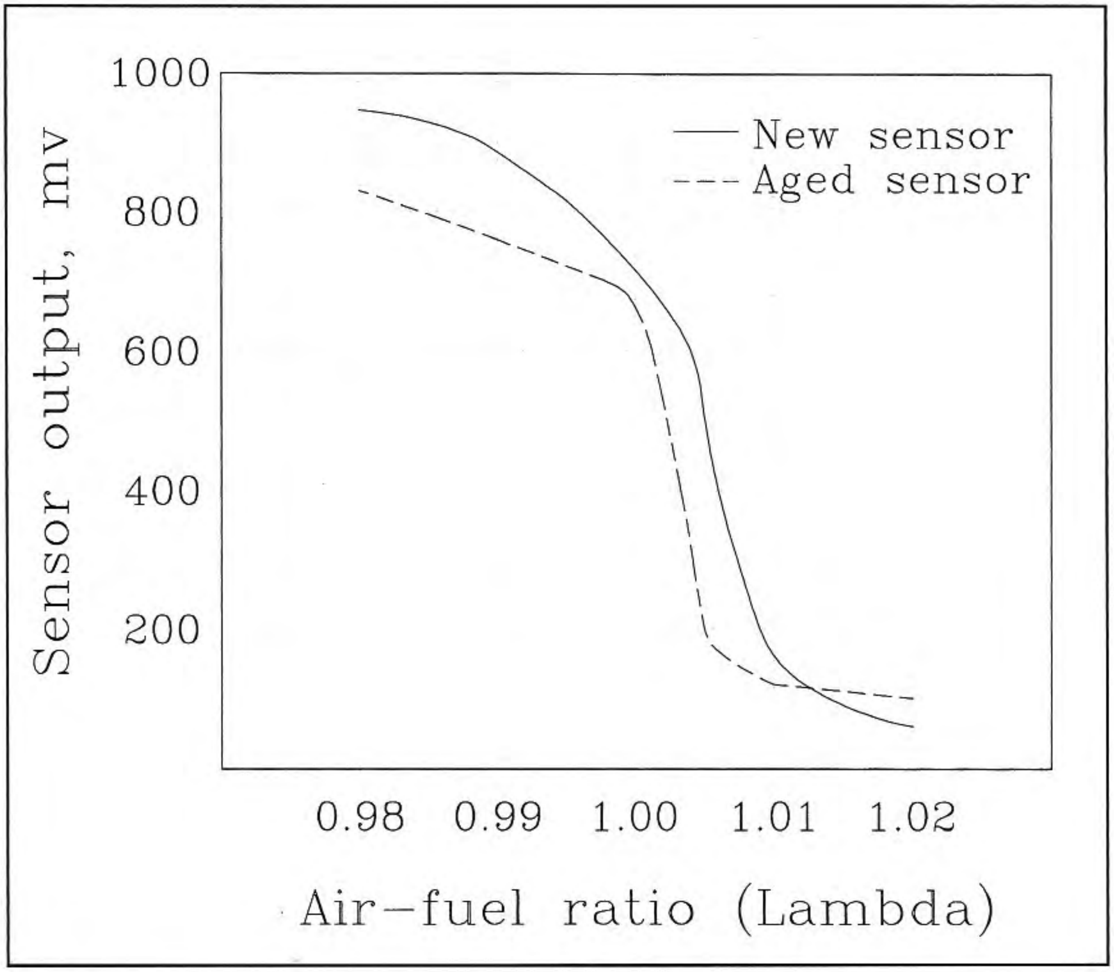
After about 1987, LH-Jetronic and Motronic systems make no provision for adjusting the mixture strength/exhaust CO level—none is needed. On earlier L-models, those having a moving vane air meter, the basic mixture strength can be adjusted by turning a screw. This screw is accessible through a small hole on the top of the air meter housing, usually closed-off with an "anti-tampering" plug. After the anti-tampering plug is pried out, turning this screw clockwise richens the mixture; counterclockwise leans it. On those LH-Jetronics that have provision for adjustment, the adjuster is located on the side of the air meter, again under an anti-tampering plug about 7/16" diameter. Note that while the adjustment is always carried out at idle, its effect is felt throughout the engine's operating envelope.

Note, too, that on systems with a lambda sensor, the lambda sensor/electronic control will attempt to bring the mixture back to the stoichiometric value no matter what you do with the CO/basic mixture adjustment. The fix is simple—before carrying out the adjustment, disconnect the lambda sensor, obliging the electronic control to operate open loop.





Three-way catalytic convertors are essential to meet current emissions limits. But convertors can only do their job if the air:fuel mixture fed to the engine is held very close to stoichiometry—the chemically correct ratio. And to achieve that, a lambda (oxygen) sensor is essential. Its electrical output varies very strongly right around the point of stoichiometry.



Most folks don't have a CO meter, but many have a multi-meter. It is tempting to gauge exhaust CO on the basis of the output of a lambda (oxygen) sensor, but beware that the sensor's output sags gradually with age, so simply aiming for about 500 millivolts may not do the trick. The shape of the curve is reliable, however, so by adjusting the mixture both rich and lean, you can establish the upper and lower limits of the sensor's output range. Aim for the middle.

An exhaust gas analyzer (CO meter) is almost essential to perform this adjustment. Before you start, however, set the idle speed using the idle air bypass screw. Note, too, that the CO meter has to "read" the exhaust gas upstream of the catalytic converter—remember, the converter is doing its best to oxidize the CO to CO_2. There is usually a port or pipe or fitting on or near the exhaust manifold for this purpose.

With the engine fully warm and an appropriate idle speed set, adjust the mixture until the meter reports a CO value corresponding to the figure on the EPA placard in the engine compartment. If the placard is missing, aim for around 0.6 percent. Without a CO meter, about all you can do is adjust for the leanest setting that still provides a smooth idle, then turn the adjuster 1/4 turn clockwise (richer).

If a CO meter is available, then on lambda-equipped engines both correct mixture strength and correct functioning of the lambda sensor and the electronic control is absolutely confirmed if the CO reading is the same with the lambda sensor connected (closed loop) and disconnected (open loop).

Auxiliary Air Valve

L-Jetronics and early LH-Jetronics use an auxiliary air valve to provide the extra air a cold engine needs to maintain an idle speed high enough that the engine will not stall. As described in Chapter 3, this is simply a small rotary disc valve that allows air to bleed around the nearly closed throttle (it is sometimes called the "auxiliary air bypass"). The position of the disc is governed by a bi-metallic coil. When the coil is warm, the valve is completely closed; when very cold, it is fully open, with a smooth and gradual transition between the two as the engine warms up. In very cold weather the auxiliary air bypass valve can take eight or ten minutes to move from fully open to fully closed.

The valve is not serviceable, but its condition can be initially diagnosed by symptom: An idle that is appropriate when cold but excessively high when warm points to this valve being stuck partly or fully open. Conversely, if the warm idle seems right but the engine requires some throttle opening to avoid stalling when cold, then the valve may be stuck closed.

If the valve is suspect, check, first, by pinching shut the connecting hose. On a cold engine, this should drop the idle speed; on a hot one it should make no difference. If the valve fails this test, sight through the valve. Because the valve is powered as long as the ignition is on, the heating element should completely close the valve within ten minutes. Ensure that 12 volts is getting to the valve, allow time for it to warm up, then look through to confirm the valve is closed. To confirm the valve is opening when cold, pop it into a freezer for ten minutes and again sight through it—there should be a clear, round passageway through it.

Idle Speed Regulator

Later LH-Jetronics and all subsequent Bosch intermittent injection systems modulate the auxiliary idle air bypass in a different way. It remains in principle a valve that bypasses more or less air around the throttle plates, and its effect is most significant during warm up. However, because its more sophisticated control enables it to maintain an appropriate idle speed, irrespective of temperature or engine age and condition, it is renamed an "idle speed regulator," or sometimes "rotary idle actuator."

In this device, the moveable valve that varies the size of the air opening is driven by a component that looks like an electric motor. Indeed, in construction it essentially is, but in action it never turns more than 90 degrees, its electrical components receiving pulses from the ECU that cause it to "dither" back and forth slightly around an average position that gives the idle speed programmed into the ECU.

Analogous to the function of the electromagnetic injectors themselves, the position of the valve, and thus the amount of air that passes, depends on the ratio of on-time to off-time—its "duty cycle," in other words. A long duty cycle—more on-time than off—drives the valve further open; a shorter duty cycle closes it further. This duty cycle can be measured with a dwell meter, set on the four-cylinder scale.

The exact values under various circumstances vary considerably among different vehicles, so check your vehicle's specs in its manual. As a general guide, the duty cycle with a warm, idling engine will read somewhere around 30 degrees on the dwell meter. Adding a fair-sized load, such as by turning on an electric rear window defroster, should have little effect on the idle speed, but the duty cycle should increase somewhat.

To simulate cold start operation, disconnect the engine temperature sensor. Disable the fuel pump (pull the fuse), and crank the starter. Dwell should be dramatically increased; expect about twice the idling figure. A defective idle speed regulator cannot be repaired; it must be replaced.

6 BOSCH CONTINUOUS INJECTION

There are a great many reasons why auto manufacturers may have been reluctant to wholeheartedly embrace intermittent EFI after it first appeared—in D-Jetronic form—in 1967/68. One of them may have been cost. While it is impossible to know what it costs Bosch to manufacture an intermittent EFI system, it is possible to gain some general indication of the OEM cost of the system to auto manufacturers. As noted on Chapter 3, the D-Jetronic intermittent EFI system first appeared as standard equipment on certain models of the Volkswagen type 3 1600. Soon after, however, the system became available as an option on some other models at a cost of $250–$300. Considering that a 1968 VW 1600 was priced at less than $2,500, this is a rather hefty premium.

Another reason may have been simply that it was an essentially brand-new and unproven technology. Although some auto executives and engineers surely were unreasonably conservative (and some remain so!), it is not necessary to assume they were all a hidebound bunch of stuffed shirts in order to understand why they might be reluctant to gamble with their own reputation in order to cement that of Bosch. The "mere" task of training thousands of mechanics at dealerships around the world in a new and mysterious technology is a daunting prospect in itself, and an expensive one. (A colleague experienced in such matters estimates that the cost of merely translating a 100-page service manual from one language to one other could amount to $30,000, in today's dollars, and VW, for example, deals worldwide in more than 50 languages!)

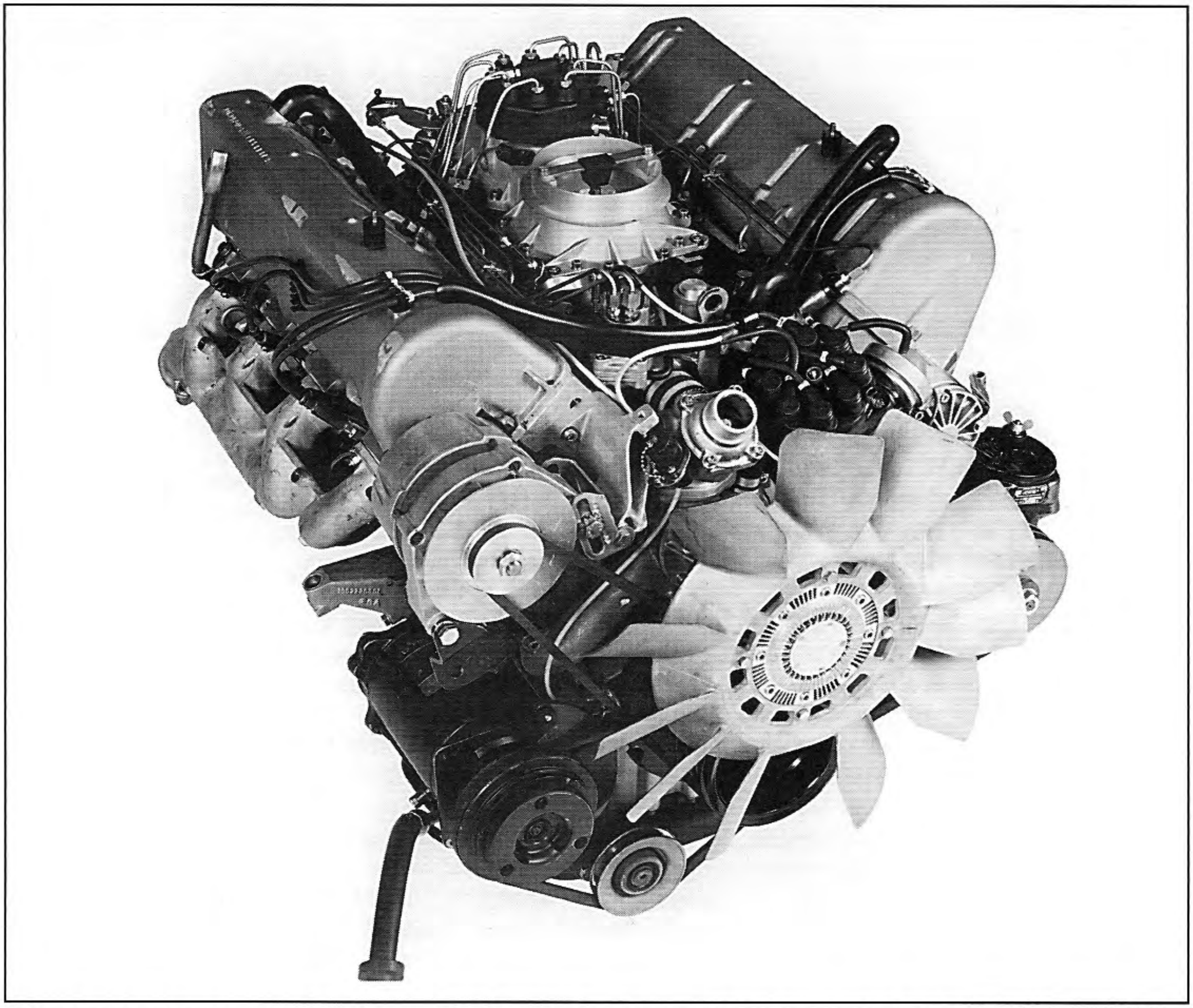
K-Jetronic

Whatever the reason for reluctance, there was evidently motivation in some quarters to find an alternative to the carburetor . . . and one that didn't have dozens of wires coming out of it. Thus, despite the fact that by eight years after its introduction the Jetronic intermittent EFI system was well developed and widely admired, Bosch introduced a purely mechanical gasoline injection system, in 1973. First used on the 1973 Porsche 911T, this "K-Jetronic" gained a significant following, and wound up on some vehicles such as the 6.9 liter Mercedes Benz, where the cost of the alternative system was, if not irrelevant, surely not the overriding consideration.

Basic System Operation & Components

The "K" in K-Jetronic stands for *kontinuierlich*, the German word for continuous. This sets out the first obvious difference between K-Jetronic and the systems we have been describing so far: the injectors on the K-system spray continuously, rather than intermittently. The quantity of fuel delivered per unit of time thus depends solely on the rate of fuel delivery to the injectors.

The regulation of fuel delivery to the injectors takes place in the mixture control unit, which comprises two parts: an air meter and a fuel distributor. The general pur-



Reduced cost could not have been a major reason that Mercedes Benz chose a K-Jetronic system for their 6.9 liter (425 cu in) V8! This installation used the comparatively rare downdraft air meter; most K-systems have an updraft meter. (Daimler-Chrysler Archive)

pose of the air meter should be obvious: to provide a suitable air/fuel ratio, the rate of fuel delivery appropriate for the prevailing conditions depends on the rate of airflow, so it is necessary to measure that airflow. The output from the air meter, in turn, acts on the fuel distributor to modify the amount of fuel fed to the injectors. All operations are purely mechanical.

Air Meter—Although the physical arrangements are different, the air metering on K systems resembles that of the L-Jetronic in that they use a moveable vane or flap within a housing through which all the engine's intake air is drawn. The flap amounts to a circular plate on the end of a lever and is positioned across a conical opening—like a funnel—at the entrance to the housing. According to the rate of airflow through the funnel, the flap is deflected to a greater or lesser degree. so the position of the plate is a measure of the airflow.

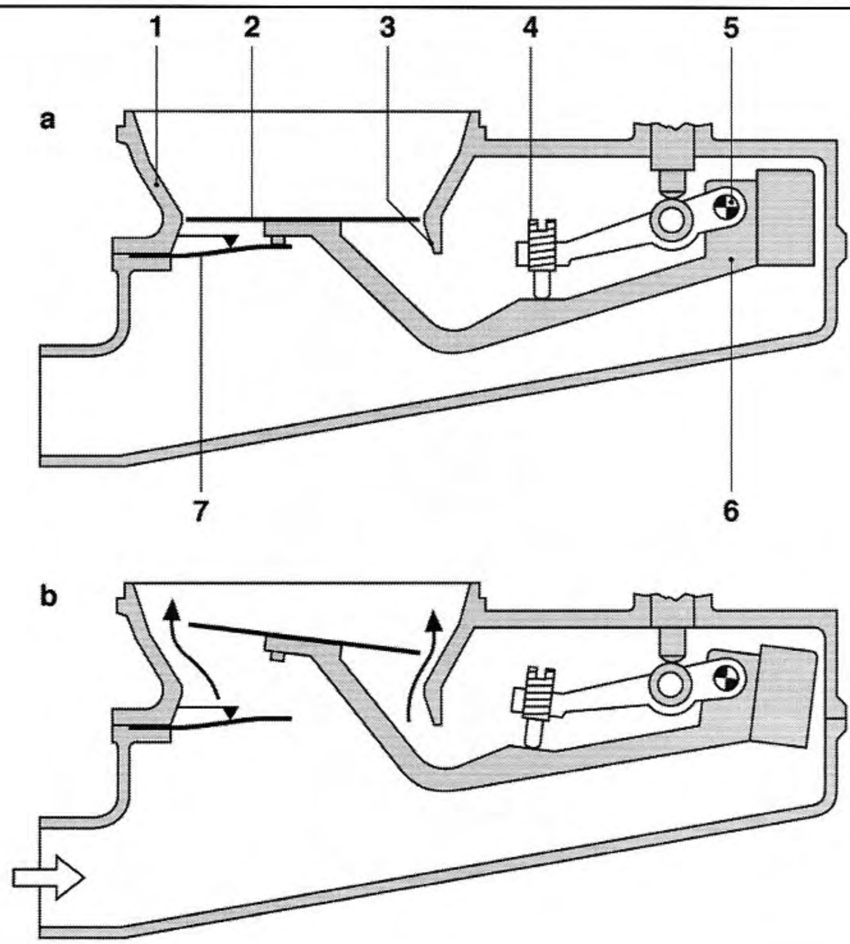
The weight of the plate and the lever is balanced by either a counterweight or, on

Components of the K-Jetronic system. (Robert Bosch Corporation)

some later versions, a light spring, so very little force is required to lift the plate. As increasing airflow raises the plate, it takes up a new position within the funnel, so the size of the gap around the perimeter of the plate—the space through which the intake airflows—depends on the details of the multi-angled taper of the walls of the funnel. (The "updraft" configuration just described is most common, but some K-Jetronics, generally those used on V6 and V8 engines, have the metering apparatus upside down, in which case the plate is pushed downward by the air.)

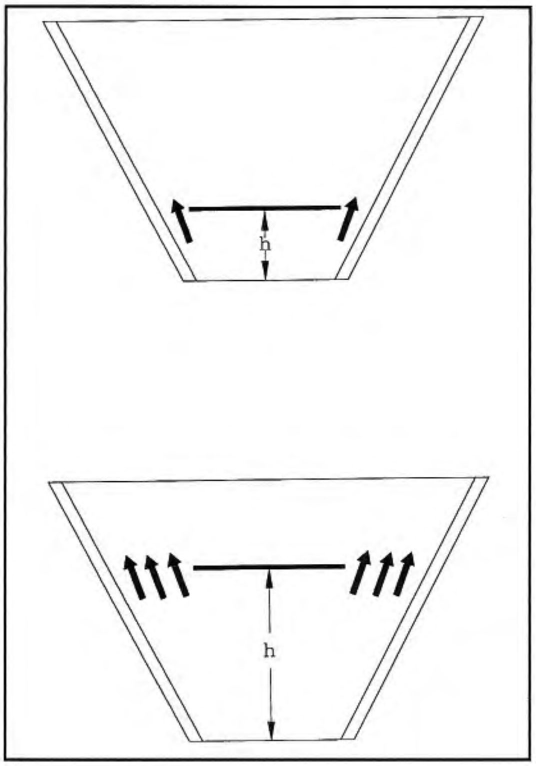
In the design of the K-Jetronic, the quantity of fuel injected is a direct, one-to-one function of the travel of the plate—a doubling of its movement from the rest (closed) position will double the rate of fuel flow. If the funnel had a simple, constant angle taper, the quantity of fuel delivered would also be directly proportional to the rate of airflow, and the mixture strength would thus be the same at all rates of airflow. We have already seen, however, that this is not appropriate for all circumstances. Accordingly, the funnel is shaped with multiple tapers so that the relationship between the position of the flap and the airflow space around it is nonlinear. Usually, this means that the fun-

a. Sensor plate in zero position
b. Sensor plate in operating position
1. Air funnel
2. Sensor plate
3. Relief cross-section
4. Idle mixture adjusting screw
5. Pivot
6. Lever
7. Leaf spring



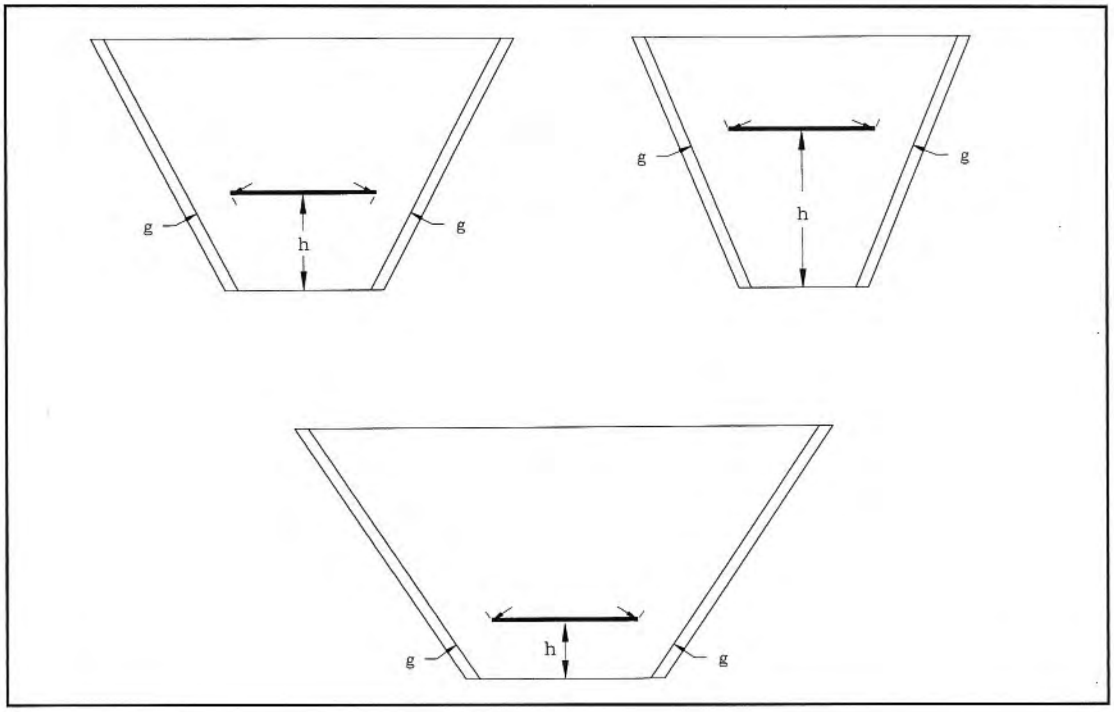
Updraft airflow sensor. (Robert Bosch Corporation)

Increasing airflow "floats" the sensor flap upward (on updraft systems), toward the larger end of the intake funnel. This opens up the gap between the sensor and the funnel.

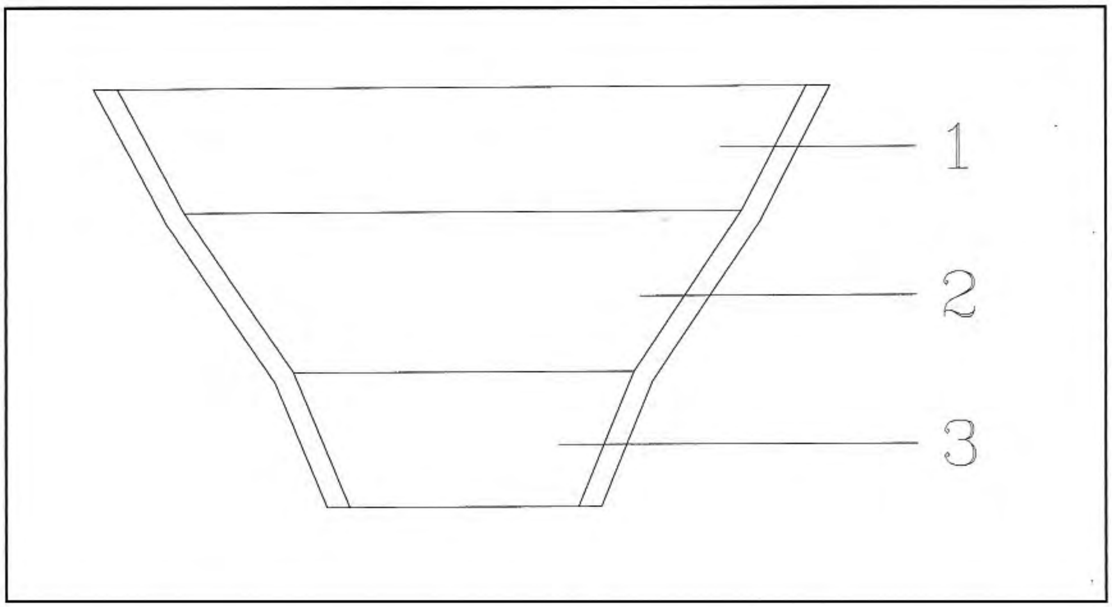


nel tapers out slowly at first, then grows steeper, then the angle becomes more shallow again.

The effect of this is that a small change in airflow at the low flow rates encountered at idle (and just off idle) requires a comparatively large movement of the vane. Because the rate of fuel flow depends directly on the vane position, this provides the slight enrichment needed for idling. As the rate of airflow speeds up to a point that corresponds to normal, light load driving, the vane moves into the wider angled portion of the funnel. Here the same amount of travel of the vane will give a more rapid increase in airflow area, so the vane moves less for a given increase in airflow, and the mixture is accordingly leaned out slightly. At maximum flow rates, the vane is pulled into the mouth of the tunnel where the taper dimin-



The height (h) of sensor plate lift needed to obtain a certain flow area (g) depends on the rate of taper of the funnel.

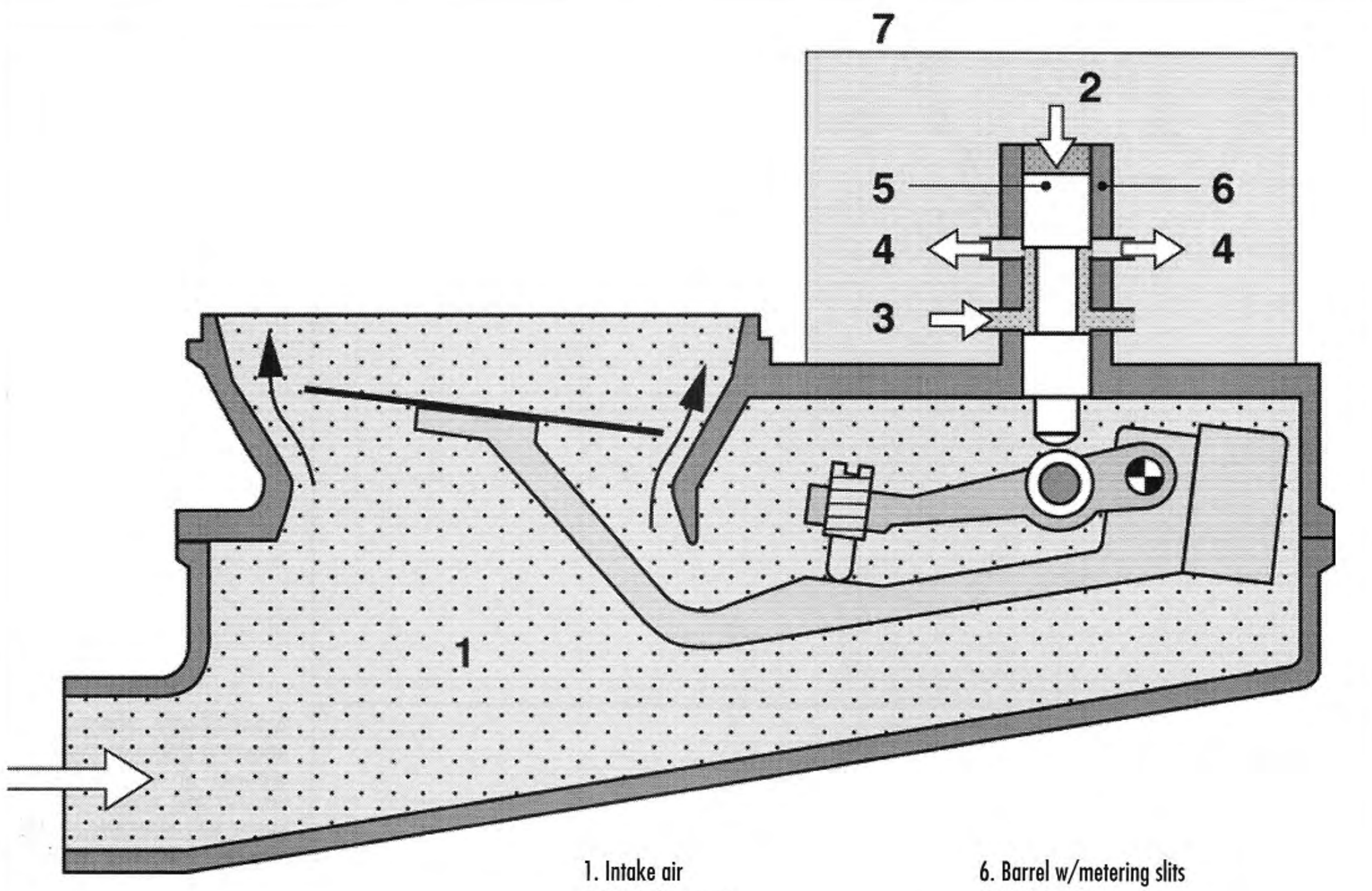


A funnel with multiple tapers allows a comparatively large amount of sensor plate lift around idle, which provides a slight idle enrichment, and a similar richening effect at maximum flow rate, yet with a taper in between the two that gives more rapid vane lift for a given airflow increase—and so a slight leaning—under light load, medium speed operation.

ishes again, so the increase in flow area for a given travel of the vane will be less, forcing the vane to move further to provide enough flow area, and so richening the mixture for large loads and high speeds.

***Acceleration Enrichment*—**As on L-Jetronic systems, acceleration enrichment is achieved automatically by "overswing" of the metering vane. A sudden increase in airflow as occurs when the driver rapidly opens the throttle will cause the metering vane to quickly lift upward, and assume some new position. The inertia of the vane and lever assembly, however, assures that it will initially "overshoot" that final position. Because the rate of fuel delivery depends on the position of the vane, there will be a momentary enrichment to meet the needs of the accelerating engine.

To prevent damage to the metering vane in the event of a backfire, "wrong way" airflow is allowed to push the vane past its rest

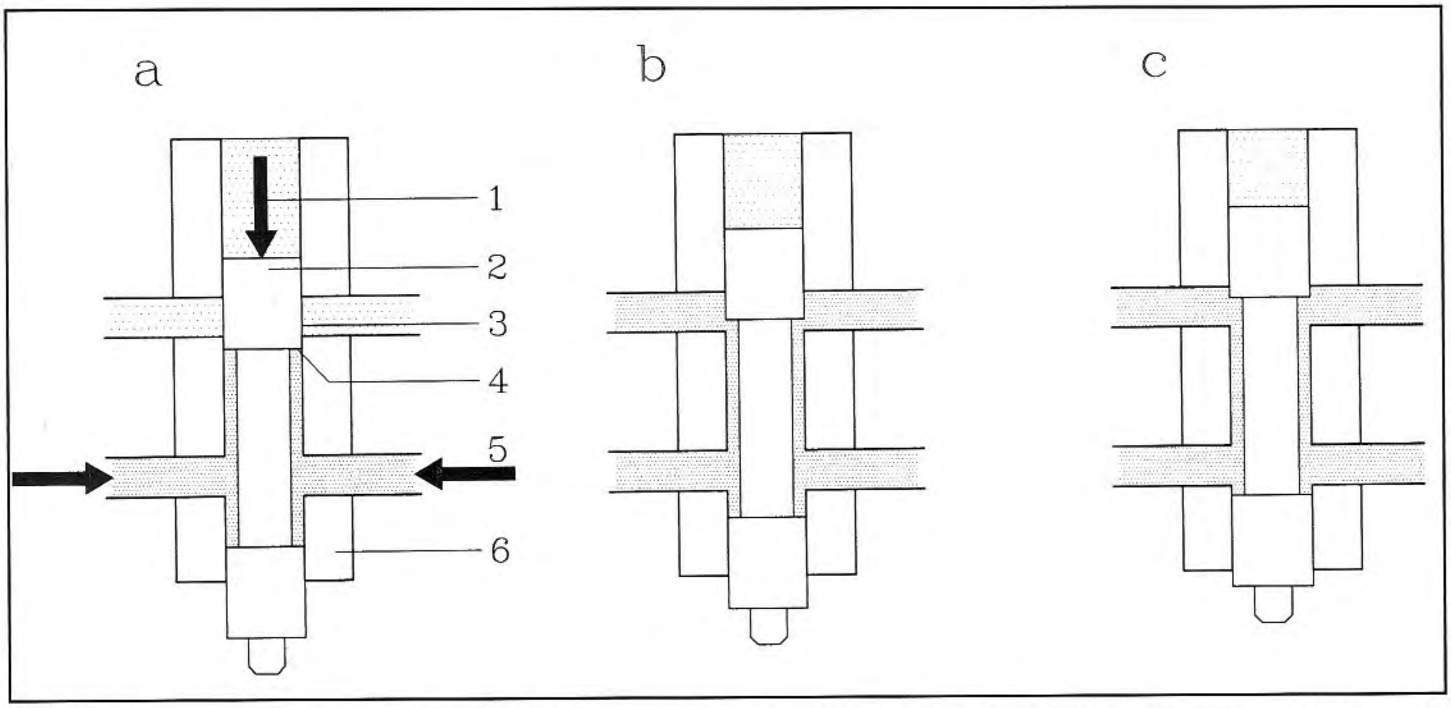


Within the air meter, the sensor plate pushes upward on the control plunger through an intermediate lever. Plunger movement is always upward for more fuel, so on downdraft sensors the pivots of the intermediate lever are reversed. (Robert Bosch Corporation)

(engine stopped) position, to a widening in the funnel that provides enough flow area to vent the backfire without harm. The final limit of travel in this backwards direction is established when the metering vane contacts a rubber bumper.

Clearly, the shape of the funnel determines the variation in mixture strength under different operating conditions. Because of the different breathing characteristics of different engines, the exact contours of the funnel vary from one installation to another. Indeed, the profile of the funnel is the means by which the design engineers tailor a K-Jetronic system for any particular installation. To learn just how the movement of the vane affects the fuel flow rate we have to look inside the fuel distributor.

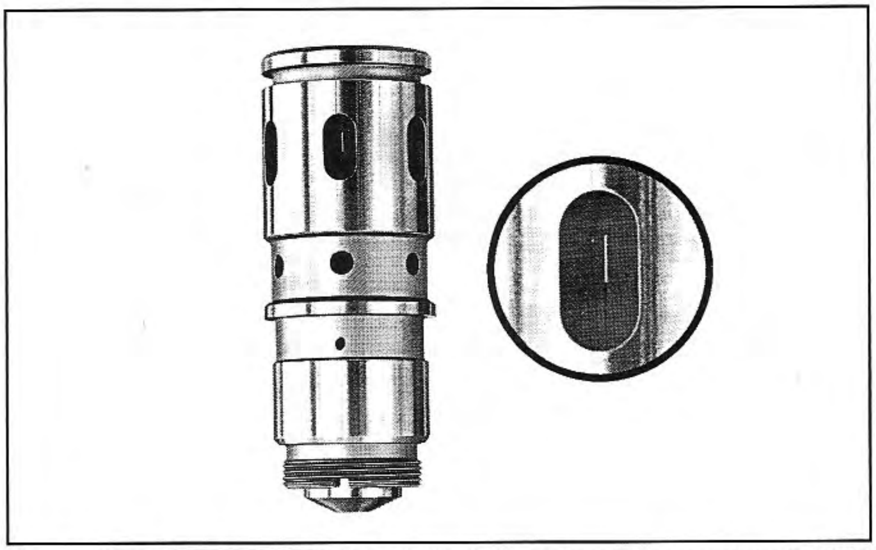
Fuel Distributor—The regulation of fuel quantity takes place in the fuel distributor. The key component here is the control plunger, which slides in a bore within the cast iron housing of the fuel distributor. The bottom of this plunger contacts the metering vane lever, and is pushed upward by the lever in proportion to the extent the air metering vane is deflected by the intake airflow. (The control plunger movement is



Barrel with metering slits and control plunger (a) engine stopped (b) part throttle (c) full throttle. (1) control pressure; (2) control plunger; (3) metering slit in barrel; (4) "control" edge of plunger; (5) fuel in from main pump; (6) barrel.

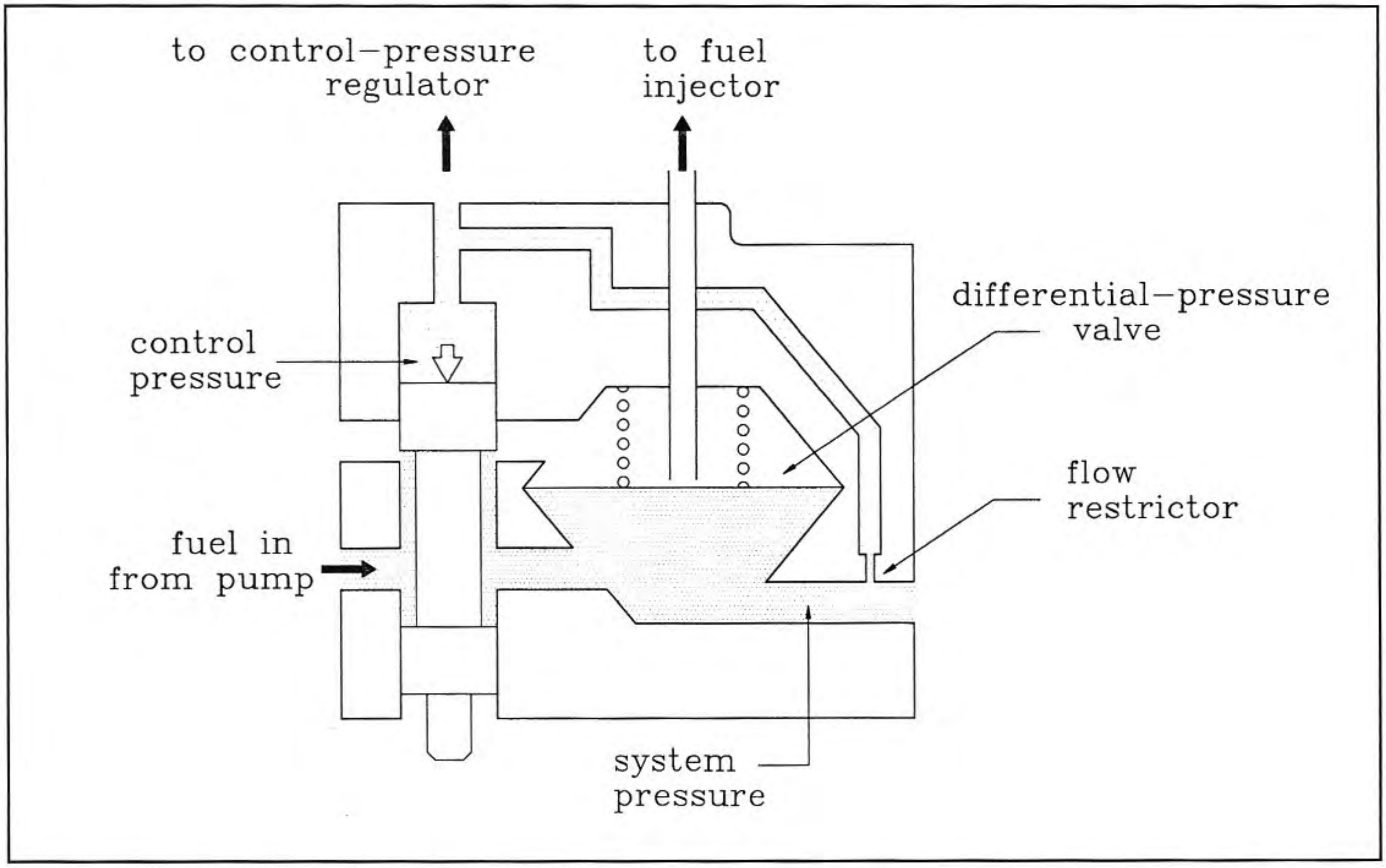
always upward for more fuel, no matter whether the air meter is an updraft or downdraft type. On downdraft versions, the fulcrum for the air vane lever is moved to the opposite side of the plunger to reverse the internal action.)

The plunger looks a bit like the moveable part of a "spool valve," such as you would find in an automatic transmission—it is dumbbell-shaped, with a thin section in the middle and fat ends, with sharp shoulders at the transitions. The bore that the plunger slides in is lined with a precision-machined sleeve (Bosch terms this sleeve the barrel) that has a number of ports cut through the upper part of its wall, in the form of very narrow (about 0.008 inch) vertical slits. With the plunger at the bottom limit of its travel, corresponding to zero airflow—and thus engine stopped—the "fat" upper portion of the plunger completely blocks these ports. As the airflow vane lever pushes the plunger upward, the control edge of the plunger—the sharp shoulder at the meeting of the large and small diameters—progressively uncovers an ever greater length of these slits. With the plunger pushed all the way up, corresponding to maximum lift of the metering vane and thus full power operation, the metering slits are fully exposed.



The position of the control plunger relative to the extremely narrow (about 0.008 in) slits in the metering barrel controls the rate of fuel flow in the K-Jetronic system. (Robert Bosch Corporation)

Fuel Flow—Fuel enters the fuel distributor through a set of ports located so they are always exposed by the reduced diameter central section of the plunger. Raising the



Differential-pressure valves—one for each injector—maintain a constant pressure drop across the metering slits, even as the slit area changes because of control plunger movement. The thin metal diaphragm separating the upper and lower halves of each valve "bulges" in response to changes in the pressure difference between supply-side and delivery-side, tending to block or open up the open end of the nearby tube feeding the injector. This does NOT vary fuel quantity; it just maintains a constant pressure drop.

plunger thus allows fuel to flow out through the metering slits and on to the injectors, in a quantity that is proportional to the height of the plunger. (In some respects, this vaguely resembles the fuel metering arrangements of the Rochester continuous FI mentioned in Chapter 2, but note that fuel escaping through the Rochester's spill ports is returned to the tank; it is the remainder of the pump output that goes to the injectors, opposite to the K-Jetronic's system.)

At first glance it might seem that this arrangement is all that is needed to provide accurate fuel metering—the area of slit exposed is linearly proportional to control plunger lift, which is linearly proportional to metering vane lift, which, in turn, is proportional to airflow rate, with mixture strength corrections for different operating regimes provided by the varying taper of the air intake funnel. Alas, it is not that simple.

Differential Pressure Valves—Fuel passing through the metering slits is propelled by the pressure difference between the supply side—below the control edge of the plunger—and the delivery side, outboard of the slits. For a given exposed area of slit, the fuel flow rate will be proportional to this pressure difference. At the same time, for a given pressure difference, the fuel flow rate will be proportional to the exposed slit area.

The awkward complication is that, without some other mechanism to perform a correction, the pressure difference across the slits varies according to how far open the slits are! If only a small length of slit is exposed, there will be a large pressure difference between supply and delivery sides; a fully open slit will experience a lower pressure difference. Thus, while there is a one-to-one relationship between vane movement and plunger lift, and between plunger lift and exposed slit area, there will not be a one-to-one relationship between exposed slit area and fuel flow rate. The greater the exposed slit area, the less the pressure difference, so while an increase in slit area will flow more fuel simply because the hole is bigger, the increase will be greater than proportional because there is now less pressure difference between the inside and the outside of the barrel to resist the flow, so the mixture strength will tend to become richer with every increase in airflow through the meter. To correct for this nonlinearity, the fuel distributor also contains a number of differential pressure valves, whose function is to maintain a constant pressure drop across the slits, no matter what the rate of fuel flow through them.

Valve Construction—Each differential pressure valve comprises two chambers—an upper and a lower—separated by a thin, flexible metal diaphragm, backed by a spring. There is one valve for each injector, and thus one for each engine cylinder. The upper chamber of each valve communicates with one slit in the barrel (there is one barrel slit for each injector), while each lower chamber is connected to the annular space surrounding the slim central part of the plunger and thus is exposed to the same, constant supply-side fuel pressure. Fuel emerging from each slit flows through the upper chamber of its dedicated differential pressure valve on its way to the injector.

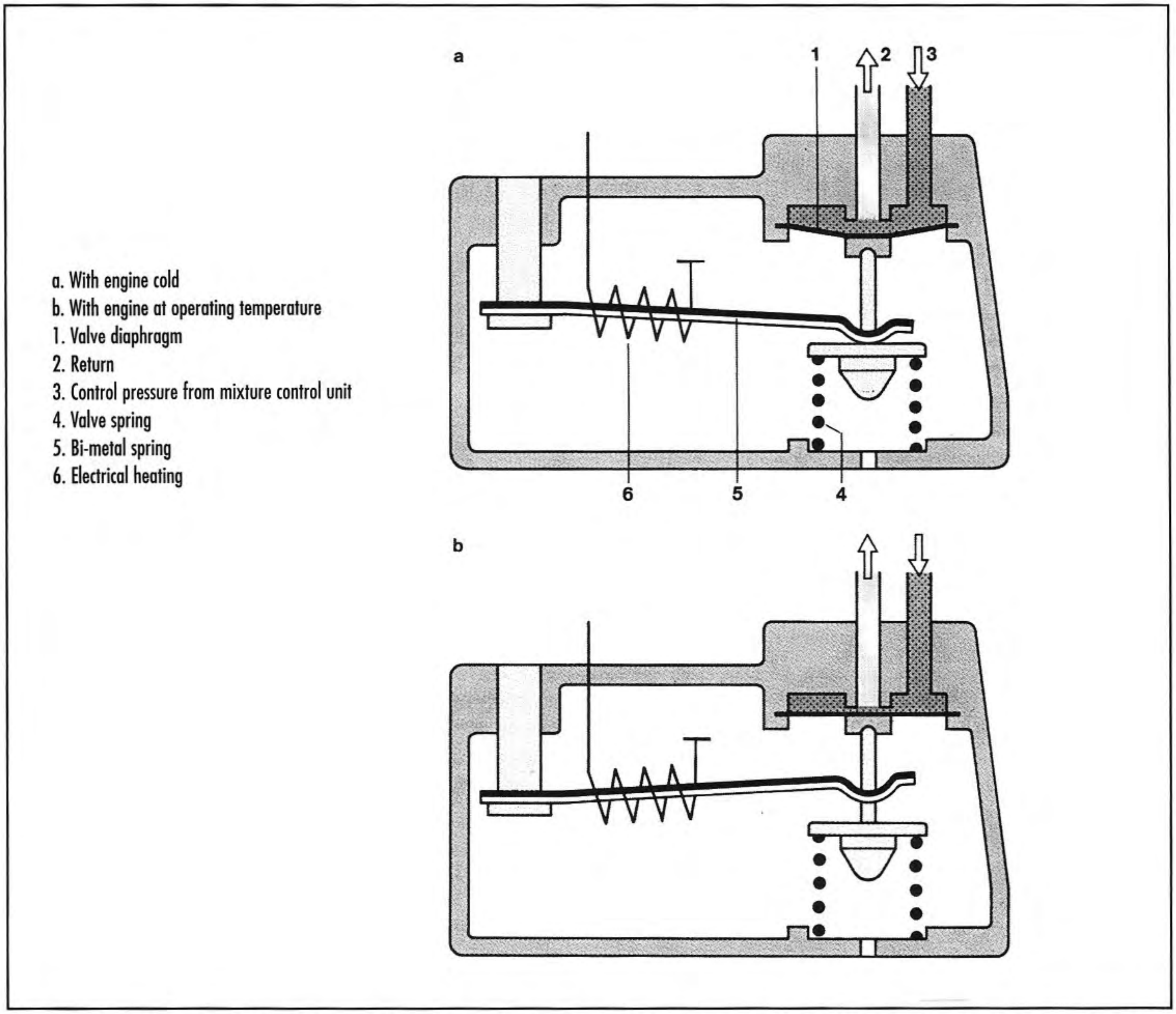
The outlet from the upper chamber of each differential pressure valve is located just above the diaphragm separating the two halves of the valve, so upward deflection of the diaphragm tends to restrict the outflow, while downward deflection provides a greater passage area. It is important to recognize that this apparent "throttling" of the flow through the valve does not affect the quantity of fuel delivered—that is established by the exposed area of the metering slits. All that the movement of the diaphragm does is to maintain a constant pressure drop across the metering slit it serves. Fuel flows out from each differential pressure valve to the injector associated with it at system supply pressure minus, typically, about 1.5psi, the difference being a result of the force of the spring acting on the valve diaphragm.

Control Pressure and Its Regulation

In reading the description of the air meter, above, it may have occurred to you that there is a component missing. Without a spring, or some other mechanism to return it to its rest position, even the smallest rate of airflow would immediately drive the metering vane to the limit of its travel, and it would stay there, with the control plunger shoved fully up into the maximum fuel flow position. The force that tends to drive the plunger—and thus the metering vane—back down is not a spring, but rather the closely regulated pressure of fuel acting on the top of the plunger.

This pressure is neither the full system supply pressure, nor the very slightly lower pressure prevailing in the upper chambers of the differential pressure valves, but rather a still lower pressure that Bosch terms the control pressure. This control pressure acting on the plunger top produces a downward force that counteracts two upward acting forces—a minor one is atmospheric pressure acting on the exposed lower end of the plunger; the major one is the force on the plunger exerted by the metering vane, via its lever.

The position of the plunger in its barrel is thus the result of a sort of hydraulic balancing act between the force of the incoming air acting on the metering vane and the control pressure acting on the plunger. An increase



The control pressure regulator, previously termed the "warm-up" regulator (a) with the engine cold (b) with the engine warm. (Robert Bosch Corporation)

in the control pressure will increase the force acting on the top of the plunger, which opposes movement of the air metering vane. The vane will not move as far as it otherwise might, the control plunger will not rise as high, and so less of the metering slits will be uncovered. Conversely, a reduction in control pressure will allow the vane and plunger to rise higher, uncovering more of the slits. Thus, a higher control pressure will lean the mixture; a lower one will richen it.

Regulator—The control pressure, in turn, is regulated by the control pressure regulator (a reasonable name!). The regulator maintains a constant pressure downstream with a spring loaded valve that opens at the set pressure and allows fuel to recirculate back to the tank. It should be clear from the above description that, in a given installation, the air/fuel ratio depends entirely on the control pressure. Use is made of this fact for warm-up enrichment, indeed the original name for the control pressure regulator was warm up regulator (WUR).

The control pressure/warm up regulator is supplied with fuel from the fuel distributor; a second fuel line leads from the regulator back to the tank. Within the regulator, a flexible metal diaphragm is held very close to the port leading to the return line by a pair of springs, one a coil, the other a leaf spring. If the control pressure tends to drop for any reason, the force of the springs forces the diaphragm even closer to the return port, obstructing the flow and so raising the pressure again. Similarly, if the control pressure attempts to rise, the diaphragm will bulge away from the return port allowing more flow and thus dropping the pressure.

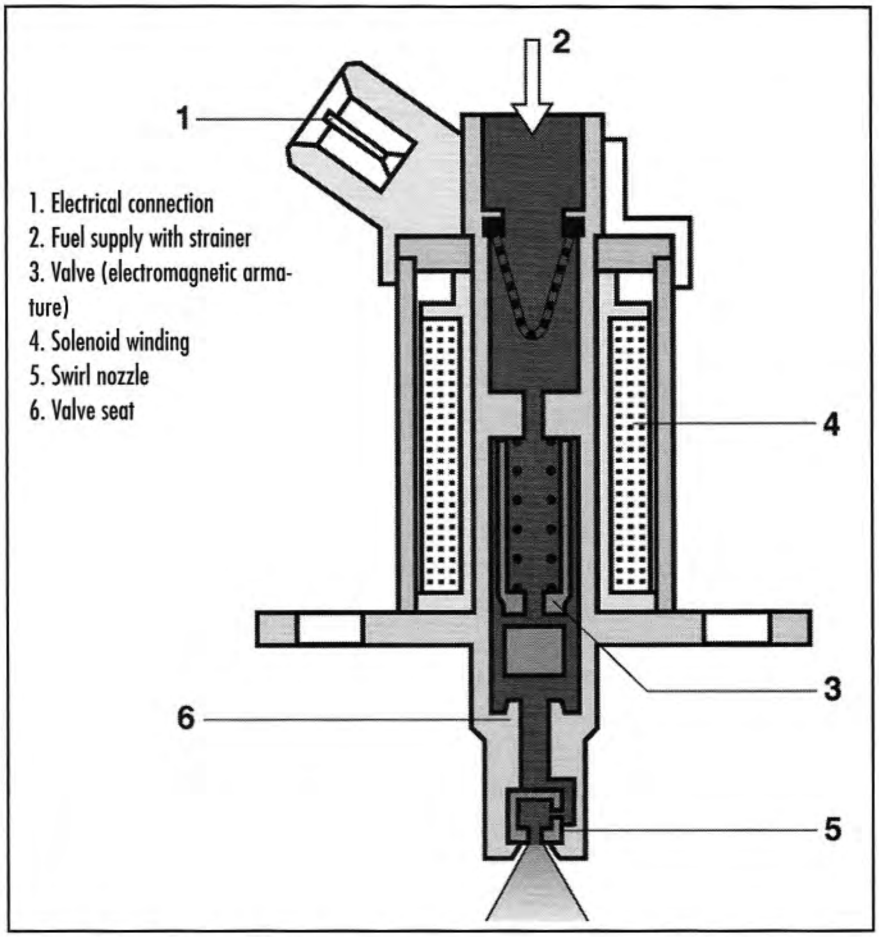
To achieve the enrichment needed for warm up, the leaf spring is made as a bimetallic strip. When cold, it bends downward, which opposes the coil spring and so allows the diaphragm to move further from the return port. That allows more fuel to flow back to the tank, thus dropping the control pressure. At Montana-in-February temperatures, a typical control pressure might be as low as 7–8 psi; on a fully warm engine, the control pressure will be about 50–55psi. The WUR is invariably mounted on the engine block, or somewhere else that runs at engine temperature, so the effect is suppressed when the engine is warm.

With an engine started from stone cold, the bimetallic leaf would gradually straighten out again as the engine warms up, which would raise the control pressure and so lean the mixture back to the standard operating air/fuel ratio. Trouble is, this would take too long—maybe ten minutes or more—and the engine would run excessively rich during the later stages of warm up. To avoid this, the bimetallic leaf has a heating coil wound around it, very much like the thermo-time switch that runs the cold start injector on the L-Jetronic, as described in Chapter 3. This heater is powered every time the ignition switch is turned on; after just a couple of minutes, even in freezing temperatures, it will have bent so as to return the leaf to its basic position, and so restore the control pressure to the basic setting.

On some versions of K-Jetronic, the control pressure regulator is given the further function of modulating control pressure according to engine load, increasing mixture strength under conditions of low vacuum/high pressure in the intake manifold. This additional function justified the name of the device being changed from "warm up regulator" to "control pressure regulator." This modified form of control pressure regulator is most often found on turbocharged engines, but some normally aspirated models use it, too.

This later, wider purpose control pressure regulator can be recognized from its two-piece construction, contrasted with the one-piece WUR. The extra section contains a second diaphragm within a separate sealed chamber. One side of the diaphragm is vented to the atmosphere, while the other side faces the "original" part of the control pressure regulator, which is connected by a vacuum hose to the manifold. That second diaphragm serves to support a second coil spring nested within the main coil, like "dual" valve springs. With high manifold vacuum, corresponding to ordinary light loads, the manifold vacuum pulls the diaphragm to the "basic" position.

When manifold vacuum drops to near atmospheric pressure, as during full throttle running (or when turbo boost drives manifold pressure above atmospheric), the diaphragm is pushed down to the high-load position. Because the supplementary coil spring is supported by the diaphragm, it no longer contributes to shoving on the other, "original" diaphragm that restricts return flow to the tank, so the return flow increases. Accordingly, the control pressure drops, the control plunger in the fuel distributor is allowed to rise further from the force applied by the metering vane, more slit area



A cold start injector (cold start valve), shown in the "on" state. (Robert Bosch Corporation)

is uncovered, and a richer mixture is thus provided for high load conditions.

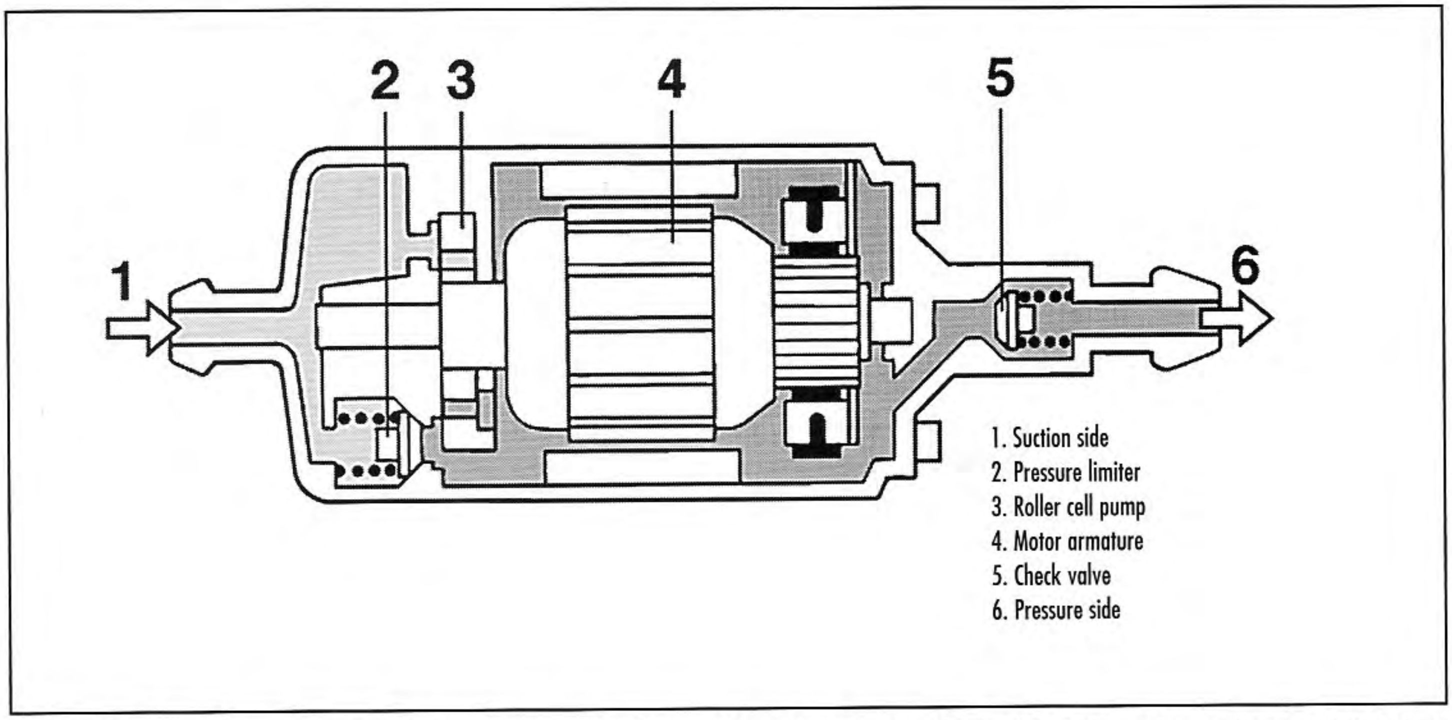
Other Cold Running Corrections

The degree of enrichment achievable by modification of the control pressure is limited by the maximum flow capacity of the fuel slits in the barrel of the fuel distributor. Since it would be uneconomical to design a distributor having enough range to accurately meter fuel for both the tiny appetite of a warm idling engine and the voracious one of an engine attempting a cold start in a Canadian winter, this latter, worst case situation is catered for by a cold start injector, or "cold start valve," as Bosch terms it, the same arrangement as that used on the intermittent systems discussed in previous chapters.

Cold Start Injector—The cold start injector is a solenoid valve, similar in design and construction to the electromagnetic injectors on the intermittent systems, that injects fuel into the intake manifold. As with the cold start injectors used on intermittent systems, power is fed to it whenever the starter is energized, but the circuit is only completed when a thermo-time switch is closed. This switch contains the by-now-familiar electrically heated bimetal spring/switch arrangement. When cold (below about 95° F), the switch is closed, grounding the injector and thus energizing it, allowing fuel to flow when the starter is energized. When hot, the bimetallic leaf bends, breaking the electrical contact and thus shutting off the injector. At sub-zero temperatures, the cold start injector will operate for five to twelve seconds, until the electric heater warms the leaf. To prevent the switch from actuating the injector on an already warm engine, the thermo-time switch is screwed into the engine water jacket (or a cylinder head on air cooled engines), where engine heat will keep the switch open.

Auxiliary Air Bypass—Another cold start feature reminiscent of the intermittent systems is an auxiliary air bypass. Because there is no fast-idle cam, the internal friction of a cold engine could reduce the idle speed so much that the engine might stall. The auxiliary air bypass (on the K-Jetronic, Bosch calls it an auxiliary air device) provides a reasonable idle speed by allowing some air to bleed around the nearly closed throttle.

This bypass comprises a housing containing a small perforated disc valve that controls airflow through an air bypass channel, according to the position of the disc, which is governed by a another electrically heated bimetallic strip/leaf spring. When the leaf is warm, the valve is completely closed; when very cold, it is fully open; at intermediate temperatures, it adopts a position somewhere in between, providing a smooth and gradual transition as the engine warms up. To prevent it admitting an excess of air when the engine is warm, the auxiliary air device is mounted somewhere on the engine



The roller cell fuel pump. The rollers fit loosely in their lands; centrifugal force pushes them against the contoured interior of the pump body. (Robert Bosch Corporation)

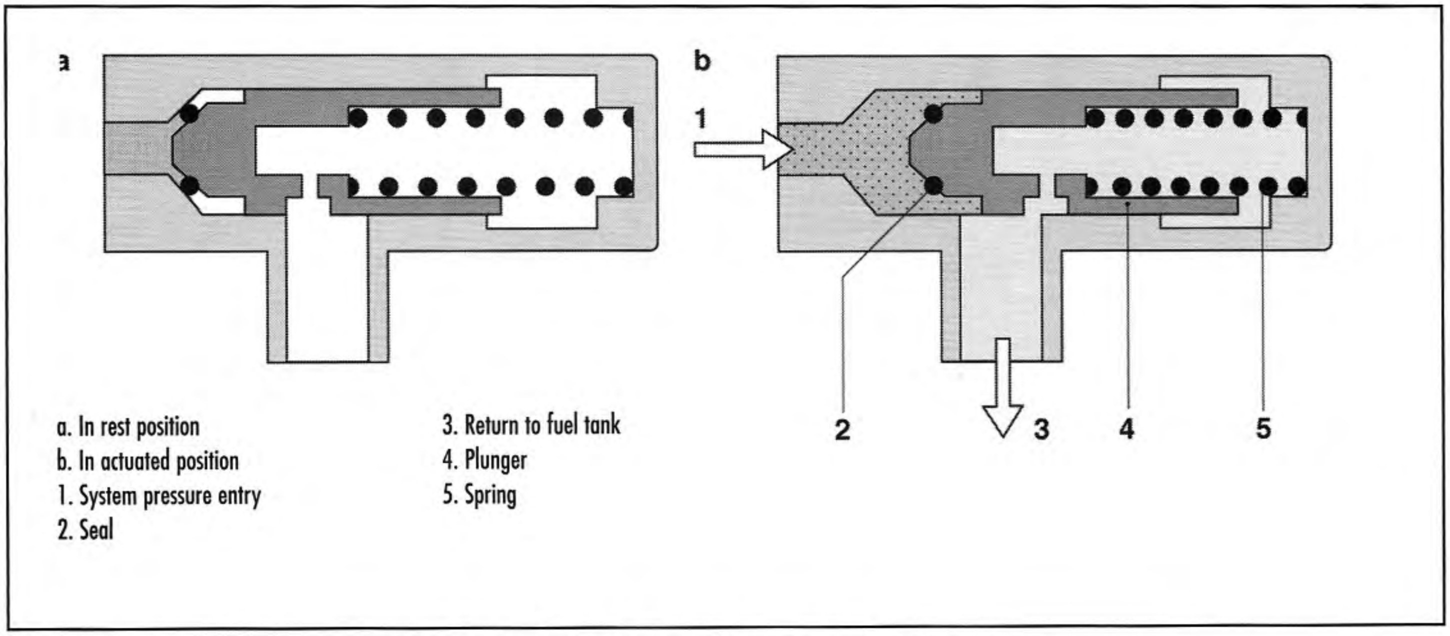
where it will be warmed by engine heat, thus it is usually mounted remote from the throttle body, with connection by hoses. In this regard it is just like the thermo-time switch for the cold start injector. However, unlike the functioning of the thermo-time switch/cold start injector, which is never in operation for more than a few seconds, in very cold weather the auxiliary air device can take several minutes to move from fully open to fully closed.

Idle Air Bypass—Do not confuse this auxiliary air device with the idle air bypass, which provides another parallel route around the throttle plate(s). To allow adjustment of idle speed, a small amount of air is allowed to bypass around the throttle through a separate small passageway. The amount of air that is bypassed in this way can be adjusted by a small needle valve, and this is the only means that should be used to adjust the idle, never the throttle stop setscrew.

Pumps and Plumbing

The K-Jetronic uses the same basic design of roller cell electric fuel pump as the intermittent systems described in previous chapters, but regulated at a much higher pressure—typically 75 psi, vs the 35 psi or so of the intermittent systems. Because these pumps push much better than they pull, the pump is mounted low down, often within the tank itself. If the pump is not physically within the tank, a second lift pump—sometimes called the "prepump," or "transfer pump"—may be used to supply the main pump from the tank.

Shut-Off Valve—Usually, the pump is energized, via a relay, whenever the ignition is on. However, if a fuel line ruptures, perhaps because the vehicle has become involved in an accident, there is clearly a severe fire hazard; the fuel pump might continue pumping fuel into a blaze. To reduce the risk of this, a safety shut-off is incorporated. In early versions of K-Jetronic—up to about 1977—this takes the form of a simple contact switch under the air metering vane. If the fuel supply to the engine is cut off because of a severed line, the engine will stop, the airflow will cease, and the vane



Primary (system) pressure regulator, fitted to the fuel distributor. (Robert Bosch Corporation)

will drop to its rest position. This opens the safety switch, which opens the circuit to the relay, interrupting current to the pump . . . unless of course the vehicle has come to a stop inverted!

To avoid the hazard potential in this arrangement, later versions of K-Jetronic, and all K-lambda and KE-systems, use the operation of the ignition system as the indication that the engine is running. Pulses from the primary circuit of the ignition coil are fed to the relay, where a simple internal circuit evaluates them. If the ignition ceases to provide regular electrical pulses, the pump relay shuts off, stopping the pump. Cranking speed is sufficiently high to satisfy the relay—sometimes called the "safety" relay, sometimes the "control" relay—that the engine is running.

Fuel Accumulator—Downstream of the system pump is a fuel accumulator. This is simply a chamber containing a diaphragm and spring. Assuming the accumulator to be empty, on pump startup the fuel pressure pushes the diaphragm against the spring resistance as fuel begins to fill the accumulator, until the force of the spring balances the pressure of the fuel. This takes about one second, during which time the pressure at the fuel distributor rises gradually, thus protecting it against the sudden pressure surge it would otherwise experience. The "shock absorber" characteristic of the accumulator also helps to damp fluctuations in fuel pressure that might result from, say, a sudden large electrical load causing the pump to briefly slow.

When the pump stops on engine shut down, the fuel pressure drops rapidly at first, but the spring in the accumulator continues to push on the diaphragm, holding a residual pressure in the system of about 30psi. This helps ensure quick restarts on a hot engine, and also helps reduce the chance of vapor lock as the now noncirculating fuel continues to pick up heat from a hot engine. A replaceable fuel filter lies downstream of the accumulator.

Pressure Regulator—Because K-series systems depend on pressure balances within the system for accurate fuel metering, exact control over system pressure is essential. Fuel pressure within the primary system (as opposed to the control pressure) is governed by a pressure regulator, built in to the fuel distributor. There are two versions of this device. The first is a simple plunger and spring arrangement, in which the fuel pressure pushes on the plunger, against the resistance of the spring, until the plunger uncovers a relief or "spill" port in the side of the regulator housing, allowing surplus fuel to be recirculated back to the tank. A later design, used after about 1978, incorporates a second check valve that seals off the return line from the fuel distributor. This second "push valve" is mechanically connected to the relief valve that governs primary system pressure. Thus, when the pump stops and the spring in the regulator shoves the plunger against its seat (which is the "dead end" against which the accumulator continues to press), the "push valve" is also pulled shut, helping to maintain residual pressure within the control circuit, with benefit to hot restarts, as noted above for the accumulator.

In the operation of the K-Jetronic, a very large fraction of the fuel supplied by the system pump winds up getting returned to the tank. This fuel passes near the hot bits around the engine, and picks up more heat by being pumped through numerous orifices. To ensure thorough intermixing of the hot returned fuel and the cool fuel in the tank, the fuel tanks on K-Jetronic systems are usually quite tall in relation to their width.

An immediately visible feature of an engine equipped with K-Jetronic is the individual fuel lines leading from the fuel distributor to each injector. Unlike the intermittent systems, there is no "ring main" that connects all the injectors.

Fuel Injectors

The injectors themselves are much simpler devices than those used on the intermittent systems. They play no part in metering fuel; their only task is to atomize it. An internal check valve opens when the pressure of the supplied fuel exceeds the resistance of a small spring within the injector, and as long as the system pressure acts, the injector sprays. While this opening pressure obviously has to be less than full system pressure, note that it is more than the residual pressure in the system when the engine is stopped, to prevent the injectors from dribbling fuel into a stopped engine.

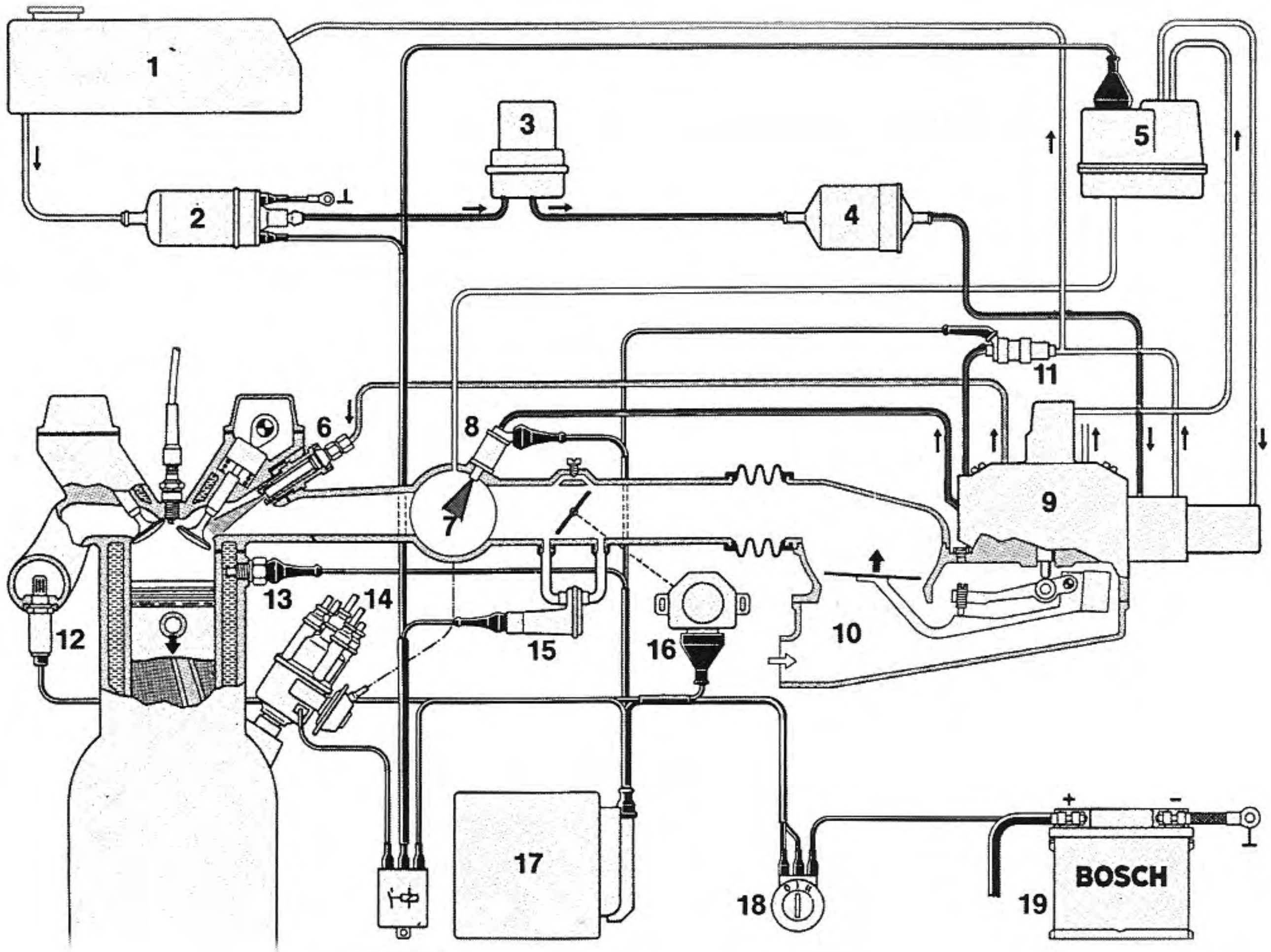
Atomization is aided by the design of the check valve, which incorporates a small pin that oscillates or "chatters" in the flow of fuel around it, helping to break the liquid fuel into tiny droplets. (The vibrations of this pin are quite audible when an injector is working). When fuel pressure ceases, the spring reseats the pin, blocking fuel flow and maintaining pressure in the lines, helping to ensure a rapid restart. There are no electrical connections, and nothing much to go wrong, unless an injector becomes plugged.

K-Lambda System

Progressively stricter emissions limits imposed throughout the latter part of the 1970s taxed the mixture control capabilities of the basic K-Jetronic system described above. In response, Bosch adapted lambda control to their K-system. Starting in the 1980 model year, almost all manufacturers using the continuous system changed to this improved version. (For more details on the lambda sensor and its operation, see the sidebar "The Oxygen Battery," in Chapter 2).

Basic System Operation & Components

In the K-Jetronic with lambda—K-lambda for short—the lambda sensor in the exhaust pipe sends information on the oxygen content in the exhaust gasses to an electronic control unit. The control unit, in turn, sends signals to a lambda valve which modifies the mixture strength. If the sensor reports a high oxygen level, then the mixture is too lean, so the electronic control commands the lambda valve to richen the mixture; if the sensor reports low levels of oxygen, the engine is running rich, so the control tells the lambda valve to lean the mix-

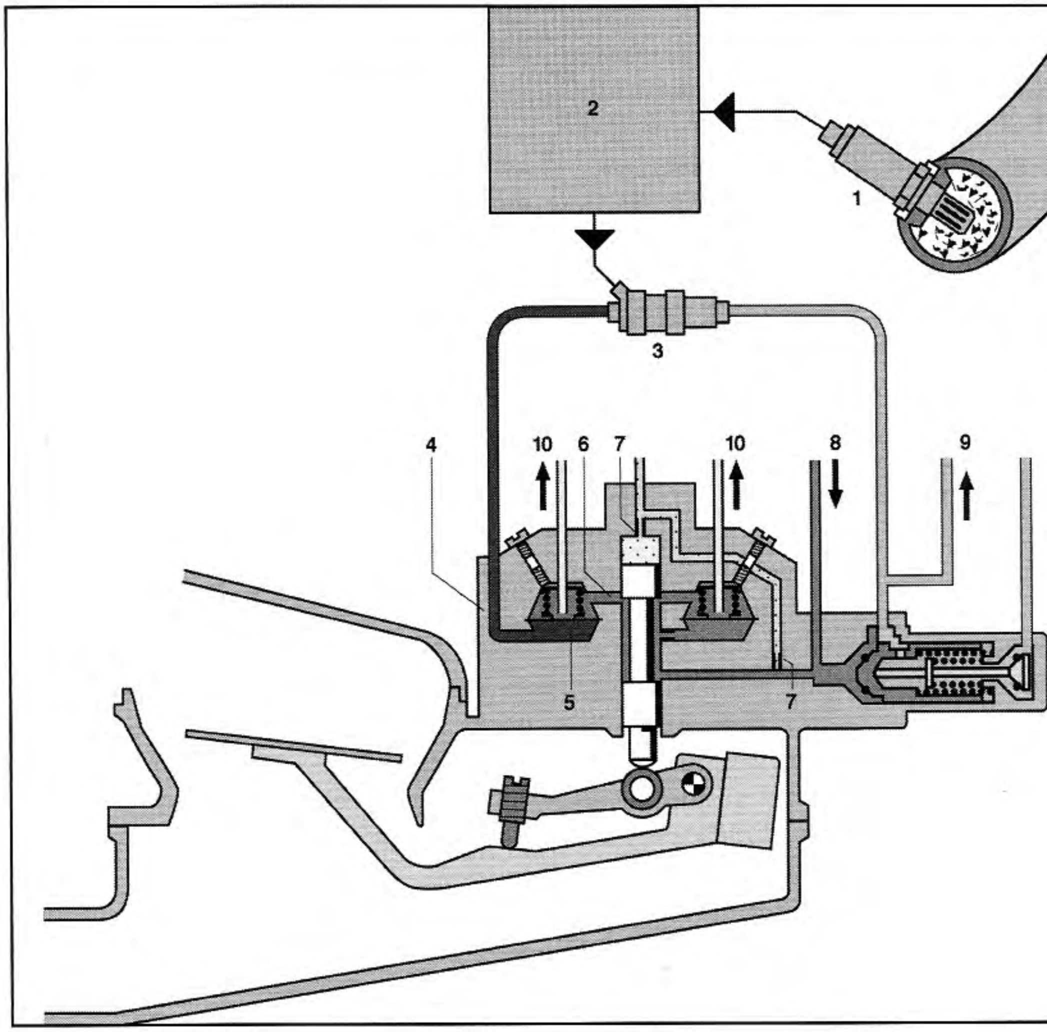


1. Fuel tank
2. Electric fuel pump
3. Fuel accumulator
4. Fuel filter
5. Warm-up regulator
6. Injection valve
7. Intake manifold
8. Cold start valve
9. Fuel distributor
10. Airflow sensor
11. Timing valve
12. Lambda sensor
13. Thermo-time switch
14.Ignition distributor
15. Auxiliary air device
16. Throttle valve switch
17. Control unit
18. Ignition and starting switch
19. Battery

Schematic diagram of the K-Jetronic system with closed-loop lambda (oxygen sensor) control. (Robert Bosch Corporation)

ture out a bit. This closed-loop feedback control means that the control unit is continuously "chasing the ball," richening in response to a "lean" signal, then leaning in response to the "rich" signal. As a result, the air/fuel ratio is constantly oscillating around the stoichiometric value that is necessary if the catalytic converter is to do its job, though always within some fraction of one percent.

To understand how the lambda valve modifies the air/fuel ratio, we first have to back up a bit. Recall that we explained that the differential pressure valves in the plain-vanilla K-Jetronic are there to maintain a constant pressure drop across the metering slits in the fuel distributor barrel, so the rate of fuel flow through the slits is purely a function of the area of slit exposed. Without this stabilizing influence, increasing the exposed area of the slits would increase fuel flow, but because of the added flow, the



Additional components for closed-loop lambda (oxygen sensor control of K-Jetronic system. (Robert Bosch Corporation)

pressure drop across the slits would decrease, so the flow increase would be greater than might be expected on the basis of the slit area increase alone.

The lambda valve functions by, in effect, fighting the stabilizing influence of the differential pressure valves, by adjusting the pressure in the lower chambers of the valves. Recall that in the basic version of K-Jetronic, the lower chambers of the differential pressure valves are always operating at primary system pressure, while the upper chambers are operating at system pressure, minus the pressure attributable to the force of the spring. If the pressure in the lower chambers were to drop for any reason, the pressure in the upper chambers will likewise drop—it will always be equal to lower chamber pressure minus spring force.

A drop in pressure within the upper chambers will increase the pressure difference between the primary pressure on the supply side of the slit and the delivery pressure inside the upper chamber, and so increase the fuel flow for a given amount of exposed slit area. Thus, a drop in pressure in the lower chambers richens the mixture for a given metering vane/control plunger position, and an increase in pressure there will lean-out the mixture.

Controlling Pressure—K-Jetronic with lambda allows the lambda valve to control the pressure in the lower chambers by introducing a new fuel circuit that supplies fuel to the lower chambers through a restriction, then bleeds fuel off for return to the tank via the lambda valve. The more the lambda valve restricts that return flow, the higher the pressure builds in the lower chambers, so the higher the pressure becomes in the upper chambers, the less pressure drop is experienced at the slits, so for a given plunger position, the mixture is leaned out. Conversely, if fuel flows more readily through the lambda valve, the pressure in the lower chambers will drop, so the pressure in the upper chambers will drop, the pressure drop across the slit will increase, more fuel will flow, and the mixture is richened.

The lambda valve "turns the tap" not, as you might suppose, by varying the size of some orifice, but rather by alternately—and very rapidly—completely opening and completely shutting a passage of fixed size. If this begins to sound familiar, then you have remembered the operating principle of the electromagnetic injectors of the L-series of Jetronics, described in earlier chapters; the lambda valve closely resembles one of those injectors, both in function and appearance.

***Duty Cycle*—**The signals sent from the electronic control to the lambda valve amount to pulses of current that hold the valve open as long as the pulse lasts; when a pulse ends, the valve closes. The average rate of flow through the valve over any reasonable time period, then, is a function of how long the valve stays open compared with how long it is shut. This relationship between on-time and off-time—called the duty cycle—establishes the average rate of flow from the lower chambers to the tank, via the valve, and thus controls the mixture strength in the way described above.

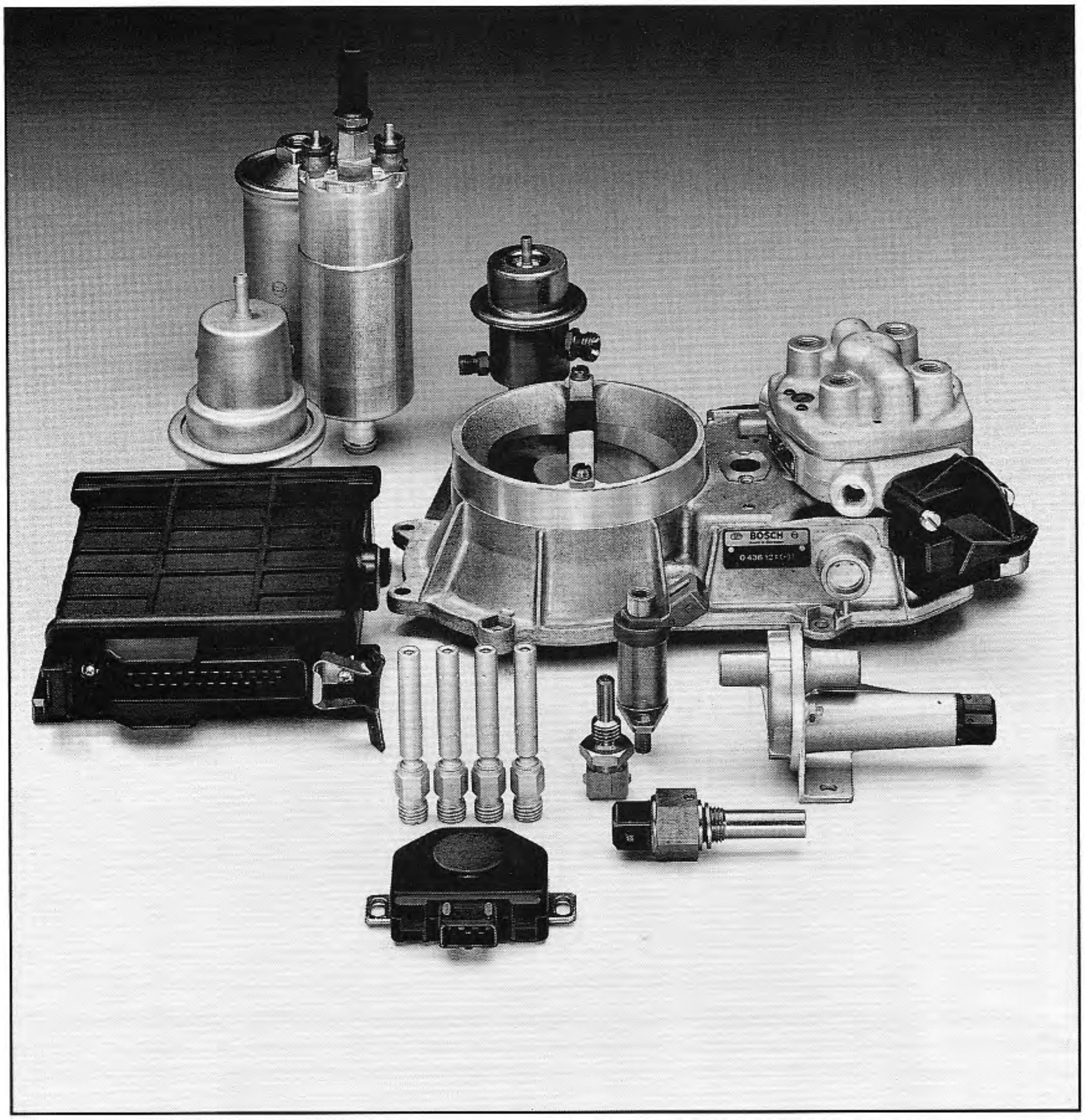
Assuming a reference duty cycle of 50% (the valve is open half the time and closed the other half), then if the duty cycle is shifted to 45% (valve open 45% of the time, closed 55% of the time), the rate of flow through the valve will diminish, the pressure in the lower chambers will increase . . . and so on, and the mixture will become leaner. If the engine is basically healthy, in practice the electronic controller keeps the duty cycle varying in the range of 45%–55%, in response to information from the lambda sensor.

As mentioned in Chapter 2, however, a lambda sensor needs to be heated to at least 300° C (about 570° F) before it functions. Thus, at cold engine startup, the sensor is inoperative, and the system operates in open-loop mode. To cope with the uncertainties in mixture strength during cold starts and warm-up, some K-lambda installations are equipped with a thermo-time switch. Information from the thermo-time switch that the engine is cold causes the controller to supply a fixed duty cycle of about 60% as long as the thermo-time switch is closed. The thermo-time switch self-heats sufficiently to switch off before the lambda sensor warms up enough to become operational, however, so at this point the controller reduces the duty cycle of the lambda valve to somewhere between the cold start value of 60% and the closed loop 45–55% value.

KE-Jetronic

While the addition of lambda control enabled K-Jetronic systems to meet emissions limits up to the early 1980s, it was not consistently able to meet the stricter limits then being introduced. To further tighten control over mixture strength, the same basic system was refined by the addition of numerous other sensor inputs, and a much expanded role for the electronic control unit, which was now equipped with the same sort of electronic memory storing engine load/speed/fuel flow "maps" as used on intermittent systems. This "KE-Jetronic" first appeared on the 1984 Mercedes 190.

The array of new sensors resembles that on intermittent systems. New sensors include: an engine rpm signal, fed from the ignition system; a full throttle and a closed throttle switch; an engine temperature sensor; a potentiometer at the air metering vane, to monitor its position; and, on some vehicles, an air temperature sensor. These, plus



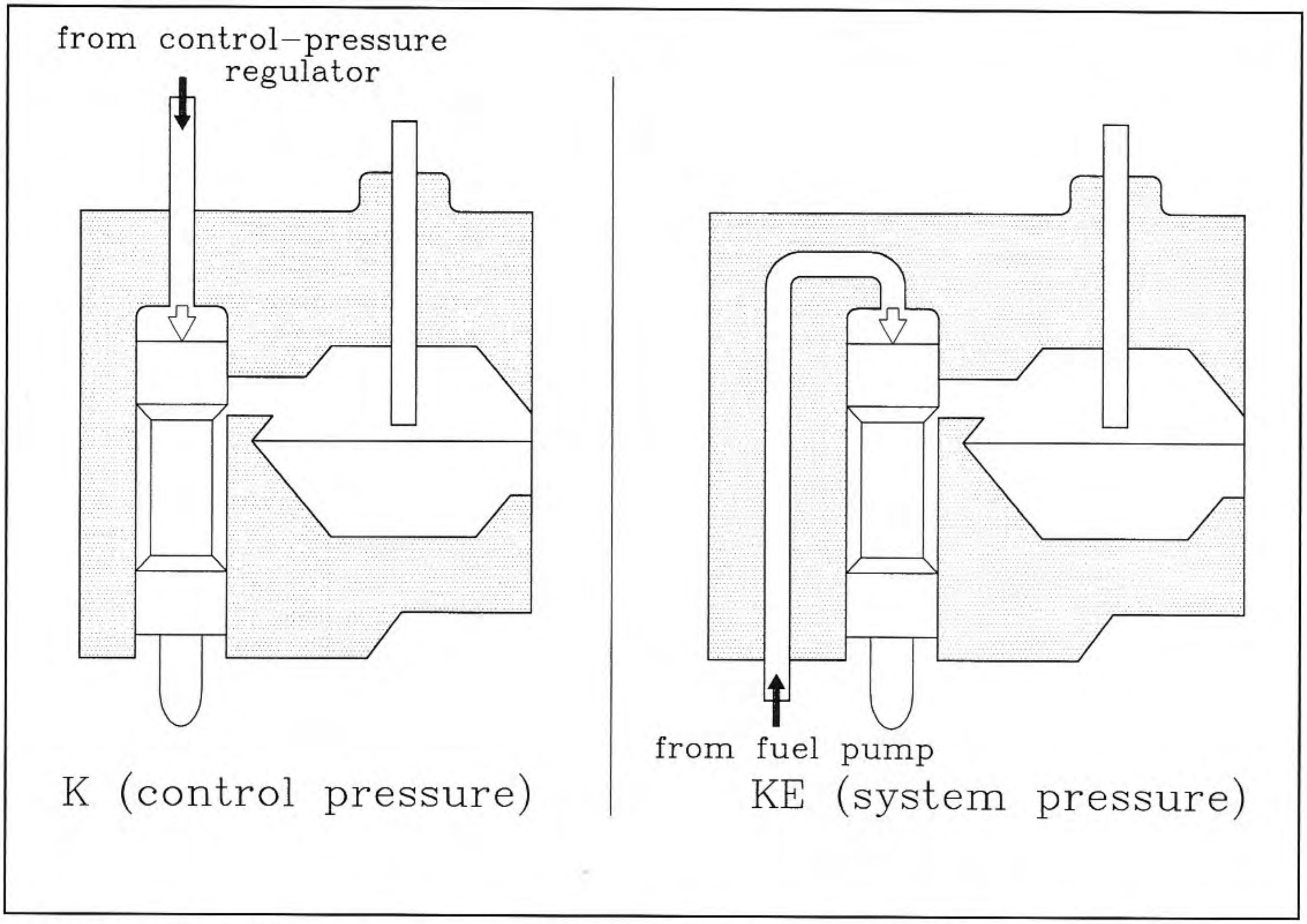
Components of the KE-Jetronic. (Robert Bosch Corporation)

the existing lambda sensor, all feed their signals to the ECU, which modulates mixture strength in a way rather different from both the K- and K-lambda systems.

The basic, all-mechanical, K-Jetronic adjusts mixture strength by varying the control pressure acting on the top of the control plunger, while keeping the pressure drop across the barrel slits constant. The K-lambda system continues to use the control pressure as the main variable, particularly when the engine is cold, but then superimposes a further control—driven by the lambda sensor—by deliberately varying the pressure difference across the slits. In contrast, the KE-Jetronic achieves control over air/fuel mixtures entirely by changes in the pressure drop across the barrel slits; the control force is constant—indeed, it is full primary system pressure, maintained that way by the primary pressure regulator. The device that executes the changes in air/fuel ratio, on instructions from the ECU, is the pressure actuator, a small, light colored box on the side of the fuel distributor.

Basic System Operation & Components

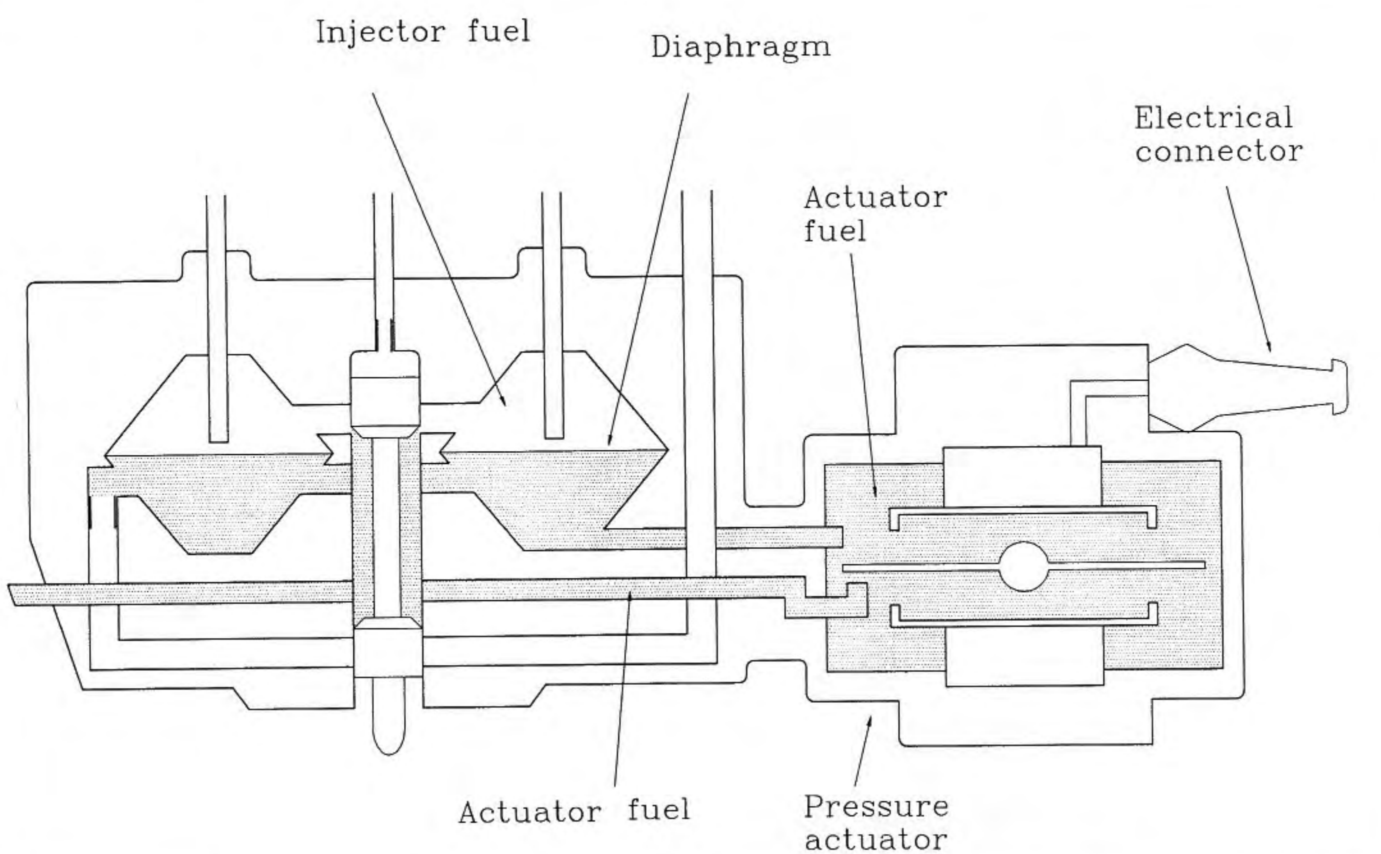
At root, the principle is the same as that in K-lambda systems: for a given position of the control plunger, the rate of fuel flow to



The basic K-Jetronic adjusts mixture strength by varying the control pressure acting on the top of the control plunger, while keeping the pressure drop across the barrel slits constant. In contrast, the KE-Jetronic achieves control over air/fuel mixtures entirely by changes in the pressure drop across the barrel slits; the control force is full primary system pressure, maintained by the primary pressure regulator.

the injectors depends on the pressure drop across the barrel slits, which depends on the difference between the primary system pressure and the pressure in the upper chambers, which last in turn depends on the pressure in the lower chambers. The trick, then, lies in modulating the pressure in the lower chambers. While K-lambda systems achieve this by starting with the fixed primary system pressure going into the lower chambers and varying the resistance to fuel flowing out, the KE systems invert this; they impose a fixed resistance (through a narrow orifice) on the way out and vary the pressure going in.

This is achieved by a thin metal plate that obscures the inlet to the pressure actuator to an extent that depends on the position of the plate. When close to the supply port, the plate restricts flow considerably, so the rate of fuel supply to the lower chambers is proportionally reduced. Because fuel is always flowing out from the lower chambers through the fixed restriction of the narrow orifice, hindering the in-flow will drop the pressure in the lower chambers. Because the upper chambers are always at lower chamber pressure minus the spring force, the pressure in the upper chambers will drop, too, so the pressure drop across the slits will increase, so more fuel will flow for a given plunger position, so the air/fuel mixture will be richened.

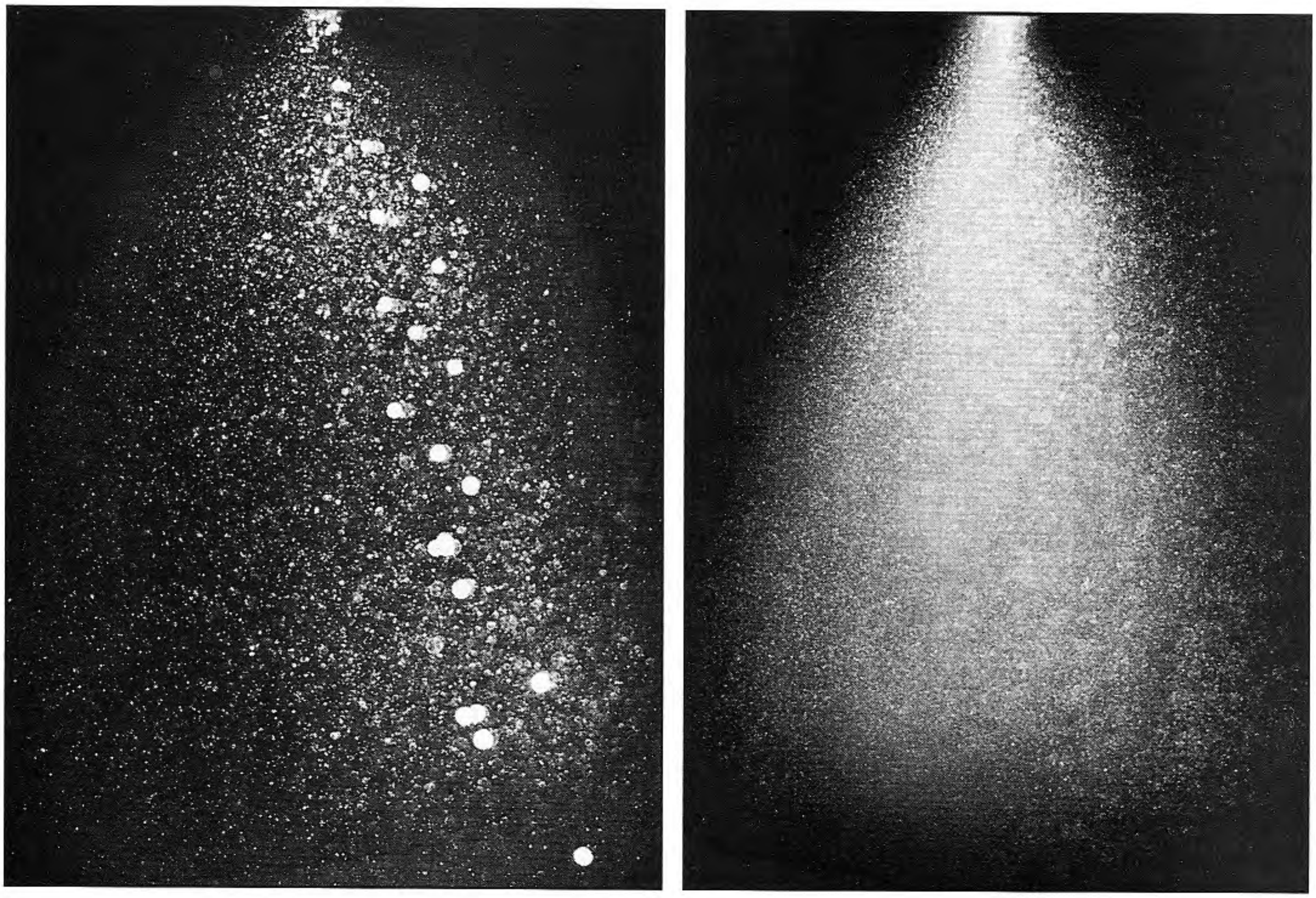


KE systems impose a fixed resistance to flow out of the lower chambers of the differential pressure valves and vary the pressure going in by having a powerful electromagnet bend a thin steel plate toward or away from the supply port.

(In view of the fact that the chambers and diaphragms in the fuel distributor are termed "differential pressure valves," it is a matter of some potential confusion that Bosch also refers to the flow controlling capability of the pressure actuator's control plate in terms of "differential pressure." Technically, of course, this is perfectly correct—the obstruction to flow creates a pressure difference between the inlet to the pressure actuator and the outlet to the lower chambers, thus a "differential pressure" exists between these points—but the possibility of confusion remains.)

The movement of the metal plate in the pressure actuator is accomplished by an electromagnet that pulls the plate down to obstruct the inlet according to the current supplied to the magnet. That current, and thus the mixture strength, is governed by the electronic control unit. With zero current flow—which only occurs with the engine stopped or if there is a component failure—the plate is at its most distant from the fuel inlet to the actuator, so the mixture will be very lean, though still rich enough that a warm engine will continue to run. This is the so-called "limp home" mode.

As long as the system is working correctly, the actuator magnet current on a running engine with early versions of KE-Jetronic will be some small positive value, say 1 milliamp (ma). On a warm idling engine, the current may be somewhere in the order of 10ma; for cold starting and full load, the current may be as much as 70ma. Later versions have different actuator current ranges. On the KE3-Jetronic, the current typically ranges from +10ma (full rich) to -10ma (full lean), while the corresponding range for



Air-shrouded injectors (right) allow a little of the engine's intake air to pass through the injectors themselves, mixing with the fuel as it does so. Very much like the emulsion tube(s) in a carburetor, this improves atomization. (Robert Bosch Corporation)

KE-Motronic systems is more like +23ma to -16ma.

The ECU determines the current to be fed to the pressure actuator on the basis of information received from the various sensors mentioned above. After about 1985, the functioning of the cold start injector was also incorporated into the ECU on some installations, so the thermo-time switch was eliminated. Improved control over the warm up phase is also achieved, by virtue of the engine coolant sensor (and, on some Mercedes Benz models, intake air temperature). Acceleration enrichment is also dealt with in a more subtle way. The "overswing" of the air meter still provides the basic momentary enrichment, but the ECU tailors this further, according to the rate of movement of the metering vane, as reported by the potentiometer there. On the KE3-Jetronic, the ECU also has control over the auxiliary air bypass (also called the idle speed stabilizer valve).

Pressure Regulator—The KE-Jetronic differs from earlier K-systems in two other respects. First, a different type of primary system pressure regulator is fitted. The regulator is no longer integrated into the fuel distributor but is mounted separately. Because there is neither a control pressure regulator nor a lambda valve, the return line from the fuel distributor is connected to the primary system pressure regulator, from where a single return line to the tank carries both the excess from the distributor and that from the regulator.

Air-Shrouded Injectors—The second difference, common to most but not all KE systems, is the use of air-shrouded injectors. In these, a small amount of intake air from a point upstream of the throttle plates is allowed to "leak" into the manifold through passages within the injector itself. This air becomes entrained with the spray of gasoline and helps to atomize the fuel. This provision has greatest effect at idle, when manifold vacuum is high (and thus the pressure difference between the supply point and the point of delivery is greatest); the small size of the "leak" means it has diminishing effect as engine speed and load rise and the total volume of air inhaled grows larger, and the leak delivers ever less as vacuum drops.

KE3-Jetronic and KE-Motronic

In addition to the enhanced mixture control achieved on the KE-Jetronic by numerous sensors and the much greater authority afforded the ECU, KE3-Jetronic and KE-Motronic systems also integrate control over ignition timing. A fundamental difference between these two is that the ignition "brain" on KE3 systems is a separate package from the fuel "brain"; on the KE-Motronic both functions are integrated into the same ECU.

Both these newer systems also include "diagnostics"—the system constantly checks itself for faults. A coolant temperature that rapidly fluctuates, for example, is surely a sensor fault rather than a real reflection of what is going on. Likewise, a lambda sensor that insists that the mixture is excessively lean even if the ECU has richened the mixture much further than its programming says should be necessary probably implies an air leak somewhere.

7 TROUBLESHOOTING BOSCH CONTINUOUS INJECTION

Preventative Maintenance

Note: The information in the first few paragraphs, up to the heading "No User Serviceable Parts Inside," is identical to the advice given in Chapter 5. However, it is repeated here for simplicity.

Before attributing some operating fault to the fuel injection system, be sure the remainder of the engine is in sound order. It is quite pointless to start to troubleshoot the injection system if the spark plugs are years old, the rubber intake ducting is cracked, or an exhaust valve is burned.

Spark Plugs

As in the days of carburetors and point-and-breaker ignition systems, the first diagnostic test should be to remove the plugs and examine them—the removed plugs can reveal a great deal about engine condition. The insulator should be a light gray-to-tan color. An insulator that is bone-white—or worse, blistered—indicates excessive leanness, or perhaps a plug of the wrong heat range; a blackened insulator may be the result of a too-cold plug, or excessively rich running, or may be a product of oil fouling, because of worn rings or valve stems, a plugged PCV valve, or even simply an overfilled oil pan. To distinguish between carbon (fuel) fouling and oil fouling, rub the plug against the heel of your hand—oil fouling will leave a greasy smudge; carbon fouling will not.

Any mechanical damage to the plug—a cracked insulator, a broken side electrode—implies detonation, which may have damaged much more than the plug. A plug that is truly wet with gasoline implies a non-firing cylinder that has continued to receive fuel.

Check Gap—Also, check the gap on removed plugs. If the plugs have seen any substantial amount of service, the gap is sure to be larger than on a new, correctly gapped one. This widening of the gap results from erosion by the hot gasses within the cylinder. An excessive plug gap can make unsustainable demands on the ignition system—the voltage required to jump the exaggerated gap may cause the secondary (high-tension) voltage to rise so high that the spark seeks another path to ground, perhaps punching a microscopic hole right through the insulation on the plug or coil wires, leaving a leak path to ground that remains even after the plugs are replaced.

Replacing Plugs—The replacement interval for spark plugs suggested by the factory is likely to be highly optimistic; except for platinum tipped plugs, they should be replaced annually, as should the air and fuel filters. Check the gap on new plugs before installing them even if they come pre-gapped, and take care when replacing the fuel filter that the act of removal and replacement does not allow dirt to enter the system. High-tension wires should be replaced every couple of years, likewise the distributor cap and rotor, if applicable.

Routine Checks

Other routine service inspections that

should be taken care of before going further are checking ignition timing and, on engines without hydraulic lifters, the valve clearances. Inspect all rubber air trunking for cracks and other sources of air leaks. Assuming all is in order so far, the next step is a compression check. This will reveal worn rings or leaking valves. Compression that is uniformly down by even as much as 20–30psi relative to the factory figure is not much to worry about, but variations between cylinders of that much is cause for concern.

Gas Pains

Many fuel injection troubles can be avoided, or at least long postponed, simply by paying attention to the quality of fuel used, and where and when it is bought. While the owner's manual may make clear that regular gas of about 87 pump octane is suitable, and while the engine may not be able to take advantage of the higher octane (about 92) of premium fuel, the premium fuel from most national gasoline brands contains a more aggressive detergent additive package than does their regular fuel. Clogged injectors are one of the more common causes of grief with fuel injection systems—all systems, not just Bosch. Higher detergency of the fuel helps prevent these faults. Even supplementing a standard diet of regular with a tankful of premium every few weeks helps. Aftermarket detergent additives may also be effective.

Running out of gas is a pain, argument enough for following the advice implicit in the old saw that "it costs no more to drive around with a full tank than a near empty one," but running most of the time with the gauge showing 1/4 tank or less is especially poor practice with fuel injection systems. The larger the air space above the fuel in the tank, the greater the amount of water that condenses out of the air, and the greater the susceptibility of steel and iron components in the system to rusting. Apart from the direct consequences of this corrosion, tiny flakes of rust can play havoc if they get into the system.

Note, too, that it is a good idea to keep an eye on when your habitual gas station gets its deliveries. The replenishment of the station's underground storage tanks stirs up rust and sediment in their tanks that may wind up in yours. Better to fill up the day before or the day after.

"No User Serviceable Parts Inside"

No matter what the results of the diagnostic tests described below, bear in mind that in most cases the only remedy for something out of spec is component replacement. Parts that cannot be repaired or adjusted include, where applicable: primary system fuel pump; lift pump; system pressure regulator; accumulator; control pressure regulator; lambda valve; pressure actuator; injectors; cold start injector; auxiliary air bypass (idle speed stabilizer); and all sensors, except for the air meter.

While the air meter can be dismantled and certain adjustments or repairs carried out, as described below, the only serviceable component in the fuel distributor is the control plunger. At that, all that can be done here is to clean the plunger of varnish and to replace the O-ring seal at its lowest part. Otherwise, the fuel distributor is essentially nonserviceable. Bear in mind, too, that without the highly specialized equipment to which service technicians in dealerships have access, there is absolutely nothing you can do with any electronic control modules; you cannot even test them. All you can do if an electronic controller is suspect is to systematically eliminate all other components as potential culprits and, as a final resort, replace the controller.

Troubleshooting Checks

Despite the dismayingly long list of things that cannot be done, there are nevertheless some troubleshooting procedures that can be helpful. These should be carried out in a log-

WARNING!

Gasoline is highly flammable and potentially explosive. It can be ignited by an electrical spark or by contact with hot engine parts. Use extreme care when working on any engine's fuel system. Work only in a well ventilated area, ban smoking or any open flame from the work area, and ensure a fully charged large capacity fire extinguisher is close to hand. Many fuel injection system circuits remain under pressure even when the engine is stopped and the fuel pump is de-activated; before loosening any fuel fitting, wrap a rag around it.

ical way, and with an understanding of how the system is supposed to work and what different components do in various circumstances. For example, if an engine starts readily from cold and runs well while first starting to warm up, but then runs progressively richer as it reaches operating temperature, guzzling gas and spewing black smoke, one plausible culprit is a cold start injector stuck open. In the same way, if the idle speed is way too high when warm, or too low when cold, one of the first places to look might be the idle speed stabilizer/auxiliary air bypass. In general, if only one part of the engine's operating regime is affected, look first at components whose function is directly related to operation in that regime.

Air Meter

After the air filter, the air meter is the component furthest "upstream." Because it and the control plunger are the primary means of controlling mixture strength, here is a good place to start. It also helps that the meter, as a rule, is fairly accessible! A basic and simple, "almost-no-tools" check is the free movement and centering of the metering vane, and its rest position.

Remove the rubber trunking that connects the air meter to the throttle body. Next, assuming an updraft sensor, use a small magnet to tug at the bolt head in the center of the metering vane. Once you can get your finger under the edge of the vane, lift it and let it drop. It should rise and fall again freely, and bounce once or twice. If it is sticky going up, but falls freely, the problem is almost certainly with the plunger. If you are sure that the plunger has not been damaged through careless handling (a dropped one is likely scrap), then the problem is probably gum and varnish from fuel deposits on the plunger.

Clean Plunger—To clean the plunger requires removing it from the fuel distributor, but unless the engine has been stopped for a very long time (hours), there is likely to be residual pressure in the system, and this pressure has to be relieved. Bearing in mind that a spray of fuel will likely erupt, wrap a rag around the fitting and relieve the residual pressure by cracking open the most accessible line on the pressure side of the system. Catch as much as possible of the emerging fuel in a container and return it to the tank.

Remove all the other fuel fittings, again catching spilled fuel, and the bolts that secure the fuel distributor. Although the reason you are doing this is because the plunger seems to be sticking, Murphy is everywhere and the plunger may just fall out of its own accord, so get a finger under the plunger before lifting the fuel distributor. A dropped plunger is quite likely a junk plunger and you can't buy them separately, you have to get a whole new distributor. Keep an eye out, too, for a spring above the plunger, used on versions of K-Jetronic after about 1983, and note that on KE systems, the plunger cannot fall out—it is retained by a stop screw. Before removing this screw to free the plunger, be sure to measure the depth of the screw below the rim of its surrounding nut. After reinstalling the plunger, be sure the stop screw is turned in to give this same depth.

Thoroughly clean the plunger and inspect it for signs of rusting. If all seems well, replace it, reattach the fuel distributor, using new gaskets, and retest for free movement. If the plunger still sticks after cleaning, you will have to replace the fuel distributor.

Sensor Vane—If the sensor vane rises freely but sticks near the bottom of its travel, it may be rubbing against the side of the air funnel at its narrowest part. This calls for recentering the vane. The bolt that secures the vane to the lever is smaller than the hole it passes through, so the vane can be recentered by loosening this bolt. It is usually possible to judge a correctly centered vane by "eyeball," or you can run a 0.004" feeler gauge all around the edge of the vane. Recheck that you haven't disturbed the centering while retightening the bolt.

Establishing the rest position of the metering vane requires that there be residual pressure on the system. To ensure there is, restart the engine, let it run for a few minutes, and switch it off again.

On K-Jetronic and K-lambda systems, the edge of the vane at rest should be at or just below (not more than about 0.020" below) the top edge of this narrowest part of the funnel. On updraft sensors, this measurement is made at the edge of the plate nearest the fuel distributor; on downdraft versions, measure at the edge furthest from the distributor. Adjustment of this rest position is made by bending the wire clip on the leaf spring (NOT the leaf itself) that forms the lower travel stop for the vane.

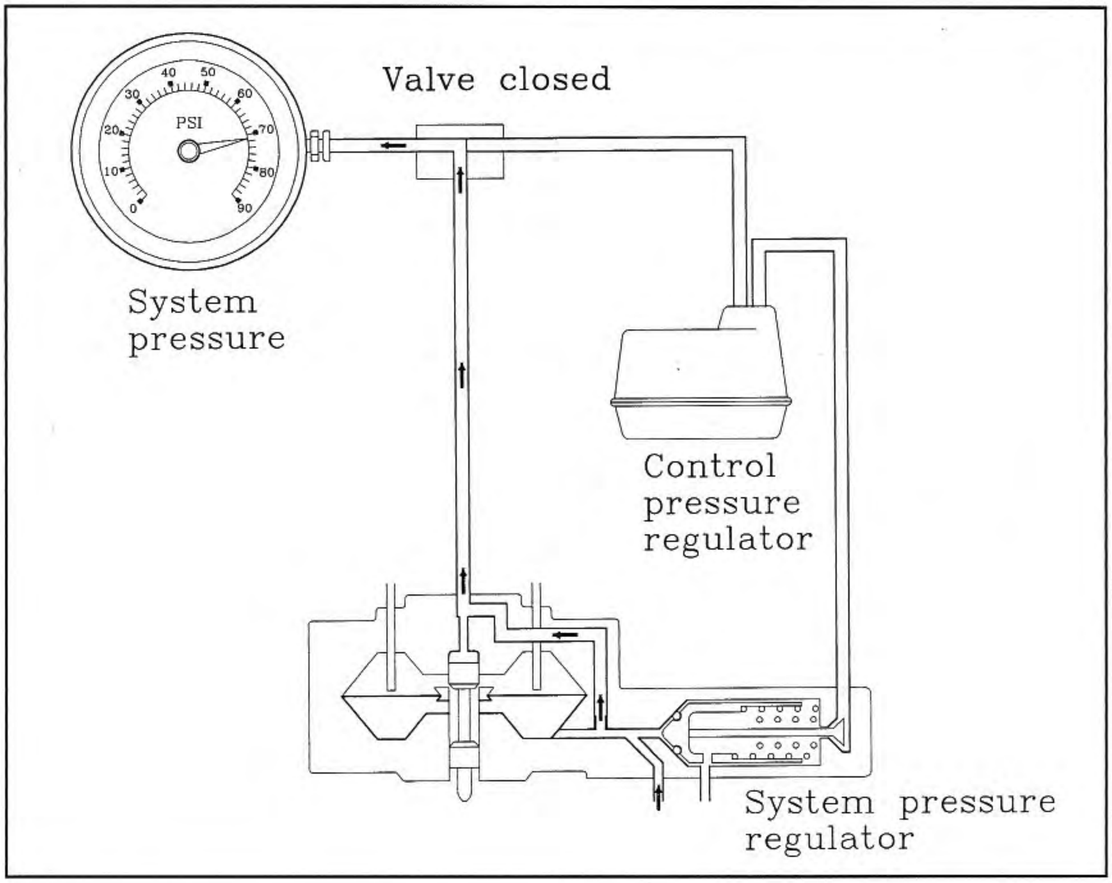
On KE-systems, there are two critical positions for the vane when the engine is stopped. The first, called the "rest" or "zero" position, is where the vane sits naturally; the second, called the "basic" position, lies slightly above the rest position on updraft meters, slightly below it on downdraft ones. When the vane on updraft meters is lifted manually from the rest position, there will be a small amount of free movement (about 0.04–0.08") before a definite contact is felt, as the vane's lever takes up the small amount of clearance between itself and the bottom of the control plunger; this is the basic position. (This clearance assures that the plunger O-ring seals firmly against its seat.)

In the rest position, most of the vertical side of the narrowest part of the funnel should be visible on updraft meters. Consult your own vehicle's manual to determine the exact distance of the vane below the top edge of this cylindrical area—it varies from one vehicle to another, although 0.07–0.08" is typical. The measurement on updraft meters is made at the edge of the vane closest to the fuel distributor. If this distance is not within spec, bend the wire clip on the leaf spring, as described above for K- and K-lambda systems.

As noted, on updraft sensors the basic position lies 0.04–0.08" above the rest position, bringing the sensor vane to the top of the narrowest portion of the funnel. If the rest position is correct but the basic position is out of spec, remove and adjust the plunger stop screw.

On downdraft meters, these relationships are inverted. At the rest position, the vane should be level with the top of the cylindrical portion of the funnel; the basic position is 0.04–0.08" below that. In this case, the reference point is at the edge of the vane furthest from the fuel distributor, and the measurement is made there.

The rest position of the vane on downdraft systems is set by a stop pin that protrudes through the air meter housing. This pin is a press fit and can be (carefully!) tapped down or prised up, as required. Again, if the rest position is correct but the basic position is out of the specification for your application, the clearance can be adjusted at the plunger stop screw.



A single test setup permits measuring main system pressure (with valve closed), control pressure (with valve open, see next page), and residual pressure, by using a "Tee" fitting and a shut-off valve (see text). Be sure to use a gauge with a high enough pressure capacity—at least 90 psi.

Fuel Flow and Pressure Checks

With the air vane centered and correctly positioned, attention can be turned to the fuel system. The checks here involve testing both flow rates and pressures. For volume (flow) tests, a graduated container of about one liter capacity will be needed. For pressure tests, a pressure gauge with a capacity of at least 100psi is needed, together with hoses and fittings, to connect it to the various circuits to be tested (threads on K-Jetronic fuel fittings are 12mm/1.5), plus a shut-off valve and a Tee-fitting. Assemble the gauge, fittings, and shut-off tap so that the single line leading from the gauge terminates in a Tee; fit the shut-off valve in one of the two lines leading from the Tee.

On K- and K-lambda systems, relieve the system pressure, then disconnect, at both ends, the return line from the system pressure regulator on the fuel distributor to the control pressure regulator. Attach the gauge line that contains the shut-off valve to the control pressure regulator; attach the other line to the port at the fuel distributor. This setup allows testing the full primary system pressure, the control pressure, and the residual pressure maintained in the system when the pump is stopped.

Remove the fuel tank cap. Unplug the electrical connections at the control pressure regulator and the auxiliary air device, then bypass the fuel pump relay, to allow the pump to be energized with the engine stopped. While a great many different means to do this are spelled out in the manuals for various makes and models of vehicle, simply feeding the pump directly from the battery with a jumper wire works in every case, but take care that the polarity is correct.

Primary System Pressure—With the shut-off valve closed, no fuel can return to the tank, so the gauge will read primary system pressure—the fuel pump is working against the "dead-end" of the closed valve.

Specifications vary from one model to another—check your vehicle's manual—but a typical primary system pressure is about 75psi. If the primary system pressure is slightly out of spec, it can be adjusted at the system pressure regulator by adding or removing shims under the spring that closes the regulator plunger/piston. Each shim added or removed increases or reduces pressure by 2 to 2 1/2 psi, respectively.

Primary System Flow—If the system pressure is very much below the specified value, the problem may lie with the fuel pump, or may be the result of a clogged filter or a clogged or pinched line. After changing the filter as a matter of course, the pump(s) can be checked by measuring the fuel delivery rate. Carefully relieve system pressure, disconnect the return line at the pressure regulator, attach a length of replacement line, and run the pump, catching the discharged fuel in a graduated vessel. Again, specific values vary from one vehicle to another, but the general range is from 750cc to about 1100cc per thirty seconds. (The specific figure for any given model appears to be pretty much in proportion to the power output per cylinder, which makes sense when you think about it.)

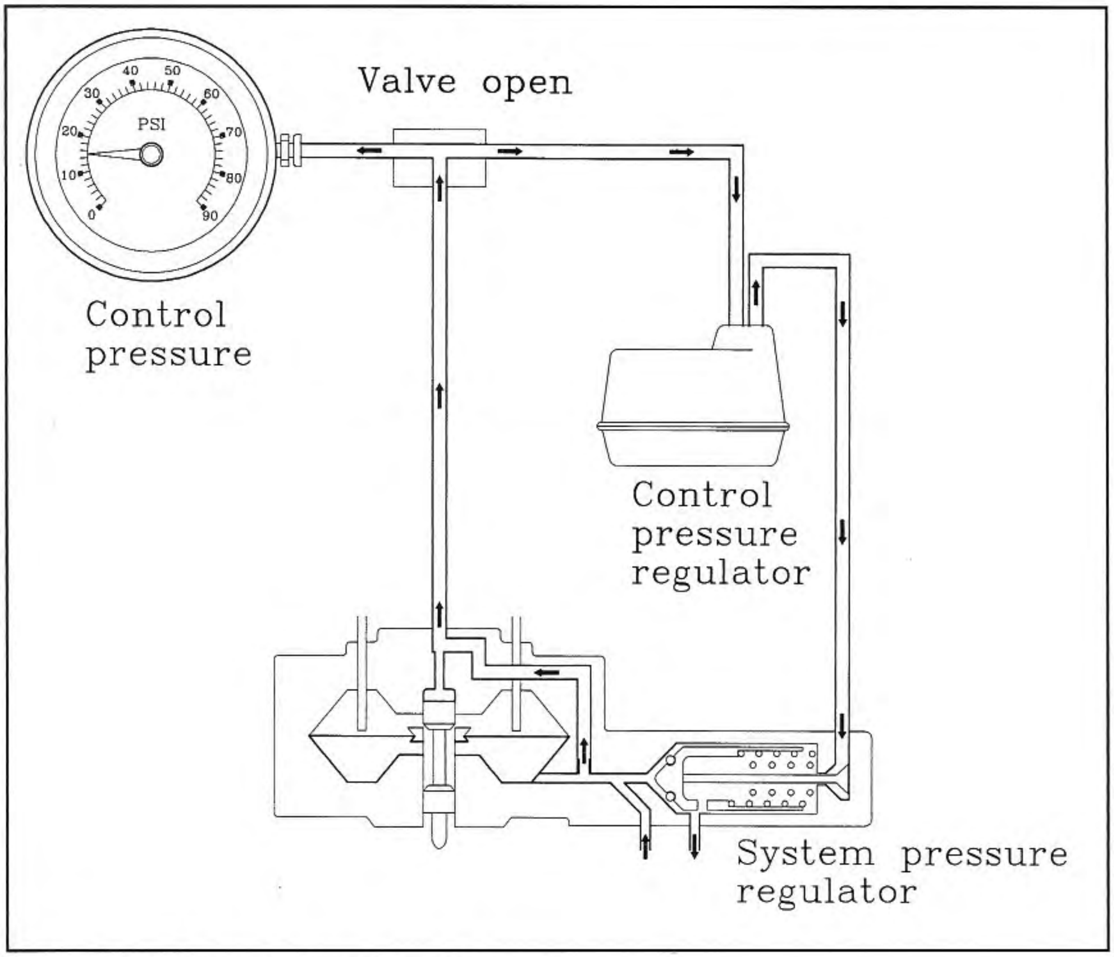
If there is zero delivery, first look to the obvious: confirm that there is fuel in the tank! If in doubt, add a gallon of fuel. Next, confirm that the pump is running. In a reasonably quiet environment, you should be able to hear it. If the pump is not running, check the electrical supply to the pump, starting with its fuse. If the fuse is OK, check for electrical power at the pump. A voltmeter with one probe applied to one of the fuel pump terminals and the other to a good chassis ground should show battery voltage (near 12 volts) at one pump terminal, and zero at the other. (You will have to fold the rubber boot around the connector out of the way to gain access to the electrical terminals.) Low voltage at the pump is likely the result of corroded terminals. If there is adequate power to the pump but it does not run, the pump is defective and will have to be replaced.

If the pump is receiving about twelve volts and runs, but its delivery measured at the pressure regulator is much below spec, inspect connecting lines for damage and/or obstructions. Disconnect both ends of the fuel supply line from the pump to the pressure regulator and blow compressed air through it. BEWARE THE FIRE HAZARD OF A SPRAY OF FUEL FROM THE OPEN END OF THE LINE. If the line is clear but the delivery remains far below spec, remove and clean the coarse strainer inside the fuel tank. If all this fails, the pump is defective.

Control Pressure—Assuming the primary system pressure is within specification, control pressure should be checked. With the pump running and the gauge hooked up as described above, open the shut-off valve in the gauge setup. Fuel is now free to flow from the fuel distributor to the control pressure regulator, and from there back to the tank. In this configuration, the gauge setup is simply measuring the pressure in this, the control circuit.

As explained in the previous chapter, the control pressure regulator on K- and K-lambda systems varies the control pressure according to temperature. If the engine is at room temperature or less, the control pressure should be low, to provide the enrichment needed for cold starting and warm up. Confirm that the electrical supply to the heater in the control pressure regulator is disconnected. On turning the shut-off valve, the reading on the gauge should sink from the system pressure to a lower value, typically 20–25 psi, but within the limits expressed in the manual for your car for cold control pressure.

If the cold control pressure is too low, the problem almost certainly lies in the control pressure regulator; if too high, the control pressure regulator may again be the culprit



To check control pressure, the valve must be open.

or, less likely, an obstructed return line from the control pressure regulator to the tank. To determine which is the case, WITH THE PUMP STOPPED disconnect the return line from the control pressure regulator to the tank and, with the pump running, allow the fuel to flow into a container. If the cold control reading is now within spec, the return line is clogged. If there is no change, the control pressure regulator is defective.

Assuming the cold control pressure to be OK, with the pump running reconnect the electrical supply to the control pressure regulator. As the electrical heating element in the regulator begins to warm up the leaf spring within the regulator, the gauge reading should gradually rise to the warm control pressure value specified for your car, typically 50–55 psi. Recall that the tapering off of cold start/warm up enrichment as the regulator gradually raises the control pressure takes some time—perhaps a couple of minutes. If the control pressure remains low and unchanged after several minutes, check that the control pressure regulator is receiving something close to battery voltage. If there is no power to the regulator, trace the electrical connection to it; if there is about 12 volts at the electrical connection, yet the control pressure remains low and unchanged after a few minutes, then the control pressure regulator is defective.

Residual Pressure—Recall from the system description in Chapter 6 that K-Jetronic systems include an accumulator that maintains a residual pressure in the system for at least ten minutes after the pump has stopped. The purpose of this is to ease hot restarts by ensuring that the lines are charged; this also helps to reduce vapor lock.

With the gauge still connected as described above for the control pressure checks—that is, with the shut-off valve open—shut off the pump. The gauge reading should drop from the warm control pressure (assuming the control pressure regulator was allowed to warm up) to some value sufficiently high as to achieve the intended purpose, but sufficiently low that it allows the check valves in the injectors to close, preventing them from dribbling fuel into the engine. Values for residual pressure immediately after pump shut down vary rather more widely than other system pressure; most, though, are in the range of 20–40 psi.

The "dead end" against which the accumulator is pushing is, at one end, the now fully seated piston in the pressure regulator; the other end of the line—at the pump—is shut by the check valve in the pump. However, there are several other leakage paths that can cause the residual pressure to dwindle away, either the pump stops immediately or more gradually, but still well before the (usually) ten minute minimum. If the residual pressure sinks below the value specified in your car's manual in less than the designated time, these numerous potential leak points can be systematically tracked down.

First, after shutting off the pump, close the shut-off valve at the gauge. If the residual pressure with the valve open rapidly dropped below the specified value, but the pressure holds steady for several minutes with the valve closed, then the problem is with the control pressure regulator.

If the pressure continues to drop with the shut-off valve closed, pinch closed the line from the pump to the accumulator. If the pressure now holds steady, the pump check valve is defective and needs to be replaced. This is surely the most common cause of loss of residual pressure.

If the pressure still drops with the pump-to-accumulator line squeezed closed, then likewise pinch shut the line to the cold start injector. If that ends the leakage, the cold start valve is defective; replace it.

If the pressure continues to drop with both these lines clamped shut, close off the return line from the fuel distributor. If that ends the leakage, the source of the leakage is either the system pressure regulator or the fuel distributor itself. In either case, the fuel distributor has to be replaced.

If all this fails to stem the drop in residual pressure, about the only remaining candidates are one or more injectors with defective check valves, or external leaks from one or more fuel fittings. With pressure on the system, carefully inspect all fittings for seepage.

Injector Flow, Pattern, Leakage

The continuous flow injectors used on K-systems are less prone to trouble than the intermittent injectors used in L-systems. Nevertheless, they do sometimes become partially or even completely clogged, especially if the fuel regularly used lacks adequate detergency. Partial clogging may result in a spray pattern that is lopsided, or a discharge that is hardly atomized at all—more like a stream than a spray—or may simply reduce the rate of delivery. Leakage is less common.

Taking care not to kink the lines, remove the injectors and temporarily plug the holes they came out of. Set each injector into the mouth of a graduated vessel. A reasonable degree of accuracy is needed here, so graduated cylinders (available at any laboratory supply outfit, or ask your druggist) are preferable to domestic measuring cups, etc. It should be pretty obvious that plastic vessels are preferable to glass ones!

For safety's sake, disable the primary ignition circuit. Now run the pump; no fuel should flow from the injectors as long as the air metering vane is in the rest position.

Manually lift the air metering vane, allowing the injectors to discharge into the graduated cylinders, and observe the spray pattern from each. It should be cone shaped and symmetrical, and the amount flowed by each injector should be the same within ten percent or less. A slight degree of asymmetry in the spray pattern is acceptable, as long as the delivery volumes match, but pronounced lopsidedness or a stream rather than a spray requires that the injectors be cleaned or replaced.

If the vehicle has seen a lot of low speed, low power operation, partially clogged injectors may clean themselves if run at maximum flow rate for a few seconds. Lift the air sensor vane all the way up and hold it there for ten seconds. If that doesn't solve the problem, a prolonged soak in solvent may work. Failing that, replace the defective injector(s).

Basic Mixture Strength/CO Adjustment

About the only truly "tuneable" aspect of K-Jetronic systems is the provision for adjusting the relative positions of the metering vane and the control plunger. The vane's lever is, in fact, made in two parts, with an adjusting screw that moves the lever connected to the vane relative to the lever that drives the control plunger. This screw is accessible through a small hole on the top of the air meter housing, usually closed off with an "anti-tampering" plug.

Because this adjustment raises or lowers the control plunger relative to the air metering vane, it effectively modifies the mixture strength. Note that while the adjustment is always carried out at idle, its effect is felt throughout the engine's operating envelope—in that sense, it resembles an adjustable main jet on a carburetor . . . (ah! memories of Stromberg 97s!)

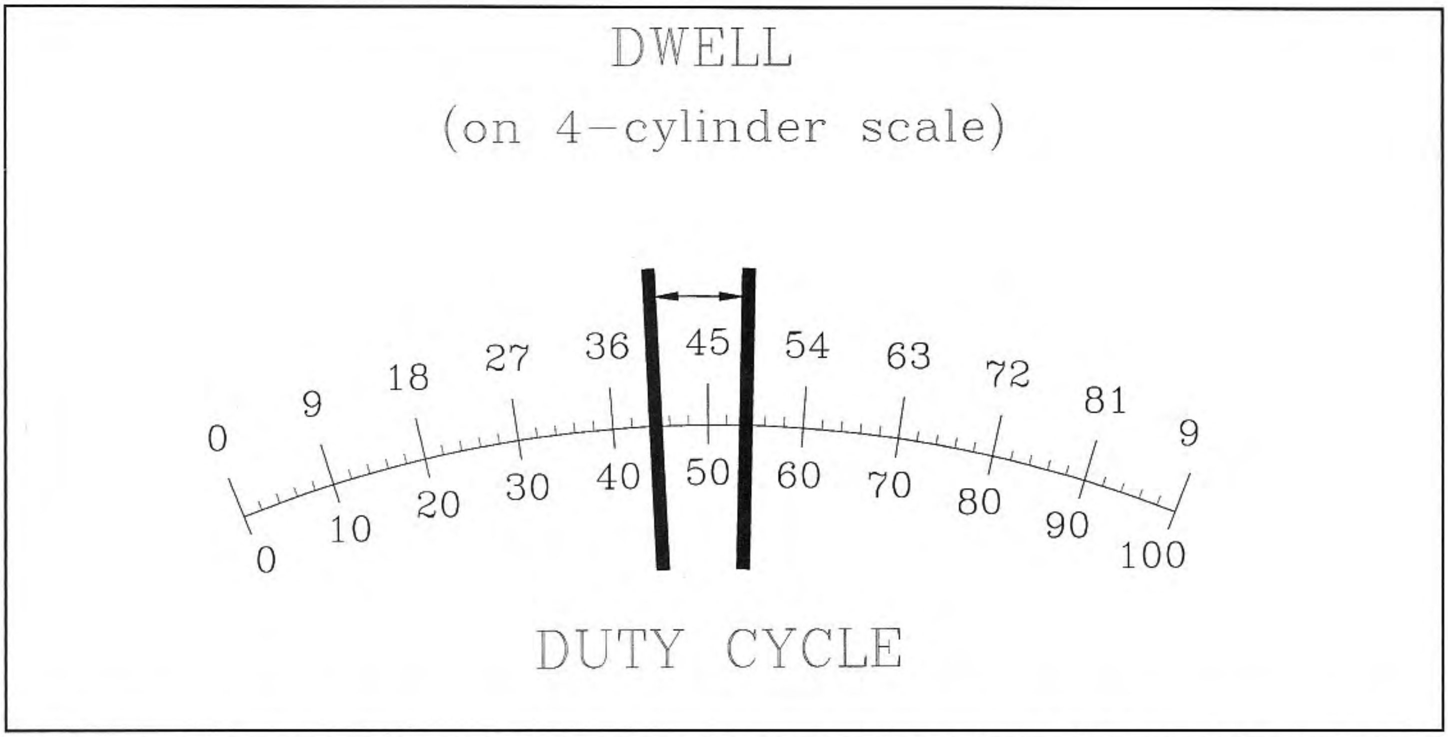
An exhaust gas analyzer (CO meter) is needed to perform this adjustment, together with an unusually long 3mm Allen wrench. After the anti-tampering plug is pried out, this wrench fits through the hole and engages the adjusting screw. Before you start, however, set the idle speed using the idle air bypass screw. Note, too, that the CO meter has to "read" the exhaust gas upstream of the catalytic converter—remember, the converter is doing its best to oxidize the CO to CO_2. There is usually a port or pipe or fitting on or near the exhaust manifold for this purpose.

With the engine fully warm and an appropriate idle speed set, adjust the mixture until the meter reports a CO value corresponding to the figure on the EPA placard in the engine compartment. If the placard is missing, aim for 1.5 percent. If you are going to "rev" the engine, to blow out the cobwebs, REMOVE THE ALLEN WRENCH before touching the throttle—remember, the metering vane will lift when the airflow increases, so its lever will rise, and the wrench will get bound up on the edge of the access hole, and bend things.

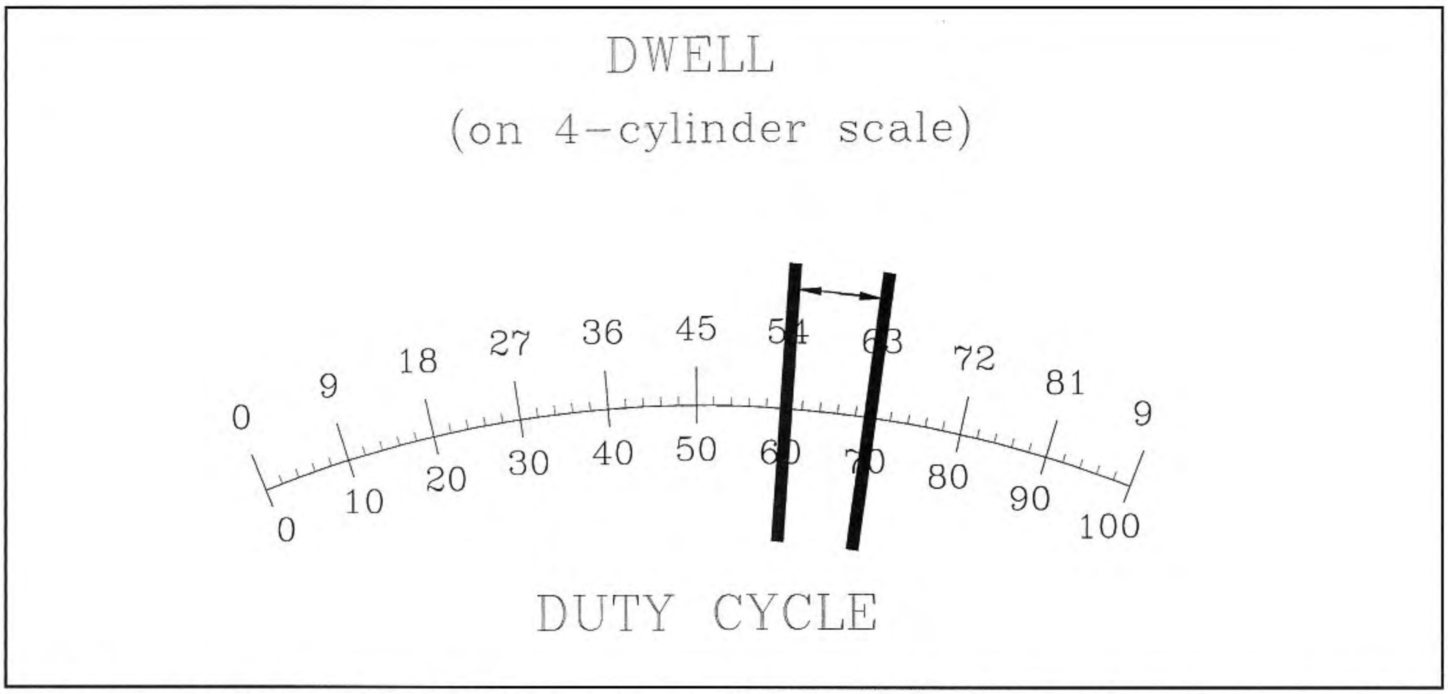
K-Lambda Mixture Strength/CO Adjustment

On K-Jetronic systems with a lambda sensor, the lambda sensor/electronic control/lambda valve will attempt to bring the mixture to the stoichiometric value no matter what you do with the CO/basic mixture adjustment. The fix is simple—before carrying out the adjustment, disconnect the lambda sensor, obliging the electronic control to operate open loop.

Recall from Chapter 6 that the lambda valve controls fuel flow at the fuel distributor by cycling between open and closed, and the electronic controller steers the system toward stoichiometry by adjusting the duty cycle (on time vs off time) of the lambda valve. There is a purpose-made meter that can "read" this duty cycle, but it can also be read by an ordinary ignition dwell meter. With the dwell meter set on the four cylinder scale, a 50% duty cycle will read as 45 degrees (50% of 90 degrees). This provides



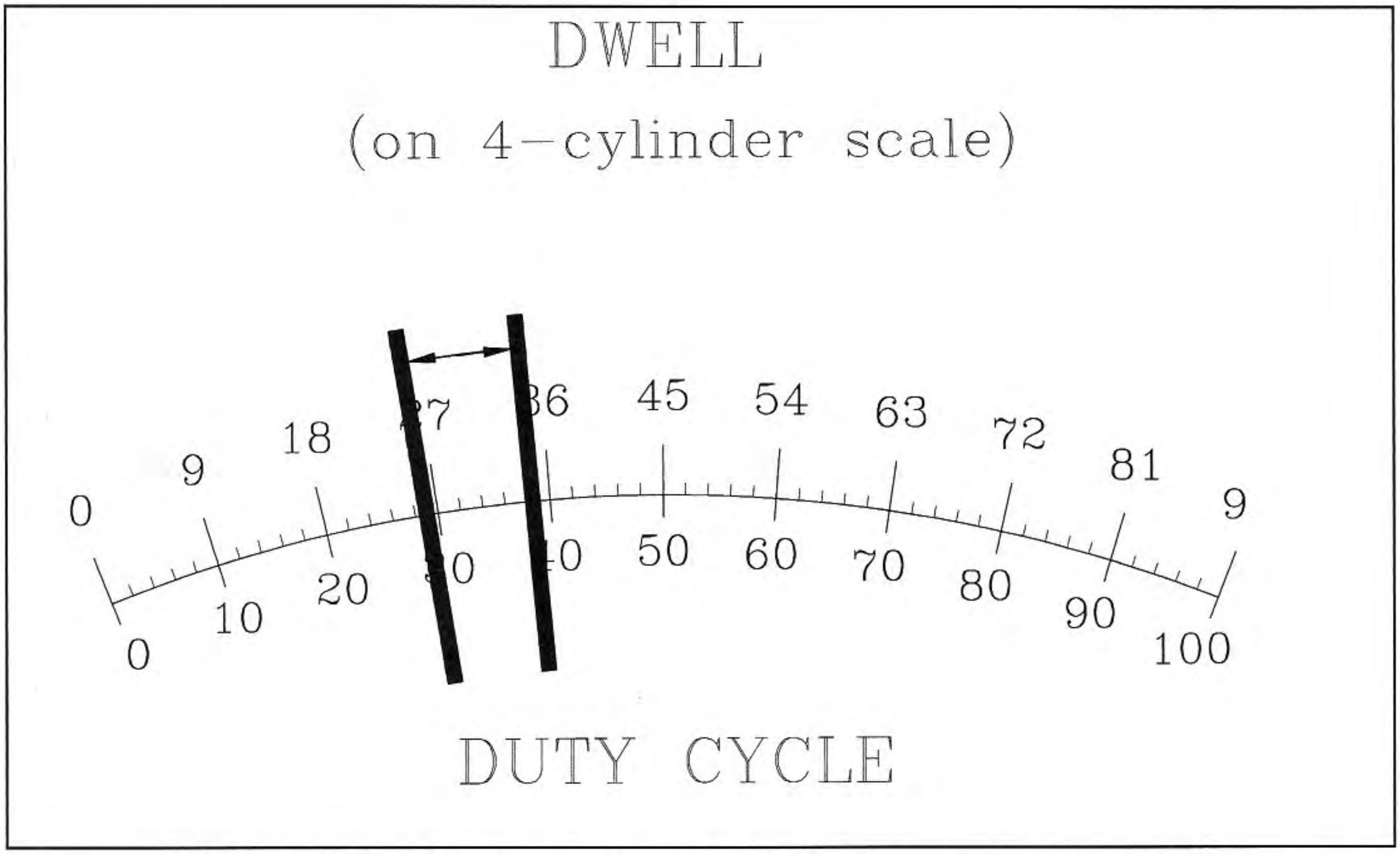
An ordinary dwell meter, set on the four-cylinder scale, can read the duty cycle of the lambda valve. If the basic mixture strength is correct, the meter will oscillate around the 45 degree (= 50% duty cycle) point.



A reading around 60–70 degrees (about 55–65% duty cycle) means the lambda valve is trying to drop the control pressure to richen up an excessively lean mixture.

the opportunity for a second check on both mixture strength and lambda system functioning; it also permits mixture strength/CO to be adjusted on K-lambda systems without need for a CO meter.

With the engine fully warmed up and the idle speed set, connect the dwell meter to the lambda valve. If the meter oscillates around the 45-degree mark (that is, indicating a duty cycle averaging 50%), then the mixture



A reading around 25–35 degrees (about 30–40% duty cycle) means the lambda valve is trying to raise the control pressure to lean out an excessively rich mixture.

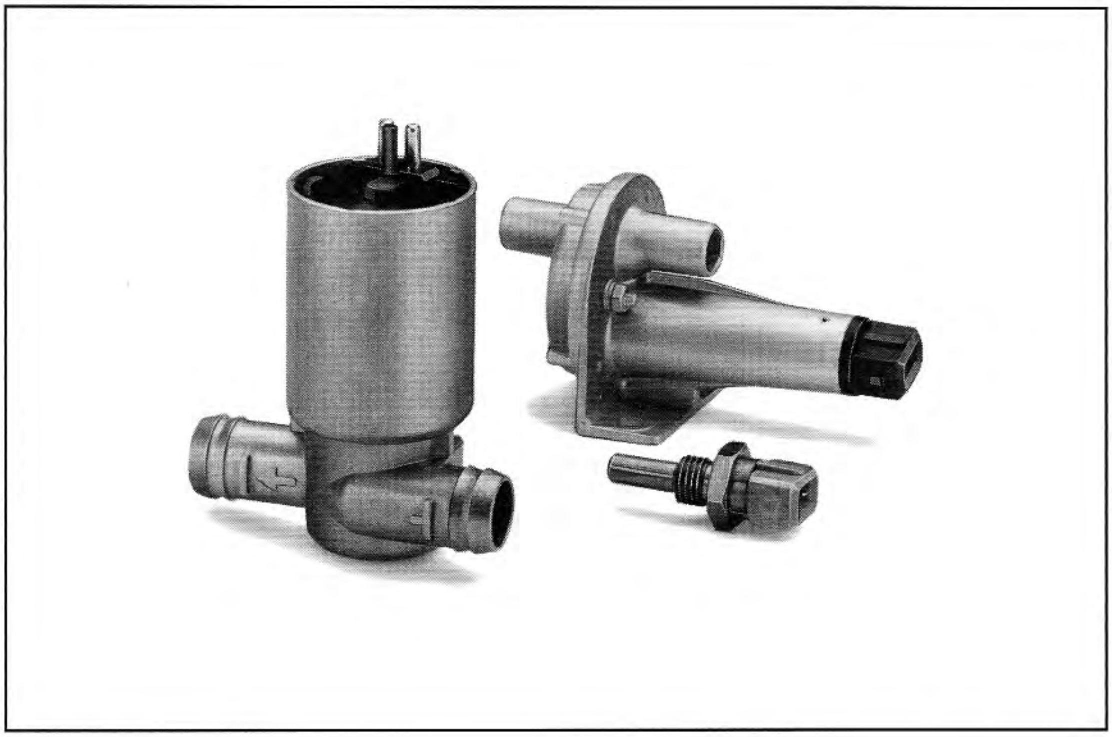
strength is right on the button and no adjustment is needed. A high figure on the meter (say 55 or 60 degrees) indicates the lambda valve is staying open more, attempting to drop the control pressure and thereby richen the mixture—the basic mixture is too lean. Conversely, a low figure on the dwell meter (say 30 or 35 degrees) indicates the system is trying to correct for an over-rich basic mixture setting.

If a CO meter is available, then both correct mixture strength and correct functioning of the lambda sensor and valve and the electronic control is absolutely confirmed if the CO reading is the same with the lambda sensor connected (closed loop) and disconnected (open loop).

KE-Jetronic and KE-Motronic Mixture Strength/CO Adjustment

The remarks above regarding plain-vanilla K-Jetronic systems apply also to KE-systems, with a few exceptions. First, it is necessary to check the current to the pressure actuator. With the engine fully warmed up and the lambda sensor connected, the needle of a milliameter should swing back and forth over a narrow range, typically 9–11ma, though this varies from model to model. This confirms the actuator and ECU are doing their jobs, constantly correcting the mixture back to stoichiometry.

On some early KE-systems, mixture strength can be adjusted exactly the same way as on other K-systems, again using a CO meter. If it proves impossible to get both CO and actuator current in spec at the same time, look for air or exhaust leaks. On later KE-Jetronic systems and KE-Motronic systems there is no provision for either idle speed or basic mixture strength adjustment—it is all handled internally by the ECU.



On most KE-Jetronics, and later systems, a rotary idle actuator (left) replaces the passive, free-standing auxiliary air device (right). The later device looks like a small electric motor. (Robert Bosch Corporation)

Auxiliary Air Valve

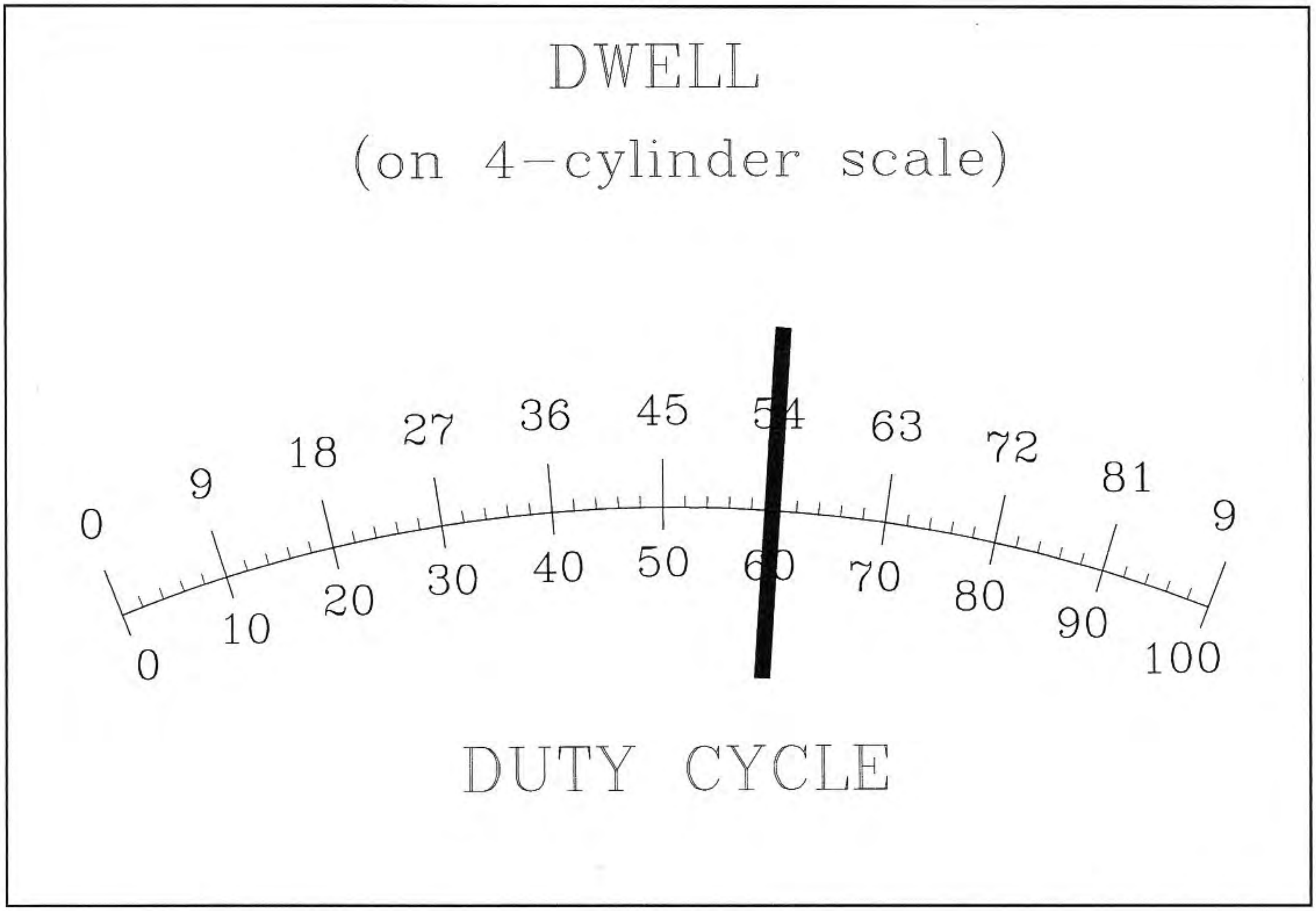
Plain K-Jetronics and some with lambda control use an auxiliary air valve to provide the extra air a cold engine needs to maintain an idle speed high enough that the engine will not stall. As described in Chapter 3, this is simply a small rotary disc valve that allows air to bleed around the nearly closed throttle (it is sometimes called the "auxiliary air bypass"). The position of the disc is governed by a bimetallic coil. When the coil is warm, the valve is completely closed; when very cold, it is fully open, with a smooth and gradual transition between the two as the engine warms up. In very cold weather the auxiliary air bypass valve can take eight or ten minutes to move from fully open to fully closed.

The valve is not serviceable, but its condition can be initially diagnosed by symptom: An idle that is appropriate when cold but excessively high when warm points to this valve being stuck partly or fully open. Conversely, if the warm idle seems right but the engine requires some throttle opening to avoid stalling when cold, then the valve may be stuck closed.

If the valve is suspect, check, first, by pinching shut the connecting hose. On a cold engine, this should drop the idle speed; on a hot one it should make no difference. If the valve fails this test, sight through the valve. Because the valve is powered as long as the ignition is on, the heating element should completely close the valve within ten minutes. Ensure that 12 volts is getting to the valve, allow time for it to warm up, then look through to confirm the valve is closed. To confirm the valve is opening when cold, pop it into a freezer for ten minutes and again sight through it—there should be a clear, round passageway through it.

Idle Speed Regulator

Most KE-Jetronics and all subsequent Bosch continuous injection systems modulate the auxiliary idle air bypass in a different way. It remains in principle a valve that bypasses more or less air around the throttle plates, and its effect is most significant during warm up. However, because its more sophisticated control enables it to maintain an appropriate idle speed, irrespective of temperature or engine age and condition, it



A dwell meter can also be used to check out the rotary idle actuator. The meter should read somewhere around 30 degrees (about 35% duty cycle) on a warm, idling engine. Cranking the engine with the temperature sensor disconnected and the fuel pump disabled simulates a cold start; the meter should show a large increase in duty cycle—say 60% (corresponding to about 55 degrees).

is renamed an "idle speed regulator," or sometimes "rotary idle actuator."

In this device, the moveable valve that varies the size of the air opening is driven by a component that looks like an electric motor. Indeed, in construction it essentially is, but in action it never turns more than 90 degrees, its electrical components receiving pulses from the ECU that cause it to "dither" back and forth slightly around an average position that gives the idle speed programmed into the ECU.

Analogous to the function of the lambda valve, the position of the valve, and thus the amount of air that passes, depends on the ratio of on-time to off-time—its "duty cycle," in other words. A long duty cycle—more on-time than off—drives the valve further open; a shorter duty cycle closes it further. This duty cycle can be measured with a dwell meter, set on the four-cylinder scale.

The exact values under various circumstances vary considerably among different vehicles, so check your vehicle's specs in its manual. As a general guide, the duty cycle with a warm, idling engine will be somewhere around 30 degrees on the dwell meter. Adding a fair-sized load, such as by turning on an electric rear window defroster, should have little effect on the idle speed, but the duty cycle should increase somewhat.

To simulate cold start operation, disconnect the engine temperature sensor. Disable the fuel pump (pull the fuse), and crank the starter. Dwell should be dramatically increased; expect about twice the idling figure. A defective idle speed regulator cannot be repaired; it must be replaced.

8 PERFORMANCE MODIFICATIONS

The issue of performance modifications to Bosch EFI systems is very much a good-news/bad-news situation. On the one hand, Bosch produces a small number of specialized EFI systems for race-only, high-performance engines, and the power outputs achieved can hardly be bettered. Moreover, many of the components in these systems are essentially the same stock, bread-and-butter parts found on millions of passenger cars. It is obvious, then, that in practice as in principle, Bosch EFI can extract the last drop of power and driveability out of a performance engine, for reasons we considered at length in Chapters 1 and 2. On the other hand, you can't buy one...unless you happen to be a top-rank racing team with a signed contract with Bosch!

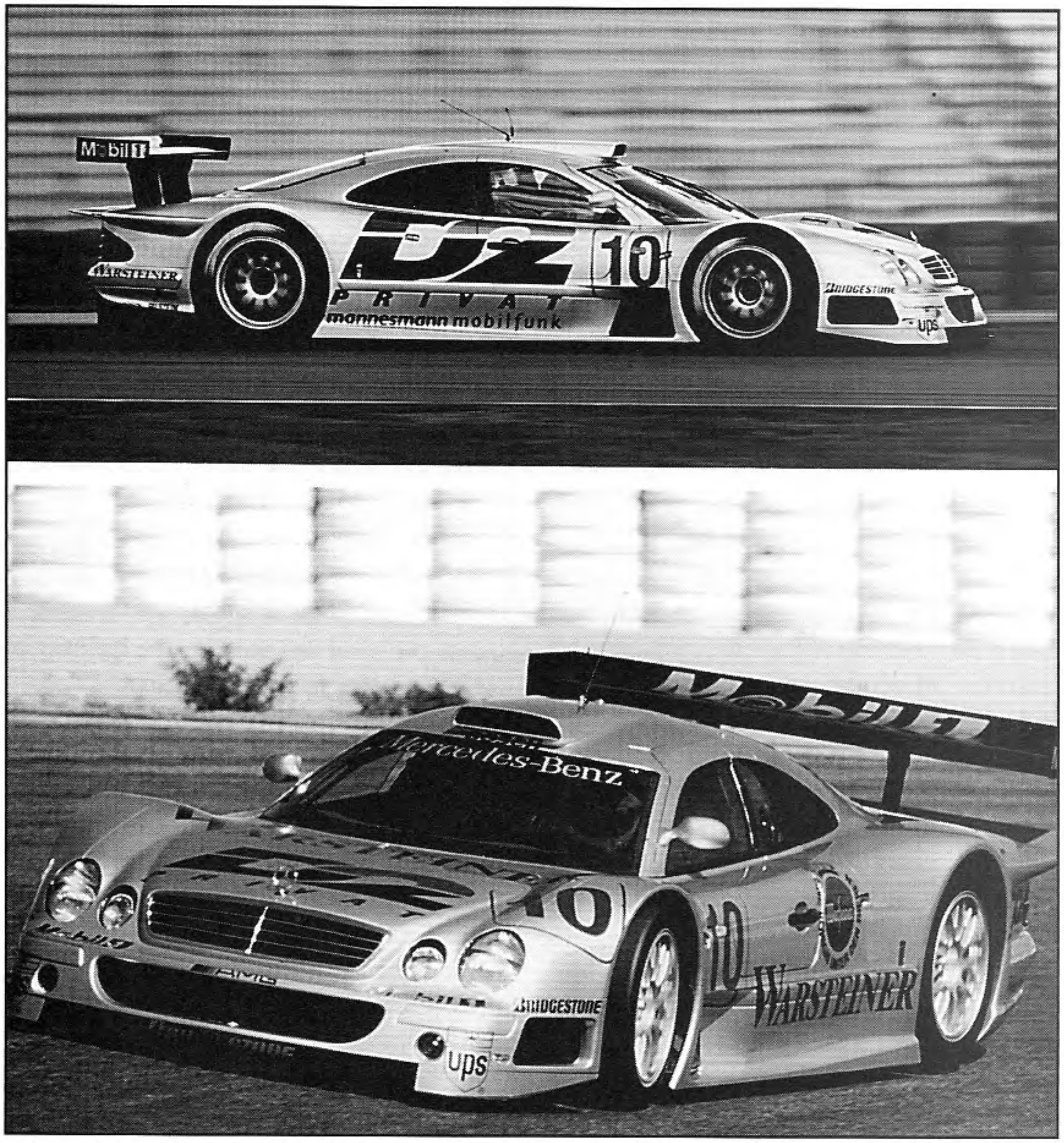
Again, the potential exists to tailor a Bosch-based EFI system to match any modified engine. But it cannot be done with ordinary tweaking and tuning; trying to apply conventional "hop-up" techniques will generally gain you nothing but grief. In addition, the fuel system is regarded by lawmakers as part of a vehicle's emissions control apparatus. ANY modification to the fuel system of a street vehicle may render you illegal. Many jurisdictions now require an annual emissions test; if you flunk, you park.

That said, if you have read the first two chapters, you should understand by now that the power an engine can potentially produce is established by how much air it can inhale and make use of per minute. That, in turn, is determined by fundamental factors—displacement, rpm, camshaft timing, compression ratio. Whether carburetors or a fuel injection system—of whatever type and brand—the only requirement of the fuel delivery system is to supply and atomize a quantity of fuel that matches the quantity of air being breathed at any moment.

System Capacity

If, in the process of measuring the airflow, the fuel system (carb or FI) restricts that airflow, then it will prevent realizing the full potential of the engine. Again, if the fuel system supplies more fuel, or less, than appropriate for that air quantity, less than peak performance will result. The fuel system, in other words, might reduce power, but it cannot increase it beyond the potential inherent in the engine's design.

More good-news/bad-news: if you make minor modifications to improve the air handling capacity of a street engine, say by fitting a low-restriction air cleaner, or a free-flow exhaust system, or by taking a light cut off the cylinder head to raise the compression, or by matching ports, then there is almost certainly enough "head-room"—reserve capacity—in your existing Bosch EFI system to match the slightly increased rate of airflow, with the same precision it handled the stock motor. You'll have a sweet running motor with a little more power. Go off the deep end with a huge overbore, a stroker crank, big valves and a cam with lobes the shape of a Hershey bar, and the



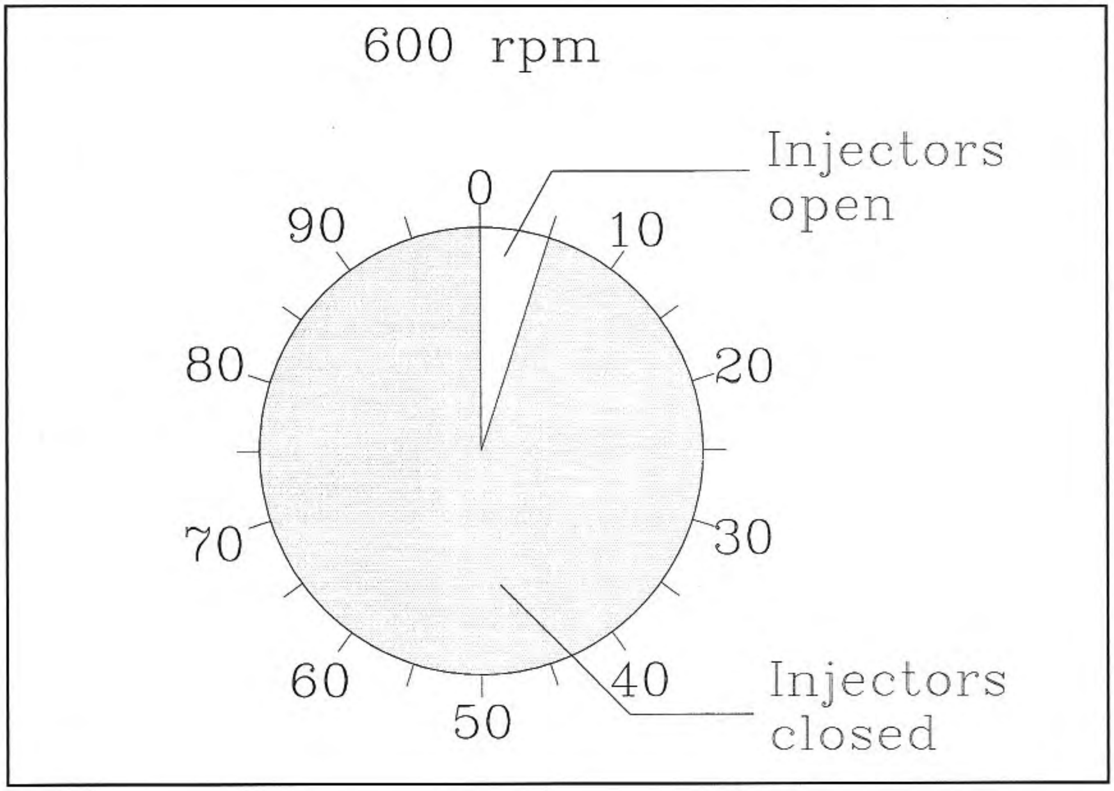
Bosch makes purpose-built racing fuel injection systems for many professional racing teams. No, you can't buy one! (Mercedes Benz)

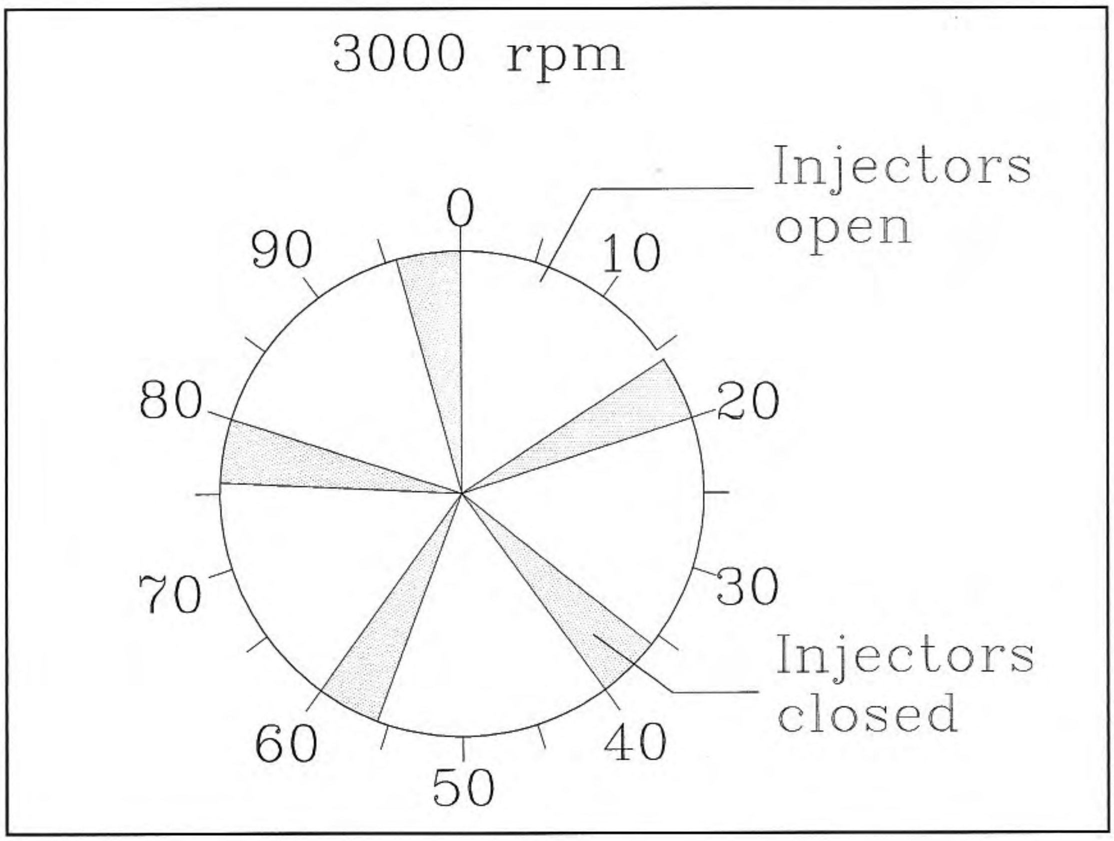
system will choke; the engine quite possibly won't run at all.

To explain, a stock Bosch EFI system is designed to have enough range to cover all conceivable operating conditions for a production car engine. These can span from –40° F at sea level, in which case the air is dense, so the engine inhales many oxygen molecules per mouthful, to 130° F on Pike's Peak, in which case the air is "thin" with many fewer oxygen molecules per bite. The power produced in the first case would be more than twice that in the latter! The system can cope with this range, with a little more added as a safety margin. Beware there are limits to this, however. On a cold day at low altitude with high atmospheric pressure, a modified engine capable of producing, say, 50% more power than stock might run right out of the available excess capacity.

System Limits

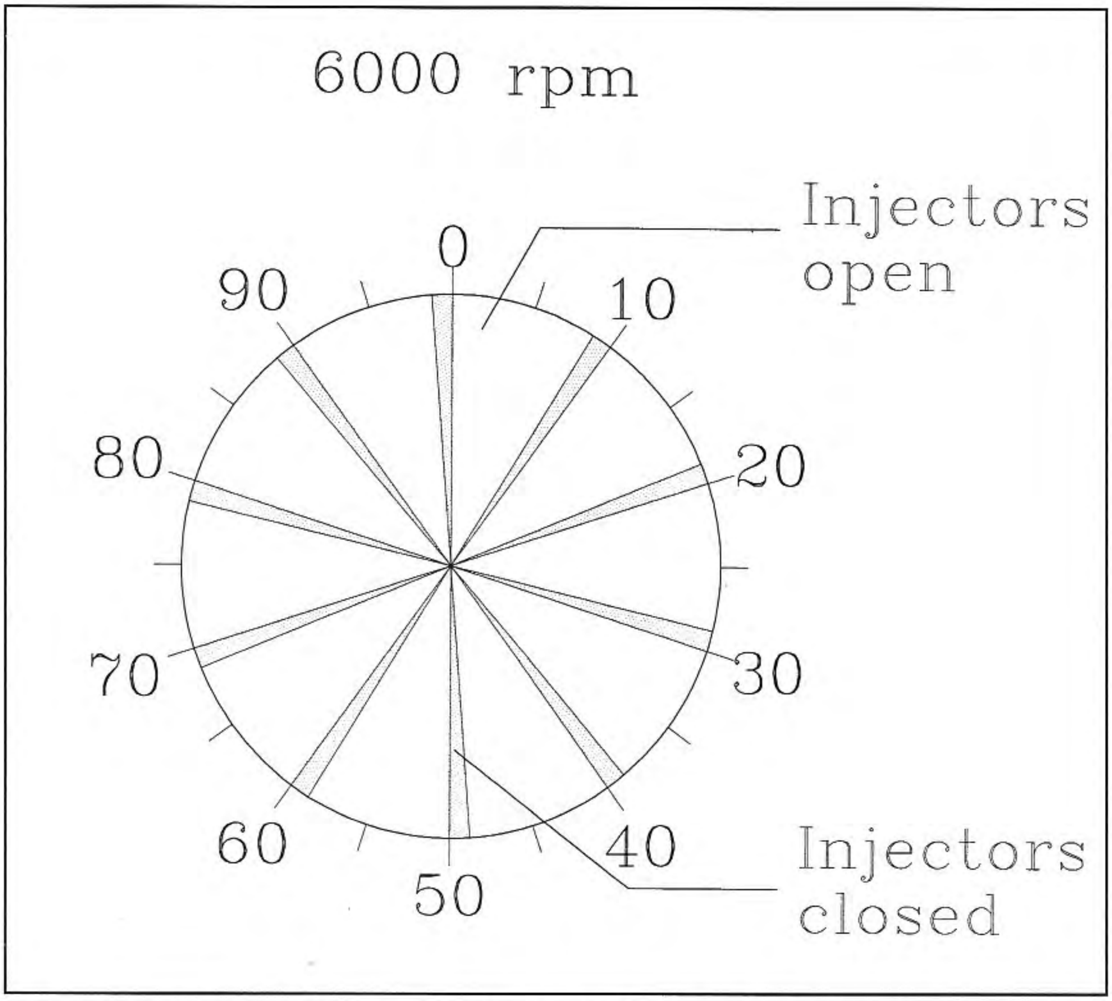
Ignoring secondary functions, like cold-starting enrichment and idle stabilization, a stock L- or LH system might run out of





Intermittent injection systems vary the amount of fuel delivered solely by varying the "on-time" to "off-time" of the electromagnetic injector. At idle, the injectors may only be "on" five percent of the time; at medium revs and load, they may spend more than half the time "on."

"head-room" in one of two basic ways (assuming here we are talking about the maximum rather than the minimum capacity). In closed loop mode, the ECU will increase the quantity of fuel supplied so that the lambda sensor reports a stoichiometric



At a given supply pressure, the upper limit to rate of fuel delivery may be set by the injectors—even though they spend almost all the time "on," they can only just keep up with the demands of an engine making maximum power. Bosch recommends that their duty cycle should not exceed 85% or so.

mixture. The limit to this is probably the flow capacity of the injectors. A heavily modified engine, such as one that has had its displacement greatly increased, might demand so much fuel that, at peak torque, the injectors are "on" virtually all the time—they are essentially working as a continuous flow system—yet are still unable to flow enough fuel to meet the engine's needs. A similar problem will be encountered if a fuel, such as methanol, is used that has a stoichiometric air/fuel ratio greater than that for gasoline. In practice, the ECU will "know" that more fuel is being demanded than called for under the worst case, according to its calibration, and so may regard the lambda sensor as defective and revert to operating on its maps, which would obviously be completely inappropriate.

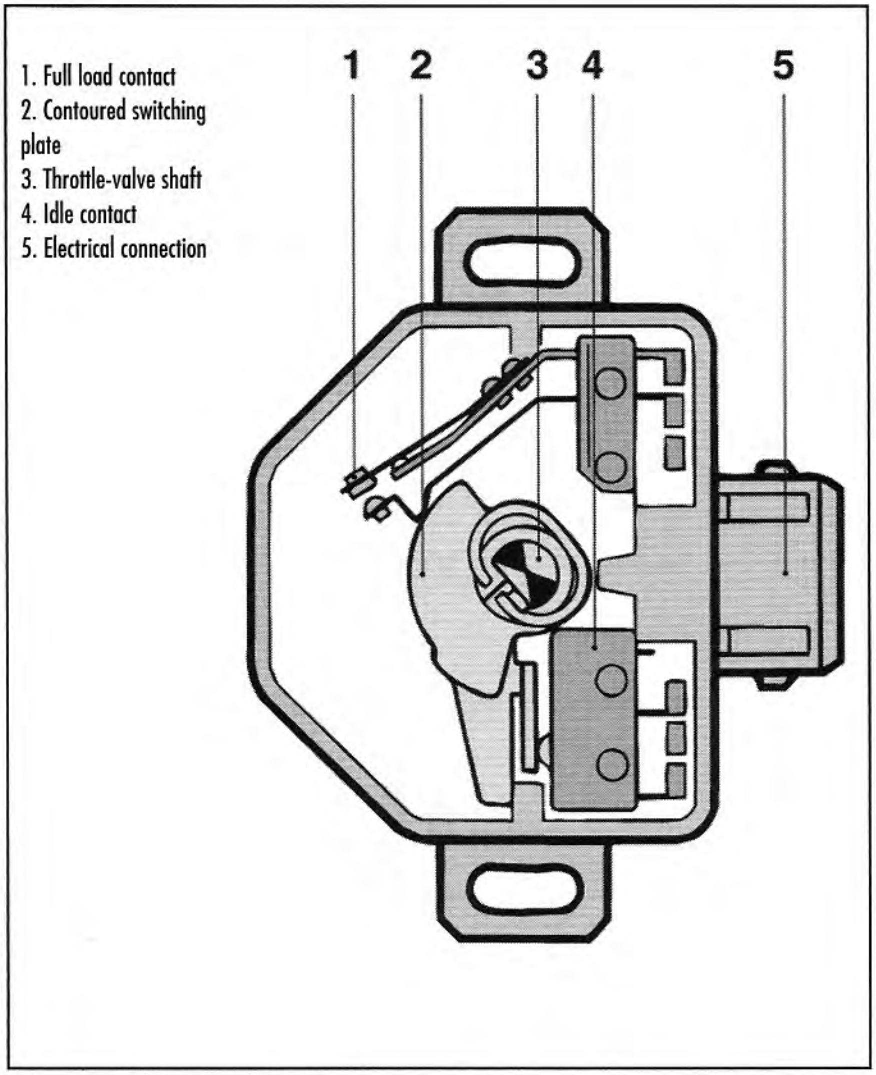
As long as more than about four to six volts is applied to its solenoid coil, an injector will remain "on," flowing fuel, so this 100% duty cycle ("on" 100% of the time; "off" 0% of the time) is theoretically attainable, at least for a short time, but Bosch contends that the injectors' duty cycle should not exceed 85%, presumably to avoid overheating the coils.

Running Open Loop

In open loop mode—that is, with a disconnected or inoperative lambda sensor, or with the engine at full throttle (on most Bosch intermittent systems)—the ECU regulates the injectors' duty cycle based on "maps" stored in its memory. These maps were developed by dyno tests on a representative stock engine, so a modified engine having a greater air capacity than that reference engine at any particular rpm will necessarily run lean. Conversely, at certain speeds a modified engine may handle less air than the stock one, depending on the nature of the modifications. Lumpy cams that move the torque peak higher in the rpm range, for example, will reduce torque at lower speeds below that of a stock engine. The maps know nothing about this, of course, so continue to provide an amount of fuel suitable for the stock engine that happens to move more air at that speed, so the mixture supplied is too rich.

Provided the basic shape of the torque curve remains essentially unchanged—such as would be the case with a moderate displacement increase, but no other modifications—then the maps will produce a mixture strength that is fairly uniformly lean. In that case, an increase in fuel pressure proportional to the hike in displacement should produce a serviceable mixture strength. Governed by the maps, the injectors "on" times will be the same as they were, but they will flow more fuel per cycle because of the increased supply pressure. Adjustable aftermarket fuel pressure regulators are available from a wide variety of sources. Note that a regulator need not necessarily be intended for a Bosch system, as long as it is adequately sized (so it does not itself present a restriction to flow) and can be adjusted to the desired pressure.

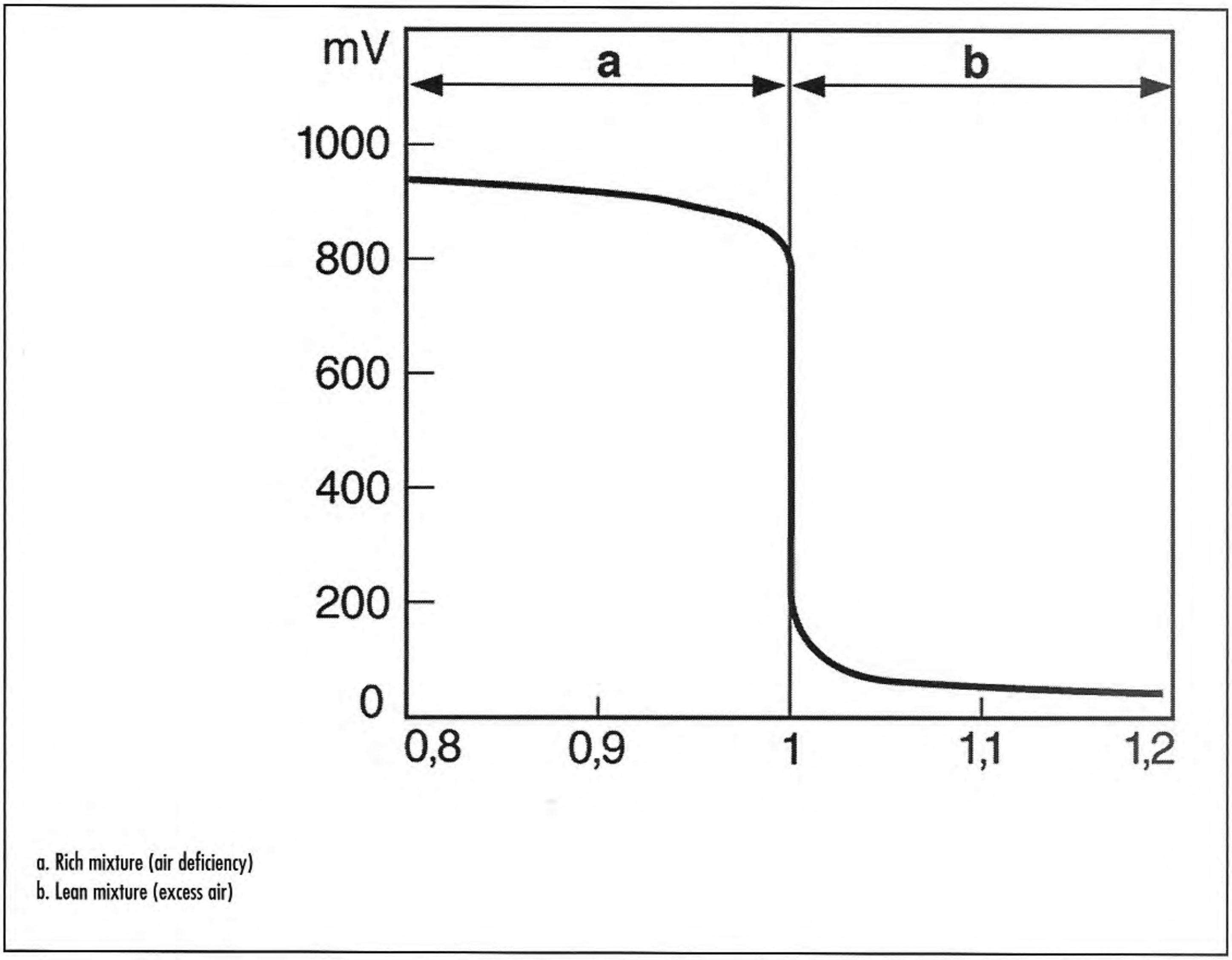
Care should be exercised here; any increase in supply pressure brings with it an increased risk of leaks. In the worst case, a hose or other component might burst. This is clearly hazardous. In addition, the added load may damage the fuel pump. Bosch plumbing components can obviously tolerate pressures somewhat above their nominal ratings, but it could be dangerous and



At idle and at full-throttle, lambda controlled systems ignore the sensor and revert to "open-loop" operation, using their preprogrammed maps to decide the length of injection pulses. The change between modes is signalled by the throttle switch. (Robert Bosch Corporation)

expensive to find out just where their true limits are. Note, too, that a hike in supply pressure will richen the mixture under all conditions when the engine is operating open loop and the ECU reverts to its maps. While this may be harmless as far as it affects cold starting, the idle mixture may be so rich as to foul plugs and cause other driveability problems.

For off-road use, and assuming no catalytic converter is fitted, an engine running in open loop mode will benefit from a slight degree of enrichment anyway. Recall that a converter needs a mixture held very near



Raising the fuel pressure will increase the flow rate through an injector when it is "on," but this hot-rodding technique will not work on an engine with a working lambda sensor. The sensor will detect the rich mixture and reduce the "on" time accordingly! (Robert Bosch Corporation)

stoichiometry in order to work properly, but the mixture strength for peak power is somewhat richer than that. This "tweak" cannot be applied to an engine running in closed-loop mode, however—the ECU, based on the "rich mixture" signal it is getting from the lambda sensor, will simply dial back the injectors' "on" time to correct for the increased flow due to the raised system pressure.

Fooling the ECU

Increased system pressure can, however, deal with the problem mentioned earlier of the fuel demands of a heavily modified engine in closed-loop mode exceeding the flow capacity of the injectors. As long as a lambda sensor is fitted and the injectors can keep up with the demand, the ECU will keep tailoring the injectors "on" time to match the engine's air consumption, pretty much regardless of what the shape of the torque curve is. While this at first appears to be a promising line of approach, note again that the ECU/lambda sensor's goal is a mixture that is somewhat leaner than that giving best power. (And, again, you might bump into the ECU's preset limits.)

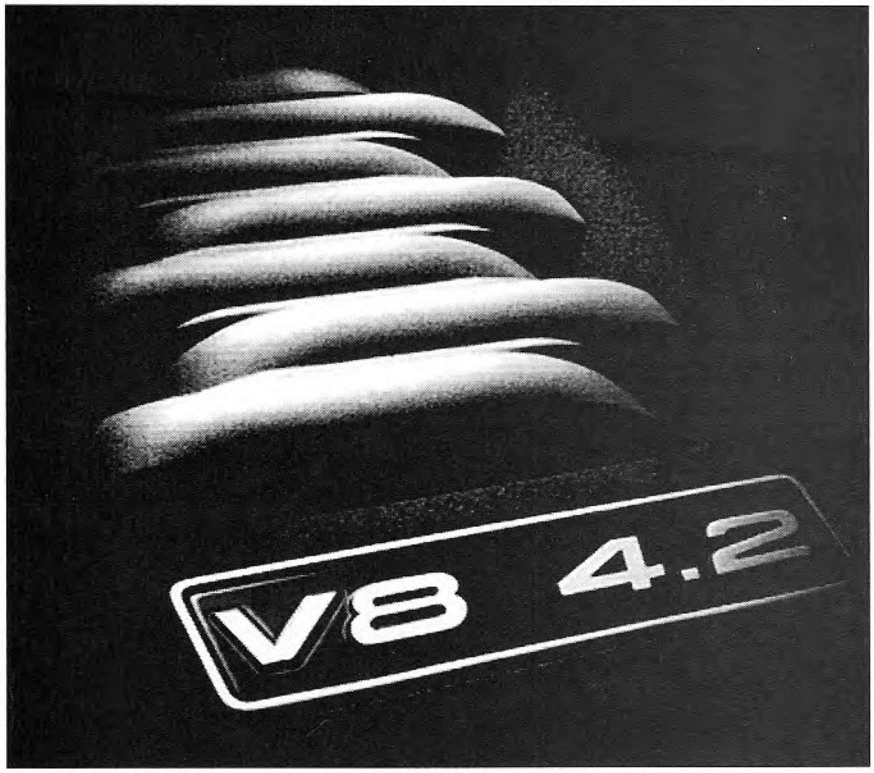
Other makeshift means of richening the mixture include persuading the ECU that the engine is cold, inducing it to provide a richer mixture even when the engine is hot. One standard "trick" (a foolish one) is to disconnect the coolant sensor. On older L-Jetronic systems, this will work but, as noted above, the mixture will be enriched under all circumstances, not just at full throttle. (And note that the stock system already enriches the mixture beyond stoichiometry when the throttle position sensor indicates full throttle.)

On more recent LH-systems, you are likely to discover that the ECU detects this tomfoolery. For example, it will not long be satisfied with information from the air temperature sensor that the air is at 100° F while the coolant temperature sensor reports that the coolant remains "cold" after many minutes of running. It will conclude the sensor is defective . . . and revert to its maps!! It is essentially impossible to "fool" the computer—at least in a productive way—and it is stupid to try.

Activating the Cold-Start Injector—Again, some folks have attempted to deal with a modified engine that needs more fuel at full throttle than provided by the maps (remember, this is what the ECU uses in open-loop mode, which most systems revert to at full throttle) by activating the cold-start injector. Yes, more fuel will be supplied, and, yes, the average mixture will thus be enriched. But the position of the cold-start injector, and the fact that there is just one, pretty much guarantees that some cylinders will get a lot more than their share and others a lot less.

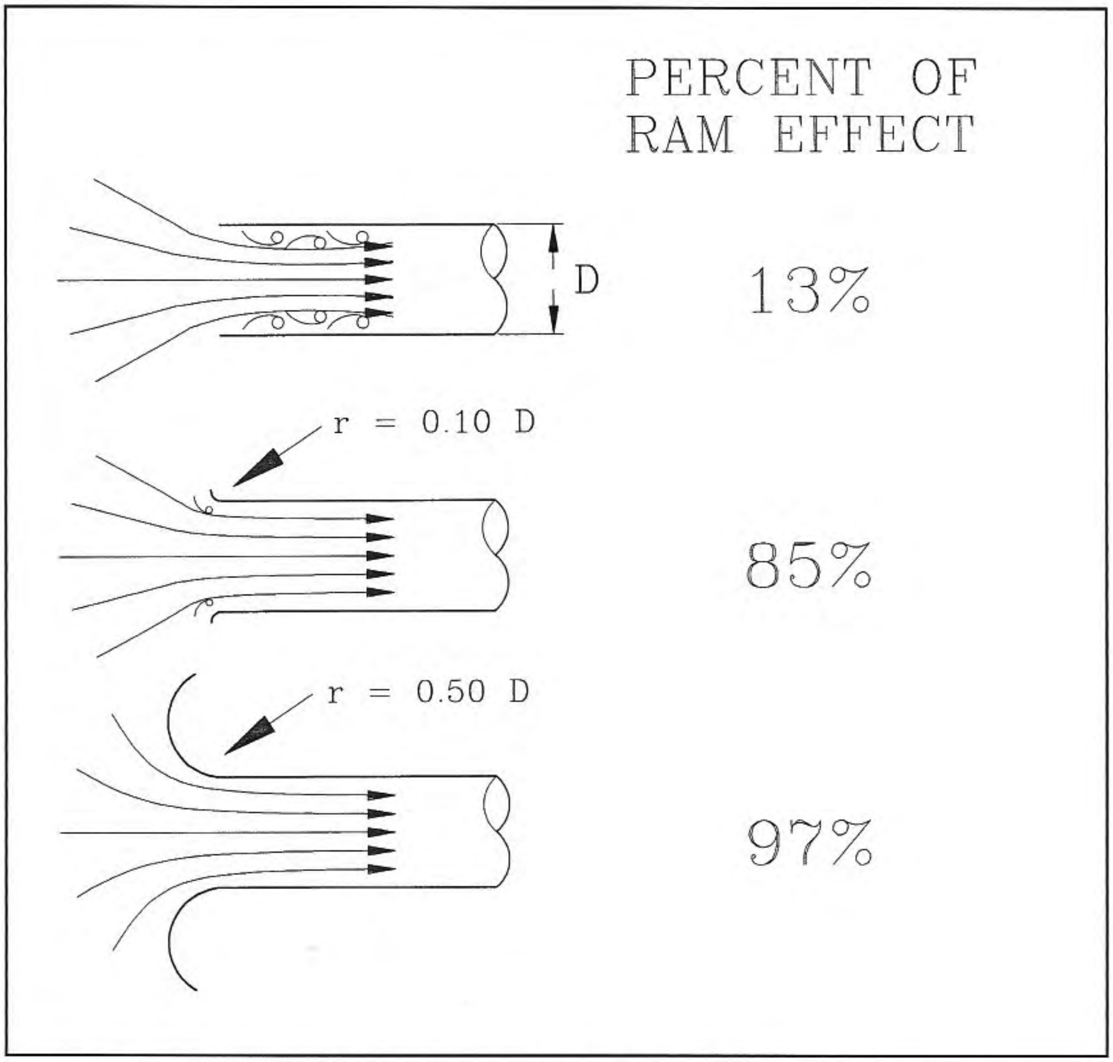
Installing New Maps

The only real solution to this conundrum is for the engine to run open-loop, using a new set of maps. With information from a throttle position sensor and an engine speed (or "tach") signal, you have the information needed to determine how much fuel to inject at any instant, provided you know what the engine's appetite is under any possible combination of those factors. That can be achieved electronically with a set of "maps" particular to the engine, established during dyno testing.



Tuned-length intake pipes can provide a degree of "acoustic ramming," pumping up the torque curve at an rpm that depends on the length of the pipes. Long ones, as on this Audi twin cam V8, beef up the bottom end of the range; short ones add top end power at the expense of low end torque. (VW Canada)

Eliminating Airflow Meter—This approach has the further advantage that it allows elimination of the airflow meter. (For all-out race use, it is not really necessary to directly measure airflow at all, if the electronic "maps" are sufficiently accurate.) While the central airflow sensor—whether vane-type or the true mass-metering hot-wire and hot-film types—is an asset in a production engine, it can be a liability for race-only use because it prevents the best possible exploitation of ram-tuning of the intake pipes; for that, individual stacks are needed. Getting rid of the air meter also eliminates the slight restriction to airflow imposed even by the LH-Jetronic's mass flow meter. Purpose-built race engines using



Most of the benefit of tuned "ram" pipes is lost if the entry to the pipe is sharp edged. A smoothly radiused edge is necessary to get maximum benefit; a large radius is better than a tight one.

Bosch racing EFI systems operate on this basis.

Dispensing with the air meter does mean that racers have to take account of air density, just as tuners of carbureted engines do. Higher air density than that prevailing at the time the maps were compiled requires a corresponding overall enrichment, and vice-versa. As long as the initial calibration is performed at an altitude where the engine will usually be operated and on a day with "typical" barometric pressure, this is a matter that need only concern cost-no-object race teams. They swap chips in the ECU to achieve this last fraction of a percent tuning.

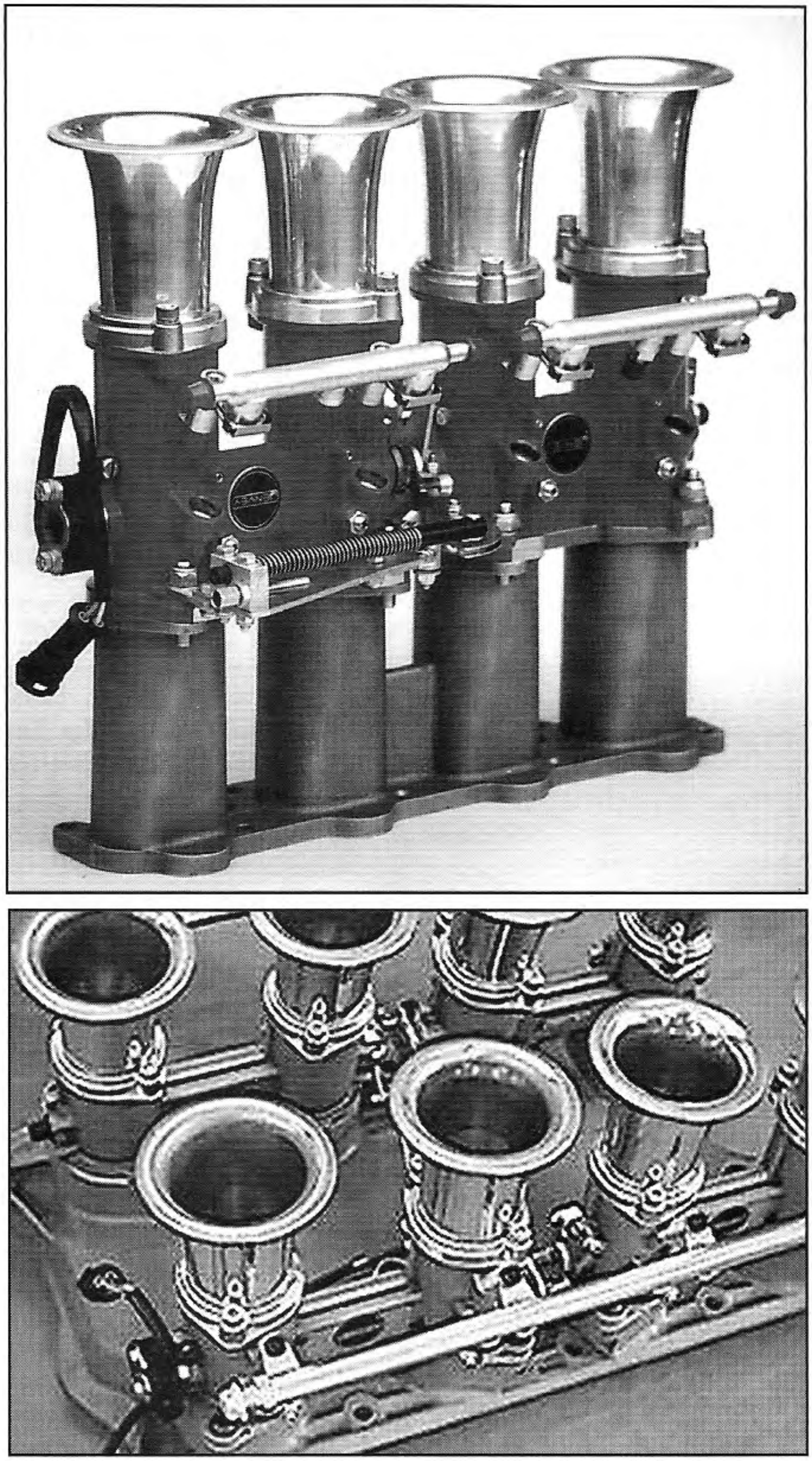
In the past, this concept of a custom-tailored set of ECU maps was understood to be theoretically ideal, but was essentially unattainable in practice because of the "deep-tech" involved in reprogramming the maps in a stock Bosch ECU. For starters, the locations of the individual data points in the electronic memory sometimes differ widely between very similar car models, so electronic wizards turned junkyard scroungers would have to essentially start from scratch every time around. And Bosch will most definitely NOT release the "codes"! They (or perhaps more correctly, the OEM manufacturers that sell cars using their EFI systems) are legally obliged to certify their vehicles' conformance with emissions limits for 50,000 miles, and to do that they have to ensure the systems are tamper-proof.

Given the impracticality of reprogramming the Bosch ECU, the only logical alternative is an aftermarket ECU that is capable of being programmed by the user. A handful of companies now offer these, together with the software necessary to allow the programming to be done from a desktop computer. In early versions, a fair bit of computer savvy was necessary to do the programming, but the more recent versions turn the whole business into a "point-and-click" operation.

Aftermarket ECU's

Among the first to ride to the rescue in this way was the Australian firm Haltech. Their most recent control module—the E6K, as of the time of writing—incorporates an ignition timing module, in the same way as Bosch's own Motronic systems. In Britain, the Autocar Electrical Equipment Co. produces something very similar under the brand name "Lumenition." Both systems are sufficiently flexible that they are compatible with not just Bosch hardware (injectors, pumps, sensors, etc.) but with components from virtually any EFI system.

The programming is done in real-time, with the engine under load on a dyno. Working with a straightforward screen display, you simply point and click to increase or decrease the amount of fuel delivered at some particular load point. The process is then repeated for all load points in each rpm range. Ignition timing data points are entered in a similar way. As long as you have the tuning savvy to know which direction to adjust mixture strength and spark timing, the programming procedure is within the capability of anyone half-bright with access to an engine dyno—no rocket science is really required.



A British firm, Jenvey Dynamics, offers throttle bodies in both side-draft and down-draft configurations. These are suitable for use with do-it-yourself EFI systems using Bosch fuel-handling and electrical components, and an aftermarket ECU, such as Haltech's. (Jenvey Dynamics Ltd)

Autocar

Under the Lumenition brand, Autocar also offers an aftermarket throttle body assembly that is a direct bolt-on replacement for Weber carburetors, in both side-draft and down-draft versions, intended for use with their ECU (but equally compatible in principle with Haltech or other ECUs) and Bosch or other fuel system hardware. Autocar are also the source for components under the Micro Dynamics brand name, having taken over that company. (It is worth mentioning here that the Micro Dynamics rising-rate pressure regulator, previously offered for both intermittent and for continuous EFI systems, is no longer available. Autocar cites a combination of insufficient demand and some technical shortcomings for discontinuing this product).

Apart from aftermarket ignition parts, including a spark retard module for turbocharged EFI engines, Autocar offers the Micro Dynamics PIC5—a supplementary electronic module and extra injector that is primarily intended for temporary full-throttle enrichment for turbocharged engines. Autocar correctly points out that while the PIC5 can be fitted to a normally aspirated engine, it is definitely not advisable because of the same problems noted above with regard to use of the cold-start injector as a means of supplementary enrichment—uneven distribution of mixture strength from cylinder-to-cylinder.

Racing Gasoline

"There is nothing special about gasoline," one fuel engineer has explained, "it is simply something that you can make from crude oil that engines can run on." And unlike many industries that produce a saleable product from a natural source, fuel refiners throw nothing away—there is no sawdust and bark left over after the tree is sawn into lumber, no chaff left over after the wheat is milled. These folks sell absolutely everything!

Refining is partly a process of sorting the bad stuff from the good stuff, and partly a matter of converting some of the rubbish into saleable product. But this is an expensive business, so the process is carried only far enough to make a serviceable fuel.

The hundreds of different hydrocarbon compounds that make up a typical gasoline blend have widely differing properties. Their specific gravities vary from 0.500 to 0.879; their octane number can be anywhere from 0 to 120; they have different heat energy contents—from 0.24 to 0.39 BTU per lb.

One characteristic that distinguishes a desirable hydrocarbon for high performance use is a high octane number. Another is a high heating value. Although there is only a slight difference between one hydrocarbon and another in the amount of heat produced by burning, say, one cubic foot of air/vapor mix, there is nevertheless a difference. There is something like 3–4% more power to be had by burning a pure sample of the most energetic hydrocarbon, compared to typical pump fuel.

By a cruel fluke of nature, the hydrocarbons that rank highest in heating value are generally the worst in terms of octane, with a few significant exceptions. The exceptions are found among the aromatics—benzene, toluene, and various xylenes—and the alkylates (also called isoparaffins). Aviation gas, for instance, has lots of alkylates, and many pump super premiums contain plenty of aromatics. (No benzene, though, beyond a mere trace—benzene is a known carcinogen.) These high-quality components are comparatively difficult and expensive for a refinery to produce, however, so for most of a human lifetime refiners added tetraethyl lead (TEL), which works like a negative catalyst, slowing down the chemical reactions that are the root cause of detonation. But TEL—long known to be lethally toxic—was banned from gasoline, perhaps not so much because of its direct effect on human health but rather because you cannot meet emission standards without a catalytic converter, and leaded fuel "poisons" the converter, rendering it ineffective.

Lead Additives

And that's where the race fuel wizards come in. Working solely with hydrocarbons, it might be just barely possible to produce a 100-plus octane gasoline, but it certainly wouldn't make economic sense. Here, race fuel producers do the same as the major refineries do—they use non-hydrocarbon additives. Government regulations for pump gas permits limited amounts of certain of these additives; gasoline rules for many classes of motorcycle, oval track, and road racing are more generous.

While many, if not most, racing gasolines contain a significant amount of lead, there are some unleaded racing gasolines, based mostly on alkylates and aromatics. To squeeze the last bit of octane out of these carefully selected base stocks, most unleaded race gas has a lead substitute added. The additive, called MMT—methylcyclopentadienyl manganese tricarbonyl is the active ingredient in many octane-boosting additives. Many premium pump fuels also contain MMT, although this varies from state-to-state.

Even though MMT is about the best lead replacement available, it doesn't work nearly as well as lead, so even if you start off with the select mixture of hydrocarbons found in race gas, you're still scraping for decent octane numbers no matter how much MMT you add. To bump up the detonation resistance further, unleaded race gasolines also contain a fat hit of MTBE—methyl tertiary butyl ether which, by itself, has a healthy octane number of 114 (Research Method). Not only does MTBE jack up octane, it is also an oxygenate—it contains oxygen—and so directly increases power. A fuel carrying its own oxygen adds to the amount the engine inhales, increasing power roughly in proportion. As much as 11% MTBE can be found in premium unleaded; some racing UL's contain twice that much.

Because of the oxygenate content, the mixture has to be richened a little. A motor that is borderline lean on straight hydrocarbon gasoline can slip right over the edge when it gets more oxygen than there is fuel to oxidize. As explained above, the programming in recent Bosch electronic FI systems has enough "head-room" to cope with the added fuel flow requirements of these oxygenated fuels. Systems with a lambda sensor will simply crank up the mixture strength until the sensor reports stoichiometry. The engine will then be ingesting just enough additional hydrocarbon molecules to burn in the few percent more oxygen molecules provided by the fuel, and power will be increased in proportion.

In drag racing, there's another problem with the oxygen content. NHRA defines gasoline a little differently than the rule makers in many other forms of racing. By specifying a maximum dielectric (electrical insulating) value for gasoline, the NHRA rules effectively place a strict limit on the amount of any added oxygen bearing compounds, including MTBE.

Avgas

Before the development of race-only gasolines, some performance enthusiasts sought increased power from aviation gasoline—Avgas. In fact, Avgas has little if any edge over ordinary pump fuel in terms of heating value; any increased performance it might provide is attributable almost entirely to the fact that Avgas's higher octane allows a higher compression ratio to be used without running into detonation.

Types of Avgas

Avgas comes in 2 (or maybe 3) grades; each is identified by a performance number—not to be confused with an octane number. In contrast to the method used to establish the Research and Motor octane numbers (see the Sidebar "Doing Octane

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 takeoff 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-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.

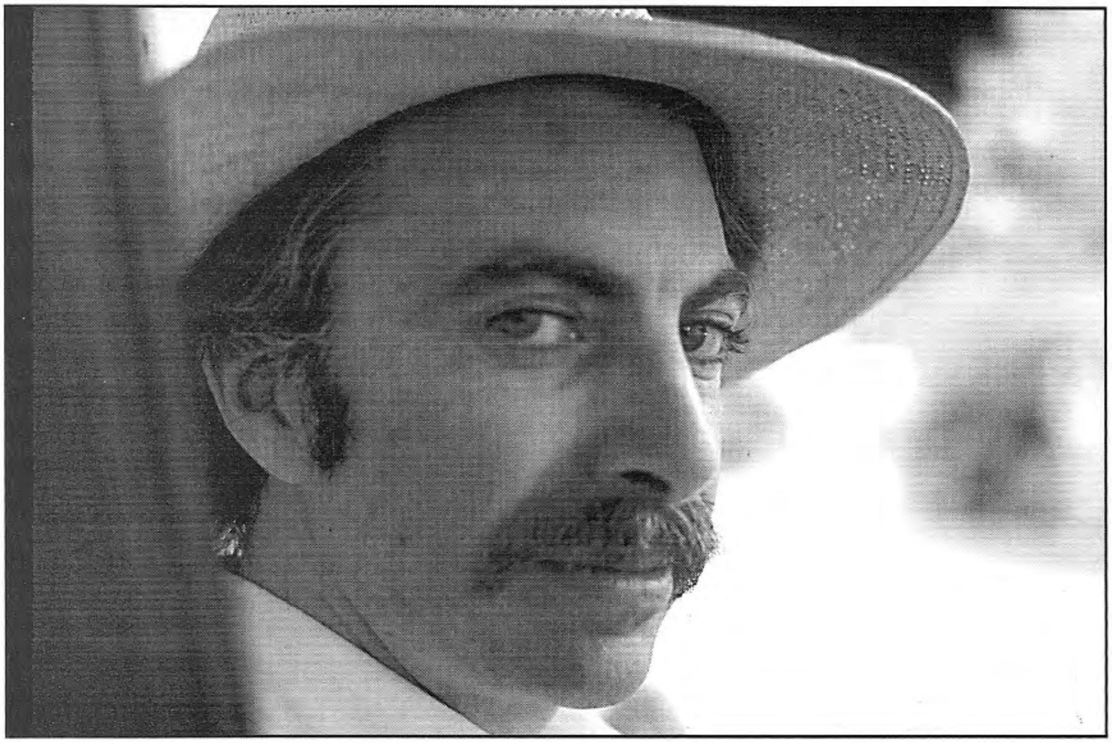
There are other problems with blending gasoline and methanol. For one thing, while a little bit of water in straight methanol may actually help performance, even a small amount of water will cause a mixture of methanol and gas to separate into two parts, with the gas floating on top of the alky. Even 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.



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.