Chapter 2

Engine Control Fundamentals

Contents

1. INTRODUCTION

In this chapter, I'll review some basic factors about fuel injection and engine control that apply to just about every engine.

- How the air-fuel ratio, spark timing, and idle-air bypass can be controlled to improve driveability and control exhaust emissions with little sacrifice of power
- The necessity for emission control and fuel economy
- The concepts of feed-back and feed-forward in engine control
- Why various engine operating modes demand different control strategies—different air-fuel mixtures, different spark timing, and different idle-air bypass

You need a clear understanding of the requirements of engine control under different conditions. This will help you to understand the operation of the sensors that send signals to the control module, and to understand the actuators that are controlled by the control-module output signals. I do it this way for two reasons:

- In spite of the different systems for different cars and trucks, these systems are more alike than they are different
- When you know what's behind these systems, you'll be much better equipped to go inside the system for service or for high performance

2. BASIC FACTORS

2.1 Air-Fuel Ratios

The main job of any fuel metering system is to mix fuel with the incoming air in the proper ratio. Small variations in air-fuel ratio can have major effects on power output, fuel consumption, and exhaust emissions. In your engine, the throttle controls the amount of air the engine takes in, but has no direct effect on the fuel metering.

The Basic Combustible Mixture

Surprising as it may seem, liquid gasoline will not burn! Combustion of gasoline requires that the particles be small enough. Also, the particles must reach the correct amount of oxygen in proportion to the amount of fuel. In internal combustion engines, the fuel is atomized into tiny droplets, and metered in correct proportion to the intake air. In round numbers, it takes about 14 parts of air to support complete combustion of 1 part of fuel—in other words, an air-fuel ratio of about 14:1.

Gasoline air-fuel ratios that are higher or lower than about 14:1 will still burn, but such combustion usually raises emissions and produces other side effects. As you read further into this chapter, you'll see what those are, and why precise control of the air-fuel ratio has become so important. You'll need to understand the relationship between air-fuel mixture and exhaust gas oxygen to relate to the electronic control of emissions. Alternate fuels, such as Methanol blends, will require different air-fuel ratios.

Throughout this book, I'll follow generally accepted practice and discuss air-fuel ratios primarily in terms of mass. "Mass Air-Flow Sensor" is an input sensor you'll hear about in the newer Ford EEC systems. You'll see carburetor flowrates expressed as volume, such as xx cubic feet per minute. Engines burn mass, such as xx pounds of air per minute. In Earth gravity, mass is about the same as weight. The combustion takes place in terms of mass, or weight, not volume. Think of weight, or mass as the simplest and best way to understand the basic factors governing fuel delivery and combustion.

Fig. 2-1. The mass of one ounce of gasoline, as in a shot glass, burns with the mass of the air in a car trunk, about 14 ounces. Yet the volume of the liquid gasoline is much, much smaller than the volume of air in the trunk. It is the mass that determines the air-fuel ratio, not the volume.

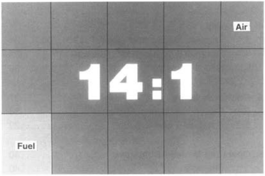

Fig. 2-2. It takes about 14 parts of air by mass to support complete combustion of 1 part of gasoline fuel. Once upon a time, an air-fuel ratio somewhere close to 14:1 was good enough.

Rich and Lean Mixtures

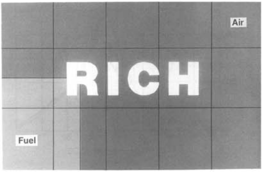

Fig. 2-3. A rich mixture burns almost all the oxygen, so exhaust gas is low in oxygen content. Exhaust gas has much unburned fuel.

You've probably heard the terms "rich" and "lean" as used to describe mixtures. A rich mixture is one with a lower air-fuel ratio. It has insufficient air (oxygen) to support complete combustion of the fuel. Rich mixtures increase fuel consumption and emissions of hydrocarbons (HC) and carbon monoxide (CO)—the products of incompletely burned gasoline. They tend to reduce power, increase carbon deposits and, in the extreme case, foul spark plugs and dilute the engine oil.

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

If the air-fuel mixture in the combustion chamber gets richer than about 10:1 for steady running, the engine loses power, and unburned fuel pours out the exhaust pipe in black smoke.

Fig. 2-4. A lean mixture burns almost all the fuel, so exhaust gas contains leftover oxygen, and very little unburned gasoline.

A lean mixture is one with a higher air-fuel ratio. After complete combustion of the fuel, the exhaust contains leftover air. The fuel will burn completely, but more slowly and at a higher combustion temperature. Lean mixtures reduce power, elevate engine temperature, and increase emissions of oxides of nitrogen (NO_x)—a product of combustion at excessively high temperature. They also cause driveability problems. In the extreme case, the high temperatures resulting from lean combustion will cause pre-ignition—violent combustion of the mixture that can cause serious engine damage.

If the air-fuel mixture gets leaner than about 17:1, misfiring in the cylinder can lead to loss of power and backfiring.

The way the air-fuel mixture affects the exhaust gas is fundamental to engine control. Remember:

- **Rich** air-fuel mixtures produce exhaust gases with little or no oxygen
- **Lean** air-fuel mixtures produce exhaust gases with extra oxygen

Stoichiometric (Ideal) Ratio

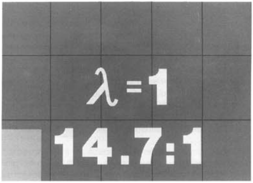

Fig. 2-5. For a warm engine, running on gasoline at part throttle, the ideal or "stoichiometric" air-fuel ratio—when there is just enough air to burn all the fuel—is 14.7:1.

"Stoichiometric" is a fancy word that roughly means "measuring the elements." A stoichiometric ratio is neither too rich nor too lean. It contains just enough fuel to burn all the oxygen in the mixture. It is the air-fuel ratio that provides the proper exhaust gas to operate the catalytic converter. More on that later. For a warm engine, running at part throttle, stoichiometric is a so-called "ideal" ratio—the one that offers the best compromise between best power and best economy.

Engines operate most of the time at part throttle at the ideal air-fuel ratio, 14.7:1 for gasoline. But conditions can change, in a fraction of a second, and over a long period of time. To handle these changes in condition, engine control must change air-fuel ratios and spark timing with great speed and accuracy.

When "gas was cheap and the air was dirty," carburetors usually delivered mixtures richer than 14:1, perhaps with an air-fuel ratio as low as 12:1. As the car aged and a little excess air leaked in around the gaskets of the carburetor or the intake manifold, the engine still got a good combustible mixture. Also, a richer *mixture was some compensation for unequal fuel distribution* with the carburetor farther from the end cylinders than from the middle ones. 1970 Ford specifications for carburetor idle air-fuel ratios were usually in the 13s, but ran as low as 12:1.

For the first emission controls, in 1968, lean mixtures reduced hydrocarbons (HC) and Carbon Monoxide (CO). More on Emission Controls in Chapter 3.

Fig. 2-6 shows another reason for setting up carbureted engines to run a little rich. Air-fuel mixture was less precise, and some variations were to be expected. Variations in a rich mixture have only a small effect on power, while variations in a lean mixture affect power dramatically.

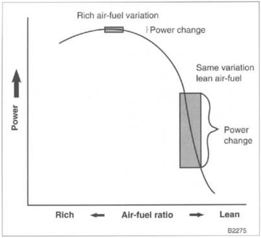

Fig. 2-6. Variation in a rich air-fuel ratio makes much less difference in power than the same variation in a lean air-fuel ratio.

2.2 Spark Timing (Ignition)

Precise control of spark timing is also important to engine control for emissions and economy, and for driveability. As the spark jumps across the plug gap, on the average, it takes about 2 ms (milliseconds—thousandths of a second) to ignite the air-fuel mixture. The spark must fire at the proper millisecond so the combustion pressure peaks just after the piston reaches TDC (Top Dead Center), shown as 0 in Fig. 2-7.

Line b shows the spark timing is too early—too advanced. Cylinder pressure builds as the piston is travelling upward. An advanced spark ignites the mixture so that it "crashes" into the piston. That can cause knocking in the combustion chamber, and that costs power.

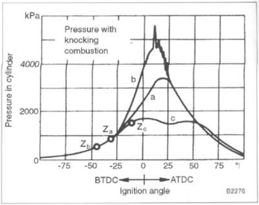

Fig. 2-7. Pressure in the combustion chamber varies according to spark timing advance.

> **NOTE —**
> The pressure-build that causes knocking depends on the octane rating of the fuel—less tendency to knock with high octane fuels because they burn more slowly.

Line c shows it's too late—retarded. The piston is already travelling downward and again, that costs power.

Line a shows the proper timing, producing maximum pressure shortly after the piston reaches TDC.

Spark timing is usually measured from TDC, considered as 0 degrees of crankshaft travel. When the spark is timed before the piston reaches the top, we say it fires BTDC (Before TDC):

- Point Za, the proper spark timing is about -30, or 30 degrees BTDC
- Point Zb, the advanced timing is about 45 degrees BTDC
- Point Zc, the retarded timing is about 10 degrees BTDC

The two most important factors affecting spark timing for power and economy are engine speed and engine load.

Engine Speed/Spark Timing

During maximum rpm operation, the piston may travel ten times as fast as during its slowest rpm. But the spark doesn't jump any faster, or ignite the mixture any faster. To build combustion pressure according to the TDC, spark timing must be advanced more as the engine rpm increases. Before the days of engine control, spark timing was advanced by a set of centrifugal weights.

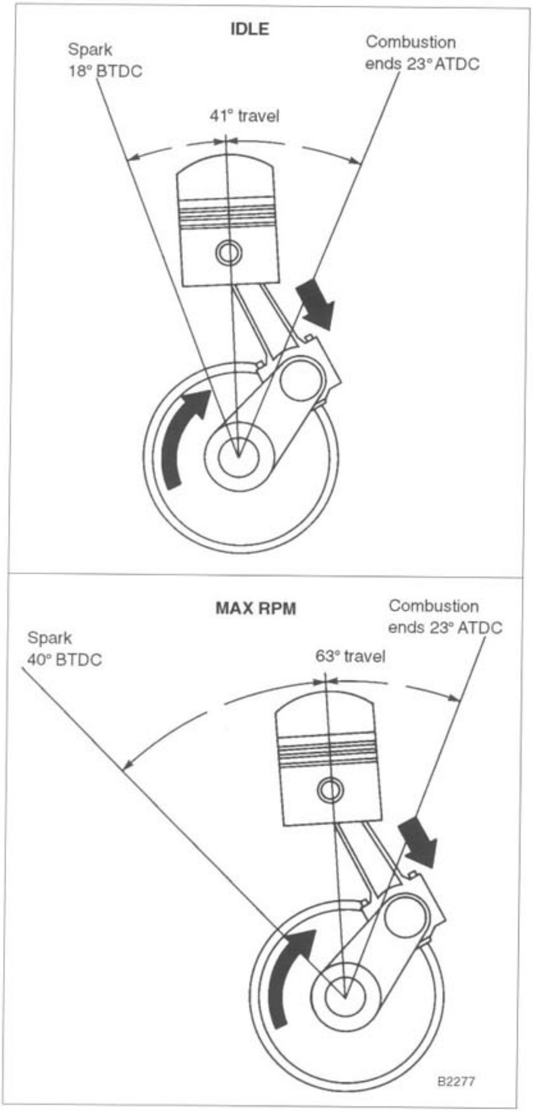

Fig. 2-8. Spark timing for idle, compared to spark timing for max rpm.

Engine Load/Spark Timing

During part-load operation, the air-fuel mixture is throttled, so there is less mixture in the combustion chamber, and it burns more slowly. Therefore, under part load, spark timing must be advanced. Before the days of engine control, spark timing was advanced by vacuum-advance diaphragms.

Engine control must also consider the effect of spark timing on emissions. Naturally, emissions are related to the air-fuel ratio, and how that will burn according to different spark timings. For more on Emission Control, see Chapter 3.

Spark timing can change power. As shown in Fig. 2-9, advancing spark timing to about 50 degrees BTDC can improve power.

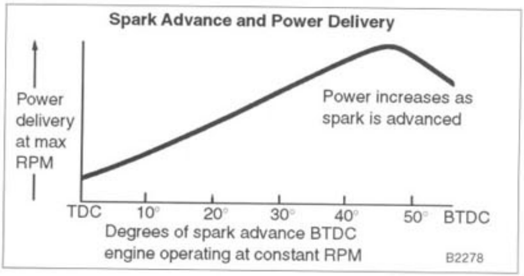

Fig. 2-9. Effect of spark timing on power.

Variations in Spark Timing

All the above is based on that old qualifier, "All other things being equal." But variations exist cylinder-to-cylinder because of variations in manifolding and in injectors, even in engines in good condition. Those variations increase with engine wear, and other factors such as carbon buildup in the cylinders, and valve seating and stem clearances. Other factors could be variations in injector clogging and intake-valve deposits, and, in SFI, variations in individual sequential injectors.

Some changes in operating conditions occur over long times, measured in years. Others over shorter times, such as warm-up time. Others occur almost instantaneously, time measured in milliseconds:

- Acceleration
- Deceleration
- Starting

Engine control of spark timing must consider all these factors, as well as idle smoothness and driveability.

Dwell Control

Dwell control refers to the instant the primary circuit is closed, beginning the saturation of the primary coil windings. Spark timing refers to the instant the primary circuit is opened, causing the coil to develop the voltage to fire the spark plug.

Today's high-compression engines, particularly turbo/supercharged require high-energy ignition systems. Yet, in the interests of coil life and reliability, the dwell period must begin at the right millisecond. The coil must be charged just enough and no more to satisfy the plug firing requirement. That means the engine control system must control dwell.

Push Starting

Late-model ('93) control systems provide spark control for push starting. When the engine is being turned at low rpm with no Crank signal from the key, the control module recognizes a push start. The battery is probably low voltage so the push-start system provides increased dwell (coil ON time). For details, see Chapter 8.

2.3 Air Flow, Fuel Metering and Engine Load

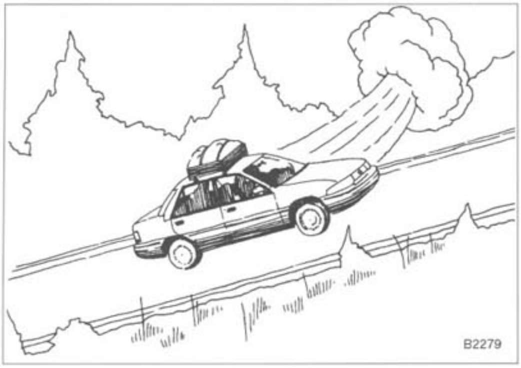

Fig. 2-10. Load changes as a result of hill, head wind, trailer, truck load, also under-inflated tires, open windows, dragging brakes, luggage/ski racks, etc.

Measuring the engine load is an important need for good engine control. The load indicates how hard the engine is working. Load tends to relate to how hard you are pressing the accelerator. Load increases with increasing speed, also for climbing hills, increasing head winds, trailer towing, increased load in the truck bed. Load measurement is most important for determining the amount of fuel to be injected, but also for spark timing. Indirectly, load is important for emission control and for control of closed-throttle air passage.

When the control module needs load measurements, it's really asking, "How much air are we burning?" Or more specifically, "What is the weight of the air we are burning? To deliver the correct air-fuel ratio, I will calculate the weight of fuel to be injected."

Load relates to the weight or mass of air intake. The control module calculates the weight of air and then calculates the weight of fuel to be injected so the air-fuel ratio is correct for the operating conditions. Control module calculations must consider that the air changes its density (pounds per cubic foot) under two influences:

- Temperature—the same volume of warm air weighs less than cool air, and so needs less fuel injected
- Pressure—at higher altitudes, the same volume of air weighs less than at sea level. So too, the same volume weighs less when there is low pressure than when there is high pressure

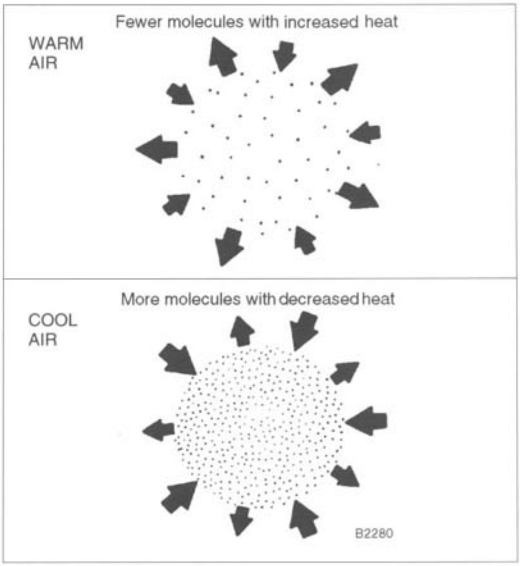

Fig. 2-11. Warm air has less density than cool air, and so, for the same volume, needs less fuel injected.

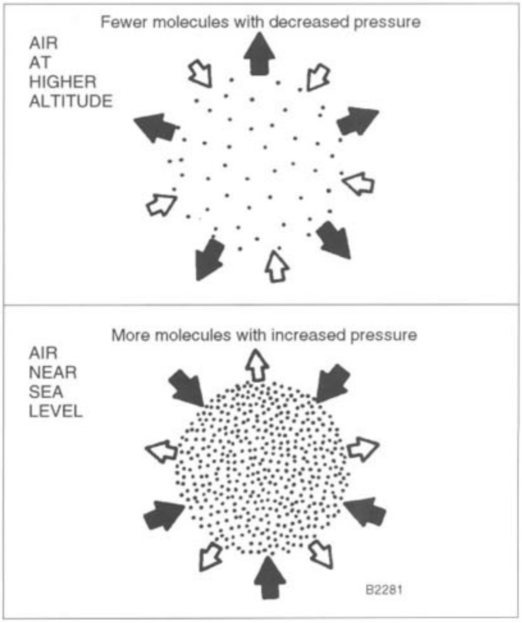

Fig. 2-12. Air at reduced pressure, such as at high altitude, or in low-pressure weather conditions, has less density than sea-level air. So, for the same volume of air needs less fuel.

3. CONTROLLING AIR INTAKE

You know that air is drawn into the engine with each intake stroke of each piston. The piston moving down on its intake stroke increases cylinder volume and lowers pressure in the cylinder. With the intake valve open, air and fuel rush in from the intake manifold to fill the cylinder. The amount of fuel necessary to create a burnable mixture depends on how much air fills the cylinder, as well as other conditions such as temperature. For turbo or supercharged engines, manifold pressure under boost is greater than atmospheric, packing in more air-fuel mixture than naturally-aspirated engines, as in most Fords.

3.1 Throttle

The throttle valve restricts intake air flow. Opening the throttle increases manifold pressure. In simplest terms, intake air flows into the cylinder because manifold pressure is higher than the pressure in the cylinder. Air rushes in during the intake stroke, trying to equalize the pressure. So the amount of air that rushes in on the intake stroke depends on the pressure difference—the difference between the pressure in the intake manifold and the pressure in the cylinder.

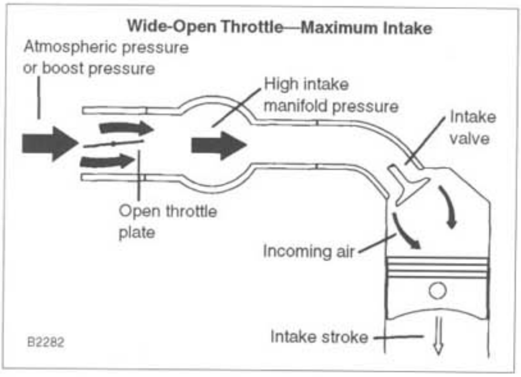

Fig. 3-1. When the throttle is open, manifold pressure is greater than pressure in the cylinders, so more air-fuel mixture moves into the cylinder as the intake valve opens. Boost increases air intake.

Pressure in the intake manifold depends on throttle opening. The greatest intake air flow occurs when the throttle valve is fully open. The throttle valve causes almost no restriction, and full atmospheric pressure (or boost pressure) is admitted to the intake manifold. This creates the greatest possible difference between manifold pressure and reduced pressure in the cylinder during the intake stroke, and the greatest intake air flow.

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

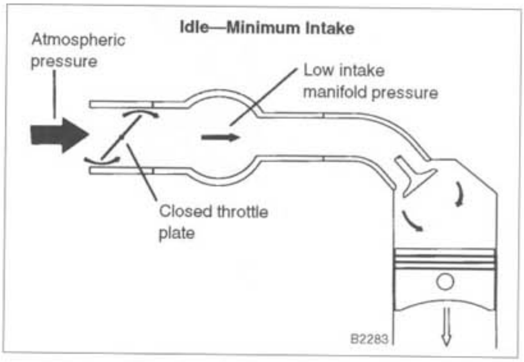

Fig. 3-2. With throttle closed, atmospheric pressure has little effect on manifold pressure. Low pressure-differential between manifold and cylinders results in little air flow. Of course, there is no boost.

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

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

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

The overall air intake is directly related to the air flow, and indirectly related to the manifold pressure. The amount of air that enters each cylinder for each opening of the intake valve(s) is affected largely by the pressure at the intake valve(s).

When you see manifold pressure as on a manifold pressure gauge, or on a vacuum gauge, it may seem constant for a given engine condition. In fact, manifold pressure changes rapidly by the millisecond as the intake valves open and close, as shown in Fig. 3-3.

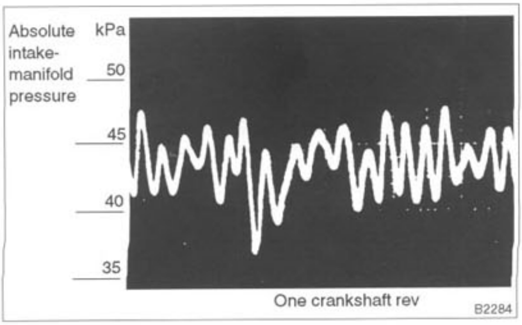

Fig. 3-3. Manifold pressure fluctuates rapidly (as much as 10%) as a result of intake valves opening and closing. This can cause changes in fuel-injection requirements.

You'll see an increasing number of Ford engines with two intake valves, four valves per cylinder. These begin with the 1989 SHO (Super High Output) 3.0L, and the 1.8L DOHC (Dual Overhead Cam) Escort/Tracer engine, first seen in 1991. DOHC 4.6L engines began with the 1993 Lincoln Mark VIII. Two intake valves provide a larger total inlet area than a single valve. Plus, each valve is lighter and can operate at a higher rpm.

3.2 Ramming Intake Air

The cylinder air intake—the mass of air that enters the engine—affects engine power. Getting more air-fuel mixture into the cylinders *per stroke* is the same as having a larger engine (more power).

With fuel injection, the intake runners carry only air instead of air-fuel mixture. The intake system can therefore ram intake air to improve engine efficiency without regard to fuel-puddling in the runners or boost limitations (typical carburetor problems).

Each column of air resonates or "bounces" back and forth in its runner. See Fig. 3-4. We say the air column has "inertia" as it moves back and forth. If the air column is bouncing toward the intake valve just as it opens, the increased pressure "rams" in extra air through each valve opening. The pressure also resists back flow caused by the rising piston on the first part of the compression stroke, while the intake valve is still open. The natural resonance depends on the length of the intake runner—longer runners take longer for the air to bounce back and forth. "Ram air intake" refers to the technique of ramming more air into the cylinders.

In general, long runners tend to improve low-speed torque and fuel economy, while shorter runners improve high-speed torque and power at a slight expense of economy.

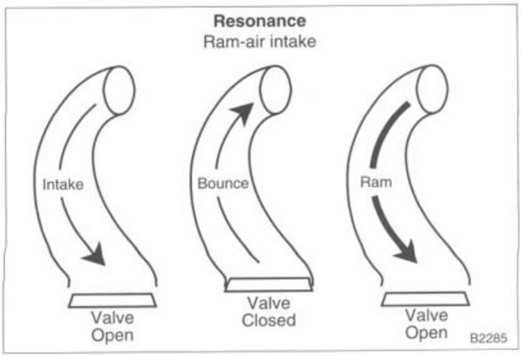

Fig. 3-4. Resonance of air column as it moves in intake runner helps ram air into cylinder.

Ford engine control involves three variations to increase intake air flow, depending on the engine:

- Fixed tuned intake-manifold runners
- Variable-length tuned intake-manifold runners
- Turbocharger or supercharger

Tuned Intake Runners

The first method of influencing intake air flow is tuning the intake manifold runners to a fixed length to take advantage of the natural inertia of the column of air. See Fig. 3-5. Ford engines use a surge tank or chamber just downstream of the throttle to dampen the effect of one cylinder on its neighbors.

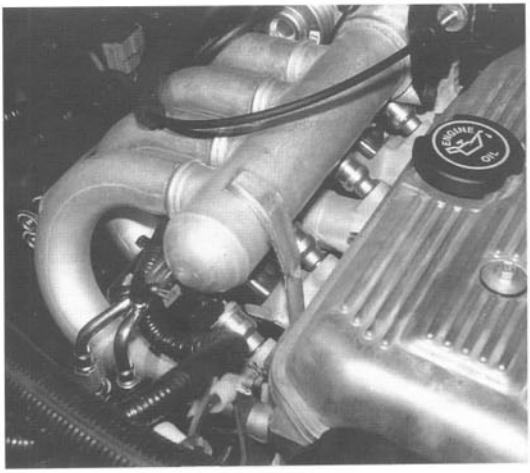

Fig. 3-5. Most Ford engines have tuned surge tank and intake runners. Objective is to use pulsations in runners to ram in more air per intake valve opening.

This separates the air column for each intake valve in its own intake runner.

It doesn't take a rocket scientist to figure that, for a fixed-length runner, this natural resonance, or inertia effect, has a fixed rate while the rate of intake valve-opening changes with rpm. In other words, the length is tuned for a highest efficiency within a relatively small range of rpm, according to the probable use of the vehicle.

Intake Air Control (IAC)

The second method of influencing intake air flow is to actively change the length of the intake runners as the engine changes speed. Ford uses a few different systems:

- Intake Air Control (IAC) on Ford Taurus SHO (Super High Output) 3.0/3.2L engines
- High-Speed Inlet Air (HSIA) control, also called Variable Inertia Charging System (VICS), on 1991and later Ford (Mazda) 1.8L DOHC engines in some Escorts and Tracers
- Variable Resonance Induction System (VRIS), similar to VICS, used on 1993 Ford Probe (Mazda) 2.5L V-6

Changing the effective length of the runners changes the tuning to match rpm. See Fig. 3-6. At lower rpm, the length of the intake runners is longer so the air column takes longer to bounce or resonate between the surge tank and the intake valve. The slower ram effect is timed to the slower rate of intake-valve opening. As rpm increases, the control module activates valves in the intake manifolds to shorten the effective lengths of the runners. The shorter air columns bounce faster to resonate with the intake valves, ramming in more air at higher rpm.

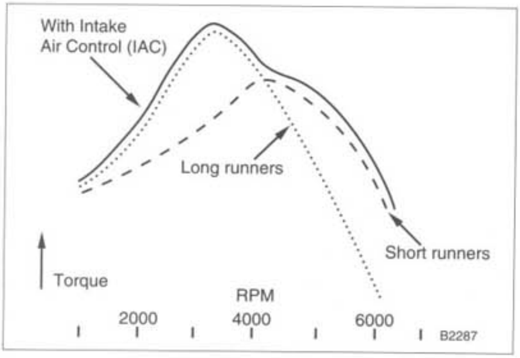

Fig. 3-6. Long runners increase torque at lower rpm. Short runners increase torque at higher rpm. With Intake Air Control, overall torque curve is better.

Turbocharging/Supercharging

The third method of influencing intake air flow is actively ramming air by turbocharging/supercharging, seen on three families of engines in the years since 1988:

- 1988–92: 2.2L Turbo 4-cylinder Mazda engines in Probe
- 1991 and later: 1.6L Turbo Mazda engine in Mercury Capri
- 1989 and later: 3.8L Supercharged V-6 in T-Bird SC/Cougar XR-7

The turbocharger mounts on the exhaust manifold to use the flow of exhaust gasses to spin a turbine. On the same short shaft, a compressor develops pressure in the intake system. Turbine speeds over 100,000 rpm are common. In these engines, Ford limits boost pressures to about 7 to 8 psi. Turbos tend to build boost pressures at higher engine rpm, increasing maximum power output, but delivering relatively little power increase at lower rpm.

Fig. 3-7. Engine exhaust drives the turbocharger (arrow). Ford uses turbochargers on some 1988 and later and some MECS engines.

The supercharger compresses air with two rotors. It is driven by the engine crankshaft through a poly V-belt at 2.6 times crankshaft speed, up to a rotor speed of about 15,000 rpm. Boost pressures of 12 psi are reached at about 4,000 engine rpm, so low-speed torque is a benefit of the supercharger over the turbocharger. The ordinary engine throttle controls boost pressures, controlling inlet to the supercharger so no wastegate control is needed.

NOTE —
Ford has dropped turbochargers from recent engines for emissions reasons. Hot exhaust is necessary for the catalytic converrter to operate most efficiently. The energy used to turn the turbo cools the exhaust. Cooler exhaust means the car may fail an emissions test.

Fig. 3-8. Engine-driven supercharger in 3.8L Ford delivers better low-speed torque than exhaust-driven turbocharger.

There are some problems with supercharging/turbocharging. At maximum power, the supercharger draws about 60 horsepower from the engine. The 3.8L engine without supercharger is rated at 140 horsepower. With the supercharger, the engine is rated at 210 horsepower net, so the gross horsepower is 270. For most operation, supercharger output is bypassed, reducing the supercharger draw to about ½ horsepower.

Also, when superchargers or turbochargers pack extra air into the cylinders, in effect they raise the compression ratio. One rule of thumb is that compression ratio rises by 1 for each 3.7 psi boost. That has two consequences:

- Some charged engines have lower compression ratios than their uncharged counterparts
- Knock sensing becomes important, even critical

Finally, the compression of ramming the intake air heats it. Remember from earlier that hot air has less mass, and therefore can burn less fuel (less power). To cool the air after compression, supercharged models have an intercooler (Charge Air Cooler) between the supercharger and the intake manifold. The cooler air—with more mass—provides increased power.

Volumetric Efficiency

Engineers use the term "Volumetric Efficiency" to describe the efficiency of taking air into the cylinders. Taking 5.0L of air into a 5.0L engine is described as 100% volumetric efficiency. Most engines run Wide Open Throttle (WOT) in the 70–80% range. With a turbo/supercharger, compressing the intake air can raise it to over 100%.

Working with a new scan tool, I was surprised to find a read-out for volumetric efficiency. Of course that's no problem for the engine-control computer: It knows the cylinder capacity, say 5.0L. Reading the rpm, it counts 2 crankshaft revolutions (intake filling of all cylinders). Reading the Mass Air-Flow sensor, it knows the air-mass intake. (Knowing the air temperature, it calculates the volume). If the intake volume calculates to 4.0L every 2 revolutions, volumetric efficiency is 80%. Why would technicians want to read volumetric efficiency, I asked myself. Well, that could be a troubleshooting clue to a clogged air filter, or deposits in the intake passages. Further, it's a guide to the effectiveness of performance modifications such as intake porting and polishing, increased valve lift, and camshaft changes.

4. PRESSURE

Fuel injection means fuel under pressure. In most Ford engines, injectors operate at a relative fuel pressure of 270 kPa (39 psi). Relative pressure means pressure above the Manifold Absolute Pressure (MAP). More on that later.

When pressurized fuel is injected into the airstream, it vaporizes and mixes with the air into a good burnable mixture. Picture how a liquid is vaporized when you spray it under pressure from an aerosol can.

Fuel in a carburetor is normally at atmospheric pressure. Vacuum at the tip pulls gasoline from the fuel jets. I'm talking about vacuum, or the pressure difference between:

- Air pressure on the fuel in the carburetor bowl, and
- Air pressure in the venturi chamber

That difference is usually small. Fuel moves into the airstream because the moving air in the venturi of the carburetor is at reduced pressure, aided by the piston pumping actions. For a cold start, the carburetor choke restricts the air entering the venturi, acting to further reduce the air pressure to pull in more fuel.

4.1 Pressure Measurement

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

Barometric (Atmospheric) Pressure

If you watch the local TV weatherperson, you'll hear talk of "highs" and "lows." They're talking about barometric pressure readings used to describe atmospheric pressure changes.

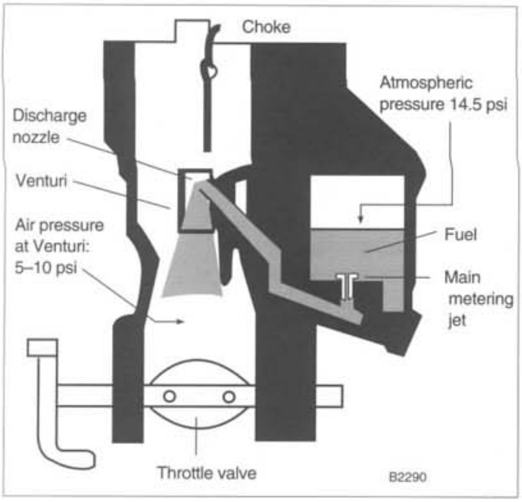

Fig. 4-1. Fuel-metering part of a carburetor operates with small differences in pressure. Atmospheric pressure on fuel in bowl moves fuel into reduced pressure at the discharge nozzle in venturi.

Changing atmospheric pressure changes the density of the air. Denser intake air can slightly alter the air-fuel ratio and may affect how your engine operates. Some Ford engine-control systems have features that allow the system to compensate for variations in air density.

Barometric pressure is the result of air pressing down (and in all directions). Typical "standard day" pressures are 101 kPa, (14.7 psi, or 29.92 in.Hg). I round off to 100 kPa because that's within day-to-day variations from standard, and besides, 100 kPa corresponds to about 500 feet above sea level. Few vehicles operate exactly at sea level.

Barometric pressure is hard to understand because we don't feel it. We live in this "ocean of air" with atmosphere pressing on all sides of us. But it's inside too, so it balances out and we don't feel it. But our engines do. When the engine pumps air in the intake strokes, it reduces the absolute pressure below atmospheric and creates what we call "vacuum." The engine control system must "feel" the barometric pressure and the manifold absolute pressure and adjust accordingly.

In any case, you'll find pressure values expressed in one or more of the following units or terms. With the appropriate conversion factors, all are interchangeable.

> Wait a minute, 14.7 is the ideal air-fuel ratio, and 14.7 psi is barometric pressure at sea level! How's that again? Pure coincidence, but that makes it easier to remember those two important numbers in engine control, particularly in U.S. measuring units.

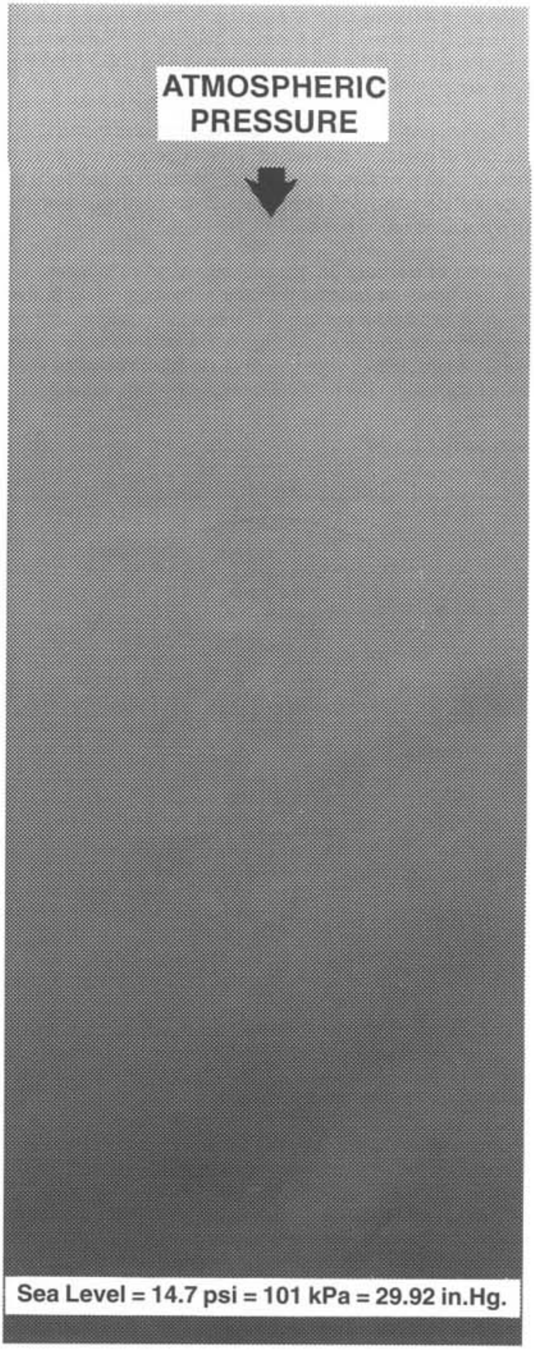

Fig. 4-2. Pressure at sea level is weight of air pressing down.

kiloPascal (kPa). SAE and most auto makers use the metric unit for pressure. Some pressure gauges now read both psi and kPa. Atmospheric pressure at sea level is about 100 kPa, easy to remember.

Pounds-per-Square Inch (psi). Widely used in the U.S., the unit of pressure defined as force in pounds, divided by area in square inches. Atmospheric pressure at sea level is approximately 14.7 psi. Most of us drive above sea level so 14.5 is a good round number.

Inches of Mercury (in. Hg.). Originally refers to measurement of pressure using a mercury manometer. (Hg is the chemical symbol for mercury.) This is a term used to specify manifold vacuum. 29.92 in. Hg. is the difference between standard atmospheric pressure at sea level and absolute vacuum. Indy racers refer to boost in terms of in.Hg., absolute.

Gauge Pressure

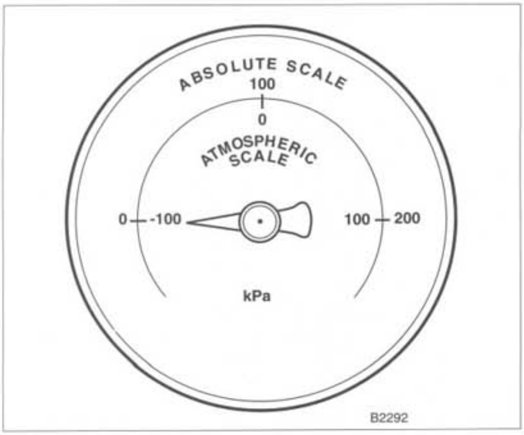

Fig. 4-3. Calibration of pressure gauge influences how you interpret pressure readings.

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

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

By the 1980s, the automotive industry had moved away from thinking in terms of vacuum. Widespread use of fuel injection under pressure called for positive thinking—in terms of the manifold absolute pressure (MAP), measuring from absolute zero. During part-throttle operation, or coasting, manifold pressure reads positive, from zero. During supercharging and turbocharging, manifold pressure also reads positive, from zero. In the world of fuel injection, and particularly, boosted systems, vacuum measurements are confusing.

Using absolute pressure as the reference point, the piston on its intake stroke is creating a low pressure in the cylinder —approaching zero absolute pressure. The absolute pressure in the intake manifold (MAP) is higher and always a positive number. Atmospheric pressure outside the engine is higher still. Your throttle controls its influence on manifold pressure. The turbocharger provides pressure above atmospheric pressure.

You must understand how barometric pressure relates to gauges you may work with:

- Vacuum gauges are referenced to barometric pressure, reading 0 when there is no vacuum
- Most pressure gauges are vented to or referenced to barometric pressure, reading zero when there is no pressure above atmospheric
- Boost gauge of turbo engine is referenced to barometric pressure. Read vacuum in in. Hg. less than barometric, boost in psi above barometric
- Absolute pressure gauges are sealed, referenced to zero pressure. With the engine off, they read absolute atmospheric pressure. In the engine control, the Manifold Absolute Pressure (MAP) sensor reads absolute pressure, always positive whether below atmospheric, as in idle or part throttle, or above atmospheric, as in boost

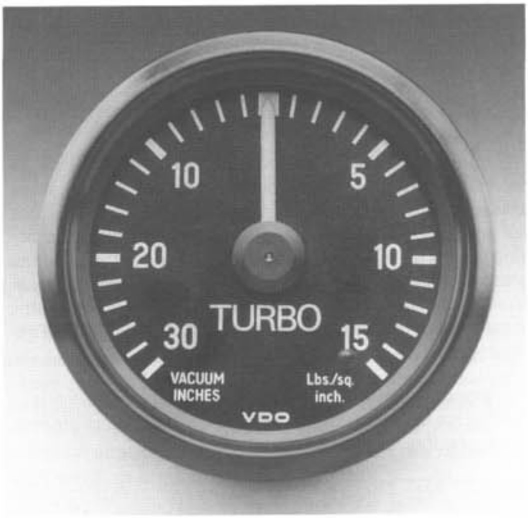

Fig. 4-4. Turbo boost gauge reads vacuum in inches of mercury, but reads boost in psi. That's like adding apples and oranges. Indy race drivers read absolute gauges, 0-60 in. Hg.

Fig. 4-5. When you open throttle for increased load, you increase MAP (Manifold Absolute Pressure). Reading a vacuum gauge, WOT decreases manifold vacuum. If you think positive—increased MAP for increased load, it's easier to understand fuel-injection control.

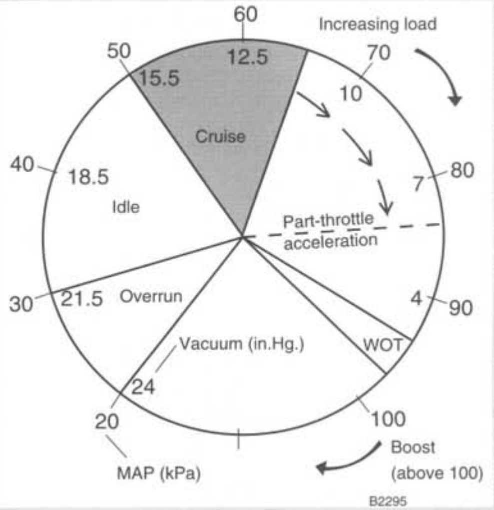

Fig. 4-6. Increasing load increases MAP. Typical OVERRUN is 20–30 kPa, IDLE, 35 kPa, CRUISE, 50–65 kPa, WOT of unboosted engine, near 100 kPa, MAX BOOST 180 kPa.

I've been driving with a vacuum gauge connected to the intake manifold of each of my last 9 cars. The gauge comes calibrated in terms of vacuum, so at Wide Open Throttle (WOT) it reads close to zero. Notice this gauge has zero on the right so increasing manifold pressure (as a measure of engine load) increases clockwise, just the same as the tachometer. I have marked my gauges to read positive manifold pressure. At or near sea level, that's close to MAP. At WOT (near zero vacuum), my gauge reads about 9 on the homemade MAP scale, as shown in Fig. 4-5. Multiply by 10 to read pressure in kPa (90 kPa). The important point is that the numbers increase as the load and power increase. Fig. 4-6 shows approximate range of gauge values for various driving conditions and throttle positions. By coincidence, 65 mph cruise reads about 65 kPa.

On a turbocharged or supercharged car, boost will read above 100 kPa (atmospheric) on the MAP scale. In Ford engines, MAP changes continuously from about 20 kPa during overrun (coasting with closed throttle) to perhaps 180 kPa at maximum boost. When we discuss the importance of manifold pressure to fuel injection, you will find it an advantage to think in terms of the positive MAP values (from absolute zero) rather than vacuum.

Vacuum is related to MAP, but differs from MAP in two ways:

- MAP increases with engine load while vacuum decreases
- MAP measures load referenced to absolute zero pressure, while vacuum is referenced to barometric pressure

5. CONTROL SYSTEMS

By now, you are aware that control plays an overwhelmingly important part in maintaining the acceptable balance of power, fuel economy, emission control, and driveability. Ford electronic engine control systems, by responding to measured inputs and precisely metering the appropriate amount of fuel for the conditions, offer unparalleled control.

Control systems may operate one-way or "open-loop." Under limited engine operating conditions, they take the information about operating conditions received from various sensors, or from computer memories and then use that information to determine signals to the actuators:

- Injector pulse time
- Spark advance time
- Idle-air bypass opening

Accuracy of the open-loop air-fuel ratio, spark advance, and idle rpm depends mainly on how well the system can predict the engine's needs based on its "knowledge" of operating conditions.

Most of the time, Ford engine-control systems operate "closed-loop." While they try still to predict the engine needs based on operating conditions, they also measure the results of their fuel metering and use that information as an input to achieve ever more precise control.

5.1 Closed-loop Control Systems

In a closed-loop control system, information about whatever is being controlled is continuously fed back to the system as an input. There's an unfortunate tendency in our business to associate closed-loop only with air-fuel ratios. But, as I'll show you here, several systems in the vehicle operate closed loop/open loop.

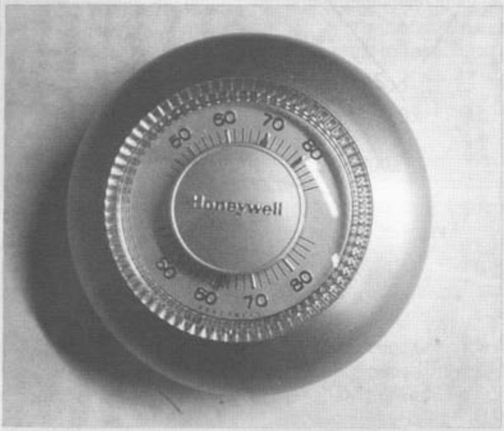

Fig. 5-1. Home thermostat is closed-loop system, using feedback from the thermometer (sensor) to control the furnace or air-conditioner (actuator).

The operation of a thermostat in an automatic heating system is an example of closed-loop control. You set a target temperature—what you want the automatic heating (or cooling) system to deliver. As the temperature falls from the target, the thermostat senses lower temperature and automatically signals the furnace to add heat. As soon as the temperature rises to the target setting, the thermostat senses the results of its own control action. The heat produced by the furnace automatically signals the furnace to cut back the heat, a closed-loop system.

An open-loop system may, for example, sense low temperature and simply turn on the heat for a predetermined amount of time, with no feedback of the results of turning on the heat. However, closed-loop control is automatic. Temperature stays relatively constant, reducing energy consumption. In all, the result is better, more precise control.

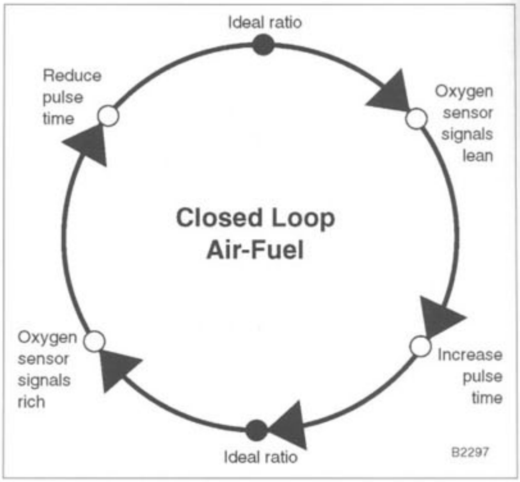

Fig. 5-2. Air-fuel ratio is controlled closed-loop by sensing oxygen in exhaust (an indirect measurement of air-fuel ratio), and changing injector pulse time.

Air-fuel ratio control operates closed-loop, comparing the actual air-fuel ratio to the desired. Measurement is indirect, based on the oxygen sensor signal to the control module. The control modules varies injector pulse time to maintain the target air-fuel ratio (oxygen content). When open loop, injector pulse times are independent of oxygen sensor input. More in Chapter 4.

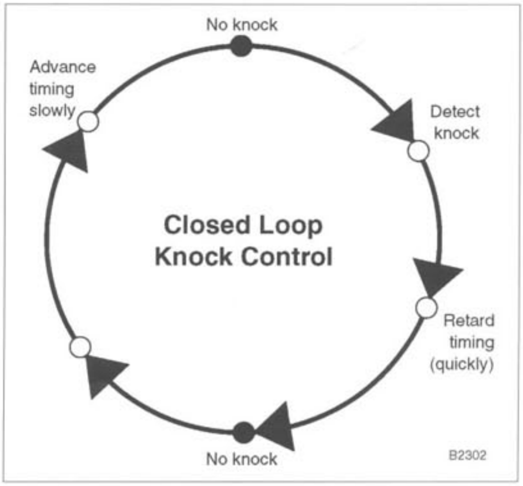

Fig. 5-3. Knock feed-back signals relate to engine detonation (spark knock) and therefore spark timing.

Knock control operates closed loop, sensing knock-sensor signals. When signals are sensed, spark timing is retarded, boost is reduced, and injectors are cut off until knock signals stop. Then the actuators return to normal—gradually—until knock signals are sensed again. To prevent engine damage, knock sensors are never operated open loop.

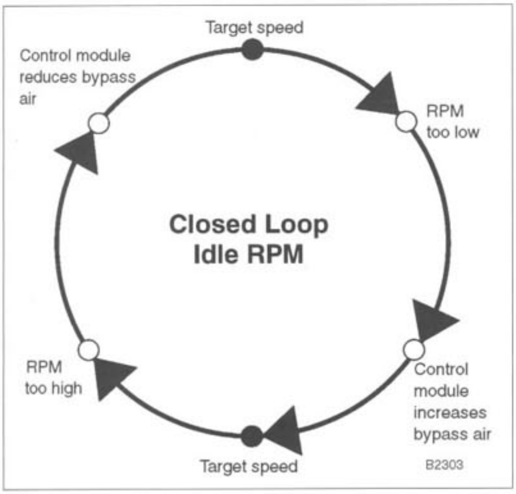

Fig. 5-4. RPM feedback signals relate to engine speed, and therefore to idle speed control (idle air bypass).

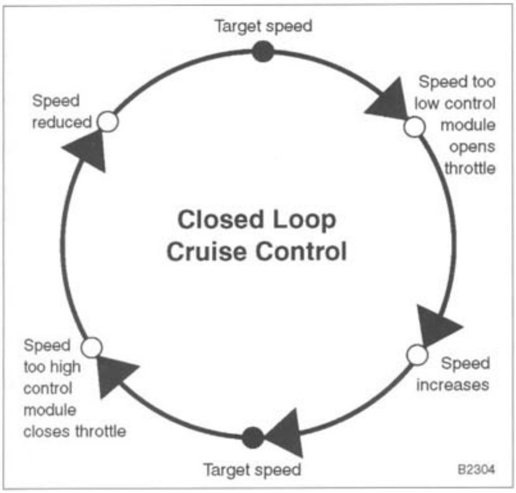

Fig. 5-5. Cruise Control operates closed loop, comparing target speed (from memory) with actual speed (sensor). Control module actuates cruise-control motor to maintain target speed. When cruise control is off, system operates open loop.

> Unfortunately, closed-loop electronic engine controls occasionally add to pollution in a strange way. One EPA engineer told me that they find what they call "gross emitter" fuel-injected cars with the driver unaware that he is so far from "green". In one worst case, one car was emitting 321 g/mi, almost 100 times the limit. The engine-control system was so flexible that the car was still driveable. If a carburetor car were running that dirty, it would be a pig to drive and the owner would be more likely to take it in for repair.

Idle rpm control operates closed loop, comparing idle rpm to target rpm. When rpm is too low, idle-air bypass is increased to prevent stalling. When idle rpm is too high, idle-air bypass is decreased.

Cruise Control, when engaged, operates closed loop. The computer compares the target speed with the actual speed, and sends signals to the cruise-control motor, opening or closing the throttle to automatically deliver the target vehicle speed. When disengaged, cruise control operates open loop, with the driver operating the throttle.

I like to describe closed-loop as the equivalent of having a skilled technician riding under the hood, continually tuning the mixture, adjusting spark timing and other engine operations for the best operation under the current conditions.

5.2 Feedback/Feedforward

Feedback is the term applied to the measurement signal to the system. It looks back to monitor the results and feeds those back to the computer—a sort of "How am I doing?" Several systems feed back measurement signals:

- Exhaust-gas feedback signals relate to the air-fuel ratio, and therefore the injector pulse-time
- Knock feedback signals relate to the detonation in the engine, and therefore to the spark timing
- RPM feedback signals relate to engine speed, and therefore to the idle-air bypass

Feedforward is a relatively new term, the counterpart of feedback. It looks ahead and feeds signals to the computer that anticipate changes about to happen—a sort of "What should I be doing?" Several systems feed forward signals that anticipate changes in engine control:

- Engine accessories feed forward signals relating to engine idle rpm, and therefore to the idle-air bypass Examples: air conditioning, power steering pressures, even the increased alternator load caused by heated rear-window or windshield
- Idle rpm is maintained to a target engine speed by the closed-loop feedback system. But the feedforward signals anticipate rpm drop caused by load, and prevent it, instead of reacting to it. The result is a smoother engine idle

6. OPERATING MODES—STRATEGIES

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

Cars and trucks, however, are a different story. We expect them to perform under the widest possible variety of operating conditions. And we have given "performance" a new definition: it is not only impressive horsepower and torque, but also maximum fuel economy, and controlled exhaust emissions.

As if these performance demands were not enough, we also expect the car to meet these demands effortlessly, at any time, under any conditions, and at the turn of a key. We expect "driveability"—the ability of the vehicle to provide smooth, trouble-free performance under virtually any condition.

Driveability is a term that evolved out of the early days of strict emission control and the '70s energy-crisis concerns over fuel economy. The carburetor technology of the time dictated an approach to both problems that often resulted in the engine running too lean. Running too lean robbed power and contributed to rough idle, poor throttle response, stumbling and stalling, as well as destructive underhood temperatures. It also increased some emissions! Retarded timing reduced some emissions, and robbed engines of their power, economy, and driveability. By 1974, the cures for emissions were almost worse than the disease. Fuel economy ratings hit a disastrous low. Since the 1980s, fuel injection and engine-control systems offer the precise control and flexibility necessary to meet modern performance requirements.

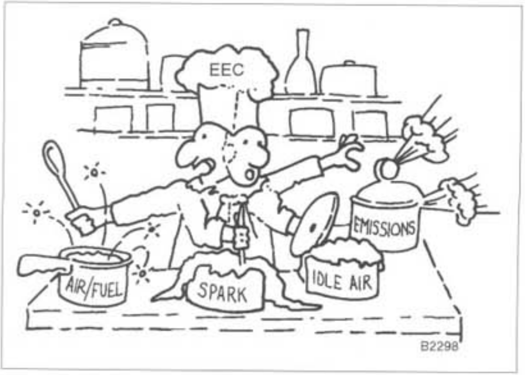

Fig. 6-1. Ford engine control systems have to watch many systems at one time.

One reason Ford engine control can seem complicated is that it has so many things to manage, perhaps something like a solitary chef keeping several dishes cooking at the same time:

- Air-fuel ratio
- Ignition timing
- Idle-rpm
- Emission control (Exhaust Gas Recirculation, Secondary Air to manifold or catalytic converter, Evaporative emissions (fuel vapors)

While you're at it, manage:

- Automatic transmission, or signal the A/T control unit
- Engine-cooling fan and engine temperature
- Air-conditioner operation
- Engine diagnostics (remember any fault codes)
- In later model engines, keep a running count of serial data (sensor and actuator data) to play back to advanced scan tools

Be sure to send information to:

- Keep Alive Memory (KAM)
- Malfunction Indicator Light (MIL) "Check Engine"
- Trip computer

Oh, yes, remember the "short-term" corrections you are making and adapt the engine control on a "long-term" basis.

Strategies

Ford uses the term "strategy" to describe the plan of the engineers' design of the engine-control system. In this chapter, I'll describe nine strategies as they relate to different engine operating conditions. I'll show how those strategies relate to the four parts of engine control: air-fuel ratio, spark timing, idle-air, and emission controls. In chapters 4–7, I'll discuss the parts of the engine control system—the sensors, the actuators, and the control module. I'll put it all together in Chapter 8—how each of the Ford systems operate to satisfy the goals of each strategy under different conditions.

6.1 Normal (Warm) Cruise Strategy # 1

I'll start with warm cruise because it is probably the simplest job for the engine management system.

Normal cruising at light load with the engine fully warmed up is the baseline operating condition. The basic engine control strategy meets the need for the proper air-fuel ratio, the proper spark timing, and the proper emission control under these simple cruising conditions. You may add power on a hill or to pass another car, or cut back power to slow down, but fuel management, timing and emission control are still relatively simple.

Ford uses the term "warm" during the first three minutes after Cold Start at room temperature. After that, it is "hot." I prefer to consider the engine "warm" when it is at normal operating temperatures, and "hot" when it is overheating. After all, "H" on your temperature gauge means too warm, "Hot!" All depends on how you look at, or how you feel it.

When you are cruising down the interstate on a level road, the engine is operating under relatively constant normal conditions. The fuel quality may vary from one tank fill to the next, weather and outside temperature may change, it may be dry or it may be damp. The ideal air-fuel ratio and timing may be different for each of these conditions. An engine-control system can adjust to these changing conditions with little challenge. It can maintain air-fuel delivery near the ideal ratio of 14.7:1. It can maintain timing slightly below the knock levels to satisfy the most important considerations of fuel economy and low exhaust emissions. Normally, the systems operate closed-loop during warm cruise.

Control Emission Systems

Warm Cruise conditions are right for emission control. Further, most of the engine operating hours are at warm cruise so emission control has the greatest total effect on emitted gasses. EEC controls emission systems such as Exhaust Gas Recirculation (EGR), Canister Vapor Purge, and Three-Way Catalytic Converter on two bases:

- When is it right for the engine? For example, the engine does not run well if exhaust gas is recirculated when the engine is cold. The engine loses maximum power if EGR is on at Wide Open Throttle
- When is it right for the system? For example, pumping air into a cold catalytic converter prevents the converter warm-up that is necessary

Control Torque Converter

For cruising economy, the strategy calls for control of the torque converter lock-up clutch most of the time, according to engine operating conditions.

Continuous Test

During all normal operation, the control module continuously tests inputs. One at a time, each individual circuit is tested for shorts and opens. Additionally, the control module notes illogical readings—an Engine Coolant Temperature Sensor changing from warm to cold to warm. The first time an error is observed, it is counted but not registered because the system does not store errors that are not repeated. After an error occurs several times, it is stored as a Trouble Code in the memory—in the Keep Alive Memory (KAM).

Provide Diagnostic Codes

For troubleshooting, strategies include signalling a malfunction to the driver, and storing EEC trouble codes of malfunctions for later readout by a voltmeter or by a hand-held tester. This applies to all strategies, even crank, signalling the possible cause of no-start.

Provide Deceleration Control

Although the engine is not idling, cruising strategy calls for providing enough airflow around the throttle plates to act as a "dashpot" in the event of sudden throttle closing.

Intake Air Control

The engine is operating at light load unless you are climbing a hill—I'm talking road horsepowers in the region of 10 to 20. The Intake air controls are operating at light load. The turbo, or the engine-driven supercharger, is coasting.

6.2 Engine Crank—Strategy #2

As an owner, you expect the engine to start instantly when cranked by the starter, unaffected by

- Temperature, whether at sub-zero temperatures or parked in the desert, too hot to touch
- Time, whether it's been sitting for five minutes at the store or for five weeks in the garage

Cold Engine

Cold crank means the engine is cold. That is, it probably hasn't run for at least 12 hours. The temperature needle is at the low end of the gauge. The engine temperature might be:

- Minus 30°C (-20°F), sometimes called cold-cold
- Plus 45°C (115°F), sometimes called warm-cold

In either case, the engine is still cold compared to its normal operating temperature of about 90°C (195°F).

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

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

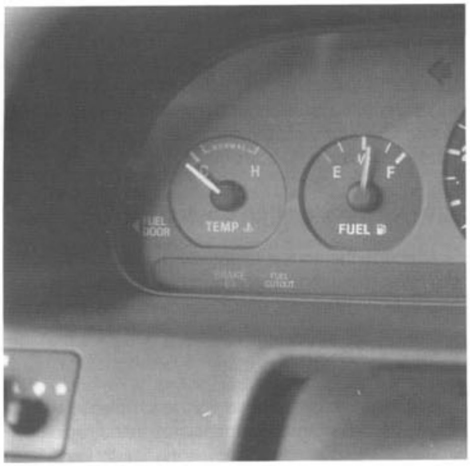

Fig. 6-2. Engine-cold temperature varies according to outside temperature. Cold start means engine has not run for several hours.

> To understand the distinctions I've made in cold-start temperature, consider the Environmental Protection Agency (EPA) definition of cold start. For EPA testing, cold is room temperature, about 20°C (68°F). All vehicles are tested on dynamometers inside the lab. The engine must cold-soak at 20°C in the lab next to the dynamometer for 12 hours before the test. Technicians push vehicles onto the dynamometer for the cold-start test. As it happens, 20°C is close to actual cold-start temperatures in Southern California and much of southern U.S. Engine temperature affects the driveability of your engine, which may be much colder than an EPA cold engine. For scientific comparison testing, and for the regulatory aspects of EPA testing for emissions and fuel economy, testing to a single set of standard conditions for uniformity is the most important factor. Cold-start emissions are so important to the total pollution effect that, beginning in 1994, EPA will test engine starts at –8°C (20°F). This will certainly affect engine control systems, and probably, your driveability.

Cranking vs. Starting

In defining strategies, Ford makes a distinction between cranking and starting. Cranking needs its own strategy because the engine-control computer cannot depend on the usual signals from the sensors to compute fuel injection, spark timing, or idle rpm. The computer can distinguish cranking from starting because the cranking rpm is slow and irregular. The most important considerations:

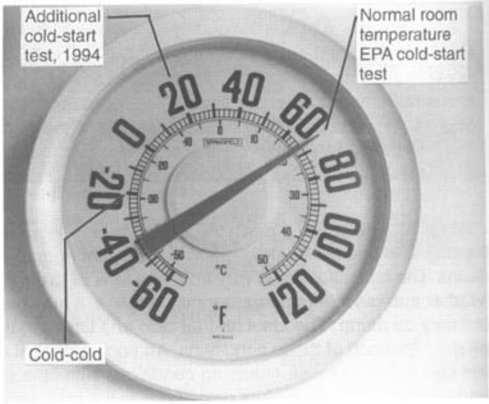

Fig. 6-3. Fuel requirement for engine starting varies according to outside air temperature: cold-cold or warm-cold. These temperatures are both cold compared to normal engine operating temperatures.

- Programmed rich mixture, with fixed air-fuel ratios:
  12:1 for a warm crank
  2:1 for a cold-cold crank
- Fixed spark timing
- Wide-open idle-air bypass to start without requiring driver's foot on the accelerator
- Withhold any emission control such as EGR, secondary air, or canister purge

Cranking enrichment quickly becomes a problem if the engine does not start right away due to a marginal battery, ignition components in poor condition, or whatever. Enrichment during cranking must be cut back after 20 seconds. If it goes on too long, the air-fuel mixture will be too rich to ignite. The spark plugs may become fuel-fouled, particularly when they are cold, and the engine will not start.

Cold cranking also needs help in terms of intake air flow. A closed throttle at slow cranking speeds does not allow enough air for starting.

De-Choking

Under some conditions, cranking may "flood" the engine in spite of the best efforts of the engine control system. "De-choking" provides for cranking without fuel to dry out the plugs and the cylinders. Cranking with the accelerator held full down signals the system to de-choke.

6.3 Cold Start—Strategy #3

Starting strategy begins after engine crank when the engine computer receives signals indicating a steady crankshaft rpm. Depending on engine temperature and intake-air temperature, the engine control calls for:

- Programmed rich mixture, probably less rich than cranking
- Advanced spark timing, cool engines are less likely to detonate
- Reduced idle-air bypass, only enough to maintain cold idle rpm
- Emission control is still cut off

> Drivers of carbureted cars develop intricate starting procedures: depress the accelerator to the floor, release, then hold the throttle about 1/3 open (for example). The first depression is necessary to set the carburetor choke and fast-idle cams. The second is to open the throttle and make sure the engine is getting enough air. And, after start, some of us would keep kicking the throttle, trying to get it off the fast-idle cam to reduce the racing idle speed.
>
> Ford fuel-injection systems can control the air by bypassing the closed throttle, admitting more air when cold without any effort or attention from the driver. In the Owners' Manual, you'll see "No-Touch" starting: "Do not depress accelerator until the engine starts."

Warm-up

Cold start includes the beginning of warm up. Enough good signals are coming from the sensors so that the engine can be controlled on the basis of temperatures.

- Mixture enrichment cut back
- Spark timing retarded from its cold advance
- Idle rpm reduced
- Emission control limited to secondary air into the intake manifold to help burn the rich mixture delivering some raw fuel into the exhaust. This helps heat up the unheated oxygen sensor and the catalytic converter so they can begin operating sooner. Exception: not when engine is colder than 13°C (55°F). Emission control cuts back air injection after 3 minutes.

One of the joys of driving cars with fuel-injected engines is the freedom from a too-fast idle that can jar the vehicle when an automatic transmission is shifted into Drive or Reverse. Most Ford cold-idle specs are slightly more than 1000 rpm.

6.4 Cold Driveaway—Strategy #4

Cold driveaway strategy must prevent cold stall caused by:

- Shifting automatic transaxle into Drive or Reverse or releasing clutch of manual transaxle vehicle
- Opening the throttle

Cold driveaway strategy includes control to:

- Enrich fuel to provide burnable mixtures with added intake air
- Advance spark timing to provide smooth acceleration

> For those accustomed to warm-up in the driveway, let me urge a "cold driveaway." Ford manuals use the phrase, "after a few seconds." Driveway warm-up is a bad habit carried over from carbureted vehicles that usually required restart if not allowed to warm up before driving. Today, both Ford and EPA encourage cold driveaway in the interests of economy and emissions. Of course,I discourage full-bore on the freeway until the engine warms enough for good oil circulation.

6.5 Warm Driveaway—Strategy # 5

- Programmed fuel injection still richer than normal, needs enrichment during throttle opening
- Spark timing is advanced, but less than cold driveaway, controlled by several factors, engine rpm, load, and temperature
- Emission control may include EGR as the engine warms

6.6 Part Throttle Acceleration, Warm—Strategy # 6

This strategy follows Warm Cruise, closed loop operation, with all emission controls operating. This strategy considers that you want to increase vehicle speed, but you're still interested in economy and emission control:

- Fuel-injection is enriched during the brief interval of opening the throttle and reaction by the air flow sensor
- Spark timing is advanced, but less than Warm Driveaway
- Emission control continues, with secondary air oxidizing in the catalytic converter

6.7 Full Throttle Acceleration, Warm— Strategy # 7

This strategy, sometimes called WOT for Wide Open Throttle, operates to provide full power, without regard to economy or emission control. Closed loop operation switches to open loop.

- Fuel injection is enriched as long as the throttle is full open
- Spark timing is advanced to increase power. With the rich mixture, extra advance can be programmed with less risk of detonation
- Emission control stops (EGR, air injection)
- Air conditioning compressor and cooling fans are turned off for 10 seconds

As soon as the throttle moves from WOT, strategy switches to Part Throttle, #6.

6.8 Deceleration, Closed Throttle— Strategy # 8

This strategy saves fuel, and prevents engine stalling by sudden cut-off of intake air. Remember, I said in Warm Cruise, or any Part-Throttle Operation, the Idle Air Bypass is always part way open, to act as an electronic dashpot.

- Closed throttle at any rpm above idle means deceleration or coasting, so fuel is cut off, and air flow is maintained to keep the engine from stalling
- Closed throttle at idle rpm means idle, requiring idle fuel and idle air flow

This strategy provides a smooth transition between deceleration, when engine braking is desired, and idle, when engine power is needed to keep the engine turning, with various loads, as in Strategy #9.

6.9 Warm Idle—Strategy # 9

Our vehicles spend much time idling, so a smooth idle is important to driver comfort and emission control. The main requirements of a warm engine running at idle speed are smoothness, and smooth response once the throttle is opened. Some engines require a richer mixture at idle for smooth running, and to ensure good off-idle response.

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

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

With engine control monitoring and constantly correcting idle speed, it is not necessary to maintain a high idle to handle variations in engine performance, changing of loads, and similar causes of stalling from idle.

Idle-Speed Stabilization

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

Condition	Transmission	Idle Speed
A/C Off PS load normal	In Neutral/Park	Lowest rpm required for engine smoothness
	In Drive/Reverse	Lowest rpm for minimum creep
A/C On PS load normal	In Neutral/Park	Increase rpm for A/C compressor load
	In Drive/Reverse	Increase rpm, but less, for creep
A/C Switch On, or hard PS turn	In Neutral/Park	Increase rpm during switch On to prevent stall
	In Drive/Reverse	Delay increase to avoid surge
Hot ECT (110° C)	In Neutral/Park	Increase rpm to cool engine
	In Drive/Reverse	Delay increase to avoid surge

Modern fuel-injection/engine control systems manage much more than fuel delivery. Chief among the extra capabilities of an engine-control system is simultaneous control of fuel delivery, spark timing, idle-air, and emissions. Controlling all these factors opens up new possibilities for power and driveability improvements while maintaining tight control of exhaust emissions and fuel economy.

Recent question to an auto editor of a Silicon Valley (CA) newspaper. "I have a Mazda MX-6 [Ed. note: same engine control as a Ford Probe]. I notice a strange change in my idle under these conditions: night, lights on, idling at stop light, turn signal blinking. Every time the turn signals are on, the engine seems to speed up slightly; when they're off, the engine seems to relax -- not enough to see on the tach, but I feel it."

And the wise auto editor understood Idle Speed Stabilization. "with the headlights on, when the turn signal lights blink on, that causes the line voltage to drop, so the alternator must increase output. The idle-air bypass opens slightly to increase engine output. As the lights go off, the alternator load reduces and the engine can relax."

7. CHANGES IN ENGINE CONDITIONS

Automatic control of air-fuel ratio continuously adjusts the amount of fuel injected to correspond to oxygen in the engine exhaust. This feedback system provides a fine tuning of the air-fuel ratios called for by the computer. For example, as the engine mechanical condition changes with time, the feedback system can accommodate, changing the air-fuel ratio to match changing engine conditions. Perhaps a leaking valve is causing a change in combustion, so a bit more fuel is required in the cylinder. The closed-loop system will tend to accommodate this change. It will also accommodate certain changes in fuel quality that may affect combustion.

7.1 Adaptive Control

Adaptive control means the computer can be programmed to "learn" the way the closed-loop control is operating. Suppose, for example, the system were continually driving slightly toward rich compared to the open-loop values stored in the memory, perhaps to counter a small vacuum leak. The computer might memorize this correction. At the same time, the engine may be operating at a high altitude that causes it to run rich. These two conditions do not cancel each other because the leakage affects the air-fuel ratio at low loads, while the altitude affects the air-fuel ratio at high loads.

Adaptive control operates to lean the mixture at low loads, and enrich the mixture at high loads until the computer memory has *stored open-loop values the same as closed-loop.* Then, when the system is operating open-loop, the computer would use a similar correction factor to the air-fuel ratios stored in its open-loop memory. With adaptive control, the system can often operate without a separate sensor for barometric pressure because the system will learn how to operate best at each altitude.

You may never notice the effect of adaptive control because the learning changes are smooth and gradual. On the other hand, you may notice it when you lose it, such as when the battery terminal is disconnected to clear a trouble-code stored in the memory, to install some electrical accessory, or to service that has nothing to do with the engine.

Disconnecting usually means loss of the memory that is storing the adaptive learning.

After disconnection, the learning process must begin all over. Vehicle performance may change. After the disconnection, with the engine warm, drive around: at part throttle, in "crowd", a little push above steady cruise, and let it idle. How long does it take to re-learn? Usually about 5 minutes. If the computer were programmed to take longer, operation could be unsatisfactory. If it were programmed to relearn in 1 or 2 minutes, the computer could be adjusting itself for short-term changes that do not count.

> From a recent Ford Owner's Manual: "If you ever disconnect the battery, install a new battery, or experience a dead battery, you must allow the computer to relearn its idle conditions before your vehicle will idle at its best. . . . Start the vehicle. Let the engine idle for at least one minute. (Engine must be warm in order to learn.) Also, allow approximately 10 miles (16 km) of stop and go traffic for your engine to completely relearn its idle. . . . Your vehicle will eventually relearn its idle while you drive it, but it takes much longer than if you use the procedure above."

8. DIAGNOSIS

Trouble codes are stored in one of the computer memories. This memory is known as a volatile memory. Another term is RAM, Random Access Memory. That means it is not permanent, but rather can be erased after it has served its purpose.

Sometimes there can be an engine control problem but the *computer is programmed to make do until repairs can be* made. The memory can include acceptable range values from each sensor. An input signal outside that range may cause a "Check Engine" signal from the computer, and a storage of the proper trouble code. The engine operates on a fixed "limp-home" warm temperature until the sensor can be serviced.

That means coolant-temperature-sensor failure may not even be noticed in engine operation. The engine will operate quite well so long as conditions do not change. You will have a hard start if it cools off, and as you know, with fuel injection, no amount of accelerator pumping will change that. The stored trouble code will lead to proper replacement of the sensor or its wiring harness or connector.

But look what else that means: If you try to play games with the sensor inputs, you better know what you are doing because the computer may be programmed to detect improper sensor input signals. More on this in Chapter 9.