Electronic Fuel Injection for Hot Rods

Part 2 – Controlling Fuel and Ignition

In Part 1, we looked at Multi Point Fuel Injection (MPFI) and decided that was the way to go as far as power plants for hot rods was concerned. What we'll look at this time is the components that make up our MPFI engine. We'll also look at the ways we can control our engine's fuel and spark, idle control and cold start control.

The brain of any EFI system is the *Engine Control Unit* (ECU) which is just a small computer. The ECU receives data from *Sensors* on the engine and transmission, and gives "instructions" to *Actuators* on the engine, transmission, and other parts of the car. For example, the main sensor on any EFI system is the *Oxygen Sensor* (O2 Sensor). If the ECU is the brain, then the O2 sensor is the heart. It tells the ECU how much oxygen is in the exhaust. If there's too much oxygen (a lean condition), the ECU increases the length of time the injectors open, which en-richens the mixture slightly. The O2 Sensor tells the ECU that the oxygen levels are now normal, and the injectors remain at their current state until the oxygen level changes again. This all happens many thousands of times per second, and is just one of the hundreds of controls that the ECU performs.

Open Loop and Closed Loop

Before we go any further, let's quickly look at the two modes of operation that all ECUs will operate in:

Open Loop. Sometimes called *Limp Back Mode* or *Limp Home Mode*, *Open Loop* means that most of the sensors are being ignored, for two reasons:

- The engine is cold, and is in the process of warming up.
- There is a fault somewhere in the system, and rather than stop, the engine is running on a pre-determined set of parameters.

Closed Loop. All sensors are working properly, the engine is warmed up to its normal operating temperature and the Oxygen Sensor is detecting the presence of oxygen in the exhaust stream.

Sensors and Actuators

Sensors are like sender units for gauges – they transfer information about the engine to the ECU. The information provided by the sensors is compared to stored data in the ECU and, if things are not exactly as they are supposed to be, the ECU changes the engine's operation by way of *Actuators*.

There are many different types and designs of sensors. Some are simply switches which complete an electrical circuit while others are complex devices which generate their own voltage under different conditions.

The following components are the more common sensors and actuators that would need to be fitted to a MPFI engine:

Sensor	**Abbreviation**	**Remarks**
Manifold Air Temperature	MAT	Measures air temperature in the inlet manifold
Coolant Temperature Sensor	CTS	Measures temperature of the engine coolant
Oxygen Sensor	O2 Sens, EGO	Measures the amount of oxygen in the exhaust
Heated Exhaust Oxygen Sensor	HEGO	Same as the EGO except that a heating

		element is added to the sensor
Manifold Absolute Pressure	MAP	Measures the vacuum in the inlet manifold
Barometric Pressure Sensor	BAR, BAP	Measures atmospheric pressure in the engine bay
Throttle Position Sensor	TPS	Measures the angle at which the throttle is open
Vehicle Speed Sensor	VSS	Measures vehicle speed
Engine Speed Sensor	ESS	Measures engine rpm
Crankshaft Position Sensor	CPS	Measures angle of rotation of crankshaft at any given time
Mass Airflow Sensor	MAF	Measures the air as it flows into the engine
Knock Sensor	Knock Sens	Detects detonation in the cylinders
Brake Sensor		Detects application of the brakes
Camshaft Position Sensor	CPS	Checks camshaft position in degrees of rotation
Exhaust Gas Recirculation valve position Sensor	EGRVP	Measures position of EGR valve
Air Charge Temperature Sensor	ACT	Measures the temperature of the air charge entering the motor
Actuators	**Abbreviation**	**Remark**
Fuel Injector	FI	An electrically operated valve, the Fuel Injector squirts atomised fuel onto the back of the intake valve.
Idle Air Control	IAC	An electrically operated stepper motor or solenoid, the IAC provides air for idling when the throttle pates are fully closed.
Electric Fan Drive	EFD	Once the temperature reaches a certain point, the EFD switches the electric fan on.
Wide Open Throttle A/C Shut-off	AC	When you tromp on the GO pedal, the AC Shut Off turns the air conditioning compressor off.
Vehicle Speed Control	VSC	What it says.

The operation of some of the more important sensors and actuators are discussed below.

Oxygen Sensor. The O2 sensor detects the amount of oxygen present in the exhaust. Given that the best air/fuel ratio is 14.7:1, the O2 sensor can tell the computer whether the engine is running rich, lean or right on target. The ECU adjusts the amount of fuel being injected to keep the air/fuel ratio at 14.7:1. O2 Sensors do not start working until they are hot, so while the engine is warming up, the system is in “Open Loop” mode. Until the O2 sensor is heated up and working, the engine assumes that the mixture is OK. O2 Sensors can be heated quickly by the battery (two or three wire sensors) or by the exhaust temperature alone (single wire sensors).

Figure 1 - Heated Oxygen Sensor. Photo courtesy of MSD

The O2 sensor generates its own voltage (typically between 0mV and 1000mV) depending on the amount of oxygen present in the exhaust. At 14.7:1 A/F ratio, a typical O2 sensor will generate 450 millivolts (mV, or thousandths of a volt). A lean mixture (more oxygen in the exhaust) will produce a voltage below 450mV, and a rich mixture will produce a voltage above 450mV (less oxygen in the exhaust). When the EMS is running in closed loop, the O2 sensor will vary constantly above and below the 450mV mark. The ECM can then maintain an average A/F ratio of 14.7:1.

Throttle Position Sensor. The Throttle Position Sensor (TPS) allows the ECU to sense the position of the throttle and to use that information to control fuel delivery. The TPS is simply a variable resistor whose output is dependent upon the position of its rotating wiper arm which is connected to the throttle shaft on the throttle body. At idle, the throttle plate in the throttle body is closed, and the air that's breathed by the engine is supplied by the Idle Air Control (IAC) Valve. When the accelerator is depressed, the throttle spindle rotates and the plate “opens” to admit more air. The TPS tells the computer exactly where the throttle plate is at any given time.

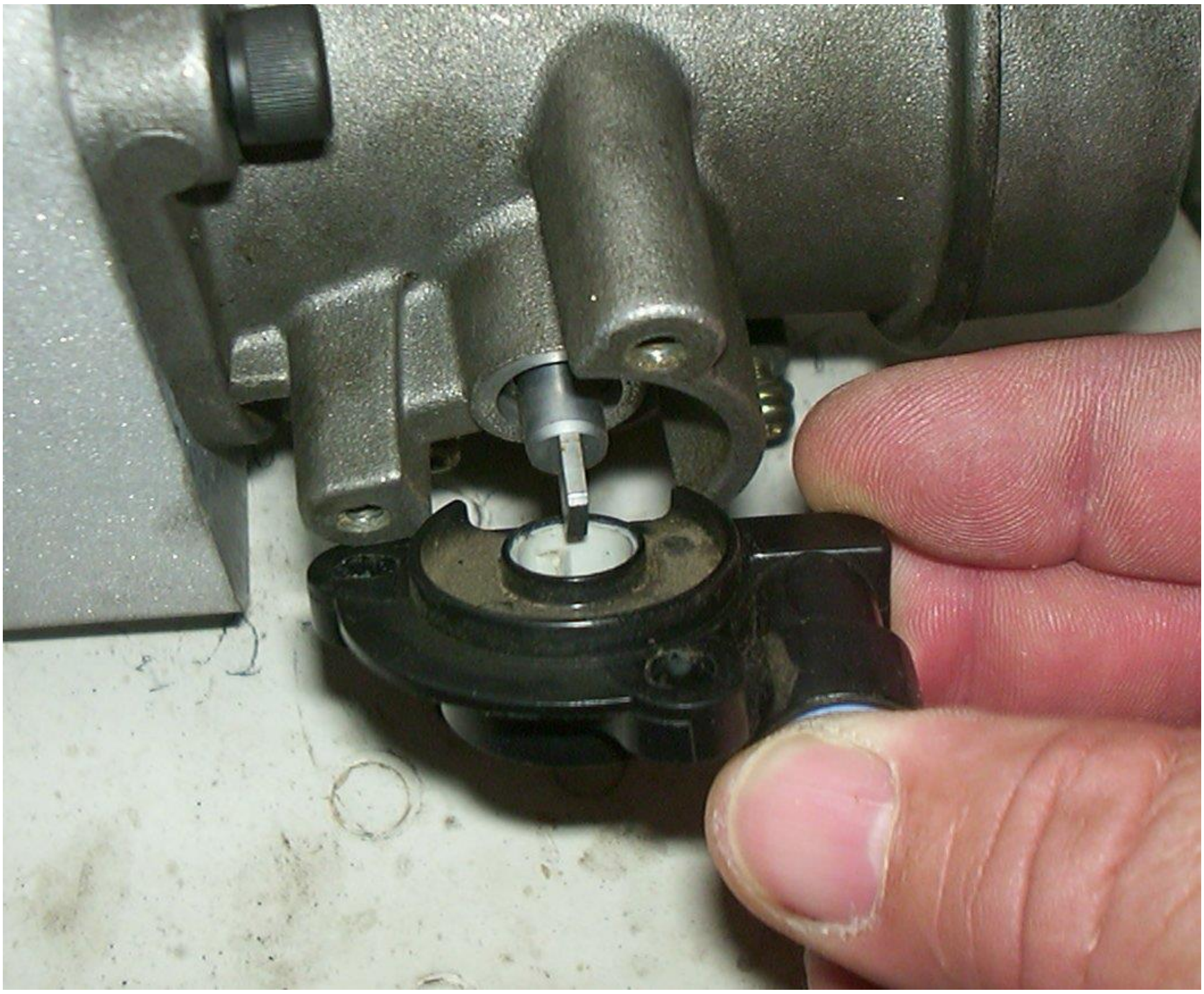

Figure 2 - Throttle Position Sensor (typical GM)

Manifold Absolute Pressure Sensor. The Manifold Absolute Pressure Sensor (MAP) measures vacuum inside the intake manifold. The ECU receives information on engine load via this sensor. High pressure (low vacuum) indicates a heavy load and high power output. The ECM issues commands to enrichen the fuel mixture and decrease the spark advance. The opposite occurs for high vacuum conditions, where there is little load. A leaner mixture is sufficient and more spark advance is required.

Figure 3 - MAP Sensor. Photo courtesy of MSD. Note the barbed vacuum connection, which connects a vacuum line to the manifold.

Manifold Air Temperature Sensor. There are more molecules of oxygen per cubic foot of cold air than of warm air, therefore the cooler the intake stream, the leaner the mixture (given the same amount of fuel). The computer has to know about the temperature of the air entering the manifold in order to keep the blend right, and that's the job of the MAT (Manifold Air Temperature) or Air Charge Temperature sensor (ACT). With a cold engine, the MAT reading should be equal to the outside air temperature.

Mass Air Flow Sensor. The Mass Air Flow Sensor (MAF) measures the volume of the air entering the engine. This information is used by the computer to supply the correct amount of fuel. There are several types of MAF sensors, but the most common is the “hot wire” type that determines air flow by measuring the current required to maintain a heated wire at a constant temperature as intake air passes over the wire. The MAF sensor is the chief compensating feature in Chevrolet's TPI. This unit must be mounted between the air cleaner assembly and the TPI throttle body. In fact, regardless of make, a sensor between the air cleaner and the throttle body is a sure sign that the ECM is Mass Air and not Speed Density.

Figure 4 - Mass Air Flow Sensor. GM LT1 Shown.

Figure 5 - MAF sensor with air filter fitted.

Fuel Injectors

There are so many different types of fuel injectors around that it would be impossible to describe them in the space available. What I shall describe here is the basics, which should be used as a guide for injector choice.

Pulse Width and Duty Cycle. The length of time an injector is open and squirting fuel is called the *pulse width*, and is measured in milliseconds (ms). That’s thousandths of a second. As engine speed increases, an injector can only be held open for so long before it needs to be held open again for the next engine revolution. This is what is known as the injector’s *duty cycle* and is measured as a percentage of open to closed.

Injector Size. Injectors are measured in accordance with their *Flow Rate* in lbs/hr (pounds per hour) or cc/min (cubic centimetres per minute). A fuel injector's flow rate is measured at its maximum duty cycle (100%), but in real life they should never be operated at more than 80%. The following formula is used to “guestimate” injector size for a particular application:
BSFC = Brake Specific Fuel Consumption, generally accepted to be around 0.5 for calculating injector sizes.

$$\text{Injector Flow Rate (lb/hr)} = \frac{\text{Engine HPx BSFC}}{\text{Number of Injectors x 0.8}}$$

For example, to calculate the individual injector size for a 650 HP V8 using 8 injectors and assuming a BSFC of 0.5:

$$\text{Injector Flow Rate (lb/hr)} = \frac{650 \text{ x } 0.5}{8\text{x}0.8} = 50.78 \text{ lb/hr}$$

To convert lb/hr to cc/min, multiply by 10.5.

Injector Types. For simplicity, these articles describe injectors as being one of two different types according to their internal electrical resistance:

- *Saturated*. High resistance. Saturated injectors are used in almost all standard production, engines, mainly because of the cost and simplicity. Saturated Injectors are more suited to Batch Injection.
- *Peak and Hold*. Low resistance. Peak and hold injectors respond faster than Saturated injectors. They require more electrical power to open (4-6 Amps vs. 0.75 -1 Amp). Peak and Hold injectors squirt fuel more accurately, and sustain the accurate squirt for longer, than the saturated type. This is important in high-pressure systems. Using Peak and Hold injectors costs more because they require one computer *injector driver* per injector in most applications. This is a design requirement in Sequential Electronic Fuel Injection (SEFI) systems where each injector is fired at a very precise time in the intake cycle.

Most massed produced cars use Saturated 12 to 16 Ohm Injectors. Peak and Hold injectors are generally reserved for high performance applications or in Turbo/Blower applications.

Fuel Control

The job of the ECU is to determine the amount of airflow, and pulse the injectors so that the amount of fuel injected provides the desired air/fuel ratio. There are two basic approaches to accomplishing this:

- **Mass Air Flow**. Mass Air Flow systems measure the airflow rate directly. These systems have an air flow meter in the inlet air ducting.
- **Speed Density**. Speed Density systems calculate the amount of air the engine is ingesting by measuring engine speed (that’s the *speed* part) and vacuum/boost (that’s the *density* part). Throttle position and intake air temperature are also used in the calculation. Speed density ECUs compare these measured criteria against known air flow characteristics of the engine.

Mass air flow systems are ultimately more accurate, since deterioration in engine condition is automatically accommodated. Speed density systems cannot adjust for loss of compression (for example leaks past rings or valves) or other departures from new engine specifications. However, for hot rod purposes, the speed density systems are at least as satisfactory in practice and have a couple of advantages. The flow meter in a mass air flow system imposes a pressure drop which degrades performance somewhat. Also the air inlet ducting must conform to certain requirements for accurate metering. Speed-density systems have neither of these limitations.

Engine Control at Idle, Cold Starts, Cruise and WOT

Idle Air Control. The Idle Air Control (IAC) can be a small stepper motor which operates an adjustable tapered valve.

Picture of IAC valve

Figure 6 - Idle Air Control valve. Typical GM stepper motor type. Photo courtesy of Castle Auto Electrics.

Some IAC valves are simple solenoids, and are either ON or OFF. The valve or the solenoid maintains engine idle speed at closed throttle by controlling the amount of air allowed to bypass the closed throttle valves in the throttle body. The engine's idle speed is determined by the ECU, and is not mechanically adjustable beyond setting what is referred to as “base idle”, which in most applications is approximately 500 rpm. Base idle is set by removing the connector from the IAC unit (which eliminates ECM control), and adjusting the throttle plate stop screw)usually referred to as the *Base Idle Screw*).

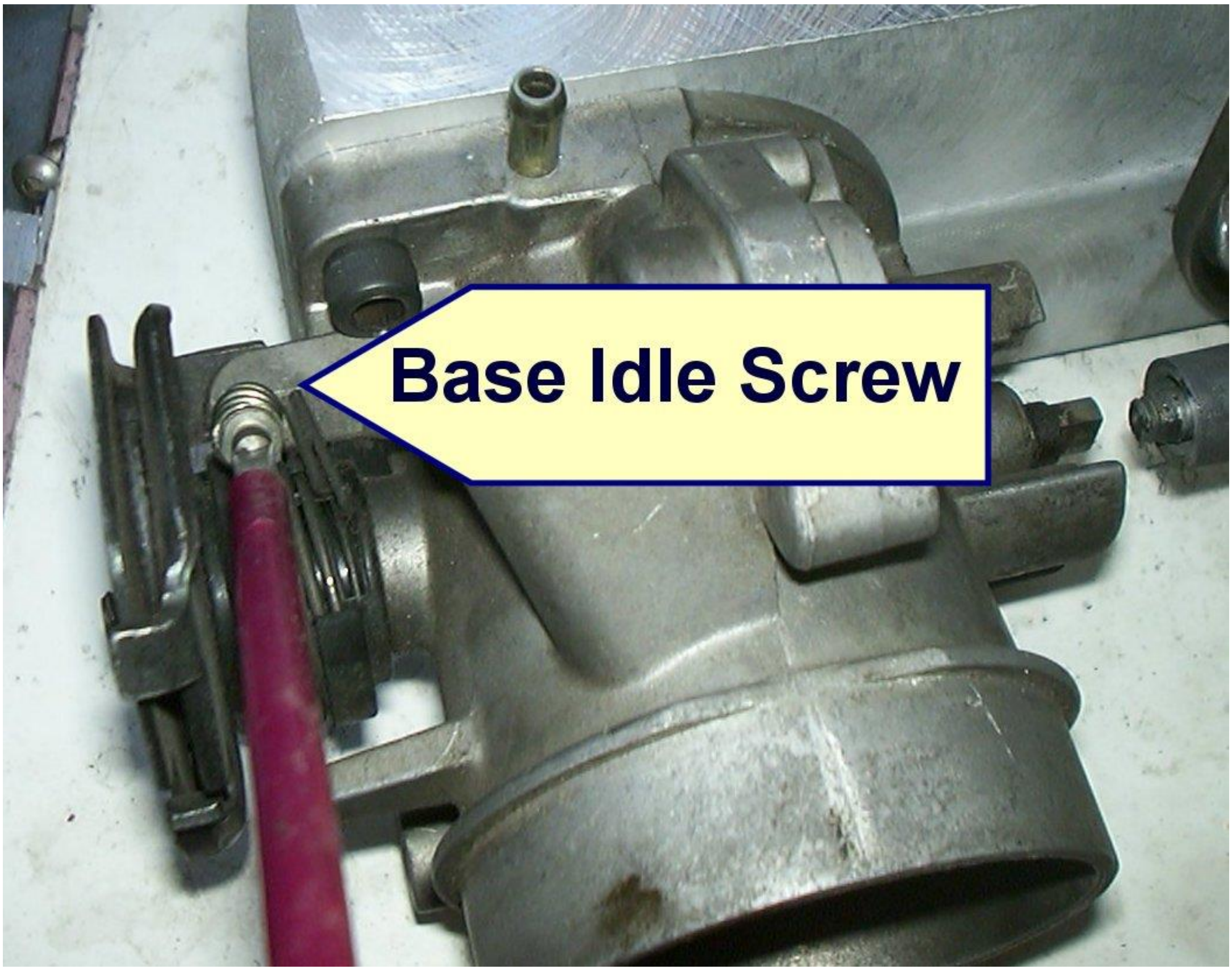

Figure 7 - Base Idle Screw on a typical Commodore Throttle Body, as viewed from underneath.

Cold Starts. When an engine is cold, the ECU will cause the injector pulse width to be a little longer than normal. This has the effect of an over-rich condition for ease of starting. At the same time, it will retard the timing, if timing control is incorporated in the system. Early GM TPI systems used a Cold Start Injector, which was basically a ninth injector that came on only when the engine was cold. Most systems today, including after-market ECUs, use the longer pulse width method for cold starts. During the cold start and warming up period, the ECU is operating in *Open Loop* mode, and remains so until the Coolant Temperature Sensor says the engine is warm and the O2 Sensor is warm enough to start detecting oxygen.

Cruise. Once the engine is in *Closed Loop* mode, the ECU determines optimum injector pulse width and ignition timing based on all the inputs coming from all the sensors.

WOT. When the TPS tells the ECU that the driver has stood hard on the accelerator, the injector pulse width changes to a slightly over rich condition and timing is advanced drastically. Some systems go to Open Loop mode temporarily, based on pre-determined fuel and ignition settings. This is because a normal O2 sensor is incapable of determining accurate levels of oxygen in the exhaust due to the temporary over-rich condition. A *Wide Band Oxygen Sensor* corrects this problem, and is used in some high performance applications. These types of O2 sensors can measure O2 levels even at WOT, so that *Closed Loop* operation is maintained.
A Wideband O2 sensor is recommended for Hot Rod EFI systems. Make sure your ECM supports it.

Ignition Control

There are different levels of ignition control depending on the ignition system used. Timing is based on the position of the crankshaft, which was the function of the distributor drive. These days, a *Crankshaft Position Sensor* (CPS) and *Camshaft Position Sensor* (CKS) are most commonly used as the timing control, giving a far more accurate assessment of piston and valve synchronisation than the distributor. Having a *Direct Ignition System* (DIS, also called *Distributorless Ignition System*) meant that ignition timing could be optimised for any condition – the ECU triggers the spark. These systems are fairly sophisticated and expensive when converting from a distributor based ignition system, but provide the best spark you could ever hope for.

A good ignition system, such as a magnetic pulse or hall effect distributor and MSD controller, will still deliver excellent results when used in conjunction with an after market ECU. Pick and ECU that uses the Tach signal to determine injection timing. For ignition advance control, however, a CPS must be used.

Next Issue, **Part 3, The Engine Control Unit**, explores the vast mysteries of the EFI computer. We find out how to choose the best one for your project, what you will need, how much it costs, where we can go to get it, how to wire it up and connect it to the sensors and actuators and advice on installing sensors.

Finally, in **Part 4, Converting to EFI**, we examine a couple of case studies. We look at some examples of Hot Rod style EFI conversions such as multi-carb adaptions, tunnel ram adaptions, blower configurations and how to choose an appropriate computer. We look at programming the computer, general wiring and combatting *Electro Magnetic Interference* (EMI) and *Radio Frequency Interference* (RFI).