<u>Austin Healey, Electronic Fuel Injection</u> ***Final Draft***

This paper discusses the final configuration of my Austin Healey electronic fuel injection (EFI) project and some of the technical issues associated with this project. One of the objectives of this installation was, to the extent possible, have the EFI system reasonably stealthy.....meaning that when you open the hood (bonnet) the casual observer would not notice anything glaringly high tech. I am not an engineer, so if you have issues with the content, understand that I am sharing what I've learned with the single goal of documenting my experiences, if that shortens your learning curve...good. If you know more than I do about the subject....great! I need to give credit to my co-conspirator on this A.H. project. The knowledge of how to put together the EFI system was solely dependent on Ric Navarro, who in addition to knowing which components to use and how to do the computer tuning, also machined many of the custom pieces that were required.

The Electronic Fuel Injection System: The EFI system is made up of two interlinked sub-systems, 1) the electronic elements, and 2) the fuel delivery components. These two sub-systems come together at the fuel injectors (see diagram). The system Ric has put together for the Austin Healey is a "closed loop" system, meaning that in steady state driving this system is constantly testing the sensors (such as O2 levels and atmospheric pressure) and working to adjust the injector firing duration to yield the most advantageous air/fuel burn rate (this is called the stoichiometric (ideal)) based on the conditions and the programmed fuel maps (i.e. delivery metrics). If, however, you are at other than steady state....such as full throttle application or start-up....the system will go into "open loop" and will follow the predefined fuel maps that are programmed into the electronic control unit (ECU, sometimes also called the electronic control module or ECM). This type of system is an infinitely variable, ever-changing fuel delivery curve instead of a single programmed set of values. In addition to the electronic elements, the EFI system is dependent on a high quality fuel delivery system, made up of a high pressure fuel pump, fuel filter, fuel pressure regulator, fuel rail, and fuel injectors. The Austin Healey electrical system needs to be converted from positive ground to *negative ground* to accommodate the EFI.

The Electronic Control Unit: The ECU is a microcomputer that is the "brains" of the fuel injection system. It controls the air/fuel mixture by evaluating the input from the sensors. Ric used a GM ECU which is readily available at junk yards and was produced in the late 80's and early 90's. This ECU is both simplistic by modern automobile standards and fairly advanced compared to general aftermarket ECU's. This system has custom injector blocks, each having 2 injectors. The ECU fires the injectors in two batches, let's call them bank A and bank B. Each bank fires 3 times in each distributor rotation, so there is a total of 6 injection firing events in each distributor rotation. Each of the injector blocks in this installation has one injector wired to bank A and one injector wired to bank B. So, each injector in an injector block is alternately fired, three times each, in one distributor rotation. This system *is not a sequential injection system*, which would require a more advanced ECU, a means of monitoring the cam position, and manifolds that place injectors directly in each intake port; this system is based on a *throttle body injection system*. The unit is programmable by a laptop PC with aftermarket software. So, Ric is using the GM ECU "thought process", but has changed the values to reflect the needs of the Austin Healey 6 cylinder engine. The ECU's chip (the program resides in the chip) is then removed and can be reprogrammed (with the new values) through a process called "burning". The resulting chip is then reinstalled in the ECU. Despite the complexity of the ECU, it is generally the most reliable component of an EFI system, as long as you have it mounted in a good location. The ECU should not be in direct proximity to engine or exhaust heat. Since temperatures should not exceed 150 degrees Fahrenheit, it would be best to mount the ECU in the cockpit area.

The SENSORS: This system is comprised of the following sensors and controls.

1- Manifold Absolute Pressure (MAP)
2- Engine Coolant Temperature (ECT)
3- Exhaust Oxygen (O2)
4- Throttle Position Sensor (TPS)
5- Idle Air Control (IAC)
6- Engine RPM and timing (RPM)
7- Oil Pressure Sensor (optional)
8- Speed Sensor (optional)

Manifold Absolute Pressure (MAP): The MAP sensor is connected to the intake manifold and indicates the operating engine load. The MAP sensor has a couple of corrective features to account for differences in altitude and temperature. The MAP sensor should be mounted close to the manifold inlet. Using a 5/32 inch I.D. vacuum line this distance should not exceed 18 inches.....to do so will reduce the accuracy and predictability of the input. Additionally, it is best to mount the MAP sensor higher than the manifold inlet to prevent the condensation and accumulation of gas, oil, or water vapors at the MAP sensor. The accumulation of these liquids will quickly deteriorate the MAP sensor and cause it to fail.

Engine Coolant Temperature (ECT): The ECT sensor obviously communicates the engine temperature to the ECU, this is particularly important during cold start and warm-up. The ECT can simply be spliced into the heater hose or attached to the *custom manifold*. The *custom manifold* mounts between the engine block and the standard heater hose turn-off valve. This keeps the ECT sensor somewhat hidden and, yet, very accessible.

Exhaust Oxygen (O2): The O2 sensor (referred to as the Lambda sensor by Bosch) resides in the exhaust pipe. This is arguably the most important information sensor in a fuel injection system. The oxygen sensor is a probe measuring the oxygen content of the exhaust gas. The amount of oxygen in the exhaust indicates the accuracy of the air/fuel mixture in the combustion. The ECU, in closed loop operation, is attempting to maintain a ratio of 14.7 to 1 air/fuel.....this is called stoichiometric. In this “ideal” condition there is no air left over, and there’s no shortage of air. Lambda is the Greek symbol which engineers use to indicate the ratio of one number to another. When discussing the control of the air/fuel ratio, lambda refers to the ratio of excess air to stoichiometric air quantity. So, in the stoichiometric (ideal) condition lambda equals 1. If the mixture is lean, say 15.3:1, there’s air left over after combustion, so the lambda ratio of excess air to the ideal amount of air is now greater than 1, say 1.04. And, if the mixture is rich say 13.5:1, there’s a shortage of air, so the lambda ratio is less than 1, say, .092. The oxygen content is expressed to the ECU in voltage terms with .5 volts being a lambda of 1. The oxygen sensor we choose to use is a *heated sensor*. The heated sensor warms up quickly during cold-engine starts and stays warm to provide more accurate readings regardless of operating conditions. The O2 sensor should be mounted reasonably close to the exhaust manifold. In my car, I chose to weld in an “H” pipe between the exhaust pipes, so I was getting average reading from both exhaust manifolds. If you have a reasonably good engine, the mounting of one O2 sensor in one of the pipes should be sufficient. One last thought for Healey owners, if you are in the habit of putting a lead additive in your fuel you should be aware that the lead will foul the oxygen sensor.

Throttle Position Sensor (TPS): The TPS signals the ECU what is happening with the throttle. The TPS is a potentiometer which is capable of registering any position from closed to wide open. This information may be used to signal a closed throttle, there-by initiating idle air control operation. When the throttle is being opened the ECU can increase injector duration, similar to the function of a carburetor's accelerator pump. And finally, when the throttle is depressed and exceeds approximately 50%, the ECU goes out of *closed loop* running and into *open loop* mapping until a steady state is once again sensed. The TPS is located on the end of the SU's throttle shaft. Since the SU's are connected via the throttle linkage, only one TPS is necessary. The mount for the TPS must be connected in a fashion that does not cause any binding of the linkage.....it must be free to travel smoothly throughout its range.

Idle Air Control (IAC): The IAC is actually a stepper motor that opens and closes a valve which lets air into the injector blocks, bypassing the SU throttle body. The ECU controls the IAC to allow constant engine speed during closed throttle body operation. This valve is particularly active during engine warm up when the SU throttle bodies are in their full closed position as the IAC continually adjusts the amount of air to try to hold the idle speed constant. All the injector blocks are connected to the IAC through flexible tubing to a common IAC manifold. When the IAC opens it allows air to all of the injector blocks. The IAC is mounted on the IAC manifold and should be mounted reasonable close to the injector blocks. However, there is flexibility in the positioning since the IAC manifold is connected to the injector blocks through flexible lines, however it is best to keep the lines the same length (mine are at 18").

Engine RPM and timing (RPM): The ECU is looking for some very specific information concerning engine rpm and the engine timing. To accomplish that, we took a GM High Energy Ignition (HEI) distributor and had it machined to fit the Austin Healey. There are a number of advantages to using a GM electronic distributor: 1) first and foremost, it is directly plug compatible with the GM ECU, 2) it is a pointless magnetic impulse distributor, 3) it is a higher energy than the stock Healey, and 4) the ECU can control its advance, eliminating the need for distributor weights and vacuum lines. The ECU, through the distributor connectivity, has full view of the engine RPM and the timing advance. The timing was set at an initial setting of 10° B.T.D.C., and then the ECU handles the advancing of the timing dependent on the engine needs. The GM distributor was indexed so that the number one cylinder places the electronic plug-ins on the back side of the distributor (away from the engine). This almost hides them from sight and adds to the stealth element. The modified GM distributor drops right into the old Healey distributors spot and allows full use of the Healey's mechanical tach drive. While some GM HEI distributors have the coil integrated into the distributor cap, we used the older version which has the coil mounted remotely from the distributor. The advantage of this is that the distributor maintains an "old" distributor look, again maintaining the stealth factor. The GM coil is plug compatible with the distributor. Even though the coil looks like a newer coil configuration, it can be mounted in an inconspicuous place to keep it out of view.

Oil Pressure Sensor (OPS) (optional): The OPS is simply a low oil pressure switch. If the OPS transmits a low oil pressure indication (below 2-7.5 PSI) to the ECU, the ECU will shut off the fuel pump. This is designed as a safety measure to keep you from frying your engine should you loose engine oil pressure. The OPS is mounted on a custom mount on the driver's side of the engine where the current oil pressure line is attached to the block. The oil pressure line is then attached to the custom OPS mounting, so your current oil pressure gauge will still function.

Speed Sensor (optional): The speed sensor translates the mechanical output of the transmission rotation into an electrical signal that is input to the ECU. The speed sensor is placed between the transmission output and the speedometer cable. You will probably need an adapter to connect these pieces. The ECU uses this "speed" information in relationship to other information (such as TPS, MAP, etc.) to asses the correct action to take on the engine management functions, i.e. injection firing duration, timing.

The other major component of the EFI system is fuel delivery. The fuel delivery portion of the EFI system is made up of a 1) high pressure fuel pump, 2) fuel filter, 3) fuel rail, 4) fuel pressure regulator, and 5) fuel injectors. The fuel delivery system must be capable of providing a constant high quality fuel source. The ECU expects that its fuel demands will be quickly met. The injectors require a clean source of fuel to respond to those demands and to stay operable.

The fuel pump must be capable of delivering a constant 40-50 psi at a minimum of 35 GPH. To accomplish this you need a good pump *made expressly for the demands of fuel injection*. Even high performance pumps (not designed for EFI) will not be capable of meeting the demands of an EFI system. There are now external tank pumps that *can* deliver that supply if you don't want to go to the trouble of getting an in-tank pump system fabricated. The advantage of the in-tank pump is that the fuel helps to cool the pump which will allow for a longer life for the pump and quieter operation. I have chosen to go with a GM in-tank fuel injection pump which has the added benefit of being generally available at parts stores across the country. Another factor to consider if you have an original Austin Healey Lucas generator: fuel injection pumps will have an amperage draw of approximately 5 amps per hour. Each injector draws approximately 1 amp. I'm using 6 injectors (some systems use only 4 injectors), so my electrical system needs to be capable of a minimum of 11 amps without discharging the battery. So your old Lucas generator may be marginal....but then it was probably marginal before the EFI if you have driving lights or modern halogen headlights.

The fuel filter needs to be a high quality element capable of filtering 10 to 20 microns to keep the injectors clean and to allow sufficient fuel delivery. Most fuel filters designed for EFI will provide that level of quality.

The fuel rail serves a number of purposes. It's a pressurized reservoir for delivering fuel to the injectors, it stabilizes the fuel pressure at the injectors, and the fuel passing the injectors cools the injectors. Since the pressure can rise and fall rapidly inside the fuel rail as the injectors open and close the supply must be stable enough to match the engine fuel requirement. If the volume inside the fuel rail is insufficient, this fluctuating pressure can affect the amount of fuel that is injected. Therefore, it is best to over engineer that fuel rail capacity, since if it is marginal it would be difficult to diagnose and is not easily corrected.

The fuel pressure regulator ensures that the ECU is always dealing with a consistent fuel supply. The ECU's ability to achieve a goal air/fuel ratio is dependent on injector size and fuel delivered at a defined fuel pressure, the ECU can then alter the duration of the injector firing for predicable results. The fuel pump does not always pump at the same pressure, and the fuel supply is also affected by temperature, so the pressure regulator is designed to maintain the fuel supply at a predetermined pressure. In the case of the Healey's system, we set the pressure regulator at 40 psi. We have installed the pressure regulator on the return side of the fuel system, down stream from the injectors. Because the fuel pump delivers more fuel than the injectors can use, the excess fuel is returned to the fuel tank via a *return line*......so, you need to plan on plumbing in a return line from the fuel rail (or after the pressure regulator, depending how you elect to plumb your fuel system). The return line should enter the tank at the top and extends down into the fuel supply. An additional consideration on the fuel delivery plumbing: A 5/16" (or - AN4) fuel supply line can handle up to 250 HP (the stock A.H. is a 5/16" line)....which should be sufficient for most of you. The return line needs to be at least the size of the supply line, this is dependent on fuel pump size, not a function of the engine HP, a 5/16" line will handle up to a 45 GPH fuel injection delivery system at 40-45 psi which is what I recommend for the AH system. To maximize the system, it is best to avoid restrictive fittings such as sharp right angles and "T" fittings. When right turns are needed it is best to use tube style fittings which smooth out the fuel flow.

The injectors are Bosch pintle-valve injectors. These are electromechanical devices that spray fuel into the injector block (mounted between the intake manifold and the SU throttle bodies) under the control of the ECU. The ECU controls the timing and duration of the injector spraying. The spray pattern is a function of the design of the injector. The delivery capabilities of injectors are expressed in lb/hr. The injectors we used are based on delivery requirements and physical size restrictions for the mounting of the injectors. The requirements of this system were calculated based on horsepower expectations and number of cylinders.

So you may be wondering what function the SU carburetors are performing......well not much. They are serving as the throttle bodies upstream from the fuel injectors to control the amount of air that is available to the injectors. The remaining inner workings of the SU's have been removed. It is important that the throttle shafts be "as new" since leakage around the shafts would cause confusion to the ECU and the IAC. To that end, I would strongly encourage replacing old throttle shafts when converting to EFI. Leaving the SU's in place, and having them act as the throttle bodies, adds to the stealth factor.

The injectors are mounted on custom aluminum injector blocks that are fitted between the intake manifold and the SU's. Since the injector blocks are 1" thick, it is necessary to install longer carburetor mounting bolts (3" worked for mine, this is somewhat dependent on the size insulator blocks you install, I used two ¼" insulator blocks, one on each side of the injector block). The injector blocks are also tapped for the lines to the IAC and one of the blocks is tapped for the mounting bracket for the TPS. The injectors are mounted on the bottom side of the injector blocks....once again to add to the stealth factor.

There are also custom aluminum fuel rail mounting brackets that fit to the injector blocks and are used to attach and stabilize the fuel rails and injectors.

The “tri-carb” look I was after required some modifications to the drivers pedal box because of the clearance required for the injector fuel rail and the fact that the SU’s are all 1” taller since they sit on top of the injector block. This means that the rear SU needed some additional clearance to mount an air cleaner; the forward two SU’s have sufficient clearance to fit an air cleaner. The twin carb arrangement on the stock log manifold did not require any modifications to the pedal box but would require somewhat taller injector blocks (or the addition of phenolic blocks) to clear the steering column.

List of custom bits:

- Injector blocks (long carb. mounting bolts)
- IAC manifold
- ECT mount
- TPS bracket
- Fuel rail mounting
- GM distributor machined to fit
- OPS mount (optional)
- Speed sensor adapter (optional)

Addendum: A few notes on electronic injection systems, this is *extensively* plagiarized from MegaSquirt information found on the internet. (MegaSquirt is an aftermarket fuel injection computer which has some nice features but requires considerably more involvement to build and is less sophisticated than GM’s ECU that Ric’s EFI system is based on.).

A. There are two common sorts of electronic injection:

Throttle body injection - usually one or two injectors for the whole engine

Port injection (aka. Multi-Port) - one injector per cylinder

Then there are three common modes of injection timing:

- **batch** - all injectors fire at once, but not timed to any specific cylinder event,
- **bank** - ½ the injectors fire at once, then the other ½, and so on, but not timed to any specific cylinder event,
- **sequential** - each injector fires at a specific point in the 4-stroke cycle for each cylinder (i.e., 8 independent timing events)

Throttle body injected cars are usually batch or bank fire. Most port injection set-ups before the mid-1990s were bank fire as well (including GM Tuned Port Injection).

Sequential injection requires:

- at least as many injectors as you have cylinders, with one dedicated to each cylinder (i.e., not a 4 injector TBI on a 4 cylinder).
- as many injector drivers as you have cylinders,
- and also requires a camshaft position sensor (a crank sensor is **not** adequate for a 4-stroke cycle engine).

The GM ECU Ric is using has two injector drivers (injection events), and no provisions for a cam sensor signal, which would be required to make it into a sequential injection system.

The benefits of sequential injection are that:

- you may get slightly better mileage and lower emissions at low engine speeds,
- you can tune each cylinder's fuel amount independently (if you know how).

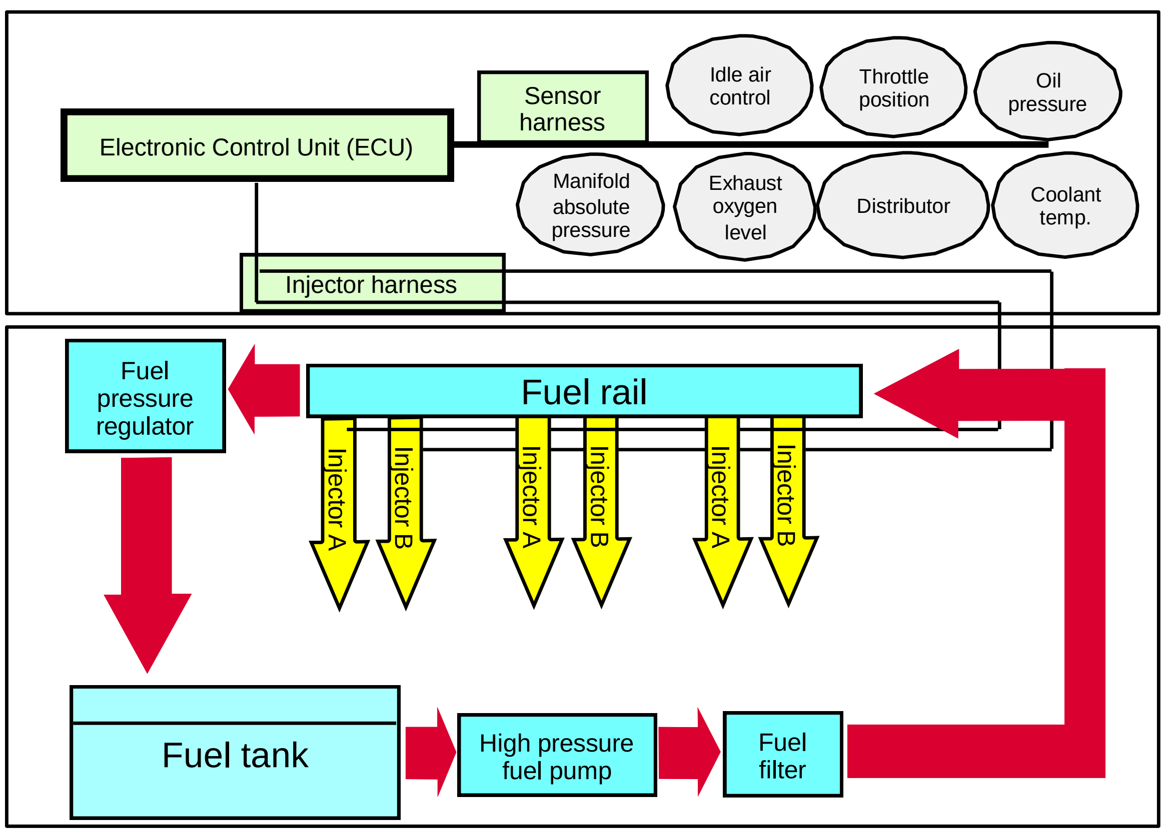
The effect on maximum horsepower is general negligible.

However, sequential injection does not necessarily mean you are injecting into an open intake valve all the time. The intake valve is only open less than 30% of the time in a typical 4 stroke engine. Once you are trying to produce more than about 25% of maximum HP your injectors are firing for longer than the intake valves are open. If your maximum HP is correctly calibrated to a safe 80% duty cycle, your injectors are injecting well over 50% of the time on closed valves. With Ric's GM ECU, fuel is injected only on ignition events, these are related to cam events, but trying to 'squirt' through an open valve under all conditions is generally a bit hopeless, because:

- fuel that is injected when the valve is closed doesn't go anywhere, it just sits near the valve vaporizing until the next time the valve opens (some OEMs deliberately squirt against a closed valve to improve vaporization). So squirting against a closed valve does not generally affect the AFR for that cylinder (though there may be a small effect on the combustion quality, good or bad, depending on the port wall temperatures, etc.)
- the valve is generally effectively open (0.050") less 300° of a 720° 4-stroke cycle (and closer to 200 for 'stock' engines). So hitting the open valve requires precise cam related timing,
- to inject the full fuel charge at high loads/RPMs through an open valve requires very, very larger injectors, about 2.5 to 4 times larger than is usually recommended,

- as the duty cycle for the injectors rises, the injectors come closer and closer to squirting all the time, and injection timing becomes irrelevant.

Austin Healey Electronic Fuel Injection



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