Pulse Width Based Water Injection Control Circuit

Circuit Objectives

This circuit is designed to permit experimentation with Water Injection (WI) via individual injectors, one for each cylinder of an existing fuel injected engine. The injectors would be supplied by their own high pressure pump (39 psi) from a sufficiently sized reservoir. The circuit will support the traditional use of WI, intake charge cooling of super charged and turbocharged engines. In addition this circuit provides very precise control of the onset and amount of water versus fuel allowing full-time use of WI to investigate possible efficiency gains at highway cruise conditions.

The original conception of this circuit was simply to trigger on the fuel Pulse Width (PW), opening a second set of water injectors for the same length of time as the fuel injectors. The ratio of water to fuel was simply determined by the difference of injector sizes. 30 pound fuel injectors and 14 pound water injectors gave just under 50% water to fuel ratio (just about optimum according to NACA MR E5H12, see references at end). The circuit simply needed to sense the On-Off of the existing fuel PW and drive the water injectors.

Of course the this method should work well at high power levels where the NACA research had investigated but it seemed a bit extreme for lower power levels such as highway cruise or idle. However, if one were to delay the WI pulse by a percentage of the fuel PW, the water pulse would deliver a smaller percentage of water/fuel. If this delay could be controlled precisely, the onset of WI could be LOAD sensitive. (fuel pulse width is directly related to the ECU's calculated LOAD). This delay of WI would also have the effect of "ramping up" the WI, low LOAD small percentage of water/fuel, hi LOAD – higher percentage of water/fuel.

The circuit would be most useful for investigating the use of WI if it had feedback to allow analyzing the input variables versus the output data. Part of the circuit is dedicated to measuring the fuel PW, delay PW and water PW. The output signal is capable of driving real-time displays and being data logged for later analysis. This output signal is 0-5 volt. The range of PW is .67mS to 30 mS. It should be noted that the frequencies and pulse width times are well within the range of the components used.

It is important to provide a power supply in the circuit that will protect the components from voltage transients and current overloads. Also important is to protect the car's ECU since this circuit will be tied into the same wiring harness.

The circuit is designed around readily available components, those selected are from Digi-Key or Mouser Electronics. These are not the only sources but were used in this case because they have very friendly web sites for ordering and securing reference data. The PCB board will be available through the author of this article hopefully in the spring of 2005..

Although not essential to the project, peak and hold (P&H) injector drivers are an integral part of the circuit. Being able to run P&H injectors (3-4 ohms) gives maximum flexibility when selecting injectors. These drivers will accept saturated (12-16 ohm) injectors without any circuit modification. One advantage of P&H is to have a smaller minimum pulse width, possibly important at the transition to WI. A second advantage of P&H capability is that very large injectors usually are P&H, so a very high output engine might need this capability for its water injectors.

Application of Circuit

This circuit should work well with most electronic fuel injection systems. It has individual injector drivers for 8 cylinders allowing use with sequential fuel injection or batch fire systems. For purposes of discussion, the reference car-engine is a 1994 Ford Mustang GT, 5.0L V-8 with basic performance modifications of aftermarket cam, intake, heads, MAF & 30# injectors. The engine is controlled by Ford's EEC IV model T4M0 computer supplemented with the piggy-back EEC Tuner (now a TwEECer) which allows full control of spark tables, fuel tables and many other control parameters. After full testing of the WI system on a naturally aspirated engine, twin turbochargers are planned for installation.

Triggering the circuit from the existing fuel PW allows the circuit to be used with many existing systems. The point that the trigger signal is taken (between the injector and the computer) provides a 12-14 volt signal when the fuel injector is OFF. When this signal drops to .6 volt or less the fuel injector is ON. Most existing fuel injection systems work this way. By utilizing the fuel injector PW, the WI system is automatically scaling the water output versus the current power level of the engine.

One or more of the references discuss that properly controlled WI will result in more complete combustion suggesting better fuel efficiency and improved emissions. The circuit has enough control authority to allow investigation of these issues.

Detailed Description

This document is intended to cover the main details of the circuit, documenting each component's function within the circuit. Although intended to be in-depth, this document will not get into all possible uses of a component. The components used all have data sheets that are quite detailed and readily available for free from the manufacturer's web sites and also on Digi-Key and Mouser Electronics web sites. If interested in the full function of any component it is highly encouraged for the reader to retrieve the data sheets and READ.

The actual PCB has a very dense placement of parts. This was necessary to keep the board manufacturing costs down. Also, a smaller finished board allows more choices of placement within the project car. This board is intended to be enclosed in a metal container and located inside the passenger compartment. Although components were chosen with the automotive environment in mind, some are only capable of 70 C for stable operation.

The discussion below splits the circuit into five sections, Injector Driver, Feed-Back, Injector Harness, Power Supply and finally PCB Connections and Enclosure. Various drawings are used to supplement the discussion. The injector driver section is discussed for just one cylinder's driver. The other seven are exact duplicates. Driver #1 is unique only in that the feed-back circuits feed off this section only. So if you are building the board for only four cylinders, ensure that you populate injector driver #1 to get feed-back functionality. Component numbers in the example drawings use actual component numbers from the main circuit; so even if there is only one capacitor in the example circuit, it may be numbered C11.

Injector Driver-

The typical injector circuit has the injector supplied continuously with 12 volt power. The injector is closed when the circuit is not grounded. When the circuit is completed by taking the circuit to ground, current flows through the injector - through the ECU's transistor to ground. Figure #1:

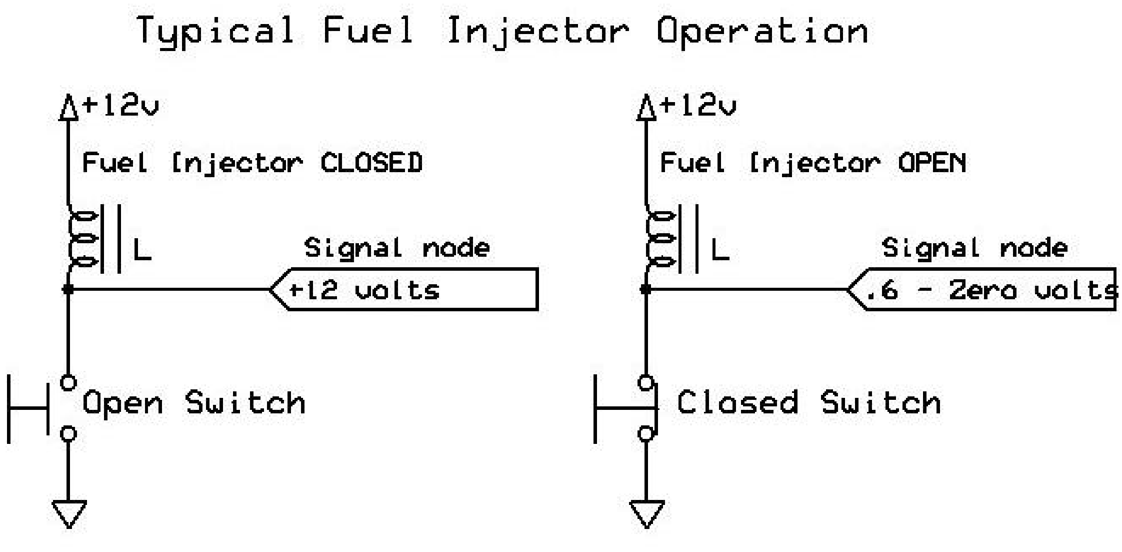

Figure #1

The switches depicted in Figure #1 are actually the transistors in the engine computer. Note that we will be taking our triggering signal right below the injector on Figure #1. This means the signal wire will have battery voltage (typically 12-14 volts) when the injector is OFF. When the computer commands OPEN injector, this point will go down to 0-.6 volts. (most transistors have .6 volts across them when they are saturated – closed switch).

The basic layout of the circuit with relation to the existing fuel injection system components is shown in figure #2:

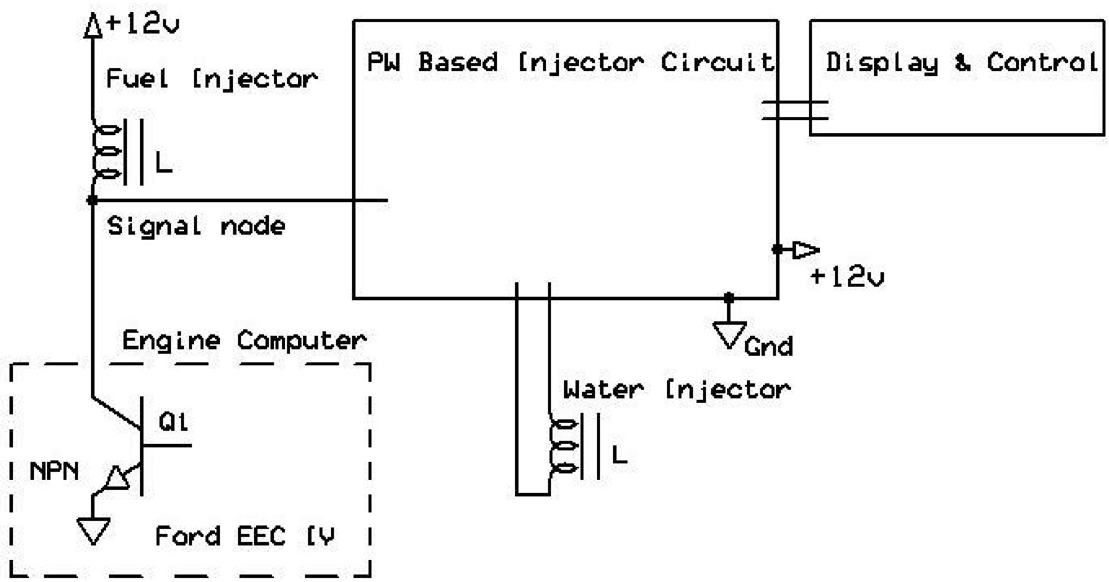

Figure #2

The basic injector driver circuit is based on the example circuit shown in the LM1949 data sheet (Figure #5):

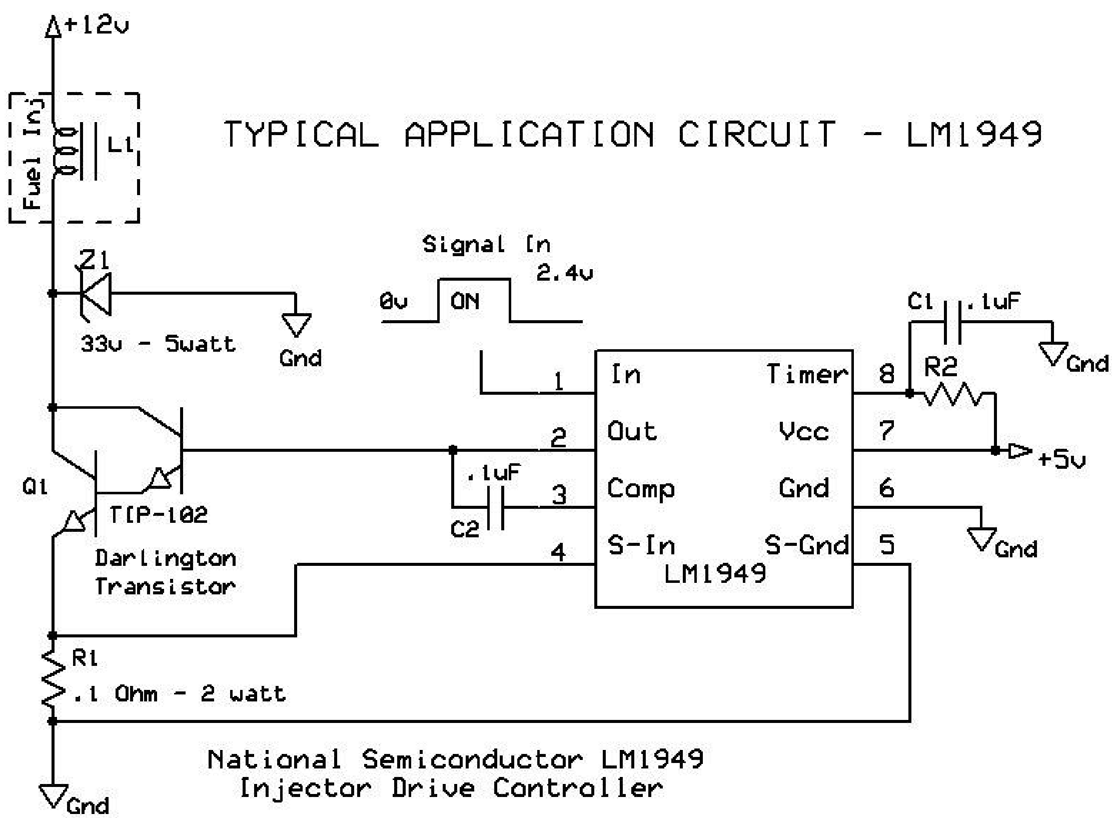

Figure #5

The actual circuit values and component labels are used in Figure #5. As configured this injector driver will command a peak of 4 amps and a hold of just under 1 amp for use with P&H injectors. If injectors are used that require different peak and hold values the resistance of R1 can be changed to achieve these new values (check data sheet for details).

The LM1949 works by monitoring the voltage across R1. At the beginning of the trigger signal, the LM1949 drives the Darlington transistor into saturation (closed switch). The current through the transistor climbs from zero to the maximum allowed by circuit resistance in a small but finite amount of time. If the injector has only 2 ohms, the current COULD go as high as 6 amps (Ohms law: I=V/R). A 12 ohm injector would only max out at 1 amp. When the current in R1 rises to create a .385 voltage drop, the LM1949 takes the Darlington transistor out of the saturated mode and modulates the base current to maintain .094 volts across R1 resulting in this case to a 1 amp holding current.

The LM1949 injector driver controls the Darlington transistor Q1, a TIP102. This transistor is well oversized for operation of a single injector. A glance at the data sheet shows it can handle maximum peak current of 15 amps and a sustained current of 8 amps. This suggests that it could handle several typical injectors if needed. But, as designed, the circuit should just use one injector per TIP102. The heat sink needed for just one injector is pretty minimal, using one side of the sheet metal enclosure should be sufficient. If the injectors need to draw significantly more than 4 amps at peak, the data sheet should be consulted to determine the heat sink needed.

<u>Feedback Allowing Data Log & Display</u>

The feedback portion of this circuit is intended to allow real-time displays (either LED or analog meter) and data logging. During the last two years of tuning the author's Mustang it has been found that being able to data log what was commanded versus what happened is very useful. In that case one channel of 0 – 5 volt analog signal can be logged with the EEC Tuner (or TwEECer). This data is stored right along with many other engine parameters such as RPM, LOAD, commanded fuel PW, spark and Air/Fuel.

So the goal in the feedback section of the circuit is to measure the pulse lengths and turn them into a voltage signal that varies between 0 and 5 volts. Interestingly, this is very doable for each and every cycle of the engine. This circuit actually only takes data off injector Driver #1. The reader might wonder how the circuit can measure each pulse when the engine could be turning in excess of 6,000 RPM. Pretty fast for mechanical things but in the electronic world this is almost in slow motion and the pulse lengths are gargantuan! The components in this circuit are capable of working at least 1,000 times faster and at MUCH shorter pulse lengths.

Specifically it is desired to measure the actual fuel PW that the fuel injector sees 0-30mS, the delay PW 0-15ms and finally the resulting water PW 0-30ms. The user may or may not have need for all three feedback circuits but it was decided to offer more options rather than less.

It should be noted that the range of pulse length's are not arbitrary. Going through the math shows that a four cycle engine at 6,000 RPM has 20mS available for a full two crankshaft revolutions (one fuel pulse, 100% duty cycle). At 4,000 RPM this climbs to 30 mS. With 30# injectors, the example 5.0L motor currently has a max fuel PW at about 4100 RPM of 14.5 mS. That is approximately a 300 Hp motor. The example motor won't max out the feedback range but other applications may end up using every bit of the range.

Injector Harness Voltage & Current Considerations

It should be pointed out that the large currents used to drive the injectors do not go through most of the "Power Supply" on the PCB (Ground connection only). Those currents and voltages (1-4 amps or more & 14.3 volts with engine running) come into the PCB at each Darlington transistor, go directly into the sensing resistor R1 and are taken back out of the PCB through the ground connection. Earlier it was discussed that the Darlington transistors are large enough to support better than four amps of current. The main ground connection will handle this 4 amp peak current and control currents with reasonable margin. If larger injectors that pull more than 4 amps peak are used, additional grounding points are provided next to where each sensing resistor (R1, R10, R19 etc.) connects to the ground trace. As you will note, this ground trace is massive and will carry in excess of 8 amps peak. Between 4 & 8 amps peak, one of these additional grounds will suffice. If your injectors pull over 8 amps peak, use the additional ground point for each injector. This will entail running dedicated ground wires from the additional ground to a common ground but should keep the ground traces from becoming overheated.

Another point of concern with regard to the injector currents and voltages, each of the injectors on a sequential system (batch system too) is fed from the same 12-14 volt source. The injector harness should be fused at that point of common connection to protect the injector harness against short circuit. This PCB cannot and is not set up to protect the injector harness from short circuit.

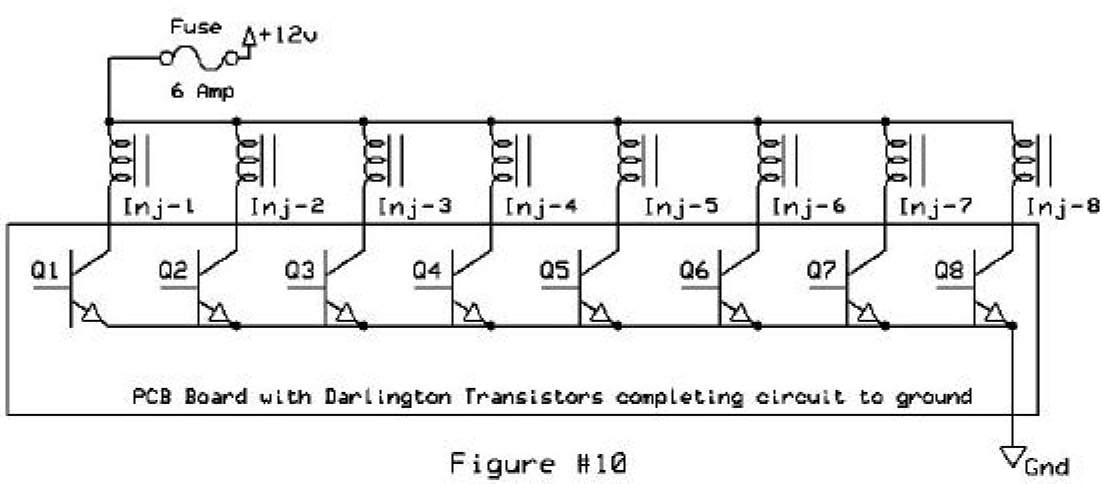

Figure #10

Figure #10 shows a 6 amp fuse. This fuse would actually need to be sized based on the expected peak amperage and primarily sized to protect the actual wire size in the injector harness. If the injector harness wires can only carry 8 amps safely, the fuse should be 8 amps. If the injectors will pull 10 amps peak, the wiring harness in this example does not use large enough wires. Most users will not have a major issue here. Saturated injectors will only pull around 1 amp peak (one reason OEM's stay away from P&H when they can). But those users pushing the edge with really large injectors might have some extra work when preparing for the installation of this circuit.

A final point on the injector harness is the suppression of voltage spikes. Every time the current is reduced in an injector there is a voltage spike released by the injector coils in its effort to resist current change. This is the basic nature of an inductor (an injector coil is a large inductor). So as the injector driver reduces from the peak current to the hold current, there is a significant voltage spike. Also, when the injector hold current goes to zero allowing the injector to close there is another voltage spike. This is where the Zener diode Z1, Z3, Z5 (etc.) come into play. Those 33volt Zeners clip any voltage spike at 33 volts and send that excess energy directly to ground. (similar to the signal in point using Z2, Z4 etc. to clip voltage spikes from the fuel injectors). This feature protects the Darlington transistors from exceeding their maximum voltage tolerance.

Power Supply

The power supply for the control section of this circuit is built in to the PCB. The only component not mounted on board is the fuse which is intended to be remote mounted to the case for easier access and replacement. The power supply has several functions. First, to supply the several voltages used by the circuit. Second, to protect the circuit from voltage transients, short circuits and reverse polarity connections. Third, the power supply should prevent this circuit from sending voltage transients back into the car's electrical system.

This circuit uses several voltages to function properly. The injector driver section gets only 5 volts and ground for operation of its IC's and logic network. The LM1949 and X9511 IC's will not operate on more than 5 volts. So this area is supplied with 5 volts regulated power by an LM7805CT voltage regulator and it's supporting capacitors.

In the Feedback section of the circuit 0-5 volt output was desired, which meant a higher regulated voltage was needed to handle the various "voltage-overheads" in the circuit and still output 5 volt final signals. A MC7808CT regulator was used to provide 8 volts. The LF398 Sample & Hold chip also needs negative voltage to have full functionality. For this a ICL7660CPA voltage converter was used to provide -8 volts.

The incoming 12-14 volt power goes directly to the PCB at the +12v terminal. Reverse polarity protection is provided by D1, a Schottky barrier diode. The positive trace then leads to a remote mounted fuse to protect against short circuit on the PCB. If anything shorts and pulls more than the fuse can handle, it will blow stopping current flow to the PCB. The final protection provided by the power supply is Z17, a 16 volt Zener diode, is connected between the positive +12v trace and Main Gnd terminal. The purpose of Z17 is to clip any voltage spikes and send the excess energy to ground.

PCB Connections and Enclosure

The PCB ends up 6.8 inches long by 2.9 inches wide. The PCB is intended to be used in a fully enclosed aluminum or steel enclosure. The four mounting holes should be marked out in the bottom of the box to allow the Darlington transistor side of the PCB to be against one side of the enclosure. This will allow the Darlingtons to be mounted (with proper isolation kits) to the enclosure sidewall using the sidewall as a heat sink.

PCB connections are through soldered leads. The designer's intention is to have each series of wires exit the enclosure through proper grommets and terminate at a multi-terminal connector. This will allow for simple disconnect in case of troubleshooting or further modification.

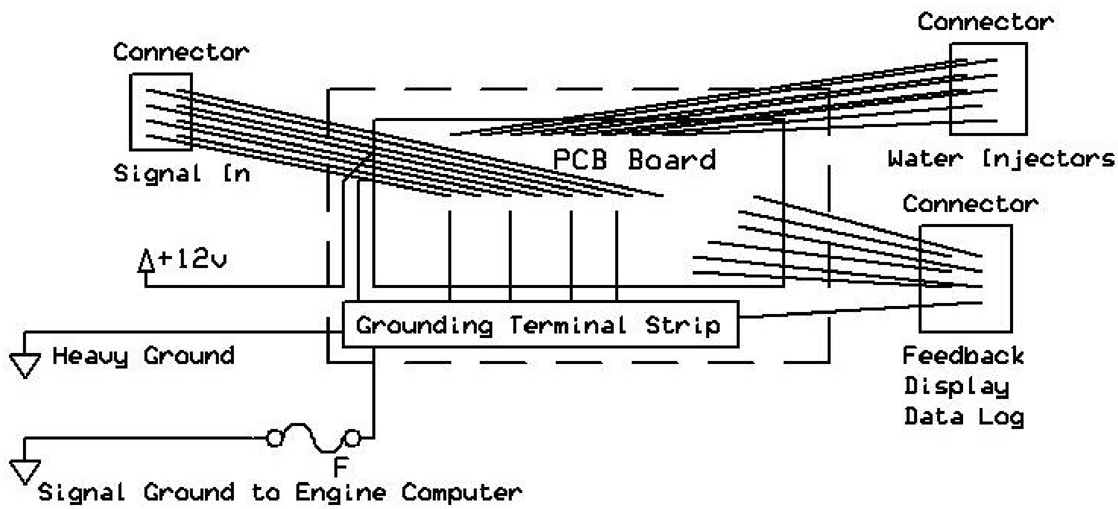

Figure #11

A word about grounds. There can't be too many grounds. The key is to ensure they are all common grounds. This helps to avoid ground loop faults in the overall circuit. In Figure #11 a Ground Terminal Strip is shown. The recommendation is to have this strip grounded to the enclosure. Run a wire from the Main Gnd to this strip. Next, if running large peak amp injectors, run the additional grounds from the PCB to the terminal strip. Finally, the Heavy Ground should be a dedicated, heavy gauge wire running to the negative battery post. This ground wire should NOT have a fuse in it. If enough current goes through this wire to fry it, you have much worse problems than a burnt ground wire. Simply running a ground to the nearest part of the uni-body structure is highly discouraged. Too many projects have had trouble with inconsistent grounds caused by uni-body construction. Sometimes they work well, other times there are intermittent failures of the ground. The dedicated line eliminates possible problems.

The Signal Ground to Engine Computer is the ONLY time a fuse on a "ground" is recommended. The point of this "ground" is to ensure the circuit has the same ground reference as the computer. We are pulling our trigger signals off the factory fuel injector harness which is controlled by the computer. This extra “ground” is probably redundant but there could potentially be minor voltage differences between the ground terminal at the computer and the Main Gnd on our PCB without this Signal Ground connection.

The point of the fuse in this Signal Ground: If the Heavy Ground were ever to fail, the next ground path is the Signal Ground. If large peak current is being pulled through the water injectors conceivably there could be an overload of the existing ground going to the computer. In this situation, if the Heavy Ground fails and too much current tries to go through the Signal Ground fuse it will simply blow, saving the stock computer’s ground wire. This fuse on the Signal Ground doesn’t need to be more than 1.0 amp. The signal load is very small.

For the wires going to a display or data log device include at least a ground wire originating on the Ground Terminal Strip. The output of the feedback signals are robust enough to run a simple volt meter type display but would need the ground from the PCB circuit for proper return path. If you are using a more involved display using LED’s etc, running both ground and a power wire up to the display is recommended. Although there is reserve capacity in both the 5 and 8 volt circuits, running 12 volts to the display and have the display create it’s own regulated voltage supply is preferred.

The Delay Pulse controls should use a ground originating at the Ground Terminal Strip. These controls are simply Normally Open switches that ground the respective lead when closed. These absolutely must have the ground from the PCB.

Other Uses of the Circuit

There are applications for this circuit other than for water injection. The other main use I could see would be for an engine combination that needs more fuel, such as a turbocharged BMW or any other car that may not have electronic tuning available to the enthusiast. Many car-engine combinations don’t have large followings that have “cracked” the control codes to allow more sophisticated electronic control of fuel. Some enthusiasts add additional fuel injectors and simply trigger them as boost builds and accept the resulting fuel mixtures. This circuit could give more control to this process with the right combination of injector size and “turn on point”.

A secondary use would simply be as a proper low impedance injector driver with an engine control computer that normally uses saturated injectors. This circuit could handle this task very well by deleting the “delay function”. A dedicated low impedance injector driver will soon be available from the author that would have a smaller PCB.

Update December 2004

The prototype was dyno tested in November 2004. Results of the testing are posted on the author’s web site www.myo-p.com. Some improvements need to be tested and incorporated to the PCB prior to release to others in the spring of 2005.

References

NACA Report No. 812, Knock-limited performance of several internal coolants
http://naca.larc.nasa.gov/reports/1945/naca-report-812/naca-report-812.pdf

NACA MR E5H12 Effect of water-alcohol injection and maximum economy spark advance on knock-limited performance and fuel economy of a large air-cooled cylinder, NACA Memorandum Report E5H12
http://naca.larc.nasa.gov/reports/1945/naca-wr-e-264/naca-wr-e-264.pdf

A Receive Signal Decoder This reference talks about turning pulse width into voltage. Not signed but the web site appears to be that of Paul Hills. Excellent information, thank you Paul! http://homepages.which.net/~paul.hills/Circuits/RxDecoder/RxDecoder.html

LM1949 Injector Drive Controller, This is the main integrated circuit that allows the injection circuit to run low impedance injectors. The circuit started with the example circuit in this document.
http://www.national.com/ds/LM/LM1949.pdf

LM555 and LM556 Timer Circuits An excellent resource for using the 555 & 556 timers. http://home.cogeco.ca/~rpaisley4/LM555.html

555 Timer Tutorials, Another excellent resource for learning about these timers
http://www.williamson-labs.com/480_555.htm

X9511 Digitally Controled Pontentiometer - Push Button Control
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http://www.national.com/ds/LF/LF198.pdf

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Mouser Electronics, Another excellent resource
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