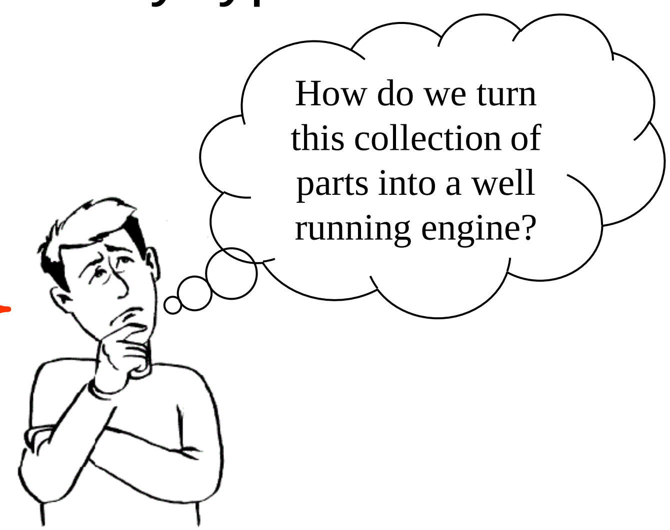
ECUs and Engine Calibration 201

Jeff Krummen
Performance Electronics, Ltd.
www.pe-ltd.com

Before we get started……..

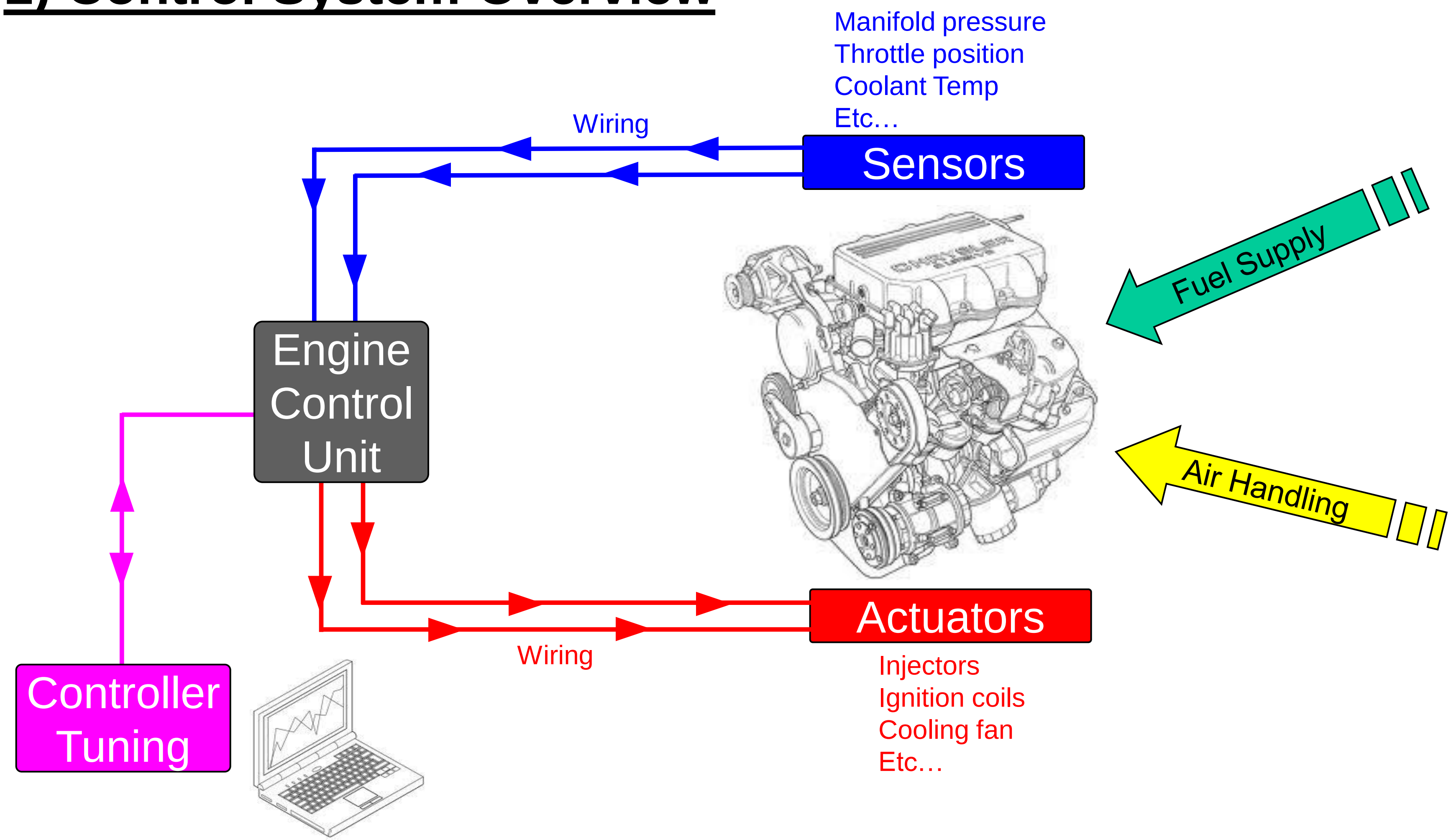
• The goal of this presentation is to explain the **PRACTICAL** application of engine control theory.

• Throughout the presentation, examples will be provided using the PE3 engine control system. However, the fundamental principles apply to almost any type of controller.



ECUs and Engine Calibration 201

1) Control System Overview



2) Sensors

In its most basic form, only 2 kinds of sensors are **ABSOLUTELY REQUIRED** to electronically control a fuel injected, spark-ignition engine….

- Load Indication (MAP, TPS, MAF)

- Engine Position/Speed (Crank or Cam)

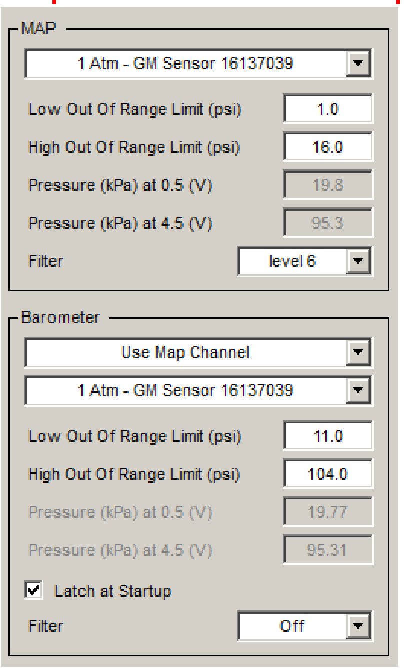
However, limiting the inputs severely hinders the control system's ability to perform at a high level.

2) Sensors – Pressure

Manifold Absolute Pressure (MAP) Sensor

- Used to indicate engine load, provides indirect measurement for mass of air entering cylinder
- Sensors read in ***Absolute*** pressure not ***Gauge*** pressure
- High pressure = low vacuum = high load
- Available up to several bar for forced induction engines
- MAP measurement can be latched at startup for barometric pressure compensation or separate BARO/MAP sensor can be used

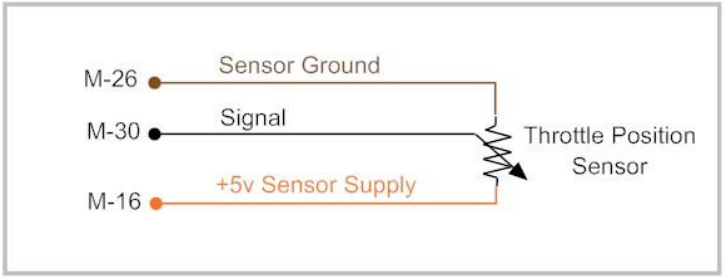
Example PE3 ECU Software Setup



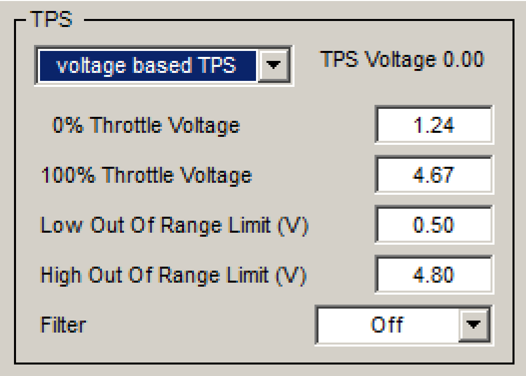
2) Sensors – Throttle Position

Throttle Position (TPS) Sensor

- Used to approximate engine load by measuring throttle angle
- Also very important for determining acceleration/deceleration compensation when the throttle is opened or closed
- Sensor creates a voltage divider as the wiper moves along a fixed resistance



Example PE3 ECU Software Setup



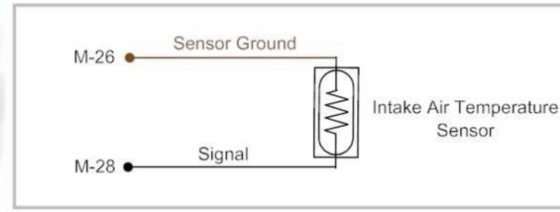
2) Sensors – Temperature

Intake Air Temperature (IAT) Sensor

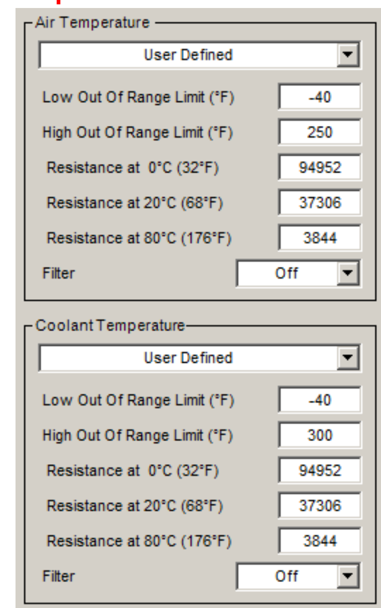
- Thermistor element, non-linear resistance change with temperature
- Compensates for changes in air density due to temperature changes

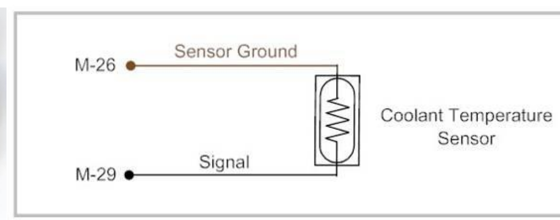
Coolant Temperature (CLT) Sensor

- Thermistor element, non-linear resistance change with temperature
- Compensates for startup conditions where more fuel and timing may be required



Example PE3 ECU Software Setup





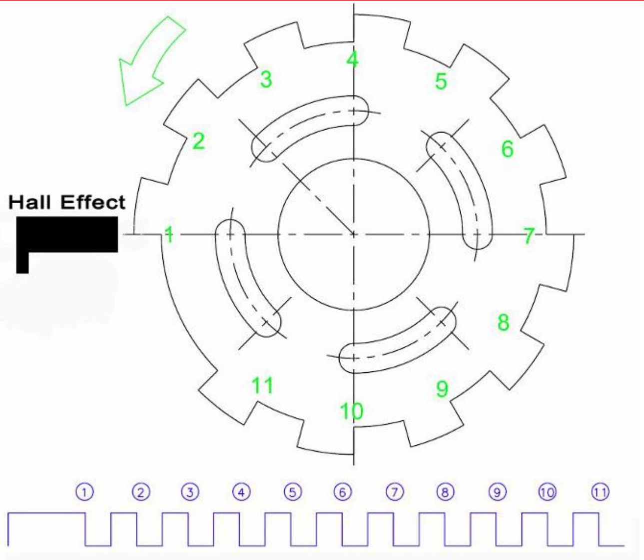
2) Sensors – Crank/Cam Position

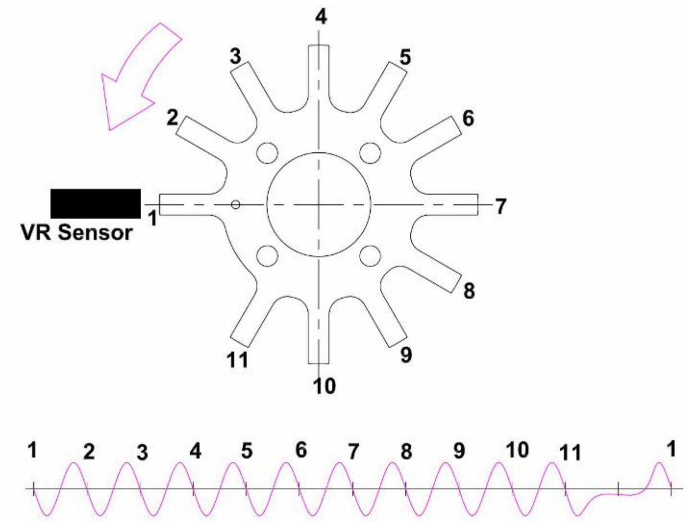
Hall Effect Sensor

- 3-wire sensor, creates square wave output
- Requires power to function
- Edge of the trigger tooth corresponds to a rising or falling signal voltage

Variable Reluctance Sensor

- 2-wire sensor, sine wave output, amplitude a function of speed, material and gap
- Center of the tooth corresponds to 'zero-crossing'. **The zero-crossing is what the ECU uses to indicate position.**





2) Sensors – Lambda

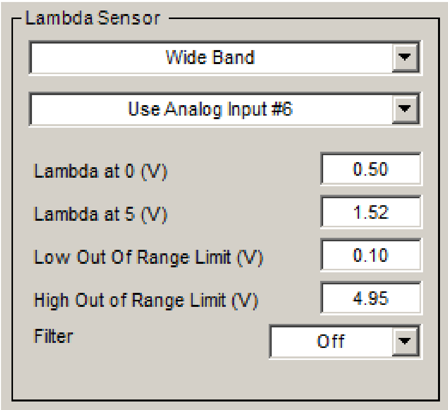
Narrow Band Sensor

- Efficient at measuring lambda at or around stoichiometric ratios
- Generally used as a ‘switch’ to indicate rich condition or lean condition
- Characterized as having 1-4 wires depending on presence of heating element

Wide Band Sensor

- Much wider range of measurement. Can be used to accurately measure rich and lean air-fuel ratios
- More than 4 wires to the sensor
- More costly and more complicated to control but worth the added expense

Example PE3 ECU Software Setup



2) Sensors – Generic Inputs

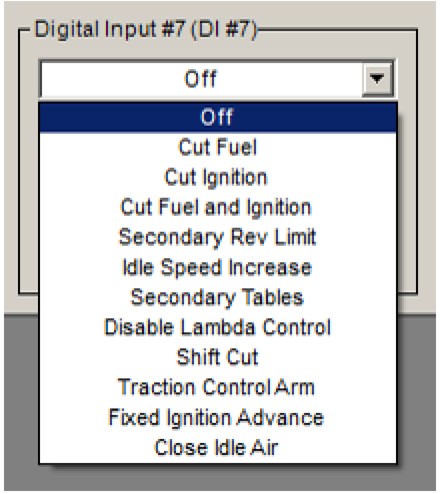
Analog Inputs

- 0-5v and 0-22v analog inputs
- Can be used to modify fuel, modify ignition timing or log for data acquisition
- Very useful for adding ‘on-the-dash’ fuel and ignition trims

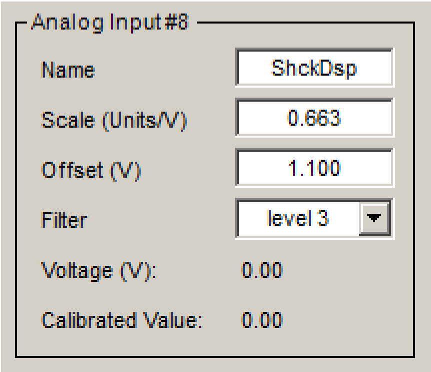
Digital Inputs

- Active pulled ‘high’ and active pulled to GND
- Many possible functions including:
  - Measuring speeds
  - Cutting fuel and/or ignition
  - Secondary rev limit
  - Traction control
  - Shift cut
  - etc

Example PE3 ECU Software Setup



Example PE3 ECU Software Setup



2) Actuators

For this discussion, actuators are defined as any component or device that are controlled by the ECU for the purpose of running the engine.

There are many types of actuators but the two most important actuators for running an engine are….

- Fuel Injectors

- Ignition Coils

2) Actuators – Fuel Injectors

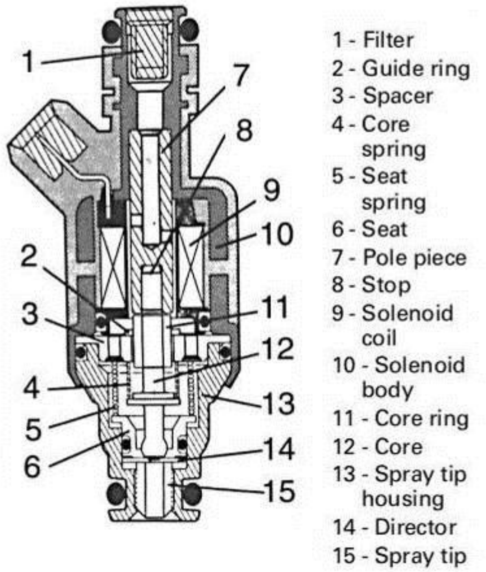
- Gasoline injectors are just valves, capable of two states open and closed.

- Reliable operation depends on a clean flow of pressurized fuel at a predictable pressure.

- Two types of injectors:

  - **Saturated** – High impedance (>10 ohms), easy to drive by just flowing 12v through the injector

  - **Peak and Hold** – Low Impedance (<3 ohms), more difficult to drive because they require high 'peak' current to open (~4 amps) then lower 'hold' current to stay on without burning up (~1 amps)



2) Actuators – Fuel Injectors, Types Pros/Cons




Type	Pros	Cons
Saturated	• Used for almost all production systems • Readily available in many sizes • Easy to drive and configure	• Slower response • Lower flow rates
Peak and Hold (P&H)	• Faster response • Very large flow rates available	• Require more complicated drive electronics and setup • More expensive and less readily available

P&H and Saturated Injectors typically look the same. Easiest way to tell them apart is to measure the electrical resistance.

FORMULA SAE TIP

If the engine that you are using came from the factory with fuel injection, use the stock injectors. There are very few cases where doing otherwise provides any real benefit.

2) Actuators – Fuel Injectors, Setup

Whether using P&H or Saturated injectors, one **VERY** important setting is sometimes overlooked when configuring the control system...

Battery Voltage Compensation (A.K.A. Injector Dead-time)

1. Added term to the final calculated injector open time
2. Compensates for decreased battery voltage at the injector when supply drops (3.5ms @ 15v = 3.5ms @ 10v with correct Battery Comp)
3. By definition, the correct Battery Voltage Compensation creates a **LINEAR** relationship between the final open time and mass of fuel.

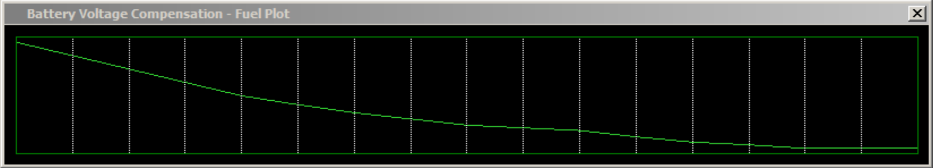
Battery/Barometer Compensation

☑ Enable

Battery Voltage Compensation - Fuel

Volts	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
ms	1.74	1.59	1.44	1.29	1.14	1.04	0.95	0.88	0.81	0.78	0.75	0.68	0.62	0.59	0.55	0.55	0.55

Battery Voltage Compensation - Fuel Plot



Example PE3 ECU Software Setup For Battery Voltage Compensation

2) Actuators – Fuel Injectors, Battery Compensation (cont)

- Injectors open faster with more voltage (non-linear)

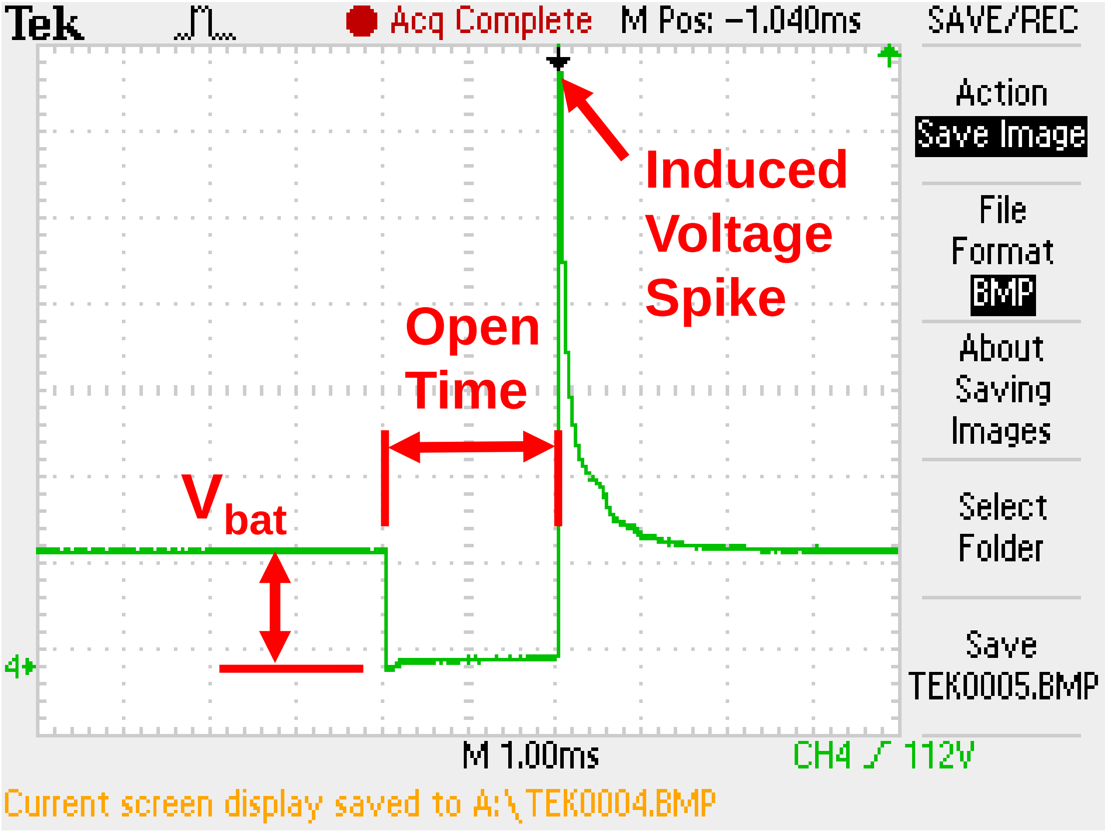
- For given base open time, with constant fuel pressure and temperature, more voltage = more fuel flow

- If no compensation is applied, at a fixed load and rpm, open time will provide different mixtures proportional to electrical load on system. **This is impossible to tune well!**

- Battery voltage compensation accounts for latency of injector and can't be measured electrically. **It must be measured and calculated using mass flow!**

- With the correct compensation, a xx% change in pulse width corresponds to a xx% change in fuel flow. This makes it much easier to tune as well as keeping all of the compensation terms happy.

2) Actuators – Saturated Fuel Injector Trace



2) Actuators – Ignition Coils

Ignition coils are step up transformers that use primary side voltage and current to induce large secondary voltages. There are several types of coils.

- **Inductive (Dumb)**
  - Used on most modern production applications
  - Uses 12v to charge the primary side of the coil
  - High turns ratio (high inductance)

- **Inductive (Smart)**
  - Same basic construction as ‘dumb’ inductive coils except they have a built in ignition driver (igniter). GM LS series motors use ‘smart coils’
  - Have 3 or more wire connections

- **Capacitive Discharge Ignition (CDI)**
  - Used on many pre-computer controlled, production, small engines
  - Still used for some performance applications (MSD)
  - Requires much higher primary voltage (>150v)
  - Generally, lower primary resistance than inductive coils

2) Actuators – Ignition Coils

• Inductive and CDI coils require entirely different types of ignition drivers. They **ARE NOT** interchangeable.

• If you have an existing OEM coil and are unsure of the type, there are several ways for determining inductive or CDI.

- Turn on ignition key. If the coil measures 12v, the coils are inductive.
- Refer to the stock wiring diagram. If the one side of the primary goes to 12v it is inductive. If both sides of the primary go to an ignition box, it is likely CDI.

• The ***PE3*** engine controller has built in inductive ignition igniters. It can drive inductive 'smart' or 'dumb' coils directly from the ECU.

> FORMULA SAE **TIP**
>
> • If possible use the stock coils. There are very few cases where doing otherwise provides any real benefit.
>
> • Most 600cc engines can benefit from running the 'hottest' available plugs. This helps to reduce fouling.

2) Actuators – Ignition Coils, Inductive Charge Time

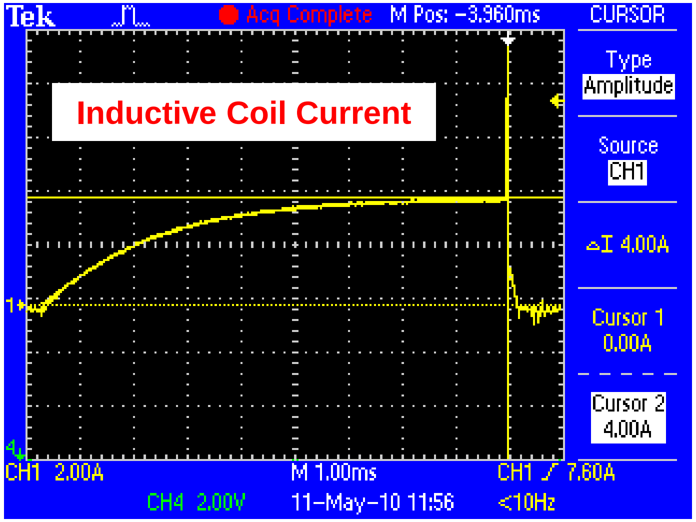
- Inductive coils require a specific amount of time to charge, *Charge Time*.

- To obtain the same output under all operating conditions, charge time must be a function of battery voltage.

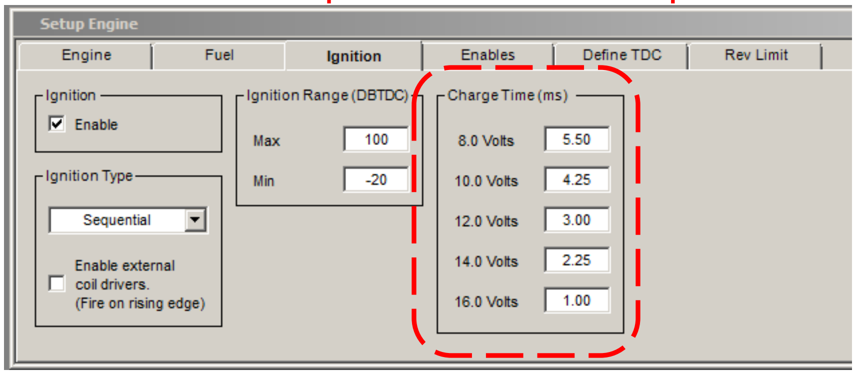
- Charge time is best determined by measuring current through the coil using an oscilloscope at different voltages.

- Generally the charge time is set so max current is at least 3 time constants.

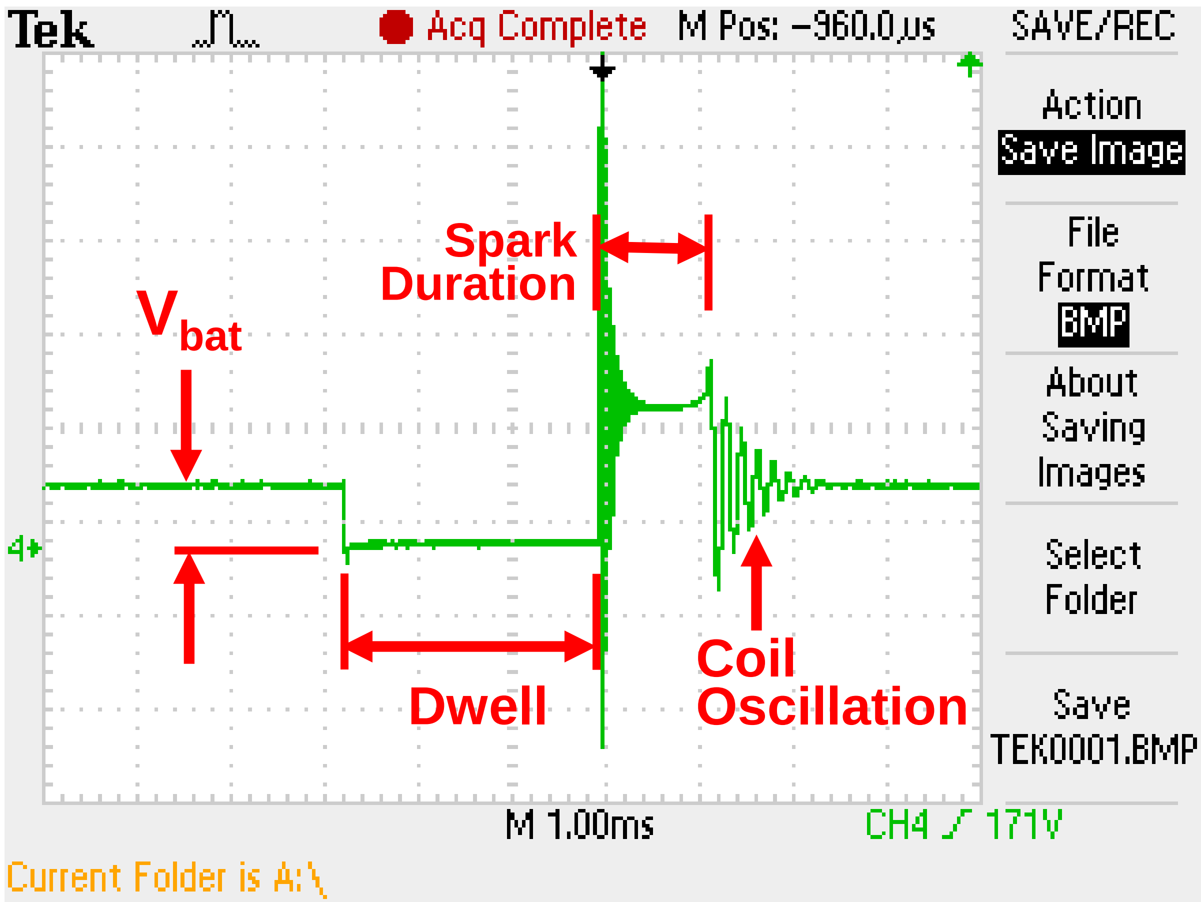
- As the coil current approaches saturation, extra charge time simply heats up the coil and the driver.



Example PE3 ECU Software Setup

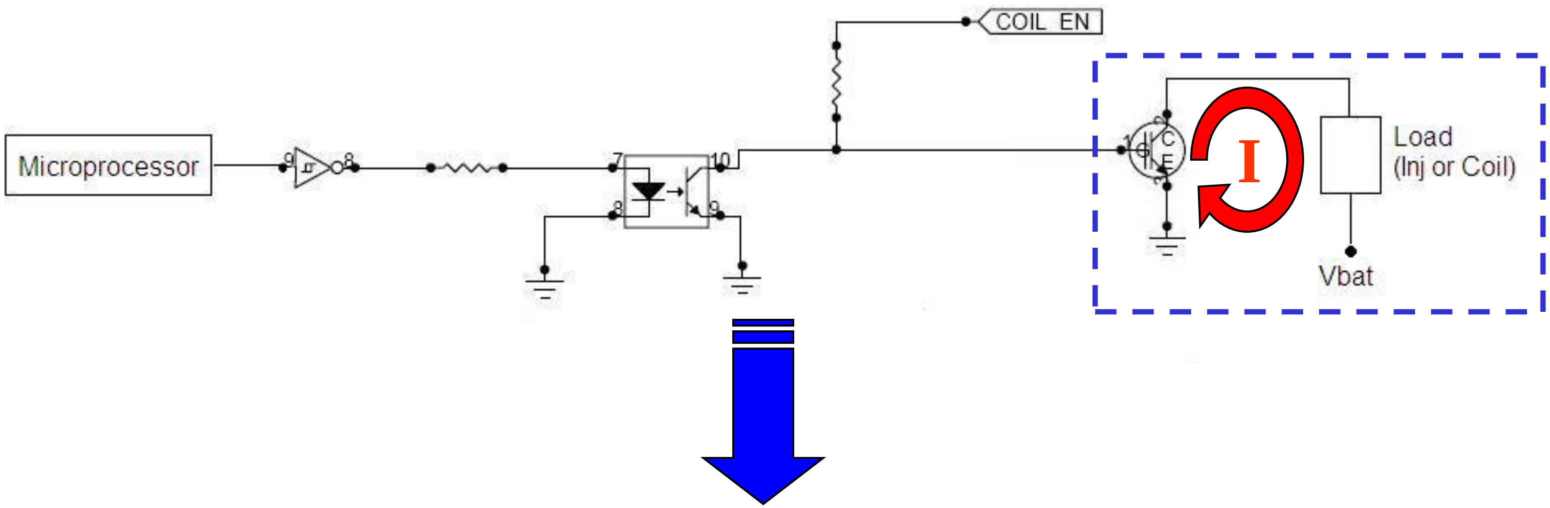


2) Actuators – Inductive Ignition Coil Trace (Primary)

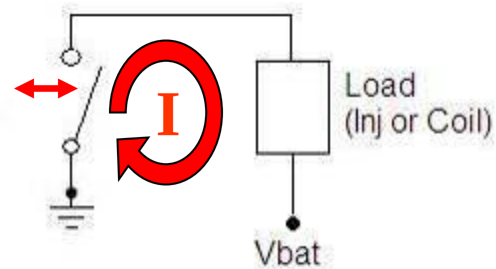


2) Actuators – Coil and Injector Driver Explanation

The following example applies only to saturated (high impedance) injectors and inductive (not CDI) ignition coils. More on the types of injectors and ignition coils later.



Simplified Driver Circuit with Switch



3) Control Strategies – Overview

• The two main jobs of an engine control system is to control the fuel flow and the ignition timing….**everything else is just fluff.**

• Optimized fueling and ignition timing are dependent on many different factors. All of these factors must be measured and accounted for in order to produce a well running engine under all conditions.

3) Control Strategies – Calculation of Inj Open Time

Open Time (ms) = (BOT x AT x CT x ST x AC x BP x MP x STF x LTF x CC x UI) + BA

Where:
BOT = Base open time from the main fuel table
AT = Air temperature compensation
CT = Coolant temperature compensation
ST = Starting compensation
AC = Acceleration compensation
BP = Barometric pressure compensation
MP = MAP compensation
STF = Short term factor for closed loop lambda compensation
LTF = Long term factor for closed loop lambda compensation
CC = Individual cylinder compensation
UI = User selectable input compensations (could be several if configured)
BA = Battery voltage compensation

3) Control Strategies – Calculation of Ignition Timing

Total Ignition Timing (deg) = BIT + AT + CT + BP + MC + CC + UI

Where:
BIT = Base ignition timing from the main ignition table
AT = Air temperature compensation
CT = Coolant temperature compensation
BP = Barometric pressure compensation
MC = MAP compensation
CC = Individual cylinder compensation
UI = User selectable input compensation (could be several if configured)

4) Engine Tuning – Overview

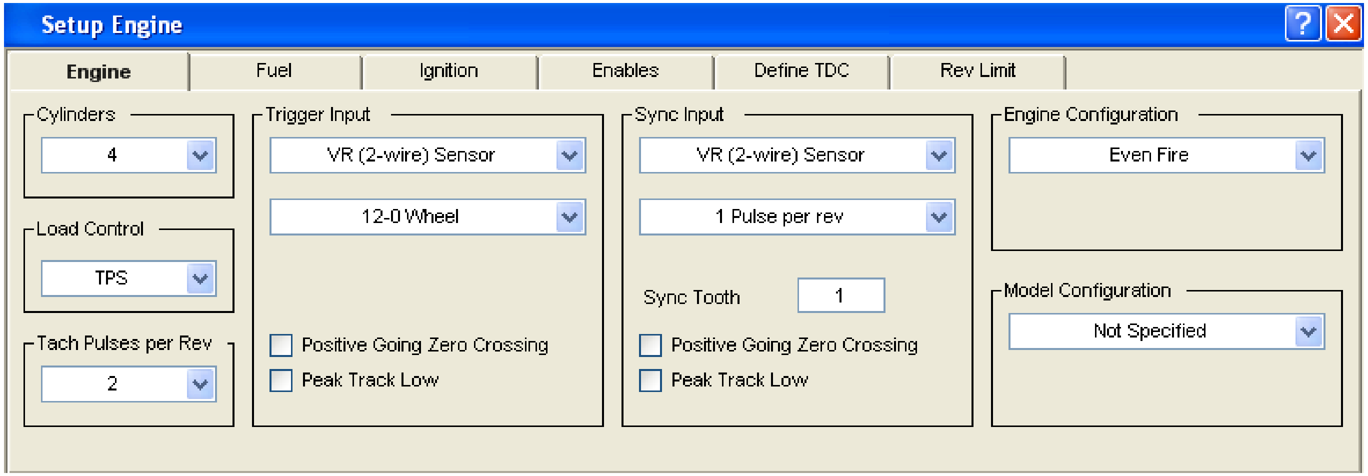
Successful Engine Tuning

1) General ECU setup (engine type, # cylinders, sensor setup, etc)
2) **Tune main fuel table**
3) **Tune main ignition table**

   Must iterate to best "tune" (applies to 2 and 3)

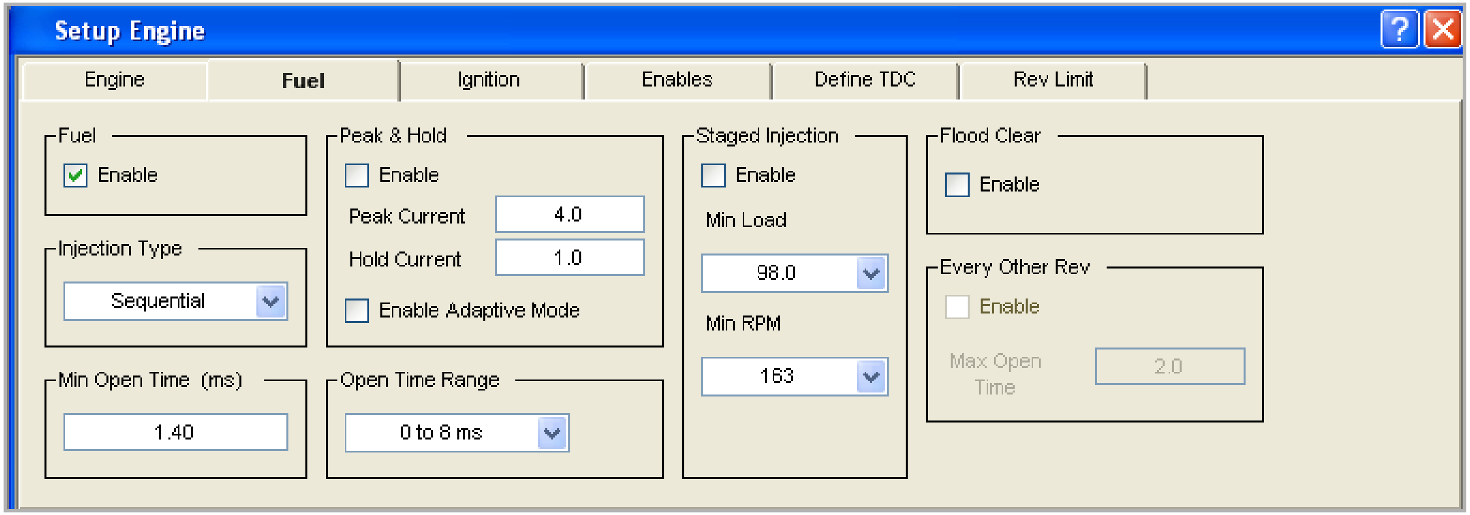
4) Add in additional compensation (air, coolant, starting, etc.)
5) Setup additional inputs and outputs (idle air, fuel cut, secondary rev limiter, etc)

4) Engine Tuning – General ECU Setup, Engine



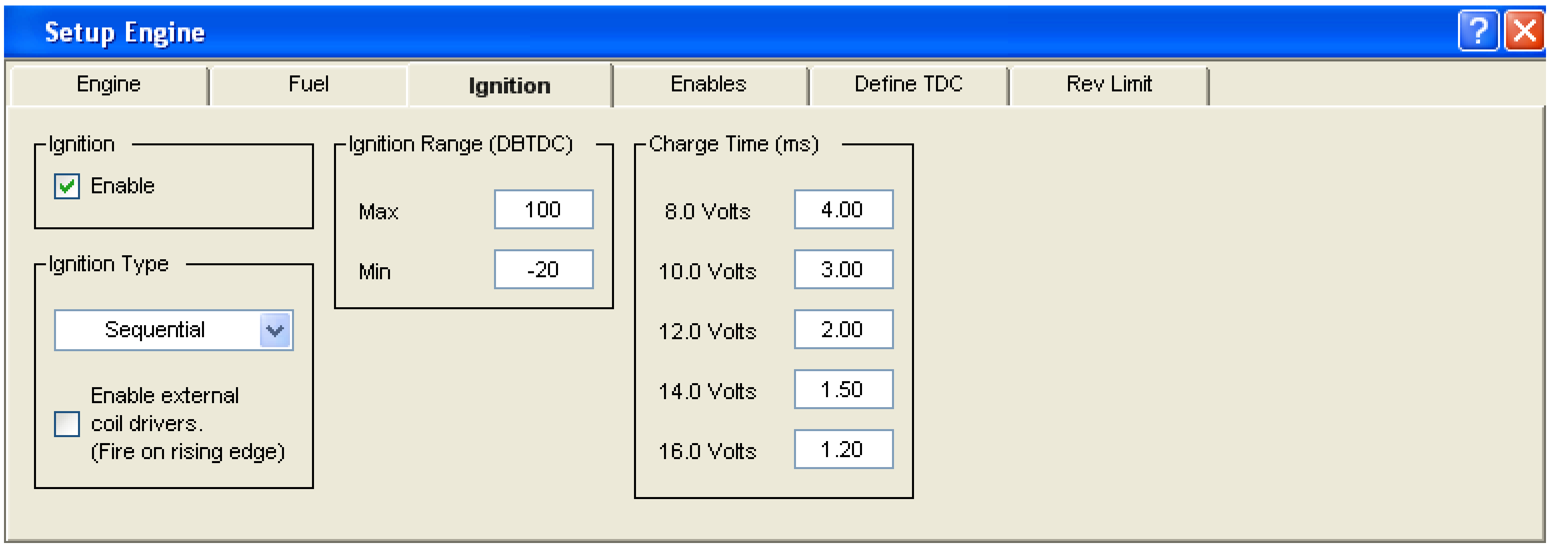
- **Cylinders** – Number of cylinders in the engine
- **Trigger and Sync Types** – Variable Reluctance or Hall Effect
  - Pick the tooth arrangement on your trigger and sync from the drop down menu
  - Choose which edge to trigger on (Positive or negative going)
  - Enable peak track low for signals that vary by more than 30% from one peak to the next
- **Load Control** – Controls which input is used to indicate engine load
- **Tach Pulses per Rev** – Sets the number of tach pulses for every crank revolution

4) Engine Tuning – General ECU Setup, Fuel



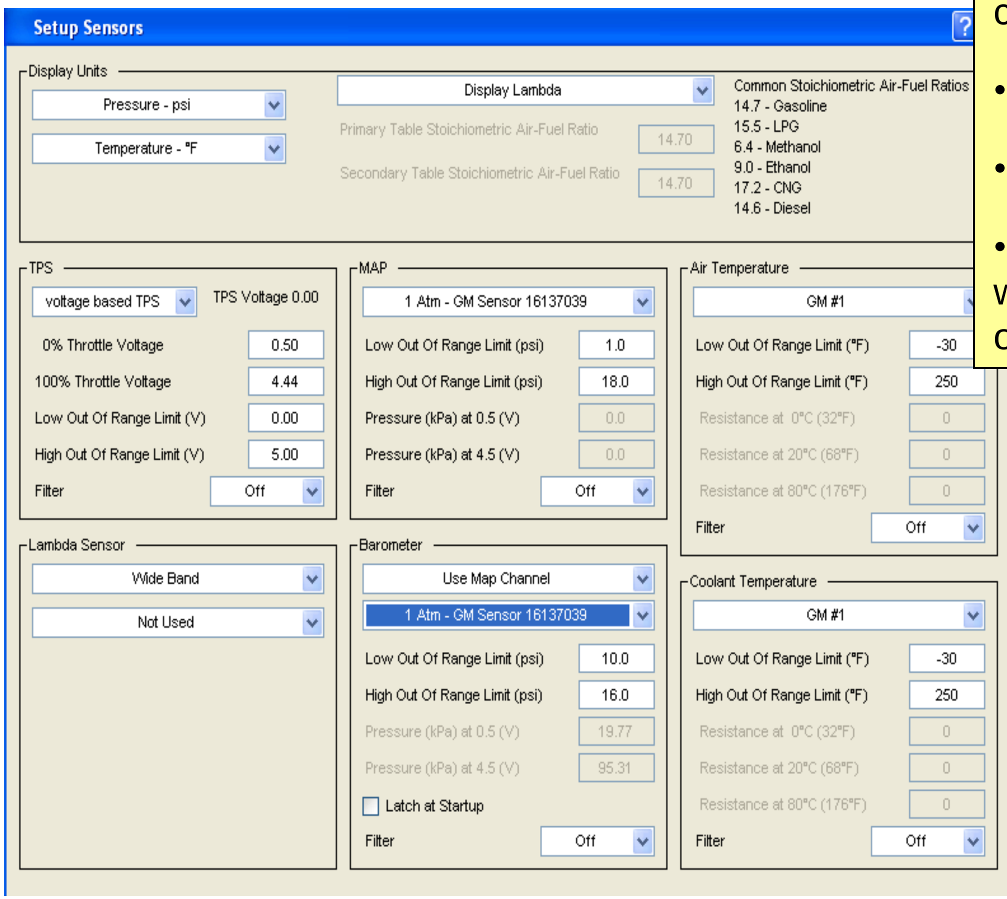
- **Injection Type** – Sequential, Semi-Sequential, Throttle Body, Random Sequential
- **Min Open Time** – Defines the minimum allowable pulse width for injection
- **Peak And Hold** – Enable peak and hold mode and set peak and hold currents
- **Open Time Range** – Sets the maximum base table open time. (The higher the range, the less resolution)
- **Staged Injection** – Enable secondary injectors and set the thresholds where they are activated.
- **Flood Clear** – With this enabled, when TPS is above 98% and RPM is less than cranking speed, no fuel is injected
- **Every other Rev** – Used to aid in idling and part throttle loads with large injectors

4) Engine Tuning – General ECU Setup, Ignition

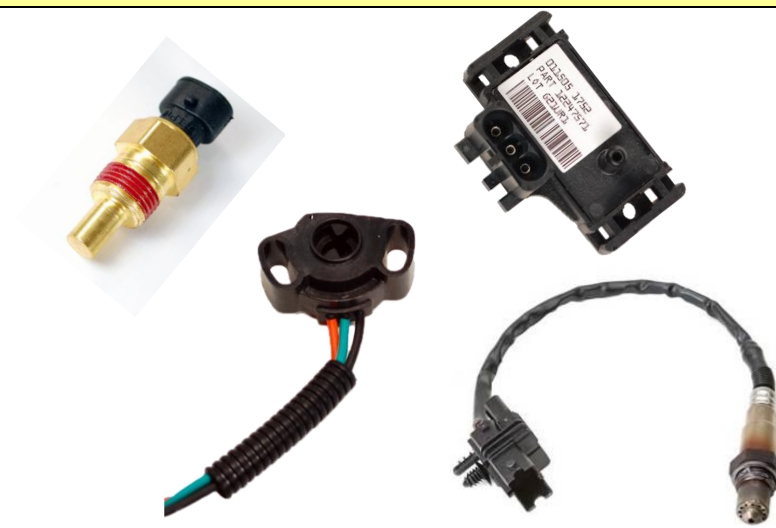


- **Ignition Type** – Sequential, Wasted-Spark, Distributor (External drivers for "smart" coils)
- **Ignition Range** – Defines the adjustable range of timing BDTC
- **Charge Time** – Sets charge time of the ignition coil

4) Engine Tuning – General ECU Setup, Sensors



- Sensors can accept a user defined calibration or choose a predefined sensor calibration.
- Units are selectable (SI or English).
- Sensors can be turned on or off independently.
- High and low 'out-of-range limits' can be set as well. Errors will be latched each time a sensor goes out of range.



4) Engine Tuning – Overview

Successful Engine Tuning

1) General ECU setup (engine type, # cylinders, sensor setup, etc)

2) **Tune main fuel table**

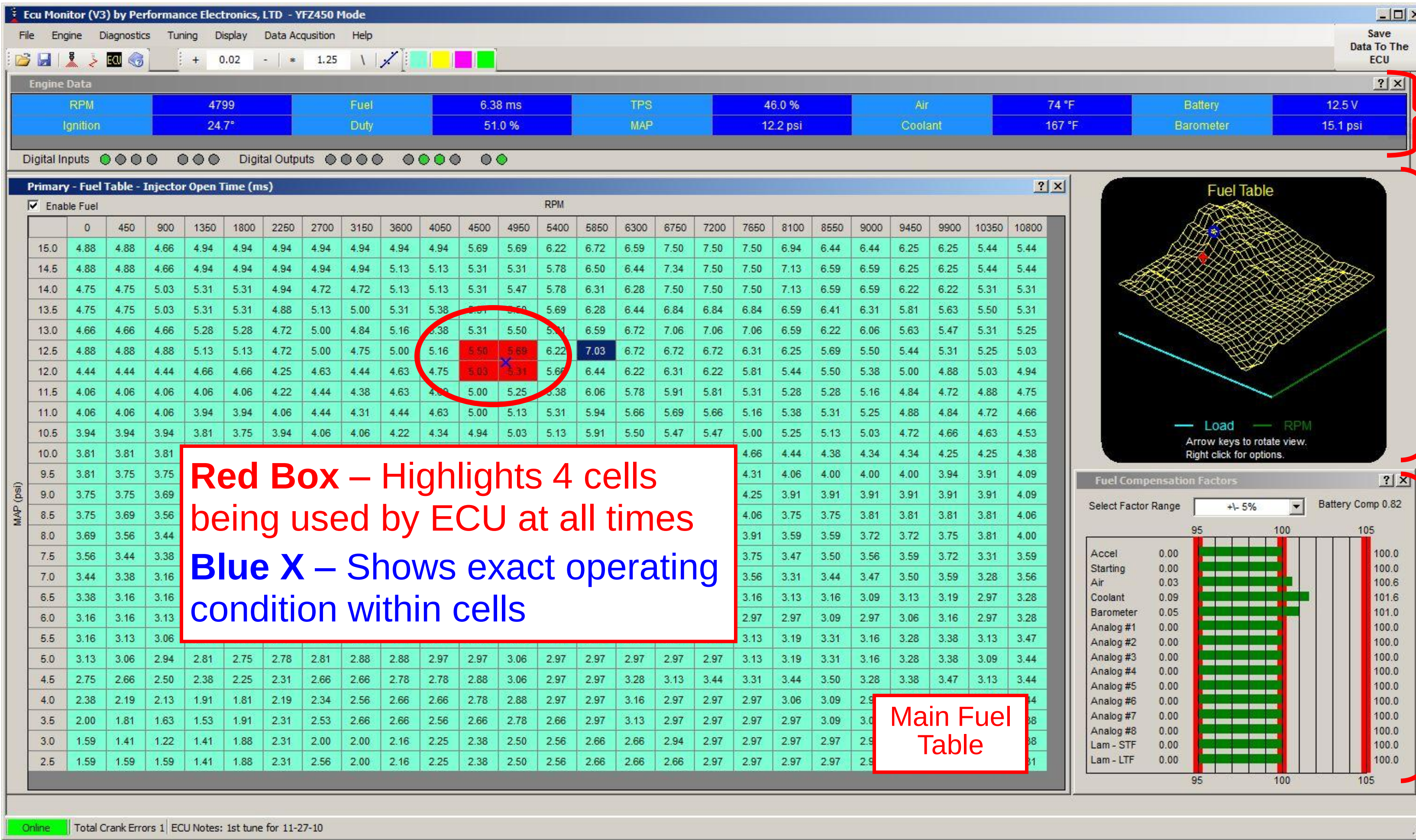
3) **Tune main ignition table**

Must iterate to best "tune"

4) Add in additional compensation (air, coolant, starting, etc.)

5) Setup additional inputs and outputs (idle air, fuel cut, secondary rev limiter, etc)

4) Engine Tuning – Main Fuel and Ignition Tables



Current Engine Conditions

3-D Table View

Bar Graph of Comp Terms

Main Fuel Table

4) Engine Tuning – Overview

Successful Engine Tuning

1) General ECU setup (engine type, # cylinders, sensor setup, etc)

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} ***Must iterate to best "tune"***

4) Add in additional compensation (air, coolant, starting, etc.)

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4) Engine Tuning – Temperature Compensation Terms

Air Temp Compensation - Fuel

Load - TPS (%)	Compensation Factor - Percent							
80.0	125.0	116.0	108.0	100.0	93.1	86.8	81.0	77.0
60.0	125.0	116.0	108.0	100.0	93.1	86.8	81.0	77.0
40.0	125.0	116.0	108.0	100.0	93.1	86.8	81.0	77.0
20.0	125.0	116.0	108.0	100.0	93.1	86.8	81.0	77.0
Temperature (°F)	-40.0	0.0	40.0	80.0	120.0	160.0	200.0	240.0

☑ Enable

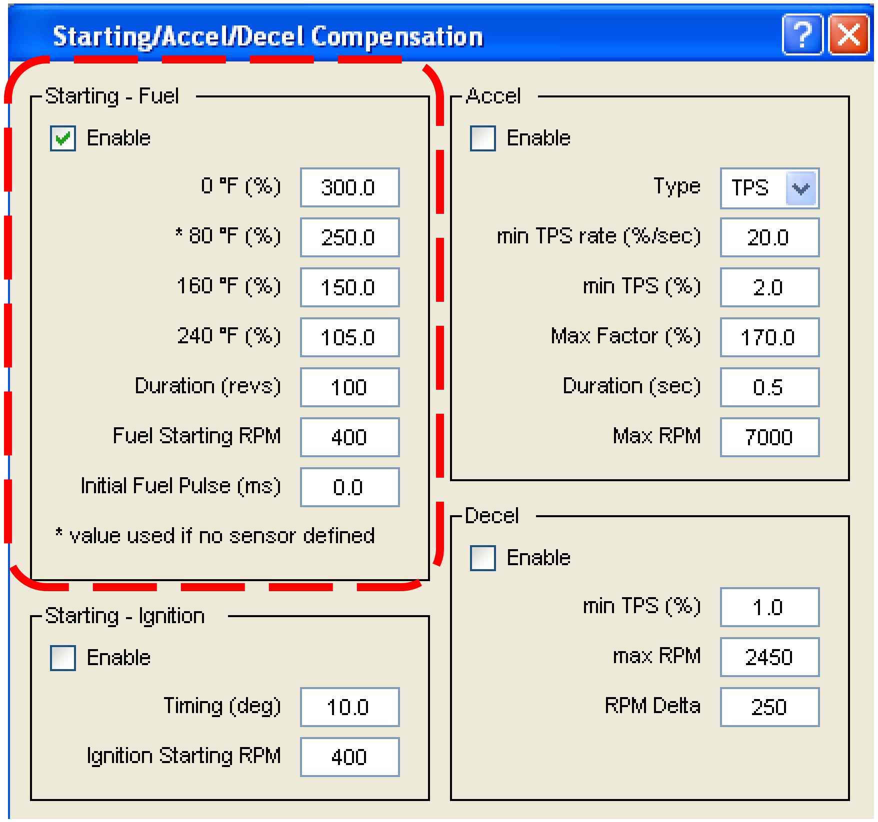
Coolant Temp Compensation - Fuel

Load - TPS (%)	Compsensation Factor - Percent							
80.0	200.0	200.0	175.0	150.0	125.0	100.0	100.0	100.0
60.0	200.0	200.0	175.0	150.0	125.0	100.0	100.0	100.0
40.0	200.0	200.0	175.0	150.0	125.0	100.0	100.0	100.0
20.0	200.0	200.0	175.0	150.0	125.0	100.0	100.0	100.0
Temperature (°F)	-40.0	0.0	40.0	80.0	120.0	160.0	200.0	240.0

☑ Enable

- 3-D Tables
- 100% = No modification for fuel compensation terms
- Air temp fuel compensations can be approximated using Ideal Gas Law (PV=nRT)
- Coolant temp compensations are determined through testing

4) Engine Tuning – Starting Compensation Terms

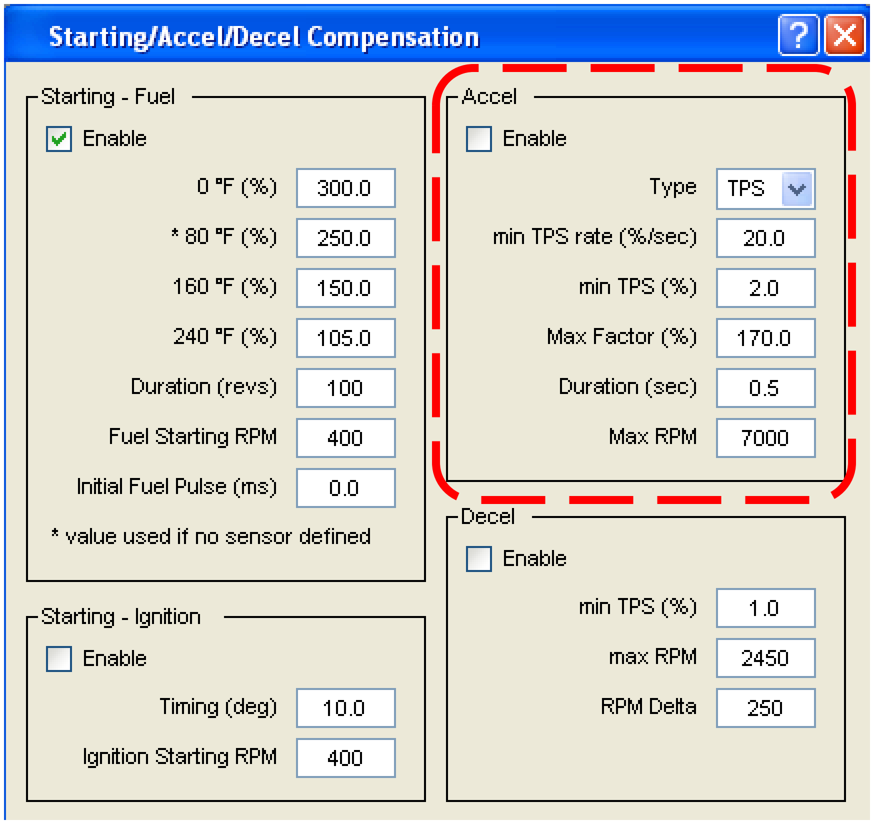


- **0°F, 80°F, 160°F, 240°F** – Compensation factors at coolant temperature values. Applied as long as the RPM is less than **Fuel Starting RPM**.

- **Duration** – The number of revolutions that the compensation decays over once the engine is above **Fuel Starting RPM**.

- **Initial Fuel Pulse** – Length of time the injectors are opened for a priming pulse on the first revolution.

4) Engine Tuning – Accel Compensation Terms



Type – Choose Map or TPS

Min TPS Rate – Determines the Accel circuit's sensitivity to throttle changes. The larger the number is, the less sensitive the circuit is.

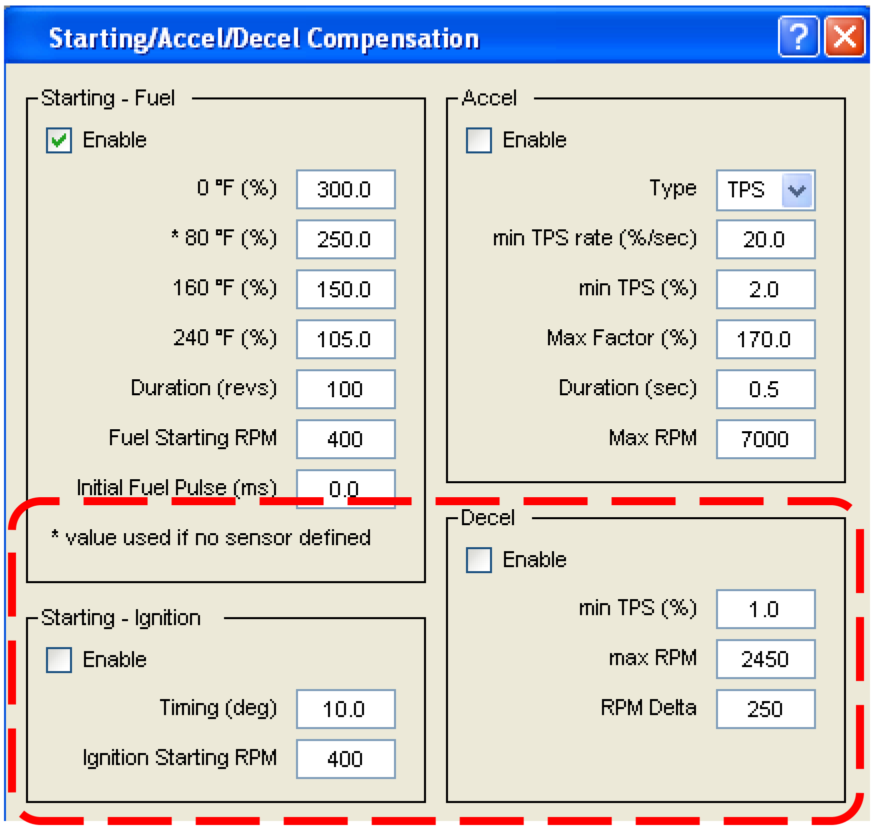
Min TPS – This is the minimum required throttle position before the Accel compensation is allowed to take effect.

Max Factor – Maximum compensation percent.

Duration – This is the amount of time that the Accel compensation degrades over.

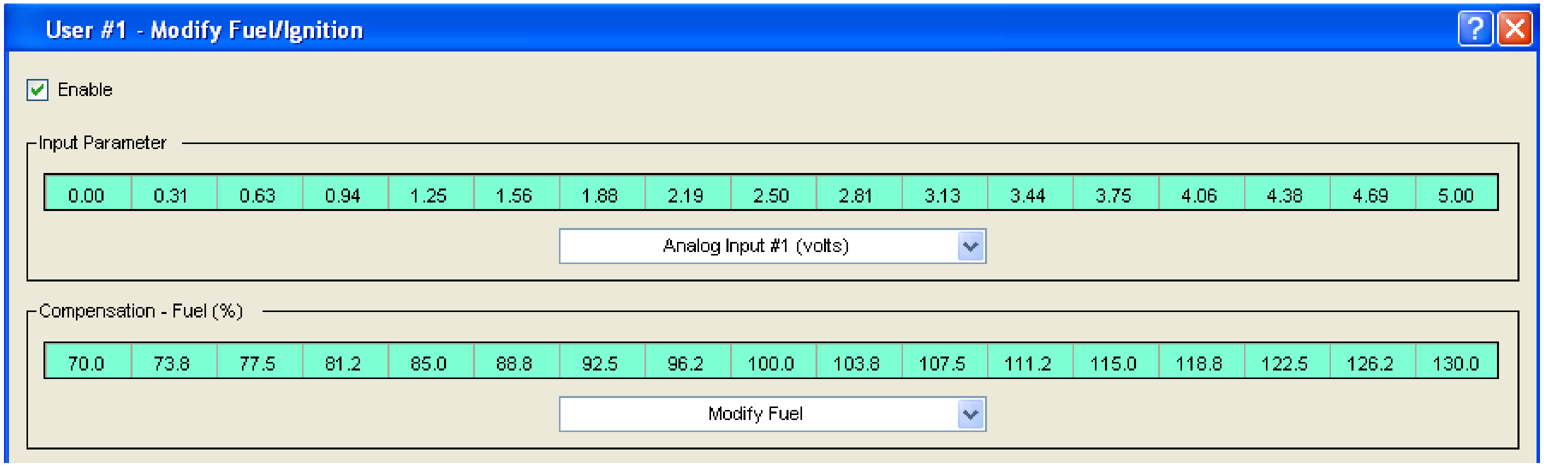
Max RPM – This is the maximum RPM allowed for Accel compensation.

4) Engine Tuning – Decel Comp and Start Ignition



- **Decel Fuel Cut-Off** – If the throttle position is less than **Min TPS** and the RPM is greater than **Max RPM** the ECU assumes that the engine is being motored and does not open the injectors until either the TPS increases or the RPM slows down to below **Max RPM – RPM Delta.**
- **Starting-Ignition** – When Enabled, this fixes the timing at specified degrees BTDC until RPM is > **Ignition Starting RPM**

4) Engine Tuning – User Inputs



- 2-D Array
- 8 User Input compensation terms that can be configured for analog inputs, frequency inputs, PWM duty cycle, IAC position, etc
- Can be used to modify fueling or ignition timing
- 100% = no modification for Fuel. 0 = no modification for ignition

4) Engine Tuning – Overview

Successful Engine Tuning

1) General ECU setup (engine type, # cylinders, sensor setup, etc)

2) **Tune main fuel table**

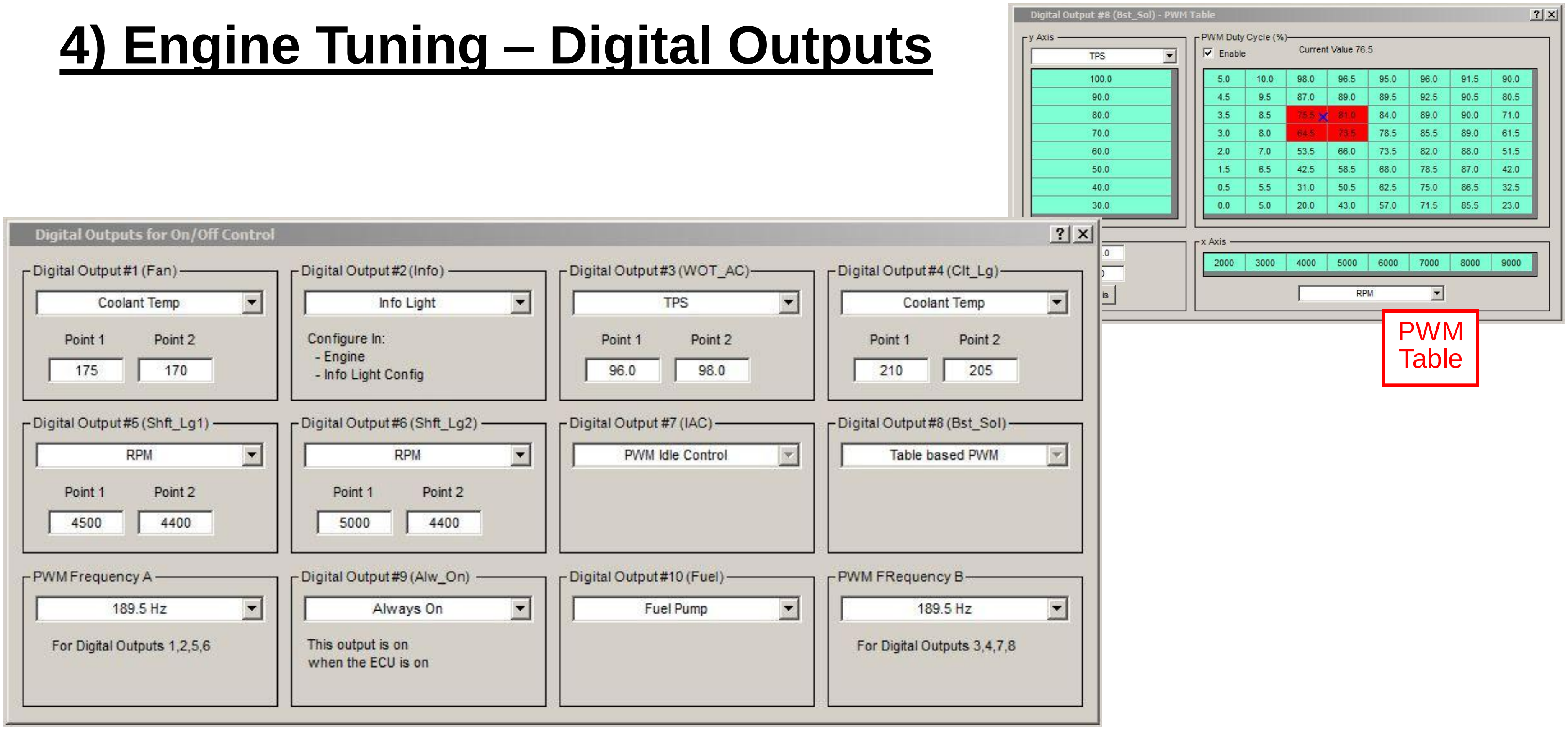
3) **Tune main ignition table**

} ***Must iterate to best "tune"***

4) Add in additional compensation (air, coolant, starting, etc.)

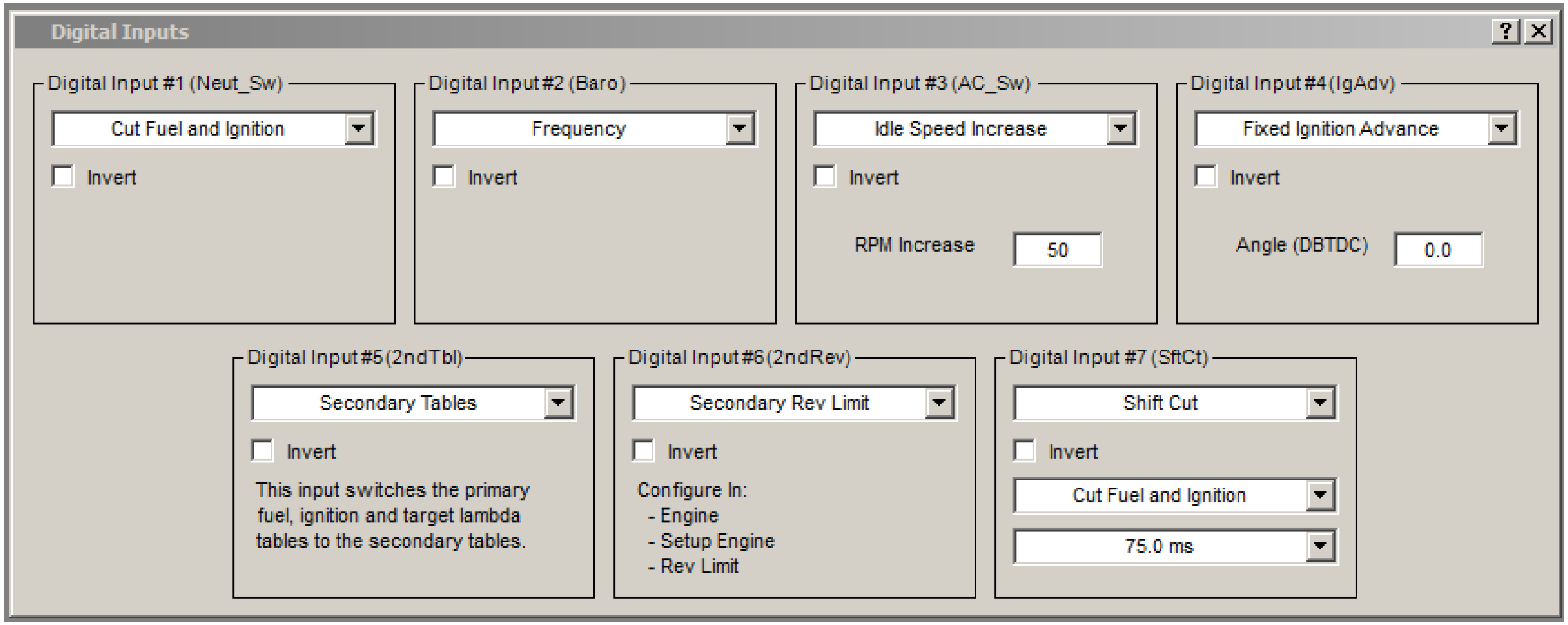
5) Setup additional inputs and outputs (idle air, fuel cut, secondary rev limiter, etc)

4) Engine Tuning – Digital Outputs



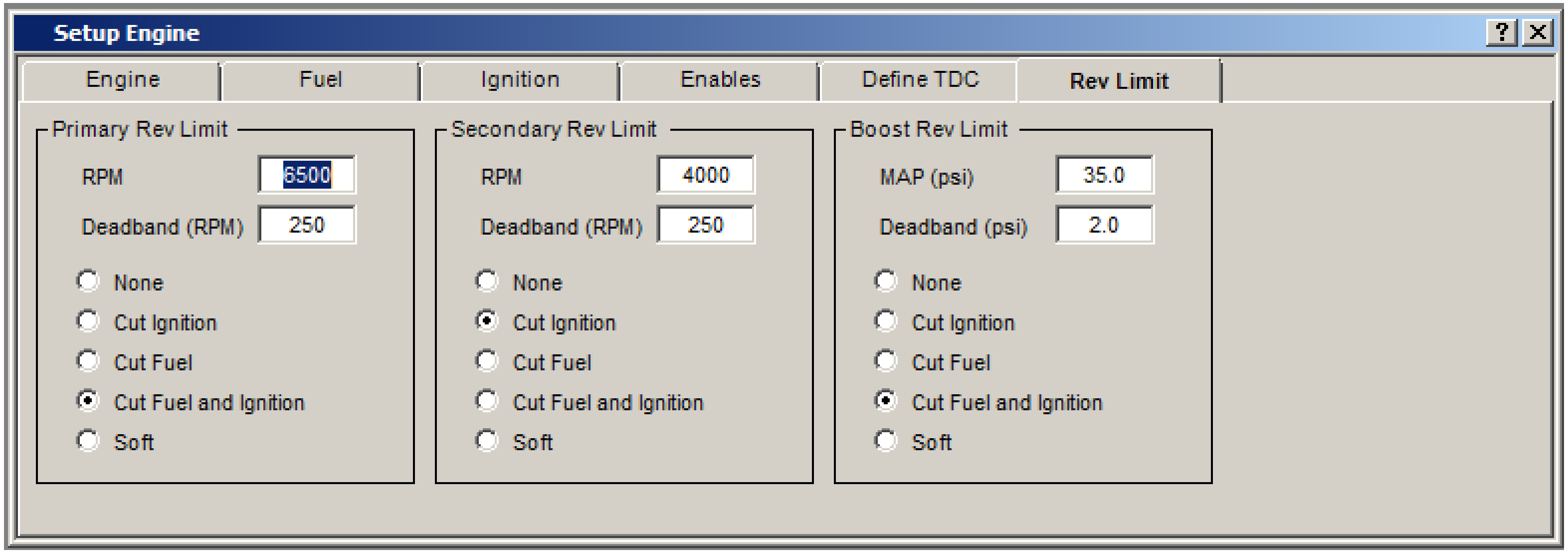
- 10 Digital Outputs, 8 can be Pulse Width Modulated (PWM) at 5 – 950 Hz
- On/Off as a function of any on-board parameter
- If PWM selected, each PWM channel has an 8x8 3D adjustable indices table

4) Engine Tuning – Digital Inputs



- *5 Digital Inputs active when pulled high (5-22 volts)*
- *2 Digital Inputs active when pulled low (< 2 volts)*
- *Can be configured to Cut Fuel and/or Ignition or to bump idle speeds, enable launch or traction control, etc.*
- *4 channels can also be used to measure frequencies (0-6000 Hz)*

4) Engine Tuning – Rev Limits



- *Can have multiple rev limits activated by MAP, RPM or Digital Input*
- *Each rev limit can be activated by controlling fuel or ignition or both*
- *Each rev limit is equipped with a **Deadband.** The rev limit is activated at the **RPM** specified, but is not de-activated until RPM drops below (**RPM – Deadband** In this case 6500-250 = 6250 RPM)*
- *The Soft option retards the timing when **RPM** is reached. If RPM still increases, then ECU will cut ignition*

Thank You and Happy Tuning!

Jeff Krummen
Performance Electronics, Ltd.
www.pe-ltd.com