Almeo
RESEARCH, LLC

Description of Diesel Engine Fuel Mapper

Part II

Ver. 1.0.

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All spreadsheet files are available upon request. Please send all comments, inquiries and requests to contact@almeotech.com

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Purpose: This report describes an electronic system performing measurements equivalent to those of brake specific fuel consumption described in the Part I report for the purpose of optimizing HHO feed rate and fuel injection for maximized fuel cost savings.

Description: This system is referred to as a Diesel Engine Fuel Mapper (DEFM) system. This instrument is installed on a vehicle and tested on the road. Instead of trying to control test conditions as would be done in a laboratory, we attempt to measure them so completely that they can be reduced down a quantitative description. This is appropriate because this must be done anyway in order to fully optimize HHO injection.

The approach is not to perform gross absolute measurement on the entire engine system as on an engine dynamometer, but to perform relative measurements on a representative part of the engine, that is, a single cylinder. In this way, the number of influencing variables are reduced down to a set that can be much more easily measured.

This technology is used in two different modes.

1. Development. Used to create a profile that characterizes the response of a given engine model to HHO injection. This procedure involves installation of special sensors on a test vehicle having the particular engine model of interest.
2. Release. The profile is downloaded into the computer controller of an HHO injection system with much simpler sensor connections on vehicles having the same model of engine.

Development mode requires installation of a pressure sensor in the cylinder head of the engine. This will entail considerable cost and effort to install such a sensor on every vehicle using this technology. It may be possible to use a downloaded engine profile data and still obtain adequate cost savings.

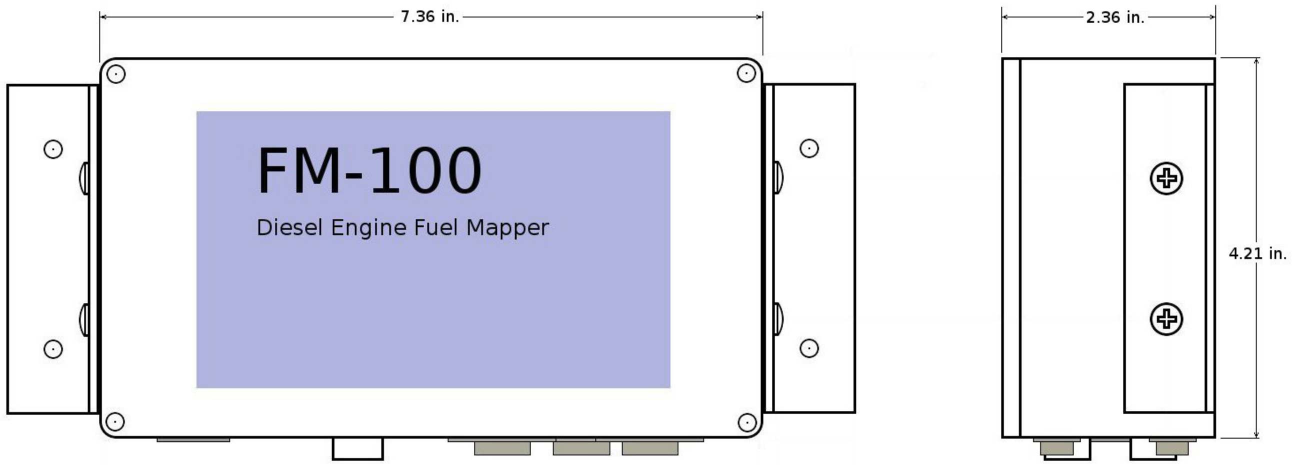
It might be possible to develop a mathematical model that describes how an engine responds to HHO injection enabling a profile to be easily derived from engine specifications. Meanwhile, profile development on test vehicle is needed to insure optimal performance over a wide range of conditions.

Installation: The DEFM system is designed for installation on more modern truck engines with ECU controlled fuel injection, a turbocharger, and six cylinders in an in-line configuration. The installation for profile development requires the following connections. Harness connectors A and B relate to items 1 through 3 of this list:

1. Fiber optic pressure transducer in the cylinder head at one of more cylinders. This transducer is designed to perform real-time pressure measurement on running engines. The fiber optic technology enables use of a relatively small transducer (3mm O.D.) which enables a simpler side mount installation. Installation requires special procedures and equipment that are described below.
2. Connection to electrical leads that control fuel injectors. Alternatively, this could be expanded to consist of a module that monitors and/or modifies injector pulses.
3. Connection to the crankshaft position sensor.

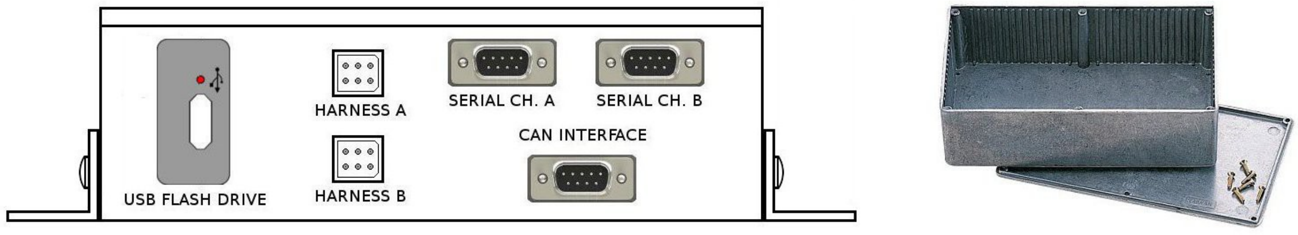
4. Connection to the CAN bus of the ECU. On a truck engine, the CAN bus protocol would probably be J1939.
5. Serial RS-232 interface to a lap top used in the cab to configure and manage test functions. Most lap tops would likely require a RS-232/USB converter.
6. Serial RS-232 interface to automatic control of an HHO generator system. Recommended generator system requirements are given below.
7. A USB flash drive is inserted into the DEFM system. This is used for mass storage of test data. This data is stored in files that can be accessed for analysis on any computer.
8. Connection to flow meter system installed on the fuel line coming from the fuel and possibly on the return line if there is one. The DEFM measures fuel injected per cycle by means of time measurements on electrical pulses to the fuel injectors and possibly pressure on the high-pressure feed lines to the injectors obtained over the CAN bus. This determination is correlated against calibrated fuel flow measurements performed by the fuel flow meter instrument [5].

DEFM mechanical drawing; The prototype DEFM system would be built using an off-the-shelf die-cast aluminum enclosure as shown in Figure 1. It would be mounted in the engine compartment. Preferably, electronic components should be rated for the automotive temperature range: – 40° C to +85° C.



Top view

Side view



Front view

Made from a stock enclosure

Figure 1. Mechanical Drawing of DEFM module.

Summary of theory: In Part I, two functions were used to estimate the effect of HHO upon vehicle fuel efficiency as expressed in gallons per mile:

- A fuel map plotting fuel consumption as a function of power output and engine speed for a given HHO feed rate and possibly other parameters.
- Engine power output as a function of vehicle speed.

By taking this two step approach, engine fuel efficiency is decoupled from vehicle fuel efficiency. Engine fuel efficiency will be largely unaffected by the many factors that affect vehicle fuel efficiency such as road, weather and tire conditions. Also, to a large extent, in any given case, these factors can be reduced down to a quantitative description, that is, engine power output as a function of vehicle speed at a specified RPM.

Both of the above functions are based on power output which is a function of engine load and speed. Engine load is obtained from a measurement of indicated mean effective pressure (imep). The DEFM performs a real-time measurement of imep by numerical integration of a plot of cylinder pressure versus cylinder volume. A system was developed by NASA in the late 70's that performed real-time measurement of imep [4]. Figure 2 is taken from the report written regarding this system. The DEFM borrows from some of the methodology described in this report.

Pressure measurement is taken using the sensor installed in the cylinder head. The cylinder volume is obtained from the output of the crankshaft position sensor. The value of the imep is given as:

$$\text{imep} = (\text{APW} - \text{ANW}) / V_D$$

where APW and ANW are the areas enclosed within the corresponding regions on the graph shown in Figure 2 and V_D is the cylinder displacement volume. Note that the units are consistent since pressure in pascals is equal to newtons per square meter. If volume is equal to cubic meters the product of pascals times cubic meters equals newton meters which is joules, a unit of energy, ($m^3 \times N / m^2 = N\ m$).

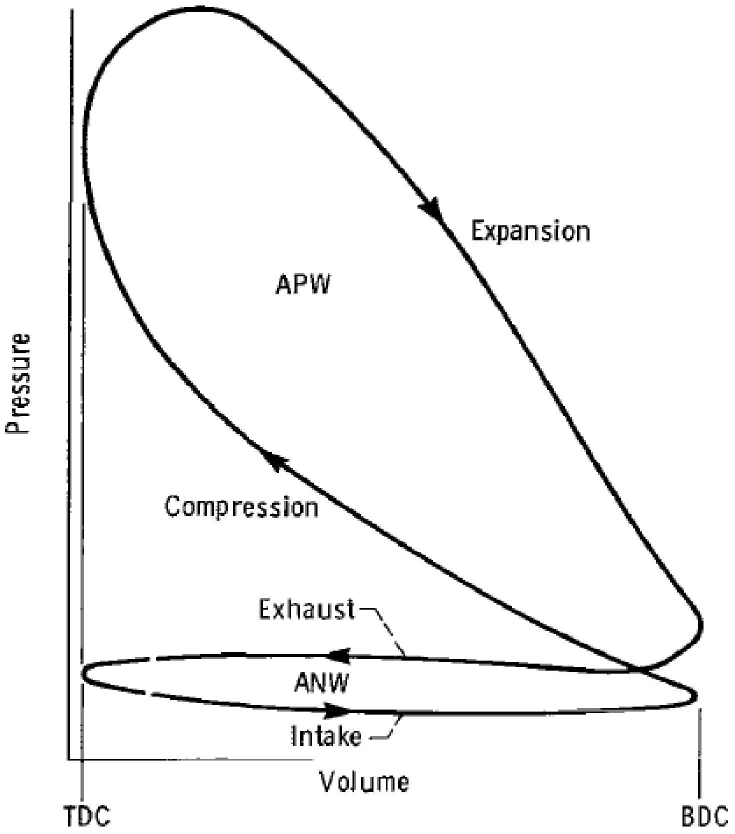


Figure 2. Pressure-volume curve with denoted enclosed areas.

A fuel map created by the DEFM will give fuel used per cycle as a function of imep and RPM. If imep and RPM are determined for a given vehicle speed, then fuel consumption can be predicted by finding the fuel consumption that corresponds to this particular imep and RPM. This would be analogous to the calculations done in Part I. However, if we already know fuel consumption and RPM, then according to this simple example, the imep value can be located on the fuel map.

Now suppose we take a series of fuel maps corresponding to different values of a parameter we wish to optimize, such as HHO feed rate. Then we compile them into a three-dimensional map that inter-relates imep, fuel consumption, HHO feed rate and RPM. This might now be applied to a system without a pressure sensor. We have three of these values: fuel consumption, RPM and HHO feed rate. Using the map, imep can be found. Then at that particular imep, we can obtain the HHO feed rate that gives the lowest fuel consumption. By checking fuel consumption at a couple of different HHO feed rates, it is possible to verify that the engine responds in a manner consistent with the data obtained on the test vehicle.

Is the imep determination necessary? An alternative arrangement for optimizing feed rate might be some sort of general purpose feedback loop that would increase or decrease HHO feed rate by a small increment at regular time intervals and determine the effect on fuel consumption. If fuel consumption goes up, then it changes direction at the next interval and if it goes down, it continues in the same direction. This might be workable if the engine were to run under a constant load at constant speed for long intervals of time. However, under normal road conditions, load on the engine is changing constantly as is engine speed. If fuel consumption changes, a general purpose algorithm would have no way to determine if it were due to a change in load, the change in HHO feed rate or combination of both. An HHO fuel map defines the response of the engine to load and HHO. Using such a map is the best way for a control algorithm to sort out the effects of different factors. Using a map, the algorithm might also have other capabilities such as being able to determine if a different gear would give better results or it could estimate the amount of fuel being saved.

There are some factors that complicate the use of this method:

1. Variability of imep from cycle to cycle under a fixed load and constant speed was observed to a considerable extent in the case of the NASA system when tested on a spark ignition system. Cycle to cycle variation for compression ignition (or Diesel) engines was not given. The average imep seems to fairly consistent but it appears that a certain number of samples must be taken and averaged in order to obtain a statistically significant estimate. Statistical tests are also needed to determine if an influencing factor exerts a statistically significant effect on the imep.

2. The air density could affect imep and response to HHO. It is known that air density affects power output of an engine. The general expression for this correction as given by Heywood [3] is:

$$P_S = C_F \, P_m$$

where P indicates power output, s subscript indicates standard conditions and m subscript indicates a measured condition. The correction factor, C_F is given as:

$$C_F = \frac{p_{s,d} \sqrt{T_m / T_s}}{p_m - p_{v,,m}}$$

$p_{s,d}$ = standard dry-air absolute pressure
p_m = measured ambient-air absolute pressure
$p_{v,,m}$ = measured ambient-water vapor partial pressure
T_m = measured ambient temperature, K
T_s = standard ambient temperature, K

It is uncertain how this may relate to HHO performance, but it is a start. Most Diesel truck engines have a turbocharger and inter-cooler. The air is heated upon compression and the inter-cooler is a heat exchanger that cools it off before it enters the intake manifold. A waste gate valve spills excess energy off of the exhaust to prevent the turbocharger from damaging the engine by overcharging it. Temperature and pressure can be controlled by offsetting the waste-gate adjustment and modifying inter-cooler flow. This would be one way to obtain preliminary data on the effect of air density on HHO fuel maps. The ECU measures ambient temperature and barometric pressure because it must adjust for cold weather and high-altitude operation of the engine. These could probably be obtained off the CAN bus in order to adjust the fuel map and speed-load curves for a different air density.

3. The cylinder temperature can effect imep. Diesel engines are very efficient so equilibrium operating temperature of the engine is fairly stable. The coolant and lubricant temperatures are generally measured by the ECU. These would probably be used to obtain a good approximation of the average temperature of the engine block and cylinder head.
4. Fuel grade might effect imep. The API grade value of Diesel fuel might be the best place to start for characterizing the quality of the quality of the fuel.
5. Composition of the inducted air might effect imep. Exhaust gas is often cooled and recirculated into the inducted air. The purpose is to reduce oxygen content of the air to lower nitrogen oxide emissions under idle and low load conditions. This may not be very relevant to the HHO fuel map since it is designed for use under moderate to high load conditions at highway cruise speeds. Relative humidity of inducted air may also effect the HHO fuel map.
6. Many Diesel engines can change the crankshaft angle where fuel injection begins. Electro-hydraulic injectors will inject a single pulse of fuel. Piezo stack injectors are able to inject more than on pulse of fuel. The DEFM monitors the signal to the fuel injector. Therefore, it can probably take this factor into account.
7. Some truck Diesels have a variable valve action. This could affect the HHO fuel map.

As can be seen from the preceding issues, a modern Diesel truck engine is very complex even when the scope of measurement is restricted to a single cylinder. The effectiveness of a multivariate optimization of HHO injection without an imep measurement remains to be determined.

To a certain extent, development of over-the-road fuel profile mapping technology will be an exploratory process. Influencing factors are identified and characterized by means of statistical analysis. That is, a factor must have a statistically significant effect on the fuel map in order for it to be included in the process of fuel map characterization. Perhaps the best place to develop engine profiles is on vehicles running over-the-road because that is where the profiles are going to be used. The various factors affecting them have to be identified and the effects must be characterized under these conditions.

Initial testing of profile development ought to be conducted at low and high temperatures, at low and high elevations, at low and high humidity, going up and down grades, running on level surfaces, on concrete and asphalt, with different grades of fuel and anything else that one might be able to think of. Somewhere on the U.S. west coast might be a suitable location for running test vehicles because the availability of a wide variety of conditions for tests.

A large number of measurements can be taken very quickly. A 4-stroke engine running at 2000 RPM will do 1000 compression/power cycles every minute or 60,000 measurements per hour. This large amount of data makes it possible to run statistical tests such as p-value in order to evaluate statistical significance of any correlations that are observed. This greatly increases the credibility of the evaluation of the fuel saving device.

Possible Test Installation: **A** possible test installation currently being evaluated is on a 2005 VW Golf TDI with a BEW series engine. Figures 3 and 4 show a possible installation on this type of engine using what is known as the Pumpe Duse injector technology.

Figure 3 shows typical installation of a fiber optic pressure transducer in the cylinder head of a 1.9L TDI engine [1] on the left side of the cylinder head. The glow plug is on the right side. The fuel injector is the center. The pressure sensor is mounted at an 8 degree angle. A glow plug-type seal is located 5.5 mm down from the thread. Between the seal and the tip, the sensor OD is 5.6 mm. In the tip, pressure is sensed by an inconel diaphragm. The pressure deflection of the diaphragm is measured by Fabry-Perot interferometry with light delivered to the tip by a pair of optic fibers. For a Diesel engine, the sensor requires a measurement range of 0-200 bar. The tip must withstand temperatures up to 400 deg. C. Such a sensor is made by Optrand Inc [2].

The tip of the sensor must be recessed somewhat because of the shallow mounting angle. However, the recess should be minimal since carbon tends to accumulate in any recess and there will a drag effect produced by air or combustion gas moving in and out of the recess. Machining the mounting hole requires removal of the cylinder head. A 6 mm hole is drilled through the head at an 8 degree angle. A block of scrap should be clamped to the exit point so that the drill makes a clean exit. Two counter bores are needed and then the hole must be tapped with a starter tap and bottoming tap. Almost any machine shop should be able to perform this procedure.

Electrical connections to an engine will vary. In the case of the BEW series engine, a current sensor is needed for the fuel injection lead and a parallel proximity switch amplifier is needed for the crankshaft position sensor. These are illustrated in Figure 4.

In addition, this system has an interface to a USB flash drive for mass data storage. There is also a serial interface for configuration and control of test test sequences. We will typically access this function using a laptop equipped with a USB to serial adapter made by B&B Electronics (costs about $30) with a special driver and an application called Hyperterm.

This system also has a CAN interface. Any engine nowadays will have some sort of CAN interface. There are various standards for Diesel engines such as OBDII or J1939. However, manufacturers will often use proprietary variants of the CAN interface which make generic access rather difficult. Volkswagen and Toyota are notorious for this practice. Nevertheless, some useful data can be accessed during a test and this can be recorded along with the rest of the data.

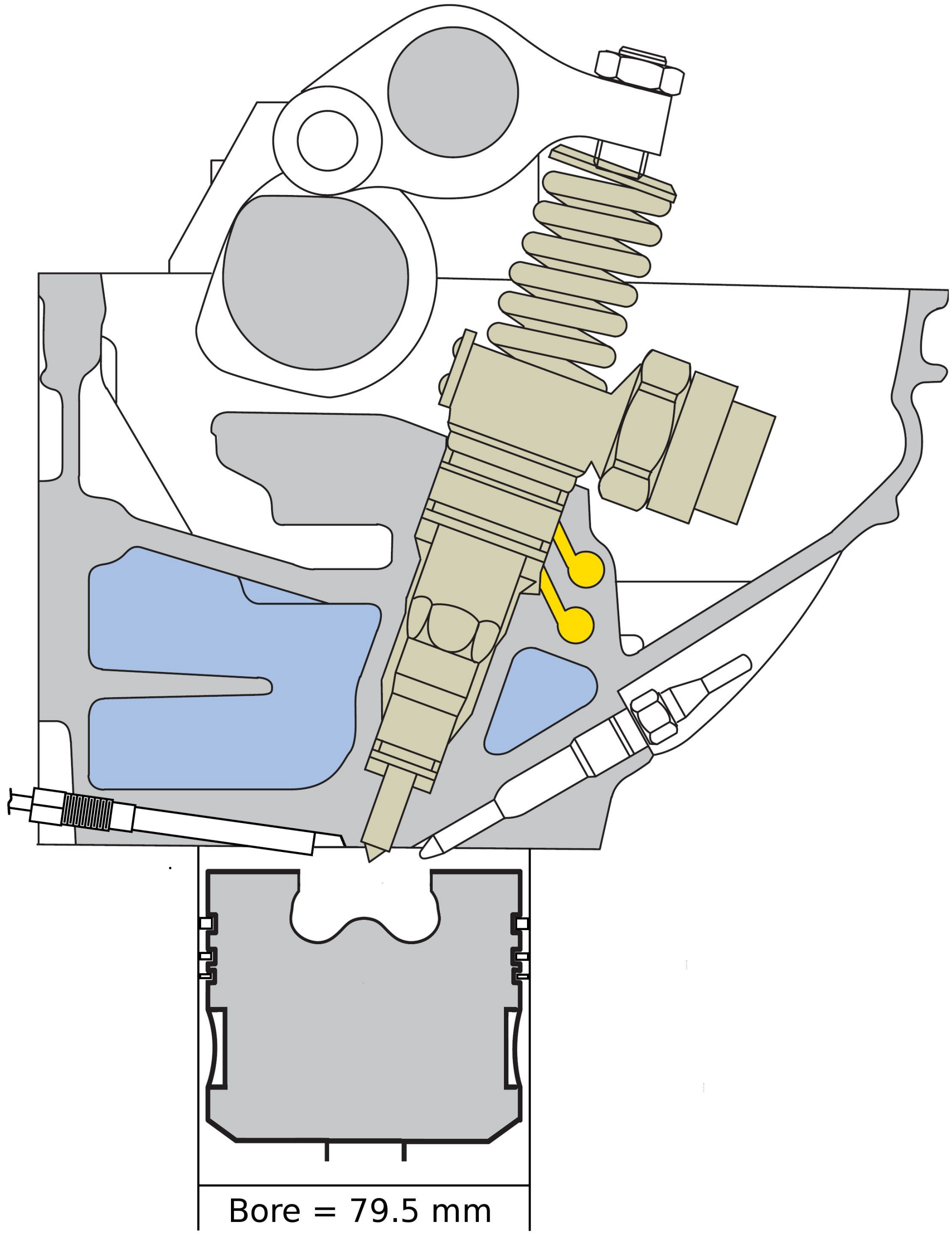


Figure 3. Installation of a pressure sensor on the left side of the cylinder head of a 1.9L BEW series Diesel engine.

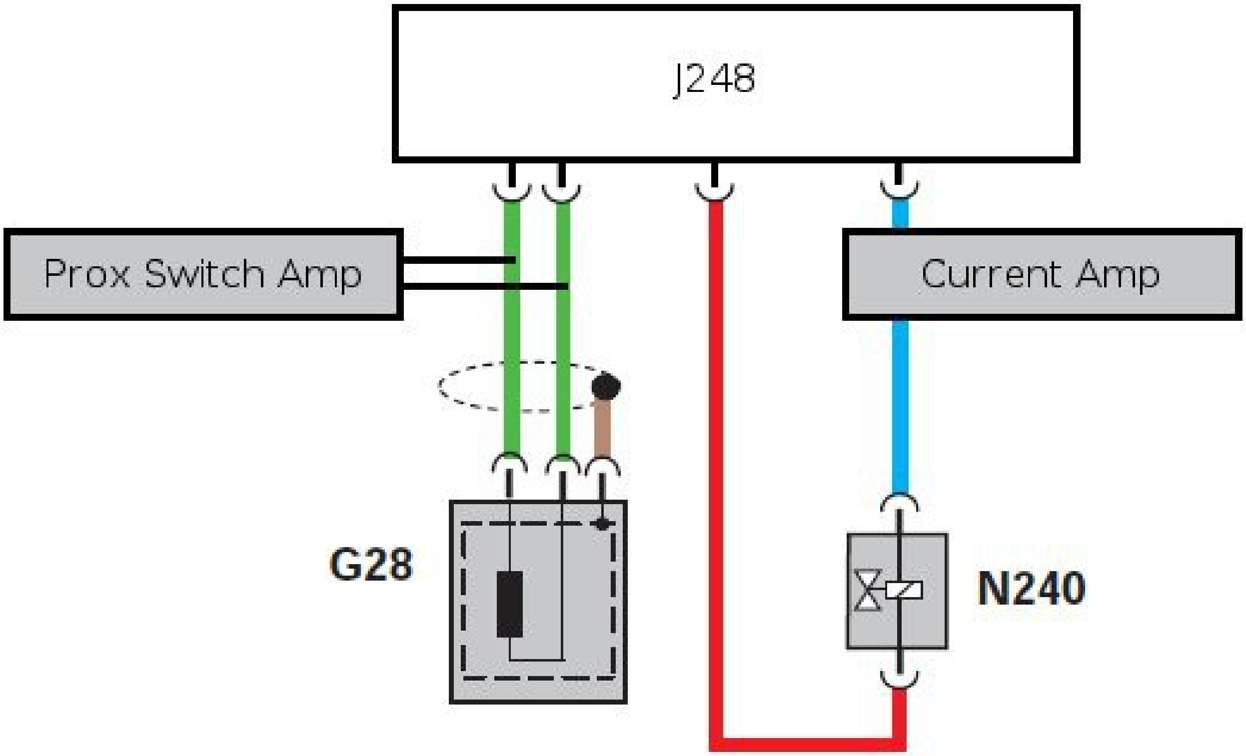


Figure 4. Electrical connections required to the engine electronics and instrumentation.

Converting crank angle to cylinder volume: One of the functions that the DEFM must perform is to convert the signal from the crankshaft position sensor to a cylinder volume. This would probably be done in software using a lookup table. The lookup table values would be calculated on the basis of the following rationale:

Heywood [3] gives the equation that defines the relationship between cylinder volume and crank angle as:

$$V / V_C = 1 + \tfrac{1}{2} (r_c - 1) k$$

where r_c = compression ratio
k = a dimensionless factor that is a function of crankshaft angle:
V = total cylinder volume
V_C = minimum cylinder volume, also called clearance volume

$$k = R + 1 - \cos \theta - (R^2 - \sin^2 \theta)^{1/2}$$

where: R = the ratio of connector rod length to crank radius
θ = angle of crankshaft rotation past TC

Since:

$$V / V_C = (V_d + V_C) / V_C$$

where V_d = displaced or swept volume, the equation given by Heywood when both sides are multiplied by V_C simplifies to:

$$V = V_C + \tfrac{1}{2} V_d k$$

Note that $k = 0$ at TC and it equals 2 at BC. Therefore, $V = V_C$ at TC and $V = V_C + V_d$ at BC as would be expected. This is the equation used by this system to convert crankshaft angle to cylinder volume.

In order to convert crankshaft angle to volume for a given engine, the displacement volume (V_d), compression ratio (r_c) , and connector rod length to crank radius ratio (R) must be determined. For a 1.9 L TDI engine, displacement is exactly 1.894 L or 0.474 L per cylinder. The compression ratio is 19.5. The piston stroke is 95.5 mm so the crank radius is half that or 47.75 mm. Center-to-center distance of the connector rod is 144 mm, therefore $R = 114 / 47.75 = 3.016$.

In the case of a VW 1.9L TDI engine, the crankshaft position indicator consists of a proximity sensor positioned near a gear-like target with 60 tooth positions attached to the crankshaft. Two tooth positions each at TC and BC are empty. Thus, there are 60 – 4 pulses for each crankshaft revolution.

If there were a single pulse per revolution, a computer device could easily perform an interpolation of crankshaft angle within this interval. However, this would be problematic for some engine control purposes due to some variation of the instantaneous rotational speed of the crankshaft.

Proposed Procedure for Installing a pressure sensor in the cylinder head. For most installations we are proposing that the sensor comes in sideways at a shallow angle, through the thickness of metal in the cylinder head that is adjacent to the engine block. Diesel engines produce peak cylinder pressures of 3000 psi at high temperature. Cylinder heads are generally made of aluminum so a substantial thickness (>18 mm) is going to be required. Also, the sensor is very small. Usually a 5mm OD sensor will be adequate so there is ample clearance to send a pilot hole in through this section of metal.

A large ½ in. thick aluminum plate should be used as a common base for the cylinder head and a small drill machine. Both are bolted to the aluminum plate. The drill machine consists of a compact air or VFD motor turning a spindle to which a drill chuck is inserted. This assembly rides up and down on linear bearings on a parallel pair of precision ground rods. The parallel rod assembly is connected to a bracket that can be bolted to the aluminum base plate. A hand operated rack and pinion mechanism could be used to move the drill motor assembly up and down on the guide rods. The guide rod assembly can be tilted at a slight angle upon an axis parallel to the base plate.

The pilot hole will generally be drilled from the outside in towards the cylinder chamber. If necessary, a block of some kind should be clamped against the bottom of the cylinder head at the point where the drill bit emerges from the metal. Otherwise, it may chatter, jam, and break. And we really don't want a broken drill bit in a hole going through a cylinder head.

The base plate should have an area cut out underneath the one of the cylinders. This allows us to clamp a block up against the cylinder head at the exact spot where we want the hole is emerge. Next we follow this procedure:

- Unbolt the cylinder head from the base plate and remove.
- Spot the drill machine on the clamp block
- Bolt the cylinder head to base plate at the exact same position.
- Use a countersink bit to spot the entry point on the outside of the head.
- Change to a long pilot drill and carefully drill the pilot hole.
- Counter bore and tap.
- Blow it out and install the sensor.

To perform this procedure, the cylinder head has to be taken off and put back on. With air-powered impact wrenches, rachets, an electric hoist and a a bit of practice, a machinist and a mechanic will be able to get the whole thing done in a couple of hours.

As was stated above, it might be possible to develop a technology that performs an adequate optimization without the need for a sensor installation. The intent is that sensors are installed on test vehicles only. If it turns out that a pressure sensor is needed on all vehicles for a good quality optimization, large scale sensor installation would not necessarily be unworkable. The fiber optic sensors are about $500-$1000 depending on the quantity.

Fuel map procedure. There are various procedures that might be used to collect fuel map data. Simply going up to speed through the various gears will run the engine through a combination of loads and speeds. Figure 3 shows positions on a plot of bmep and RPM at 2 mile per hour increments obtained from the spreadsheet used to generate the speed-load curve shown in Part I. Heywood [3] gives the equation for mep in U.S. units as:

$$\text{mep (psi)} = \frac{\text{P (hp)} \times 2 \times 396{,}000}{V_d \text{ (cu. in.)} \times \text{RPM}}$$

where P = power and V_d = displacement (12.7 L x 61.024 cu. in. per L = 775). The seven tracks correspond to the top seven gears of the ZF Meritor transmission used as an example in Figure 5 of Part I. Tracks are labeled by gear ratio of the corresponding gear in Figure 5.

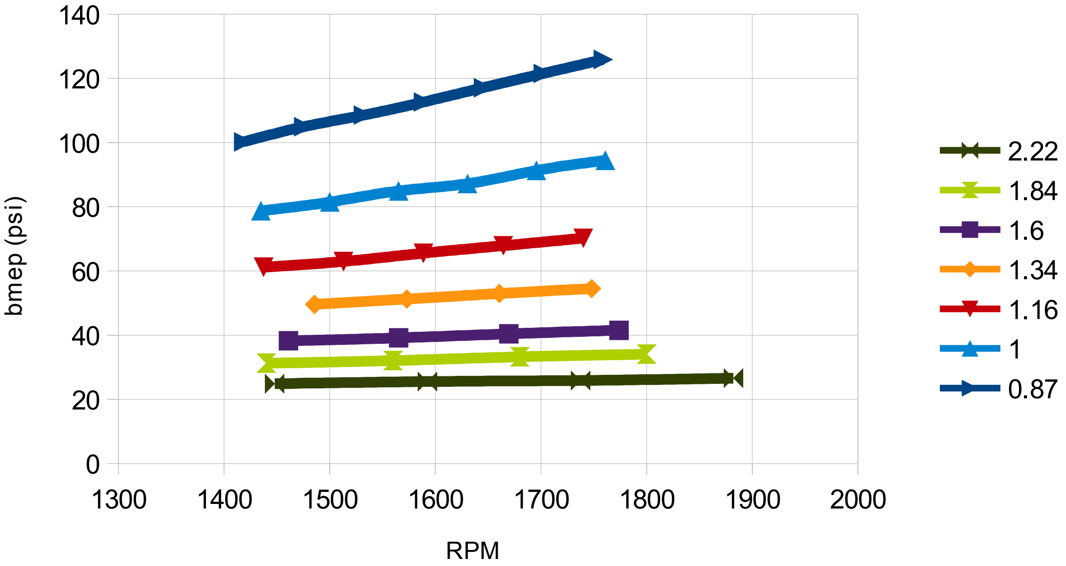


Figure 5. Tracks through the bmep vs. RPM space for various gear ratios of the sample transmission.

As can be seen, a fairly good coverage of the bmep space can be obtained. Additional tracks can be produced by variation of the rate of acceleration.

Vetting: There exists a lot of skepticism about HHO. However, an investor or venture capital firm would keep in mind that if they wait until HHO gains a more mainstream acceptance, a certain amount of opportunity for investment will have closed. One way to manage risk would be to have the product development team work with a third party that will vet their work. Vetting procedures will help ensure that testing and design methodologies are valid and that data is not being misinterpreted or unintentionally misrepresented.

Vetting procedures might involve use of instrumentation such as digital oscilloscopes or data loggers in parallel with the fuel mapper and fuel flow meter. Then there would be two or more independent sets of data that could be compared against each other. The performance of the fuel mapper could also be characterized against a digital oscilloscope using a bench top test fixture and procedure.

A number of professional engineers or engineering firms could perform this function. They might prefer that any reports they prepare remain confidential since any affirmation in the report might be misconstrued as an endorsement of the viability of HHO technology and possibly affect their credibility as an engineering firm. Hopefully, if HHO gains greater acceptance, they would be more willing to accept credit for their role in the development of the technology.

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