Model for optimizing performance of HHO gas injection on Diesel engines

by Charles Ware

Abstract: Laboratory and field data is analyzed that indicates a spike in efficiency increase under certain conditions when HHO gas is injected into a Diesel engine. A simple model is developed that defines engine speed, load and gas flow rate conditions for this spike. The possibility of using this model to improve fuel efficiency of Diesel vehicles is briefly considered. Prior to developing a retrofit technology, however, further laboratory testing should be conducted to validate these results. Various experiments that should be included in this evaluation are described. Use of this optimization model may enable a consistent efficiency increase of over 30%.

Background: HHO is a gas mixture of indeterminate composition containing hydrogen, oxygen, and water vapor. It is produced by water electrolysis and is purported to increase efficiency of internal combustion engines when fed into the air intake. This effect serves as the basis for various retrofit products. Class 8 Diesel vehicles[*], in particular, use sufficient amounts of fuel to justify a cost of over 5,000 USD for hardware and installation. This provides an adequate margin for manufacturing and testing of professional quality levels. Average savings typically observed are about 15% [1] compared with 30% that may be possible using an optimization model.

Laboratory data: On February 25, 2010 tests were conducted a 2004 Series 60 12.7 L Detroit Diesel engine at the engine lab of the University of Northwestern Ohio[2]. Brake specific fuel consumption was measured at 4 loads, 2 speeds, and 3 different current levels supplied to an electrolytic gas generator by a regulated current source (battery chargers). The reactor current levels were 32 and 46 amps and 0 amps to provide the baseline. The data is shown in Table 1.

Hp	RPM	0 amps	32 amps	46 amps
100	1400	0.639	0.556	0.472
	1800	0.722	0.597	0.618
200	1400	0.986	0.840	0.938
	1800	1.167	1.042	1.021
300	1400	1.375	1.375	1.375
	1800	1.694	1.424	1.514
400	1400	2.042	1.910	1.854
	1800	2.049	1.993	1.590

Table 1. Kg fueled used during a 2 minute test run

* Class 8 has a Gross Vehicle Weight Rating (GVWR) of 33,000 lbs. Or more

Analysis: The spike effect is illustrated in plots of efficiency increase versus baseline efficiency in Figures 1 and 2. The baseline efficiency of the engine varies with speed and load. This efficiency value is actually fuel conversion efficiency assuming a lower heating value of 43.4 MJ/kg for Diesel fuel. Heat conversion efficiency is the fraction of total energy latent in the fuel that is converted to useful mechanical output. Baseline efficiency is plotted on the horizontal axis. As can be seen, it varies from about 0.28 to just below 0.44 which is typical of a Diesel truck engine.

The percentage increase in efficiency resulting from the HHO injection is plotted on the vertical axis. At the maximum efficiency value of 0.44, HHO actually has no effect on engine efficiency. On this plot, the increase is slightly negative because the load of the electrolytic reactor was taken into account. The voltage was assumed to be 14.4 volts and the alternator efficiency was assumed to be 55%. On both plots, at about 90% of optimal efficiency, the percentage increase spikes.

The linear plot of the lower six data points is determined by a least squares linear regression. There are actually 2 spike points. The points at lower efficiency do not produce as great of an increase because they start with a lower efficiency. The points that occur at 0.39-0.4 is of more interest since it results in a higher overall efficiency.

Because the two plots follow the same pattern, they tend to corroborate each other to the extent that it is unlikely that the two spikes of main concern are outliers resulting from some measurement or calculation error. All calculations are done in spreadsheets located on-line[3].

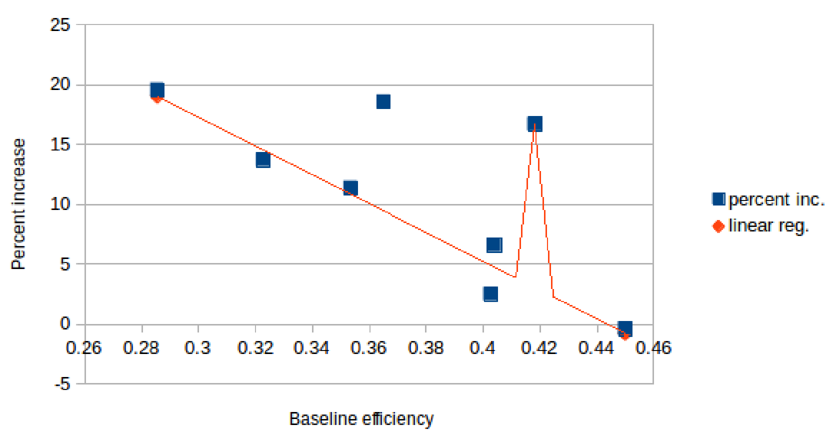

Figure 1. Percent increase in efficiency vs. baseline efficiency. 32 amps

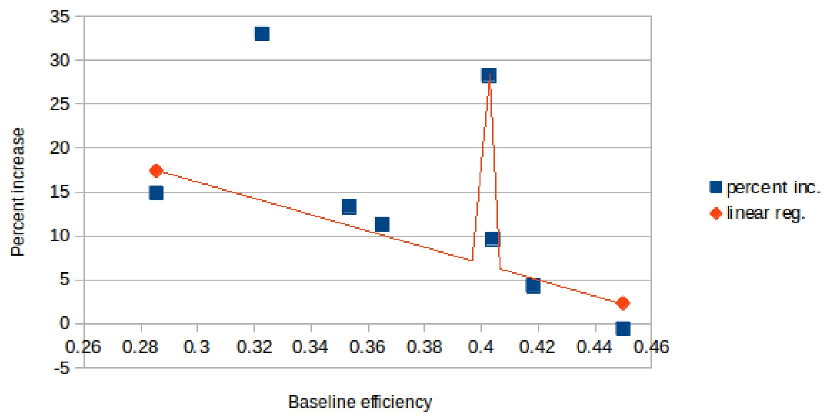

Figure 2. Percent increase in efficiency vs. baseline efficiency. 46 amps

Both points are at about 90% of optimal efficiency. Being around 90% of optimal efficiency is perhaps a characteristic of the spike for any current between 32 and 46 amps. Assuming this interpolation is an approximately linear function, it is possible to develop a rough optimization model shown in Eqn 1a and 1b. If the load on the engine in Hp is known, then RPM is given as:

$$RPM = 2\ Hp + 1000 \qquad \text{Eqn. 1a}$$

Reactor current I in amps as a function of RPM shall be:

$$I = 0.035\ RPM - 17 \qquad \text{Eqn. 1b}$$

Field data. In various field tests of HHO systems, maximum percent decrease values are often obtained that are considerably higher than the average decrease value.

	F350 6.4	Dodge 5.9	GMC 5.2
baseline	17.655	18.784	24.69
average	14.232	15.617	21.25
min.	12.082	13.092	18.45
percentage decrease			
average	19.39	16.86	13.93
max.	31.57	30.30	25.27

Table 2. Evaluations on Diesel pickups.

Table 2 show a distribution of values from an evaluation done on pickup trucks[4]. Fuel values are liters of fuel used on a 100 km test run. In each case, the average value is based on six runs. The maximum value obtained is excluded from the average. These calculations are available online[5].

Another evaluation was done by Innovative Hydrogen Solutions[6]. This extensive evaluation consists of 7 highway driving and 12 city driving trials. Fuel consumption was measured gravimetrically with a weigh tank. Each trial consisted of an average of tests lasting 11 and 15 minutes for highway and city driving respectively. Baselines were established. The double tailed t-test p-values for all trials were under 0.0001 indicating a wide margin of statistical significance. An average reduction of 30.96% occurred on the highway trials with a maximum value of 38.37%. The average value for city trials was 11.51%. However, on Oct 13, 2005 a city trial of 15 test runs gave a result 2.05% higher than the baseline. It turns out that the hose to the engine had been disconnected. On Oct. 18, 2005, 12 trials were run and an average reduction of 25.65% occurred. On Oct. 21, another run of 7 tests was conducted and the average reduction went back down to 11.34%. This indicates the possibility that a slight shift in engine response can produce a large change in the efficiency increase which would be consistent with a spike response model. It should be noted that the test vehicle was a “semi” tractor without the trailer. The HHO flow rate was about 1 LPM but was not measured precisely for the purpose of these tests. Still, these trials clearly show that increases of over 30% are quite possible under certain conditions.

These results are not definitive. However, they are examples of a common observation in field testing of a high degree of variability in the efficiency increase that would indicate some sort of sensitivity to input parameters consistent with a spike response model.

Optimized retrofit technology. Designing a retrofit technology based on this spike effect would essentially be an optimization problem. Two input variables that can be adjusted are HHO gas feed rate and engine RPM. The output variable that is to be optimized would be fuel efficiency. This would be expressed in gallons per mile (GPM). The GPM value is preferred over its inverse, the MPG value because GPM is proportional to fuel costs. Minimizing fuel costs (or GPM) would be the main concern of the vehicle operator.

The device would use a bypass of the accelerator position sensor so that it could regulate RPM and would function something like a cruise control system except that it would regulate the vehicle speed for optimal fuel efficiency. The load on the engine will change continually under most highway conditions due to ever changing terrain, pavement and aerodynamic conditions. Therefore, a computer controlled feedback loop would make needed adjustments to the HHO gas feed rate and the engine speed. The optimization model used by computer software to make these adjustments would be something like the functions giving in Eqns. 1a and 1b. More details of this system are described in another report.[7] Optimization for low speed marine Diesels is also described[8].

Additional lab tests. Before under taking development of an optimized retrofit technology, it would be very appropriate to go back to the lab and take a much closer look at this spike effect. Such tests should include the following:

- A higher resolution plot of the spike at several speeds between 1400 and 1800 RPM would be helpful. The width of the spike would indicate the sensitivity of the regulation and thus the amount of precision that is needed. The UNOH tests were of such low resolution that the actual maxima of the spike is probably higher than the peak points that were recorded.

- The engine should probably be outfitted with more temperature sensors, particularly, a thermocouple in the exhaust manifold just upstream from the turbocharger. Waste energy is dissipated through two main pathways: (i) heat loss through the coolant, lubricant and engine block radiation, (ii) through the exhaust. The increase might draw from either of these two paths. Most researchers feel that the increase is some sort of pressure effect, therefore, more energy would be drawn from the exhaust. This could be useful for developing a practical retrofit system since exhaust temperature may combine precision with responsiveness.

- A pressure sensor should be installed in the heads of one or more cylinders. There are piezo sensors designed for this purpose and lower cost fiber optic sensors are also available. A digital oscilloscope should be connected to this sensor as well as the crankshaft position sensor. This data can be exported to generate indicator diagrams. These will give some insight as to why the effect occurs. Some researchers feel that HHO increases the rate of combustion. If this is true, peak pressures will be higher and they may exceed design limits of the engine, particularly at the spike maxima. Current probes should also be clipped onto the leads of the injector pump on the cylinder being tested in order to estimate the amount of fuel injected on each cycle.

- A diagnostic scanner should be connected to the ECU of the engine. A full read out should be obtained at regular intervals for general reference. In particular, the intake manifold boost pressure should be monitored. If energy is being drawn from the exhaust, then the boost pressure may drop particularly at the spike.

- Researchers who have considered the composition of HHO have generally proposed the presence of some quasi-stable component derived from water[9]. A simple experiment would be to run the gas stream through a drying tube containing dessicant which would presumably remove water vapor as well as any water related components. If this causes the effect to vanish, then the effect may have more to do with water than hydrogen. Further investigation could lead to lighter, more compact and more efficient technologies that do not even require electrolysis.

Additional comments: Some might question the validity of the UNOH data. The data were collected in a university engine lab by a qualified technician. Measurement of brake specific fuel consumption is routine for such a lab. If the same equipment in the same lab was being used to investigate a more conventional topic, the data probably wouldn't be questioned. Although these results could be more definitive for various reasons, they are still indicative of the need for further investigation.

To say that the results violate the laws of thermodynamics is misguided. Efficiency of Diesel truck engines almost never exceeds 50%. So, there is certainly the possibility for improvement. The laws of thermodynamics do not prohibit increasing the efficiency of an engine. In fact, increasing the efficiency of heat engines was a main motivation for formulating the laws of thermodynamics.

Explanations of the effect of HHO often refer to the high flame speed of hydrogen. This is problematic since the combustion in a Diesel engine is mostly a diffusion type[10] and the rate of combustion is largely unaffected by flame speed. Instead, the rate of combustion is limited largely by the rate at which fuel vapor diffuses into air to produce a fuel-air mixture within combustibility limits. Combustion in spark ignition(SI) engines is a pre-mixed type. It is a very different process. Taking data on an SI engine and applying it to Diesel or compression ignition (CI) engines and vice versa is a questionable rationale. An early study on increasing efficiency of (SI) engines by injecting hydrogen was sponsored by NASA[11]. Most of the idea about flame speed can probably be traced back to this study. The main difficulty with referring to this study is that the maximum energy yield was only 15 kJ/g H_2[12], far short of at least 100 kJ/g H_2 needed to produce the hydrogen.

It is also said that the efficiency increase occurs because of improved combustion efficiency. Combustion efficiency on a Diesel engine is generally very high (>98%) while fuel conversion efficiency* is generally less than 50%[13]. Even if combustion efficiency were increased to 100%, it would have little effect on fuel conversion efficiency.

The small proportion of HHO used (about 8-10 grams of H_2 per hour)[14] would suggest that it acts more as a catalyst rather than a reactant. A catalyst reacts with various intermediates in a reaction, however, the net concentration remains largely unaffected. On the other hand, the concentration of a reactant drops as it is consumed by the reaction. There are examples of combustion catalysts. Tetraethyllead (TEL), used to reduce knocking in spark ignition engines[15], is added in a proportion of only 1 part TEL to 2050 ** parts gasoline. Prof. Heywood of MIT comments in his widely used textbook that the exact mechanism of the effect of TEL is not fully understood[16].

* Percentage of total energy latent in the fuel that is converted to useful output.

** The additive formula was 1:1260 but the additive was 61.45% TEL. Thus, the actual ratio is 2050 (1260 / 0.6145).

From the standpoint of ideal gas models, there are two variables that affect efficiency. They are compression ratio and the effective adiabatic index of the combustion gas[17]. The adiabatic indexes of various gases range from about 1.1 to 1.6. It is the ratio of constant *pressure* heat capacity divided by the constant *volume* heat capacity. At constant pressure, the gas is free to expand. Thus, it does work so it absorbs more heat. A higher adiabatic index results in higher efficiency. Adiabatic index is a function of molecular degrees of freedom, which is roughly determined by the number of atoms in the molecule. Molecular species with 3 atoms have an adiabatic index of about 1.3. It is roughly 1.4 for diatomic molecules and it is about 1.6 for single atoms.
There is a significant concentration of the OH radical in a combustion process[18]. It is unstable and is only momentarily present. However, the combustion process occurs on a millisecond time scale so a spike in the OH concentration may be very brief and still have a significant effect on the process. There are ways to measure the effective adiabatic index by analyzing indicator diagrams. The indicator diagram technique was briefly referred to on Pg. 5 of this document. Rate of heat release can be estimated from a pressure volume curve for a given adiabatic index[19]. Integrating the heat release curve will give the total energy release which should be consistent with the amount of fuel injected. The effective adiabatic index can be iteratively adjusted until the calculated energy release coincides with the amount of fuel injected. These are commonly used methods familiar to automotive engineers.

There might be ways that a catalytic effect could cause a spike in OH concentration. Laser absorption spectroscopy with shock tube tests would be one way to investigate such possibility[20]. A shock tube produces a supersonic shock wave by pressure bursting a metal diaphragm. The shock wave travels down the tube, is reflected at the end and returns back. High temperatures and pressures (600-4000 K, 0.1-1000 atm) are briefly produced in a plane perpendicular to the tube axis. A laser beam across the tube will take a sample at a roughly uniform temperature and pressure on a microsecond time scale. The low pressure side of the tube can be filled with a mixture of gases to be investigated. If the low pressure side is filled with air at 1 atm and 127.1 deg. C. then n-cetane vapor pressure will be 3.37 mmHg according to the Antoine equation[21]. This produces a vapor/air mixture that is 70% lean of the stoichiometric ratio[*]. Diesel engines operate continuously leaner than this ratio since a richer mixture will produce sooting. A very small amount of HHO could be added to study its effect as a catalyst.

Developing a more verifiable scientific basis for *why* this effect occurs may lead to improvements in the technology, but it will also improve its credibility which will be helpful in getting resources to run lab tests on a wider range of equipment such as large marine, generator and locomotive engines.

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* Stoichiometric molar ratio of O_2 to cetane is 33:1. (33 / 0.70 = 47.14) Air is 21% O_2 , molar ratio of other gases to O_2 (1.00 - 0.21)/0.21 = 3.762. Therefore, partial pressure of O_2 is 158.89 mmHg. Partial pressure of the remainder gases is 596.74 mmHg. (158.89 / 3.37 = 47.14. 596.74 / 158.89 = 3.762. 3.37 + 158.89 + 596.74 = 760.00 mmHg or 1 atm.

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