Optimized HHO injection for large marine Diesels and Diesel electric generators.

by Charles Ware

Overview.

Potential: HHO is a mixture of oxygen and hydrogen gas produced by water electrolysis that is purported to increase efficiency of diesel engines when fed into the air intake[1]. An earlier report developed a model for optimizing efficiency performance of HHO injection for use with Diesel engines[2]. The model was developed from data taken on a 515 Hp Detroit Diesel Series 60 truck engine. The model was in units of horsepower and RPM which makes it specific to that particular engine. If units are converted to Brake Mean Effective Pressure[3] (BMEP) and Mean Piston Speed[4] (MPS), then the model could possibly be applied to a whole range of engine technologies. Large Diesels on ocean going ships and Diesel electric generators are two applications that use large amounts of fuel. A method such as this for producing a consistent 30% increase in the efficiency of such applications would have a large economic and environmental impact.

Limitations: The model indicates that efficiency increases drop as the engine approaches the optimal baseline efficiency*. In these applications, the range of speeds and loads are much more restricted than would be the case with a typical truck engine. They tend to stay much closer to optimal efficiency, therefore, the increases will be smaller than the 15% efficiency increase typically observed in "semi" trucks. The model also indicates that a spike in the efficiency increase occurs when the engine runs at 90% of optimal baseline efficiency. To do this, <u>marine and electrical power plants would have to be re-engineered to take advantage of the 30% efficiency increase that may be possible with HHO injection</u>. Therefore, a retrofit of HHO injection on to such systems as they currently exist, would generally not produce a 30% efficiency increase according to the optimization model.

Possible methods of re-engineering these power plants are described. Various calculations are also performed to evaluate characteristics and limitations of these systems.

* Baseline efficiency refers to fuel conversion efficiency of the engine without HHO injection.

Model application to marine propulsion systems: For optimizing marine Diesel applications, the entire propulsion system must be considered as an integral unit. Figure 1 shows a typical system that would be found on the great majority of ocean going tankers, container ships, etc.

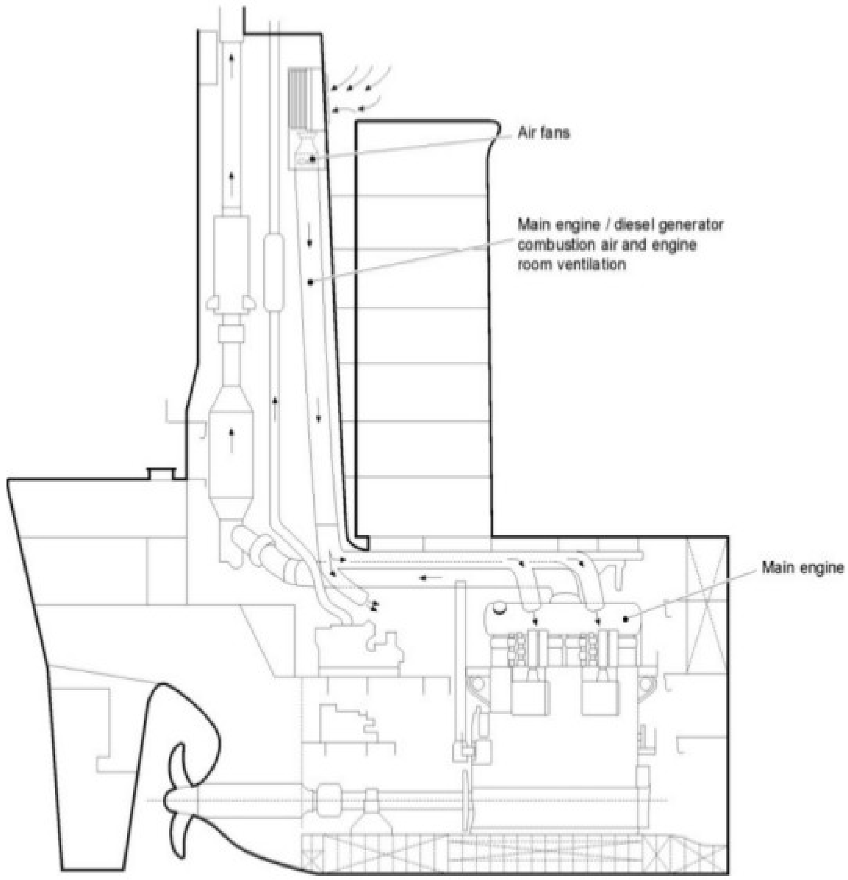

Figure 1. Layout of Diesel propulsion system and electrical generators.

The prop or screw is connected directly to the engine. The engine must therefore produce a speed/ torque combination that gives optimal efficiency matched to the screw. Conversely, it is actually the screw that determines the required power output for a given speed. To reverse thrust, the engine is capable of operating in the reverse direction. The timing of fuel injection and a single exhaust valve on each cylinder can be configured for either forward or reverse directions. Compressed air is used to start rotation of the engine in either direction. These engines are always 2-stroke. At the bottom of the stroke, ports are uncovered through which air is injected by a turbocharger system. At lower speeds, electric blowers are often used to supplement the air pressure.

The particular engine used for these calculations is an 8 cylinder Wärtsilä RTA68-D[5] Figure 2 shows a plot of bmep vs. mps for this engine as the 100% line. The optimization model can be adequately approximated by the yellow line running from point [7.47, 9.13] to point [9.6, 14.2]. If the 100% load line is multiplied by 0.65 (or derated to 65%) then it coincides with the line defined by the model. Thus, if the screw is replaced with one that produces only 65% of the thrust, the performance of HHO injection may be optimized assuming that the HHO flow rate is set properly. This illustrates the basic method used to verify the optimization model for a particular application: the line defined by the model must intersect the load line. A spreadsheet containing these calculations is found on-line[6].

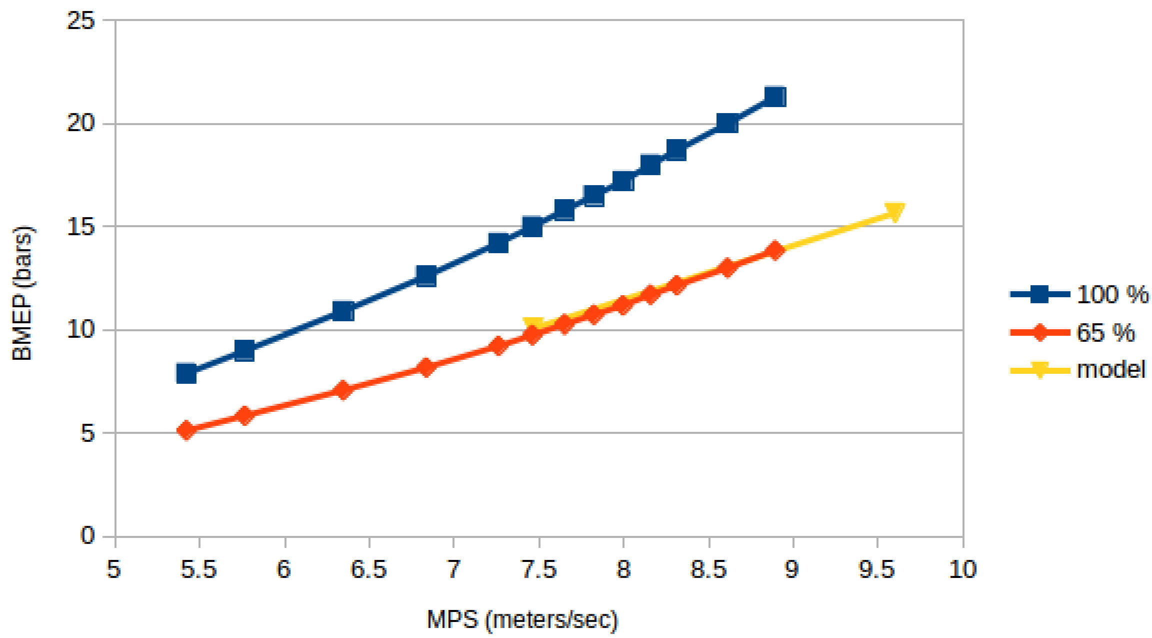

Figure 2. 100% and 60% load lines with model curve.

Replacing a screw is quite feasible. Steel hulled ships must be scraped down and repainted about every two years. For this, they go to a dry dock. It is common to replace the screw at this time. The problem is that reducing speed can be very expensive because it decreases the number of trips that can be made per year thus reducing revenue. An increase in fuel efficiency can be used to reduce fuel costs or it can be used to get higher speeds without increasing fuel costs. The economic constraints for a particular set of operating conditions can be entered into an optimization formula to solve for the best blend of fuel economy and cruising speed.

According to the model, an engine should run at a lower bmep than what is ordinarily optimal without HHO. To get the same power output at a lower pressure would require a larger engine. The engine would have to be a bit larger still in order to get additional power at the same rate of fuel consumption. Increasing the engine size of a design series prior to construction of a ship would not be so difficult. However, to retrofit an existing ocean-going ship with a larger engine would be very difficult. The engine used for these calculations has a dry weight of 593 metric tons (See reference 4). It would probably be easiest to cut the ship open at the engine room, pull out the old engine, move in the new engine and weld the ship back up. It is not unusual to do this sort of thing to lengthen a ship. However, engine replacement is not as common.

Typical installation: The model can be used to estimate the size of a system based on power output. Solving for reactor current in amps as a function of Hp gives Eqn. 1:

$$\text{reactor current (amps)} = 0.07\ \text{Hp} + 18 \qquad \text{Eq. 1}$$

There is not much information on how to scale HHO injection systems. Whether or not this equation can be used to predict current required by a scaled-up injection system is uncertain. Assuming that is can, the requirements of the electrical equipment for a ship's system would be as follows:

Power output of the RTA68-D cruising at 80% capacity is about 20,000 kilowatts. This must derated by 60% in order to be compliant with the model which is 12,000 kilowatts. Since there are 1.341 Hp per kW, that gives a horsepower output of 16,092 Hp. Plugging this into Eqn. 1 gives 1,114 amps. This is amps at 14.4 volts. This would require a power supply output of 16.48 kW (1,114 x 14.4). The Diesel generator aboard a ship might have a capacity of 0.5 to 1 MW so it could easily handle this load.

An HHO system might an HHO generator unit for each cylinder. Thus, each generator would have an output of 2.06 kW. The generator would probably use an electronic switching supply so that a computer control system could automatically adjust the output current. If the supply is 90% efficient, the input power will be 2.29 kW (2.06 / 0.9). Ship's mains are 440 VAC. Therefore, each generator will draw about 5.2 amps (2289 / 440) off the ship's mains. That would actually be considered a light duty circuit for equipment aboard a ship. It would probably be more convenient for the power supply to put out 57.6 VDC (14.4 x 4) and it would run 4 reactors in series. The reactors will draw 39.74 amps (2289 / 57.6). Reactors used for “semi” truck service could be used for this application.

This analysis indicates that building a prototype HHO injection system for evaluation purposes would be quite feasible. There are three companies that make large, low-speed marine Diesels: Wärtsilä-Sulzer, MAN Diesel, and Mitsubishi[7]. All three probably have engine test labs where large Diesel engines can be run on hydraulic dynamometers. The initial test might be conducted on just one cylinder of a test engine. Engineers would probably be very interested in the possibility of increasing efficiency by 30% but they would likely require engineering data that is much more comprehensive than what is presented here. See “Additional Lab Tests” section on page 5 of reference 1.

Comparison of energy budgets: Low-speed marine Diesel engines are more efficient than automotive or truck Diesel engines. According to Heywood, this is because friction and thermal losses are less[8]. The 8-RTA68-D has a displacement of 31,610 L compared to 12.7 L for the Series 60 engine. So the cylinder area to volume ratio for the Series 60 is vastly greater than the 8-RTA68-D. Also, total bearing area per kilowatt of power output is much greater for the Series 60. Marine Diesels are also 2 stroke whereas truck engines are 4 stroke. According to Pounder's, typical energy loss before the turbocharger is 50-55%[9]. Heywood states that exhaust energy losses for an automotive engine are 25-35%. Exhaust losses make up a larger portion of the energy lost in a marine Diesel.

If the spike response is a pressure effect, the energy to increase efficiency will be drawn from the exhaust. If that loss is proportionately larger on a marine Diesel, than the efficiency increase may be larger as well. On a 2 stroke engine, a certain amount of boost pressure in the air inlet is needed to scavenge the cylinders properly. If energy in the exhaust drops, the turbochargers may not supply adequate air pressure. Supercharging or electric blowers might be needed to supplement the air pressure.

On the other hand, if the spike response is a thermal effect, the efficiency increase is going to be smaller for a marine Diesel. Pounder's[9] gives coolant losses as 20% [*]. Coolant losses for automotive engines are listed as 16-35% [10]. There are anecdotal observations that HHO injection causes intake manifold boost pressure to drop on turbocharged equipment. That would suggest that spike response is a pressure effect.

Diesel electric generator plants: An AC generator will generally have a resonant frequency. The impedance is very low at this frequency therefore efficiency is very high. The generator can run at any speed, but if the speed does not match the resonant frequency, it will overheat under load due to reduced efficiency. A 4 pole generator running at 1800 RPM will produce a 60 Hz output. (1800 / 60 = 30 rev/sec, 4 poles produce 2 cycles per rev. 30 rev/sec x 2 = 60 Hz). On a diagram of bmep vs. mps, the load line is vertical since the engine must turn at the same speed over a range of loads.

There will be only one point where this load line intersects the model line as shown in Fig. 3. So the efficiency of the generator will be optimal at only one power level. This is an appropriate application for a doubly-fed generator. Such a machine uses a 3-phase AC with a variable frequency that is electronically generated by an IGBT-type inverter as the excitation for the stator windings. The excitation frequency is the difference between the optimal and actual frequencies that correspond to rotational speeds. Therefore, the inverter can generate a frequency that tracks the optimization model perfectly for any load.

If the generator must provide an average of 400 kW around the clock, the average efficiency is 30%, and the heating value of the fuel is 43.4 MJ/kg then annual consumption will be 484.4 metric tons of fuel. At 600 USD per ton, the annual cost will be 290,654.38 USD. A 30% reduction will be 87,196 USD annual savings. The operator of the power plant will be able to decide whether or not this will recover additional cost of equipment quickly enough.

* Pounder's Sankey diagram shows: exhaust = 50%, output = 40%, waste heat = 20%. The total = 110% but 10% is recovered and recycled by the turbochargers, so the final outputs equal 100% of the input.

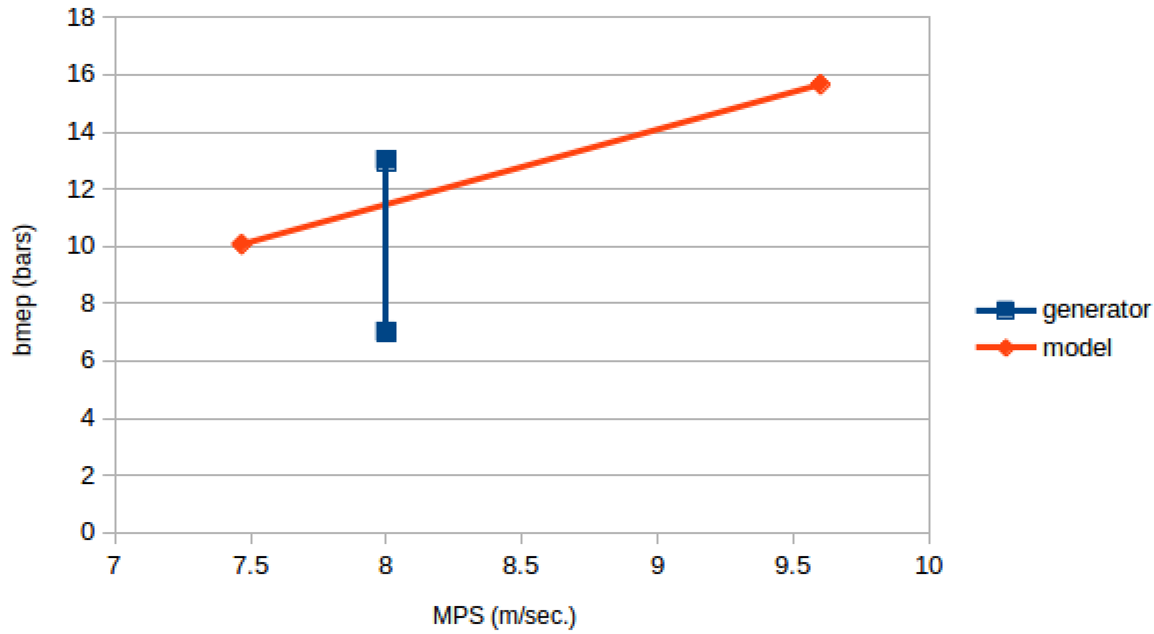

Figure 3. Generator load and model lines

Speed vs. power: These two examples show how using an optimization model produces two kinds of mismatch between optimal and actual applications: (i) in the case of low-speed Diesel engines, the load or BMEP must be changed, (ii) in the case of generators and other applications, the speed must be changed over the range of load. Doubly fed induction machines resolve the second case, but not the first.

In the case of over-the-road, heavy trucks the axle/gear ratio must be selected so that the load line intersects the model line at an appropriate highway speed[11]. This speed will vary as the vehicle goes up and down grades or travels at different orientations to the wind. Also, traffic conditions will place restrictions on vehicle speeds so that maintaining the optimal speed would be considered overly troublesome and impractical by many drivers. The use of an electric drive train with a doubly fed inductive generator on the engine would circumvent this issue.

Electric drive trains can also have the capability of dynamic breaking. The traction motors can be switched to charge a battery while decelerating or going down a grade. This makes extra power available when accelerating or traveling up a grade. This feature along with the savings that result from HHO injection could help to justify the additional cost of a hybrid electric drive train.

Calculations.
In 2011, an effort was begun to systematically analyze data about HHO that was available on-line and in the literature. Eventually, this effort also took into account data that was not publicly available. The results are described in a series of monographs available on www.hho-research.org. Reading all of them and following the overall logic is not an easy task, though. So this section will trace development of a few ideas from raw data to the figures in this report.

Scientific study of anything involves measurement. We are primarily interested in HHO and fuel efficiency, so we devised a measurement for comparing results of different tests of the effect of electrolytically generated oxyhydrogen gas mixture on Diesel engine efficiency. It is essentially a yield value of the additional amount of energy produced per gram of hydrogen gas injected. In reference 1, eight studies were evaluated. In all cases, the fuel consumption of a Diesel engine was measured at various speeds and loads running on a dynamometer. Tests were done with and with out HHO gas. In most of the tests, multiple HHO flow rates were tested. Maximum and average yields are shown in Table 1.

Study	Avg.	Max,
Bari	0.081	0.257
Birtas	0.034	0.042
Milen	0.149	0.233
FVTC	6.545	13.263
Purdue	2.639	12.415
UNOH	6.529	19.797
Wang	0.034	0.044
Yilmaz	0.541	1.054

Table 1. Energy yield value results.

This would seem to indicate that results are highly variable. It has been suggested that HHO may contain a secondary component that has a sort of catalytic effect on engine efficiency. In some cases, maximum yields were many times greater than the combustion energy of hydrogen which is about 0.1 MJ/g. The argument of conservation of energy seems to overlook the fact that Diesels are seldom more than 50% efficient. There is plenty of additional energy available here, if some way can be found to divert it from the waste streams.

The study done at University of Northwest Ohio (UNOH) seems to come closest to getting everything right. Load was automatically controlled, a feature that not all dynamometers have. The flow rate was also controlled by applying a constant current to the electrolytic reactor. The actual amount of HHO used was quite small for the engine size. Otherwise, a catalytic effect would not have been observed. The reactor was also described. It was a common duct, parallel plate, wet cell design typically used for HHO experiments. In many of the studies, specific information was not given about the electrolytic reactor, as if, this is irrelevant. The range of test results would suggest that perhaps, the design of the reactor does matter. The procedure used for the UNOH study was essentially the same as that used in the other trials. No specific reason has ever been given that would explain such large differences.

The data was available only in graphic form. An image taken from the website is found at www.hho-research.org/docs/png110/unoh.png. The vertical pixel counts of data points start at cell D5, sheet 1 of a spreadsheet found at www.hho-research.org/docs/xls120/opti_model3.xlsx. We wish to convert pixel counts into Kg of fuel used during a two minute test run. A linear equation is used:

$$\text{pixelCount}\ a_1 + a_2 = \text{Kg} \qquad \text{Eq. 2}$$

where $a_1 = -0.0069444444$ and $a_2 = 4.5138888889$.

These are obtained from solving these two linear equations which are taken off the vertical axis of the plot.

$$650\ a_1 + a_2 = 0 \qquad \text{Eq. 3a}$$
$$290\ a_1 + a_2 = 2.5 \qquad \text{Eq. 3b}$$

Column F of the table is used to test the equation by plugging 650 and 290 back in to get back 0 and 2.5 respectively. The converted Kg values begin at G5.

The objective now is to find a pattern to the data. Such patterns may reveal a relationship that could have general applicability for various purposes such as optimizing performance of injection technology. This is meant to serve as an example of how such an analysis might work, so even if this particular data may not apply in all cases, the basic method may still be useful.

We notice that there is a pattern if baseline efficiency is plotted against percent increase in efficiency. The same pattern could result from plotting equivalent variables. All we really need to do is identify two data points that appear to represent end points of a load/speed function where a spike in efficiency increase seems to occur.

To convert Kg of fuel to fuel conversion efficiency, we start by estimating the amount of energy in the fuel used. The equation is:

$$\text{Kg} \times \text{LHV (MJ/Kg)} \times 1000000 = \text{fuel energy (joules)} \qquad \text{Eq. 4}$$

where Kg is weight of fuel used during a two minute test run and LHV is the lower heating value of Diesel fuel (43.4 MJ/Kg). Thus, 0.639 Kg in cell G5 converts to 27727777.8 in cell D25. The energy output is simply Hp x 745.7 watts / Hp x 120 since joules = watt/sec. Fuel conversion efficiency would be:

$$\text{energy output / fuel energy} = \text{efficiency or } \eta \qquad \text{Eq. 6}$$

Conversion efficiency is 0.323 in the case of the first value in cell G25 or 100 x 745.7 x 120 / 27727777.8 = 0.323.

In the case of efficiency with HHO, the power drain from the reactor is subtracted from the power output. This correction has a negligible effect on efficiency, but it is done anyway, thus, neutralizing the claim that efficiency values are overly high because the reactor power drain is not subtracted. The power drain estimate also considers that the efficiency of an automotive alternator is about 55%.

Percent increase in efficiency is taken as:

$$100 \times \left(\left(\eta \,/\, \eta_0 \right) - 1 \right) \qquad \text{Eq. 7}$$

where η = efficiency with HHO injection, η_0 = baseline efficiency.
Starting at cell B46, sheet1 the 32 amp data is arranged for a scatter plot. At cell B61, sheet1 the 46 amp data is arranged for a scatter plot. Two series are plotted:

1. all the data points
2. linear regression end points for the lower six data points. The two outliers omitted from the linear regression are indicated by the cells shaded gray.

The 32 and 46 amp plots are shown in Figure 4. The right hand outlier is shown as a spike on the linear regression plot. The left-hand outlier is probably a spike as well but is disregarded in this case.

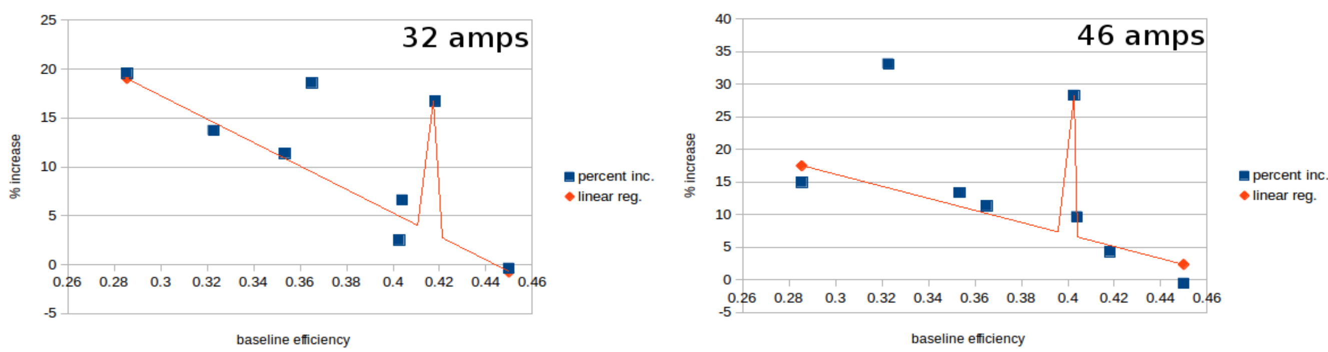

Fig. 4. Linear regression line and spike were added to the images.

The outliers are points 3 and 6 on the 32 amp plot, 1 and 8 on the 46 amp plot. So the pattern is: efficiency increase drops to zero as the baseline efficiency approaches its optimum value. However, at about 90% of optimum baseline efficiency, the efficiency increase spikes. This corresponds to the right hand outliers on both plots. We'll assume that a similar spike occurs for all current values between 32 and 46. If speed vs. power is plotted, this would result in a continuous function with end points at (200 Hp, 1400 RPM) and (400 Hp, 1800 RPM).

For further discussion of whether the correlations shown in Figure 4 are statistically significant, see Appendix A.

There is a plot of speed vs. load that an engine must produce for any given application. We typically call this an application load line (or simply load line). The HHO spike function might intersect the load line. That point will correspond to an optimized response to HHO injection assuming that the HHO flow rate is adjusted properly. In many cases, however, the functions do not intersect. In such a case, the application would have to be modified to move the load line if it is to intersect the HHO spike function.

For application to marine propulsion, we will assume that the spike function is a straight line. Since low speed marine Diesels have a large environmental and economic impact, it would be worthwhile to see how this model might be applied to such engines. Applicability of engine data can sometimes be widened by converting Hp to Brake Mean Effective Pressure (BMEP) and RPM to Mean Piston Speed (MPS). In reference 7, Heywood gives BMEP as:

$$\text{output (watts)} \times N \,/\, V_D \text{ (liters)} \times \text{revs / sec} = \text{BMEP kPa} \qquad \text{Eq. 8}$$

where power output is in watts, N = 2 for a 4 stroke engine, V_D is displacement (12.7 liters in this case) and revs / sec is simply RPM / 60. BMEP for the Wärtsilä RTA68-D is given in bars. The kPa units can be converted to bars using a conversion factor of 0.01. Heywood also gives MPS as:

$$\text{stroke (meters)} \times \text{revs / sec} \times 2 = \text{MPS (m /sec)} \qquad \text{Eq. 9}$$

The stroke of the Detroit Diesel Series 60 12.7 L engine is 6.3 in. or 0.16002 m [12]. The BMEP / MPS conversion of the model is given in a table that starts at cell B112, sheet1.

Sheet 2 contains the model for a large low-speed marine Diesel engine. The model line is compared with a load line taken from data found in Reference 5. The table starts at cell B12, sheet 2. The RPM and BMEP data were copy/pasted directly from reference 5. The stroke of the 8RTA68-D is 2.72 meters. This is used to convert RPM to MPS. The scatter plot includes 3 series:

1. The load line of the 8RTA68-D as given in reference 5.
2. Load line derated by 65% so that it intersects the model line.
3. The model line taken from sheet 1.

This is the plot that is shown in Figure 2. Again, it is hard to say whether data taken on a truck engine is necessarily applicable to a low speed marine Diesel engine. If testing could be conducted on progressively larger engines, this method may still prove useful. The HHO gas flow rate must also be adjusted properly. Linear equations can be solved which will give the required current, assuming that the function is linear.

Current would be given by the equation:

$$Hp\ a_1 + a_2 = amps \qquad \text{Eq. 10}$$

The two coefficients can be obtained by solving these two equations:

$$200\ a_1 + a_2 = 32 \qquad \text{Eq. 11a}$$
$$400\ a_1 + a_2 = 46 \qquad \text{Eq. 11b}$$

Solving gives $a_1 = 0.07$ and $a_2 = 18$. This calculation is given on the table at cell B101, sheet 1. Use of this formula provides the rationale for very specific calculations of the size of the HHO generators needed and associated electrical equipment. This is found in the table that starts at cell B22, sheet2. This calculation was already described in the preceding "Typical Installation" section.

Finally, on sheet3 of the spreadsheet is a model for a Diesel electric generator. Two series are plotted:

1. The model line.
2. Generator load line.

This plot is shown in Fig. 3. The load line is vertical because the speed is always the same in order to maintain the correct frequency of the output current. Therefore, there will be only a single intersection point with the model line.

Conclusion: This analysis is a very preliminary result. The relationship between efficiency increase resulting from HHO injection and the baseline efficiency requires further investigation. Applying the optimization model to various applications requires detailed knowledge of the requirements and constraints of each application. However, the use of a more systematic method may very well give better results than previous efforts which have often followed more of a trial-and-error approach.

The fact that there does seem to be a correlation between baseline efficiency and efficiency increase could be used as a basis for optimization models. However, correlation does not necessarily prove a cause and effect relationship. One issue with the model proposed above is that it implies that a given efficiency results in a certain efficiency increase. The actual cause and effect relationship may involve one or more other variables that have not been measured. This could possibly explain the outlier points. Influencing this variable or variables for the purpose of improving performance of HHO injection may actually be easier than trying to get the engine to always operate at 90% of optimal efficiency. Further investigation could certainly be worthwhile.

Appendix A.

The purpose of this section is to describe a more formal determination of whether a correlation exists between baseline efficiency and percent increase in efficiency. There are various statistical methods that are commonly used to evaluate correlations of this kind. One method often used is a linear regression. A formula is used to obtain the slope and intercept of a linear function that is the best fit to a data set of ordered pairs. Since there is often some variance or scatter associated with the data, the extent to which the function fits the data is oftentimes a matter of degree. Statistical analysis is not going to provide a yes/no answer as to whether or not a correlation exists. Instead the analysis will provide a relative determination of the extent to which the correlation is statistically significant. The p-value is one method for making this sort of determination.

In general terms, the p-value is the upper limit of the probability of what is called the null condition. In this case, the null condition is that the slope of the linear regression function equals zero. In such a case, the y value would be a constant and would have no direct correlation to a set of x values, (where x is the horizontal axis variable and y is the vertical axis variable). A smaller p-value is a stronger indication of statistical significance. A common rule of thumb is to use 0.05 as a p-value threshold. Statisticians will often be trying for a p-value of less than 0.05. The value itself is somewhat arbitrary and originates from the 1920's before computers because the threshold of 0.05 was easier to verify by manual calculation. The p-values for these regressions were obtained using a computer language called R [13].

In the case of the 32 amp plot, the p-value is 0.0005773, about 100 times smaller than 0.05. In the case of the 46 amp plot, the p-value for a linear regression is 0.01285, roughly one fourth of 0.05. The 46 amp plot is a bit less linear. If the percent increase values are squared as shown in Figure 6, then the p-value is 0.002397, more than 20 times smaller than 0.05. This would suggest that a function containing a squared term would be a better correlation between baseline efficiency and percent increase. The outliers are not included in this calculation.

Figure 5 shows the plot of a non-linear regression for the 46 amp data that was done using R. Figure 6 shows the linear regression of the square of the percent increase vs. baseline efficiency for the same data.

Because of the low p-values, it is very reasonable to propose that there is a correlation between these two variables, regardless of whether it is linear, non-linear or a combination thereof.

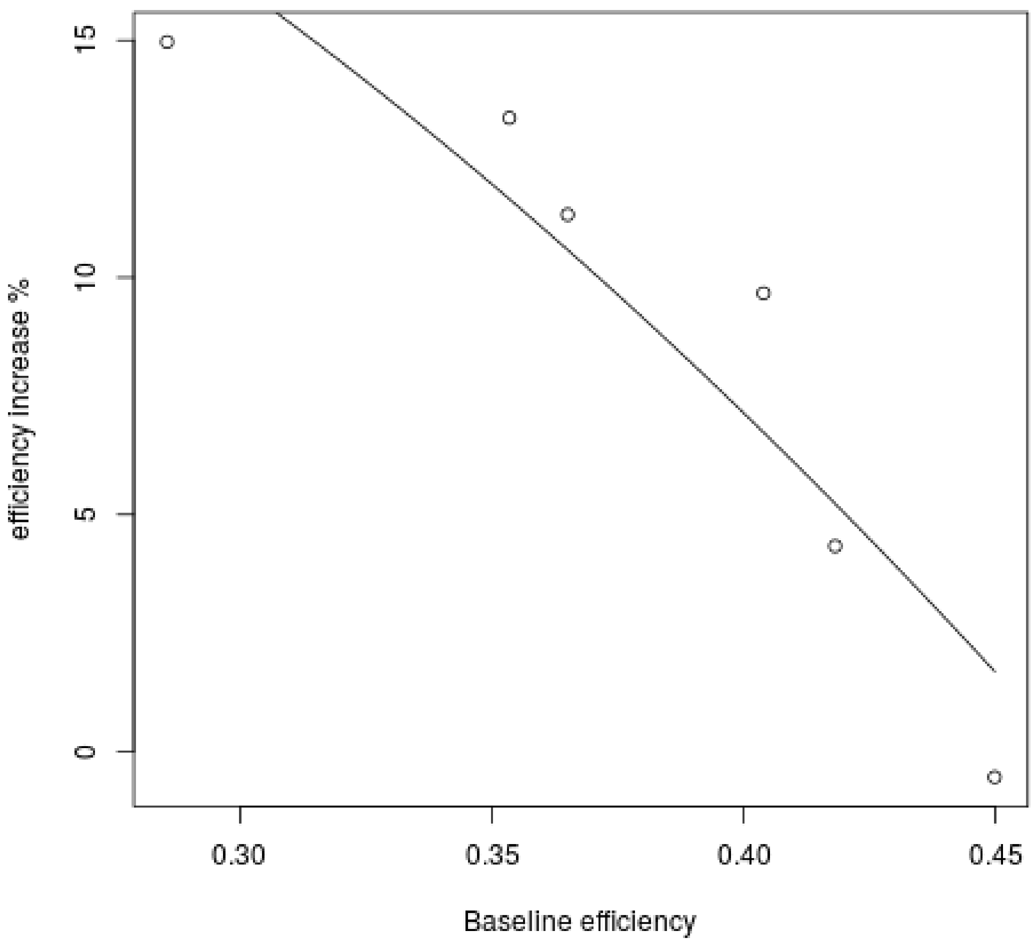

Figure 5. Baseline efficiency vs. percent efficiency increase with a non-linear regression based on a function with a squared term..

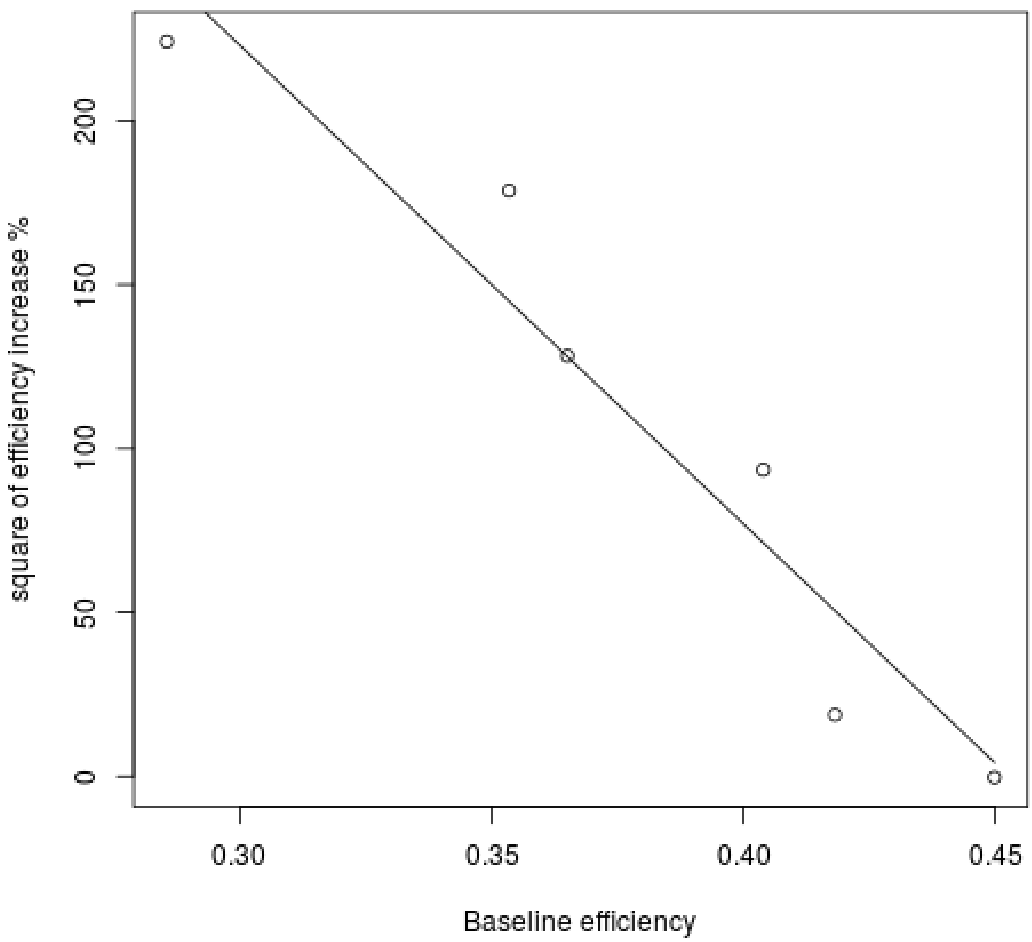

Figure 6. Baseline efficiency vs. square of percent efficiency increase with least squares linear regression.

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12 http://www.hho-research.org/docs/xls120/DetroitSeries60EngineSpecs.pdf
13 R script file found at http://www.hho-research.org/docs/xls120/stat1.R To run this script, install R and download the script file. Open the console window, go to the folder where the script file is located and enter the command: "Rscript stat1.R". The results will print out in the console window. Plots will be stored in .png files created in the same folder.