Almeo

RESEARCH, LLC

Product for fuel cost reduction on Class 8 vehicles

Part I

Ver. 1.1.

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None of the companies referred to in this report are affiliated in any way with Almeo Research LLC.

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 a technology for optimizing vehicle fuel efficiency of Class 8 Diesel vehicles*. Part I outlines the product concept supported by relevant available data. Part II will outline practical aspects of implementing the technology.

Part I of this report will analyze some existing laboratory data [1] and from this analysis develop some ideas for increasing fuel savings obtained by using HHO gas injection systems such as optimized HHO feed rates and fuel injection. More extensive data is needed to realize actual product improvement, therefore this discussion is intended to illustrate concepts rather than provide definitive validation.

Background: On Feb. 25, 2010, a 2004, 12.7 liter Detroit Diesel Series 60 engine rated at 515 Hp set up on an engine dynamometer in a test lab at the University of Northwest Ohio (UNOH) was run at two different speeds under four load settings with an HHO generator attached. Brake specific fuel consumption (BSFC) was measured with the HHO generator running at 32 amps, 46 amps and no current to serve as a baseline. Current was supplied by a constant current regulator (a battery charger). In many cases, an increase in fuel efficiency was observed.

In this report, we shall take this data along with a typical plot of engine load versus vehicle speed for a Class 8 truck to obtain mileage values. Several interesting points come out of doing this that are contrary to what might be expected:

- Engine fuel efficiency does not translate directly to vehicle fuel efficiency. That is, a twenty percent increase in engine efficiency usually does not produce a twenty percent increase in mileage.
- Graphs of mileage versus speed for 32 amps and 46 amps suggest that a *lower* cell current produces a greater increase in mileage at speeds over 50 mph.
- We evaluated a rationale that involves running on 4 of the 6 cylinders. This may be helpful for increasing mileage at speeds over 60 mph.

Mileage is affected by many different factors. Obtaining mileage values that can be validated for repeatability and reproducibility is time consuming and difficult. It is easier to get good quality data for fuel efficiency of the engine and compute vehicle fuel efficiency from a speed vs. load plot for a given set of conditions. This could serve as the basic principle for an advanced HHO system designed for Class 8 trucks.

Product Target: Why class 8 vehicles? According to 2002 U.S. Dept. of Energy figures [3], 52% of Class 8 trucks travel over 100,000 miles per year. At 6 mpg and $4 per gallon of Diesel fuel, that is an annual fuel cost of about $67,000 per year. A 15% reduction in fuel cost would be about $10,000 per year. <u>The greater savings justifies a more advanced product</u>, that is, a computerized system which by sensing the operating conditions, can optimize cost savings at a particular speed. See Appendix A for a more detailed description of product cost justification.

* Class 8 refers to a truck with a Gross Vehicle Weight Rating (GVWR) in excess of 33,000 pounds. Typically, such vehicles consist of a tractor unit and at least one trailer and use Diesel, i.e., a "semi" rig.

Data Analysis: The calculations in this report are based on data listed in Table 1. These measurements were taken on a 2004 Series 60 12.7 liter Detroit Diesel Engine with a rated maximum output of 515 horsepower. Weight value of a fuel container was recorded before and after a two minute run under the given load and RPM. The difference values are listed on Table 1. Both load and RPM were automatically regulated by the computer system controlling the dynamometer. Each of these values is apparently the result of a single run.

Load	RPM	0	32	46
100	1400	0.639	0.556	0.472
	1800	0.722	0.597	0.611
200	1400	0.972	0.833	0.931
	1800	1.167	1.028	1.028
300	1400	1.389	1.389	1.389
	1800	1.694	1.431	1.528
400	1400	2.042	1.917	1.861
	1800	2.056	1.986	1.597

Table 1. Fuel consumption in Kg during a 2 minute test run.

In Table 2, the fuel consumption values have been converted to pounds per hour per horsepower. These figures compare favorably with a typical value of 0.35 lbs / Hr Hp given for Diesel engines [2] .

Load	RPM	0	32	46
100	1400	0.423	0.367	0.312
	1800	0.478	0.395	0.404
200	1400	0.322	0.276	0.308
	1800	0.386	0.340	0.340
300	1400	0.306	0.306	0.306
	1800	0.374	0.315	0.337
400	1400	0.338	0.317	0.308
	1800	0.340	0.328	0.264

Table 2. Fuel efficiency in lbs / Hp Hr. with 0, 32, and 46 amps applied to the HHO cell.

The conversion is simply done by multiplying each Table 1 value by 2.20462 x 30 / Hp. The 2.20462 value is to convert Kg to lbs. The 30 is 60 min / 2 min. A sample calculation: 0.6389 x 2.20462 x 30 / 100 = 0.423 which is the first value on Table 2.

Calculating Mileage.
To calculate mileage increase from these values, we must start with a plot of typical engine versus vehicle speed as shown in Figure 1 [4]. Some of the load increases linearly with speed. Rolling resistance, that is, the friction of the tires on the road, make up the main part of this component. About 10% of this linear component comes from the power train, valve train, drive train, and loads from various accessories including pumps for lube, fuel, and coolant as well one or more alternators.

At highway speeds, aerodynamic drag increases quickly. Above 50 mph it passes the linear component of load on the engine. These are only typical curves. These will be affected by road conditions, weather conditions, the state of the tires and the vehicle and other factors.

The graphic file taken from the source of this information was digitized by counting pixels at 2 mph increments. These counts were then entered into a spreadsheet. Linear interpolation of the “Total” curve within 2 mph segments, gave speeds for 100, 200, 300 and 400 Hp loads. Fuel use in pounds per hour is obtained by multiplying the efficiency values in Table 2 by their respective horsepower values. Fuel use in gallons per hour is obtained by dividing pounds per hour by pounds per gallon. We use a value of 6.951 lbs. / gal. for API 32 Diesel fuel. Finally, miles per hour are divided by gallons per hour to get miles per gallon. These values are shown below in Table 3.

These would be poor mileage figures for a passenger vehicle. However, they are typical for a 33,000 pound Class 8 Diesel “semi”.

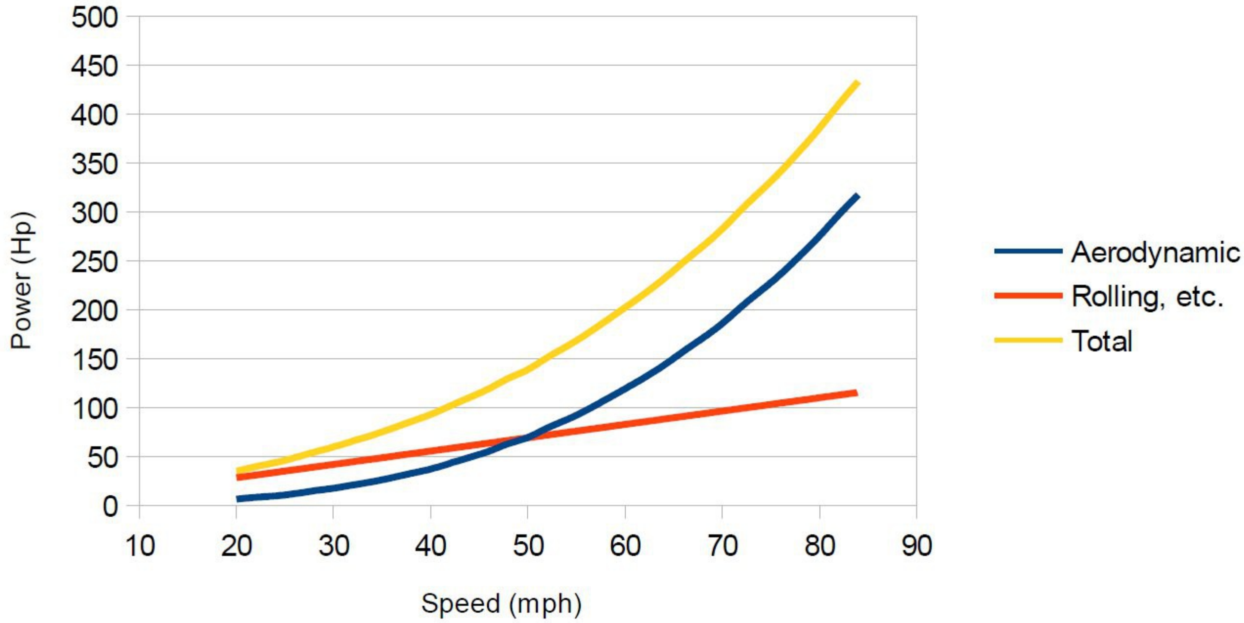

Figure 1. Engine load as a function of vehicle speed. Total resistance is the sum of rolling and aerodynamic curves.

HP	Speed	0 amps, 1400 RPM	0 amps, 1800 RPM	32 amps, 1400 RPM	32 amps, 1800 RPM	46 amps, 1400 RPM	46 amps 1800 RPM
100	41.57	6.84	6.05	7.86	7.31	9.25	7.15
200	59.65	6.45	5.37	7.52	6.10	6.74	6.10
300	71.71	5.43	4.45	5.43	5.27	5.43	4.93
400	81.16	4.18	4.15	4.45	4.29	4.58	5.34

Table 3. Mileage (mpg) at 100 Hp increments for 32 amps and 46 amps applied to attached HHO cell.

In Figure 2, we compare the 1400 RPM columns by plotting mileage increase versus vehicle speed for 32 amps and 46 amps. Sample calculation: For the 46 amp point at 41.57 mph.
35.32% = 100 x ((9.25 / 6.84) - 1). The curve smoothing used by Apache Open Office spreadsheet function was used to produce this graph.

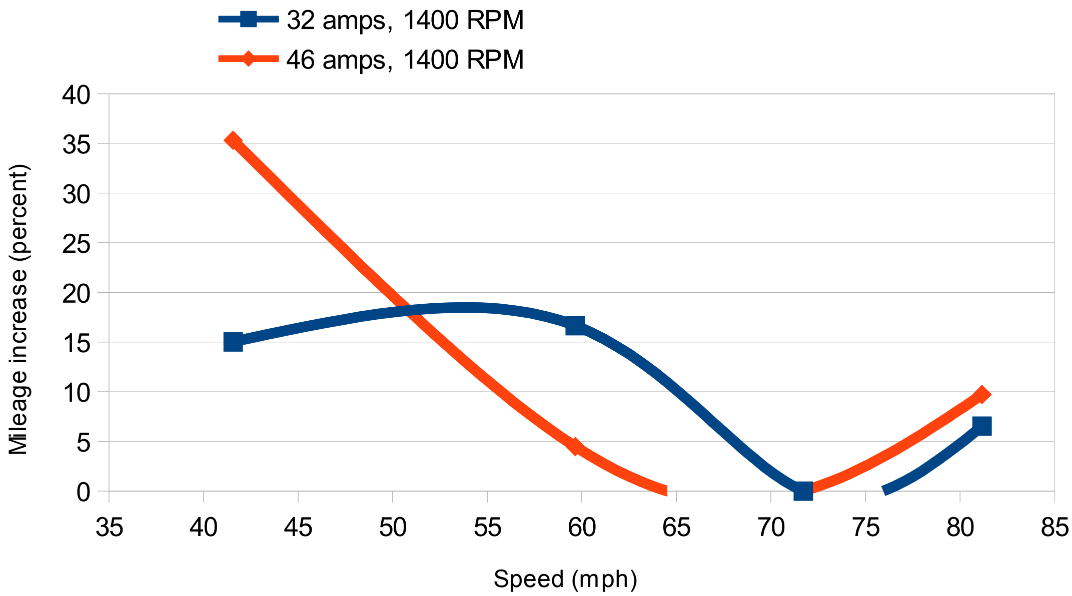

Figure 2. Percent increase in mileage as a function of vehicle speed for 32 amps and 46 amps at 1400 RPM.

Gear ratios. We have made an assumption in performing these calculations being that the vehicle can travel at any speed regardless of whether the engine speed in 1400 or 1800 RPM. This is true only to a certain extent. Figure 3 shows the sample graph of engine speed versus vehicle speed for a vehicle with a ZF Meritor 13 speed transmission, a 4.1 rear axle ratio and size 11.00-22R tires [7].

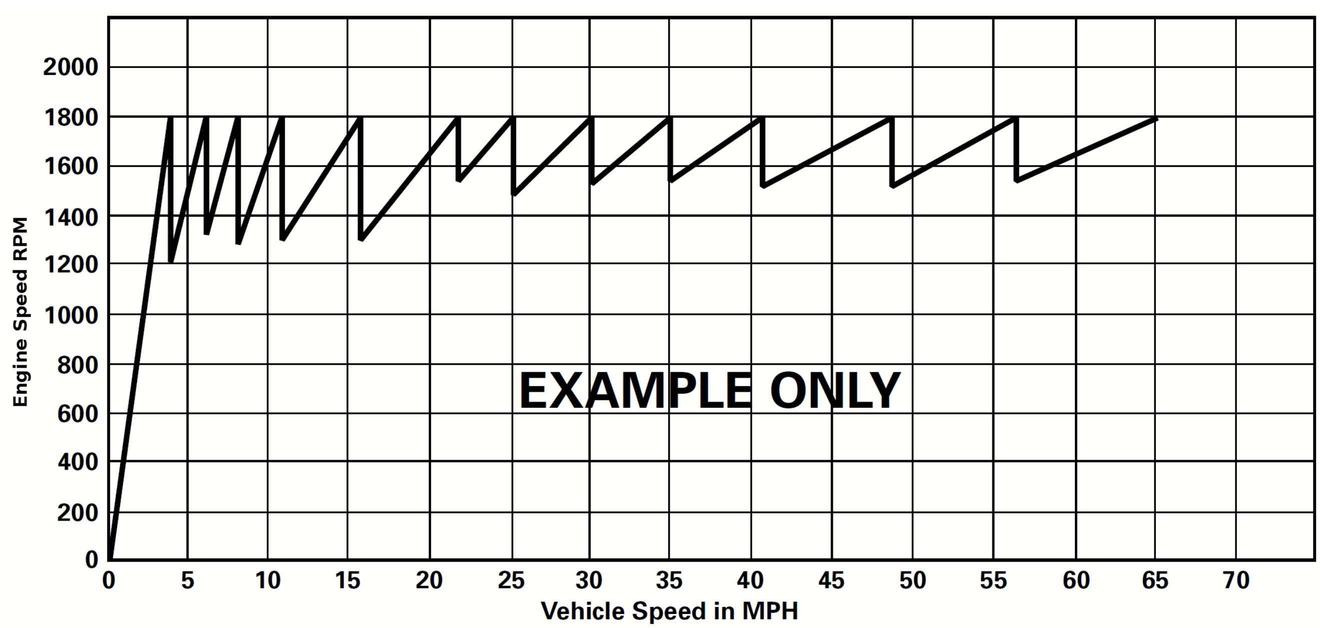

Figure 3. Plot of engine RPM versus vehicle speed for the 13 gears of a typical truck transmission.

Gear ratios range from 13.39 for the very lowest gear down to 0.89 for the last gear. Given that the eighth gear up has a ratio of 1.84 and in eighth gear the vehicle is moving at 30 mph at 1800 RPM, gear ratios for 1400 RPM at 41.57 mph would have to be 1.03, at 59.65 mph would be 0.72, at 71.71 mph would be 0.60, and at 81.16 mph would have to be 0.53. Of course, we cannot arbitrarily set gear ratios, but must use those available on the vehicle transmission. This is one reason why high resolution fuel efficiency maps such as the one shown in Figure 8 and 9 must be used in order to do optimizations on actual vehicles.

Estimating Fuel Costs.

It is a common convention to express vehicle fuel efficiency in terms of miles per gallon. However, for a Class 8 vehicle and indeed for most drivers, the purpose of an HHO system is to maximize savings on fuel costs. Gallons per mile would be proportional to fuel costs, not miles per gallons. A 20% increase in mileage does not results in a 20% decrease in fuel costs. Rather, the reduction is about 16.7%.

Here is a sample calculation: suppose we get 6 mpg before and 7.2 mpg after. That is a 20% increase. (120 = 100 x 7.2 / 6.0) The gallons per mile (gpm) would be 0.167 gpm (1/6) and 0.139 gpm (1/7.2) respectively (rounded to 3 digits.) Note that 83.3% = 100 x 0.139 / 0.167. The “after” figure is divided by the “before” figure in both cases. Note that 100 – 83.3% = 16.7% reduction. Figure 4 shows a plot of mileage increase versus fuel savings. This may seem like a rather small difference, but even a small difference is important if we are doing careful, systematic work. Note that the function is slightly curved. It is not quite linear.

Expressing performance of HHO systems in terms of fuel savings is important since this is the basis for cost justification of this technology. The difference between mileage and cost savings may be a few percentage points. But if annual fuel cost is $67,000 per year, each percentage point represents $670. No cost accountant would accept a $670 discrepancy.

Table 4 shows gallons per mile (gpm) values that correspond to mileage values given in Table 3. We are so accustomed to mpg, that this presentation seems harder to interpret, but it is a more correct.

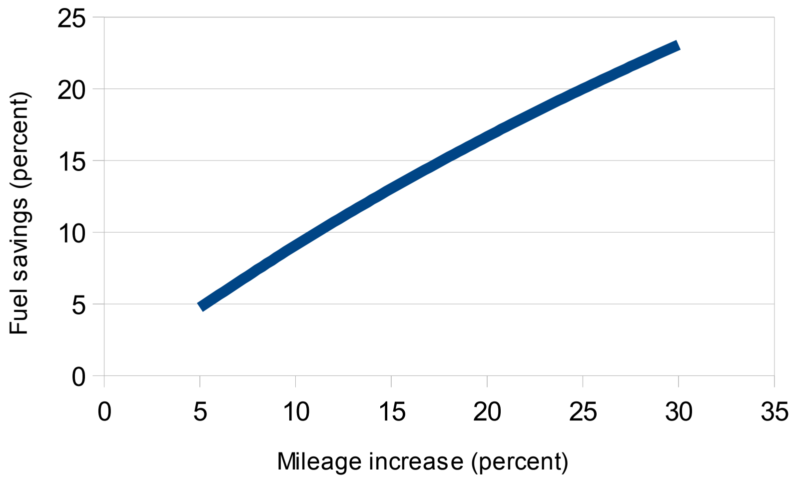

Figure 4. Percent fuel savings as a function of percent mileage increase.

HP	Speed	0 amps, 1400 RPM	0 amps, 1800 RPM	32 amps, 1400 RPM	32 amps, 1800 RPM	46 amps, 1400 RPM	46 amps 1800 RPM
100	41.57	0.146	0.165	0.127	0.137	0.108	0.140
200	59.65	0.155	0.186	0.133	0.164	0.148	0.164
300	71.71	0.184	0.225	0.184	0.190	0.184	0.203
400	81.16	0.239	0.241	0.225	0.233	0.218	0.187

Table 4. Fuel consumption in gallons per mile (gpm) at 100 Hp increments for 32 amps and 46 amps.

Figure 5 shows a plot of percentage increases in fuel savings. These curves are very similar to the mileage curves, however, the actual percentages are less. Expressing mileage in terms of miles per gallon became the common convention perhaps because the concept is easier to visualize. However, it introduces a bias towards higher percentage values and it is an inaccurate rationale for purposes of cost accounting.

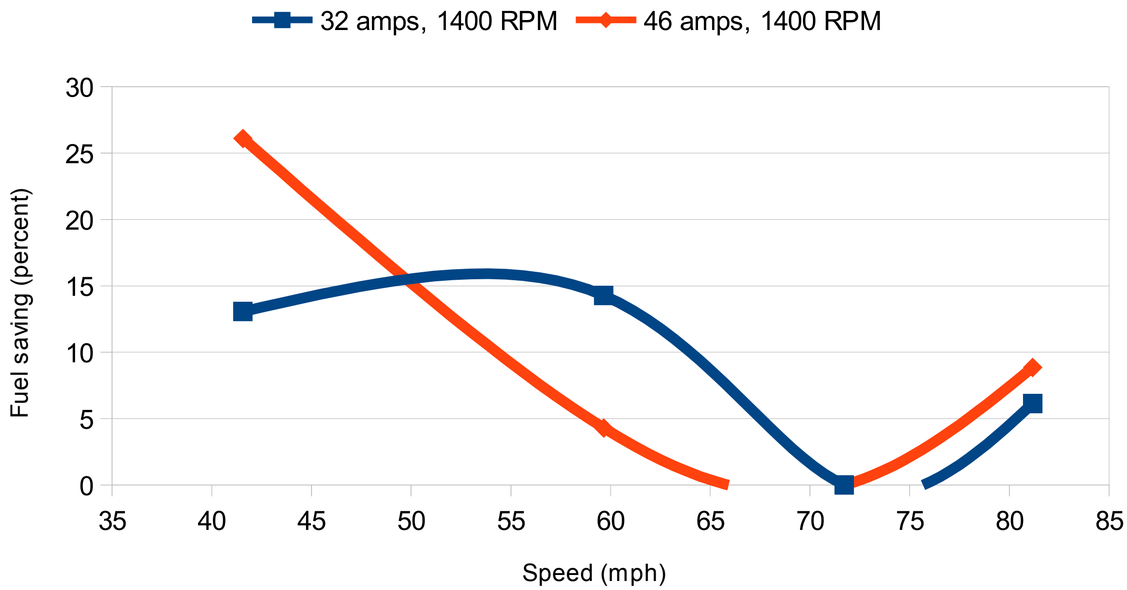

Figure 5. Percentage reduction in fuel costs as a function of vehicle speed.

Using a reduced number of Cylinders.
One of the values that is rather interesting is the fuel consumption value on Table 2 for 400 hp, 1800 RPM, and 46 amps. This is the lowest of all the values. However, it is not very useful because it corresponds to over 81 mph on the load curve we are using. Most truck Diesels have 6 cylinders in-line. That works out to about 66.7 Hp per cylinder (66.7 = 400 / 6). If two cylinders were disabled (an even number needs to be disabled to maintain engine balance), the output equals 266.7 Hp (266.7 = 66.7 x 4). Interpolating on the load curve, this works out to about 68.2 mph which is a bit more practical. The cylinder would be disabled by injection of a reduced amount of fuel. Since fuel injection is electrically controlled, this reduction can be accomplished by modifying the electrical signal to the injection pump. On some Diesels without electronic controls, the injector pump does or does not inject fuel depending on whether the centrifugal governor is below or above the speed set point so a reduced injection of fuel into a cylinder not entirely unheard of.
Figure 6 shows a fuel consumption plot with and without 32 amps at 1400 RPM. A single point for 46 amps, 1800 RPM on 4 cylinders is also plotted. By counting pixels, the 0 amp curve was found to correspond to 0.170 gpm, the 32 amp curve corresponds to 0.165 gpm, and the 46 amp data point corresponds to 0.15 gpm. For 32 amps, the reduction is about 3.1%. For the 46 amp point, it is very nearly 12%. This illustrates how cylinder reduction might be used to get some additional saving at higher speeds. A similar estimate is done for two cylinders. Two cylinders works out to 133.3 Hp and 48.72 mph. Pixels are counted to estimate a fuel savings of 15.7% for 32 amps, 1400 RPM and 23.6% for 46 amps, 1800 RPM.

Air drag that results from the energy required to move air in and out of the cylinder is not taken into account. However, this may be taken care of automatically by the turbocharger. Turbocharger boost in the intake manifold is regulated using the waste gate that spills excess energy off from the exhaust. If volumetric efficiency changes because of the reduced temperature of the off-line cylinders, the turbocharger regulation will automatically compensate.

On modern truck engines, injectors are controlled by the Engine Control Unit (ECU). The electrical pulses that activate the injectors could be intercepted to improve performance for HHO. One product designed to intercept and modify injector pulses on Diesel engines is shown in Figure 7 [5]. This product might be modified to test various fuel injection rationales for optimizing performance of HHO injection.

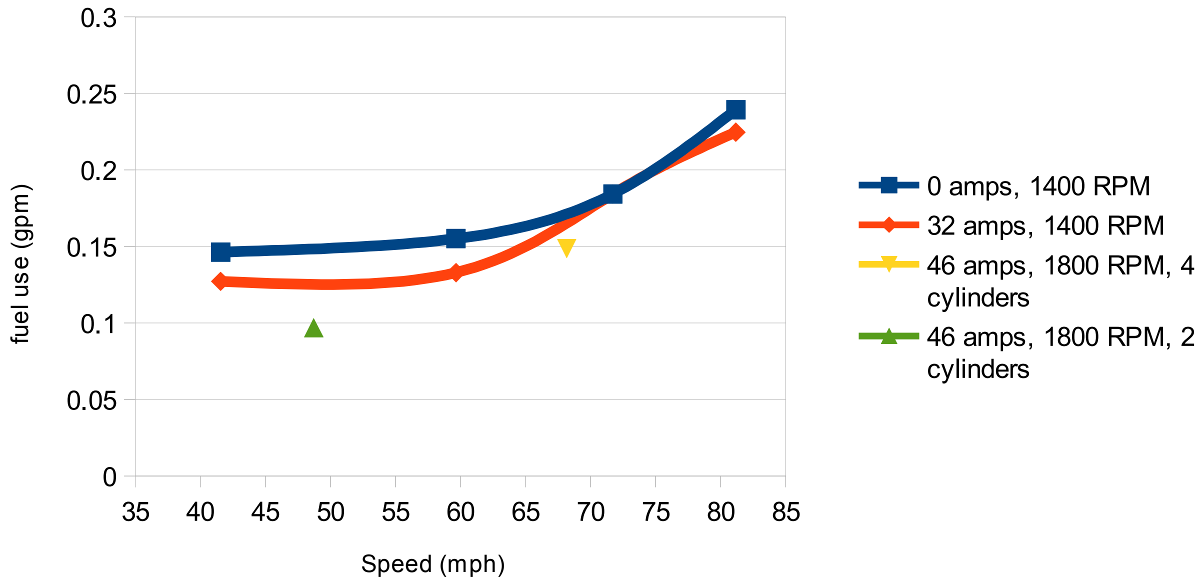

Figure 6. Fuel consumption is gallons per mile (gpm) for 32 amps, 1400 RPM as well as 2 and 4 cylinders at 46 amps, 1800 RPM

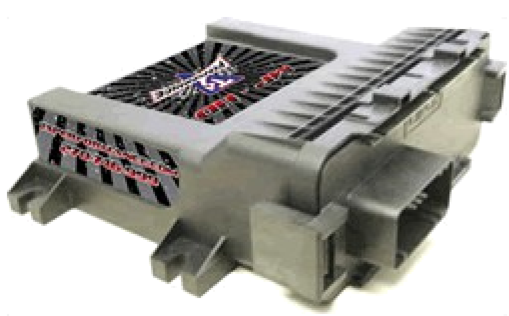

Figure 7. MPHD engine unit. Plugs into Cummins ISX and ISM engines using existing connectors. Intercepts and modifies control pulses to fuel injectors.

Adjusting Fuel Injection Angle.
Note that fuel consumption is not reduced as much at 400 Hp at the lower speed of 1400 RPM in Table 2. Normally, fuel injection starts at about 17 degrees before the piston gets to the top center (TC) position because it takes a while for the combustion to get started. HHO may increase combustion flame speed so that at 1400 RPM, there is too much pressure increase before the piston reaches the TC position. This could be remedied by advancing the angle where injection starts. The point of doing this is to get the high pressure effect at a lower speed. At lower RPM the load of moving air in and out of the cylinders is less as is friction load of the drive train and valve train.

Use of the MPHD may be useful for development purposes, but in the long run the manufacturer of an HHO injection system should probably obtain third party agreements with engine manufacturers to reprogram the ECU's of engines. Several companies have third party agreements for reprogramming Diesel ECU's on pickup trucks. This includes the Cummins Diesel used on Dodge Ram pickups. So, for example, it may be possible to obtain a third party agreement for reprogramming ECU's on Cummins ISX and ISM engines used on Class 8 trucks.

Better Qualified HHO feed rates.
Up to this point, HHO cell current has been used as an equivalent for feed rate. It is approximately equivalent, but this measurement could be more precise. A volumetric flow measurement is problematic since HHO is compressible and the amount of HHO in a given volume is affected by pressure and temperature. A thermal mass flow meter might be used to obtain a mass flow measurement. However, the calibration is gas specific. Since the properties of HHO are not fully understood, a more flexible method might involve the use of a small orifice plate flow meter being used to sense volumetric flow and an absolute pressure sensor, a temperature sensor and humidity sensor used to provide compensation so that a computerized control can calculate a corrected equivalent mass flow value.

Once mass flow rate output of an HHO cell has been characterized, it may be possible to infer mass flow rate from such measurements as cell current, voltage drop across the cell and electrolyte temperature.

High Resolution Fuel Maps.
Table 1 contains a comparatively small amount of unvalidated data. What is really needed to develop and test optimization rationales are high resolution fuel maps such as those shown in Figures 8 [16] and Figure 9 [17].

A fuel map plots some measurement of fuel efficiency or fuel consumption against the two variables having the greatest effect on fuel consumption: engine load and engine speed. For purposes of optimizing HHO technology a number of such maps could be generated for various HHO feed rates. Then these could be arranged in order and by means of trend analysis or other kinds of interpolation a type of high resolution fuel map is generated in three dimensions: engine speed, engine load and HHO feed rate.

We shall briefly discuss various ways of expressing engine load because this is very relevant to the material covered in Part II. On an engine dynamometer, two values are generally measured: shaft speed in RPM and torque (T) on the torque arm of the absorber brake. The relationship between torque (in foot pounds) and power output in horsepower is given in U.S. units as:

$$\text{horsepower} = \text{RPM} \times T / 5252.113$$

The exact value for the denominator of the horsepower equation is $150 \times 220 / 2\pi$ which comes from the observation of James Watt that each stout, little pony harnessed to a winch could haul 150 lbs. up a mine shaft at 220 feet per minute. Both horsepower and torque can be used to express the engine load. Another measurement of engine load is mean equivalent pressure (mep). There are different types of mep. Heywood [10] gives the relationship between torque and brake mean effective pressure (bmep) for 4-stroke engines as being:

$$T = \text{bmep} \times V_d / 4\pi$$

where V_d = displacement or swept volume and T = torque. Another type of mep is indicated mean equivalent pressure which can be obtained by numerically integrating area enclosed within the plot of pressure versus volume within a cylinder.

The maps in Figure 8 and 9 illustrate that it is considered appropriate to express the engine load in various ways. Figure 8 uses brake horsepower as the measurement of engine load. Fuel efficiency is expressed in terms of pounds of fuel per horsepower hour. In Figure 9, efficiency is given as grams of fuel per kilowatt hour. The vertical axis is given as bmep in bars.

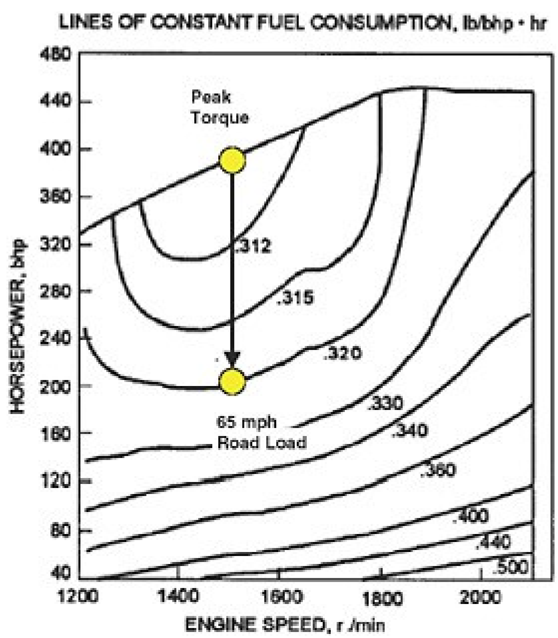

Figure 8. Map of BSFC in U.S. units.

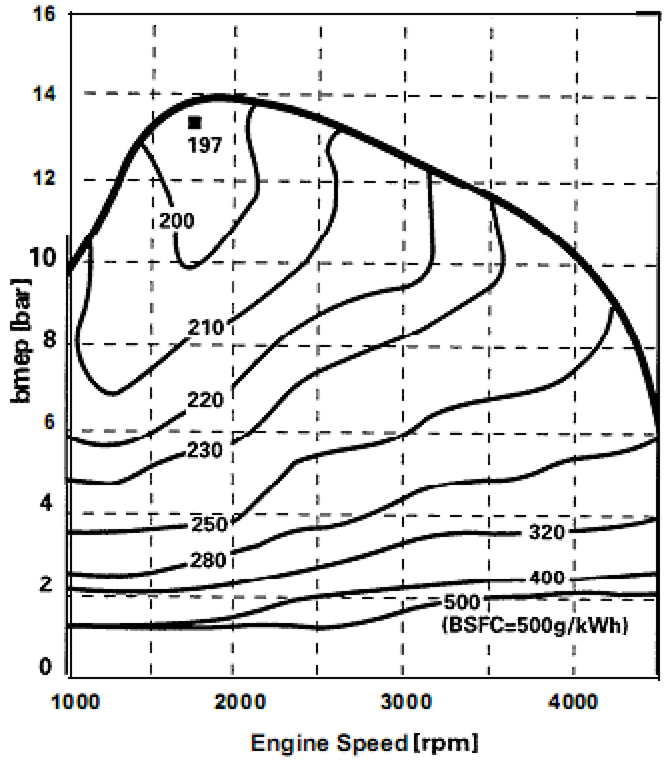

Figure 9. Map of BSFC for 1.9L Volkswagen Diesel in SI units

In the late 70's, a computer device was developed by NASA that used a water-cooled piezo pressure sensor mounted in the engine cylinder head to sense pressure and an encoder connected to the crankshaft to estimate cylinder volume [15]. It would compile this data to generate an imep estimate. An engine outfitted in this way was placed on a dynamometer test stand so that bmep measurements could also be taken. Figure 10 compares a corrected value of bmep against imep as a function of fuel used per cycle. The value of imep is higher than bmep because some energy is dissipated by friction from the power and valve trains, pumps for lube, fuel, and coolant and accessories such as alternators. Figure 10 was taken from a NASA report on this system. It shows a very close correlation between bmep and imep that is probably within the bounds of statistical variance.

Figure 11 is taken from Heywood [10]. It shows sample data giving both imep and bmep. The difference between imep and bmep is the mean equivalent pressure of the friction force within the engine (fmep), thus, imep = bmep – fmep. The power equivalent of each mep value is also shown. Heywood gives the relationship between power and mep for a 4 stroke engine in SI units as:

$$\text{mep (kPa)} = (\text{P (kW)} \times 2 \times 1000) \;/\; (V_d \text{ (liters)} \times \text{N (rev / sec)})$$

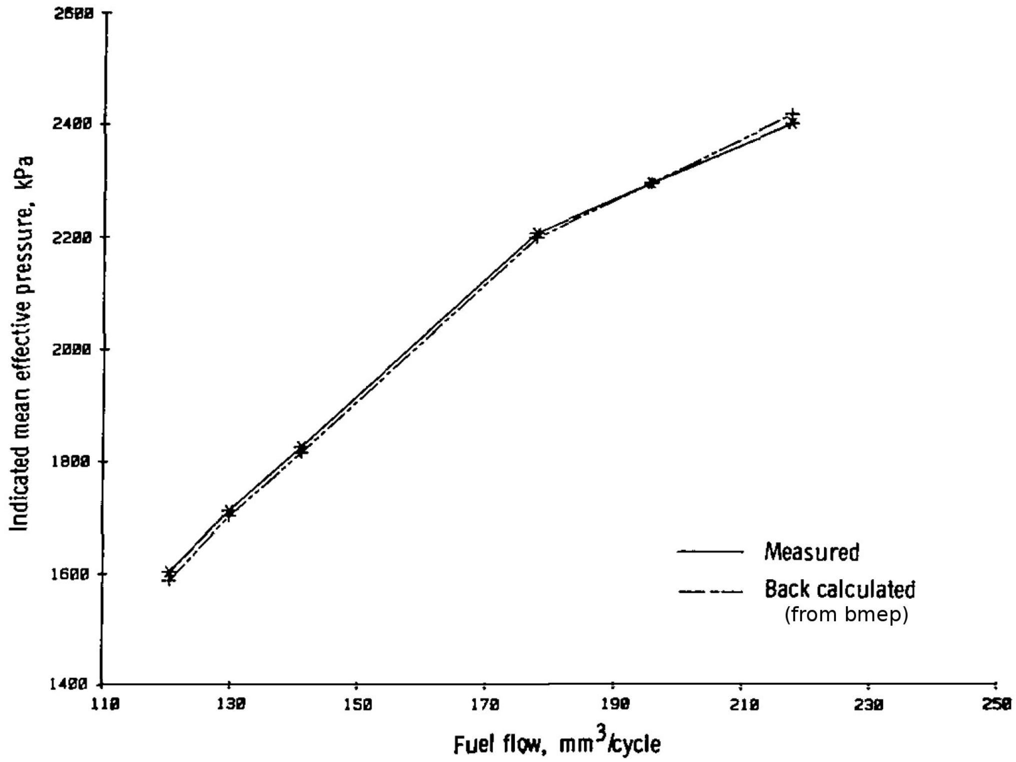

Figure 10. imep and bmep versus grams of fuel used per engine cylce. at 1500 RPM.

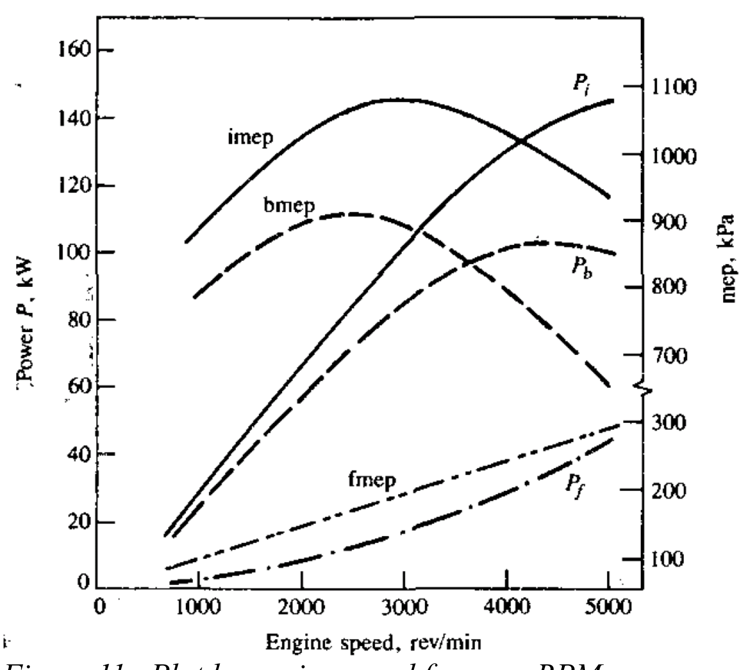

Figure 11. Plot bmep, imep and fmep vs. RPM.
Equivalent Power is also shown

Use of statistical methods: Our approach to taking a measurements is to take multiple readings under a given set of conditions and average them together to obtain an estimate of a value. Such readings are generally not identical but show a small amount of variance around an average value. It is a commonly observed tendency for the output of an instrument to “jitter” or “dither” about an average or mean value. We go a step further, however, by also calculating a standard deviation. This is one method of quantifying the random variance of a data set. The term data set refers to the set of readings or data points used to compute an average.

If both the averages and the standard deviation values are retained, statistical tests can be applied to the data to determine the extent to which observed correlations are “statistically significant”. This is commonly considered to be a characteristic of good quality experimental work. It improves the credibility of test results when they are presented to scientists and engineers. It is explained in greater detail in Appendix C in case the reader is not very familiar with these concepts.

Conclusion:

Part II describes an electronic system similar to the NASA system mentioned but it goes a few steps further. It measures load on the engine by measuring imep.

But then, it can generate a fuel map plotting fuel consumed per cycle against imep and RPM.

It also can plot imep as a function of vehicle speed and RPM. Road grade, wind and proximity to other vehicles are among many factors that can cause constant variation of the load curve as the vehicle travels along the highway. So, the speed-load curve must be measured in real-time as the vehicle travels over the road.

In this way, we can correlate engine fuel efficiency with vehicle fuel efficiency in the manner described in this part of the report. The imep value is used to correlate engine efficiency with vehicle speed in the same way that we used horsepower in this report.

That is why we went through an explanation of how horsepower and bmep are equivalent methods for defining engine load. Also, imep and bmep track each other very closely. For this particular purpose, imep can be used in the same way as horsepower.

The difference is that we don't need an engine dynamometer to measure imep. Instrumentation installed on a test vehicle running over-the-road (OTR) can be used can be used to perform these measurements. This is useful because it can form the basis for a real-time optimization of HHO feed rate and other variables for a given set of actual road conditions.

An advanced HHO gas injection system would have these features:

- High resolution, statistically validated, three-dimensional fuel map for the specific engine model.
- Mass flow based control of HHO feed rate.
- Real-time speed-load curve evaluation.
- Use of statistical multivariate analysis to identify influencing factors and characterize their influence.
- Systematic, mathematically based rationale for reduction of fuel use at whatever speed the driver chooses.

This will enable three basic types of optimization:

- Optimized HHO feed rate adjusted to the speed of the vehicle as well as other factors
- Optimized cylinder reduction.
- Optimized fuel injection angle.

These might seem like impractical and overly demanding requirements. However, there is a practical and economical technique that can be used to accomplish these objectives. It is described in Part II of this document.

As was said, Part II of this report describes a system that can fulfill these objectives for the purpose of optimizing HHO injection by measuring instantaneous pressure in one of the cylinders by means of a pressure sensor installed in the cylinder head. Engine load in imep is measured by numerical integration of the area within a plot of pressure versus volume. It also measures the pulse width of each fuel injector pulse to estimate fuel consumption and it can interrogate the CAN bus to obtain an estimate of vehicle speed from the ECU.

To optimize HHO injection, it is not necessary to measure overall engine performance. Relative performance of a representative part of the engine (a single cylinder) can serve the same purpose. This also eliminates extraneous variability from other factors that have nothing to do with the interaction between HHO and the combustion process. Thus, the control system can be more tightly bound to the process that it controls.

Appendix A.

Purpose: Outline the business model for a company grossing $50M per year.

According to 2009 U.S. Dept. of Energy figures[3], there are 2,617,000 compound vehicles (compound means having one or more trailers) in the Class 8 range. According to figures last compiled in 2002, the annual mileage of 52% of these exceeds 100,000 miles. This data is compiled in Figure A1. The U.S. target market for this product would be about 1,360,000 vehicles (2.617M x 0.52 = 1.36M).

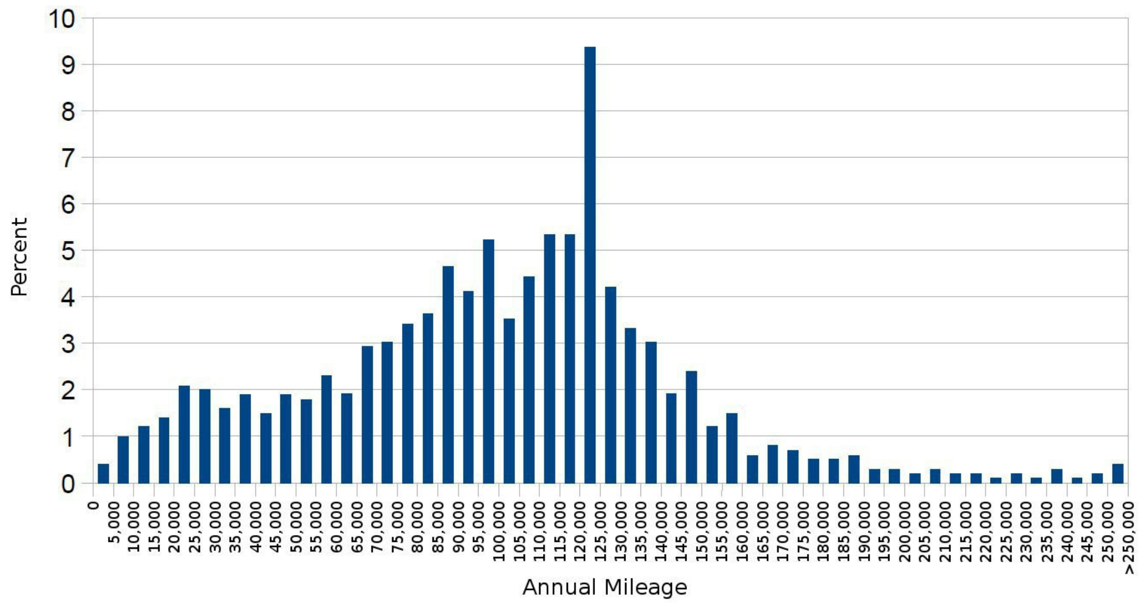

Figure A1. Histogram for annual mileage of Class 8 trucks in 2002. Sample data point: Percentage of vehicles between 120,000 and 125,000 was 9.4%.

A price of roughly $5,000 for each HHO system can be justified for a vehicle traveling over 100,000 miles per year. At 6 mpg and $4 per gallon of Diesel fuel, that is an annual fuel cost of about $67,000 per year ($67,000 = $4 x 100,000 miles / 6 mpg). A 15% reduction in fuel cost would be about $10,000 per year. Most companies look for a payback of 6 months for a capital investment which would be about $5,000.

The size of the target market for U.S. trucks would be 1.36 M vehicles x 5K USD per vehicle equals 6.6 billion USD. There are many other potential markets as well.

If a company sold 10,000 units per year, that would be an annual U.S. market penetration of only 0.7% which would be quite conservative. The gross for this volume would be 50M USD with considerable potential for additional growth.

The spreadsheet used for the above calculation can also be used to calculate total cost savings that would result if this technology were installed on each truck logging over 100,000 miles per year. Total miles logged comes out to 181,079,009,207. At 6 mpg and $4.00 per gallon, total fuel costs will come to $120.7 billion. A 15% cost reduction would be $18.1 billion. Technologies tend to become cheaper and more optimal as time goes on. This technology could conceivably be mass produced at a cost low enough to install it on all vehicles. The same calculation performed for all 2.617 million Class 8 vehicles using the 2002 mileage profile gives $26.09 billion dollars in savings.

On this basis, it might be possible to obtain grants from the U.S. Dept. of Energy or private foundations to do further research and testing on HHO. Further research and development is certainly needed to make optimal use of the technology.

Class 8 trucks are a convenient starting point. Diesel engines are used on virtually every type of heavy logistics surface transport. Almost all locomotives and cargo ships run on Diesel engines. As Diesel engines are scaled up, they become even more efficient and improving efficiency becomes more difficult. A large tanker or container ship can use 250-300 metric tons of bunker fuel per day. At about 600 USD per metric ton (the price fluctuates quite a bit), this is a significant expense. However, a savings of even a fraction of a percent could easily amount to over 1M USD per ship per year.

Appendix B.

Purpose: Give an example of a company already producing HHO technology similar to that described in this report in order to:

- Show that fuel savings are comparable to what would be expected.
- Show practicality of installation of HHO systems on modern equipment.

A Canadian company called John Henry Hydrogen (JHH) [6] specializes in HHO injection systems for Class 8 vehicles. Their website gives mileage results of some of their installations. They are summarized in Table B1. Most of these vehicles use satellite tracking systems to monitor mileage. Mileage was monitored over a period of months in many cases. Therefore, these figure are probably fairly meaningful.

The average percentage cost saving is 15.14%. This is based on a gpm calculation described above. Average percent reduction in fuel use in Table 1 is 11.27%. This indicates that engine efficiency must be scaled through a load curve to be translated to fuel savings per mile. This also helps validate the use of 15% average savings in the Appendix A cost estimate.

Vehicle make	Year	Available Engine Description	Mileage (mpg)		cost savings percent
			Before	After	
Freightliner	2010	Cummins	6.4	7.1	9.86
Western Star	2009	Caterpillar w/Acert	4.7	5.4	12.96
Peterbilt	1995	Caterpillar 500 Hp	5.8	6.9	15.94
Western Star	2005	Caterpillar w/Acert	5.7	6.5	12.31
International Pro Star	2009	Cummins ISX w/EGR	6.1	7.1	14.08
International Pro Star	2009	Cummins ISX w/EGR	5.6	6.7	16.42
Western Star	2001	Detroit Diesel Series 60	5.8	6.79	14.58
Western Star	2006	Detroit Diesel Series 60	6.5	7.79	16.56
Western Star	2006	Detroit Diesel Series 60 w/EGR	4.9	5.6	12.50
Freightliner	2009	D-15 w/EGR	5.5	6.5	15.38
Peterbilt	2004	Caterpillar 475	5.89	7.52	21.68
Peterbilt	2004	Caterpillar 435 Hp	4.3	5.28	18.56
Freightliner	2001	Caterpillar 435 Hp C12	5.9	7.02	15.95
		Average			**15.14**

Table B1. Mileage and fuel cost savings for a sampling of Class 8 vehicle installations.

Installation. Using pictures from the JHH website, it is possible to illustrate different types of installations on actual vehicles. They include:

1. Installing system components in a non-dedicated enclosure such running board tool storage. See Figure B1.
2. Installing a dedicated enclosure containing the HHO system. This is generally done:
   a) On the cat walk behind the cab. See Figure B2.
   b) On the side of the chassis and to the rear of a fuel tank. See Figure B3.
   c) Under the fairing beneath the cab door. See Figure B4.

Figure B1. System installed in tool storage under a running board.

Figure B2. System installed on the catwalk behind the cab.

Figure B3. Chassis mount system located to the rear of a fuel tank.

Figure B4. System mounted under a fairing. Right side view shows system with fairing removed.

Appendix C.

Purpose: This appendix will review two aspects of the statistical characteristics of experimental data relevant to fuel mapping: repeatability and reproducibility.

Repeatability.
Suppose we are measuring imep of an engine. There is often a certain amount of cycle-to-cycle variability in engine cycle measurements. It is common for there to be a random variability inherent in a measurement.

Our fuel mapping system allows us to take hundreds of readings per minute. Suppose we take 100 measurements of imep in some scaled unit of pressure. A simulated variation in the readings as shown in Table C1.

203.3	0
203.4	1
203.5	1
203.6	4
203.7	7
203.8	12
203.9	18
204	16
204.1	17
204.2	6
204.3	9
204.4	4
204.5	3
204.6	1
204.7	1
204.8	0
204.9	0
205	0
total	100

Table C1. Simulated efficiency measurements.

The nominal value is 204 but the readings vary a bit from this value. This sort of scatter is actually typical for many kinds of instrumentation. Oftentimes, the value that an electronic instrument displays is actually an average of hundreds of individual readings. However, it may be able to take readings so quickly, that the displayed value seems to be quite responsive yet it also seems to be quite precise, that is, it is not dithering around.

These values can be plotted on what is called a histogram as shown in Figure C1. The height of each bar corresponds to the number of readings having that respective value. For example, there were 16 readings with a value of 204.0, 17 readings with a value of 204.1, etc. Superimposed over the histogram is a function known as normal distribution or bell curve. The distribution of data points often conforms to this type of curve. One way to quantify the width of this curve is to calculate a standard deviation.

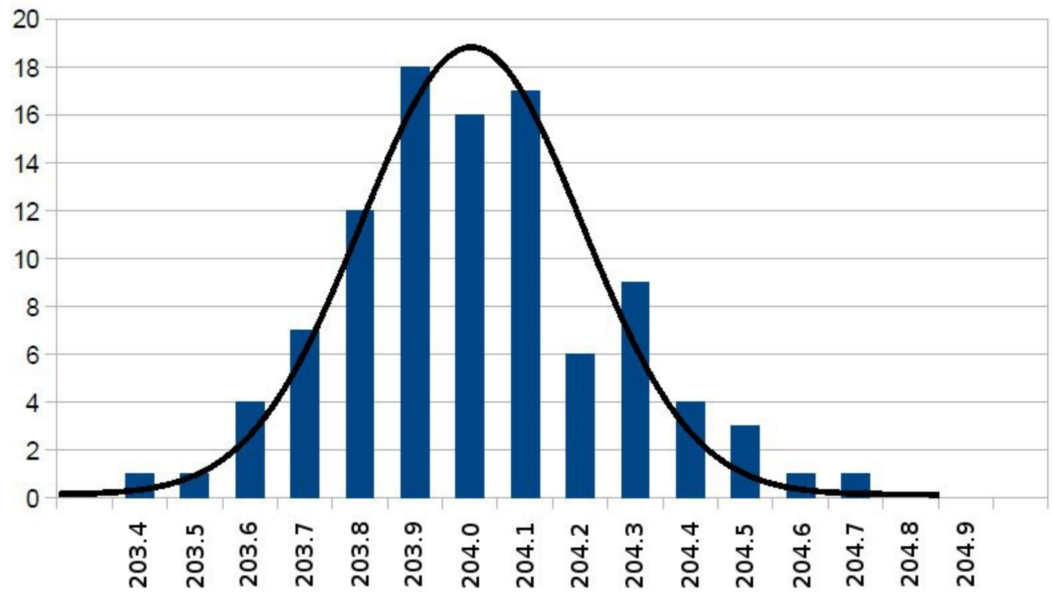

Figure C1. Normal distribution of data samples.

The relationship between the normal distribution and standard deviation is shown in Figure C2 on the next page [7]. Standard deviation is denoted by the lower case Greek letter sigma: σ. Within the interval of the average $\pm\,\sigma$ should lie 68.2% of all the data points. About 95% of all data points lie within the interval of $\pm\,2\sigma$ and 99.7% of the data points lie within the interval of the average $\pm\,3\sigma$.

Standard deviation serves as a method of quantifying the amount of scatter in a set of measurements. Therefore, unless you tell someone the standard deviation of an average, they have no way of knowing the precision of the measurement.

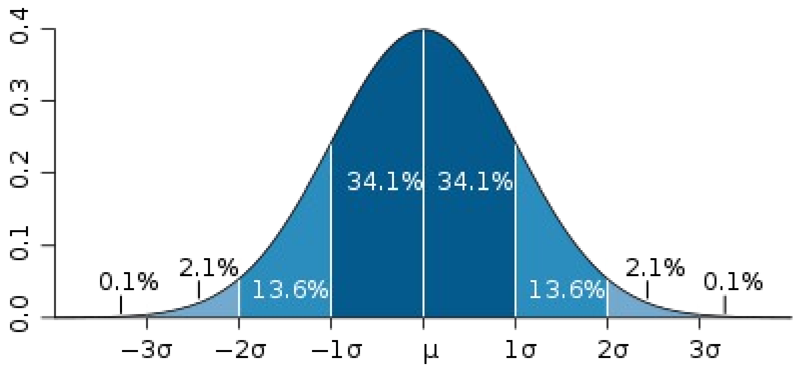

Figure C2. Relationship between standard deviation and a normal distribution.

A result or difference is called statistically significant if it is unlikely to have occurred by chance, that is, a result of the variance normally inherent in the measurement process. There is no single definition or formula for statistical significance. However, there are various commonly used tests for statistical significance. Whichever one is used depends on the requirements of the particular situation.

A commonly used test is p-value which calculates the probability that the difference between two average is the result of chance. A p-value of 0.05 is considered to be a marginal indication of statistical significance. A value of 0.01 is considered to be a good indication of a statistically significant difference and 0.001 is considered very good. The p-value test is rather simplistic and does not account very well for differences in the distribution. Other more advanced tests are used if a finer discrimination is required.

An important feature of the Part II technology is that it easily generates and stores enough data to enable statistical analysis of test results. In this respect, it is an improvement over other procedures that are commonly used.

Reproducibility.

While repeatability measures the amount of variance within an averaged data set, reproducibility involves variability between data sets that were taken under conditions that are presumed to be equivalent.

In the case of fuel mapping, we are interested in the extent to which a map can be reproduced in different instances on same vehicle as well as different vehicles with the same engine model. The maps are not going to be exactly identical. That is why we need to determine if the difference between the maps is statistically significant.

Many factors can affect engine efficiency. Characteristics of inducted air exert a particularly strong influence. Temperature, barometric pressure and relative humidity are the principle variables that define this influence. Correlation tests can be used to determine if a particular variable has a statistically significant effect on the fuel map and they can also be used to characterize this influence.

Appendix D.

Purpose: This example is intended demonstrate the high variability of mileage values under long haul service conditions. We shall show that the difference seems to statistically significant by calculating a p-value. Nevertheless, obtaining the mileage data is a very slow process. The electronic fuel mapper system described in Part II is a much faster way to get higher quality data.

HHO experimenters often measure mileage by filling the fuel tank on a vehicle and recording the odometer reading and the amount of fuel added. The safety shut-off in the nozzle of the dispensing pump is essentially being used as a point level sensor so that the level is the same each time the tank is filled. However, these shut-off devices vary somewhat is sensitivity and they are certainly not calibrated for accuracy as a level sensor. Mileage will vary a great deal anyway. An HHO experimenter may drive between two refills without HHO, then drive until the next refill with HHO and compare mileage estimates for these refills. Given the variability of mileage values, two samples are probably not statistically significant. In fact, a p-value cannot be calculated for a data sets having a single data point so statistical significance cannot even be evaluated in such an instance.

A better procedure would be to take a set of mileage values without HHO. Then take a set of mileage values with HHO. Then compare averages of these two sets. In such a case, it is possible to compute a p-value which is essentially the probability that the difference between the two averages is the result of chance.

Below, the p-value is calculated for data taken from a mileage log on the John Henry Hydrogen web site [6]. The p-value came out at 0.0003 which indicates an extremely high probability of statistical significance.

#	KM	miles	difference	gallons	listed	computed	error
	236325	146845.5		230.0	6.980		
1	238091	147942.9	1097.3	146.9	7.513	7.470	0.994
2	239122	148583.5	640.6	87.0	7.406	7.364	0.994
3	240717	149574.6	991.1	141.8	7.030	6.989	0.994
4	243144	151082.7	1508.1	233.6	6.490	6.456	0.995
5	244948	152203.6	1121.0	156.4	7.209	7.167	0.994
6	246420	153118.3	914.7	137.4	6.695	6.657	0.994
7	247175	153587.4	469.1	68.0	6.939	6.899	0.994
8	250050	155373.9	1786.4	274.0	6.557	6.520	0.994
9	251972	156568.1	1194.3	183.4	6.549	6.512	0.994
10	255532	158780.2	2212.1	363.9	6.114	6.079	0.994
11	256556	159416.5	636.3	83.0	7.710	7.666	0.994
12	259094	160993.5	1577.0	216.1	7.340	7.298	0.994
13	260097	161616.8	623.2	86.6	7.238	7.197	0.994
14	260939	162140.0	523.2	74.0	7.111	7.070	0.994
15	262755	163268.4	1128.4	213.0	5.328	5.298	0.994
16	267151	165999.9	2731.5	412.0	6.668	6.630	0.994
17	268855	167058.8	1058.8	143.2	7.437	7.394	0.994
	273036	169656.7					
18	274882	170803.8	1147.1	164.0	7.035	6.994	0.994
19	276951	172089.4	1285.6	200.0	6.465	6.428	0.994
20	280574	174340.6	2251.2	420.1	5.390	5.359	0.994
21	282217	175361.5	1020.9	128.7	7.978	7.933	0.994
22	284084	176521.6	1160.1	223.0	5.232	5.202	0.994

Table D1. Mileage log.

These numbers are taken from a hand written mileage log for a 2004 Peterbilt rig. These are mileage values with the HHO generator running. The “listed” values are mileage values in mpg copied from the log. The “calculated” values are computed by dividing the “difference” value by “gallons” to obtain miles per gallon. The “error” value is simply the ratio between the calculated and listed values. Evidently, this driver used a kilometer to miles conversion factor that was slightly high. However, it confirms that all values were copied correctly. Some corrections were required because the handwritten “4” looked very much like a “9”. The gap after sample 17 occurred because the HHO system was off-line for a short time. These values were taken over a period of about 3 months. The error for sample 4 was off slightly, but not enough to affect the listed value at 3 decimal places of precision.

First, it is necessary to calculate a t-value given by the equation [14]:

$$t = \frac{|\overline{x_1} - \overline{x_2}|}{\sigma \sqrt{1/N_1 + 1/N_2}}$$

where $\overline{x_1}$ and $\overline{x_2}$ are the means of the sets of data denoted as data set 1 and data set 2. N_1 and N_2 are the number of samples in the respective data sets.

The σ term is the composite standard deviation of the two data sets. It is given as:

$$\sigma = \sqrt{\frac{N_1\, s_1^2 \ + \ N_2\, s_2^2}{N_1 + N_2 \quad 2}}$$

where s_1 and s_2 are the standard deviations of data set 1 and data set 2 respectively.
The expression in the denominator is commonly referred to as the number of degrees of freedom for the combined data sets. A similar log was kept for three months prior before the HHO generator was installed. The average mileage was 5.89 mpg. This log is unavailable so we have to make some assumptions. We will assume that the standard deviation is about the same and that it contained about the same number of samples. Table D2 lists numerical values of the different terms:

Average 1	5.89
Average 2	6.7924545455
difference	0.9024545455
Std dev	0.7500389023
Std dev squared	0.562558355
degrees of freedom	42
composite squared	0.5893468481
composite std. Dev.	0.7676892914
sample size adjustment	0.3015113446
T-value	3.8988470353

Table D2. Values used to compute t-value.

Sample size adjustment is simply the square root of 2 / 22. The t-value is thus:

$$t = 0.9024545455 \ / \ (0.7676892914 \ \times \ 0.3015113446)$$

It is then necessary to look-up the two tailed p-value on a table where t-value = 3.899 and degrees of freedom = 42. It comes out at 0.0003 indicating an extremely high degree of statistical significance. The rig from which this data was taken is pictured in Figure D1. The before and after mileage for this truck is listed on Table B1, third from the bottom. The “after” mileage value is given as 7.52 mpg. This is perhaps a miscalculation.

Figure D1. Mileage log shown was taken for this 2004 Peterbilt rig.

Appendix E

What is HHO?

Purpose: Describe two different types of HHO cells. Compare HHO with a 2:1 molar mixture of molecular hydrogen and oxygen gas.

Figure E1 shows a cross-sectional side view of a "wet cell" type HHO gas generator. These consist of a stack of 5 to 6 rectangular metal plates (generally 316 stainless for corrosion resistance) immersed in an electrolyte solution (10-30% potassium hydroxide of KOH). An electric current is applied across the plates generally from the 12 volt DC electrical system of a vehicle. There are 4 spaces in this particular cell so that would be an approximate potential of 3 volts across each plate (12 / 4 = 3).

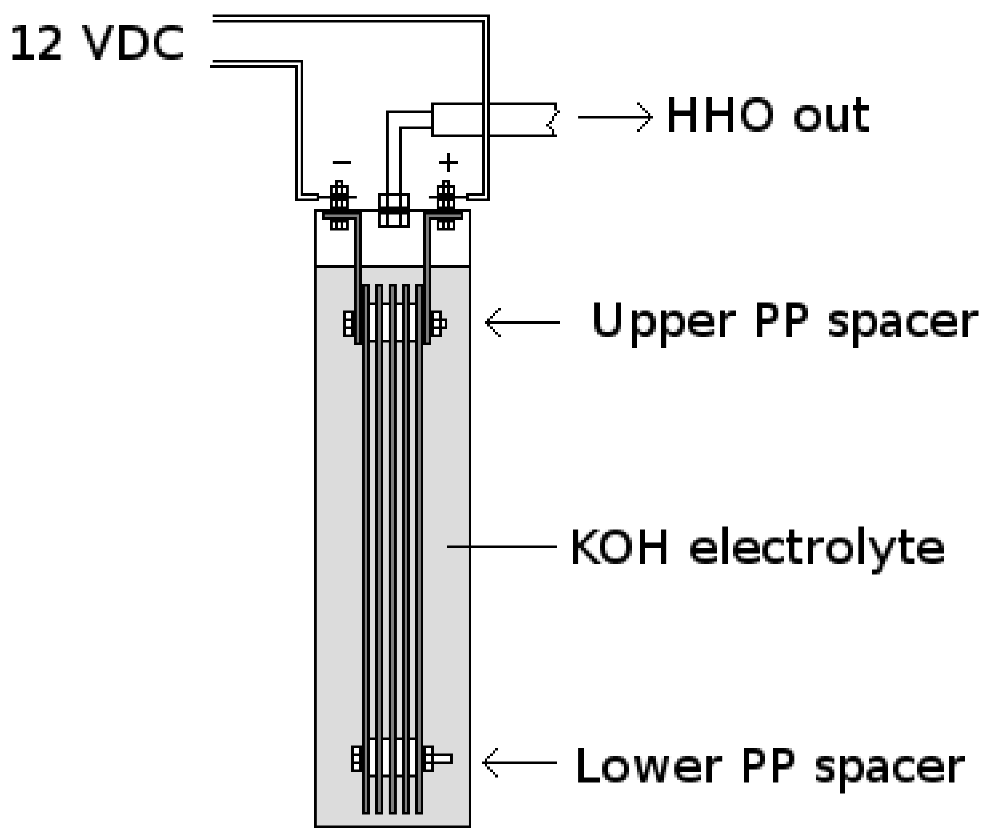

Figure E1. HHO cell, wet-cell type.

KOH is very corrosive. Nylon, polycarbonate, brass and aluminum are inappropriate materials because of low resistance to corrosion. Suitable plastic materials are polypropylene (PP), PVC, acrylic and epoxy.

In the wet cell design, a stack of plates is immersed in a sealed container of electrolyte. See Figure E2. In the so-called “dry cell” design, gasket material between each plate serves to contain the electrolyte. The metal plates are clamped between a pair of plastic sheets. (See Figure E3) In this case, threaded vent holes for the HHO are located on both sides of the cell. PVC lines are shown attached to ¼ in. NPT fittings threaded into these vents. This particular wet cell requires about 3 liters of electrolyte where as the dry cell is filled with about 0.6 liters. The maximum output of the wet cell is approximately 1 liter per minute. That of the dry cell is about 4 liters per minute. This dry cell has 21 plates divided into 4 stacks with 5 spaces each. At 12 volts, the potential across each plate would be about 2.4 volts (12 / 5 = 2.4).

Figure E2.. HHO gas generator. Wet-cell type.

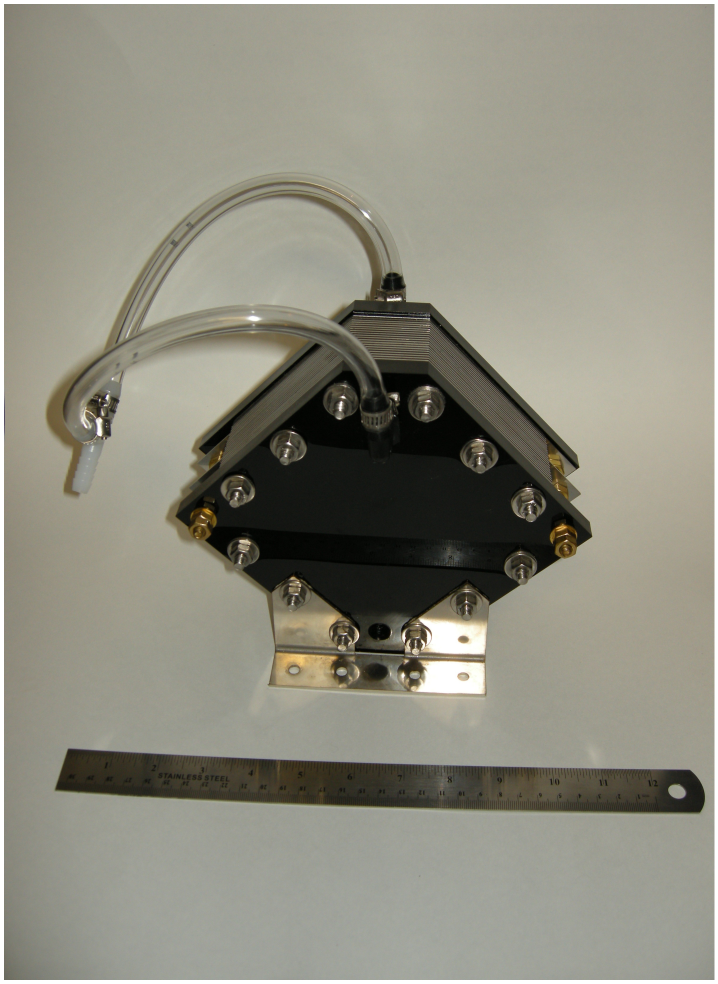

Figure E3. HHO gas generator. Dry-cell type.

This particular wet cell has brass connectors on the top. Although they are not immersed in electrolyte, they would probably come in contact with electrolyte because the bubbling action of the gas is quite vigorous, therefore, they would probably become corroded over time. The dry cell design also has brass bolts on the side for electrical connections, however, they do not come in contact with electrolyte in any way. Dry cells are generally thought to run a bit cooler than wet cells. In this case, this dry cell is approximately the same size as those used by JHH and for the UNOH tests and would probably be suitable for use in HHO gas generator systems for Class 8 vehicles.

Is HHO just oxygen and hydrogen gas? Many chemists and engineers would say that the only thing going on here is a very conventional water electrolysis. That would be reasonable except that engine dynamometer data indicates that this is not the case. Yield of additional energy per gram of H_2 contained in an injected gas mixture is given by the equation [18] :

$$(1 - k) \times E / m_g$$

where E = total energy output in a unit of time, m_g = mass of H_2 injected in the same unit of time, and k is a dimensionless ratio of fuel used with gas injection over fuel used without gas injection. The time units cancel out so units of measurement generally used are megajoules per gram of H_2 in the gas mixture. NASA ran dynamometer tests injecting hydrogen from compressed gas tanks into a spark ignition engine. Yields came out at 0.015 MJ / gram H_2. It requires at least 0.5 MJ to generate a gram of H_2 [18].

Dynamometer tests run at Fox Valley Technical College (FVTC) and Univ. of Northwest Ohio (UNOH) using HHO both got average yields of about 6.5 MJ/grams of H_2. That is over 12 times the amount of energy needed to generate the H_2 and over 400 times the value obtained in the NASA tests using H_2 from compressed cylinders.

We made email contact with persons at both FVTC and UNOH who confirmed that such trials actually were conducted. Fran Giroux who sponsored these trials was also contacted and provided some additional information.

Another study was done using a 2:1 molar mixture of hydrogen and oxygen from compressed tanks. Again, energy yields fell far short of the amount of energy needed to generate the gas mixture [13].

Reviewing this report: Engine fuel efficiency was translated to vehicle fuel efficiency. Estimated fuel savings were roughly consistent with savings obtained in long haul service on Class 8 vehicles. We attempted to determine if the reduction in fuel consumption in a sample set of fuel logs was statistically significant and it was. Nevertheless, we stop short of saying that this proves HHO is a viable concept. A lot more data is needed and it needs to be statistically qualified.

Still, even if a good knowledge of *how* HHO works is developed, people may still have a hard time getting past the fact that there is no satisfactory explanation for *why* it works.

Incorrect explanations: One explanation often given is that hydrogen increases the flame speed of combustion. This can probably be traced back to the study done by NASA. However, this would apply to molecular hydrogen gas which seems to be quite different from HHO. Also, HHO enthusiasts will sometimes confuse thermal efficiency with combustion efficiency. Combustion efficiency is the fraction of fuel that is burned. On Diesel engines three emissions components result from incomplete combustion: carbon monoxide, hydocarbons, and particulate carbon or soot. These are routinely measured and combustion efficiency can be calculated from these values. Combustion efficiency on Diesels is generally better than 98%. Thermal efficiency, on the other hand, is the amount of heat energy that gets converted to useful mechanical output. This is about 30-40% on most truck engines. The rest goes out the exhaust stack or is dissipated by the radiator. The point is: improvement of combustion efficiency is not sufficient to explain energy yields that are typically observed.

Other explanations: There is some suggestion that HHO is a sort of atomic/molecular aggregate that is not completely stable [8]. According to one researcher, its properties dissipate about 8 minutes after being generated [9].

One method for studying gas molecules and atoms is near-infrared spectroscopy. Gas molecules can act as quantum harmonic resonators with frequencies in the range of the near-IR spectrum. A gas molecule will generally have a number of different vibrational modes that will correspond to various adsorption peaks in the near-IR spectrophotometer scan. Sometimes a molecular structure can be backed out of an analysis of the near-IR spectroscopic data. Some results might be gained by examining near-IR spectrophotometer scans of HHO as a function of time within 10 minutes of being generated.

Obtaining data on the composition of HHO may be helpful in developing better HHO technology. Also, validated data indicating that HHO is different from a mixture of diatomic gas molecules will contribute to the credibility of the concept.

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