Optimized HHO injection for Class 8 Diesel Vehicles.

by Charles Ware

Abstract: Earlier reports described a model for optimizing the performance of HHO injection on Diesel engines[1]. This report will describe the application of this model to Over The Road (OTR) Heavy trucks pulling Class 8 loads[*] at highway speeds. The efficiency spike may not be so easy to locate under normal use conditions. An electronic system that measures engine load (more specifically Indicated Mean Effective Pressure or imep) is likely to be useful for adjusting the engine RPM and HHO gas flow rate to the performance spike. Once this rationale is developed and tested, it can be used to develop more practical control rationales. Optimized HHO injection (OHI) is also compared with other fuel efficiency technology for heavy tractor/trailer vehicles. The use of OHI technology in combination with other these technologies is also considered.

Background: HHO is a gas mixture of indeterminate composition containing hydrogen, oxygen, and water vapor[2]. It is produced by water electrolysis and is purported to increase efficiency of internal combustion engines when fed into the air intake. Dynamometer tests indicate that a spike in the increase in efficiency occurs engine load (Hp), speed (RPM) and HHO gas flow rate fulfill conditions defined by Eq. 1a and 1b. HHO gas flow rate is essentially defined in terms of reactor current. The flow rate will be roughly proportional to reactor current as measured in amps.

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

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

$$I = 0.04\ \text{RPM} - 24 \qquad \text{Eqn. 1B}$$

The vehicle speed can be defined in terms of this model between engine speeds 1400 and 1800 RPM. Vehicle speed in terms of RPM is given by the Eq. 2:

$$(\text{RPM} * 60) / (\text{axle ratio} \times \text{gear ratio} \times \text{tire revs/mile}) = \text{speed (mph)} \qquad \text{Eqn. 2}$$

Figure 1 shows a plot of vehicle speed vs. Hp for a Class 8 truck with full aerodynamic treatment[3] with superimposed model lines derived from this equation for two common gear ratios, 0.73 and 0.86. The selected axle ratio is 3.9 and tire revs. per mile are 476 corresponding to size 24.5/11R tires. The speed at which the spike occurs will be the intersection point between the load and model lines. In the case of Figure 1, for the 0.86 gear ratio, the speed is about 65 mph.

Figure 2 gives the same data, however, the axle ratio is 3.55. Now the model line for the 0.86 gear ratio misses the load line completely. The model line for the 0.73 gear ratio intersects at a point below 1400 RPM so it is necessary to extrapolate a little bit further down to 1300 RPM. The speed at the intersection point is about 56 mph. Figures 1 and 2 are generated from a spreadsheet that is available on-line[4].

This illustrates how specific the requirements are for OHI. Changing the axle ratio from 3.9 to 3.55 gave a completely different set of results. This kind of spike response will often have a very delicate sensitivity to influencing variables. Trying to home in on the spike with a prototype unit installed aboard a tractor/trailer rig speeding down the highway may be difficult since these are noisy, complex conditions.

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[*] Class 8 indicates Gross Vehicle Weight Rating (GVWR) greater than 33,000 pounds.

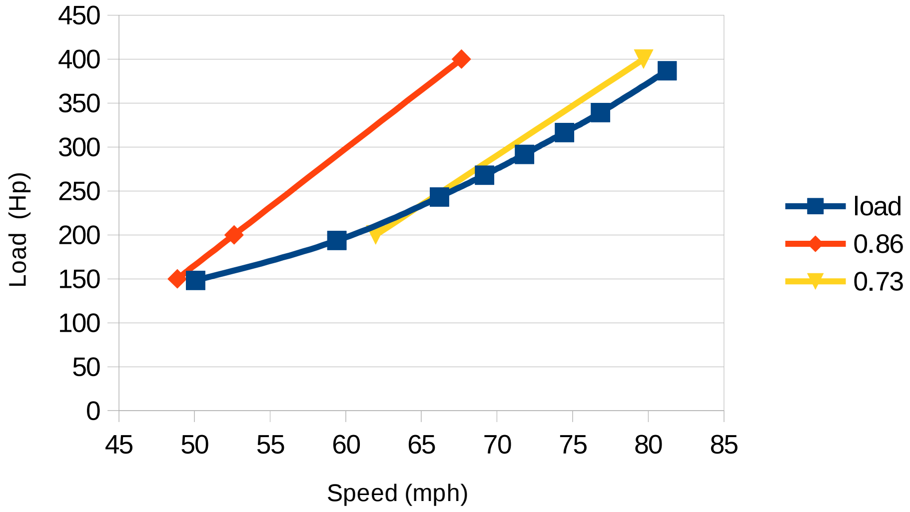

Figure 1. Load and model curves. Axle ratio: 3.9

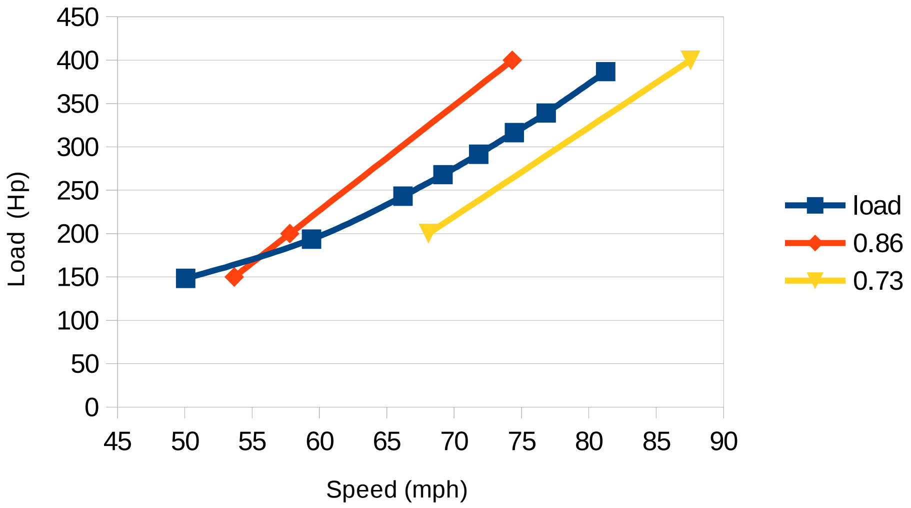

Figure 2. Load and model curves. Axle ratio: 3.55

If there is a way to measure reduction in fuel consumption is real-time, a prototype controller can use this input to automatically home-in on the spike response when the control is engaged. Also, it would be very helpful from the standpoint of testing a prototype if the control indicates that the load line is not going to intersect the model line for a particular gear selection.

Fuel Consumption Reduction: An OHI system represents an optimization problem. In analyzing an optimization problem, the output variable to be optimized should be identified. Is this variable to be maximized or minimized? Since we are primarily interested in minimizing fuel costs, we want to minimize fuel consumption for a given distance traveled. Expressed in English units, this would be gallons per mile (gpm) or the inverse of miles per gallon (mpg). From the standpoint of proportional change, the two are not equivalent. For example, a 30% increase mpg represents a 23% reduction in gpm. If a truck gets 6 mpg, a 30% increase is 7.2 (6 x 1.3). 6 mpg = 0.1667 gpm (1/6 = 0.1667) 7.8 mpg = 0.1282 gpm. (1/7.2 = 0.1282) 0.230769 = 1 – (0.1282/0.16667) or approximately 23%. It is equal to a 23% reduction in fuel costs. Even though a maximized mpg will also be a minimized gpm, the convention of measuring output in the form most valuable to the end user should be established from the outset of the development program. Therefore, we attempt to minimize gallons per mile (gpm).

Accurate and precise measurement of a variable is needed to optimize it effectively. Real-time measurement will make the optimization much faster and more efficient. The definitive standard of fuel consumption for heavy vehicles is generally considered to be SAE J1321 Feb. 2012 revision. This procedure is not real-time and it would be prohibitively expensive to use it to perform the type of optimization described here. Therefore, this document describes a method that can be used on a single vehicle under normal service conditions to perform real-time estimates of fuel consumption. In order for it to be sufficiently definitive, it is "functionally equivalent" to J1321.

Functional equivalence means identifying 3 functional requirements of J1321[5] and then showing how the same requirements are met using the more efficient method. These requirements are:

1. Normalize measurements for the test conditions. The J1321 standard uses two vehicles of the exact same model and options. One is used as a test vehicle and the other is designated as the control vehicle. A treatment under evaluation is applied to the test vehicle. Baselines are established by measuring fuel consumption of the control vehicle and the test vehicle without the treatment. Then the test is conducted by measuring fuel consumption of the control vehicle and the test vehicle with the treatment. The two baselines are close but usually not exactly the same. To some extent this reflects differences specific to each vehicle. By comparing these measurements, it is possible to estimate the change in fuel consumption that results from application of the treatment under the conditions of the test while adjusting for the small difference between the two vehicles.

2. Gravimetric measurement of fuel consumption. Both vehicles are outfitted with fuel tanks that can be detached easily and weighed. The weight of a tank is taken before and after a test run. The difference gives the weight of fuel consumed during the test. The weight of the fuel is unchanged by variables that affect the density of the fuel. Therefore, a weight measurement is considered more accurate than a volumetric measurement. It also tends to be very precise.

3. Use of statistical tests. Estimates are not based on single measurements but rather sets of measurements that are averaged. These averages are more stable than single measurements. This also enables measurement of variance. There is always some variance in this type of measurement. The question arises: How do we know if the difference between two averages is simply the result of random variance in the measurement? This kind of issue is addressed by means of a statistical test such as a t-test or j-test and the calculation of a p-value. The p-value

can be thought of as the probability that the difference between the two averages is not "statistically significant", or, they are approximately the same within their range of their variance. A smaller p-value is considered to be a stronger indicator of statistical significance. A p-value of 0.05 is commonly considered to be the upper limit for statistical significance. A p-value less of than 0.0001 is considered negligible and is a very strong indication of statistical significance. The p-values for J1321 evaluations are often negligible. If that is the case, then p-values are more of a way to check for irregularities in the evaluation process.

Verification Module Description: For development and test of OHI system and definitive measurement of fuel consumption reduction, a specially designed electronic system is needed. It would be a "black box" installed on a a test vehicle along with an OHI system. A description and theory of such a system has been prepared by the author [6]. Some test driving would be done to verify that the installation is operating in an optimized condition. Also, extended operation under long haul service conditions is needed to verify the OHI technology for its intended application. This testing might go on for some time even after beta units are released for general use. Once the production version of the OHI product is released, this sort of testing will be phased out unless issues occur that merit further investigation. Only a limited number (< 10) of these systems might be used in a test program and would probably be installed on various makes and models of Class 8 trucks.

The verification module (VM) is likely mounted somewhere in the engine compartment. It should have the following interfaces:

- Pressure sensor installed in the head of one or more cylinders. This measures the pressure of combustion inside the cylinder. There are various types of sensors made specifically for this purpose. An fiber optic sensor costs less than $1,000 and is the most likely selection [7]. Piezo sensors are about 4 times more expensive. However, they also have a bandwidth of 100 kHz while fiber optic sensors have a bandwidth of 10 kHz. The higher frequency is useful for detecting supersonic detonation that accompanies knocking on spark ignition engines. This is generally not an issue on Diesel engines. There are several reasons why cylinder pressure measurement would be better than other alternatives. This is covered below in the section, "Use of imep to determine engine load".

- On the cylinder(s) that have pressure sensors, current probes should be clipped onto the electrical leads to the fuel injector. On solenoid actuated injectors, two probes are needed: one for the solenoid to open the injector and another for the solenoid to close the injector. If piezo technology is used, then one probe is needed to monitor the piezo stack.

- Connection to the crankshaft position sensor. On any Diesel engine with an ECU, there will be a crankshaft position sensor. It is usually a proximity sensor mounted by a target gear on the crankshaft. The sensor detects the individual teeth as they pass by electromagnetic induction and produces a square wave timing signal. A commonly used target has 60 teeth with 1 tooth missing at the top center position. At 1400 RPM the sensor will give a 1.4 kHz timing signal. The VM will need a connection to this signal.

- A connection to the cam shaft position sensor may be needed, particularly if the engine has variable valve timing. Usually, these are similar to the crankshaft position sensor.

- A flow meter is installed on the fuel lines. On most trucks, the fuel pump is a constant displacement type that pumps the maximum amount of fuel needed. A return line sends the unused volume back to the fuel tank. Therefore, a differential flow meter is used that measures flow in both directions. Nominal accuracy of this instrument is generally 1%. For definitive work of this kind, a special gravimetric calibration is performed. This is described below under item 2 of the next section. Temperature sensors upstream from the meter in both directions are also needed for temperature compensation of the flow measurement. For purposes of energy efficiency, trucks are starting to use variable displacement pumps that have brushless motors with electronic drives. Of course, this technology requires only a single fuel line.

- An interface for a USB flash drive. This will serve as mass data storage for the VM. The module should have its own mass storage even if the OHI also uses a USB flash drive for diagnostic and troubleshooting purposes.

- Serial connection to the OHI controller. The OHI controller must perform various control functions regardless of the type of installation. Therefore, it will request engine load and fuel consumption estimates from the VM. The VM will return packets containing this data. The VM and the OHI controller must also have some arrangement for sharing a time base. The J1321 standard recommends the use of a GPS receiver to record distance traveled by the vehicle. The OHI controller would provide this interface since it could be used to anticipate conditions affecting optimized control.

Comparison with J1321 Requirements: The three conditions given above are fulfilled as follows:

1. Normalize measurements for test conditions. The VM is able to measure indicated mean effective pressure (imep) and engine speed. The imep is obtained numerically by plotting cylinder pressure against cylinder volume and integrating the areas enclosed within plots on a two dimensional graph. The cylinder volume is based on crank angle which is obtained from a pulse count off the crankshaft position sensor. Brake specific fuel consumption (BSFC) can be plotted on a contour map as a function of imep and RPM. This gives a baseline fuel consumption for a given imep/RPM combination. Comparing this with actual fuel consumption gives the required difference value.

   This method is complicated by the fact that the BSFC map will vary a bit from one engine to another and is also affected by ambient conditions such as barometric pressure, air temperature and relative humidity. This method has a broader scope than J1321 because it is attempts to measure fuel consumption savings under the full range of typical service conditions. Several factors help offset needs created by the larger scope of the evaluation:

   - A more extensive set of baseline data can be collected. The amount of data collected is much greater than J1321. This enables a more complex analysis.
   - The pressure/volume curve prior to fuel injection can be used to estimate mass and temperature of the inducted air. The ECU usually measures external barometric pressure and air temperature. This data is also helpful. There may already be a thermal mass air

flow sensor in the air intake or one might be installed.

2. Gravimetric calibration. A continuous, volumetric measurement is better suited for real-time use under service conditions than the batch-type weigh tank method. But volumetric meters are more subject to temperature and viscosity effects. Flow meters used in this program require calibration curves for diesel fuel at different flow rates and temperatures generated using a gravimetric flying-start-and-finish method[8]. Flow rates to an engine will be less than 1 liter per minute so a rather small flow loop apparatus should probably be assembled for this program. The loop should be small enough so that it can be filled with a 2 gallon fuel sample. A reference meter might be used to check fuel samples that are collected.

3. Use of statistical tests. The imep values will often very quite a bit from one cycle to the next. At 1400 RPM, there be 700 imep measurements per minute on a 4 stroke engine. According to the central limit theorem, the variance of the average values is inversely proportional to the square root of the number of samples in a data set. More precise averages will give more precise estimates. This is a simple example of how larger data sets and many more data sets will support a much more nuanced and complexed analysis than anything that would possible with J1321.

   In item 2 above, the issue of normalizing the baseline for the air intake and other factors is considered. Even without such normalization, the baseline is useful for optimized control purposes. Regardless, statistical analysis should be used to determine the accuracy of the estimated fuel savings using a percentage notation, e. g., ± 1%.

Use of imep to determine engine load: Direct determination of load on the engine is important for verification and OHI regulation. Once various control algorithms have been evaluated and verified, indirect methods of measuring engine load will likely be more practical for widespread use of OHI technology. Various other means of measuring engine are possible. One option is to install an electronic wireless rotational load cell sensor module on the drive shaft to measure drive shaft torque and RPM. There are several reasons why the imep method is preferable:

1. Since OHI is having an extreme effect on the combustion dynamics, there would be some concern that peak cylinder pressures are exceeding engine design limits. This can easily damage the engine or increase need for engine maintenance. A laboratory check of this issue would be helpful. However, if cylinder pressure is measured extensively under actual service conditions and no issue with peak pressure is observed, potential users will no doubt find this to be more reassuring.

2. The pressure sensor is installed by removing the cylinder head assembly and performing machining operations to make the installation port for the sensor. Then the cylinder head assembly must be reinstalled on the engine. This may seem like a lot of effort. However, the valves and interior of cylinders should be checked before and after a test period of several months running on OHI to insure that these components are not being damaged. Therefore, the equipment, procedures and qualified technicians needed for fast, high-quality swaps and replacements of cylinder head assemblies will be a necessary part of the program anyway.

3. Mathematical analysis of a system generally involves creating a model of the system being

studied. It is possible to create a model of the entire vehicle. However, the actual process being studied is confined mostly to the inside of the cylinders. A model of a single cylinder is probably adequate for most purposes of this program. Therefore, measuring engine load from this perspective is consistent with the single cylinder model.

OHI system recommended features: Various features are needed for an OHI system to perform optimized control. Other features are important for purposes of safety and reliability. These features are listed as follows:

1. There are various types of reactors purported to produce HHO. A particular reactor will be used as a design reference for purposes of this specification. It is a 6 in. 21 plate, dry cell design shown in Fig. 3. It has two ports on top, two on the bottom and an upper just below the level of the electrolyte. The ports are ¼ in NPT threaded. The reator produces approx. 4 liters of gas per minute. Materials are 316 stainless steel plates, EPDM gaskets and acrylic end plates. Estimated operational life is 3 to 5 years.

2. Power is supplied to the reactor by a PWM current regulator, with a 60 amp fuse and a back up relay to break the circuit in case the MOSFET transistor shorts out. The MOSFET and current sense resistor should be attached to a heat-sink of adequate size. The heat-sink should have a fail-safe temperature sensor. The feedback current regulation loop should be handled through the OHI control module.

3. A fail-safe temperature sensor should be installed in the lower entry of the reactor to monitor electrolyte temperature.

4. A pump should circulate the electrolyte pulling it out an upper port below the electrolyte level and feeding it back in through one of the lower entry ports. This pump circuit performs four functions:

    1. Electrolyte can be diverted through 316 SS tubing attached to the heat sink if it overheats in warm weather.
    2. The pump circuit aids in keeping a uniform electrolyte concentration, particularly when distilled water is added.
    3. Electrolyte can be diverted to a drain for the purpose of draining the cell for maintenance.
    4. Electrolyte can be pulled from a supply container to fill the cell.

5. A piece of clear PVC tubing should connect upper and lower entry points to serve as a sight tube for the electrolyte level inside the cell. Some type of automatic level sensor should be attached to this tube to allow the OHI control module to maintain the electrolyte level.

6. A metering pump should pull distilled water from a reservoir tank and inject it into the electrolyte circulation line. The OHI control module will activate this pump as needed.

7. As HHO comes out the top two ports, it generally carries some bubbled electrolyte. A liquid/gas separator should return any electrolyte back to the reactor. A second liquid trap should remove all remain electrolyte. This trap should be externally accessible so that it can be

emptied periodically.

8. An instrumentation package may be needed to measure HHO gas pressure and temperature. Volumetric flow might be determined by measuring the differential pressure across a metering nozzle or orifice.

9. A water reservoir is installed separately from the generator system in a location allowing convenient refill. A plastic line connect the reservoir to the generator. Adequate cold weather provision should be made to thaw ice in the reservoir and the supply once the vehicle is started. Diesel vehicles generally require about 20 minutes to warm up in weather that is cold enough to freeze the supply line. The supply line heat element should be sized to thaw it out in this time interval.

OHI control module. General Requirements. The OHI control module should have the following interfaces in addition to the input/output lines used to control the reactor system:

1. Blue tooth interface. This allows a technician or vehicle operator to access the OHI control module. Drivers can engage/disengage optimized regulation using a mobile device. Current rate of fuel savings and regulation status can also be displayed. Technicians will be able to view many more functions.

2. GPS receiver interface. This interface is used for testing and verification. It could be used to anticipate conditions affecting optimized control.

3. CAN-bus J1939 interface to the vehicle ECU. This is used to obtain a number of perameter that are needed or helpful in OHI regulation.

4. VM interface for testing and verification.

5. A retrofit OHI system will need some way to adjust engine RPM. A 2 way switch or relay would connect either the accelerator position sensor to the ECU or an output from the OHI control module that simulates an accelerator position sensor. If either the brake, clutch or accelerator pedals are depressed, this switch will flip back to the accelerator position sensor and optimized control will be disabled.

Additionally, the OHI control module should meet various requirements related to reliability engineering.

1. The power supply of the module should be compliant with Distributed-power Open Standards Alliance (DOSA) industry-standard specifications. It should also meet UL/EN/IEC 60950-1 safety standards.

2. The watchdog timer in the micro-computer chip should be enabled and other reliability features should be enabled where appropriate.

3. A fail-safe design rationale should be applied to the system. That is, the under-correction factor is zeroed at the expense of over-correction. That is, the probability that a fault occurs and the fault is not indicated is zero. The probability that a fault is not present but a fault is indicated is finite. The latter condition is called the over-correction or alpha condition and is likely caused by a failure in the fault indication system itself. The system should shut down if a critical fault condition is indicated. There might be non-critical faults in which case the system might operate in a contingency or "limp-along" condition.

OHI comparison with other fuel efficiency technologies: There are a number of technoogies that can be used to reduce fuel consumption on heavy Diesel vehicles. Operators of vehicles will generally have some approach or method of evaluating alternative technologies. One rationale is to divide the total cost of the upgrade by the percent savings. In the case of OHI the cost of a system might be $8,800 and $1,200 for installation giving a total of $10,000. If the average savings is 30%. Then that gives an investment rate of 10,000 / 30 = $333 per percent of savings. If an operator requires that the cost of an upgrade should be recovered within 6 months and a vehicle uses $70,000* worth a fuel each year, then the maximum investment rate would be $350 per percent of savings. (Given that $35,000 x pct / 100 = upgrade cost, where pct equals percent savings. Dividing both sides by pct gives 35.000 / 100 = upgrade cost / pct or $350 per percent. Therefore, an OHI system priced in this manner would meet a rather stringent requirement of recovering upgrade cost in less than 6 months.

The National Highway Traffic Safety Administration (NHTSA) sponsored a study of fuel efficiency technologies [9]. Saving rates of various technologies are listed in Table 2.

Technology	Savings
Aerodynamics	11.50%
Engine	20.00%
Weight reduction	1.30%
Tires	8.00%
Transmission	7.00%
Hybrid	10.00%
Fleet mgmt. & training	6.00%
Added wt. 2500 lbs	-1.03%
Total	**48.90%**

Table 1: NHTSA study. Percent savings of various technologies.

Note that the sum of all savings values would be 63.8%. The reduction rate is 1 – savings rate. The combined reduction rate is the product of the reduction rates of the individual technologies. Therefore, 0.885 x 0.8 x 0.987 x 0.92 x 0.93 x 0.9 x 0.94 x 1.0103 = 0.511 and 1 - 0.511 = 0.489 or 48.9%. The weight of all upgrades was estimated at 2,500 pounds which increased fuel consumption by 1.03%. The cost of all upgrades was estimated at $84,600. The investment rate would be $1,731 / % benefit. With an investment of $700 / % for one year to recover costs, it would take 2.47 years to recover this cost.

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* Reference case is taken as 6 mpg, 105,000 miles per year, $4 per gallon of fuel. ($4 x 105,000 / 6 = $70,000). The figure 105,000 miles is approx. annual median mileage for long haul vehicles and it produces round figure.

A large part of the energy losses occur in the engine. In proposing a 20% savings in energy costs because of improved engine efficiency, the authors of the study perhaps had in mind upgrades being tested in the Cummins / Peterbilt "super truck" program. Figure 3 shows improvements resulting from various engine and power train improvements [10]. Efficiency is improved to 51.25% over the 42.5% DOE baseline.

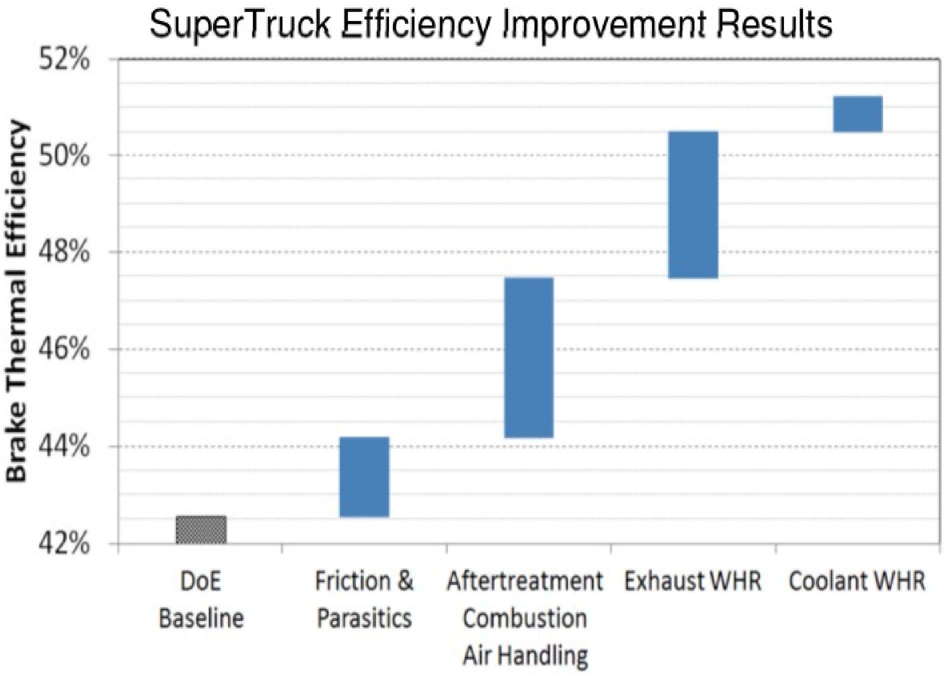

Figure 3. Engine technologies used by Cummins/Peterbilt program

Of course, brake thermal efficiency is the inverse of brake specific fuel consumption. As was noted above with mpg versus gpm, a 23.5% increase in engine efficiency is equal to a 19% decrease in fuel consumption. This is comes close to the NHTSA estimate.

A 48.9% reduction in fuel consumption would work out to 11.74 mpg. The Peterbilt supertruck which incorporates many of the technologies evaluated in the NHTSA study as of Feb. 18, 2014 gets an average of 10.7 mpg [11] over a 312 mile trip cycle test. The average mileage while driving under typical highway conditions at 64 mph with a 65,000 pound weight is closer to 11.1 mpg. This works out to a 46% reduction over the 6 mpg baseline. (1/6 = 0.16667, 1/11.1 = 0.09009, 0.09009 / 0.16667 = 0.54054 reduction and 1 - 0.54054 = 0.45946 savings) This lines up fairly well with the estimate of the NHTSA study.

The OHI technology is likely to be largely compatible with the other technologies used on this test program. Table 2 combines the 46% reduction of the super truck program with an additional 30% reduction that may be possible with the OHI technology following the same method used on Table 1.

Super truck	45.95%
OHI	30.00%
Total	**62.16%**

Table 2. OHI technology added.

This savings applied to the 6 mpg baseline gives 15.8 mpg. (1 - 0.6216 = 0.3784 reduction, 1/6 = 0.16667 gpm baseline, 0.16667 * 0.3784 = 0.06306 gpm or 15.85 mpg).

Other Aerodynamics Technology: This section considers a possible tweak to the technologies tested as part of the Peterbilt super truck program. The proposed device may also act synergistically with OHI technology.

At highway speeds, a larger part of the load on the engine is aerodynamic and a larger part of the aerodynamic load results from the pressure difference between the front and rear of the vehicle. Therefore, mitigation of the partial vacuum created in the wake of the vehicle is an important part of the aerodynamic treatment of Class 8 vehicles. Figure 4 shows the “boat tail” flaps used during the February 2014 test runs of the super truck program.

Figure 4. Super truck boat-tail flaps installation.

Extensive research has gone into optimization of fairings of this kind, testing length and angle to determine the best values [12]. A 4% savings is one optimal value described in the literature [13] (0.3778 / 0.3941 = 0.9586, 1 – 0.9586 = 0.0436 or 4% saving. A 6% savings may be possible with a vortex generator device that is installed along the trailing edges of the tractor and trailer. Such installations are shown in Figures 5 and 6.

Figure 5. Vorblade tractor installation

Figure 6. Vorblade trailer installation.

These devices generate individual vortex streams that reduce the scale of turbulence and stabilize the air flow trailing behind the vehicle. A J1321 evaluation done by Texas A&M on August 13th and 14th , 2012 determined that total reduction of a tractor trailer installation is 9.2% at 62 mph [14]. About 65% results from the trailer and the rest results from the tractor.

The separation between the tractor and trailer on the super truck program was greatly reduced. This could present various operational and maintenance difficulties in the face of the many varied conditions and contingencies under which a vehicle must operate. Use of the Vorblade device along the trailing edge of the tractor may be a more robust and practical method for reducing drag that results from the gap between tractor and trailer.

Turbulence will introduce fluctuation into the engine load. This could reduce the precision of the feedback control of an OHI system. If this turbulence fluctuation is decreased, the more precise OHI feedback control may result in further a increase in fuel cost savings. Therefore, the Vorblade devices may act to enhance the performance of OHI systems to some extent in addition to giving better results than boat tail flaps.

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