Cleaning up Diesel and Automotive Exhaust with Hydrogen

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Summary:
Addition of hydrogen to the air intake of a combustion engine can dramatically cut the pollutants in the engine's exhaust. Reductions up to 50% have been observed in studies, some dating back into the 1950's. Hydrogen bums more fiercely, propagating the flame front faster, increasing the efficiency of combustion, and burning the fuel more completely. In the Hydrogen Generator, distilled water is converted by electrolysis into hydrogen and oxygen gas, which is then pulled into the engine through the air intake. This uses some of the engine's power, but the return from increased efficiency in a lot of cases is more than the cost of the electricity. Fuel efficiency can increase, as stated in both customer letters and formal test results. The main benefit, however, is a reduction in exhaust emissions, which is fast becoming more important to independent truckers. Several states, California and New Jersey for example, are heavily fining truckers for smoky exhaust, making a device like this invaluable.

Background:

There have been a large number of studies where hydrogen has been added to the fuel to reduce the engine's emissions. (See references 1,2,3,4,5,6.) In reference 6, Hoehn and Dowdy of the Jet Propulsion Laboratory performed a feasibility demonstration of a road vehicle fueled with gasoline, with hydrogen added to the air-fuel mixture.

"The JPL concept has unquestionably demonstrated that the addition of small quantities of gaseous hydrogen to the primary gasoline significantly reduces CO *and NOx exhaust emissions while improving engine thermal efficiency.* " (6)

"The addition of hydrogen to combustion mixtures can provide additional thermal energy release, lower ignition temperatures, advance flame speeds, reduce the undesirable emissions of nitrogen oxides and carbon monoxide and generally affect a more efficient combustion". (1)

It emerges from reading the studies that the key factor in adding hydrogen is the increased flame speed. The flame front speed for hydrogen is four times the speed of most other fuels. Take a quick look at the table below.

Fuel	**Flame Velocity** (cm/sec)
Hydrogen	225
Ethylene	42
Methane	39
Ethane	38
Propane	43
Butane	70

Increasing the flame speed in the combustion chamber has a distinct advantage. More fuel is burned in a smaller volume, increasing the thermal efficiency of the engine (7,8,9,10). Increased efficiency translates into better utilization of the primary fuel rather than adding power, which results in lower average combustion temperatures and pressures. These reduce NOx formation, since NOx formation is both time and temperature dependent (11). More fully utilizing the fuel also reduces the unburned hydrocarbons in the exhaust, again reducing the engine's emissions.

To provide a more technical explanation, quoting Roy McAlister, President of the American Hydrogen Association,

"Mixing hydrogen with hydrocarbon fuels provides combustion stimulation by increasing the rate of the molecular - cracking processes in which large hydrocarbons are broken into smaller fragments. Expediting production of smaller molecular fragments is beneficial in increasing the surface-to-volume ration and consequent exposure to oxygen for completion of the combustion process. "

Making it work:

The amount of hydrogen required to increase flame velocity is less than 1 % of the inducted air volume (2,3,4,7). You would think this small amount of hydrogen could be easily supplied, but herein lies the main problem. Laboratory techniques have generally used bottled hydrogen, which isn't an option for anyone driving a truck or car. Over the years many attempts have been made to crack a portion of the primary fuel to get the hydrogen (3,5) including MIT with their Plasmatron (12). Trying to crack the fuel requires extensive modifications to the engine, or draws so much power from the engine like the Plasmatron does, that it becomes impractical. Another technique has been to crack the fuel using a simplified steam reformer, which also has proven bulky and impractical since steam isn't readily available onboard most vehicles.

Sometimes the simplest approach is the best. In the Hydrogen Generator, distilled water is split into hydrogen and oxygen gas using electrolysis. Most people have seen this demonstrated in their high school chemistry class using a couple of batteries. The electricity required for the Hydrogen Generator is drawn from the alternator, pulling about 6 amps at 12 volts using about 72 watts of power in an automobile. This is less power than the headlights draw, minimizing the impact on the engine. A diesel truck draws more, but it is still comparatively low compared to the power of the engine.

Formal testing was conducted by California Environmental Engineering (located in Santa Anna, California) on the Hydrogen Generator, which will be summarized. A 1500 hp Cummins BC4 diesel engine on a dynomometer was tested. The engine was extremely clean and well tuned, meaning the engine had very clean exhaust to start with. Carbon Monoxide (CO) was reduced by 2.9%, which was good considering the baseline was only 1 gram per bhp/hr before testing with hydrogen. The hydrocarbons (HC) were reduced by 8.3%, which was also very good considering the low baseline. The Nitrogen Oxides (NOx) were reduced by 4.6%, which was deemed "amazing" because diesels produce a lot of NOx and since most catalytic converters (the alternative) can't reduce NOx's at all. The testing also showed a reduction in brake specific fuel consumption (BSFC) which means the fuel economy improved by 2.1 %. The results are tabulated below.

	CO	**HC**	**NOx**	**BSFC**
Baseline	1.01	0.36	5.23	0.349
w/Hydrogen	0.98	0.33	4.99	0.342
Difference	0.03	0.03	0.24	0.007
% Change	-2.90%	-8.30%	-4.60%	-2.10%

It's important to remember the engine used in the test was well tuned prior to testing. It would be interesting to see results from an operating engine, not a pampered test engine. Results on a dirty, poorly tuned engine are significantly better, as seen in the letters which came in unsolicited from customers using the Hydrogen Generator on their vehicles. Customers observed that emissions improved steadily over the first 4000 miles as the engine was cleaned out by the added hydrogen, and they saw increases of over 50% in the clarity of the exhaust. Numerous letters cited significant mileage increases, which was the main reason they had written the letters. Increases averaged over 20% in the letters, although these must be considered on the high end of the scale. Some saw no increase in fuel economy, only a decrease in emissions which was the main reason for installing the unit in the first place.

In addition to selecting the simplest method for providing the hydrogen, the Hydrogen Generator also doesn't use any throttle control. The unit provides what would be 1 % of the air stream at full power as hydrogen and oxygen gas. This further simplifies the device, making it much easier to retrofit to an existing engine

Afterward:

In summary, the Hydrogen Generator is based on proven engineering methods for reducing emissions, which date back several decades. Test results confirm this, and also show that the technique can increase fuel economy in some cases. From an external viewpoint, it appears that the equipment is simple and relatively easy to install and operate, which should result in increased reliability. All it takes is pure water.

References:

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(11) K.C. Tsao and C.L. Wang; "Performance of Gasoline-Water Fuel in a Modified SI engine" ASE #841399

(12) L. Bromberg, D. R Cohn, A. Rabinovich and N. Alexeev; "Experimental Evaluation of SI Engine Operation Supplemented by Hydrogen Rich Gas from a Compact Plasma Boosted Reformer" SAE 2000-01-2206

(13) Manufacturers of Emission Controls Association; "Retrofitting Emission Controls on Diesel Powered Vehicles", www.meca.org, March 2002.

Diesel Truck Application	*Typical Cost*	*Fuel Cost Increase*	*Fuel Cost Decrease*	Effective On... PM	*HC*	CO	*NOx*	*Loss In Horsepower*
Hydrogen Generator	$3,000		2%	X	X	X	X	
Catalytic Converter, 2 Stage	$3,500	2%		X	X	X		2 to 3%
Catalytic Converter, 3 Stage	$5,250	2%		X	X	X	X	2 to 4%
Particulate Filter	$7,500	1%		X	X			up to 1%
Selective Catalysts	>$10,000			X	X	X	X	
EGR System	$13,000						X	est. 2%

PM = Particulate Matter
HC = Unburned Hydrocarbons
CO = Carbon Monoxide
NOx = Nitrogen Oxides

The Competition:

There are several choices for competing technologies, but catalytic converters rise to the top of the list. Other options include particulate filters, selective catalysts, and EGR systems, so we'll look at all four. The data used in this article came directly from the Manufacturers of Emission Controls Association (13) which oversees the entire industry.

Catalytic Converters:

Catalytic converters are flow-through devices, which can be retrofitted onto an existing engine in much the same way as the Hydrogen Generator. We'll take a look at the most significant factors; the ability to clean up exhaust gasses, cost and the effects on the engIne.

First, lets look at what a catalytic converter actually does. Exhaust gasses flow through the device and react with added oxygen, to chemically combust the unburned gasses. A catalyst is used rather than a spark to react the unburned gasses, and oxygen is added by pumping additional air in with the exhaust gasses. Carbon monoxide (CO) reacts to form carbon dioxide (CO2) and unburned hydrocarbons combust further towards CO2 and H2O.

The gasses have to be hot enough to combust (550 degrees F where conversion begins and 750 degrees F where efficiency is high) which can be a problem with diesel engines since the exhaust gasses aren't generally hot enough all the time to burn the sooty particulates. Typically, an engine has sensors which tightly control the Air/Fuel Ratio to target the optimum range for the catalytic converter. Take a quick look at a diagram published in the Toyota Autoshop-lOl manual. On a properly tuned engine, a catalytic converter works very well in reducing emissions.

<u>*Catalyst Efficiency*</u>

Efficient catalyst purification relies on the Closed Loop Control system to maIntain a very narrow A/F mixture range around the "ideal" 14.7/1 ratio.

Diesel oxidation catalysts are the ones we are specifically looking at here. Oxidation catalysts have been used on vehicles for over thirty years, and when used with low-sulfur diesel, show significant reductions in particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO) but they have no effect on nitrogen oxides (NOx).

The main disadvantage of a catalytic converter is a drop in engine efficiency. A typical engine will lose between 2 to 4% of it's horsepower due to the back pressure of adding a catalytic converter. This results in additional fuel costs, and that's the last thing an operator wants to hear. He has to pay up front for a device he didn't want in the first place, and has to continue paying for it in fuel for the life of the truck. We'll finish up with installation cost. An oxidation catalytic converter designed to retrofit a diesel truck costs about $5250 for a three-stage catalytic converter, $3500 for an older two-stage design. In addition to this, the decrease in efficiency of the engine after adding the catalytic converter will increase fuel costs by around 2%, which the operator must also consider. This factor may have the larger impact, since fuel costs directly affect the profitability of each and every run. Overall, a catalytic converter is more expensive up front and costs even more as the miles add up; the advantage goes to the Hydrogen Generator.

Selective Catalytic Reduction:

Selective catalytic reduction (SCR) is another quite different option. In this method, the system feeds a urea solution into the exhaust prior to a catalytic converter. The urea chemically reacts to directly remove pollutants from the exhaust stream. It can achieve significant reductions in PM, HC, and CO, but it also reduces NOx pollutants as well. Selective catalytic reduction is experimental, and since SCR's are estimated at over $10,000 per installation, they are not even in the running.

EGR Systems:

This method has been used by automobile manufacturers for years, and stands for exhaust gas recirculation. It works by re-routing a portion of the exhaust gasses back into the intake manifold under high-temperature conditions to reduce NOx production. The pre-burned gasses reduce the amount of air and fuel in the combustion chamber to lower the engine's power in order to reduce combustion temperatures and pressures. High combustion temperatures and pressures increase N Ox production in the engine. EGR systems do not affect particulate or any other pollutant besides NOx, but it can achieve up to a 40% reduction. It works on NOx, but it reduces engine horsepower in the process.

EGR systems are generally combined with a particulate filter and are by far the most expensive option. Retrofitting an engine costs between $13,000 and $15,000. Clearly the cost

alone causes most operators to look for another answer.

Particulate Filters:

Filters provide the most direct approach to reducing diesel engine emissions. Second-generation systems are very effective, and can reduce the exhaust particulate up to 90%. They can also reduce unburned hydrocarbons as well. Filters, however, do not reduce CO or NOx at all without the help of a catalytic converter, which is why they are commonly combined in production vehicles. The filters also fill up over time, and must employ a way to bum off the accumulated material. Regeneration of the filter is done in a number of ways, including using catalysts, fuel-borne additives, exhaust fuel injection, and onboard heaters.

There are disadvantages to particulate filters similar to the ones for a catalytic converter. A filter by it's nature increases the back-pressure to the engine. This causes a drop in fuel economy similar to a catalytic converter, but it is lower, down in the 1 % range. The regeneration technique has a much larger impact. Exhaust fuel injection can reduce fuel economy by up to 5%, making it the least-preferred method. Heaters have less impact, but still sap power directly from the engine. Additives don't affect engine performance significantly, but they do add to the fuel costs. One of the more common methods is to combine a filter with an upstream oxidation catalytic converter. This is effective, but significantly increases the cost of the overall system.

This type of emission system is rather expensive, but costs much less than an EGR system. They average $7500 each, making them somewhat competitive with catalytic converters, but still much more expensive than the Hydrogen Generator. Add to that the 1% increase in fuel cost, which stays with the owner as long as the truck is operating, and other options begin to look a lot more attractive.