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Impacts of HHO gas utilisation on the operating parameters in internal combustion engines

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Abstract: Social pressure is forcing manufacturers to make huge investments in development in order to reduce the harmful emissions of passenger cars. However, there are also cheaper solutions that promise to reduce pollutants with minimal investment. One way is to enrich the fuel/air mixture with HHO gas (oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen). HHO gas is produced by the electrolysis of water using the vehicle's electrical system. This study investigated the impact of an HHO generator on the operating parameters of an internal combustion engine. The testing took place on two levels. The first was a laboratory test with an spark ignition (SI) engine connected to a dynamometer where complete load characteristics were measured and the function of the engine in various steady-state modes was monitored. The second was a laboratory test of a compression ignition (CI) engine vehicle in a chassis dynamometer where the engine behaviour was observed during simulated driving. During the measurements, it was clearly demonstrated that there is a serious change in the fuel/air mixture. The HHO gas mixture caused engine control instability. The control unit was not able to sufficiently regulate the engine parameters. During the test on chassis dynamometer, the steady-state regimes did not last long enough for this instability to occur.

Keywords: CO_2; fuel consumption; hydrogen; NO_X; particulate matters

Social pressure to reduce harmful emissions can lead to many different solutions to the problem of how to reduce the emissions. One way to reduce harmful emissions is to use hydrogen to support combustion in the burning of fossil fuels.

However, working with hydrogen brings many complications, for example, hydrogen is difficult to transport and hydrogen storage is very problematic. High pressures bottles are necessary for its storage. A possible solution is, therefore, the production of hydrogen directly in a vehicle.

Brown's gas, oxyhydrogen or HHO are different names for a gaseous mixture of oxygen and hydrogen. Oxyhydrogen is formed during the electrolysis of water. A plant for the production of hydrogen oxygen is called an alkaline electrolyser (Yilmaz et al. 2010). In addition, this electrolyser can be placed in a vehicle.

The positive impact on harmful emissions and performance of using HHO is greater for spark ignition (SI) engines. Sharma et al. (2015) observed the effect of an oxyhydrogen gas addition on different performance characteristics of a four stroke SI engine. The brake power of the engine increased by about 11.5% on average. The specific fuel consumption of the engine decreased by about 6.35% on average. The brake thermal efficiency of the engine increased by about 10.26% on average. Furthermore, the NO_X emissions were reduced.

De Silva et al. (2015) measured the impact of oxyhydrogen in an SI engine. The use of oxyhydrogen in SI engines enhanced the combustion efficien-

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cies, consequently reducing the fuel consumption by about 20 percent. The use of oxyhydrogen in an SI engine increased the power output by 5.7% and the thermal efficiency increased by 5 percent.

Dhananjay et al. (2015) measured on a four-stroke SI engine with oxyhydrogen as a fuel supplement. The use of oxyhydrogen in the SI engine increased the combustion efficiencies which led to a decrease in the fuel consumption by 20%. A decrease in harmful carbon monoxide (CO) and hydrocarbons (HC) emissions was observed. Use oxyhydrogen in an SI engine led to an increase in the power output of the engine by about 5.7%.

Yilmaz et al. (2010) examined the impact of different electrolytes on the HHO production. Both SI and compression ignition (CI) engines were tested. An approximate 32.4% and 19.1% increase was observed in the torque with the SI and CI engine, respectively.

A second experiment by Yilmaz et al. (2010) tested HHO gas in 3.6 L CI engine. During the experiment, HHO was added to the engine without any modifications. It led to an increase in the torque output by an average of 19.1%, reducing the CO emissions, HC emissions and specific fuel consumption (SFC) by an average of 13.5%, 5% and 14%, respectively. EL-Kassaby et al. (2016) tested oxyhydrogen in a Škoda Felicia 1.3GLXi engine. The results showed an obvious 34%, 18%, 14% and 15% reduction in the fuel consumption, CO, HC and $NO_{X,}$ respectively.

Lilik et al. (2010) reported on oxyhydrogen, from 0% to 15%, added into the intake system in a diesel engine by the aspiration of hydrogen into the engine's air intake. The authors show that the carbon monoxide and carbon dioxide emissions decreased with an increase in the oxyhydrogen, but NO_2 emissions increased.

Dahake et al. (2016) studied various methods to improve the poorly flammable properties of diesel to improve combustion using oxyhydrogen. A mixture of HHO and air in the intake air led to increases in the thermal efficiency by about 9.25%, while the specific fuel consumption was reduced by about 15 percent. The HC and CO emissions were reduced by about 33% and 23% on average, respectively. In this experiment, an increase in the nitrous oxide production was observed during full load conditions.

The electrolyser design has a major influence on the amount of gas generated. The influence of the electrolyser design on the oxyhydrogen production and its impact on the emissions were investigated by Trujillo-Olivares et al. (2019). The effect that the amount of oxyhydrogen added had on the emissions was monitored. Their studies show that the electrolyser assembly with four hole electrodes achieved the best performance with an oxyhydrogen gas (OH2G) productivity of 2 L·min^{-1} when using: seven serial plates at the anode, a 3 mm gap and a 5% solution of NaOH. The results of which are very interesting. In this experimental configuration, a 14% reduction in the fuel consumption, a 22% reduction in the HC, a 23% reduction in the CO, a 7% reduction in the $CO_{2,}$ and a 15.5% NO_X reduction were observed with the 2 L·min^{-1} of the OH2G at 2 500 rates per minute.

The use of hydrogen as a fuel in agricultural technologies can bring many positives. During performed experiments was showed space for reduce harmful emissions (Kolbenev 1993).

Oxyhydrogen adds additional oxygen and hydrogen to the fuel-air mixture, both in a gaseous form. The theory assumes that the enrichment of the mixture with highly flammable hydrogen will lead to faster and better fuel combustion. The electrolyser is located in the engine compartment and connected to the engine's electrical system. In the case of an SI engine, the output from the electrolyser is fed behind a throttle valve. For a CI engine, it is located behind a mass air flow (MAF) sensor. This is due to the maximum use of the generated gas from the electrolyser. This will result in increased torque and power, reduced consumption as well as emissions.

Low-volume engines can be expected to have a lower specific fuel consumption. The effect of decreasing the specific fuel consumption can be supported by installing an HHO gas generator to the engine.

This experiment verified the use of an HHO generator in small engines. The aim was to verify the viability of the concept in both diesel and petrol engines as well as the impact on the operating parameters.

MATERIAL AND METHODS

Two engines were selected for the experiment. The engines were chosen because they both had three cylinders with a similar performance. Both engines are designed for small a family car.

Spark ignition engine. The first type was a spark ignition engine with a displacement of 1.2 L from a Škoda Fabia. This engine was connected to a V125 whirl dynamometer (VUES, Czech republic). The engine was measured in steady-state modes. The settings of the dynamometer during the measurements are shown in Table 1.

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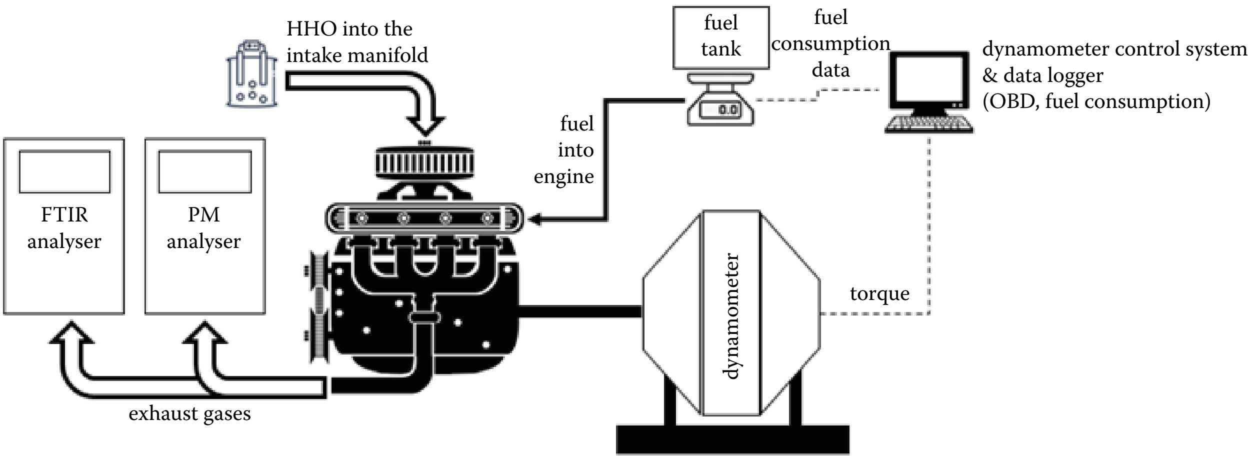

Figure 1. Measurement scheme of HHO with the SI engine

HHO – oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen; SI – spark ignition; OBD – on-board diagnostics

The wiring diagram of the measuring devices and engine for this experiment are shown in Figure 1.

The basic parameters of the measured engine are given in Table 2.

Compression ignition engine. The second tested engine was a 1.4 L diesel engine. This engine was housed in a Škoda Roomster. Measuring took place on a Schenk 3604 chassis dynamometer (Schenk company, Germany) during the worldwide harmonized light vehicles test cycles (WLTC) driving cycle. The driving cycle was repeated three times. The scheme of the measuring instruments, data logger and test vehicle are shown in Figure 2. The basic parameters of the measured engine are given in Table 3.

Oxyhydrogen generator. The HHO generator was supplied by H2I. This is a 2 500 cm^{-3} model designed for engines up to 2.5 L or 120 kilowatts. It was separately connected to the tested engines according to the manufacturer's instructions. The output of the hydrogenerator was connected to the engine intake system after the MAF sensor.

The HHO gas production was 2.5 $L\cdot min^{-1}$ by the generator. Pure water was used as the electrolyte with potassium hydroxide (KOH) in a concentration of 20 g of KOH per 1 kg of water.

Emission analysers. The gaseous and solid components of the exhaust gases were investigated during the experiment. A Matrix MG-5 gas analyser (Bruker, USA) was used to measure the gaseous component. It is an infrared spectral analyser with Fourier transform. To measure the solid compo-

Table 1. Operating parameters of the dynamometer during the measurements

Dynamometer setting during measurement	
Speed (rpm)	Torque (Nm)
1 400	15
2 000	25 50 75 100
3 000	25 50 75 100
4 000	25 50

Table 2. Technical information of the tested SI engine

SI engine (1.2 HPI)	
Design	spark ignition, atmospheric
Fuel system	multi point injection
Number of cylinders and valves	3 in row, 6 valves
Displacement	1 198 cm^{-3}
Power	40 kW at 4 750 rpm
Torque	106 Nm at 3 000 rpm
EU limit	EU4
Mileage	136 000 km
Total weight	1 570 kg
Fuel consumption	7.8/4.8/5.9 ($L\cdot 100\ km^{-1}$)

SI – spark ignition

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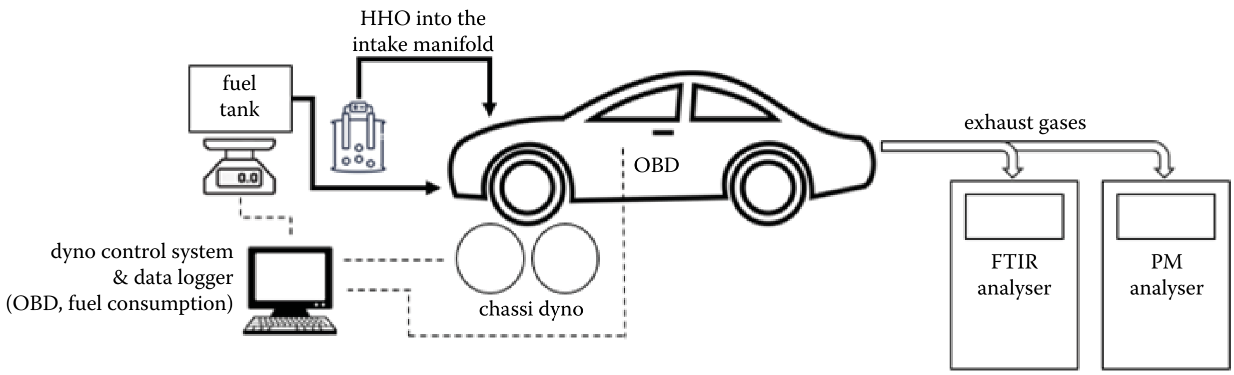

Figure 2. Measurement scheme of HHO with the CI engine

HHO – oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen; CI – compression ignition; OBD – on-board diagnostics

nent of the exhaust, a counter and a particle classifier, model EEPS 3090 (TSI, Germany), were used.

The particulate matter production was measured as the absolute frequency in the diluted exhaust gas charge. The TSI EESP 3090 was set to a dilution ratio of 1 : 200 during the measurement. Equation (1) shows the calculation of number of particulate matters per 1 kilometre.

$$\# = \frac{\int_{t_{start}}^{t_{end}} \frac{MAF}{M_{air}} \cdot V_{air} \cdot 200 \cdot C_{PM} \cdot dt}{d} \quad (1)$$

where: # – number of particulate matters per 1 km; t_{end} – end of cycle (1 800 s); t_{start} – start of cycle; MAF – instantaneous mass of the intake air (g·s^{-1}); M_{air} – molar mass of air (28.96 g·mol^{-1}); V_{air} – molar volume of air (22.4 dm^3·mol^{-1}); C_{PM} – concentration of the particulate matter in the exhaust gases (#·cm^{-3}); 200 – exhaust dilution ratio 1 : 200; d – distance travelled in the driving cycle (23.266 km).

Table 3. Technical information of the tested CI engine

CI engine (1.4 TDI)	
Design	compression ignition, turbo charged
Fuel system	unit injector system
Number of cylinders and valves	3 in row, 6 valves
Displacement	1 422 cm^{-3}
Power	59 kW at 4 000 rpm
Torque	195 Nm at 2 200 rpm
EU limit	EU4
Mileage	102 000 km
Total weight	1 755 kg
Fuel consumption	5.1/3.76/4.26 (L·100 km^{-1})

CI – compression ignition

The production of gaseous emissions will be processed by conversion from the amount of the intake air determined by the on-board diagnostics depending on the concentration of the gaseous particles in the exhaust system, according to the Equation (2):

$$m_{xy} = \frac{\int_{t_{start}}^{t_{end}} \frac{MAF}{M_{air}} \cdot C_{poll} \cdot M_{poll} \cdot dt}{d} \quad (2)$$

where: m_{xy} – mass flow of the harmful substance per 1 km; t_{end} – end of cycle (1 800 s); t_{start} – start of cycle; MAF – instantaneous mass of the intake air (g·s^{-1}); M_{air} – molar mass of air (28.96 g·mol^{-1}); M_{poll} – molar mass of the pollutant; C_{poll} – concentration of the pollutant in the exhaust gases (%); d – distance travelled in the driving cycle (23.266 km).

Specific fuel consumption. The fuel consumption was measured directly as the fuel weight loss. For accurate weighing, we used AJ-6200CE laboratory scales (Vibra, Japan). The engine fuel was pumped from an external fuel tank on the weighing machine.

RESULTS AND DISCUSSION

The results of the experiment are divided into two parts due to the use of two different engines.

The first part of the results is devoted to comparing the measured values of the SI engine. The fuel consumption results are shown in Figure 3. The results do not show any significant impact of the use of oxyhydrogen on the fuel consumption. On average, the

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use of HHO resulted in a 1.1% increase in the fuel consumption. Engine control instability occurred during the HHO measurements. The control unit was unable to respond to the changes in the fuel-air mixture after the addition of HHO. This problem often caused fluctuations in the set engine speed or inability to the electronic control unit (ECU) to maintain the required torque for a sufficiently long time. In the results, this was reflected by a decrease in the stability of the measured values. Figure 3 shows that the variance in the values was wider when using HHO.

The CO and NO_X emissions show no effect with the use of oxyhydrogen.

However, the engine power dropped by 4% when using HHO. Originally, the engine had 40 kW. The power drops to 38.4 kW after using HHO. The maximum torque also decreased, from the original 105.8 Nm to 99.6 Nm, thus by 5 percent.

These results are inconsistent with those presented by Musmar and Al-Rousan (2011). During their experiment, the consumption was reduced by 20 percent. The NO_X emissions decreased by 42% and the CO emissions decreased by 82 percent. Al-Rousan (2010) achieved similar results to Musmar and Al-Rousan (2011).

The measured results in our research are consistent with those conducted by Becerra-Ruiz et al. (2019). During their experiment, the direct NO_X production increased up to 30 percent. However, the HHO generator and oxyhydrogen production have great influence on the results.

The second measurement was carried out on a chassis dynamometer during the WLTC driving cycle with a Škoda Roomster. The average fuel consumption over the cycle was 5.22 L·100 km^{-1} for pure the diesel and 5.58 L·100 km^{-1} for the HHO. This means a 6.9% increase in the fuel consumption.

On average, the NO_X emissions were 131 mg·km^{-1} with the clean diesel, while it increased to 176 mg·km^{-1} when using the HHO, which is a 34% increase.

The effect that the oxyhydrogen had on the performance was again negative. With the pure diesel, the engine generated 64.4 kW of power and 199.7 Nm of torque. When oxyhydrogen was used, the power dropped to 60.2 kW and the torque decreased to 197.4 Nm. The graph of torque and power is shown in Figure 4. The figure also shows that even in this case, the ECU had problems maintaining the required engine parameters. The torque curve is not smooth, but it has a ripple effect. When driving on a roller dynamometer, this ripple was reflected in the jerking of the vehicle, which significantly reduced the comfort. This was due to the reduction in the total cetane number of the mixture. This led to the fuel burning faster. The ECU responded to the sharp increase in the burning speed by reducing the fuel dose. This led to the creation of ripples in the power and torque curves. This problem is further described in the following section of the results.

During the experiment with diesel engine, the particulate matter production and basic emission

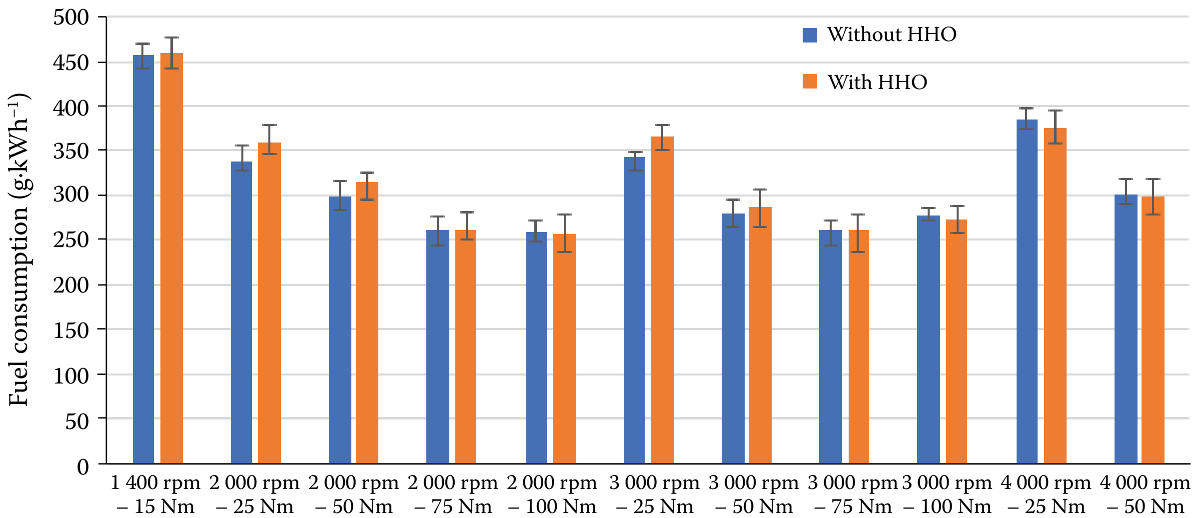

Figure 3. Fuel consumption – dependence of specific fuel consumption on the engine mode when using HHO in an SI engine

HHO – oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen; SI – spark ignition

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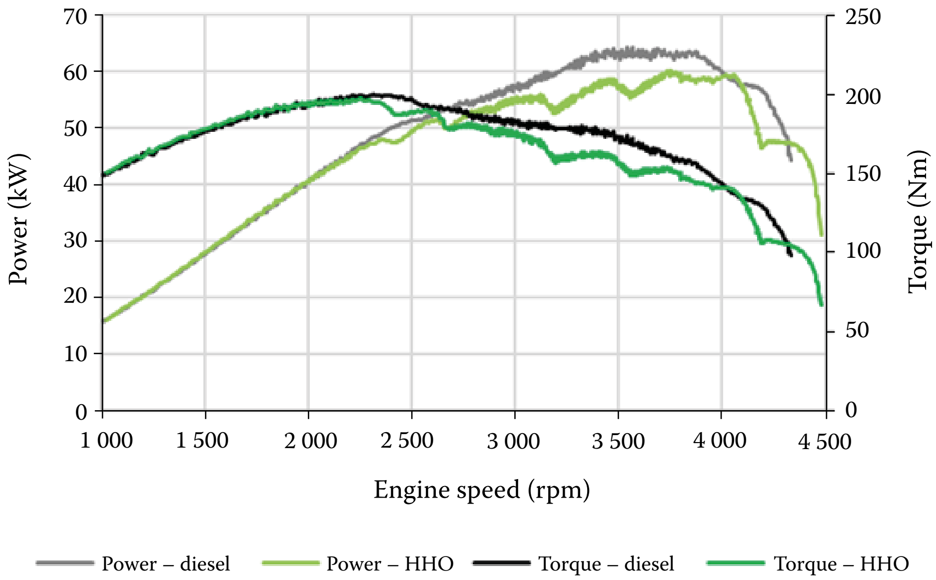

Figure 4. Dependence of the power and torque using HHO when using HHO in a CI engine

HHO – oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen; CI – compression ignition

components were measured, the average values during the cycle can be seen in Table 4. Using HHO decreased the production of hydrocarbons to zero. The particulate matter production increased 13 percent. The production of carbon monoxide was 2.3× higher. This was probably due to the change in the cetane number. The cetane number of the diesel is independent of the intake air. However, there was a mixture of air and hydrogen in the combustion chamber. Hydrogen has a very low cetane number, and it burns very fast. This leads to the mixture burning faster. The mixture does not have enough time for complete oxidation and the products of incomplete combustion occur. The results are partially consistent with past research. The research by Bari and Mohammad Esmaeil (2010) confirmed an increase in the NO_X production using oxyhydrogen.

Similar results were obtained by Rimkus et al. (2018), who found that the presence of HHO in the intake air reduces the engine's CI torque.

Table 4. Average production of the selected emission components when using HHO in a CI engine

Emission component	Fuel		Unit
	pure diesel	with HHO	
HC	1.65	0	$mg \cdot km^{-1}$
CO	0.37	0.86	$mg \cdot km^{-1}$
PM	4.87	5.61	$\# \cdot 10^{13} \cdot km^{-1}$

HHO – oxyhydrogen with a 2 : 1 ratio of hydrogen and oxygen; HC – hydrocarbons; CO – carbon monooxide; PM – particulate matters; CI – compression ignition

Nabil and Khairat Dawood (2019) achieved quite the opposite results. In their experiment, it was found that the presence of oxyhydrogen in the intake air reduced the CO emissions by about 40% and the fuel consumption decreased by about 20 percent.

CONCLUSION

Most oxyhydrogen experiments have been performed on small internal combustion engines. These were mainly chosen because even a small generator can produce enough HHO to show a positive impact on the measured parameters. In our experiment, both spark ignition and compression ignition engines were used, but with a significantly larger displacement. The ratio of aspirated air to HHO was, therefore, greater. The results obtained show that a small amount of HHO may not have a positive effect on the measured parameters. In some cases, there may be a significant deterioration of the endpoint. It can be concluded that the installation of a small generator as a source of HHO for a relatively large engine is not advantageous. There is no expected improvement. The assumption that changing the cetane number by adding hydrogen to the mixture will lead to improved combustion has not been confirmed. Another possible evolution of systems that add HHO to the fuel-air mixture should be to modify the control unit to expand the possibilities of the ECU control. This could lead to better combustion and, thus, improve the measured parameters.

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