Study of the effect on performance and consumption of hydrogen injection in light vehicles powered by spark-ignition internal combustion engines

Montúfar Paz Paúl Alejanddro
paul.montufar@espoch.edu.ec
Escuela Superior Politécnica de Chimborazo-ESPOCH

Quevedo RiosAngel
angel.quevedo@epsoch.edu.ec
Escuela Superior Politécnica de Chimborazo-ESPOCH

Razo Andrea
arazo.istt@gmail.com
Instituto Técnico Superior Tungurahua-IST

CuaicalAngúloBolivar
bacuaicala@istx.edu.ec
Instituto Técnico Superior Cotopaxi-ISTX

Abstract

Climate change and the requirement for energy sources are priority issues that have opened the requirement for Hydrogen technologies due to the remarkable capacity to use alternative energy sources. Several governments have implemented alternatives to primary energy use to eliminate carbon and generate different energy management habits. Over-inhabited countries with significant energy demands, such as China, the United States, and India, have enormously boosted the need for fossil fuels, significantly decreasing crude oil reserves and increasing fuel prices.

Although there are several alternatives for alternative energy sources, Hydrogen is one of the most viable due to the high energy density that this fluid can store.

Being one of the most abundant elements in the universe, it opens up a series of possibilities for using Hydrogen once the production process is over, which typically uses renewable energy processes; the most common way of using it is thanks to hydrogen batteries. The mechanism

for using Hydrogen can be from the reaction with oxygen for its subsequent production of electrical energy that is capable of feeding the batteries that, in turn, will deliver the stored energy to the electric motor.

One of the great strengths of the use of Hydrogen lies in the variety of methods for obtaining Hydrogen with meager contamination rates.

Keywords: hydrogen, combustion engine, polluting emissions, fuel consumption

Introduction

Hydrogen can be obtained in a variety of ways and in turn it is also possible to obtain energy from many methods with very low environmental impact and with high efficiencies compared to other types of alternative fuels that have been used. Another great advantage is the high energy density that hydrogen is capable of carrying compared to other forms of energy [1].

The results of experimental research involving the addition of hydrogen to a gasoline-fueled SI engine are reported. Up to 66% by volume (3.7% by mass) of hydrogen was added as fuel as part of the air with few engine modifications. Cylinder pressure traces were used to calculate the indicated mean effective pressure and mass fraction burned. Electrochemical analyzers were used to measure the concentration of CO, NO and O2 in the exhaust gases. The added hydrogen resulted in better working output and a reduction in burn duration and variation from cycle to cycle while operating in poor conditions ($\phi > 0.85$) little difference in engine performance was observed. This dependence of the hydrogen addition effect on the fuel/air equivalence ratio was confirmed by proof-of-variance analysis [2].

When verifying which is the best energy carrier when it comes to propelling a vehicle, it is necessary to consider a series of elements that refer to the environmental footprint generated by one or another fuel (hydrocarbons, biofuels, electricity, hydrogen, etc.) this footprint is known from well to wheel or from cradle to grave. In addition, it is necessary to consider other aspects such as the costs associated with production and the qualification by the customer regarding the performance of the vehicle.

When talking about vehicles powered by hydrogen it is necessary to be aware that they are cars that use hydrogen to produce electrical energy that will propel an electric motor that receives the energy of the hydrogen cell in certain cases or lithium batteries that were previously powered by the electrical energy produced by the oxidation of hydrogen. The fuel cell is an electrochemical element capable of producing electrical energy from the chemical energy produced from the reaction of hydrogen with oxygen with very low levels of emissions consisting basically of water vapor and heat. The principle of operation was first proposed by the English scientist William Grove in 1839.

The hydrogen is stored in special containers built in carbon fiber to withstand 700 bars of pressure, in such a way that the fuel cell is fed and then directly supplied to the electric motor. One of the main advantages of containing energy all the time in the hydrogen itself is its high specific density of 40,000 w/kg, i.e. 240 times more than the amount of energy stored in lithium batteries. In such a way that cars can be lighter and with greater autonomy with brief recharges of a few minutes (between 4 and 6 minutes) well below the charging time of conventional electric vehicles, the same ones that year after year have been increasing in sales with an average growth of 147% over previous years. While there are many advantages in the use of hydrogen the handicap that still remains to overcome is the production of hydrogen, the most widespread method to date is the Steam Reforming which uses huge amounts of fossil fuels for production, in addition the transport mechanisms are also a challenge to overcome even due to the complexity of the process, This is why hydrogen production is promoted at each of the supply stations[3].

An additional drawback to overcome is the storage in industrial quantities for later use, this in view of the very low density of 0.09 grams / liter so it is necessary to subject them to processes that compress it to 800 bars and thus increase the stored mass, although this decreases energy efficiency by 13% or decrease the temperature to -253 C ° with a loss of efficiency of 40%. This last strategy reduces the space used for collection, but uses large amounts of energy required, which is why pressurizing the containers is preferred [3].

As an alternative strategy that allows the use of hydrogen on conventional internal combustion engines, the use of hot hydrogen or H2ICE has been proposed and in this way dispense with fossil fuels using the conventional engine adapted for the use of hydrogen as fuel with the consequent generation of nitrogen oxide emissions, due to the reaction with the air, so they become ecological vehicles but not zero emissions as is the case of those powered by H2FC electric motors.

In the effort to rethink trends in the use of alternative fuels such as hydrogen in combination with conventional fuels in order to reduce the consumption of fossil fuels, a third method has been proposed in which proportions of gasoline or diesel are combined with hydrogen.

The present study analyzes the effect of adding hydrogen in different amounts to the internal combustion engine powered by gasoline, determining a positive effect regarding torque and power as the injection of hydrogen into the system increases. In addition, the analysis of the effect produced on the emissions generated in this type of engines is carried out, noting a positive effect on the reduction of nitrogen oxides. [4]

One of the main problems that prevents a greater massification of vehicles that use hydrogen as a source of direct or indirect propulsion is the difficulty in obtaining it by isolating it from the natural compounds that normally accompany it. Over the last 30 years a number of studies have been conducted around the use of hydrogen in such a way that it can be used in combination with other fossil fuels.

In Figure Figure 1 is possible to verify about the different types of fuels and their production process such as Hydrogen and its different and varied possibilities of obtaining which make it an alternative with many advantages over another process.

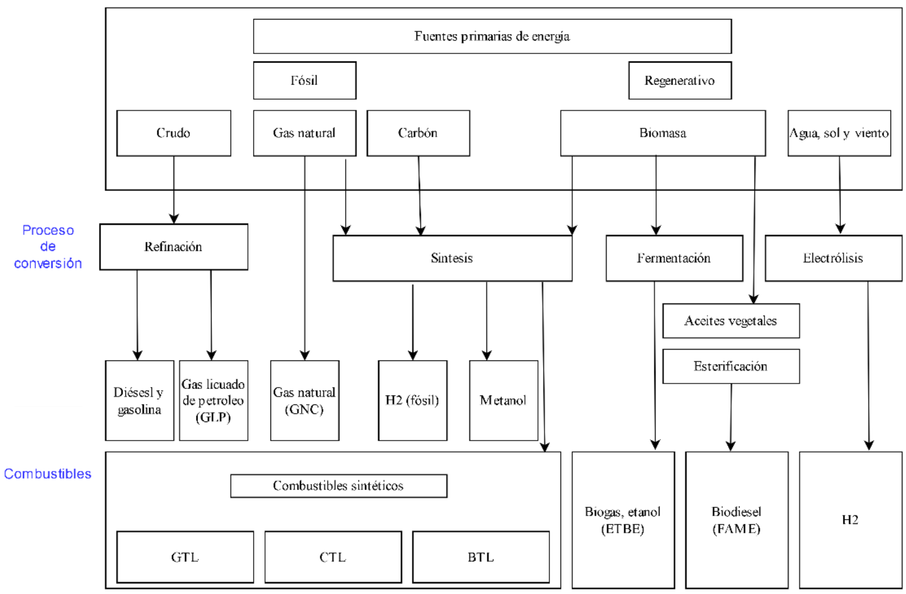

Figure 1 Fossil and renewable fuels

By using hydrogen as an alternative oxidizer without the presence of carbon as in the rest of conventional fuels, certain emissions to the exhaust are canceled, such as: carbon monoxide and dioxide and hydrocarbons to the exhaust, considerably reducing polluting emissions. It is predicted that within 20 years new hydrogen-powered light vehicles will reduce CO2 emissions by 35%, while heavy-duty vehicles by 40%. [5]

It is seeking to obtain Hydrogen under simple and economical processes to be able to offer alternatives within the transport sector in such a way that environmental pollution concerning the following emissions can be reduced: CO2, CO, NOx, without making too many modifications on the original version of the combustion engine powered by fossil fuels. This study seeks to analyze the impact of the use of hydrogen in hybrid engines in terms of consumption, emissions and performance, since in certain studies it is mentioned that this addition of oxidizer generates a positive impact on the performance of the engine [1]. For the development of this study, hydrogen has been used as an additive on the conventional operation of the car for which road tests have been carried out under real driving cycles and the performance of the car has also been evaluated in a roller dynamometer.

Hybrid internal combustion engines that have been enriched with hydrogen have a better performance with respect to consumption and emissions, especially for conditions of high load, in addition another of the advantages present is the greater flexibility in the use of energy stored in the battery and in this way it is possible to further increase efficiency and reduce environmental impact. In previous studies, mixtures of gasoline and hydrogen are made where the latter is in a volumetric proportion of 10% and in this way it was possible to increase the efficiency from 18.7% to 23.5% comparing a conventional hybrid with one enriched with hydrogen. In the case of comparison with conventional internal combustion engines the increase was from 14.2% to 23.5%. Another of the strong advantages found was the reduction of CO2 emissions, 29% and 42% for conventional hybrid technologies and internal combustion engines respectively. [6]

Table 1. Effect on consumption and emissions of engines enriched with H2

PARAMETER	Valor AF-HEV	Conventional hybrid vehicle value	Value vehicle with conventional internal combustion engine

Ratio of hydrogen mixture in fuel	10%	-	-
Fuel efficiency (on-road simulation)	23.5%	18.7%	14.2%
CO2 emissions	29% less	-	47% less
NOX emissions	80% less	-	-
Optimum cruising speed (maximum efficiency)	60 km/h	-	-

Another significant advantage that emerges from the use of hydrogen is that it can be used in engines with higher compression ratios of up to 13:1, given that the octane of the mixture suffers an increase due to hydrogen enrichment and it is also possible to obtain greater power. Given this circumstance it is necessary to study the possible premature wear that could arise from the use of hydrogen.

The higher energy density of 140 MJ/Kg makes it one of the most energetic fuels.

The use of hydrogen as an additive in internal combustion engines according to several authors manages to significantly increase thermal efficiency and with respect to nitrogen oxides a reduction between 15 and 95% has been verified depending on the amount of hydrogen injected in the case of CO2 emissions can be reduced up to 50% [3].

Methodology

The development of the present study was based on the comparison of operating parameters before and after adding hydrogen to the system, using for the effect a hydrogen generator that obtains it from water electrolysis. This process uses a current line that manages to decompose the liquid into its most basic components (hydrogen and oxygen). An electric current was used to drive a non-spontaneous chemical reaction this involves the use of an electrolyte, which is a substance that can conduct electricity when dissolved in a solvent, and two electrodes, which are normally made of metal. During electrolysis, an electric current passes through the electrolyte, causing ions in the solution to travel toward the electrodes. At the negative electrode, called the cathode, the positively charged ions shrink and gain electrons, while, at the positive electrode, called the anode, the negatively charged ions oxidize and lose electrons. In general, electrolysis is an important process that allows the conversion of electrical energy into chemical energy and is used in many different industries and applications.

When hydrogen is used as an enricher of the mixture it is necessary to consider that energy efficiency will decrease compared to an engine that uses hydrogen as a fuel cell that generates energy to charge high voltage batteries, which is considered the best alternative regarding energy optimization however it requires a large technological implementation for the collection and accumulation of appropriate doses of hydrogen that allow them to be the car's only fuel. To optimize the operation of a combustion engine enriched with hydrogen it is necessary to make certain modifications to the combustion system due to the variants that are induced to the mixture in such a way that the variations do not cause uncontrolled explosions. In addition, it is necessary to consider that hydrogen is injected into the engine fuel system from the fuel tank gas recirculation valve [7]. In addition, it is necessary to consider that the addition of hydrogen causes an increase in the burning speed so the ignition advance must also be increased to ensure efficient and safe combustion. In Figure Figure 2, it is possible to verify the location of the hydrogen dosing valve which takes advantage of the vacuum generated by the downward movement of the piston.

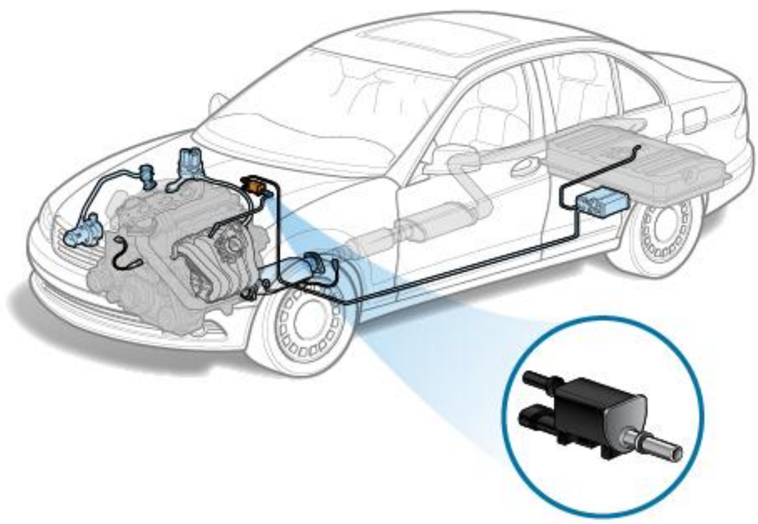

Figure 2. Location of the hydrogen injection valve to the internal combustion engine.

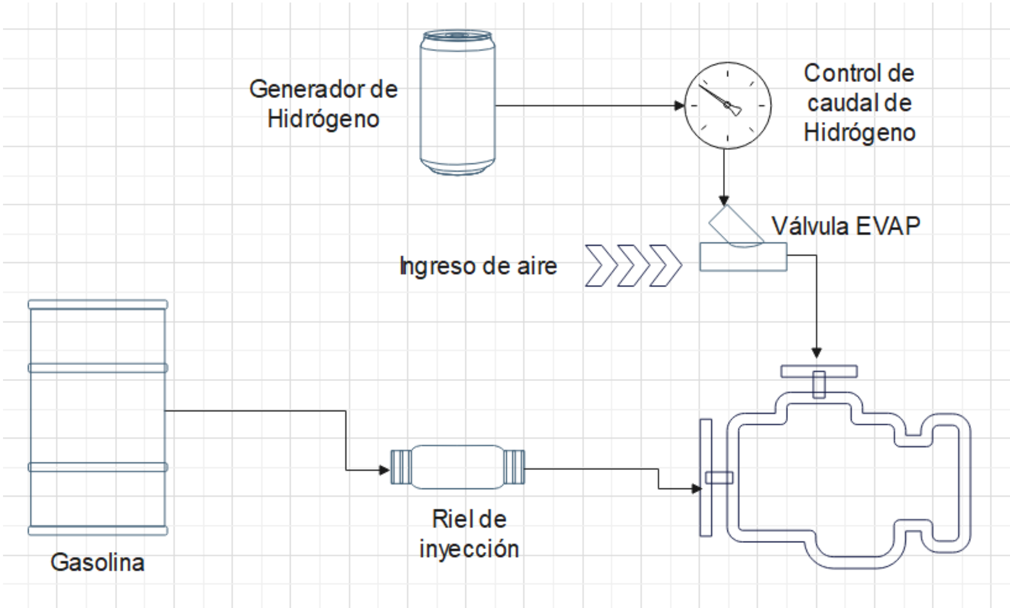

Figure 3 Component Diagram

To obtain information regarding the performance of the car was used an automotive data logger (ELM 327) that retrieves the information of the different parameters of the vehicle at a frequency of 1 Hz, Elm327 is an electronic device that is used as a diagnostic scanner for vehicles this device connects to the diagnostic socket of a vehicle (OBD-II), which is located under the driver's dashboard, and communicates with the vehicle's computer to provide information on its status and performance. The Elm327 is compatible with most vehicles manufactured after 1996, and can read diagnostic trouble codes (DTCs) stored on the vehicle's computer. These codes can indicate problems with the engine, transmission, brake system, and more, helping technicians and vehicle owners identify and fix problems. The Elm327 can also display real-time information on vehicle performance such as speed, engine temperature, fuel consumption and other data. In addition, the device provides detailed and real-time information on its performance and status in such a way that the behavior, performance and consumption can be analyzed at the time the hydrogen generator is activated and deactivated.

Torque and power measurement

Car performance is evaluated from torque and power, which are two important measures of an engine's performance. Torque refers to the force that the motor can apply through its output shaft and is measured in units of force and length while power refers to the rate at which work is performed. The measurement of torque and power is essential to understand the performance of a vehicle and optimize its operation under the conditions of use of hydrogen for this reason the use of the dynamometer was used, which is an equipment used in the automotive industry to measure the power and torque of a vehicle in controlled and reproducible conditions for which the vehicle is placed on the rollers, that simulate the resistance of the pavement, and accelerates to a specific speed while measuring the power and torque values of the engine, this operating condition also favored the measurement of fuel consumption, because the gravimetric consumption evaluation method was used and the stability with which the test can be performed allows to reduce the effect of vibrations on the measurement of fuel consumption.

1. Vehicle Preparation: The vehicle must be fully powered on and in working condition, with the engine at its normal operating temperature. It is also important to make sure that the wheels are properly aligned and inflated.
2. Vehicle placement: The vehicle is placed on the dynamometer rollers and ensures that it is in the correct position to avoid displacement during the test.
3. Dynamometer adjustment: The dynamometer must be calibrated and adjusted for the weight and configuration of the vehicle.
4. Test execution: The vehicle is gradually accelerated until it reaches its maximum speed on the roller dynamometer. The dynamometer measures the force exerted by the vehicle on the rollers and calculates the torque and power.
5. Analysis of the results: Once the test is completed, the results are analyzed to determine the maximum power and torque of the vehicle.
6. It is important to note that torque is measured in units of force-foot (ft-lb) or newton-meters (Nm), while power is measured in units of horsepower (HP) or kilowatts (kW). In addition, power is calculated by multiplying torque by motor angular velocity (RPM) and dividing by a constant.

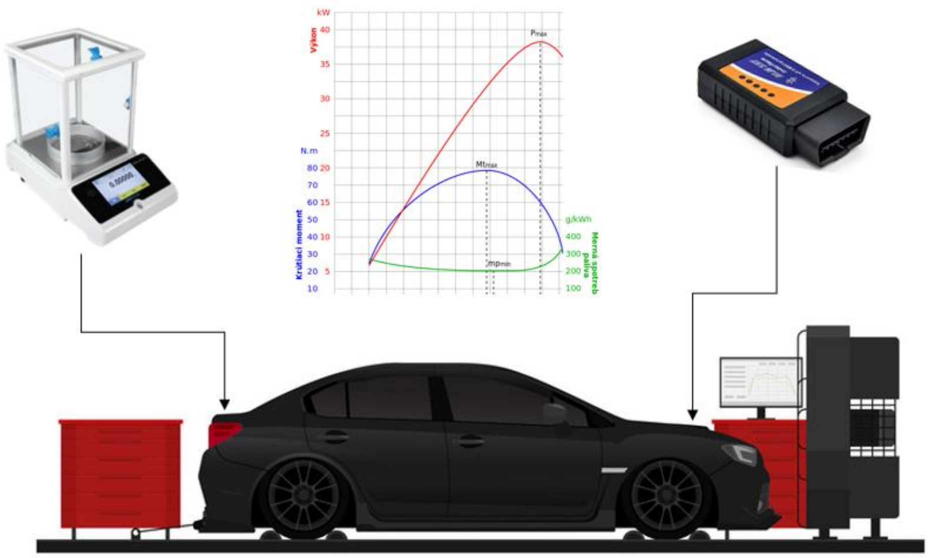

Fig. 1 Test vehicle instrumentation diagram

Results

Once the torque and power tests were carried out, the following results were obtained by comparing the condition in which hydrogen enrichment is used and in which the engine works without H2.

Performance

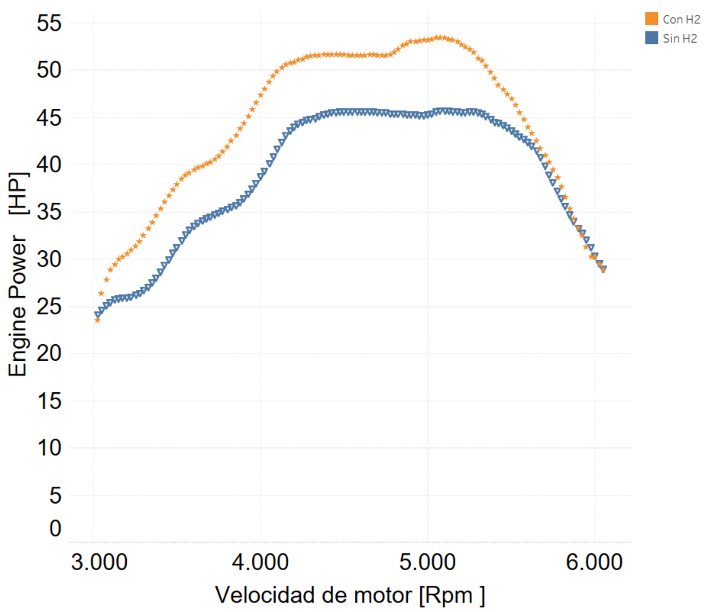

Figure 4 Power comparison with H2 and without H2

In Figure 2 you can see the power of the engine and compare the graphs when using the H2 and without the enrichment of H2, also in Figure 3 it is possible to observe the increase in torque when adding H2 to the operation of the engine. Considering the average percentage increase in torque it is possible to verify in Figure 4 that by adding 10% hydrogen intake in the engine the touch increases considerably with an average value of 15%, in conditions of low rpm (<4000 rpm) the increase in power is greater while as the rpm increases the torque gain decreases with respect to the average.Figure 4Figure 6

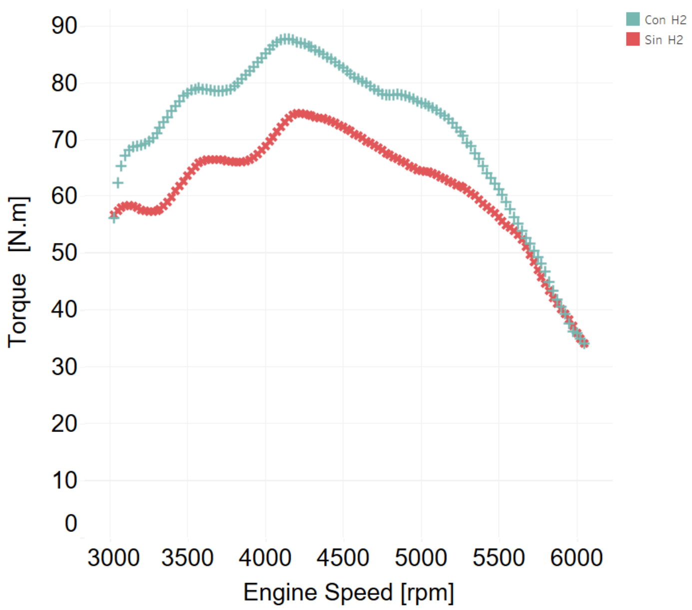

Figure 5 Comparative diagram between torque under H2 enrichment and without H2

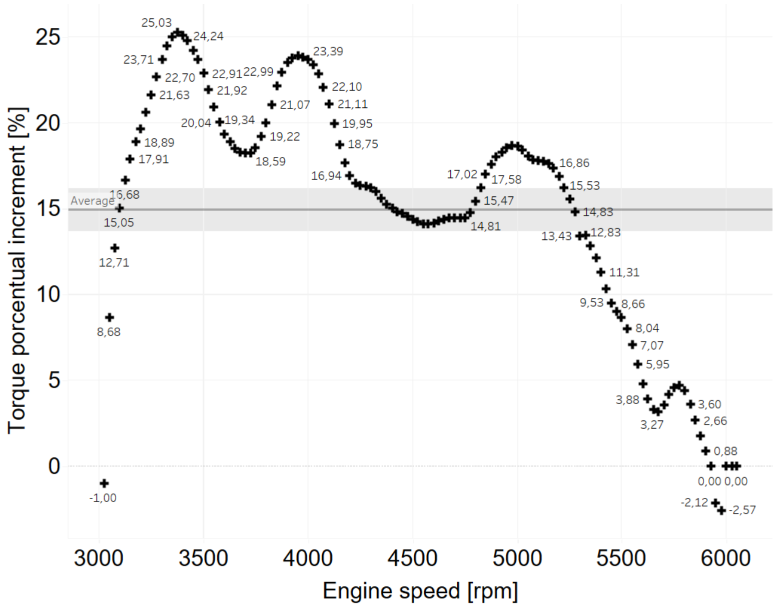

Figure 6 torque with respect to motor speed in H2 increase considerations

The next factor that was considered in this study was fuel consumption per unit of energy, which also showed a considerable improvement that will have a direct effect on the generation of emission factors.

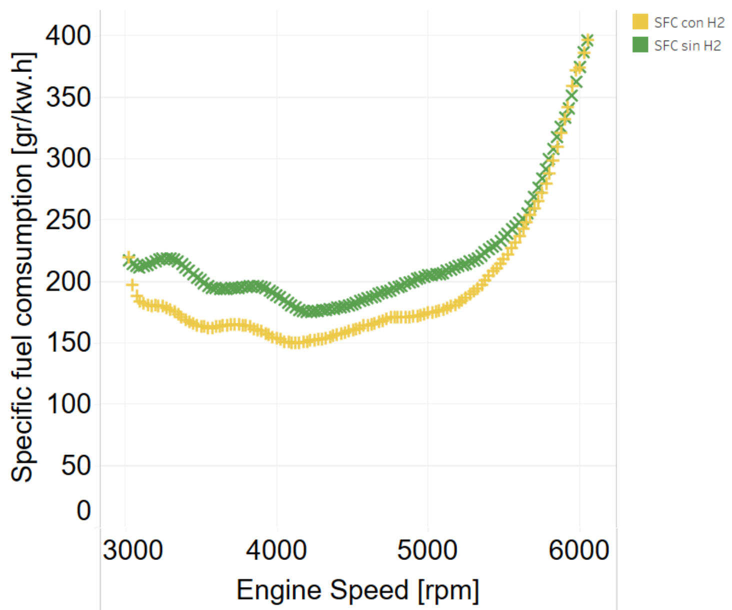

Figure 7 Comparison in fuel consumption under mixture enrichment situation are H2

Regarding fuel consumption, a decrease of 12% can be seen on average and as in the case of torque and power it can be seen that this improvement is more noticeable in conditions of low engine revolutions while this decrease is less evident for high rpm, this can be seen in Figure Figure 8.

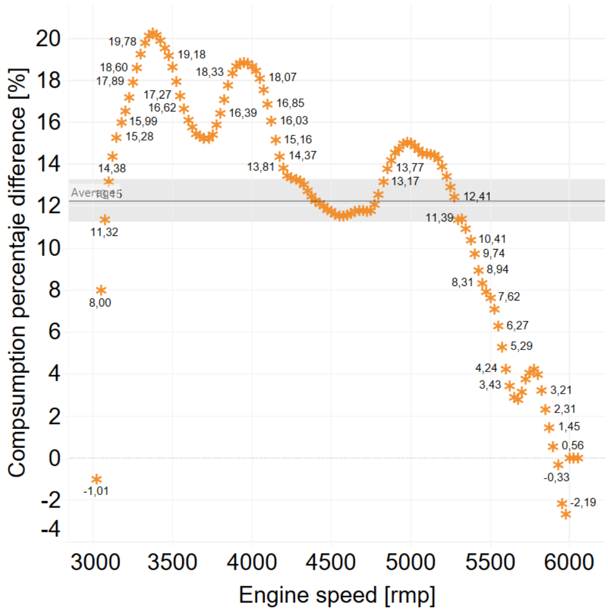

Figure 8 Percentage change in fuel consumption under H2 enrichment conditions

Emissions

Similar studies in provoked ignition engines showed that the addition of hydrogen results in a decrease in carbon monoxide, CO, while the concentration of nitrogen oxides, NOx, shows an increase when concentrations between 2 and 8% by volume are injected into the combustion process [8]. Lean combustion has been identified as a way to improve the thermal efficiency of gasoline engines. However, it is difficult to run gasoline engines in poor conditions, because the stability of combustion deteriorates.

Hydrogen has properties that can be used to improve the stability of combustion and, therefore, solve the problem of combustion instability, in spark ignition engines it was also verified that the use of hydrogen as a fuel enricher manages to reduce emissions except the generation of nitrogen oxides, it was also verified in this study where a turbocharged ignition engine with direct injection, T GDI, was used, pointing out that the behavior in a conventional engine could vary [9].

Regarding the emissions generated in the present study, a decrease in the emission factors of CO, NOX and HC could be found when the mixture was enriched with Hydrogen, which compared to Euro regulations allowed a decrease in each of the readings obtained.

Figure Figure 9 shows the values of the emission factors obtained using hydrogen enrichment with respect to an operating condition without the use of hydrogen and is also compared with the current Euro regulations.

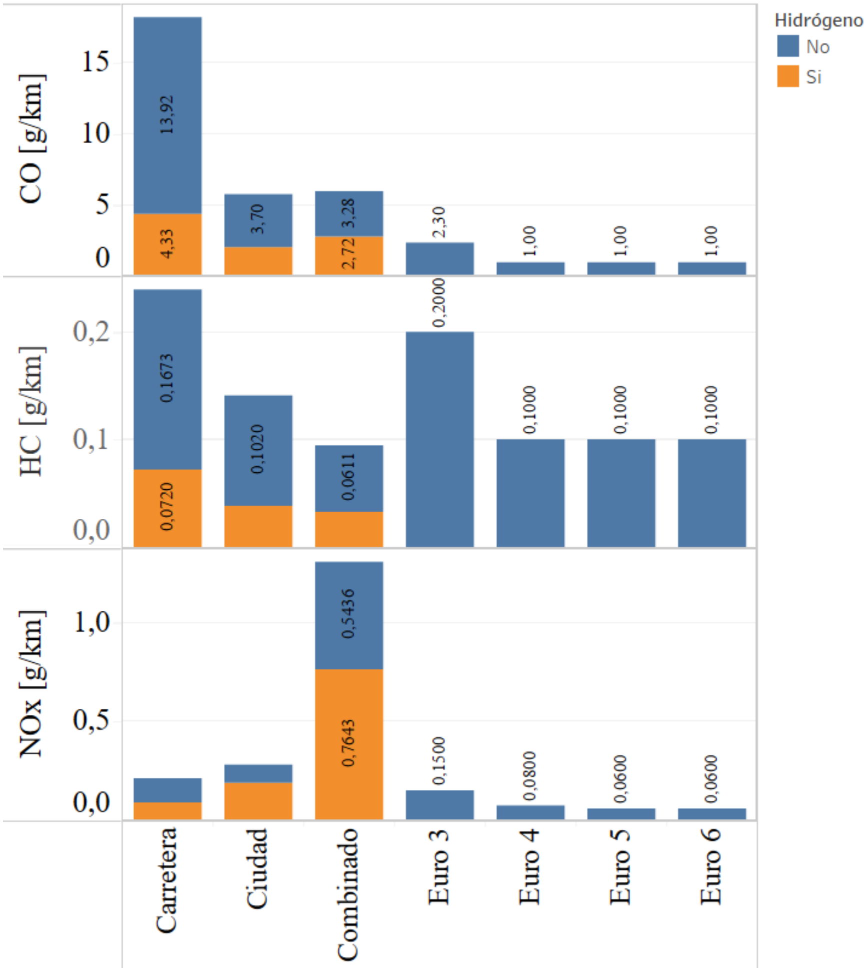

Figure 9 Emission factors with hydrogen enrichment compared to Euro standards

Conclusions

The addition of hydrogen as an enricher of the fuel air mixture significantly improves the torque and power obtained from a spark ignition internal combustion engine and this effect is mainly observed at low rpm where on average it can be increased by 15% and under 4000 rpm the average increase is 5%.

Regarding consumption, there was also evidence of greater efficiency in consumption at low revolutions, where the decrease in consumption on average is 12% compared to spark ignition engines that are not enriched with Hydrogen.

Regarding emissions in all driving conditions it is evident that there is a decrease in the emission factors generated when hydrogen is used as an enricher of the mixture of air and fossil fuels, hydrocarbons are the ones that show the greatest reduction mainly on the road and allows compliance with the latest Euro regulations, in the case of carbon monoxide there is also a considerable reduction however it is not enough to comply with the current Euro regulations like nitrogen oxides.

References

[1]H. T. Arat, "Alternative fuelled hybrid electric vehicle (AF-HEV) with hydrogen enriched internal combustion engine," *Int. J. Hydrogen Energy*, vol. 44, no. 34, pp. 19005–19016, 2019, doi: 10.1016/j.ijhydene.2018.12.219.

[2]T. D. Andrea, P. F. Henshaw, and D. S. Ting, "The addition of hydrogen to a gasoline-fuelled SI engine," vol. 29, pp. 1541–1552, 2004, doi: 10.1016/j.ijhydene.2004.02.002.

[3]Y. Hames, K. Kaya, E. Baltacioglu, and A. Turksoy, "Analysis of the control strategies for fuel saving in the hydrogen fuel cell vehicles," *Int. J. Hydrogen Energy*, vol. 43, no. 23, pp. 10810–10821, 2018, doi: 10.1016/j.ijhydene.2017.12.150.

[4]D. Akal, S. Öztuna, and M. K. Büyükakın, "A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect," *Int. J. Hydrogen Energy*, vol. 45, no. 60, pp. 35257–35268, 2020, doi: 10.1016/j.ijhydene.2020.02.001.

[5] *Green Energy and Technology*. 2006. doi: 10.2174/97816080528511060101.

[6]M. Gurz, E. Baltacioglu, Y. Hames, and K. Kaya, "The meeting of hydrogen and automotive: A review," *Int. J. Hydrogen Energy*, vol. 42, no. 36, pp. 23334–23346, 2017, doi: 10.1016/j.ijhydene.2017.02.124.

[7]F. Ma, Y. Wang, H. Liu, Y. Li, J. Wang, and S. Ding, "Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine," *Int. J. Hydrogen Energy*, vol. 33, no. 2, pp. 823–831, 2008, doi: 10.1016/j.ijhydene.2007.10.043.

[8]F. Christodoulou and A. Megaritis, "Experimental investigation of the effects of simultaneous hydrogen and nitrogen addition on the emissions and combustion of a diesel engine," *Int. J. Hydrogen Energy*, vol. 39, no. 6, pp. 2692–2702, 2014, doi: 10.1016/j.ijhydene.2013.11.124.

[9]J. Kim, K. M. Chun, S. Song, H. K. Baek, and S. W. Lee, "Hydrogen effects on the combustion stability, performance and emissions of a turbo gasoline direct injection engine in various air/fuel ratios," *Appl. Energy*, vol. 228, no. June, pp. 1353–1361, 2018, doi: 10.1016/j.apenergy.2018.06.129.