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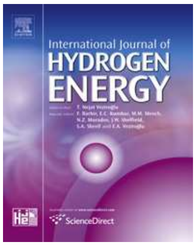

Conversion of a commercial gasoline vehicle to run bi-fuel (hydrogen-gasoline)

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ABSTRACT

Bi-fuel internal combustion engine vehicles allowing the operation with gasoline or diesel and hydrogen have great potential for speeding up the introduction of hydrogen in the transport sector. This would also contribute to alleviate the problem of urban air pollution. In this work, the modifications carried out to convert a Volkswagen Polo 1.4 into a bi-fuel (hydrogen-gasoline) car are described. Changes included the incorporation of a storage system based on compressed hydrogen, a machined intake manifold with a low-pressure accumulator where the hydrogen injectors were assembled, a new electronic control unit managing operation on hydrogen and an electrical junction box to control the change from a fuel to another. Change of fuel is very simple and does not require stopping the car. Road tests with hydrogen fuel gave a maximum speed of 125 km/h and an estimated consumption of 1 kg of hydrogen per 100 km at an average speed of 90 km/h. Vehicle conversion to bi-fuel operation is technically feasible and cheap.

1. Introduction

Almost all important world car manufacturers are developing hydrogen fueled vehicles. Most of them are fuel cell electric vehicles (FCEVs) [1] although some companies are also developing cars and buses powered by hydrogen fueled internal combustion engines (H_2ICEs); this is the case, for example, of BMW, Ford and Mazda [2]. This fact, along with the parallel development of hybrid and full electric powered vehicles [3], evidence the current interest and at the same time concern for the transport sector. This is due to its almost complete dependence on oil-derived fuels and its main associated enviromental problems: urban air pollution and greenhouse gas emissions. Cost-effective production of hydrogen and electricity, ideally from renewables, but also from nuclear energy and low-CO_2 technologies (e.g. natural gas reforming and coal gasification with CO_2 capture and sequestration) and their introduction in the transport sector are key milestones towards a sustainable energy economy [4–7].

Critics with the hydrogen fueled internal combustion engine vehicles (H_2ICEVs) often argue that these vehicles are inefficient and that require large fuel tanks, concluding that they do not offer any advantage [4]. Against this argument it should be not forgotten that both fuel cells and ICEs are constrained by the same maximum efficiency that is established by the second law of Thermodynamics [8]. On the other hand, some recent thermodynamic studies [9,10], as the work by Nieminen and Dincer [9], show after a comparative second law analysis for naturally aspirated gasoline and hydrogen fueled spark ignition ICEs, that the H_2ICE achieved an exergetic efficiency of 41.37% whereas for the gasoline engine it was 35.74%.

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Experimental results by Verhelst et al. [11] confirm the superiority of the H_2ICE in terms of brake thermal efficiency over the entire load and speed ranges. Of course, the hydrogen fueled engine suffers from a reduction of the power output of about 35% under stoichiometric combustion conditions mainly due to the low volumetric energy density of hydrogen and the lower mean effective pressures achieved [12]. However, this problem can be solved by means of exhaust gas recirculation and supercharging stoichiometric mixtures, as demonstrated by Verhelst et al. [13], who found power outputs up to 30% higher compared with a gasoline ICE albeit at the expense of a reduced efficiency compared to lean burn operation. Advantages of using hydrogen fueled ICEs are not limited to the gasoline spark ignition (SI) engines. Indeed, significantly improved fuel efficiencies can be obtained with the direct injection of hydrogen [14,15] or diesel-hydrogen in dual-fuel mode operation [16,17] of the compression ignition ICEs. As concerns hydrogen storage, it continues being an issue that seriously affects all hydrogen applications, not only its use in ICEs. A recent technical assessment of compressed hydrogen in storage tanks at 350 and 700 bar concludes that this technology will not meet the targets for volumetric capacity and cost of the U.S. Department of Energy for transportation applications [18]. In the case of the BMW Hydrogen 7 demonstration vehicle, probably the most advanced example of H_2ICEV developed to date, storage is made by means of a vacuum insulated 170 l cryogenic tank with capacity for about 8 kg of hydrogen [19], with an energy content equivalent to around 30 l (8 gallons) of gasoline. In this regard, many hopes are placed in solid-state storage methods [20] as the use of Mg-based hydrides [21] and adsorption and hydrogen spillover on carbon-based materials [22]. Nevertheless, much more reasearch effort is still needed to improve the storage capacity, enhance the sorption-desorption kinetics and lower the cost to accomplish the established targets.

Fuel cells have experienced important technological advancements in the recent years proving their capacity to greatly contribute in the future to a more sustainable transportation sector, with zero pollutant and greenhouse gas emmissions at the point of use [1,23]. A number of worlwide bus demonstration programs and the implementation of modern high power density fuel cell engines in numerous prototype FCEVs have demonstrated the superior characteristics of this technology. Nevertheless, there are still significant obstacles to overcome before fuel cells and FCEVs become widely available. This is the case of the economic competitiveness issue as well as the required further optimization of the fuel cell systems [1]. Substantial economic investments will be required for the development of the whole production-distribution-storage-use chain of hydrogen fuel. Under the best conditions it is estimated that FCEVs can become competitive compared to other technologies in some countries by 2025–2030 [24]. Within this context, the H_2ICEVs are considered a transitional or bridging technology that would allow a faster introduction of hydrogen in the transport sector. This is mainly due to their lower cost, immediate availability, the possibility of using the current manufacture infrastructure of the automotive industry and the remarkable experience existing in H_2ICEs design and operation [2,25–28]. Moreover, the possibility of fabricate H_2ICEs capable of operating in bi-fuel (either with pure gasoline/diesel or pure hydrogen) or dual-fuel (with gasoline-hydrogen or diesel-hydrogen blends) modes is very important. This feature is considered essential during the transition period for a rapid introduction of hydrogen in the transport sector which is believed the driving force towards a hydrogen infrastructure [29,30].

In a previous paper we reported on the modifications performed to convert the spark ignition gasoline ICE of a Volkswagen Polo 1.4 to run on hydrogen [31]. More recently we have described the modifications carried out to convert a gasoline carbureted engine-generator set to an electronic fuel-injected power unit capable to operate bi-fuel (hydrogen-gasoline) [32]. In the present work we report on the adaptation of a commercial Volkswagen Polo 1.4 A04 vehicle to be capable of running bi-fuel, that is, with gasoline or hydrogen as desired by the driver. Since the modification of the engine is a crucial step for the adaptation of the vehicle, the work carried out previously will be summarized in the next section.

2. Previous work: engine modification

A very interesting history of the H_2ICEVs can be found in the excellent review by Verhelst and Wallner [2]. According to these authors the idea of an H_2ICE seems to be almost as old as the internal combustion engine itself. What is considered the first successful ICE was powered by hydrogen in 1860. In the recent years, a number of conversion and dedicated H_2ICEVs have appeared. As concerns conversion vehicles, the most important measures affect the injection system and the mixture (air/hydrogen) formation and load strategies in order to avoid abnormal combustion phenomena (pre-ignition, backfire and autoignition or knocking) [2,25–28].

The Volkswagen Polo 1.4 A04 considered in this work incorporates an engine that is almost identical to the one that was previously converted by our group to mono-fuel operation with hydrogen [31]. It is a four-cylinder in line naturally aspirated spark ignition (SI) engine of 1.4 l. Running on gasoline, the engine provided maximum brake torque (MBT) and maximum brake power (MBP) of 132 N m at 3800 rpm and 59 kW at 5000 rpm, respectively. The original engine block was preserved while the main modifications affected the fuel feeding system and the electronic management system. As for the hydrogen feeding system, naturally aspirated gaseous port fuel injection (PFI) was adopted. The gasoline injectors were substituted by hydrogen injectors (Quantum Technologies). A gas accumulator was manufactured and connected to the injectors to maintain constant the pressure at the injectors inlet. Regarding the electronic management system, the original electronic control unit (ECU) was replaced by a progammable MoTeC M400 unit. The original lambda sensor was replaced by a wide band lambda sensor (Bosch LSU 4.9) suitable for lean operation, that is, feeding mixtures with air to hydrogen equivalence ratios (λ) above the stoichiometric value ($\lambda = 1$). Sensors and actuators were connected to the MoTeC M400 unit and calibrated.

The modified engine was tested in a bed cell consisting of an eddy current dynamometer AVL 80; more details about the test facilities can be found elsewhere [31]. A test program was carried out that allowed to obtain the injection and ignition timing maps of the modified engine running on hydrogen. Injection timing maps were developed for λ values between 1.6 and 3, from unloaded engine to full load and engine speeds between idling and 5000 rpm. SI advance maps were obtained choosing advance values getting MBT compatible with low NO_x emissions. The H_2ICE was capable of providing an MBT of 63 N m at 3800 rpm and MBP of 32 kW at 5000 rpm. These modest results are in part due to the very conservative operation adopted retarding the ignition advance to values which are far from producing knock. The brake thermal efficiency of the H_2ICE was greater than that of the original engine except for $\lambda > 1.8$. A significant effect of the spark advance on the NO_x emissions was found, specially for mixtures with λ below 2. Small changes of spark advance with respect to the optimum value for MBT gave rise to an increased NO_x emissions. Operation at λ ratios higher than 1.8 produced low NO_x emissions of the order of 50–75 ppm.

3. Vehicle conversion

The main challenges in this project were to get bi-fuel operation of the Volkswagen Polo 1.4 A04 so that it could circulate either on gasoline or hydrogen, and simultaneously, that the exterior appearance of the car is not altered in any way.

The vehicle mounted an in line 4 cylinder SI engine of 1.4 l with sequential timed multipoint fuel injection and sequential electronic ignition system. The engine block was identical to that of the engine modified previously [31]; however, the new engine running on gasoline achieved slightly lower MBT and MBP of 126 N m and 55 kW, respectively.

Bi-fuel operation required maintaining intact the gasoline injection system and incorporating a new one for hydrogen. Due to the large size of the hydrogen injectors and the little space available in the injection area, it was decided to assemble them outside the intake manifold. Taking into account the proper functioning of the gas fuel injectors obtained in our previous work by installing a hydrogen accumulator [31], a similar container was built and incorporated as shown in Fig. 1. The accumulator has four machined fittings where the hydrogen injectors are hermetically inserted with the help of O-rings. Welded screws and mounting plates allow firmly fixing the injectors that incorporate suitable fittings for connecting flexible hoses. The ends of each of the hoses are connected to stainless steel tubes that are hosted behind the gasoline injectors and directed towards the intake valves thus allowing hydrogen to be fed. Fig. 2 shows the modified intake manifold with the bi-fuel (hydrogen and gasoline) injection systems. The intake manifold is finally assembled in the engine compartment as shown in Fig. 3. With the adopted arrangement of the hydrogen injection system it was possible to keep the original air filter that is fitted on the throttle valve and above the engine block.

One of the drawbacks of the hydrogen fueled ICEs is the risk of backfire. As it is well-known, to avoid backfire the engine is fed with lean hydrogen-air mixtures [25,26], that is, mixtures with air to hydrogen equivalence ratios (λ) above 1. As a result, the original lambda sensor is not useful for

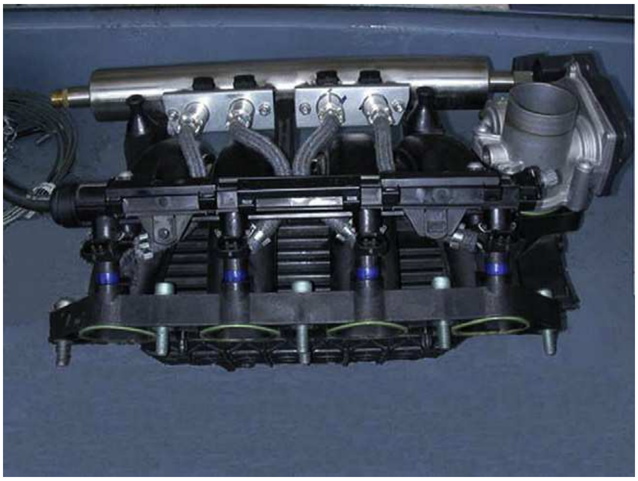

Fig. 2 – Intake manifold with the bi-fuel (hydrogen/gasoline) injection systems.

Fig. 1 – Hydrogen accumulator with the four hydrogen injectors.

Fig. 3 – Bi-fuel intake manifold assembled in the engine compartment.

Fig. 4 – Gas cylinders for hydrogen storage at 200 bar placed in the car boot.

hydrogen operation because it is designed for mixtures close to stoichiometric conditions. For this reason, a wide band oxygen sensor (Bosch LSU 4.9) was mounted in the exhaust.

Hydrogen was stored at 200 bar in two austenitic stainless steel gas cylinders (CE 1370 UT 5.3 MM) of 18 l and 20.2 kg each. This allowed storing about 0.5 kg of useful hydrogen. The gas cylinders were placed horizontally in the car boot (see Fig. 4) inserted into a body of rigid foam that prevented them from moving. Although, in contrast to fuel cells, the engine can be fed with commercial hydrogen of industrial quality, we have used our alkaline water electrolysis facilities to produce and store the hydrogen in the gas cylinders [33-35].

The hydrogen feeding line schematized in Fig. 5 was assembled in the vehicle. A first pressure regulator placed in the car boot allowed maintaining at 9 bar the hydrogen pressure in the line connecting the gas cylinders with the accumulator. A second pressure regulator located at the accumulator entry reduced the pressure to 3 bar, the operating pressure of the hydrogen injectors. A purge valve was also mounted in the accumulator for gas line venting purposes. As concerns the safety measures, a portable hydrogen sensor (QRAE Plus PGM-2020) was placed in the car boot and another in the vehicle interior. No significant hydrogen leaks were recorded under normal driving conditions.

Electronic management is an essential feature of modern cars. The strategy followed to get bi-fuel operation was to preserve the original electronic unit (ECU) that controls the operation with gasoline (Magneti Marelli 4EV), adding another programmable ECU (MoTeC M400) that manages the operation with hydrogen and finally, integrating an electrical junction box (see Fig. 6). The change from one fuel to another is simply done by pressing a switch button on the dashboard and it is managed by the electrical junction box that switches the injectors and coils in the proper mode of operation according to the scheme shown in Fig. 7. After switching the button, the injectors corresponding to the desired fuel are activated whereas disabled injectors are replaced by load resistances. As concerns the coils that excite the spark plugs, they are controlled by the ECU managing the corresponding fuel while the other ECU is connected to load resistances. It is important to note that switching from a fuel to another neither requires stopping the car nor causes perceptible changes in the driving.

The MoTeC M400 unit was connected in parallel to the original electronic unit and both shared the main engine sensors: crankshaft speed, camshaft and throttle position sensor, cooling water temperature, intake manifold pressure, air temperature and accelerator pedal position. The electronic unit was connected to a computer via CANbus for programming the engine operating parameters.

4. Vehicle performance: results and discussion

After the above-described modifications the bi-fuel Volkswagen Polo was ready for its performance evaluation. As shown

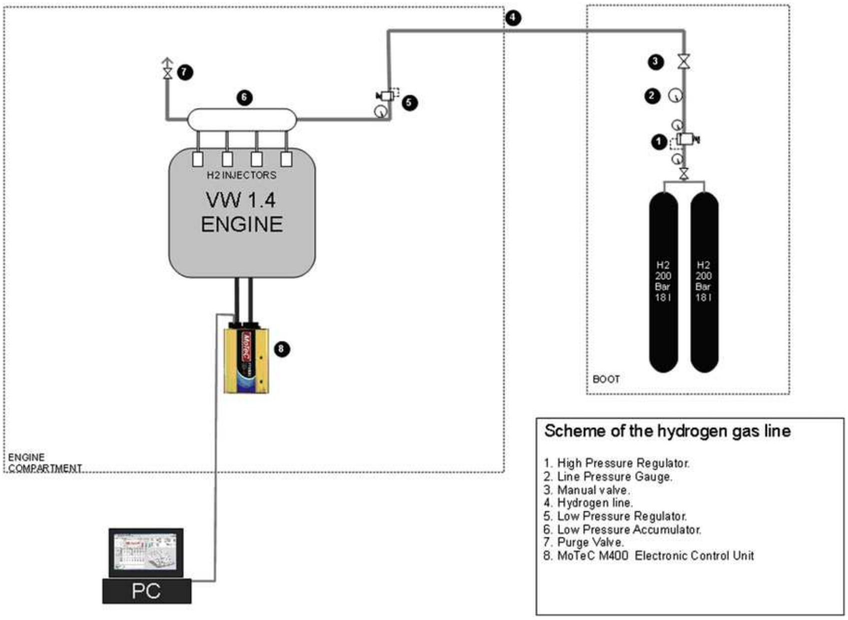

Fig. 5 – Scheme of the hydrogen gas line installed in the vehicle.

Fig. 6 – New MoTeC M400 programmable electronic control unit (bottom) connected to the electrical junction box.

Fig. 8 – Appearance of the vehicle once converted to bi-fuel operation.

in Fig. 8 its external appearance is identical to that of the original vehicle.

The performance was first tested in a rolling testbed. The MBT and thermal efficiency obtained as a function of the engine speed and throttle opening (load) for the vehicle running on hydrogen with $\lambda = 1.6$ are presented in Figs. 9 and 10, respectively. A maximum torque of about 65 N·m is achieved at 4000 rpm and full load. As expected, this value is considerably lower than the MBT of 126 N m obtained at 3800 rpm under full load gasoline operation. Obviously, the much leaner fuel-air mixture employed in the case of hydrogen is on the basis of this difference. It should be noted that performance under hydrogen operation was also negatively affected by the fact that the drive ratio of the original vehicle was preserved. This was due to the technical complexity and economic cost entailed by the modification of the drive ratio. On the other hand, a relatively high thermal efficiency close to 35%, which is better than the typical values for gasoline engines, was provided by the hydrogen fueled vehicle at suitable combinations of the speed and load. The considerably higher speed of a hydrogen flame compared to that of gasoline enables a faster and almost isochoric (constant volume) combustion that is closer to the ideal Carnot cycle, which explains the improved thermal efficiency running on hydrogen. Nevertheless, lean burn operation is penalized with lower power outputs as evidenced by the results presented in Fig. 11. It can be seen that the maximum engine power barely reaches 30 kW at 5000 rpm, $\lambda = 1.6$ and full load. If the hydrogen-air mixture becomes leaner, the power decreases dramatically, up to about 16 kW at $\lambda = 2$ and 10 kW at $\lambda = 2.5$. Comparing these results with the maximum power of 55 kW of the original vehicle demonstrates the superiority of gasoline in this respect. It can be seen also in Fig. 10 that the evolution of the maximum power is notably flat for the leanest mixture at high engine speed. This can be viewed as the result of the compensatory effect between the increased velocity and the drop of toque that also takes place (see Fig. 9).

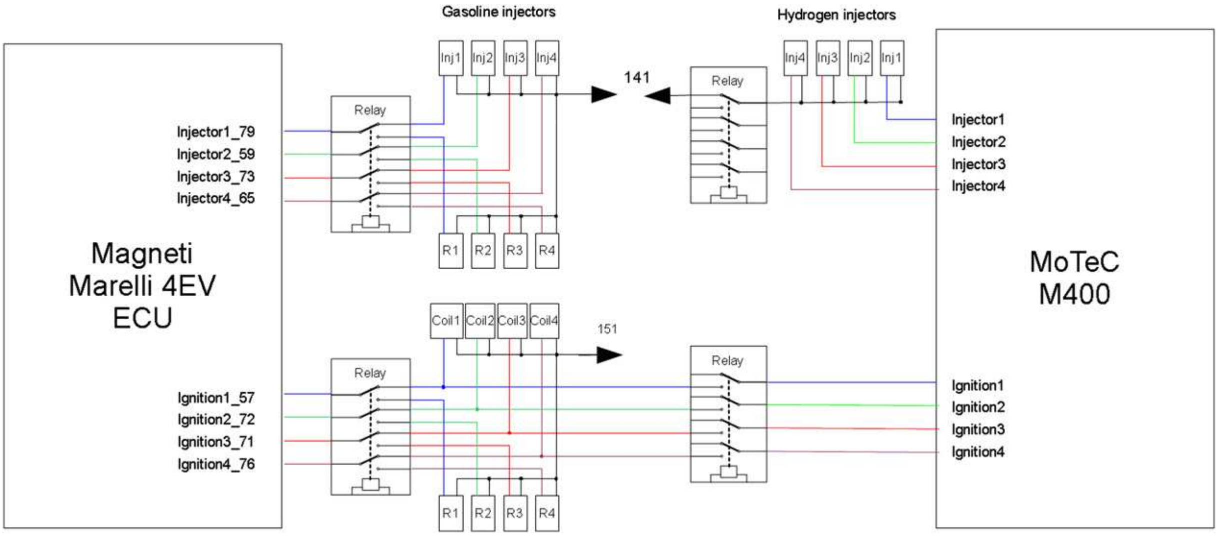

Fig. 7 – Operating scheme of the electrical junction box.

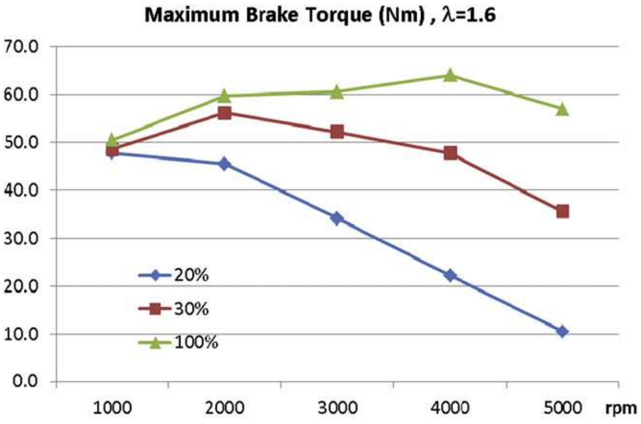

Fig. 9 – MBT of the engine running on hydrogen ($\lambda = 1.6$) as a function of the engine speed and load.

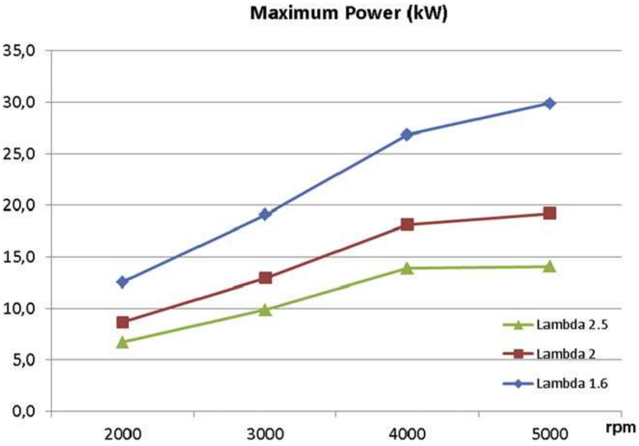

Fig. 11 – Maximum power of the engine running on hydrogen as a function of the engine speed and air to hydrogen equivalence ratio (λ).

Acceleration measurements were also performed and the comparison of the results obtained with the vehicle running on gasoline and hydrogen is shown in Fig. 12. The drive ratios used were 3.77, 2.78 and 2.22 for the 3rd, 4th and 5th gears, respectively. All the measurements were conducted at $\lambda = 1.6$ and full load. Acceleration performance was better running on gasoline than hydrogen, as expected from the fact that the drive ratios were not optimized for hydrogen operation. Maximum vehicle speeds achieved with hydrogen in the rolling testbed were 113, 153 and 191 km/h after 12 (3rd gear), 23.5 (4th gear) and 37 s (5th gear), respectively. It is remarkable that the maximum speeds obtained with hydrogen are only slightly lower than the ones achieved with gasoline. As concerns the wheel power, the results are shown in Fig. 13. As can be seen, a maximum wheel power of about 24 kW is obtained running on hydrogen which is about half the maximum power obtained with gasoline (50 kW). As mentioned before for the engine power, this low power is mainly due to the lean burn operation.

Road tests were performed in a racetrack (Circuit of Navarra, Los Arcos, Spain). In this case, a maximum speed of 125 km/h was achieved on a straight stretch of about 650 m long. As for fuel consumption, during the road tests the car traveled 25 km with the only weight load of the driver and the hydrogen storage system. At an average speed of 90 km/h and 1800 rpm the hydrogen consumed amounted to about 250 g. A rough extrapolation gives a consumption of 1 kg of hydrogen per 100 km, which is equivalent to 3.8 l of gasoline in terms of heating value. Taking into account that according to the vehicle specifications the optimal consumption running on gasoline is 4.8 l per 100 km it is clear the advantage of using hydrogen from the energetic efficiency viewpoint.

The only significant pollutants emitted to the atmosphere by the bi-fuel vehicle under hydrogen operation were nitrogen oxides (NO_x). The NO_x concentration in the exhaust gas as a function of the engine speed and the air to hydrogen equivalence ratio (λ) is shown in Fig. 14. As can be seen, the

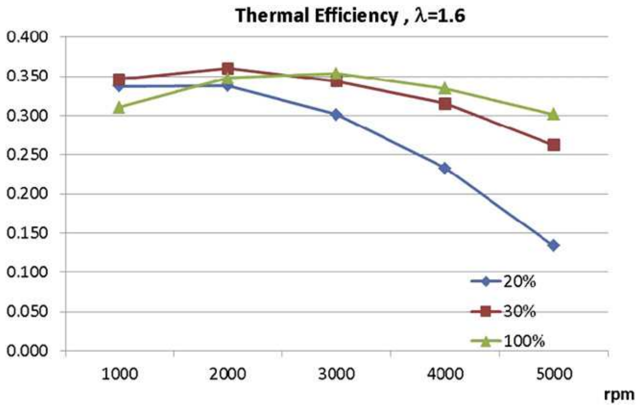

Fig. 10 – Thermal efficiency of the engine running on hydrogen ($\lambda = 1.6$) as a function of the engine speed and load.

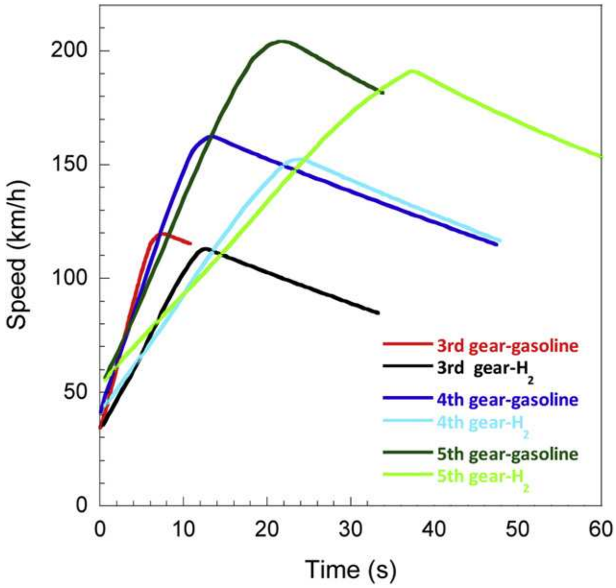

Fig. 12 – Acceleration curves obtained in the rolling testbed with the vehicle running on gasoline and hydrogen at $\lambda = 1.6$ and full load (see text for the drive ratios used).

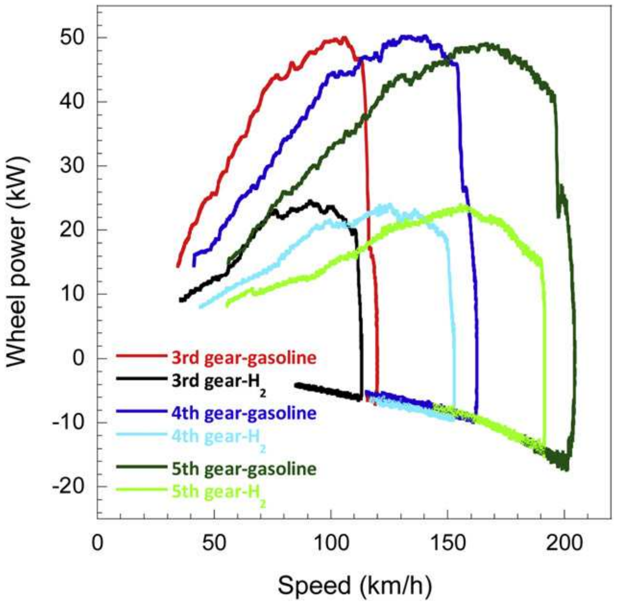

Fig. 13 – Wheel power measured in the rolling testbed with the vehicle running on gasoline and hydrogen at $\lambda = 1.6$ and full load (see text for the drive ratios used).

concentration of NO_x mainly depended on λ. Lean operation with $\lambda > 2$ guarantees the absence of abnormal combustion phenomena and low NOx emissions, of the order of only 40 ppm. However, as the hydrogen-air mixture becomes richer (λ decreases), the NO_x concentration in the exhaust gas rapidly increases mainly due to the higher combustion temperatures [2]. As a result, at the λ value of 1.6 at which the maximum thermal efficiencies were obtained the NO_x concentration were in the range between 110 and 160 ppm.

In order to compare the NO_x emissions with the limits of the european regulations, data obtained at 1800 rpm in the rolling testbed have been used to calculate the mass of NO_x emitted per km during hydrogen operation. The results are compiled in Table 1. Any comparison of these results with the emission limits has to be considered only as orientative because we have not applied the European drive cycle established as the official test procedure. Bearing this in mind and that the Euro 5 and Euro 6 emission limits [36] for NO_x are between 60 and 82 mg/km, it can be seen that the emissions of the hydrogen fueled vehicle are reasonably low. It should be noted that the regulation is established regardless of the type of fuel by which the vehicle is powered. Only at high loads and relatively rich hydrogen-air mixtures the limits seem to be exceeded. This should not be a serious problem for further development because, in spite of the lean operation, an effective control of this level of NO_x emissions can be performed by means of catalytic converters. In this regard, it may result specially interesting for the H_2ICE vehicles the use hydrogen as reductant, which constitutes a promising NO_x emissions reduction technology [37].

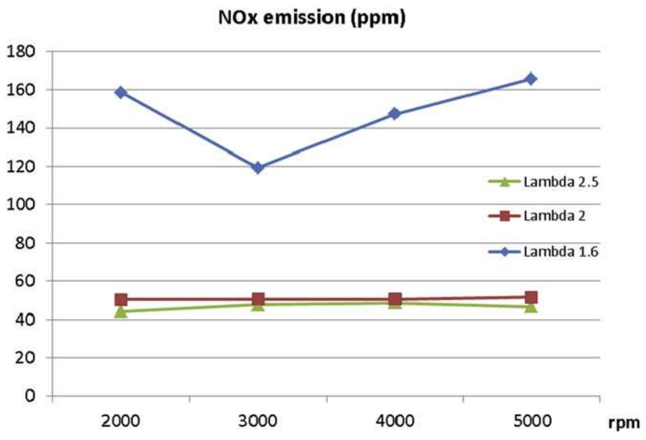

Fig. 14 – NO_x concentration (ppm) in the exhaust gas running on hydrogen as a function of the engine speed and air to hydrogen equivalence ratio (λ).

Table 1 – NO_x emitted by the bi-fuel engine running on hydrogen.

λ	Throttle (%)	NO_x (ppm)	NO_x (mg/km)
1.6	30	113	56
1.6	100	213	105
2.5	30	38	31
2.5	100	40	32

5. Conclusions

It has been shown in this work that the conversion of a commercial gasoline vehicle into a bi-fuel (hydrogen-gasoline) car is technically feasible and relatively cheap (about 6000 € in equipment and 200 man-hours). Obviously these costs would be much lower in the event of a series production. The possibility of bi-fuel operation is considered very important as it is possible to use hydrogen for undemanding urban routes and reserve the use of gasoline for longer trips by road. The change from a fuel to another is very simple and does not require stopping the car. This type of vehicles have the potential of reducing the problem of urban air pollution and accelerating the introduction of hydrogen in the transportation sector because the current infrastructure of the powerful automotive industry could be exploited for their mass production. Perhaps the main problem that would remain is the storage of a sufficient amount of hydrogen to assure a reasonable autonomy although bi-fuel operation could significantly alleviate the requirements of the storage system in the short term.

As for the vehicle conversion the main modifications are as follows:

i) Adding a hydrogen storage system, in our case hydrogen gas cylinders at 200 bar placed in the car boot, and a new fuel line connecting the storage system with a low-pressure hydrogen accumulator where the hydrogen injectors are assembled.
ii) Machining the intake manifold to allow the entry of hydrogen.

iii) Incorporating a new programmable electronic control unit that manages hydrogen operation and an electrical junction box that allows controlling the change from gasoline to hydrogen and vice versa.

The performance of the bi-fuel vehicle has confirmed the superiority of hydrogen over gasoline operation in terms of thermal efficiency and fuel consumption. Nevertheless, the bi-fuel vehicle described in this work is not fully optimized. Aspects such as the modification of the drive ratio and improved hydrogen storage systems are under consideration for future works.

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We would like to express our gratitude and affection to our friend Carlos Sopena tragically deceased on December 18, 2009. This work is to some extent the completion of the project we started with Carlos some years ago and that unfortunately he was unable to see completed. His spirit has been with us permanently during this time and has helped us to achieve the goal so we wish to dedicate this work to his memory.

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REFERENCES

[1] Veziroglu A, Macario R. Fuel cell vehicles: state of the art with economic and environmental concerns. Int J Hydrogen Energy 2011;36:25–43.
[2] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energy Combust Sci 2009;35:490–527.
[3] Thomas CE. Fuel cell and battery electric vehicles compared. Int J Hydrogen Energy 2009;34:6005–20.
[4] Armaroli N, Balzani V. The hydrogen issue. ChemSusChem 2011;4:21–36.
[5] Gardner D. Hydrogen production from renewables. Renew Energy Focus; 2009:34–7. January/February.
[6] Neef H-J. International overview of hydrogen and fuel cell research. Energy 2009;34:327–33.
[7] Wallington TJ, Grahn M, Anderson JE, Mueller SA, Williander MI, Lindgren K. Low-CO_2 electricity and hydrogen: a help or hindrance for electric and hydrogen vehicles? Environ Sci Technol 2010;44:2702–8.
[8] Lutz AE, Larson RS, Keller JO. Thermodynamic comparison of fuel cells to the Carnot cycle. Int J Hydrogen Energy 2002;27: 1103–11.
[9] Nieminen J, Dincer I. Comparative exergy analyses of gasoline and hydrogen fuelled ICEs. Int J Hydrogen Energy 2010;35:5124–32.
[10] Ismail S, Mehta PS. Second law analysis of hydrogen-air combustion in a spark ignition engine. Int J Hydrogen Energy 2011;36:931–46.
[11] Verhelst S, Maesschalck P, Rombaut N, Sierens R. Efficiency comparison between hydrogen and gasoline, on a bi-fuel hydrogen/gasoline engine. Int J Hydrogen Energy 2009;34: 2504–10.
[12] Nieminen J, D'Souza N, Dincer I. Comparative combustion characteristics of gasoline and hydrogen fuelled ICEs. Int J Hydrogen Energy 2010;35:5114–23.
[13] Verhelst S, Maesschalck P, Rombaut N, Sierens R. Increasing the power output of hydrogen internal combustion engines by means of supercharging and exhaust gas recirculation. Int J Hydrogen Energy 2009;34:4406–12.
[14] Gomes Antunes JM, Mikalsen R, Roskilly AP. An experimental study of a direct injection compression ignition hydrogen engine. Int J Hydrogen Energy 2009;34:6516–22.
[15] Boretti B. Advances in hydrogen compression ignition internal combustion engines. Int J Hydrogen Energy 2011;36: 12601–6.
[16] Saravanan N, Nagarajan G. Experimental investigation in optimizing the hydrogen fuel on a hydrogen diesel dual-fuel engine. Energy & Fuels 2009;23:2646–57.
[17] Boretti A. Advantages of the direct injection of both diesel and hydrogen in dual fuel H_2ICE. Int J Hydrogen Energy 2011; 36:9312–7.
[18] Hua TQ, Ahluwaila RK, Peng J-K, Kromer M, Lasher S, McKenney K, et al. Technical assessment of compressed hydrogen storage tank systems for automotive applications. Int J Hydrogen Energy 2011;36:3037–49.
[19] Wallner T, Lohse-Busch H, Gurski S, Duoba M, Thiel W, Martin D, et al. Fuel economy and emissions evaluation of BMW hydrogen 7 mono-fuel demonstration vehicles. Int J Hydrogen Energy 2008;33:7607–18.
[20] Lim KL, Kazemian H, Yaakob Z, Wan Daud WR. Solid-state materials and methods for hydrogen storage: a critical review. Chem Eng Technol 2010;33:213–26.
[21] Jain IP, Ch Lal, Jain A. Hydrogen storage in Mg: a most promising material. Int J Hydrogen Energy 2010;35:5133–44.
[22] Wang L, Yang RT. Hydrogen storage on carbon-based adsorbents and storage at ambient temperature by hydrogen spillover. Catal Rev Sci Eng 2010;52:411–61.
[23] Brouwer J. On the role of fuel cells and hydrogen in a more sustainable and renewable energy future. Curr Appl Phys 2010;10:S9–17.
[24] Rosenberg E, Fidje A, Espegren KA, Stiller C, Svensson AM, Møller-Holst S. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. Int J Hydrogen Energy 2010;35:7267–79.
[25] Verhelst S, Sierens R. Aspects concerning the optimisation of a hydrogen fueled engine. Int J Hydrogen Energy 2001;26:981–5.
[26] Verhelst S, Sierens R. Hydrogen engine-specific properties. Int J Hydrogen Energy 2001;26:987–90.
[27] White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: a technical review. Int J Hydrogen Energy 2006;31:1292–305.
[28] Escalante Soberanis MA, Fernandez AM. A review on the technical adaptations for internal combustion engines to operate with gas/hydrogen mixtures. Int J Hydrogen Energy 2010;35:12134–40.
[29] Das LM. Near-term introduction of hydrogen engines for automotive and agricultural application. Int J Hydrogen Energy 2002;27:479–87.
[30] Wietschel M, Ball M, Seydel P. Hydrogen today. In: Ball M, Wietschel M, editors. The hydrogen economy. Cambridge, UK: Cambridge University Press; 2009. p. 254–70 [chapter 8].
[31] Sopena C, Diéguez PM, Sáinz D, Urroz JC, Guelbenzu E, Gandía LM. Conversion of a commercial spark ignition engine to run on hydrogen: performance comparison using hydrogen and gasoline. Int J Hydrogen Energy 2010;35: 1420–9.
[32] Sáinz D, Diéguez PM, Urroz JC, Sopena C, Guelbenzu E, Pérez-Ezcurdia A, et al. Conversion of a gasoline engine-generator

set to a bi-fuel (hydrogen/gasoline) electronic fuel-injected power unit. Int J Hydrogen Energy 2011;36:13781–92.

[33] Gandía LM, Oroz R, Ursúa A, Sanchis P, Diéguez PM. Renewable hydrogen production: performance of an alkaline water electrolyzer working under Emulated Wind conditions. Energy & Fuels 2007;21:1699–706.

[34] Diéguez PM, Ursúa A, Sanchis P, Sopena C, Guelbenzu E, Gandía LM. Thermal performance of a commercial alkaline water electrolyzer: experimental study and mathematical modeling. Int J Hydrogen Energy 2008;33:7338–54.

[35] Ursúa A, Marroyo L, Gubía E, Gandía LM, Diéguez PM, Sanchis P. Influence of the power supply on the energy efficiency of an alkaline water electrolyser. Int J Hydrogen Energy 2009;34:3221–33.

[36] Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information. Off J Eur Union 2007;L 171:1–16.

[37] Savva PG, Costa CN. Hydrogen lean-DeNO$_x$ as an alternative to the ammonia and hydrocarbons selective catalytic reduction (SCR). Catal Rev Sci Eng 2011;53: 91–151.