EVS24
Stavanger, Norway, May 13-16, 2009

Development of a Light Duty Commercial Fuel Cell Vehicle – by Intelligent Energy and PSA Peugeot Citroën

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Abstract

Fuel cell technology is widely considered as the most suitable alternative to conventional internal combustion engines for low carbon vehicle transportation. However, for acceptance as a viable alternative a number of technical challenges need addressing, for example in terms of cost, durability and vehicle range. When configured with a high voltage battery pack to form a hybrid powertrain arrangement, the benefits of both devices can be optimised for maximum efficiency. This paper discusses how a fuel cell system and associated hydrogen storage system were installed into a conventional battery electric vehicle to form a Fuel Cell Range Extender vehicle. The fuel cell is based on proton exchange membrane technology with evaporative cooling utilised such that system complexity is reduced compared to conventional liquid cooled fuel cell systems and the resulting system may be installed within the engine bay of the vehicle. Hydrogen is stored in gaseous form at 70MPa within a swap rack packaged in the rear load area of the vehicle. To date the vehicle has completed over 1000 km on a combination of pseudo urban drivecycles and real world operation on public roads, with samples of the data collected presented here.

Keywords: Fuel Cell, PEM Fuel Cell (Proton Exchange Membrane), HEV (Hybrid Electric Vehicle)

1 Introduction

PSA Peugeot Citroën continues to expect the first mass production vehicles with fuel cells to be introduced over a sensible period of time. However, three main challenges must be met:

- The cost is not currently competitive with the top-performing internal combustion or hybrid technologies.
- The durability and reliability required for volume production. Meeting this objective will require continuous progress, ultimately enabling compliance with automobile manufacturing requirements.
- The size and weight of hydrogen storage systems, which are continually improving but must achieve further reductions to make them totally ‘auto-compatible’.

In the interim, PSA Peugeot Citroën will pursue research and evaluations focused on a basic building block that harbours immense promise as a viable power source for individual and collective transport systems.

2 Fuel Cell System

The fuel cell power system used in this application is developed by Intelligent Energy and based on a proprietary low cost, simple architecture PEMFC (Proton Exchange Membrane Fuel Cell) technology. The fuel cell system is extremely compact and develops a net power of 10 kW. This small size results in a system which can be housed in the engine compartment, along with all auxiliary equipment and the electric motor. The power delivered from the fuel cell system significantly increases the range of an electric vehicle. Hence, the fuel cell is used as a range extender which is the most feasible solution from both the economic and design standpoints to enable timely application of this technology on mass-produced vehicles.

The proprietary fuel cell technology developed by Intelligent Energy for the H_2Origin allows starts within two minutes from temperatures as low as -20°C. Fuel cell system start-up time at temperatures above 0^oC is of the order of 10s. This represents a significant improvement in fuel cell use under winter conditions, since until now this was a major obstacle to the development of the technology in automotive applications.

Cold-weather starting performance is made possible by the introduction of heating systems, along with the development of appropriate 'start & stop' strategies. Fuel cell cooling is designed for normal operation at temperatures up to 37°C.

This temperature range therefore enables vehicles to be operated in a wide variety of climates, excluding only certain exceptionally cold or hot areas of the world.

The Intelligent Energy fuel cells target an endurance of 5,000 hours for mass-produced units, or about five years with an average use of three hours/day.

Intelligent Energy's EC7 fuel cell systems were designed from the outset with the long-term objective of minimising the manufacturing cost for a mass-produced product. Accordingly, the stack and system have minimum complexity and a minimum number of components. The system has the ability to be flexibly packaged hence will fit into a range of vehicles and is able to start quickly and operate over a wide range of temperatures. It also operates at high efficiency maximising the vehicle range.

By designing the stack to have a single sheet stainless steel bipolar plate constructed with no welded parts and no cooling channels, component count can be reduced and manufacturing complexity minimised. Furthermore the cell packing density can be twice as high as in conventional designs, maximising volumetric power density.

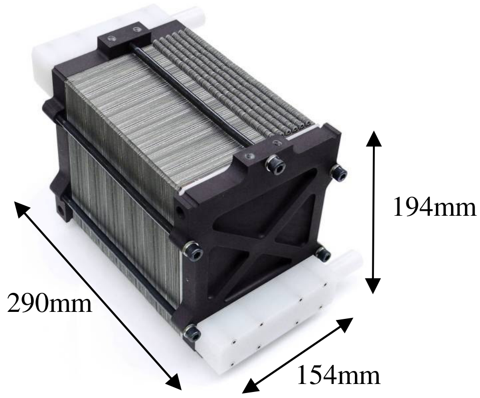

Figure 1: 192 cell, 12kW fuel cell stack

Cell cooling is managed using direct water injection. This water partly evaporates providing the necessary stack cooling and also eliminates the need for humidified reactants and the associated high thermal energy transfers within the system. This design approach reduces the requirement for much of the conventional balance of plant, resulting in fuel cell power generation systems that show improved reliability and are compact and less costly to manufacture.

Although the peak stack power is over 17kW, when it is operated within a system, the current is normally limited to approximately 100A. This ensures a high cell voltage and a low parasitic power demand and insures a system efficiency approaching 50% (lower heating value) at full load.

Figure 2 shows the general arrangement of the evaporatively cooled system.

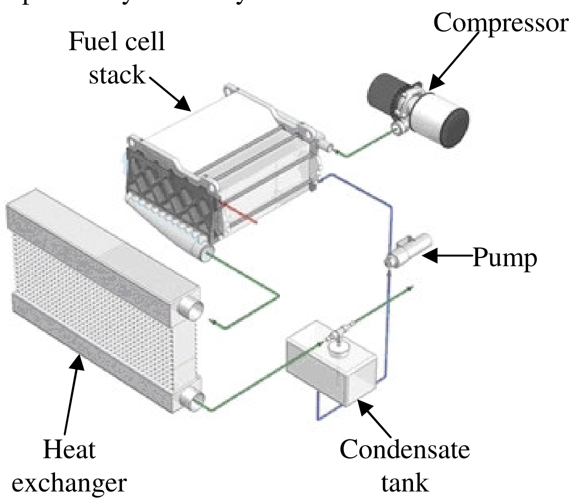

Figure 2: Evaporatively cooled system architecture

Air and hydrogen are injected into the stack and pass over the surface of the anode and cathode electrodes. These electrodes are separated by a proton exchange membrane. Reactions occur in the electrodes, which oxidise the hydrogen producing heat, water and electrical power. The water aids the humidification of the membrane and the electrical current is drawn from the terminal at the ends of the stack. The injected water is partly evaporated within the stack, removing heat from the cells. The stack exhaust consists of a liquid/vapour mix, which carries the thermal energy from the stack. Water is condensed in the heat exchanger to recover sufficient water to maintain a net water balance within the system. A small buffer condensate tank is included that enables the heat exchanger to be sized to be able to recover sufficient water for the average power and not the peak. The system is designed to operate at low air pressure, less than 0.3bar, thus reducing the parasitic losses due to the blower and maximising efficiency.

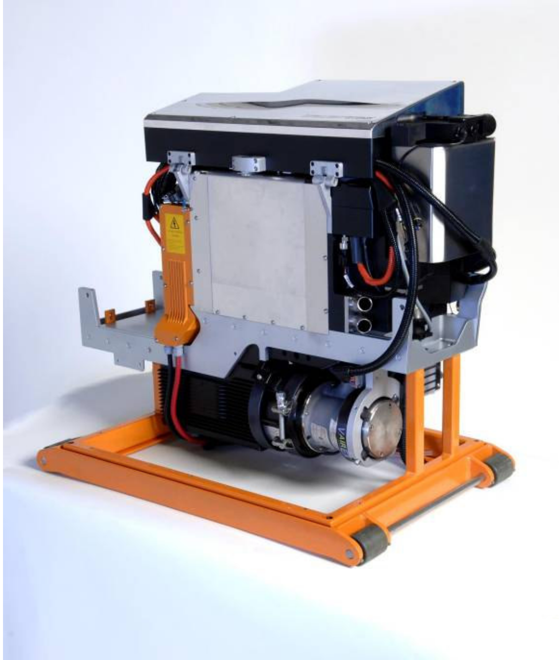

Figure 3: EC7 Fuel cell system

Figure 3 shows the general arrangements for the EC7 fuel cell engines. The architecture of the fuel cell power system was designed to fit within the space available in a conventional electric Peugeot Partner vehicle and to meet the specifications issued through the collaboration with PSA Peugeot Citroën. The system was sized to work as a range extender, combined with high voltage batteries. The stack and hydrogen valves are segregated into a separate enclosure where a hydrogen sensor monitors the environment for traces of flammable gas. The blower and filter are positioned under the main chassis and the electronics mounted in the enclosure on the top. The chassis is designed to bolt directly onto a vehicle sub-frame.

The system specification is shown in Table 1. The width of 650 mm included space for the DC-DC converter and physical support structure. This results in the whole system being a self-contained, 'hydrogen in, regulated DC out' unit ready to mount in a vehicle.

Table 1: Fuel cell system specification

Performance	Continuous power output	10kW
	Current	100A
	DC Voltage	100-200V
	Noise	70dbA at 1m
	Temperature range	-20oC to +37oC
Fuel	Composition	99.99% Hydrogen
	Pressure	3.0 bar
	Consumption	<150 SLPM (at rated power)
Physical	Length x width x height	310 x 650 x 670mm
	Mass (dry)	115 kg

3 Hydrogen Storage

PSA Peugeot Citroën continues to work on what seems to be the most promising hydrogen storage technology, namely the storage of gaseous hydrogen under pressure with some standards already being agreed such as ISO 13985:2006. The group is participating in a joint European programme between vehicle manufacturers and technology partners, mainly involving the storage of hydrogen at a pressure of 70 MPa: StorHy (Storage of Hydrogen for Automotive Applications).

Storing hydrogen under higher pressure increases the range of electric vehicles by increasing the amount of hydrogen that can be kept in a given volume by nearly 70%.

The hydrogen tanks, similar to the tanks used by scuba divers, undergo extremely rigorous tests to ensure their resistance to fire, shock and over-pressure. Real bullets are fired at these tanks which are made of carbon fibre and resin to make sure

they are strong enough to stand up to all events that could occur in actual operation and in particular as a result of vehicle accidents. The leak tightness of the complete storage system must also meet extremely demanding standards to avoid even the slightest gas leak that could lead to a concentration involving ignition in a closed area. A hydrogen tank meeting these leak rate standards would take 200 years to empty completely.
The hydrogen tanks are placed on a sliding platform and housed in the rear cargo area of the vehicle thus keeping most of the standard payload area free (Figure 4).

Figure 4: re-moveable hydrogen storage

A specification for the hydrogen storage system is provided in Table 2.
A new safety device is implemented on this swap-rack: an Excess Flow Valve that automatically shuts off hydrogen stream in case of any rupture on the H2 line or any large leakage. This device is directly mounted on the cylinder neck so as to keep the hydrogen safely inside the cylinder. The cylinders are protected from any over pressure due to fire by a 70 MPa thermally activated pressure relief device similar to those fitted on all compressed natural gas (CNG) vehicles.

Table 2: Hydrogen storage specification (70MPa)

Mass of gas stored	2.7 kg (1.6 kg for 35 MPa storage)
External volume	215 l
Storage system mass	120 kg
Gravimetric density	2.2 wt% (0.73 kWh/kg)
Volumetric density	12.6 g/l (0.42 kWh/l)
Cylinder construction	Stainless steel liner fully wrapped with carbon fibre, Type III
Cylinder manufacturer	Faber

4 Vehicle Specification

The basic design specification for the vehicle, based on a Peugeot Partner Origin and known as H_2Origin, was to offer a range of 300 km, equipped with an advanced technology fuel cell to make it a ZEV (Zero Emission Vehicle), capable of being used as a technical baseline for future-generation delivery vehicles in urban and suburban environments.
Figure 5 shows a picture of the EC7 fuel cell system mounted in the engine compartment of the H_2Origin demonstrator.

Figure 5: Fuel cell shown in vehicle engine bay

H_2Origin's energy strategy is designed to maximise the vehicle's range, while also ensuring long-term performance stability. To achieve this goal, the vehicle's control unit makes maximum use of the intrinsic characteristics of onboard systems, such as energy storage (HV batteries or compressed Hydrogen), or of the fuel cell system (figure 6).

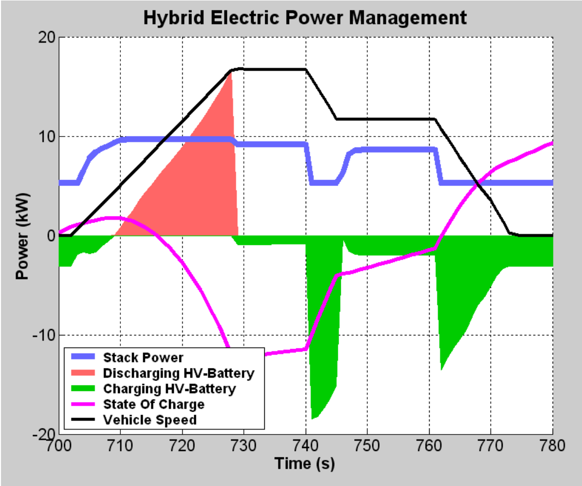

Figure 6: Range Extender Strategy

Vehicle technical data is provided in Table 3:

Table 3: Vehicle technical data

Vehicle	Peugeot Partner H_2Origin
Tyres	175/65 R14 C
Electric Motor	Leroy-Somer SA 18
Max mechanical power	35 kW
Max mechanical torque	180 Nm
Maximum speed	6,500 RPM
Transmission	Single ratio: 7.16
Fuel cell system	Intelligent Energy EC7
Stack max/min voltage	180/130V
Stack min/max current	0/100A
Stack gross/net power	12/10 kW
HV DC/DC Converter	A2E Soprano
Position	Range extender hybrid
HV Battery	Panasonic EV95 Ni-MH
Nominal pack voltage	180 V
Nominal pack capacity	95 Ah
Nominal pack power	±45 kW
Nominal pack energy	15.4 kWh

5 Vehicle Testing

Following successful validation and verification of the fuel cell system in the laboratory, it was integrated into the full vehicle package for validation and optimisation on board.

5.1 Validation and Optimisation

This period of testing was carried out under controlled conditions on PSA Peugeot Citroën's private test facility at La Ferté Vidame, France. Part of the facility is a dedicated urban test track - this section was used for the development of H_2Origin. A hydrogen fuelling station is available on site as is suitable vehicle storage. The urban test track comprises a number of traffic lights and stop signs in order to emulate an urban route (Figure 7). A single cycle of the test track is 2.4km with a maximum vehicle speed of 85km/h achieved.

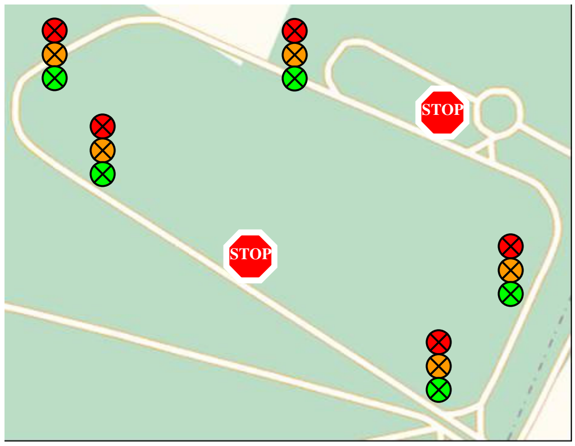

Figure 7: Urban Test Track

The first element of validation was carried out with the fuel cell in manual mode, i.e. the current drawn from the fuel cell was dictated as a manual set point, with this setpoint adjusted via the vehicle's man-machine interface (MMI). The main purpose of this phase of testing was to sweep the full operational range of the fuel cell over the full vehicle speed range with a view to identifying any interactions (e.g. electromagnetic compatibility or vibration issues). Sample data captured during these manual tests is shown in Figure 8.

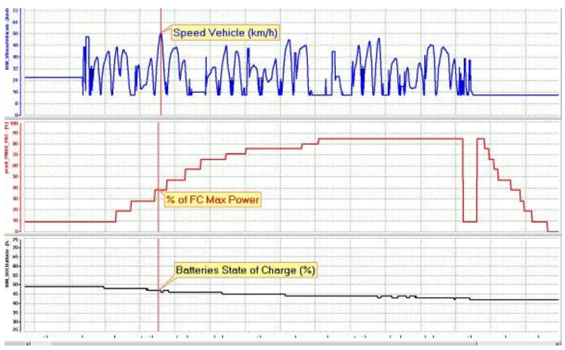

Figure 8: Manual mode testing

Following the manual tests, the vehicle was trialled with the fuel cell system in automatic mode. In this state the vehicle supervisor automatically adjusts the fuel cell power load according to a defined control strategy. For example, the supervisory control of the vehicle uses the battery state of charge, hydrogen storage pressure, vehicle speed and vehicle acceleration to operate the fuel cell system such that the range of the vehicle is maximised (Figure 9).

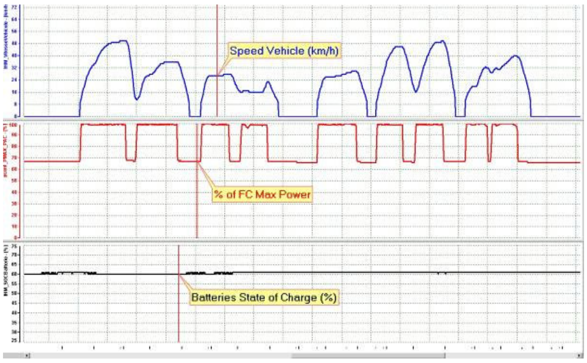

Figure 9: Automatic mode testing

During the initial period of this test phase the vehicle control system was optimised, and in addition to proving the robustness of the vehicle, both simulation and road tests were performed to validate the vehicle performance (Table 4).

Table 4: Vehicle performance

Maximum speed	100 km/h
0-400 m	25.2 s
0-1000 m	48.1 s
0-50 km/h	8.3 s
30-60 km/h	7.3 s
Range, hybrid mode (NEDC)	308 km
Range, battery mode (NEDC)	78 km

As can be seen, addition of the fuel cell system results in an increase on NEDC in range from 78km to 308km when compared to the conventional battery electric vehicle.

Further vehicle optimisation was carried out in Loughborough, UK at a test track situated on the Holywell Park site of the Loughborough University campus. This section of campus contains a series of privately owned roads from which a suitable pseudo-urban vehicle duty cycle was derived (Figure 10). In addition to providing a suitable drivecycle profile for vehicle proving, the site was also close to that of the Loughborough University hydrogen fueller.

Figure 10: Loughborough Test Circuit

Various tests and validation were performed on the Holywell site, mainly for optimisation of the fuel cell and vehicle control systems. Figure 11 shows data collected from one of the final runs with the vehicle fully optimised, and photographs of the testing are shown in Figure 12 and Figure 13 During the testing at Loughborough 250km were covered without incident.

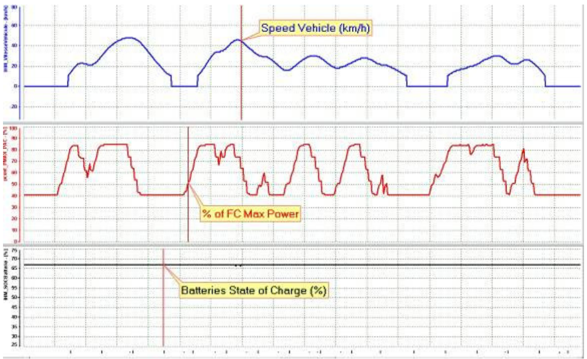

Figure 11: Test in automatic mode - validation & improvements for UK Demo profile

Figure 12: H2Origin Testing at Loughborough

Figure 13: H2Origin Testing at Loughborough

5.2 Evaluation

The Andrésy circuit consists of a 12km loop on public roads close to the PSA Peugeot Citroën test facility at Carrières-sous-Poissy, France (Figure 14). The circuit consists of elements with vehicle speed in excess of 70km/hr whilst also maintaining a large urban element, as can be seen via collected data in Figure 15. The main purpose of this circuit was to validate and demonstrate the operation of the H_2Origin on public roads, as shown in Figure 16. No issues arose during this phase of testing which to date has amounted to over 300km.

Figure 14: Vehicle test route: public roads

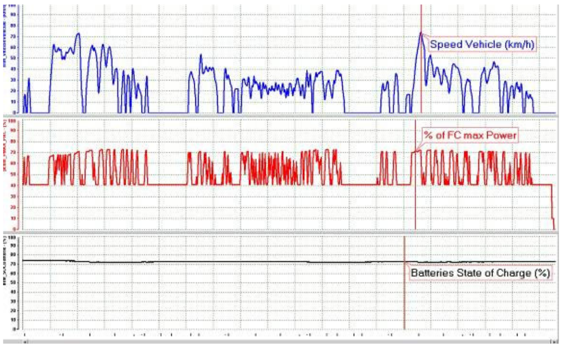

Figure 15: Test data from evaluation on public roads

Figure 16: Vehicle evaluation on public roads

6 Conclusions

A fuel cell system and associated hydrogen storage has been developed such that the range of a conventional battery electric Peugeot Partner vehicle can be increased. The fuel cell system used is based on proton exchange membrane technology and packaged within the engine bay of the vehicle. Hydrogen storage is provided as a removable swap rack in the rear load area of the vehicle.

When comparing the results, the fuel cell equipped vehicle has a range of 308km compared to 78km of the battery vehicle when completing repeated NEDC drivecycles. Thus, inclusion of the fuel cell system has demonstrated that the potential customer base for a zero emission vehicle is increased. One further advantage is that the fuelling time is more comparable to that of conventional internal combustion engined vehicles when compared to the typical recharge time of a pure battery electric vehicle.

Acknowledgments

The authors acknowledge the financial assistance provided by the UK Technology Strategy Board via their Low Carbon Energy Technologies programme and additional project partner Prodrive.

References

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