Available online at www.sciencedirect.com
SCIENCE @ DIRECT®

ELSEVIER

Journal of Power Sources 154 (2006) 489–496

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Dynamic behavior of gasoline fuel cell electric vehicles

William Mitchell [a], Brian J. Bowers [a,*],
Christophe Garnier [b], Fabien Boudjemaa [b]

[a] *Nuvera Fuel Cells Inc., 20 Acorn Park, Cambridge, MA 02140, USA*
[b] *Renault, Research Division, 1 avenue du Golf, Guyancourt 78288, France*

Abstract

As we begin the 21st century, society is continuing efforts towards finding clean power sources and alternative forms of energy. In the automotive sector, reduction of pollutants and greenhouse gas emissions from the power plant is one of the main objectives of car manufacturers and innovative technologies are under active consideration to achieve this goal. One technology that has been proposed and vigorously pursued in the past decade is the proton exchange membrane (PEM) fuel cell, an electrochemical device that reacts hydrogen with oxygen to produce water, electricity and heat.

Since today there is no existing extensive hydrogen infrastructure and no commercially viable hydrogen storage technology for vehicles, there is a continuing debate as to how the hydrogen for these advanced vehicles will be supplied. In order to circumvent the above issues, power systems based on PEM fuel cells can employ an on-board fuel processor that has the ability to convert conventional fuels such as gasoline into hydrogen for the fuel cell. This option could thereby remove the fuel infrastructure and storage issues.

However, for these fuel processor/fuel cell vehicles to be commercially successful, issues such as start time and transient response must be addressed. This paper discusses the role of transient response of the fuel processor power plant and how it relates to the battery sizing for a gasoline fuel cell vehicle. In addition, results of fuel processor testing from a current Renault/Nuvera Fuel Cells project are presented to show the progress in transient performance.

Keywords: Gasoline fuel processor; On-board hydrogen production; Automotive; Polymer electrolyte membrane fuel cell; Response time; Battery size

1. Introduction

For a long time, economic development of countries has been highly correlated with energy consumption. As a major player in economic development, the automotive industry has always been concerned by energy issues. But as we start a new century, new energy demands are surfacing, especially when we see the needs of countries like China and India with billions of inhabitants. The main environmental issues that must be faced by the automotive sector are: pollutant emissions and energy consumption for the short-term, Green House Gas emissions and diversification of energy sources for the mid-term and sustainable development with use of renewable energy for the long term. Among other innovative technologies, there is promise that fuel cells may play a major role for solving mid and long term issues.

Nevertheless, many breakthroughs are needed to achieve commercial availability of fuel cell powered vehicles. One main question concerns which fuel will be used by a fuel cell power plant. Hydrogen is the desired fuel, but many technical, financial and social issues must be solved such as hydrogen storage on-board the vehicle, a hydrogen distribution network that requires a huge investment and public acceptance of the new fuel [1]. So, a mid-term alternative may be to use power systems based on proton exchange membrane (PEM) fuel cells that employ an on-board fuel processor with the ability to convert conventional fuels into hydrogen and thereby remove the fuel infrastructure and storage issues.

In that context, Renault and Nuvera decided at the beginning of 2002 to jointly explore the feasibility of an on-board fuel processing system [2]. Technical targets of the project and the status are further discussed in this paper. The project is now in its final phase with the development of a fuel processor prototype compatible with most of the requirements of an automotive application [3]. However, in order for these fuel processor/fuel cell vehicles to be commercially successful, issues such as start

---

[*] Corresponding author.
E-mail address: bowers.b@nuvera.com (B.J. Bowers).

0378-7753/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2005.10.089

time and transient response must be addressed. Cold start time and cold start fuel consumption [4] is probably the most difficult issue to be solved. It is also the most known issue. So, we have chosen to discuss in this paper another important issue: the role of transient response of the fuel processor in the overall system architecture and how it relates to efficiency and emissions of a gasoline fuel cell vehicle.

2. Fuel cell power plant

2.1. General overview and layout

To make a fuel cell stack work, numerous components are necessary. Indeed, a fuel cell stack is a passive device that requires supporting components to produce and control the desired power. This overall system needed to produce electricity is called the fuel cell power plant. So, the power plant is composed of a fuel processor system (FPS) (or reformer) to produce hydrogen, a fuel cell stack and management systems for water, gasoline and air as described in Fig. 1. The fuel cell power plant has to be water-balanced; therefore, condensers are present to recover enough water to feed the fuel processor system.

To be competitive, fuel cell vehicles have to show better performance than current and emerging power trains. Renault's target for a commercial on-board fuel processor/fuel cell vehicle is a well-to-wheels CO_2 emission of 100 g of $CO_2\,km^{-1}$ with 80 g of $CO_2\,km^{-1}$ for the on-board tank-to-wheels portion. Correlating these emissions with the properties of the primary design fuel (gasoline), the fuel consumption should be around 3.2 l/100 km. To reach this value, a high efficiency power plant is needed. An initial target of 40% efficiency has been defined for the 2004 power plant prototype, although higher efficiencies may eventually be needed.

Of the 200 kWth fuel input, more than half of the energy is rejected via thermal power, creating a challenge for radiator packaging. The parasitic power, which is dominated by the air compressor system, should not be above 4% of the fuel energy to reach our objective of 40% net efficiency for the power plant. This value will define the maximum allowable power of our air compressor system as roughly 9% of the gross electric power. The overall energy balance for a system that could achieve 40% efficiency is presented in Fig. 2. For a 200 kWth fuel input, 80 kW of electricity would be produced. For the first phase of this project, the target power is slightly lower at 70 kWe while the system integration is optimized.

To be integrated in the vehicle without modification of the passenger space, the power plant's volumetric density should be around 0.25 $kWe\,l^{-1}$ with a mass density around 0.3 $kWe\,kg^{-1}$. For the targeted SCENIC II vehicle, approximately 200 mm of height will allow integration under the passenger floor. This integration shows lack of space for a large water tank. As a consequence, the power plant should internally recover and recycle enough water for hydrogen production. In theory, this water balance can be positive since the fuel cell stack produces water. Operation parameters just need to be defined to condense enough water. The key parameter is the operating pressure of the power plant. With an external temperature of 45 °C and a PEM fuel cell stack operating at 80 °C, a pressure of around 3 bars at the condenser is needed to recover enough water for the fuel processor at full power.

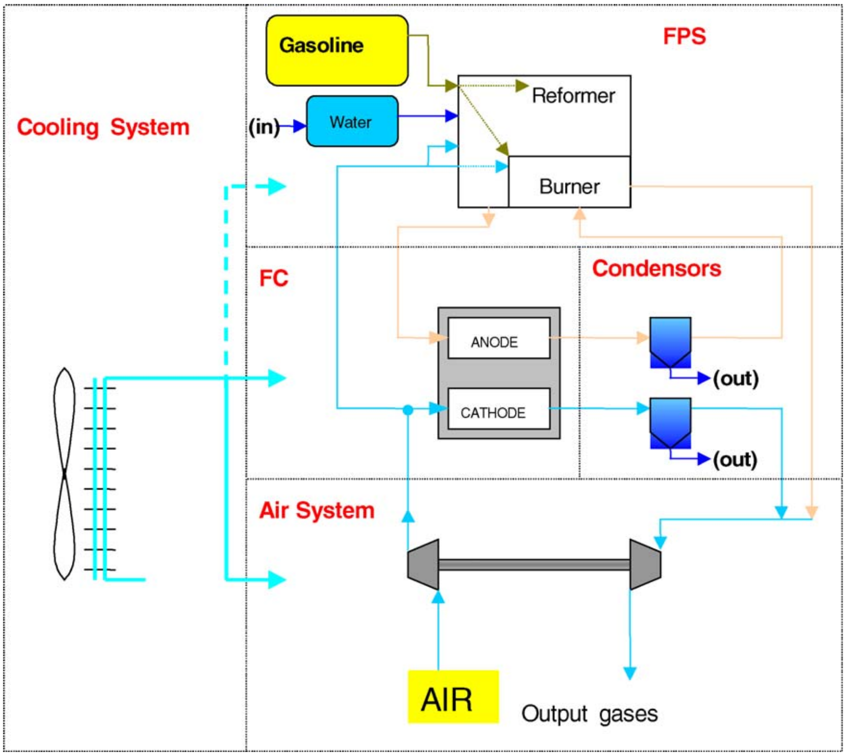

Fig. 1. Fuel cell/fuel processor power plant.

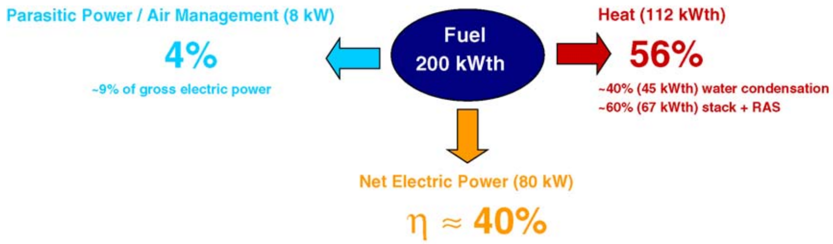

Fig. 2. Power plant target energy balance.

Table 1
Renault power plant objectives for 2004

Characteristic	Objective
Fuel type	Sulfur free gasoline
Electric power	70 kWe
Volume	280 l
Mass	235 kg
Full power efficiency	40%
Water requirements	No water addition to vehicle
Transient	3 s
Starting time	2 min

To be competitive with emerging and future power trains, the fuel cell vehicle has to allow similar speeds, response and startup time as other options. Our objective is for the power plant to produce electricity within 2 min to minimize the battery size. Battery technology developed for electric vehicles can provide energy to move the vehicle during the power plant startup. Using the constraints of vehicle integration and performance, specifications of the overall power plant were defined and are summarized in Table 1.

Realization of such a power plant will give us the possibility to build a gasoline fuel cell vehicle. Integration of components on a SCENIC II vehicle is shown in Fig. 3. The performance of this vehicle can be simulated and compared to current and future ICE and hybrid vehicles. To be compared on the same baseline, a normalized driving cycle has been defined, as describe in Section 2.2.

2.2. *Drive cycle requirements (power and dynamics)*

2.2.1. *Definition of NEDC*

To compare vehicle performance, a standard driving cycle has to be defined. There exists numerous driving cycles for different markets (mainly Japan, USA and Europe), each with a different purpose and different profile. The New European Driving Cycle (NEDC) has been defined to allow comparisons of fuel consumption and emissions of different vehicles. It is representative of driving condition in Europe. It is composed of four elementary urban cycles and one extra-urban cycle, as describe in Fig. 4.

The NEDC is chosen as the primary cycle for study of fuel cell vehicles. This tool gives us the possibility to calculate the power requirement of different cars. In the case of fuel cell vehicle, we can convert the mechanical power requirement into net electrical power at the fuel cell power plant outlet. For that we have developed a hybrid gasoline fuel cell vehicle model. The simulation result presented in Fig. 5 shows the net power of the fuel cell power plant required for the reference vehicle.

It is interesting to note that the urban driving portion requires quick electric power transients between Idle, ∼5 and ∼13 kWe. On the extra urban portion, the net electrical power goes up to

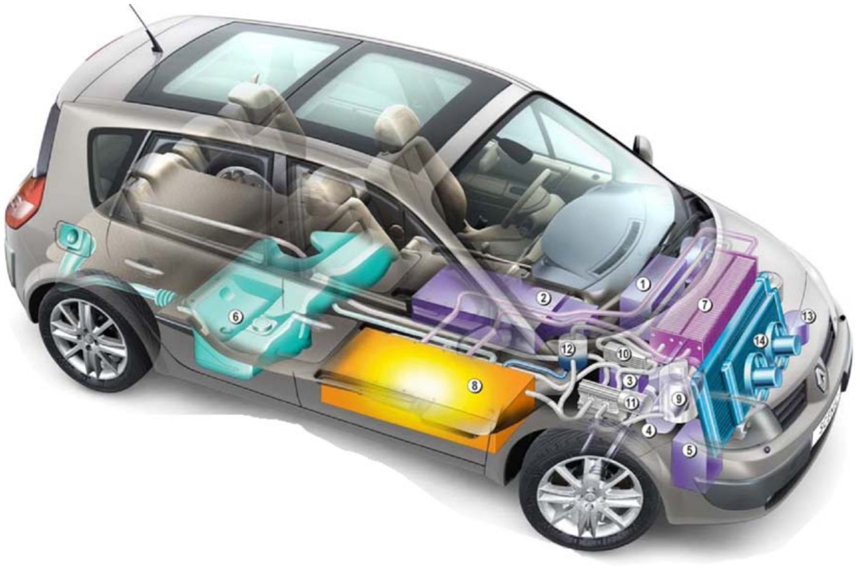

Fig. 3. Gasoline power plant layout in SCENIC II vehicle.

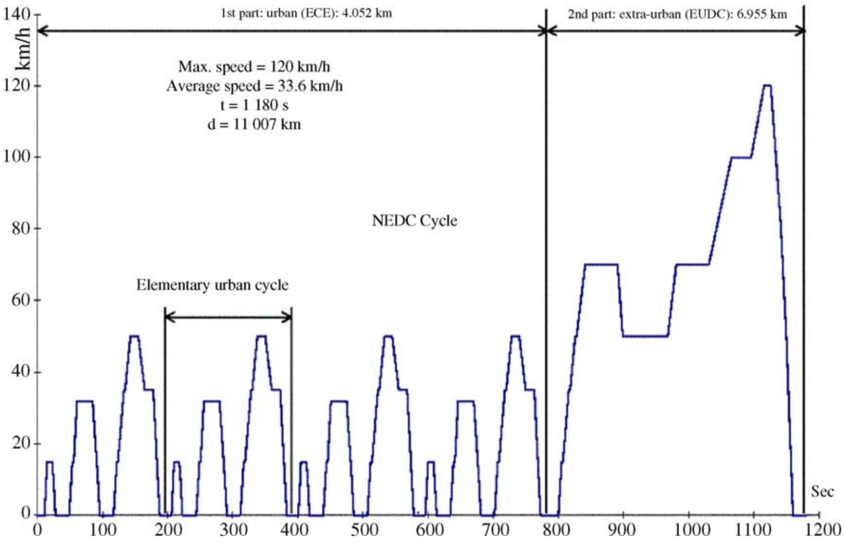

Fig. 4. New European Driving Cycle.

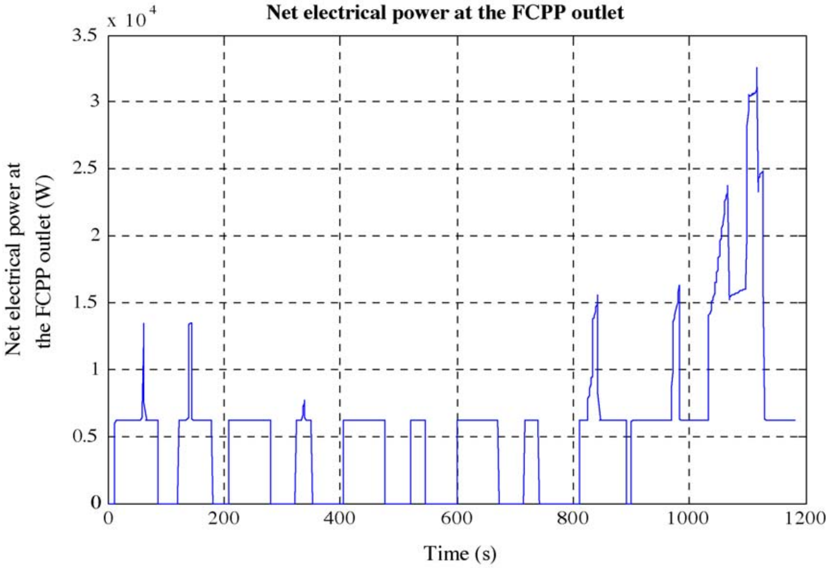

Fig. 5. FCPP net electric power to be delivered by the fuel cell power plant on NEDC (NMVEG) cycle vs. time.

33 kWe. Generally we can see that the up and down transients are very fast and there are numerous periods where the output power is equal to zero during deceleration and the recovery of energy from the regenerative braking. These conditions, orientate the definition of our vehicle as a hybrid vehicle. It is obvious that a battery package will be necessary to provide boost of power during up-transients, to give possibility to have regenerative braking during down-transients and finally to manage "stop and go" of the power plant.

Although the power plant only needs to deliver a maximum of 33 kWe on the NEDC cycle, other operating modes require the power plant to produce up to 70 kWe. The high-power operating modes include high speed and hill climbing and accelerations from moderate speeds to high speed. Currently, a power plant with a continuous output of 70 kWe is expected to give acceptable performance for sustained high speed or hill climbing while a battery can assist during acceleration.

3. Fuel processor system

3.1. Goals

The power plant specifications were used to create a detailed gasoline fuel processor specification. The main focus for the first phase of the program is on power density, which means achieving a size small enough to fit on a vehicle while producing the required amount of hydrogen with low CO. These goals as shown in Table 2 include an 80 l volume, 1.3 g s^{-1} of hydrogen production and CO concentrations of 100 ppm for steady state and 1000 ppm for transients. The 80 l volume contains every-

Table 2
Fuel processor specification

Characteristic	Design goal	Comments
Fuel processor volume (without balance of plant components or plumbing)	≤80 l	Includes everything between cold feed streams and ~100 °C fuel-cell-quality reformate outlet stream
Height	<229 mm	"Flat" aspect ratio for vehicle installation
Fuel type	Sulfur free gasoline	On-board or refinery desulfurizer assumed
Maximum hydrogen in reformate	$1.3\ \mathrm{g\,s^{-1}}$	~157 kWth based on LHV
Full power hydrogen efficiency	≥78%	LHV H2/LHV ATR fuel
CO concentration		At PrOx exit
Steady state	≤100 ppmv (dry)	
Transient	<1000 ppmv (dry)	
Reformate pressure	3 bar	At PrOx exit

thing required to convert the room temperature feed streams (air, fuel, water) into fuel-cell-quality hydrogen-rich reformate gas at ~100 C. This includes five catalyst and reaction zones ((1) autothermal reforming (ATR); (2) high temperature water gas shift (HTS); (3) low temperature water gas shift (LTS); (4) preferential oxidation (PrOx); (5) tail gas combustion (TGC)) and all of the associated heat exchangers for thermally managing these reactions and vaporizing fuel and water.

3.2. *Transient work (initial)*

The initial testing of the fuel processor focused on steady state validation of the power, efficiency and CO. Fig. 6 shows testing with gasoline flows of 60–195 kWth (based on LHV). This testing showed that the fuel processor can achieve the targets of 78% hydrogen efficiency with 100 ppm of CO over this range of power. Between steady state testing points, the power was changed relatively slowly due to limitations of the laboratory control system, which was based on industrial valves and sensors. However, the transient "spikes" of CO were kept well under the target of 1000 ppm. This testing validated the design and gave confidence that the system could be controlled to give high efficiency and low CO. Therefore, the next step was to focus on the control system.

3.3. *Controls, balance of plant and packaging work*

As described in the previous section, the fuel processor design was initially validated over a range of steady state power conditions. While the fuel processor design is crucial for the success, it is also important to have good control over the flows in the system. These controls components are typically located outside the fuel processor and are referred to as the "balance of plant" (BOP). The initial laboratory BOP was not designed for rapid transients and thus limited the speed of power changes. To overcome this issue, a parallel effort researched automotive-type BOP components that would not only respond quickly but would also be small enough to package on a vehicle. A packag-

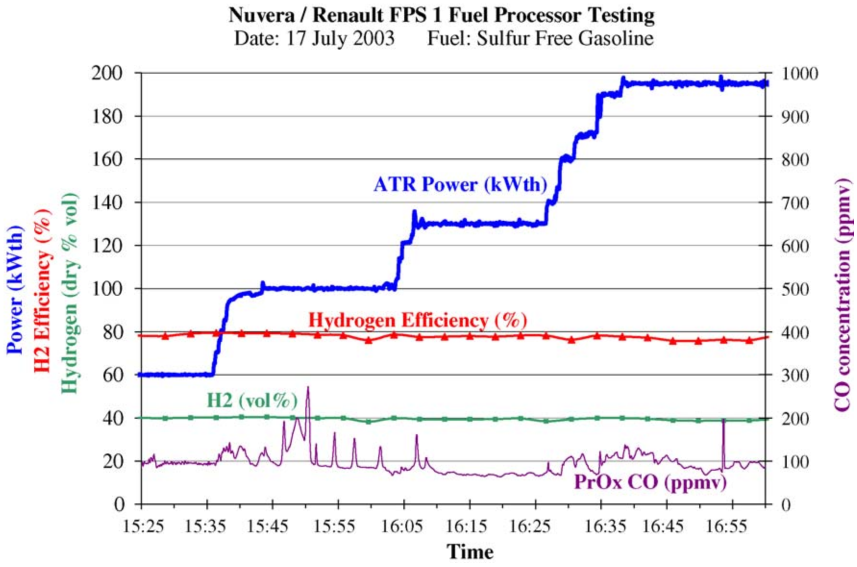

Fig. 6. Steady state validation of fuel processor with mild transients between power levels.

Fig. 7. Fuel processor packaging study using automotive-type components.

ing study showed that these components and the fuel processor could fit into a small, "flat" space that would allow installation under the vehicle (Fig. 7).

The first BOP components available from this research effort were the fuel and water systems. Fast-acting compact valves and associated components were tested for performance and used to develop fuel and water control strategies. In addition, a dynamic model was built from first principles and then calibrated using experimentally determined transfer functions of the fuel processor. The model was then used to develop controls strategies to manage the multiple flows inside the fuel processor (fuel, air, water, steam, reformate, exhaust).

3.4. *Transient (with new controls and BOP)*

After installing the fuel and water BOP and adding the new algorithms to the control computer, the fuel processor showed significant improvements in transient response. These systems allowed much faster power changes than with the laboratory BOP. Fig. 8 shows that the power was changed in only a few seconds instead of the several minutes needed with the laboratory BOP. While it may take several minutes for all thermal effects to equilibrate [5], the control system can compensate to keep the CO low. In addition, the CO concentrations show a much smoother steady state trend with smaller spikes at the power changes due to the improved control of the process flows. This initial testing gives confidence that the fuel processor can be controlled over a range of conditions. Further upgrades are planned for the remaining BOP components and the controls development will continue to focus on transient response and packaging as the project works toward driving cycle testing.

3.5. *Previous work on transients*

While the current system has not yet run a NEDC cycle, experience from previous fuel processor systems shows that it is possible to control them through a driving cycle. Fig. 9 shows data from a previous Nuvera fuel processor undergoing a modified version of the NEDC cycle. This fuel processor covered a smaller operating range than the current fuel processor, so the cycle was modified to accommodate a maximum gasoline power input of about 45 kWth and a minimum of 10 kWth and the cycle was slowed to about half speed to accommodate the control system. The results show CO levels well below 100 ppm during rather aggressive power changes and give confidence that a fuel processing system can be properly controlled over driving cycles. This type of testing will be the next step in the controls evolution of the current fuel processor as the system is tested against the type of cycles shown in Figs. 4 and 5.

4. Effect of power plant response time on power train hybridization (battery size)

As mentioned above, a hybrid system with a battery and fuel cell power plant will be used to help with regenerative braking and to make up for the instantaneous difference between the power demand and power available from the power plant. To

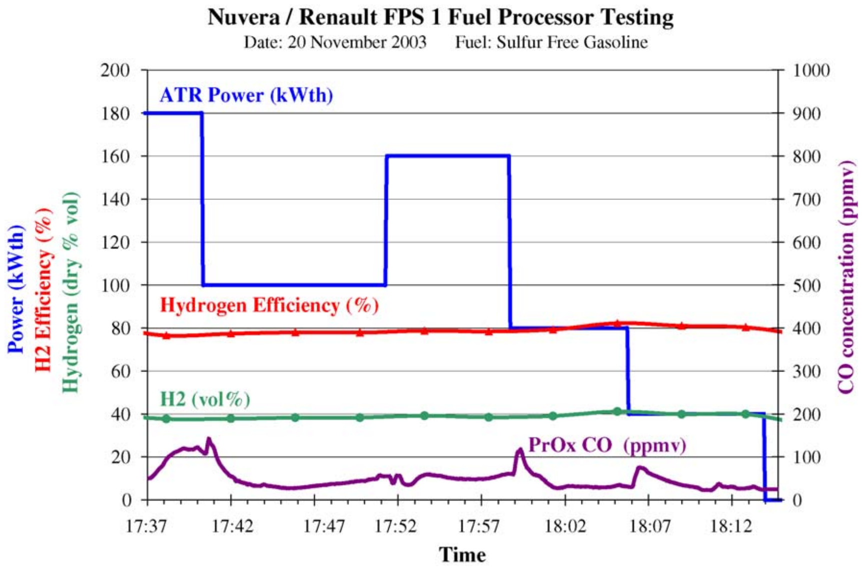

Fig. 8. Transient testing of fuel processor with automotive fuel and water systems.

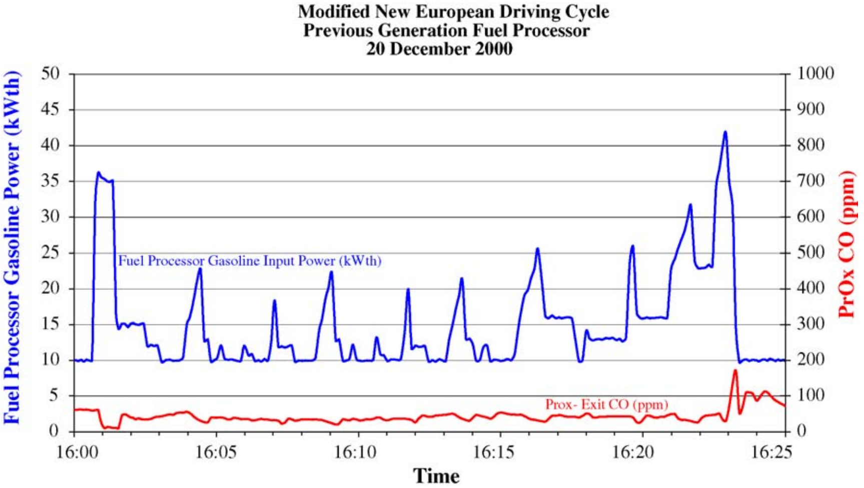

Fig. 9. Modified NECD performance of previous generation fuel processor.

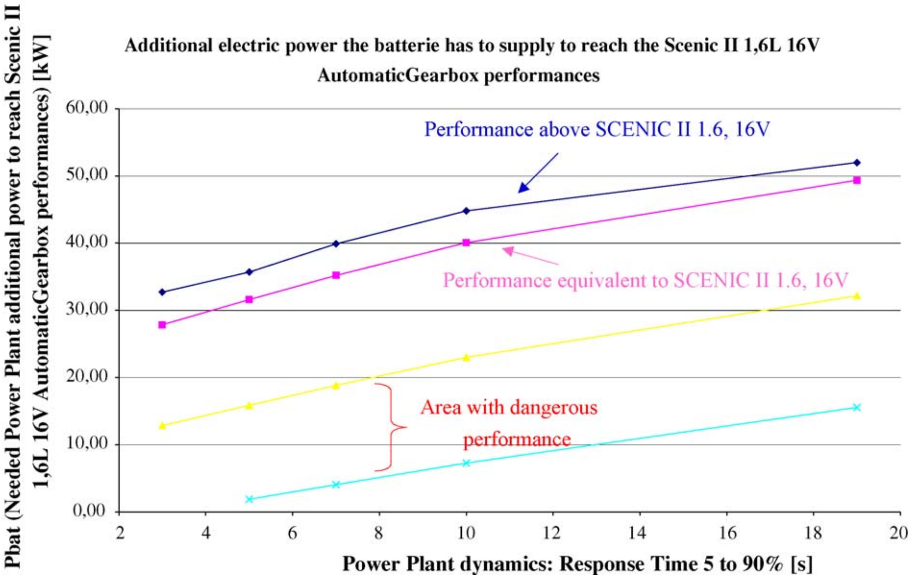

Fig. 10. Power plant dynamic response vs. additional electric battery power.

help size the battery, we carried out a tradeoff study on power plant response time and battery size. We wanted to answer to the following question: what will be the impact of a power plant's transient delay on the vehicle performance?

To answer to this question, we used our hybrid gasoline fuel cell vehicle model and evaluated the performance for different battery sizes. The performance of this vehicle has been compared to our "baseline" vehicle, which is the 1.6, 16 V automatic gearbox SCENIC II. First, a range of performance criteria is considered, including acceleration, top speed and fuel consumption on driving cycles. Once these criteria have been selected, we can calculate the battery power needed to give different levels of performance for a range of power plant response times. Results of these simulation and comparison are shown in Fig. 10.

The main output of this tradeoff study is that a battery pack is required for the gasoline fuel cell vehicle. Even if our power plant transient target of 3 s is achieved, a battery is required to avoid delays in acceleration that could be dangerous when in traffic. If we want performance equivalent to our baseline vehicle, we need a battery power of around 30 kW for a 3 s power plant response time. With this additional power we will have a marketable vehicle in term of performance. This 30 kW battery also corresponds to the maximum regenerative braking power on the standard cycles and would allow the most benefit to the system efficiency.

5. Conclusions

Today, there is promise that fuel cell vehicles can use onboard fuel processors as an alternative to hydrogen storage. With our current development work, we are confident that a fuel processor system can be integrated in a vehicle. Steady state and packaging specifications have been achieved. Nevertheless, attention to the transient performance is still necessary. Today the project is orientated toward a hybrid gasoline fuel cell vehicle since a battery will allow for regenerative braking and maintain a transient performance comparable with our current vehicle. The response time of the power plant affects the battery size. Today we estimate a need of a 30 kWe battery pack to realize a marketable vehicle.

The fuel processor system response time is important to the overall power plant response. An automotive controls development effort has identified components and designed algorithms that improved the FPS response time from a few minutes to a few seconds. Our target is a FPS response time of about 3 s, which will help to minimize our battery pack. Continuing controls development will allow driving cycle tests on the compact fuel processor and lead toward power plant integration testing.

References

[1] S.G. Deshanais, J.Y. Routex, M. Holtzapple, M. Ehsani, SAE 2002-01-0097.

[2] Renault/Nuvera press release, June 2002. www.renault.com.

[3] B. Bowers, J. Zhao, D. Dattatraya, V. Rizzo, F. Boudjemaa, SAE 2004-01-1473.

[4] S. Springmann, M. Bohnet, A. Docter, A. Lamm, G. Eigenberger, J. Power Sources 128 (2004) 13–24.

[5] M. Sommer, A. Lamm, A. Docter, D. Agar, J. Power Sources 127 (2004) 313–318.