Hydrogen Automobile Heads Toward Series Production HydroGen3 Puts Fuel Cells on the Road

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Abstract

General Motor's concept vehicle HydroGen3, based on the Opel Zafira production model, represents the third generation of fuel cell concept vehicles. Groundbreaking new technical and engineering improvements have been reached, e.g. the integration of the latest generation of fuel cell stacks. The fleet demonstrations will start this year. Given the current stage of development at GM/Opel, hydrogen-powered automobiles could be mass-produced in about eight years. An efficient fuel cell technology suitable for everyday use is the essential pre-condition for the development of an alternative propulsion system, which would replace the classic crude oil-based fuels for the vehicles of the future. However, this technology alone is not sufficient to establish fuel cell automobiles as viable substitutes for conventional vehicles with gasoline and diesel engines. Factors such as purchase price, safety, engine performance and driving dynamics also play a decisive role for the customer. General Motors (GM) has therefore invested more than one billion dollars to develop an automobile incorporating state-of-the-art fuel cell technology with vehicle characteristics suited to the marketplace. The hydrogen concept vehicle HydroGen3 (Figure 1) marks the newest and most comprehensive advance made by GM/Opel on the road to fuel cell vehicle market readiness. Test drives conducted by an international group of expert journalists at the Grand-Prix course in Monte Carlo in December 2002 confirmed that the HydroGen3 has brought mass production of hydrogen-fuelled automobiles within reach.

Keywords: Fuel cell technology, Hydrogen-powered automobile heads, HydroGen3 vehicle

1 Third Generation Test Car

The HydroGen3, based on the Opel Zafira production model, represents the third generation of fuel cell concept vehicles. It was first presented at the international automobile show IAA 2001 in Frankfurt. GM/Opel had already established the feasibility of a vehicle with a fuel cell propulsion system with the predecessor model, the HydroGen1. Under the supervision of journalists and motor sport experts, the HydroGen1 set a total of 15 international records for fuel cell vehicles – including records for distance, speed and endurance. While GM/Opel engineers used the successor model, the HydroGen2, solely to achieve system improvements and to test alternative detailing, the HydroGen3 emerged as the first prototype devoted to worldwide fuel cell vehicle testing in fleet demonstrations. Further improvement of performance and of the propulsion system's suitability for everyday use as compared to the HydroGen1, were the primary developmental goals. Experts at the German fuel cell development centre

Fig. 1 The HydroGen3 based on the Opel Zafira series model.

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in Mainz-Kastel, together with colleagues at GM locations in the U.S. in Honeoye Falls near Rochester, New York, in Warren, Michigan, and in Torrance, California, were responsible for the research and development work within the scope of the GM Fuel Cell Activities (GM FCA). Currently, there are a total of some 500 people employed at these research institutes.

2 Latest Generation Fuel Cell Stack

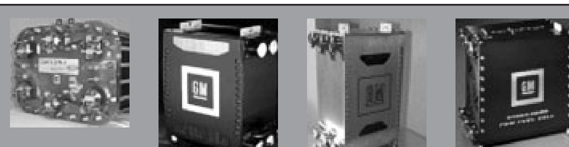
The latest generation of fuel cell stack is at the heart of the HydroGen3. This improved stack, like its predecessor, is comprised of a block of 200 individual, in-line fuel cells. However, its measurements (length × width × height: 472 × 251 × 496 mm) are considerably smaller compared to the HydroGen1. Nonetheless, the power density has been increased. They amount to 1.60 kWl^{-1}, or 0.94 kWkg^{-1} as compared to values of 1.10 kWl^{-1} and 0.47 kWkg^{-1} in the case of the HydroGen1. This represents a decisive step closer to the goal set by developers of a fuel cell unit power density of 2.0 kWl^{-1} and 1.0 kWkg^{-1}. These improvements could be achieved by a higher electric current density and by using thinner bipolar plates for the fuel cells, Figure 2.

The HydroGen3 stack delivers a constant performance of 94 kW (previously 80 kW) and a peak performance of 129 kW (predecessor 120 kW). It works at a temperature of 80 °C and at a pressure between 1.5 and 2.7 bar. The fuel cells develop, depending on load conditions, a DC electrical voltage of between 125 and 200 V. This voltage is boosted to between 250 and 380 V by a DC converter, changed from power electronics to AC current then directed to an asynchronous three-phase AC motor, which produces a maximum 60 kW. The motor, with a maximum torque of 215 Nm and 12,000 rev. min^{-1}, drives the HydroGen3 front wheels through a planetary transmission at a gear ratio of 8.67:1. This efficient propulsion system accelerates the vehicle from 0 – 100 kmh^{-1} in about 16 s and produces a top speed of 160 kmh^{-1}, Figure 3.

These features have been tested between freezing temperatures and also at up to 43 °C.

The fuel cells are fed by tanks containing either liquid hydrogen, at a temperature of –253 °C, or hydrogen, compressed to a maximum 700 bar. This provides for a driving range of 400 or 270 km, respectively.

Fuel Cell Stack Technology Progress



	Gen 3 – 1997	Gen 4 – 1998	Gen 7 – 1999	Stack 2000
Maximum Power:	37 – 41 kW	23 – 40 kW	80 – 120 kW	94 – 129 kW
Power Density:	0.26 kWl^{-1} 0.16 kWkg^{-1}	0.77 kWl^{-1} 0.31 kWkg^{-1}	1.10 kWl^{-1} 0.47 kWkg^{-1}	1.60 kWl^{-1} 0.94 kWkg^{-1}
Number of cells:	220	106	200	200
Active Area:	500 cm^2	500 cm^2	800 cm^2	800 cm^2
Pressure:	2.7 bar	2.7 bar	2.7 bar	1.5 – 2.7 bar
Temperature:	80 °C	80 °C	80 °C	80 °C

Fig. 2 Fuel cell stack advances 1997–2000.

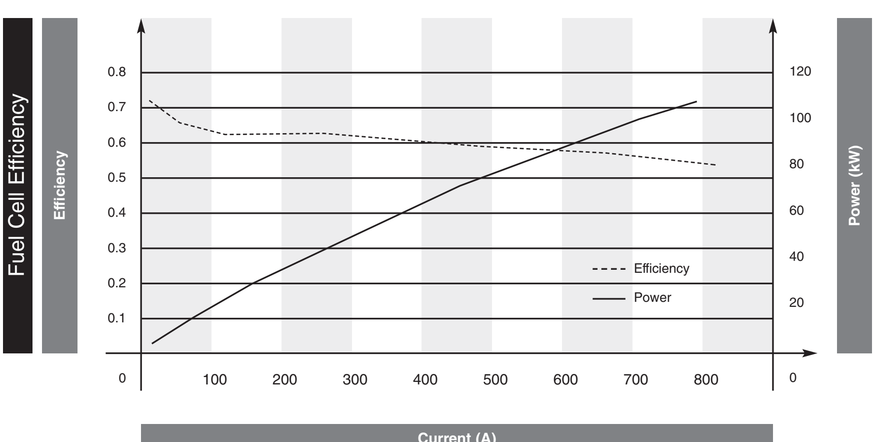


Fig. 3 Efficiency and power of the fuel cell stack against the electric current.

3 Groundbreaking New Developments

Compared to the predecessor model HydroGen1, numerous important details were markedly improved. One example was the elimination of the high performance buffer battery. In the HydroGen1 this energy storage unit had the job of dealing with performance peaks in the drive unit, but with the HydroGen3 engineers have successfully managed to optimise the fuel cell system so dynamically that it can provide the required power immediately on its own. This achievement has saved nearly 100 kg in weight. The improved packaging increased the HydroGen3's full load capacity to that of the Zafira (600 l) in the five-seater arrangement.

The optimisation of the entire fuel cell system's architecture has meant that the water produced in the cells as a result of the reaction between the hydrogen and the oxygen is enough to cover the moisture requirements of the fuel cell mem-

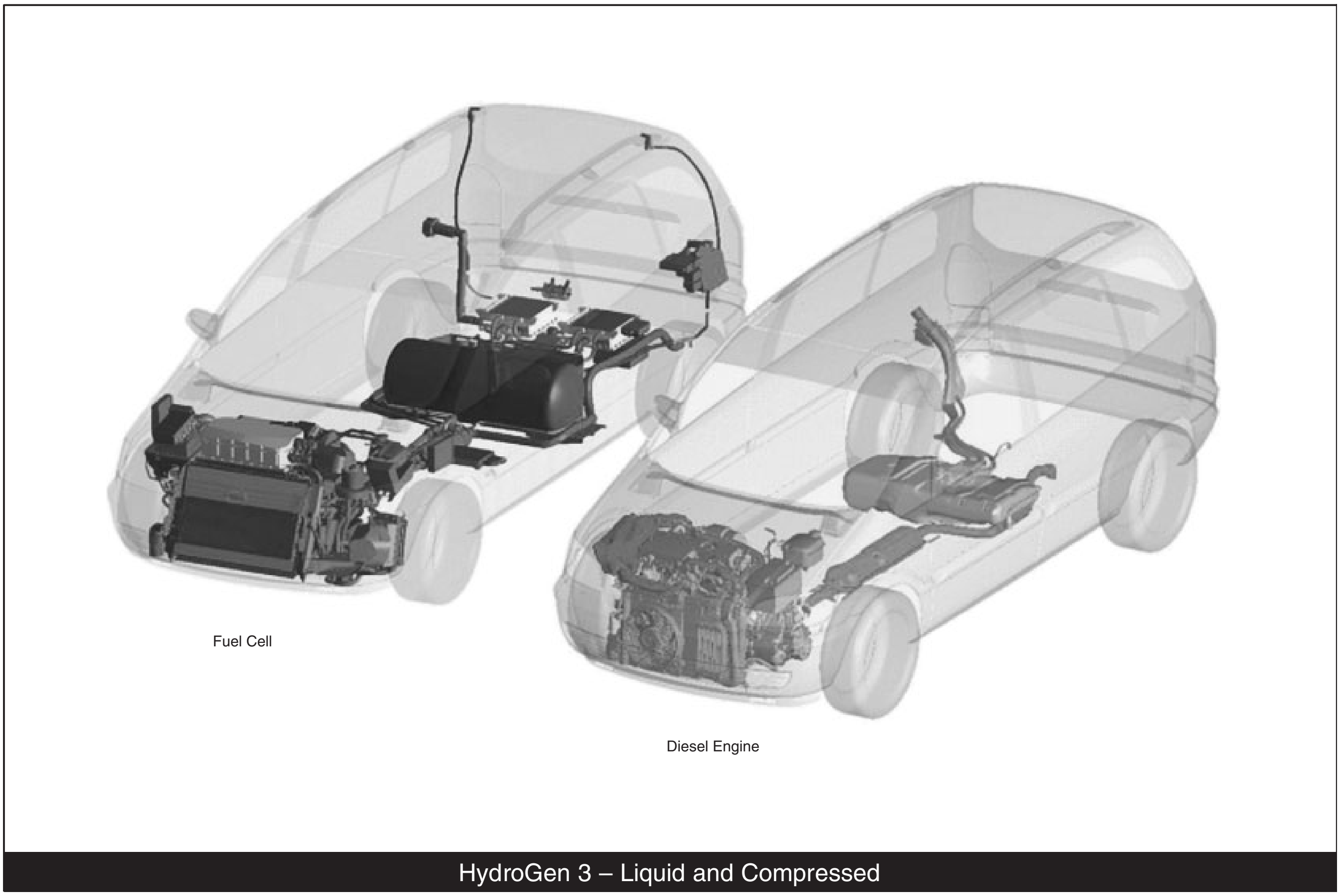


Fig. 4 Comparison of the vehicle package of a fuel cell propulsion system and a diesel engine.

branes. This obviated the need for additional external humidifying components for the cells, creating even more extra space and weight savings.

The electrical traction system has also undergone further development and is now more compact. The complete module, comprising the DC/AC converter, electric motor, and transmission with parking brake and differential, which is placed between the voltage transformer and the drive shaft differential, weighs only 92 kg. Above all, the entire propulsion system unit of the HydroGen3, as a single, so-called PDU Module (Propulsion Dress Up, Figure 4) can be preassembled.

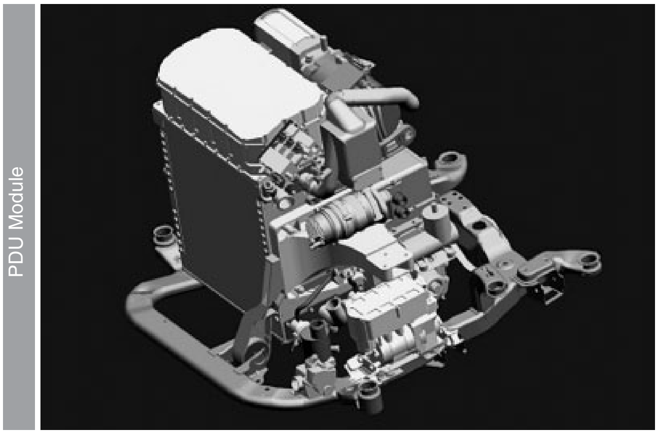


Fig. 5 Propulsion Dress Up Module corresponds to the powertrain in a conventional vehicle. It contains the necessary components apart from the storage system, i.e. the fuel cell stack, the electric traction system and additional units. The propulsion dress up module can be fixed to the engine mounts of the volume production Zafira with ICE enabling a wedding of the PDU module and the body on the assembly line.

The result: the module, weighing some 300 kg can be delivered to the assembly line as a unit and, just as in the case of the traditional automobile "wedding", it can be built into the Zafira using the existing mounting points, Figure 5.

This structural advance by GM/Opel fulfils one of the important conditions for mass production of fuel cell vehicles at a price acceptable to the marketplace – and price is one of the most important customer criteria with regard to acceptance of this new vehicle.

4 Successful Safety Tests

Safety aspects are of special importance when considering the prospects for market acceptance of hydrogen-powered automobiles. This is why GM/Opel was particularly diligent when developing and testing the hydrogen storage system. The companies took the extra step of having the 700 bar

(10,000 psi) pressure tank for gaseous hydrogen (700 bar) certified by Germany's Technical Inspection Association (TÜV – Technischer Überwachungsverein). In addition, GM FCA studied fuel cell vehicle safety aspects in depth via simulation and actual testing. Results showed that the simulation and the actual crash test coincided very well. The tests (56 kmh^{-1} – Offset-Deformable-Barrier-Test with 40% overlap) were carried out according to – and were in full compliance with – European legal directives ECE-R94 and 96/79/EG. The HydroGen3 would have passed the type approval test.

5 Highly Efficient

Efficiency and cost effectiveness will also be decisive factors when it comes to the question of customer acceptance of the hydrogen-powered cars of the future. These new cars must at least be on par with, and preferably superior to, classic automobiles with combustion engines. Thus one important advantage of the HydroGen3 is its exceptional vehicle efficiency rates; in other words its engine energy utilization rate, Figure 6.

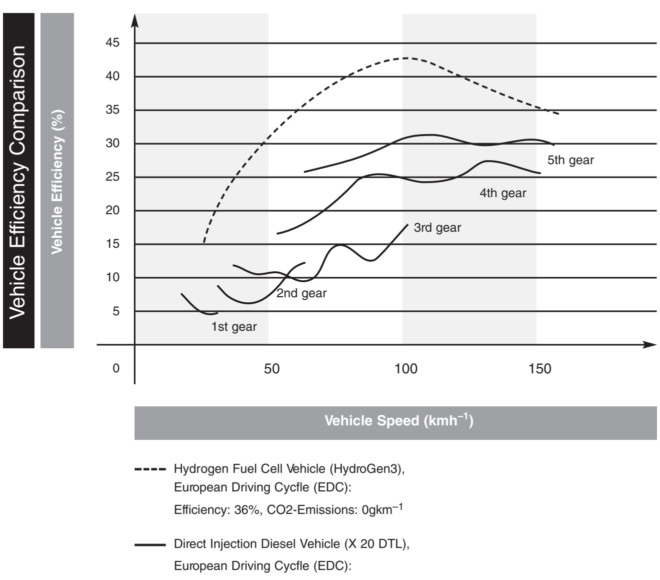


Fig. 6 Efficiency rate comparison of the HydroGen3 and direct injection diesel engine vehicle.

GM/Opel's hydrogen fuel cell vehicle achieves an efficiency rate well above 40% at a speed of 100 kmh^{-1}. It also has a markedly higher efficiency rate, at any speed, than a modern diesel-powered vehicle. In the European driving cycle the HydroGen3 achieved an efficiency rate of 36% while a direct injection diesel vehicle with the same performance managed only 22%. In addition, the fuel cell vehicle produces no carbon dioxide emissions at all. The diesel, on the other hand, generates 177 g of CO_2 emissions per km, Figure 7.

The energy flow diagram (Figure 7) for hydrogen and diesel energy use at a constant speed of 100 kmh^{-1} shows that the mechanical activity which fuel cell vehicles bring to the street is about 35% higher than that of a diesel-powered vehicle.

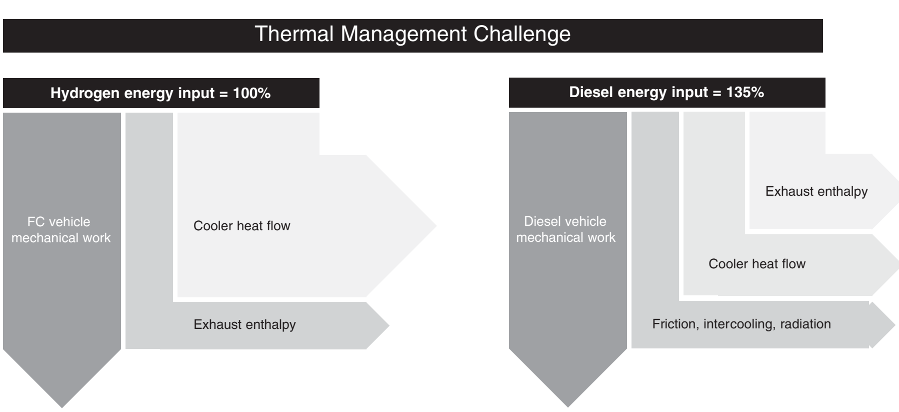


Fig. 7 Energy flow diagram: a comparison of hydrogen and diesel energy use.

6 Outlook

Following the successful driving tests with the HydroGen3 in Monte Carlo, GM/Opel will start fleet demonstrations this year. These will include utilization in Berlin within the scope of the Clean Energy Partnership (CEP). The CEP is a joint initiative between the automobile industry, the power industry and the German government. Its goal is to determine the everyday suitability of hydrogen as an energy source for road traffic.

At the same time the GM/Opel development teams are working on the broader aspects of the individual mobility of the future. In 2002 they introduced the Hy-wire concept car and made it available for test drives. This study is unique in that it is the first vehicle to combine a fuel cell propulsion system, employing fuel cell technology virtually identical to that used in the hydrogen-powered Zafira, with by-wire technology which features electronic rather than mechanical controls for steering, braking and other vehicle systems. These features provide the driver with a greater degree of freedom than ever before. Hy-wire allows the driver to use either the left or the right hand to brake or to accelerate. Drivers accelerate the car with a slight rotation of either the left or the right handle bar and squeezing the level on the handle bar activates the brakes. The handlebars slide up and down for steering.

All the engine and control systems are located in a 279 mm thick skateboard style chassis, which serves as the foundation for a completely new kind of vehicle configuration, Figure 8.

On the road to the sustainable individual mobility of the future, a mobility which eliminates pollutants and greenhouse gas emissions and which is based on a renewable source of energy, concept vehicles like the HydroGen3 and the Hy-wire are defi-

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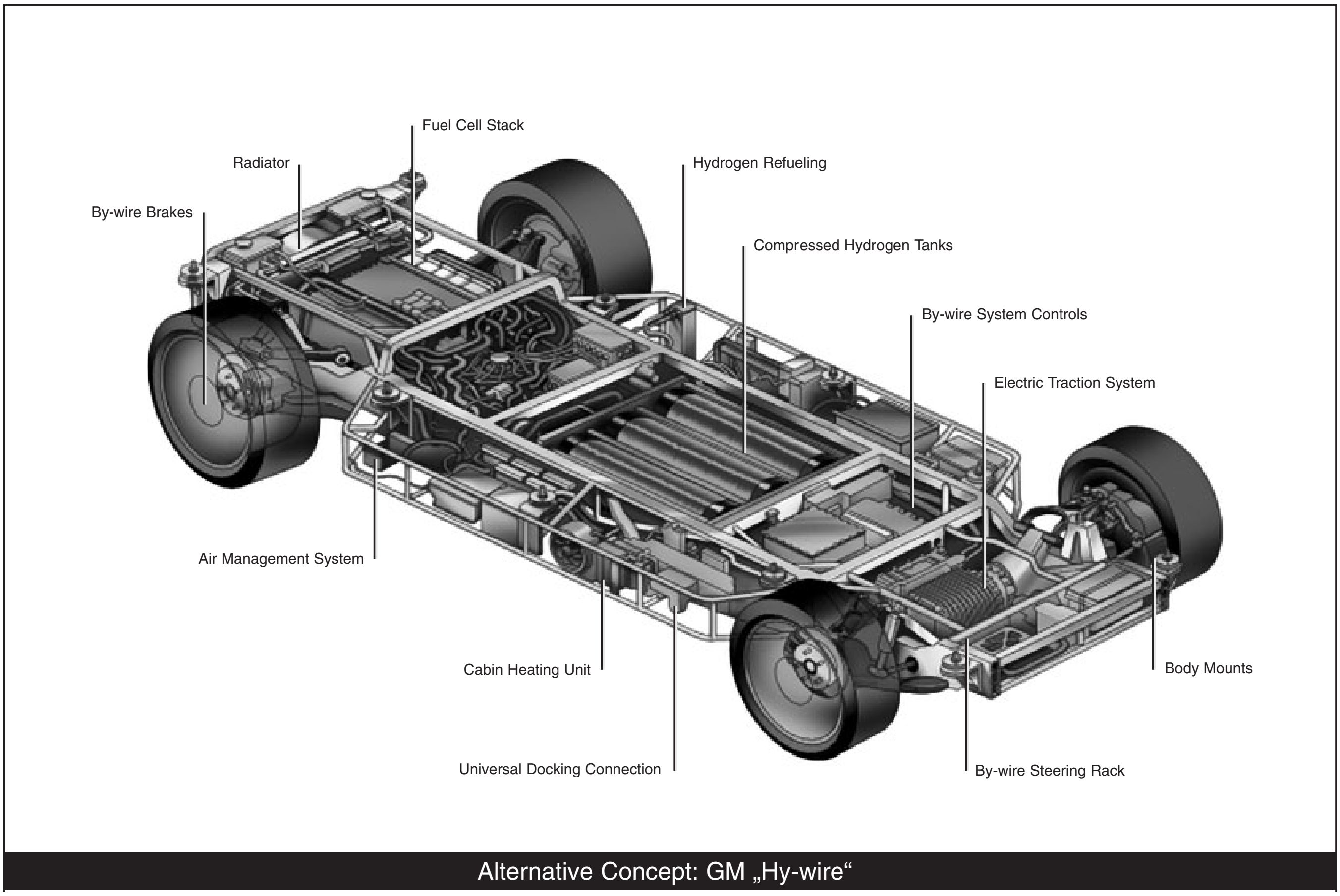

Fig. 8 GM Hy-wire concept vehicle contains the same fuel cell propulsion system as the HydroGen3 but in a completely different package.

nitely not simply some of the more exotic expressions of an engineer's fantasy. Indeed, they represent the final steps toward mass production. Given the current stage of development at GM/Opel, hydrogen-powered automobiles could be mass-produced in about eight years. And when mass production becomes a reality, the fuel cell will undoubtedly establish itself as the technological foundation for the passenger cars driven by future generations.

Overview of HydroGen3 Technical Data

Design:	Five-seater front-wheel driven prototype based on the compact van Zafira
Fuel storage system:	Stainless steel liquefied hydrogen tank, installed ahead of rear axle under rear seat
	Length/Diameter: 1,000/400 mm
	Capacity: 68 l / 4.6 kg
	Gross weight: 90 kg
	respectively
	Two tanks for compressed hydrogen made of carbon composite material, installed ahead of rear axle under rear seat
	Service pressure: 700 bars
	Length/diameter:
	Tank 1: 954 / 356 mm, Tank 2: 732 / 239 mm
	Capacity: 77.4 l / 3.1 kg
	Gross weight: 95 kg
Fuel cell unit:	200 individual fuel cells wired in series
	Voltage: 125–200 V
	Length/Width/Height: 472/251/496 mm
	Active area: 800 cm^2
	Pressure: 1.5–2.7 bar
	Continuous output: 94 kW / peak
	output: 129 kW
	Power density: 1.60 kWl^{-1} respectively 0.94 $kWkg^{-1}$
Electronic traction system:	Three-phase asynchronous electric motor with integrated power electronics and planetary gear
	Operating voltage: 250–380 V
	Maximum output: 60 kW
	Maximum torque: 215 Nm
	Maximum engine rpm: 12,000 min^{-1}
	Gear ratio: 8.67:1
	Gross weight: 92 kg
Dimensions / Weight:	Length/Width/Height: 4,317/1,742/1,684 mm
	Vehicle curb weight: 1,590 kg (goal)
	Rear seat: 25 mm higher than in series production Zafira
Performance:	Acceleration 0–100 kmh^{-1}: 16 s
	Top speed: 160 kmh^{-1}
	Operating Range: 400 km / 270 km respectively