

Mercedes-Benz B-Class Fuel Cell: the world largest hydrogen vehicle fuel cell fleet experience

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Short Abstract

Mercedes-Benz put the world largest fuel cell vehicle fleet into operation in December 2009. The B-Class F-Cell was produced 200 times under standard production process at Mercedes-Benz facilities and delivered to customers worldwide. During the production phase it was possible to learn more about all the specific challenges to handle high voltage components like batteries and electric drive as well as hydrogen components like hydrogen tank system and fuel cell system.

At the 125th birthday of the invention of the automobile, Mercedes-Benz launched the “F-Cell World Drive”. The extraordinary positive experience confirmed the technical maturity of the fuel cell electric vehicle technology and at the same time provided the technical guidelines for the definition of the next generation fuel cell program. This event in addition to the daily customer use is giving positive momentum for the introduction of the hydrogen infrastructure.

This paper reports on the technical experience of more than 3,3 Million kilometers cumulated so far from the vehicle fleet operation as well as the main technical targets envisioned for the next generation fuel cell electric car. The learning and challenges of the hydrogen infrastructure are also reported as well.

1 Introduction

All the most motorized countries are drastically reducing the average fleet CO₂ target by 2020, furthermore discussing even more stringent targets. Europa is having a leadership role in driving the CO₂ reduction at 95g/km. Figure 1 gives an overview of the targets in Europa, USA, Japan and China.

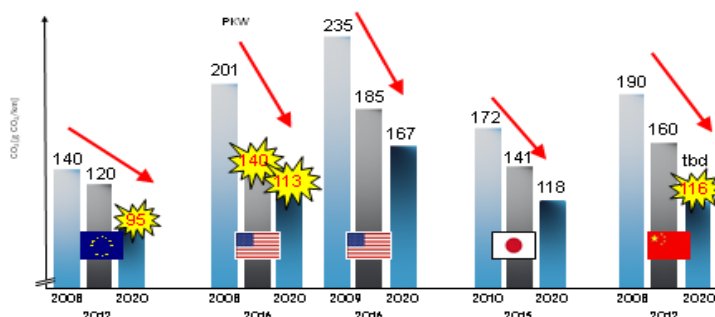


Figure 1. CO₂ g/km Emission target for Europa, USA, Japan and China. Source: Daimler AG

A comprehensive analysis of the potential technologies to meet the European target has been performed within the European Program – Joint Technology Initiative [1].

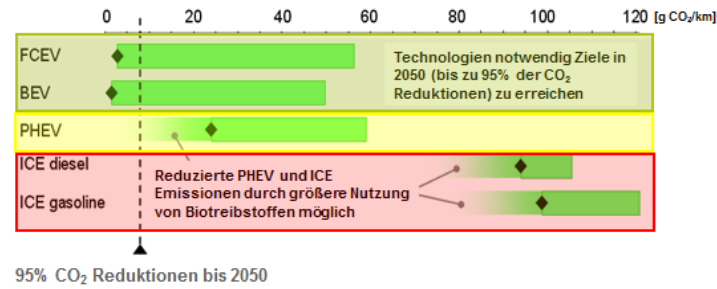


Figure 2. Alternative Powertrain comparison with conventional engines to reduce the CO2 emission according to the European target of 95g/km [1].

Among the different alternative powertrain technologies available (e.g: battery electric vehicle or range extender) , the fuel cell electric vehicle offers a great potential to be successfully introduced into the market. This zero emission technology (ZEV) compared to the battery technology offers two key advantages: short refuelling time of less than 4 minutes and higher range of more the 380 km/mi on real driving cycle [2].

All leading car makers have more than two decades of R&D in fuel cell technology, Daimler is the car maker that pushed the technology more constantly over the year with the largest spectrum on vehicle demonstrator as well as fleet experience, as shown in figure 3.

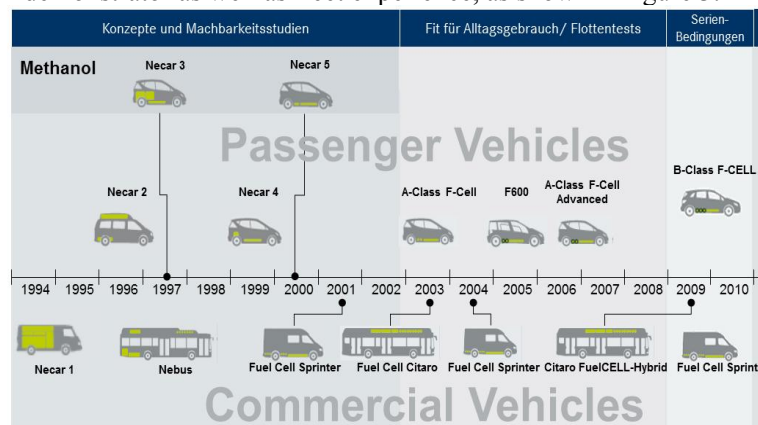


Figure 3. History of Daimler fuel cell vehicle technology.

2 The B-Class F-Cell

The hydrogen fuel cell electric vehicle from Mercedes is based B-Class basis vehicle, with necessary light modification to support the integration of the fuel cell system, the hydrogen tank system as well as the electric drive. The fuel cell system as well as the hydrogen tank system have been integrated in the under floor compartment, the electric drive and the air system in the front of the car and the battery system in the rear as shown in figure 4.



Figure 4. Schematic of the fuel cell system electric drive modules in the B-Class F-Cell. Source: Daimler AG

The B-Class F-Cell vehicle is the Mercedes-Benz's second generation fleet experience. The A-Class cumulated more than 2 Millions of kilometers. The main improvements of the B-Class compared to the A-Class are showed in figure 5.

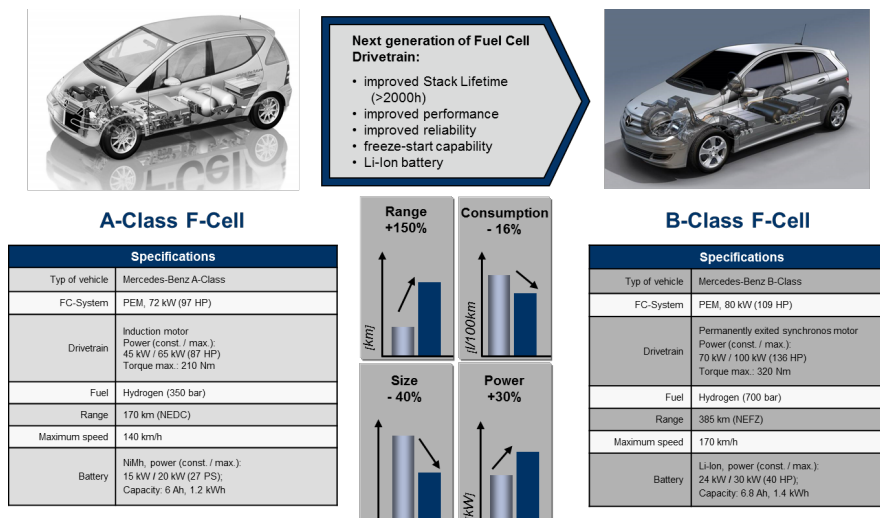


Figure 5. Comparison of the performance improvement between the A-Class F-Cell and B-Class F-Cell. Source: Daimler AG.

3 The fuel cell system

3.1 Main hardware

The hydrogen fuel cell system, as shown in figure 6, comprises: the fuel cell stack which convert the hydrogen and oxygen's air into electricity, water and heat, the air system module which supply the necessary air at the right pressure, the hydrogen module which supply the right hydrogen quantity and the power distribution module which connect the stack bus bars and the high voltage components.

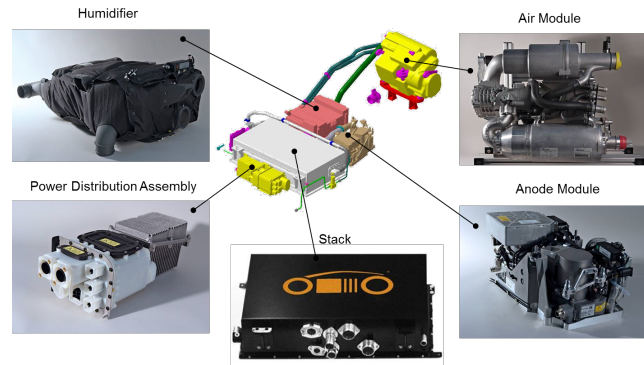


Figure 6. Modules of the fuel cell system delivered at Mercedes-Benz production site.

The fuel cell stack is composed by 440 cells connected in series, with carbon based bipolar plates. The stack performance is shown in figure 7.

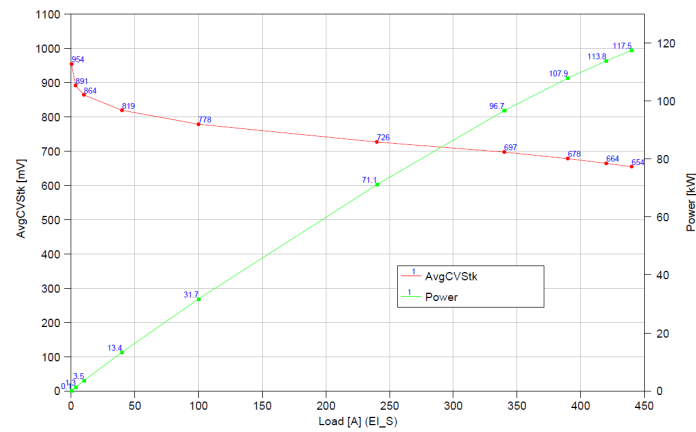


Figure 7. Stack performance at nominal operating condition. Source: Daimler AG

The air system is an electric air compressor including silencers, power electronic, piping and noise cover. The compressor technology is a constant displacement screw which through a clutch is connected to the electric motor. For more detailed description of air system and its challenges, read [3]. The performances of the air system are shown in figure 8.

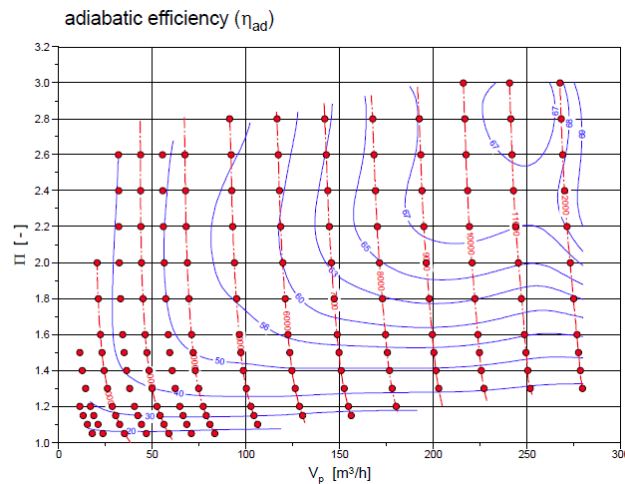


Figure 8. Efficiency of the screw compressor of the Mercedes B-Class F-Cell air supply [5]. Source: Daimler AG

3.2. Control strategy

The operating strategies implemented in the fuel cell control unit (FCU), are necessary to proper control all the parameters influencing the stack performance. The vehicle controller requires current and dynamic under all ambient condition, the operating strategies verify under the actual conditions and prognoses, how to deliver the required current.

One main task of the operating strategies is to maintain a defined humidity level in the fuel cell stack, to avoid the drying out of the fuel cell membrane or the flooding of electrodes. Both cases would lead to performance loss and cause additional risk for permanent degradation. Therefore the control strategy has been developed in a way that there is always a well defined balance between coolant temperature, air and hydrogen flow rates and pressure of cathode and anode at each individual load point. Since the humidity of the membrane is not directly measured, the control system is a feed-forward control. This control is subject to several noise factors, e.g. the humidity of the environmental air, which leads to a broad bandwidth of the achieved cathode and anode humidities around the theoretical set point, which is shown in Fig. 9 and 10.

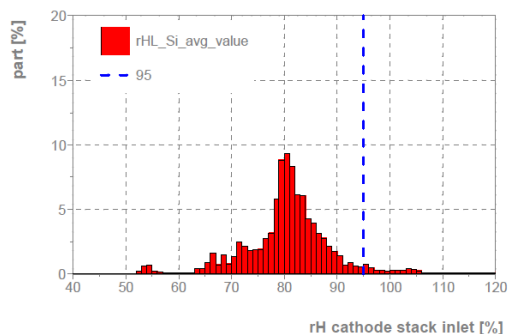


Figure 9. Cathode humidity control under dynamic condition and its theoretical set point. Source: Daimler AG

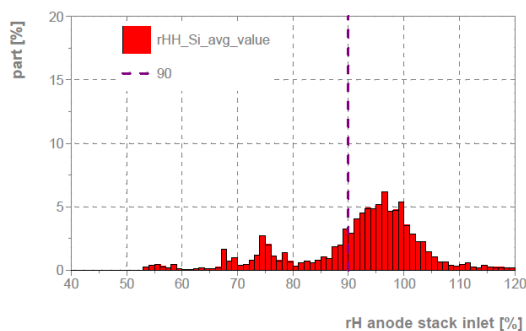


Figure 10. Anode humidity control under dynamic condition and its theoretical set point. Source: Daimler AG

3.3. Cold start capability

The cold start is one of the most challenging technical features in a fuel cell system because it is completely embedded in a wet environment. The stack is producing pure water, the membrane needs to be kept humid to allow proton conductivity, anode and cathode flush water to system components and the humidifier introduces humidity back to the stack. All the pure water that after the shutdown still remains in the stack or system components may block the feeding line of hydrogen or air, thus preventing a start. More challenging is a reliable and reproducible cold start power supply. [10]

The Mercedes B-Class F-Cell fuel cell system has a reliable and reproducible cold start behavior, as shown in figure 11.

The required cold start time is mainly depending on the temperature of the fuel cell system, and mainly depends on the achieved operating temperature of the system at shut-down, the environmental temperature and the duration of the soak time.

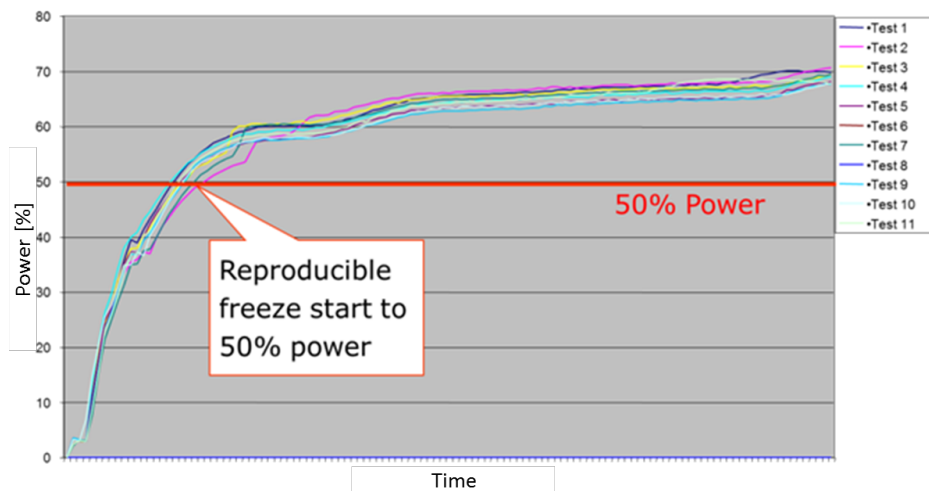


Figure 11. Reproducible freeze starts until 50% power availability at -15°C. Source: Daimler AG

4 Fuel cell system assembly

The fuel cell system has been assembled in the NuCellSys facilities in Nabern. For the first time ever a small “series” production process has been applied to fuel cell technology. The production lines were constructed according to lean manufacturing guidelines. By doing this it was possible to simultaneously manufacturing the hydrogen module, the air system and the power distribution unit. The humidification module has been completely assembled from a supplier as well as the stack. Figure 12 shows the manufacturing lines of hydrogen and air modules.



Figure 12. On the left side the production line of the air module, on the center the automated leak test and on the right side the assembly line of hydrogen module. Source: Daimler AG

This assembly line is radically different from the first generation fuel cell system manufacturing which powered, between 2000 and 2008, the A-Class F-Cell. That production system was a single point of assembly, having more worker assembling components simultaneously. The probability to have errors during the assembly process was high and for this reason it was always necessary after the “marriage” between the balance of plant and the stack module to perform an intensive end of line test (factory acceptance test). Sometimes it was necessary to dismount the whole balance of plant to recover the mounting errors.

With the new assembly concept huge steps in efficiency has been reached and because the modules were develop according to the standard automotive rules, the marriage between the balance of plant and stack was no longer necessary. This represents the largest improvement compare to the previous manufacturing experience. The assembly line is capable to manufacture about 300 modules per year at one shift. Since there was no need to have higher output, there were no automatic processes.

A new step toward the robust design and assembly has been achieved, opening the doors for the next manufacturing challenges: on sequence production including on-line testing with a target of more than 100 systems per day output [7].

5 The World Drive

The Mercedes-Benz World Drive has been an amazing experience from a technology stand point of view. It was necessary to demonstrate to hundreds of journalist “live” that the technology is technically ready for the market introduction [5], [6].



Figure 13. Mercedes F-Cell vehicles during World Drive 2011. Source: Daimler AG

The world drive was a demonstration of the technical maturity and performance of Daimler fuel cell technology and their potentials for sustainable mobility. The fuel cell drive train and the car worked well all over the trip. No technical challenges occurred except one accident in Kazakhstan. A SUV hit the rear of one world drive F-Cell. None of the fuel cell drive train components were damaged. A displaced axle could be replaced in a Mercedes-Benz repair shop nearby within a day. Continuous fuelling of the three cars was one real challenge. Support was given by the Linde AG with trucked hydrogen in the outback where no stationary hydrogen fuelling was available, or by simple hydrogen bottles.



Figure 14. Mobile refuelling of Mercedes F-Cell vehicles during World Drive 2011 in USA. Source: Daimler AG

6 The fleet world wide

Presently the B-Class F-Cell fleet operation looks back on an experience of already more than 2.4 million km in customer hands, as shown in figure 14, plus additional 2.0 million km during the development phase. One endurance test vehicle has already collected more than 310.000 km. In total the Daimler fleet cumulated more than 9.0 million km emissions free driving – nearly ten times to the moon and back - more than any other manufacturer. This extensive experience has a deep influence onto the development of the next generation of fuel cell engines.

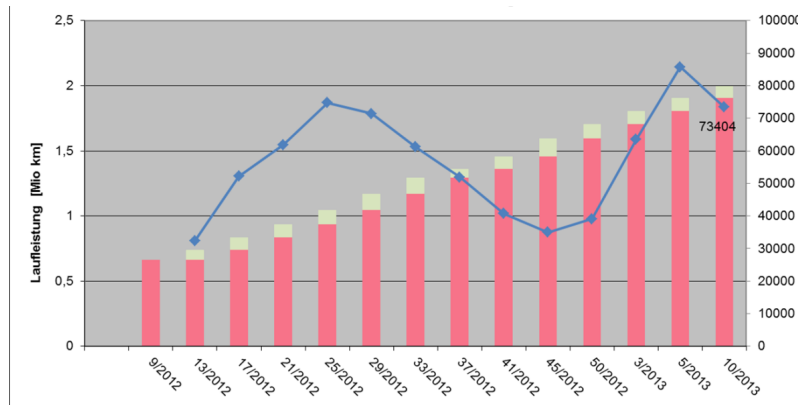


Figure 14. Growth of the cumulated mileage of the F-Cell fleet worldwide over calendar time; Source: Daimler AG

The F-Cell vehicle fleet is in daily operation in customer hands and at different locations worldwide. The biggest number of the vehicles fleet is operated in California around Los Angeles. This fleet operation gives a valuable feedback for the development of the next generation fuel cell vehicle. All occurring failures are getting tracked and statistically evaluated. The reliability of the fuel cell system is growing steadily during the fleet operation. To further improve the reliability of the fuel cell system new component development would be required, meanwhile the weaker components are substituted regularly at given planned inspections. One component that requires further development to increase the reliability is the H2 sensor. The technical challenges of this sensor are well described in [4].

During the world drive the fuel consumption of each vehicle was tracked and clustered for each continent, as shown in figure 15. The results show, that the lowest fuel consumption was achieved during the operation in the USA. The good fuel economy is caused by the long distant cross country highway operation at constant speed and a low number of stops in combination with the speed limit. In some cases a fuel consumption of less than 1kg/100km was achieved.

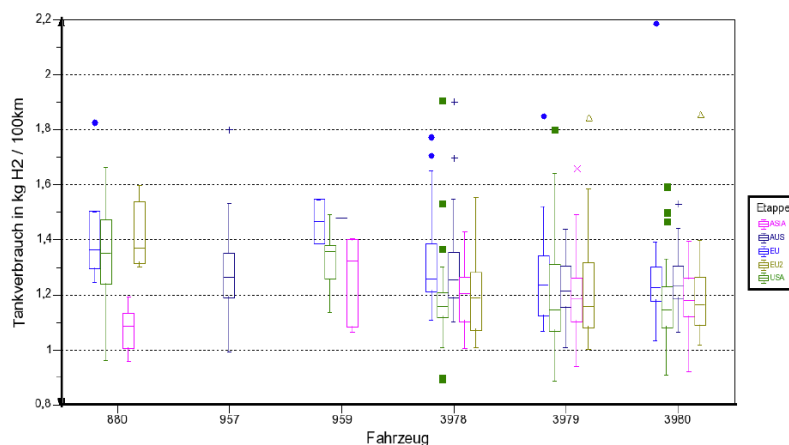


Figure 15. Average fuel consumption of the 3 F-Cell World Drive vehicle on different continents; Source: Daimler AG

In Europe the fuel consumption was a slightly higher than the other continents. This is mainly due to the higher traffic density with less constant speeds and shorter cross country distances between cities and towns. A further analysis of the fuel consumption data of Europe shows also a variation for the different

countries. Figure 16 shows that the fuel consumption of the world drive vehicle in Germany was below the average of Europe, while the fuel consumption of Norway was above.

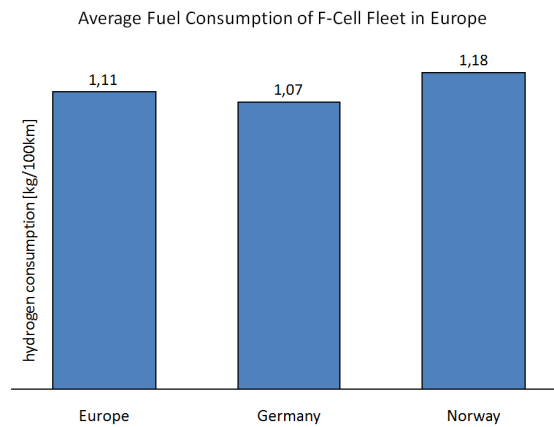


Figure 16. Current status of the average fuel consumption of the F-Cell fleet in Europe; Source: Daimler AG

For the durability of a fuel cell vehicle also the stack degradation is of fundamental interest. An investigation on stack durability in vehicle shows the influence of soak times on the stack degradation. Figure 17 shows the stack voltage degradation over usage time, respectively vehicle mileage for different fuel cell stack currents. These data show that a higher number of long soaks lead to an increase of the degradation rate of the fuel cell stack.

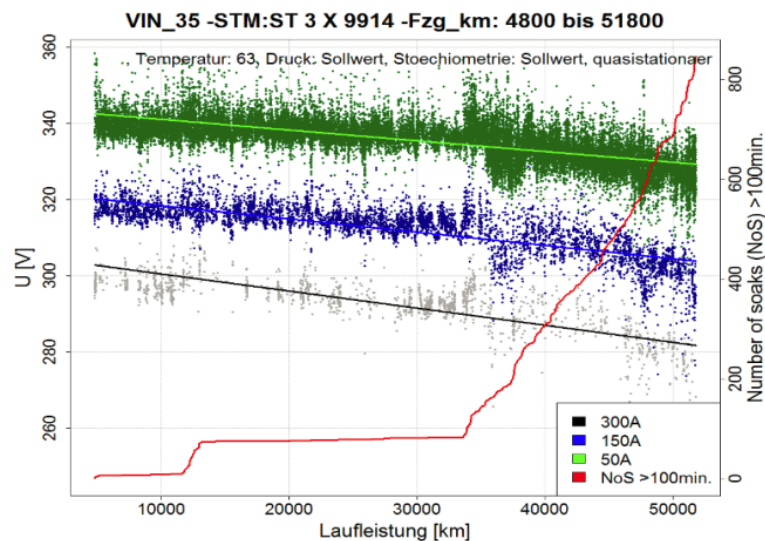


Figure 17. Stack degradation as function of duration of soak times on Y-axis on the right, on the X-axis the mileage [km], Y-axis left voltage [V]. Source: Daimler AG

7 Hydrogen infrastructure experience

Today the hydrogen-infrastructure build-up in the main markets California and Germany is in progress but the actual number of hydrogen refueling stations (700 bar) is still insufficient for the market launch of fuel cell vehicles. There are 7 stations in operation in California and 15 stations in operation in Germany (June 2013).

In California Stakeholders and trade organizations are working to support State-level legislation (Senate Bill 11 and Assembly Bill 8) which will fund the early hydrogen infrastructure network in California. In the interim, the State of California is establishing the initial station network of approximately 31 stations, which are all under development.

Due to the intensive work in various committees of CEP (clean energy partnership) and H2-Mobility the infrastructure built-up has intensified in Germany. A built-up of 85 stations is expected in the coming years.

The experiences with the hydrogen infrastructure in the fleet demonstration of the current generation fuel cell vehicles are in general:

- Demo infrastructure is not sufficient for envisaged commercialization roadmap.
- For full customer acceptance an area wide and convenient H₂-filling station is necessary.
- Repair times in case of a station breakdown need to be shortened.
- The purity of H₂ needs to be discussed in a more detailed and bilateral (station-side/vehicle-side) way to see which contaminants need to be tightened or even could be lowered.
- Seal problems with Dispenser (and only one manufacturer).
- The compressor is the component that fails most often.

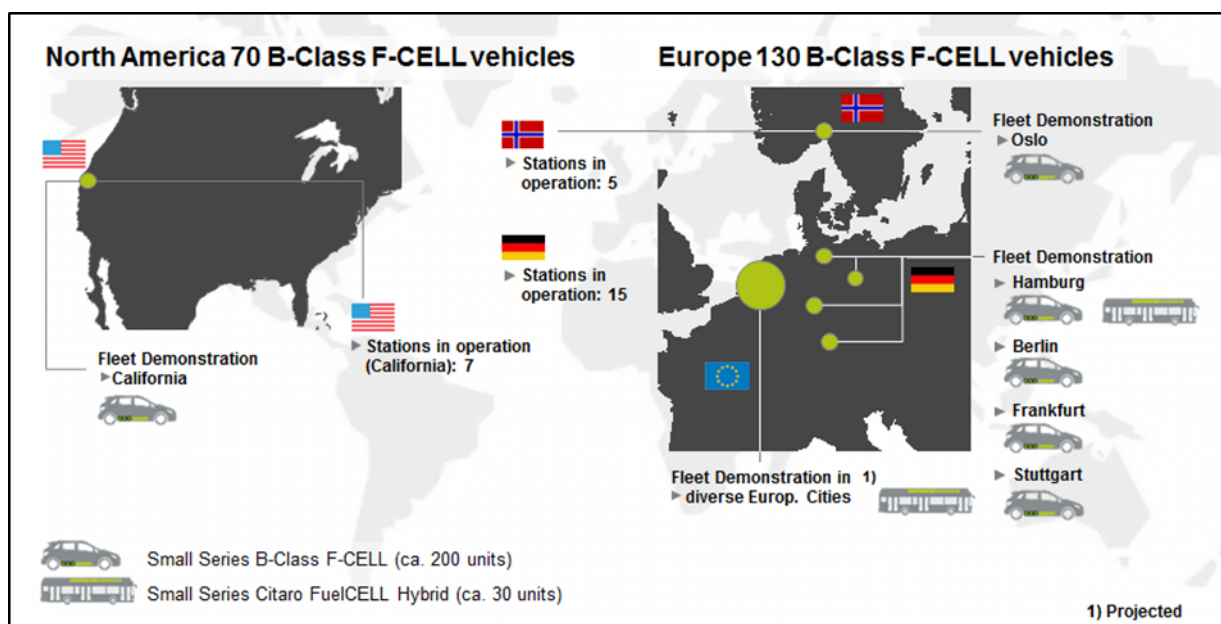


Figure 18. Deployment of the Daimler fleet and the relevant existing hydrogen infrastructure. Source: Daimler AG

8 Outlook and conclusion

The maturity of the fuel cell technology has been demonstrated worldwide with the Mercedes-Benz World Drive in 2011. The successful deployment of the fleet in USA and Europa having cumulated more than 2.4 million km is a further confirmation of the technology's maturity.

The next generation for the market introduction of fuel cell technology is currently under development in the framework of the co-operation between Daimler, Nissan and Ford Motor Company [8]. Several technologies changes, functional integration as well as packaging improvement has been incorporated which allow the next generation fuel cell system to be integrated in the front of the car, as shown in Figure 19 20.

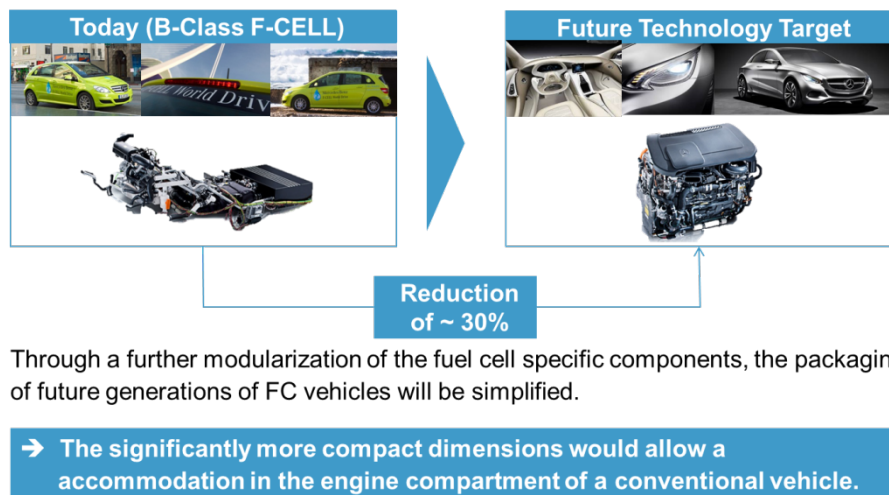


Figure 19 . Significant improvement of the technology development as of 2013 [9].

Acknowledgments

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Reference

- [1] http://ec.europa.eu/research/fch/pdf/a_portfolio_of_power_trains_for_europe_a_fact_based_analysis.pdf
Visited on 04.03.2013
- [2] J. Schneider, – SAE J2601, *Worldwide Hydrogen Fueling Protocol and Fuel Cell Vehicle to Station Communication and the validation thereof*. SAE Congress 2013 – Oral Presentation
- [3] M.Venturi, J.Sang, „Air Supply System for Automotive Fuel Cell Application”, Society Automotive Engineering 2012-01-1225
- [4] M.Venturi, F. Henkel, R.Fischer, *Hydrogen Sensors for Automotive Fuel Cell Applications*, Society of Automotive Engineering 2013-01-0497
- [5] M. Venturi - *Technology Maturity of Fuel Cell System installed in Mercedes B-Class during the World Drive* , Electric Vehicle Symposium 26
- [6] Auto Motor Sport – Special Edition n. 3 ISSN:0940-3833
- [7] M. Venturi *Fortschritte bei der Lieferanten-Produktentwicklung und der Produktion für die Brennstoffzellentechnologie*, F-Cell Stuttgart 2012
- [8] The Hydrogen & Fuel Cell Letter – January 2013 Vol XXVIII/No.2 ISSN 1080-8019
- [9] C. Mohrdieck, Progress of DAIMLER AG on FCEV development and boundary conditions for FCEV introduction and implementation in Europe, FC Expo Tokyo 2013.
- [10] FC Award 2007. NuCellSys GmbH, „Zuverlässiger Gefrierstart eines Brennstoffzellensystems für den Pkw-Einsatz“, f-cell Award Gold: NuCellSys GmbH, www.f-cell.de/deutsch/award/preistraeger/jahr-2007