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Crash Safety of Fuel Cell Electric Vehicles

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Abstract

The new Mercedes-Benz GLC Fuel Cell Plug-In will be presented on the IAA 2017 in Frankfurt, Germany. In comparison to standard electric vehicles, fuel cell vehicles produce electric energy themselves through a fuel cell system fed by the hydrogen which is stored in a special hydrogen tank. This paper discusses the challenges of this vehicle type in accident safety and the appropriate Mercedes-Benz safety concept to address these challenges.

Besides the legal requirements and safety standards, primarily the relevant findings from accident research were incorporated, in particular the integration of all safety related components like hydrogen tanks, gas-bearing and HV-components. Furthermore, best practice solutions will be illustrated, such as the establishment of a maximum HV safety level by implementing an automatic HV shut down, pyrotechnical short-circuit devices or a voltage relief by internal resistances.

In order to ascertain acceptable gas leakage rates in a severe vehicle crash, specific component tests were performed - both load tests with fuel cell stacks and ignition tests with hydrogen leakages. In order to address the specific safety hazards of Fuel Cell Vehicles, specific full scale crash tests with crucial impact conditions were conducted in addition to the legal requirements and the relevant standard crash tests.

Keywords: Fuel Cell Electric Vehicles, Crash Safety, Hydrogen Safety, High Voltage Safety

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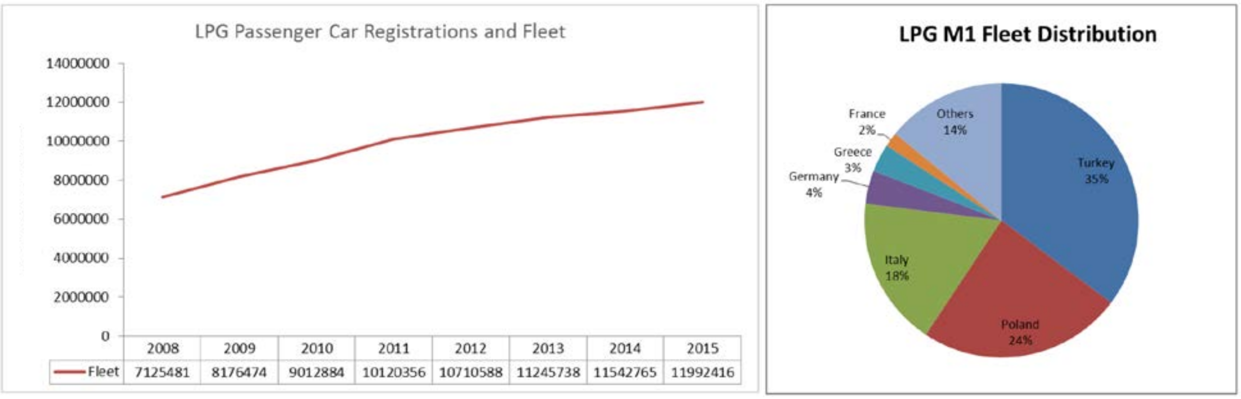
1. Accident Research

Based on real world accidents, no negative impact of the gas tanks for the safety performance of Fuel Cell Vehicles are expected. In some regions, gas-powered vehicles are widely used. This is particularly true for liquid petroleum gas (LPG) cars with more than 12 million vehicles in Europe, and even higher shares in some South-American and Asian markets.



Picture 1: LPG Passenger Car Fleet and Fleet Distribution in Europe (Source: EAFO Newsletter Special Edition –Autogas LPG Vehicles & Filling Infrastructure)

In addition, only 1.2 million compressed natural-gas-dedicated vehicles (CNG) were registered in Europe by 2016 as a result of the more costly technology and the limited gas station network.

Due to the safety requirements to gas-powered cars, the gas tanks with a nominal compressive strength of 200 bar must be integrated adequately in crash protected areas of the vehicle. As a result, CNG--powered vehicles are offered nearly exclusively by car manufacturers.

Since liquid gas is stored only with 20 bar, many add-on kits for conventional cars are widely offered. Typically, the cylindrical or curved gas tanks are integrated in existing hollow spaces such as the spare wheel well. Despite the unprotected location in crash zones without any additional safety precautions, no noticeable problems in real world accidents are known given the high vehicle population. The few known issues are related to corrosive pre-damages to the gas tanks resulting in a reduction of the compressive strength even without any external impact (i.e. during refueling).

Both, vehicles with compressed natural gas (CNG) and vehicles with liquefied petroleum gas (LPG) being in the field in very high volumes worldwide, have been absolutely inconspicuously with respect to the specific risks of tank defects, such as burst, leakage or blast. Hennessey [2] reports on a database of 11 Mio CNG vehicles and 100-200 Hydrogen vehicles worldwide in 2012 from 100 serious cylinder failures for CNG and no serious failure for hydrogen vehicles.

Utilizing data from the GIDAS (German In-Depth Accident Study) database, the frequency of deformation areas were analyzed, and best practice solutions for the safe integration of gas tanks and other safety related components were recommended [3].

The analysis of the GIDAS accident data sample made a first view on the potential situation where all passenger cars are equipped with hydrogen propulsion systems. A methodology was developed to determine deformation characteristics of about 9,000 vehicles in the GIDAS data sample independent of the vehicle shape. These deformation characteristics were used to generate the cell frequency matrix that shows the frequency of deformation in different regions of the car. However, the relevance of deformation in particular regions of the car with respect to the whole accident situation cannot be derived from the cell frequency matrices alone. Thus, a cumulative frequency matrix was introduced together with an algorithm to compute the cumulative frequencies from cell frequencies. The analysis of the cumulative frequency matrix showed that in 98% of all accidents with at least one person injured, the area of current hydrogen-tank integration concepts is not affected. As it was verified on component level that hydrogen tanks can sustain even higher loads than expected for the 2nd percentile region, this statement is a positive assessment for 98% of all cases, but no negative assessment for the remaining 2%. Additionally, external accident parameters were determined for those cases, in which deformation reaches the area around the hydrogen tank. It was shown that these accidents were predominantly rear-end crashes in rural areas with a crash pulse force direction of 180°. Possible further research could include the analysis on different subsets of the data, other parameters mapped to the matrix cells, or further analysis of the external accident parameters.

2. Safety Requirements

2.1 Specific challenges to the crash safety of fuel cell vehicles

Compared to conventional cars FCEVs are equipped with an electrified power train, the fuel cell and the gas storage. The high-voltage power supply (HV) provides voltages up to several hundreds of Volts Direct Current (DC), along with high voltage batteries with capacities up to 25 kWh. The capacity of the high pressure hydrogen tanks is up to 120 liters, with a total hydrogen storage mass of about 5 kg, pressurized at 700 bar. In addition to pure electric cars, which obtain their electric energy from external battery charging stations, fuel cell electric vehicles are offered. For FCEV, the batteries are continuously charged during driving by the electric energy generated in the fuel cell. Figure 1 illustrates a typical schematic of key components in a fuel cell electric vehicle:

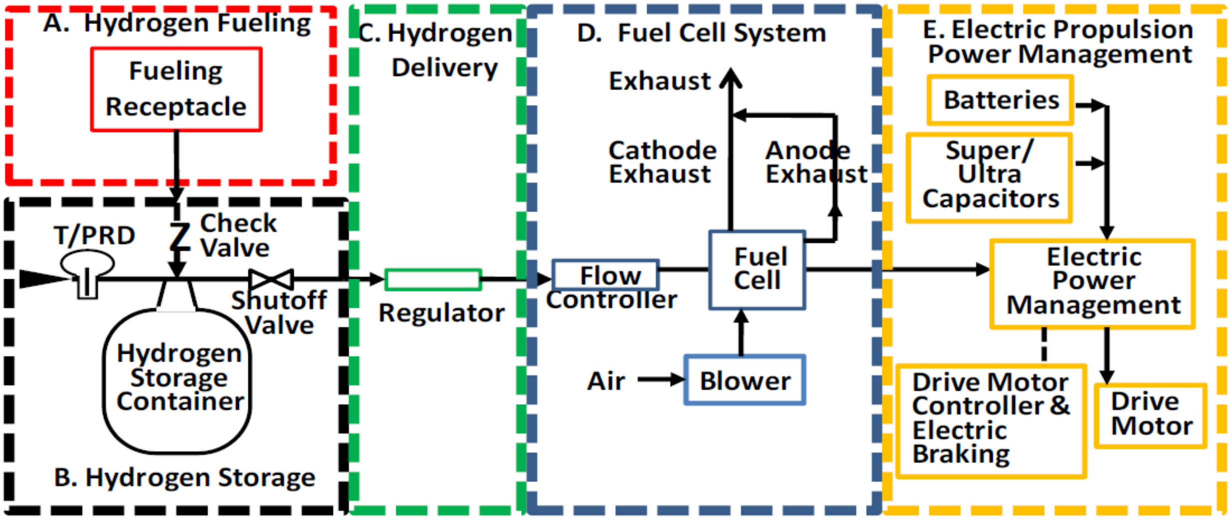
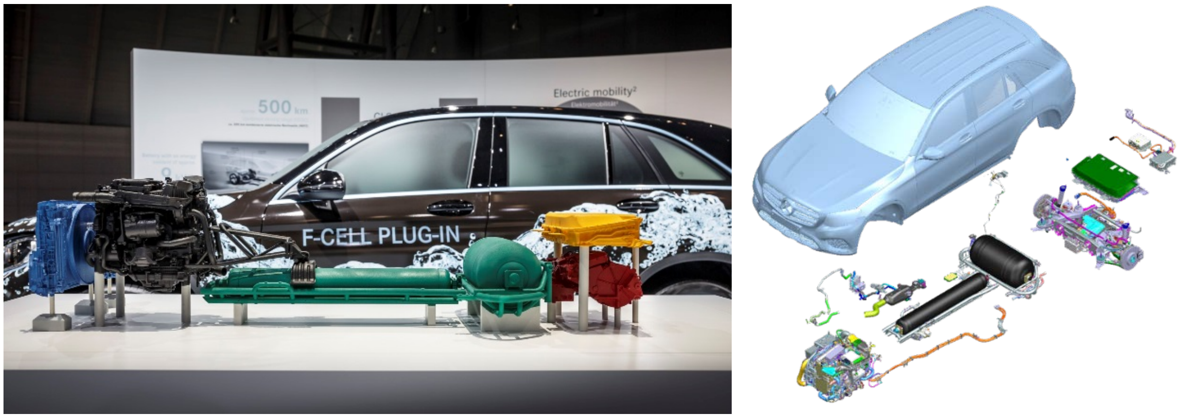


Figure 1: Example of high-level schematic key systems in FCEVs

According to these characteristics, the following four new challenges must be addressed for the safety of fuel cell electric vehicles:

2.1.1. Structural safety

Like in any other model changeover, the impact of newly integrated, additional components to the deformation characteristics of the car have to be studied. The fuel cell stack, gas tank, HV-battery or the electric motor could potentially change the length of the vehicle crush zone and - due to their stiffness - change the crash deceleration characteristics. This may have an effect on the triggering of the restraint systems, for instance. Other consequences may include a different behavior in head-on collisions with other cars due to the different stiffness of the vehicle front structure or the higher vehicle weight. Furthermore, repair costs after a minor accident can be increased depending on which components are affected.



Picture 2: Powertrain of the Mercedes-Benz GLC F-Cell Plug-In

2.1.2. High-Voltage-Safety

The electric drive train of electric and hybrid vehicles is powered by high voltage supplies up to several hundred volts. High voltage > 60 V DC and > 30 V AC (Alternative Current) are already classified as isolated systems B. Since a contact or electric shock may result in severe injuries for the human body, stringent requirements against electrocution must be implemented in the safety devices. Relevant legal requirements are defined in ECE R100 [4] for In-Use, and for Post-crash in ECE R94&95 [5], and FMVSS 305 [6].

2.1.3. Gas tanks

Two major risks are associated with the extremely high pressures up to 700 bar in the hydrogen tanks of fuel cell electric vehicles: (a) burst of the tank, and (b) inflation or even explosion of gas leaking as a consequence of an accident. General requirements for gas storages are defined in [7-9].

2.1.4. Fire protection

A vehicle fire during or after a vehicle crash could theoretically be initiated by a damage to the high voltage systems or to the energy storage resulting in a short circuit. Lithium-Ion batteries, designated for battery driven vehicles, bear special characteristics due to the chemistry of the cathode, anode and electrolyte materials, which are inflammable. Worst case is a thermal runaway, a situation in which an increase in temperature changes the conditions in a way that a further increase in temperature is caused, often leading to a destructive result. Corresponding to the high variance of battery types, i.e. energy batteries in electric cars and power batteries in hybrid vehicles, there is a wide spectrum of the safety characteristics and issues.

2.2 General Design Guidelines

The fuel system consists of a high-pressure section, where the inner pressure is the same as in the fuel container, and an intermediate- to low-pressure section, where the inner pressure is lower than that of the high-pressure section.

In standards and regulations like ECE R134 [10], ISO 23273 [11] SAE J2578 [12] or GTR 13 [13], the following general design and performance requirements are specified for the fuel system:

- The fuel system shall be equipped with:

  - a fire protection system incorporating one or more temperature-triggered pressure release devices (PRD),
  - a check valve that prevents reverse flow to the fill line
  - an automatic shut-off valve that shall be closed when the energizing power to the valve is lost, and which shall also be closed when the vehicle fuel cell system is not operating,
  - a hydrogen shut-off system that prevents unwanted discharge of hydrogen or other hazards arising from single-point failures and
  - an excess flow valve or a system providing the same function.
- All components and interconnecting piping and wiring shall be securely mounted or supported in the vehicle to minimize damage and prevent leakage and/or malfunction.
- Components shall be located within the vehicle to reduce the possibility of accidental damage, unless the components are adequately protected and no part of the component lies outside of the protective structure. Requirements on installation of the hydrogen storage system are:
  - The container shall be mounted in a position which is reward of a vehicle plane perpendicular to the center line of the vehicle and located 420 mm rearward from the edge of the vehicle
  - The container shall be mounted in a position which is between the two vertical planes parallel to the center line of the vehicle and located 200 mm inside from the both outermost edge of the vehicle in the proximity of its container(s).

2.3 Vehicle Requirements

Safety performance in full scale vehicle crash tests are subjected to crash tests applied in the jurisdiction of the different market regions. Beside HV-safety, the following post-crash requirements are addressed for fuel system integrity:

- Fuel leakage limitation
  - The volumetric flow of hydrogen gas leakage shall not exceed an average of 118 Nl per minute. (The unit norm liters Nl is a measure for the volume at atmospheric pressure)
- Hydrogen concentration limit in enclosed spaces
  - Hydrogen gas leakage shall not result in a hydrogen concentration in the air greater than 4% in the passenger and luggage compartments
- Container displacement
  - The storage container(s) shall remain attached to the vehicle at a minimum of one attachment point

2.4 Component Requirements

Beside the safety requirements in full scale vehicle crash tests, much more specific requirements must be addressed on a component level. In context to crash safety mechanical impacts were specified to gas tanks:

- Burst pressure
- Drop impact test
- Surface damage test

3. HV-Safety

A fundamental precondition of HV-safety is the crash-compatible integration of all HV components [14]. Any damages to these components must be prevented as far as possible in all crash tests.

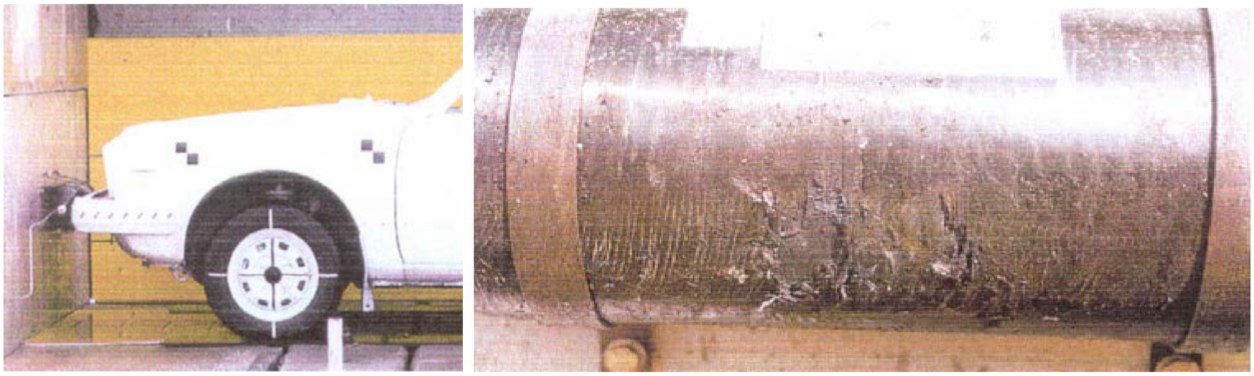
Furthermore, the standard solution for severe accidents is the cut-off and discharge of the HV system. In order to prevent any electrical shocks, the HV system will be separated from the battery. Typically, this HV deactivation will be triggered by the restraint triggering crash sensors, including rollover detection. Additional measures like the isolation of the HV system or a physical protection against contact, will further increase the safety level up to very high crash severities.

The biggest challenge to the safety of electric vehicles is the crash performance of the batteries. Due to the high risk of fire after short-circuit faults, this is particularly true for Li-Ion batteries. In the Mercedes GLC F-Cell Plug-In, the Li-Ion battery is located above the rear axle (see Picture 2), which is one of the best possible positions to avoid crash induced damages to the battery. Independently of a safe battery location concept, HV batteries must have a high degree of internal robustness and stability. The legal requirements to the battery safety can be fulfilled either by a crash test (battery integration and structural safety) or by mechanical battery and component tests (battery integrity and robustness). However, to guarantee a maximum battery safety, both a good integration in the vehicle structure and an inherent battery stability should be implemented.

4. Crash Safety of the Gas System

Since the safety requirements for gas containers and for HV batteries are quite similar, the safety concept is very much the same. If the crash sensors register an accident of a certain severity, the tank system is shut-off, and the tank valves are closed irreversibly. Even if, in a worst case scenario, the gas remaining in the hydrogen lines and the fuel cell stack may exit due to a leakage and even inflame. However, due to its small volume of less than 10 norm liters (Nl), this will result only in a minor deflagration.

Due to the high inherent stability of the gas tanks, damages resulting in a burst can be avoided with an extremely high probability. The usual wall thickness of a 70 MPa container in Type 4 configuration is in the range of 30 mm what results in a very high mechanical robustness. This is already reported and studied in many publications including a crash test onto a loaded 35 MPa container, fixed to a rigid wall and directly loaded with a 56 km/h vehicle in a frontal crash [15]. This container still showed a burst pressure of 1700 bar – close to the normal rupture pressure – after the vehicle crash test. Test configuration and tank damage can be seen in Picture 3.



Picture 3: Test configuration and resulting tank damage after 56 km/h vehicle impact [15]

Since the environmental vehicle structure typically shows a lower stiffness than the tank, usually the tanks can be shifted in a car crash without serious damages on the surface. The most vulnerable part of the gas tank is the valve system which must be protected particularly carefully.

Consequently, a good location for the tanks would be in an area of the car which usually shows low deformations especially in the tank end plug and valve region. Such a location could be, for instance, right in front of the rear axle. In the case, in which the end plugs with integrated valves and other safety features may be loaded in a crash event, additional protective countermeasures help to prevent these instruments from malfunctions in case of a mechanical load. So for the two hydrogen tanks in the GLC-F-Cell, Mercedes-Benz implements a support frame to mount the containers in the tunnel and under the rear seat. This frame acts as protection against hitting the ground and as protection against loadings on the end plugs and tank valves in the event of a crash.

Picture 4: Tank supporting frame of the Mercedes-Benz GLC F-Cell Plug-In

In the new fuel cell generation of Mercedes-Benz, the fuel cell stack moves from the underfloor to the engine compartment. As long as the stack contains H2, it acts as an electric energy conversion device. Even though with far less energy content compared to the HV-battery, it still has to fulfill the requirements for HV legislations (FMVSS 305) as well as for compressed gas components (FMVSS 303). Both requirements were also adapted for hydrogen driven fuel cell cars in the GTR No. 13 resp. ECE-R134.

The FMVSS303 allows a gas leakage rate of 10.62 bar per hour (equal to 1062 kPa or 154 PSI per hour) from a high pressure natural gas container. The ECE-R134 mentions 118 Nl Hydrogen in 1 hour. These leakage rates are derived from liquid fluids like gasoline or diesel, for which also defined leak rates are allowed in case of a crash.

For real-life safety reasons, Mercedes-Benz doesn't allow fuel leakage from the fuel containers in any legislative or rating crash test. Consequently, no gas leakage is accepted for hydrogen from the H2 container and the high pressure line. Nevertheless, as real world accidents may occur under different conditions, a leakage of hydrogen esp. in the engine compartment has to be taken into account. Accidents like high speed impacts on trees and other parts of the road infrastructure or truck underrides may still occur. For this case, the possible gas leakage amount outside the high pressure system, which may operate at up to 700 bar, needs to be investigated.

The principle flow of Hydrogen from the 70 MPa tanks to the stack is shown in fig. 2.

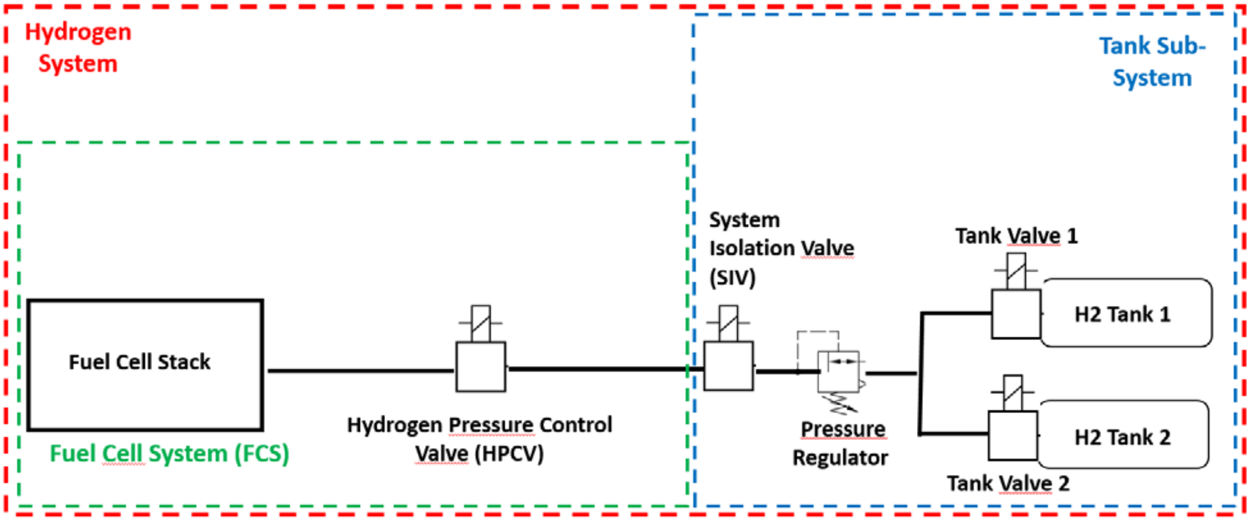


Figure 2: Principle of a Hydrogen System with Tank and Fuel-Cell System

As the tank valves on the hydrogen container and the system isolation valve will be closed by the airbag controller in the event of a crash within a few milliseconds, there is only the remaining hydrogen outside the high pressure system left. The system isolation valve is combined with a pressure regulator, reducing the tank pressure of up to 700 bar down to 10-12 bar in the intermediate pressurized hydrogen system. At the inlet of the fuel cell stack the hydrogen pressure control valve (HPCV) reduces the fuel cell stack pressure on the Hydrogen side down to 1-3 bar – according to the required power output of the fuel cell system. As Tab. 2 shows, the maximum H2 amount behind the system isolation valve (SIV) is in the range of 8 Nl.

Max. H2 content of the stack at 3 bar	7,7 liter / 1,1 gram
Max. H2 content gas line behind SIV at -25°	0,165 gram

Table 2: Hydrogen content behind system isolation valve and pressure regulator (mid and low pressure system)

Hydrogen, which is released into the atmosphere, disperses very quickly. Nevertheless it must be assumed that these 10 Nl were released into a closed engine compartment. This is an unrealistic worst-case assumption, because an engine compartment is open in many cases after a crash, allowing a fast dispersion of Hydrogen. Nevertheless, ignition tests were carried out with 5 and 10 Nl H2 released into the closed engine compartment of a B-Class F-Cell prototype. For this test, an active ignition system mounted inside the engine compartment constantly fires ignition sparks at different locations as shown in fig. 3 leading to a combustion as soon as an ignitable H2 mixture is reached.

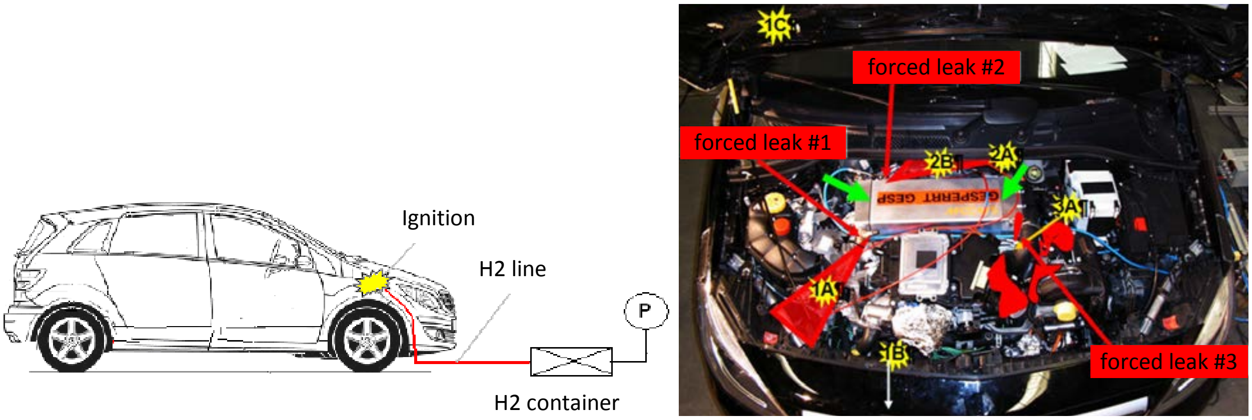


Figure 3: Ignition tests on a HyWay4 Stack with defined leakage positions on a current B-Class Prototype

The tests carried out at a fully functional vehicle did not show any effects that could set the car on fire. The combustion of the ignited hydrogen was very short, the pressure was released over the engine bonnet and the grille. Outside the car there was no visible flame.

As a conclusion from these tests with the ignition of 5 and 10 Nl of hydrogen inside the engine compartment, Fig. 4 shows the following results:

- Max. Overpressure in Passenger Compartment ca. 1,5 / 4,2 mbar
- Max. Overpressure in Engine Compartment ca. 25 / 70 mbar
- Sound level 2m in front of the vehicle 95 – 126 dB(A)
- Sound level in Passenger Compartment 80 – 110 dB(A)

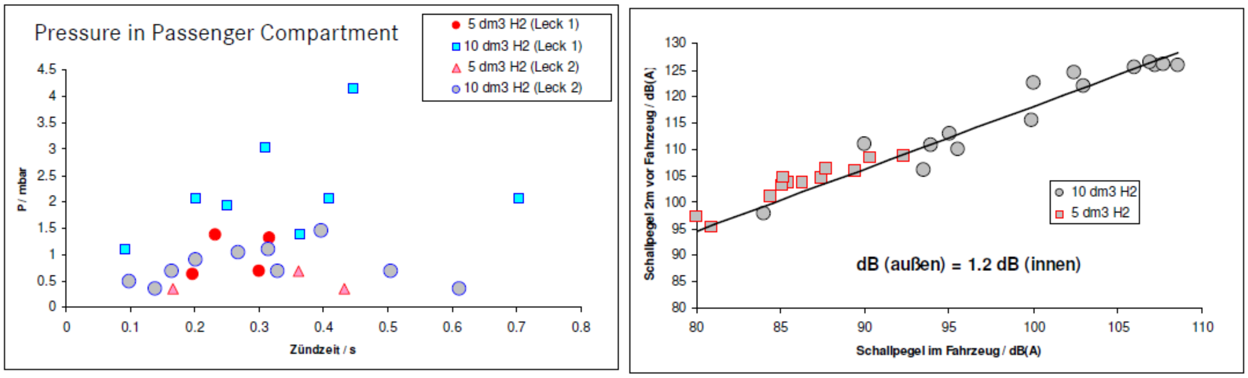


Figure 4: Pressure inside the passenger compartment and max sound level outside the car in 2m distance

These tests represent an absolute worst case scenario due to the fact that:

- These ignition tests were carried out with an active ignition, which may not be onsite in case of a crash.
- 10 Nl were higher than the theoretically maximum value that can occur when the stack is running at max. power output, which is very unlikely in the event of a crash.
- The 10 resp. 5 Nl of hydrogen were released within a time period of max. 650 ms. This time frame is so short that the amount of leaked hydrogen can reach an ignitable mixture much faster than it would usually occur from a real leak. In case of smaller leaks – which may happen in severe crashes – hydrogen is released much slower at lower leak rates so that there is a good chance for a volatizing before an ignitable mixture arises.

In order to further minimize the risk of a fire and an electric shock, additional actions are taken. As soon as the system isolation valve and the tank valves are closed in the case of a crash, a pyrotechnic short cut device (PCD) on the fuel cell is activated. This PCD is activated from the airbag controller and it disconnects the fuel cell from the vehicle and concurrently connects the positive and negative bus bar of the stack. At the same time, the traction battery is separated from the vehicle grid via the opening of its contactors. This short cut of the stack has the following positive effects:

1. Immediately after firing the PCD, the voltage level of the stack drops down to 0V so there is no risk resulting from high voltage.
2. During the internal short cut in the stack, a very high hydrogen consumption inside the stack occurs.

Figure 5 shows the gradient of pressure on the anode and cathode side of the stack. Voltage and current are not plotted because both drop immediately to zero after deploying the PCD that short cuts the fuel cell stack. The test set up required a manual closing of the tank valves and the SIV short after the PCD ignition. In the case of a vehicle crash test, these devices are shut off from the airbag controller via pyro fuse. This test on a HyWay 4 fuel cell stack running with a net power output of 34 kW shows that in less than 1 ms after deploying the PCD, an immediate drop in HV starts as well as the reduction of the H2 pressure after closing the tank valves. 64 ms after closing of the hydrogen tank, the pressure in the hydrogen loop drops below atmospheric pressure, so that H2 will stop to leak behind that point. By using this technique, another step to enhanced HV and fire safety protection for first responders and maintenance personnel is achieved. One visible indication for a deployed PCD and thus no more H2 or HV on the fuel cell stack is any deployed airbag after a front or side crash of the vehicle.

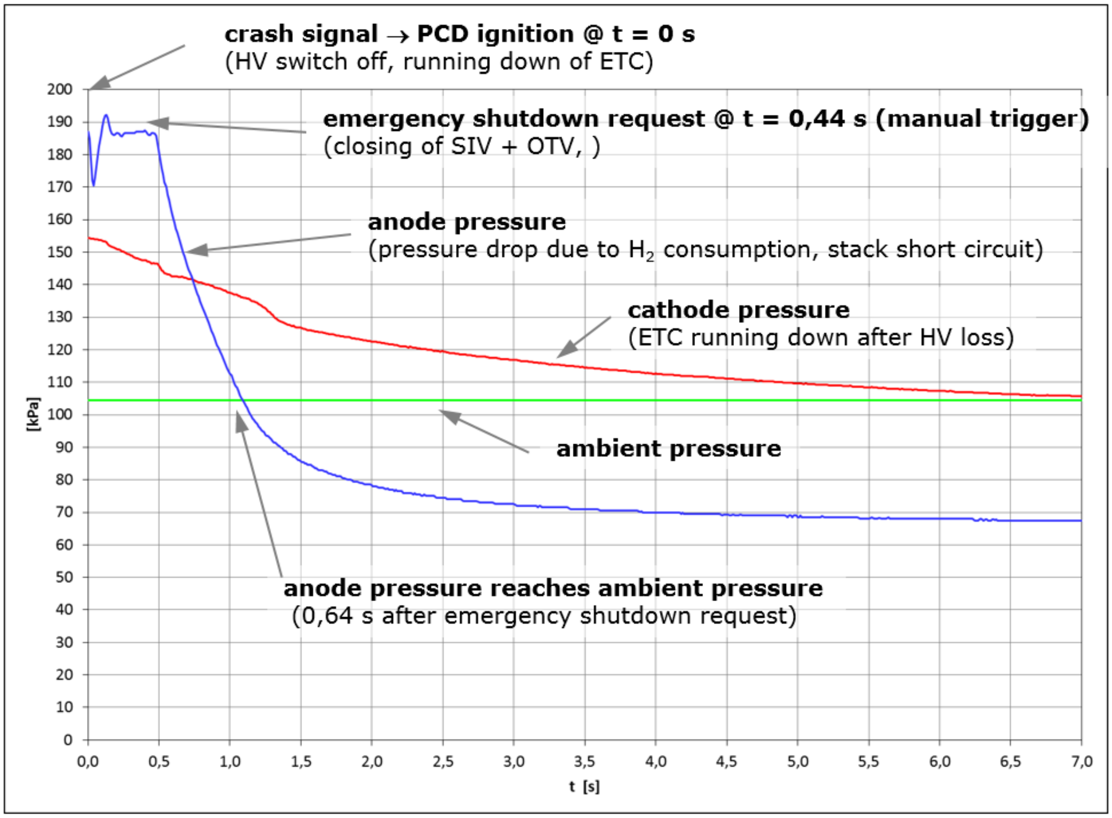


Figure 5: Hydrogen and HV gradient of a HyWay 4 fuel cell stack after deploying a pyrotechnical short cut, stack running on 34 kW net power

5. Crash Tests

Similar to other Mercedes-Benz cars, the GLC Fuel Cell Plug-In has to pass all worldwide required legal crash tests. The safety level has to be comparable to the base vehicle with combustion engines. For all worldwide ratings, the goal is to reach the highest rating level, which is usually a 5 star rating based on a certain assessment year.

To ensure a high safety level in real life accidents, Mercedes-Benz performs additional OEM specific full-scale crash tests in addition to the mandatory legal crash tests and rating tests supplemental. The relevant test scenarios are adapted to the specific vehicle concept.

Examples for the Mercedes-Benz GLC F-Cell specific crash tests are:

- a trailer underride to assess the crash performance of the fuel cell stacks in the engine compartment
- a lateral pole test with increased velocity and aligned to the valves of the gas tanks

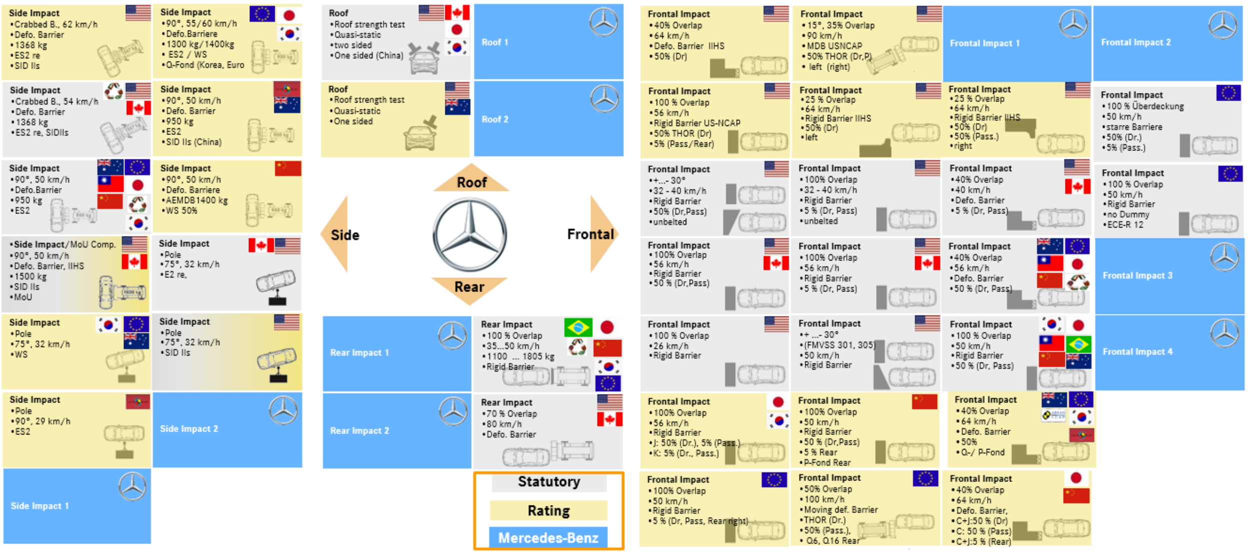


Figure 6: Mercedes-Benz Crash Test Portfolio

From a certain development status, crash tests are carried out with a fully functional and operating fuel cell system. This is even true for the predecessors of the GLC, such as the A-class f-cell based on the first A-class with long wheel base as well as some B-Class F-Cell prototypes. To prevent the stack from idling, the HV-battery is prepared for the test with a low state-of-charge so that the fuel cell system is charging the battery while the car is pulled towards the barrier. The H2-system is tested during the various vehicle development stages with different pressures up to a fully loaded H2 container with 700 bar during the homologation tests.

5.1 Truck underride

For the fuel cell, one of the goals of this test is to ensure the safety of hydrogen and high voltage components. During a truck underride, the main energy absorbing structure is located in a lower position than the rear end of a truck without an underride protection bar. As a consequence, the airbag controller, which also initiates the shut-down of the H2 and HV-system via pyro fuse and PCD, may not recognize a crash because the overall acceleration is relatively low at low speed. This could be the case at collision speeds in the range of 15 km/h.

The Mercedes-Benz truck underride test is thus carried out at a speed of 15 km/h with 100% overlap against a rigid underride barrier. This barrier is located 30 mm above the front bumper or the front longitudinal beams in order to hit the car in an area in which no other main energy absorption structure is affected. The impact energy is therefore mainly acting against the radiator unit and the fuel cell stack. The goal of this test is to prove a high robustness of all loaded fuel cell and H2-containing components in order to completely prevent hydrogen leaks at a speed range at which the shut-down mechanism may or may not be effective. For this test mode, the HV-components need to be packaged and designed in a way, which ensures the HV-safety according to the FMVSS 305 requirement option of a completely isolated system.

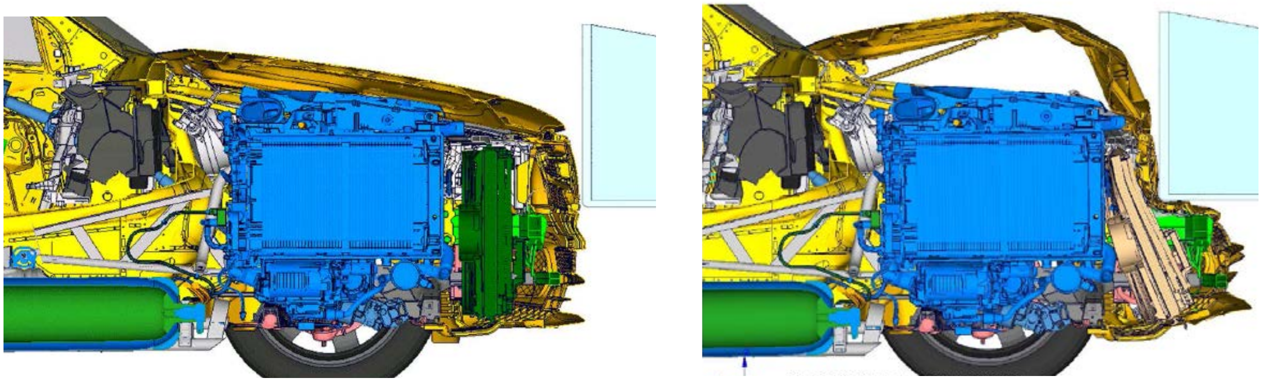


Figure 7: Truck underride example with the Mercedes-Benz GLC F-Cell Plug-In Hybrid

5.2 Lateral Pole Test

To ensure a high level of safety, pole crash tests, are carried out in a worst-case position. These energy storage system integrity tests are not implemented in current legal regulations. The requirements for high voltage safety and electrolyte spillage according to the FMVSS 301/303/305 have to be fulfilled as an OEM-specific requirement.

The pole test originates from the FMVSS201 or Euro-NCAP 90° pole at 29 km/h but at a 10% higher collision speed of 32 km/h. The worst case position for the H2 container is obtained from crash simulations carried out for pole impacts in various positions between the front and the rear axle. The goal is to check the loading of the H2 container in locations other than the FMVSS 214 or the new ECE-R 135 pole impact locations, which are tested anyway. Thanks to the support frame carrying the hydrogen tanks, impacts induce only minor loadings to the container. One example, in which the pole impact points right to the valve position of the rear tank, causes a lateral movement as can be seen in figure 8.

Figure 8: 90° Pole tests according to FMVSS 201 with increased velocity up to 32 km/h instead of 29 km/h

In this configuration, a contact of the rear container with the rear seat cross member of the body in white was observed. Therefore, an additional burst test of the container was conducted following the vehicle test. The result showed a burst pressure still above the required 2,25 * maximum operating pressure, which is a proof that this damage to the H2 container was not safety-relevant.

6. Conclusion

Fuel cell cars show some specific topics that need to be considered in the design of the model and checked in vehicle crash tests. All tests carried out with the present and earlier fuel-cell cars from Mercedes-Benz show that it is possible to reach at least the same high safety level as other modern cars with internal combustion engines. The additional operation of the fuel cell system during the crash test allows the testing of all combined safety relevant systems in one full scale vehicle crash test.

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Rainer Justen is Manager Passive Safety and Restraint Systems Mercedes-Benz Electric Vehicles. After his studies in mechanical engineering with a focus on automotive engineering he started his career in 1987 in the automotive development for Mercedes-Benz at Daimler AG. Several career milestones in the fields of vehicle safety, project management, safety concepts and active safety / driver assistance systems made him an expert on all relevant topics of automotive safety. Since 2008 he is working in the field of safety for alternative propulsion vehicles. Rainer Justen is author of numerous publications and papers on this topic. In 2015 Rainer Justen received the SAE (Society of Automotive Engineers) Automotive Safety Award for his work on the Safety of Li-Ion Batteries in Electric Vehicles.

Dr. Andreas Dehn is project coordinator and speaker of the vehicle integration group for passive safety (crash, pedestrian protection and durability) of the B-class E- and F-Cell and the GLC E- and F-Cell. After a degree in mechanical engineering in the discipline construction and a Ph. D. work on energy absorption with fiber reinforced thermoplastics at the Institute for Composite Materials in Kaiserslautern he started at the Mercedes-Benz development. At the Passive Safety department he worked in several projects on pedestrian safety, bumper testing and crash test engineering on A- and B-class generations before he continued with projects for alternative propulsion systems like fuel-cells, CNG, LPG and battery electric vehicles.

Stefan Boneberg is the responsible project coordinator for the H2-Safety of the GLC F-Cell vehicle and powertrain. After his degree in physics (FH) he has been working in the fuel cell system (FCS) development at the Daimler AG since 1993. As he has worked in several fields of the FCS development, from component to FCS and H2-Storage system development, he became an expert for H2-systems in vehicles. Since 2010 he is responsible for the H2 safety in various vehicle and bus projects. He is the lead engineer, planning and executing vehicle Hydrogen safety tests, hazard analysis, specifying the Hydrogen Safety Concept, as well as conducting Functional Safety for the H2 system according to ISO26262.