HYDROGEN SAFETY: NEW CHALLENGES BASED ON BMW HYDROGEN 7

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ABSTRACT

Part 1: The new BMW hydrogen 7 with a bi-fuel power train.

The BMW Hydrogen 7 is the world's first premium saloon with a bi-fuelled internal combustion engine concept that has undergone the series development process. This car is also displaying the BMW typical driving pleasure. During its development the features of the hydrogen energy source were emphasised. Engine, tank system and vehicle electronics were especially developed for being integral parts of the vehicle for use with hydrogen. In terms of a safety-oriented development process strict hydrogen specific requirements were generated for the Hydrogen 7. The performance of these requirements was proved in many tests and experiments, including every necessary and additionally specific crash test, like side impact to the tank coupling system or rear impact. Furthermore the behaviour of the hydrogen tank under extreme conditions was tested for instance in flames and by strong degradation of the isolation. In terms of total car test more than 1.7 million km were covered. All tests were passed successfully proving the intrinsic safety of the vehicle.

Part 2: Development of a Safety Concept for future BMW hydrogen cars.

In constructing the Hydrogen 7 BMW succeeded in making a series production of a bi-fuelled vehicle fulfilling every required safety requirement. The applied safety-oriented development process has been proven successful and shall be continued during the development of future vehicles. A safety concept for future hydrogen vehicles creates new challenges for vehicles and infrastructure. It is necessary to develop a car which is only fuelled by hydrogen, while simultaneously optimizing the safety concept, i.e. by reduction of the used hydrogen sensors. Another important goal is the permission of parking in closed rooms like garages. Part 2 will show a vision for requirements and ways to fulfil them.

INTRODUCTION

BMW is looking back on more than 25 years experience in developing automotive hydrogen vehicles. After the successful presentation of the hydrogen technology in the BMW 7 Series by a small vehicle fleet 7 years ago, the BMW Hydrogen 7 with a bi-fuel drive has been developed as a small series that has undergone the series development process. Also a safety-oriented development process was carried out, which will be introduced in the first part of the presentation. The second part of the presentation describes potential targets and shows future prospects on new challenges to establish hydrogen as a common and safe energy source in the vehicle.

1.0 THE NEW BMW HYDROGEN 7 WITH A BI-FUEL POWER TRAIN.

1.1 Vehicle concept

The Hydrogen 7 is based on the long-wheelbase version of the current BMW 7 Series model. There are scarcely any visible changes to the body, but a number of components have been newly developed on account of the vehicle's higher weight and the need to handle the hydrogen fuel (Fig. 1). The super-insulated liquefied hydrogen tank is entirely new as are several weight-optimized body areas of composite construction using carbon-fibre reinforced plastic (CRP) and steel [1].

Figure 1: Hydrogen 7

For hydrogen-fuelled vehicles, BMW relies on the combustion engine (H_2-ICE), which is derived from the power engine of the BMW 760i. The engine has a power output of 191 kW (260bhp) from a displacement of 6.0 litres. The maximum torque is 390 Nm, reached at an engine speed of 4300 rpm (Fig. 2). It is designed to burn either hydrogen or petrol in its cylinders. While driving, the engine can be switched from hydrogen fuel to conventional operation on petrol without any noticeable delay. Operating on hydrogen, the range before refuelling is more than 200 kilometres, to which a further 500 kilometres can be added when running on petrol. The bi-fuelled operation is an important option, particularly in the transition period in which the H_2 filling station network is still poor.

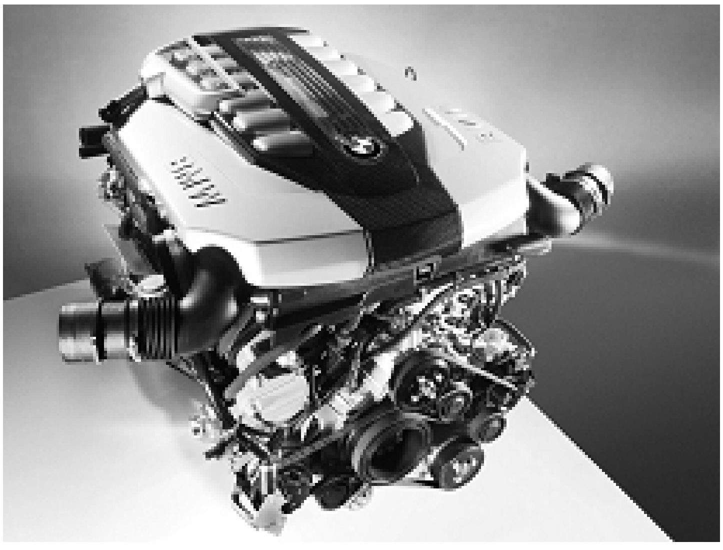

Figure 2: Bi-fuel internal combustion engine

The bi-fuel power train concept calls for two separate fuel storage systems to be integrated into the car. As well as the 74-litre petrol tank, there is a LH_2 tank capable of holding about 8 kilograms of liquefied hydrogen (Fig. 3). BMW has adopted hydrogen in liquefied form, because LH_2 storage systems have the highest volumetric and gravimetric energy densities compared to gaseous hydrogen, which is stored at high pressure [2]. This increases the action radius of the vehicle. The tank system is a major challenge, because hydrogen liquefies only at the extremely low temperature of -253°C, and this low temperature must be maintained in the tank for as long as possible. In order to achieve this, the double-walled tank has got a vacuum super-insulation (Table. 1).

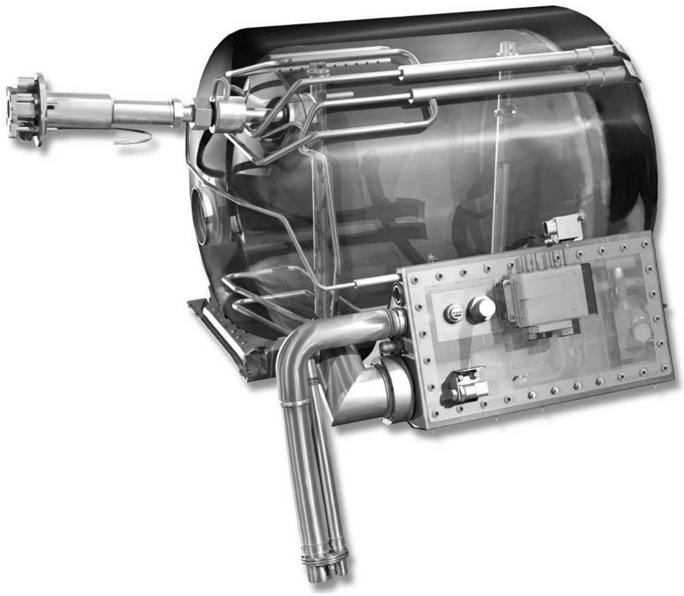

Figure 3: LH_2-fuel storage with filling pipe

Despite this excellent tank insulation, it is impossible to prevent a slight amount of heat from reaching the tank. As a result, a small proportion of the hydrogen evaporates (‘boil-off’). The Hydrogen 7’s fuel system can keep back boil-off gas for about 17 hours if no gas is consumed, after which it is supplied to a boil-off management system, where the gaseous hydrogen is mixed with air and oxidized in a catalytic converter to yield water. [2]

Table 1: Vehicle data in hydrogen operating mode

Max. power at engine speed	191 kW / 5100 rpm
Max. torque at engine speed	390 Nm / 4300 rpm
Acceleration, 0-100 km/h	9.5 s
Top speed v_{max}	230 km/h
Usable hydrogen storage capacity	7.8 kg LH_2
Overall consumption (H_2)	3.6 kg/100 km
Operating range on hydrogen	> 200 km
CO_2 emissions (H_2)	5 g/km*
Other emissions (H_2)	<< EU4 limits

* The combustion of essential lubricating oil and rinsing the active carbon filter lead to very low emissions of CO_2.

1.2 Safety concept

Special attention was devoted to safety against the background of the specific properties of hydrogen during the vehicle development process. In addition to passive safety, the operating safety of the hydrogen system had to be taken into close consideration.

The basis for the safety system ratings is functional safety as laid down in IEC 61508; which specifies processes for the design and validation of electrical/electronic systems. For the BMW Hydrogen 7, these requirements were interpreted in respect of vehicle operation in its environment, and extended as necessary. As a result, evidence of safety is available for all the relevant functions and components, including external expertises. Furthermore, the vehicle and filling station safety concepts have been coordinated and special situations for example in repair shops were evaluated in terms of technical safety. [3]

The safety concept has got four levels: [1]

"Design": All components are designed from the start to comply with the highest possible standards of safety.

"Fail Safe": To comply with the remaining safety requirements, all components are designed to revert to a safe condition in the event of malfunctions.

"Safety Function": In order to satisfy further requirements, safety functions that identify faults at an early stage are incorporated as a means of either avoiding or reducing risk.

"Warning": Even if faults develop despite all these precautions, the driver is supplied with a warning: the driver information system receives and displays information of the defect and instructions on how to proceed.

The gas warning system consists of five hydrogen sensors monitoring the entire vehicle, a control unit initiating the necessary reactions, and a power supply, independent of the car's own electrical system (Fig. 4). This ensures that any concentration of H_2 in the vehicle will be detected – a particularly important matter, since hydrogen lacks odour, taste or colour, and therefore its presence cannot be sensed by human organs. If a hydrogen leak occurs, the valves of the tank are closed immediately and a warning is given by the locking buttons at all doors, which display a flashing red light. The driver gets additional information by indicating instruments if the ignition is on. If the engine is running, it is switched over automatically from the hydrogen to the petrol operating mode.

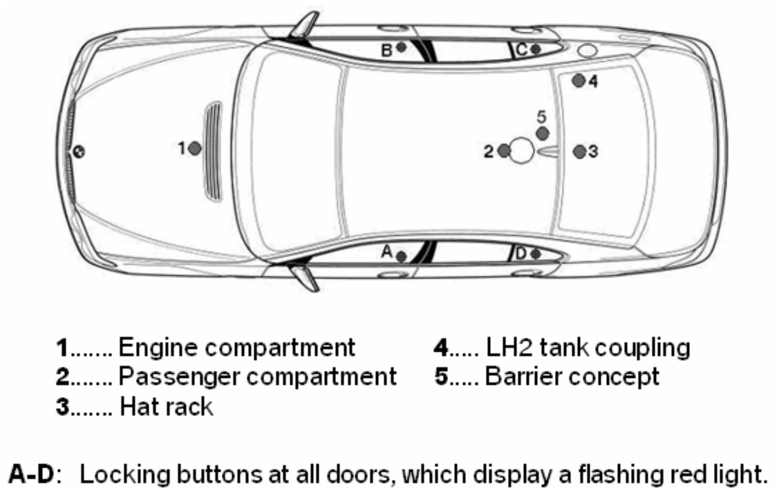

Figure 4: Gas warning system

1.3 System and vehicle tests

The single authorization by the German TÜV took place after the concept for an ECE-regulation: TRANS/WP.29/GRPE/2003/14 including Addendum 1, by the 29.10.2003. The ECE-regulation is similar to the EIHP-draft (Rev. 14a) for the authorization of liquefied or gaseous hydrogen driven vehicles. This regulation required component and system tests. Amongst others, tests in flames (external outer effect of the heat) were carried out, where the tank had to endure a temperature of more than 590°C for at least more than 5 minutes. During this period the security valve, which prevents bursting of the tank, had to stay closed off.

Additionally to the tests demanded by law, the safety of the hydrogen system of the Hydrogen 7 was verified intensively by further tests. Especially LH_2 tanks were tested extensively. Workloads provided by BMW were carried out on the LH_2 tank including the misuse of a customer by driving across a road kerb. Getting documented evidences of conformity about the vacuum-tank brought satisfying results: so far no safety critical malfunctions occurred.

If the tank looses its vacuum, for example by a rear end crash, a safety valve reacts by a defined internal pressure of the inner tank. The safety valve blows off the gaseous hydrogen into the air through safety lines on the vehicle’s roof. In an extra test a break of the vacuum-tank was simulated and deliberately sparked off the exhausting hydrogen by 3 ignition plugs in order to examine this situation. The flames burnt upwards, but the roofline in the passenger compartment sparked off after about 5 minutes, enough time for occupants to leave the vehicle or to be saved by helpers.

In view of the car’s increased weight and the presence of the hydrogen tank, passive safety represented a major challenge. The Hydrogen 7 was subjected to a selected crash-programme including the US-NCAP Front-crash (50 km/h, 100% depth of coverage, against a fixed barrier), the EU-NCAP Offset-Crash (64 km/h, 40% Offset, against a deformable barrier) and the FMVSS301 Rear end-crash (80 km/h, 70% Offset, against a mobile barrier). The aim was to achieve the same low risk of injury for the occupants in case of an accident as in the normal BMW 7 series. This could be reached by the cooperation of airbags and an additionally strengthened body, which is reinforced by CFK, in the compartment.

One of the most important objectives is inhibiting fuel from escaping, both petrol and hydrogen, during or after a crash. In view of this, none of the carried out crash tests had to result in any damage to connections or deterioration in the quality of the tank insulation. The intrusion did not reach the hydrogen system in any of the already mentioned crash tests. We developed special crash tests to examine the behaviour of the LH_2 tank under extreme conditions, which do not occur normally in real accidents, but they could.

First a collateral pole collision with 30 km/h in the centre of the LH_2 tank coupling was simulated. The tank showed no damage and locked up by the tank valves, which were actuated by the safety electronics. The outer shut-off valve at the tank coupling was leaky, but the pipe to the interior remained proof.

The second extreme test was a rear crash by EES (Energy Equivalent Speed) of 45 km/h (Fig. 5). The mobile barrier especially constructed for this test crossed at a height of 700 mm the longitudinal carriers of the Hydrogen 7 and distorted the LH_2-tank. The result turned out well, as the safety system closed the tank valves and the tank remained proof despite its distortion. Even the tank vacuum was in order after the test. During all crash tests the guidelines could be accomplished [4].

Figure 5: Crash test truck override

During the testing program, Hydrogen 7 cars covered more than one and a half million kilometres in the hydrogen and petrol operating modes all over the world. A considerable proportion of this total distance took place as part of a “time-compression” program, with the loads on the vehicle equivalent to three to five times the distance actually covered.

In conclusion, it should be pointed out that all tests were passed successfully and proof was provided for the intrinsic safety of the Hydrogen 7.

2.0 DEVELOPMENT OF A SAFETY CONCEPT FOR FUTURE BMW HYDROGEN CARS.

2.1 Safety goals for the future

After an adequate transit time with bi-fuelled or alternatively driven cars, which depends as well on infrastructure as on progress in hydrogen technology, BMW will be able to deliver mono-fuel hydrogen cars to our customers. This implies that we not only develop safe cars but also include the infrastructure into our integrated safety concept. Comprehensive efforts have been made for the Hydrogen 7, which affect as well the testing-, production-, and service locations as exclusive public gas stations worldwide and special hydrogen service stations like the CEP in Berlin. The Hydrogen 7 is permitted to drive through tunnels, underground garages or car wash plants as well as to stop in closed rooms for a limited time. One yet unsolved challenge is parking in closed rooms like single garages or underground car parks. A clearance of garage parking was not granted despite a comprehensive testing program for the safeguarding of the LH_2 vacuum, because we don’t know yet how and when a tank is going to be damaged. A main goal for the future will be to prevent this. As there are different regulations in different countries BMW generally does not give allowance for parking in garages. That’s why a lot of results from researches tests and simulations will have to be combined. Until today no safety critical incidents have occurred with the Hydrogen 7.

2.2 Parking in closed rooms

Since a certain amount of heat penetrates the tank despite its super insulation, very small amounts of liquefied hydrogen evaporate in the tank. This causes the pressure to rise over a period of time. In order to limit the pressure, a certain amount of hydrogen has to be discharged (“boil-off”). To control this discharge and render the boil-off gas harmless in normal conditions, a boil-off management system (BMS) is part of the hydrogen car system, which works in the Hydrogen 7 as follows: Above a predetermined overpressure in the tank, the boil-off valve opens and the boil-off gas is allowed to escape into the atmosphere via a catalytic converter, in which the gas is converted to water vapour with the aid of atmospheric oxygen, no other source of energy being needed. In case of malfunction the maximum amount of H_2-gas emitted through the boil-off valve is limited by a throttle to less than 60 grams per hour which we consider not to be harmful. For the future BMW aims at bringing boil off-losses to a minimum.

In order to prevent the explosion of the tank by a large overpressure (e.g. due to increased heat entrance after a defect in the super-insulation), a release of pressure is provided by a safety line combined with a safety valve. In case of being activated this can lead to a big amount of released H_2. The severity of a possible accident depends on size of room, existence of ignition source, existence of ventilation presence, if the ignition source works immediately or delayed and if people are nearby. If the tank is prevented from bursting, a large amount of H_2 will be released within a short time. This leads to a hazardous event in case of a delayed ignition in a small room whether there are people nearby or not. In a large room there might be the chance to take out a warning by people who realize the emission of H_2 which is accompanied by a crackling sound. A big but slow leakage tends out to be hazardous as long as it is undetected. But this could be handled by ventilation which is able to thin down the concentration of explosive mixture fast enough. In order to guarantee the safety of H_2 vehicles in garages, BMW proposes a combination of measures to be taken on the vehicles and in the buildings. The interface between vehicle and garage has been defined as a maximum escape volume of 200 grams of hydrogen per hour in the event of a fault. In other words in garages approved for H_2 vehicles, due to safety reasons the ventilation must be designed that if this limit volume of gas is emitted, no ignitable concentration can build up at any point inside the garage, with the exception of the immediate vicinity of the actual emission point (the permissible volume has to be defined). For reasons associated with the safety concept, the ventilation needed for this purpose should preferably be passive in nature. Some of the assumptions are still to be verified by tests. The next steps are researches on the following topics.

Sophisticated consideration of closed rooms

- Behaviour of customers in every day use and in cases of misuse
- Behaviour of real garages with stored materials of any kind
- Minimum ventilation of different garages

Boil-off management

- Secure handling of boil-off gas
- Variants of boil-off-management systems
- Thin down of H_2-vapour instead of catalytic combustion

Safety of storage system

- Permanent surveillance of tank vacuum quality
- Permanent surveillance of safety valves
- Recognition of slow degradation of insulation

Risk Assessment

- Conditions under which the hazard exists
- Propagation of H_2 under different conditions
- Possible ignition sources for H_2 at different concentrations

The more we know about the aspects, the safer we can design our vehicles in terms of allowing parking in enclosed rooms.

2.3 Mono-fuel hydrogen vehicles

If a vehicle is converted from a bi-fuel to a mono-fuel mode, some components needn't be applied any more, like all parts necessary to supply the system with petrol. In order to enable a mono-fuel use of BMW cars it has to be analyzed, which operating conditions excite the automatic change from H_2-mode to petrol mode. If you want to switch to a mono-fuel mode you have to analyze every condition under which you can allow the continuation of the operation with H_2. This won't be possible in every case. In cases where this is not possible an appropriate concept of warning and degradation has to stop the car's operation after an adequate time. Sometimes it will be possible to continue the operation with a suitable degradation of functions. Liberated from the history of bi-fuel drive are more possibilities to improve the car's availability. Mono-fuel-drive with H_2 provides the advantage of improving efficiency and exhaust-emission quality, because the construction of engine components can be adapted to H_2-operation without making compromises, while a bi-fuel power train takes a lot of work and expenses.

The most important failures are:

Failure of sensors

- icing of H_2-keeping components
- overheating of H_2-keeping components
- too high pressure in the tank
- too low pressure in the tank
- H_2-emission into the double barrier

In case of one of these failures during the bi-fuel mode you can convert to petrol mode. It is impossible with a mono-fuel car.

In the event of an identified failure of a sensor an expert can decide for the best solution in this situation. He can go on with driving, while knowing the failure of a sensor does not mean danger. At the next opportunity he will replace the sensor. An alert prompts a usual consumer to drive immediately to a service station for solving the problem. In case of all other failures a multi-stage degradation concept is intended. For example if the H_2-keeping components are frosted, first the output of H_2 will be reduced and the driver is asked to stop the vehicle safely as soon as possible. If the system cools down even though the power is reduced or the driver does not stop in time, the H_2-mode must stop.

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