HYDROGEN SAFETY: NEW CHALLENGES BASED ON BMW HYDROGEN 7

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ABSTRACT

The BMW Hydrogen 7 is the world's first premium sedan with a bi-fuelled internal combustion engine concept that has undergone the series development process. This car also displays the BMW typical driving pleasure. During development, the features of the hydrogen energy source were emphasized. Engine, tank system and vehicle electronics were especially developed as integral parts of the vehicle for use with hydrogen. The safety-oriented development process established additional strict hydrogen-specific standards for the Hydrogen 7. The fulfilment of these standards were demonstrated in a comprehensive experimentation and testing program, which included all required tests and a large number of additional hydrogen-specific crash tests, such as side impacts to the tank coupling system, or rear impacts. Furthermore the behaviour of the hydrogen tank was tested under extreme conditions, for instance in flames and after strong degradation of the insulation. Testing included over 1.7 million km of driving; and all tests were passed successfully, proving the intrinsic safety of the vehicle and also confirming the success of the safety-oriented development process, which is to be continued during future vehicle development. A safety concept for future hydrogen vehicles poses new challenges for vehicles and infrastructure. One goal is to develop a car fuelled by hydrogen only while simultaneously optimizing the safety concept. Another important goal is removal of (self-imposed) restrictions for parking in enclosed spaces, such as garages. We present a vision of safety standards requirements and a program for fulfilling them.

1 INTRODUCTION

BMW looks 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 paper. 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.

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

2.1.1 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. Bi-fuelled operation is an important option, particularly during the transition period in which the H_2 filling station network is still sparse.

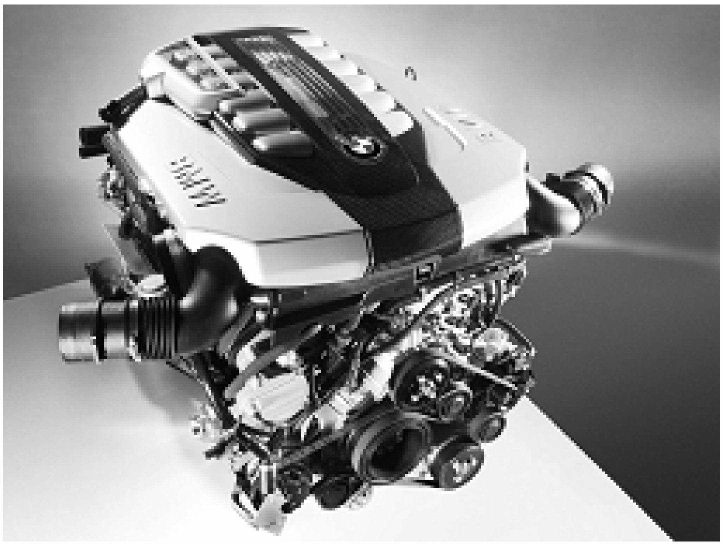

Figure 2: Bi-fuel internal combustion engine

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 range for a given storage volume. 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 is equipped with vacuum super insulation (Table 1).

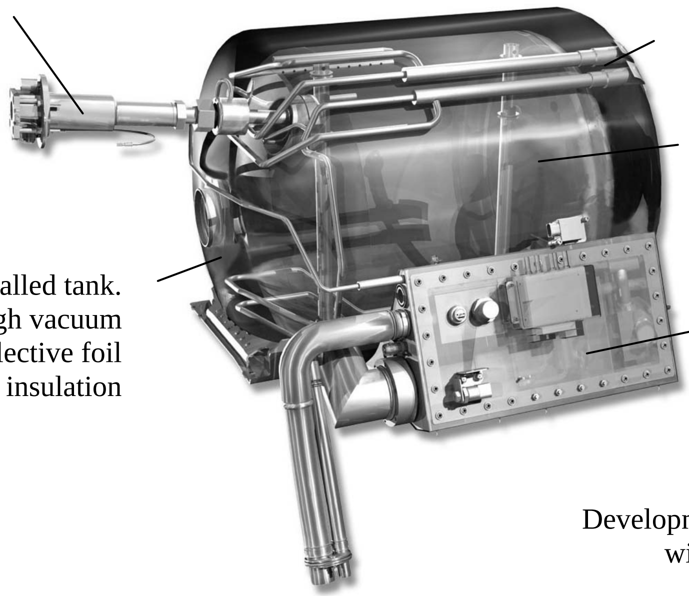

Figure 3: LH_2-fuel storage with filling pipe

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

	hydrogen	**petrol**
Max. power at engine speed	191 kW / 5100 rpm	191 kW / 5100 rpm
Max. torque at engine speed	390 Nm / 4300 rpm	390 Nm / 4300 rpm
Acceleration, 0-100 km/h	9.5 s	9.5 s
Top speed v_{max}	230 km/h	230 km/h
Usable hydrogen storage capacity	7.8 kg LH_2	74 litre
Overall consumption	3.6 kg/100 km	13,9 l/100km
Operating range	> 200 km	> 500 km
CO_2 emissions	5 g/km*	332 g/km
Other emissions	<< EU4 limits	< EU4 limits

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

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 with respect to vehicle operation in its environment, and extended as necessary and appropriate. As a result, safe operation has been confirmed by both internal and external experts for all the relevant functions and components. 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 comprises 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 identification”: Safety functions that identify faults at an early stage are incorporated as a means of avoiding or minimizing risk.

“Warning”: In the unlikely event that a hazard develops despite all these precautions, the driver is provided with a warning: the driver information system receives and displays information on 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 indicator instruments if the ignition is on. If the engine is running, it is switched over automatically from the hydrogen to the petrol operating mode.

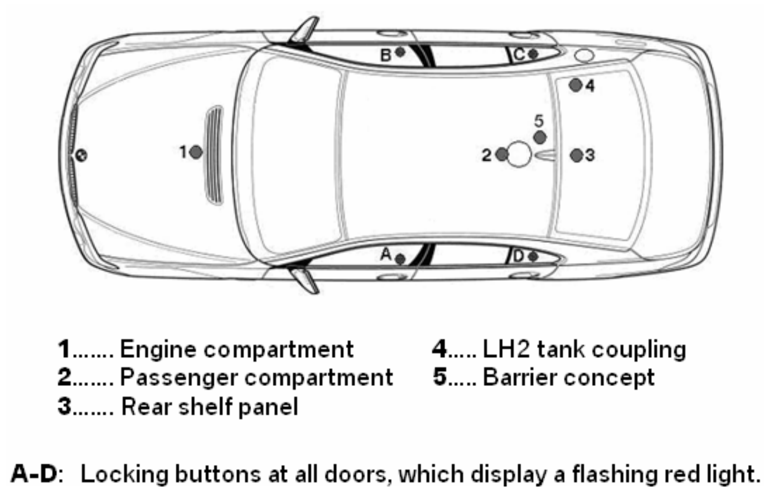

Figure 4: Gas warning system

2.1.3 System and vehicle tests

Uniform provisions of the certifying agency in Germany (the TÜV) were implemented following the concept for a proposal for an ECE-regulation: TRANS/WP.29/GRPE/2003/14 including Addendum 1, of the 29.10.2003. The proposal for 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. Among other things, tests in flames (external outer effect of the heat) were carried out, in which 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 required by law, the safety of the hydrogen system of the Hydrogen 7 was verified comprehensively by further tests. In particular, LH_2 tanks were tested extensively. The LH_2 tank was subjected to workloads provided by BMW, such as misuse due to customer driving across a road kerb. The accumulated evidence of the vacuum-tank's safety conformity has been quite satisfactory: so far not a single safety critical malfunction has occurred.

If the tank loses its vacuum, for example in a rear-end crash, a safety valve reacts at 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 the exhaust hydrogen was ignited deliberately by 3 ignition plugs in order to examine this situation in detail. The flames burnt upwards, but the roofline in the passenger compartment did not start to burn until after about 5 minutes, enough time for occupants to leave the vehicle or to be rescued 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 was achieved by the combination of airbags and an additionally strengthened body, which is stiffened by carbon-fibre reinforced plastic (CRP), in the passenger compartment.

One of the most important objectives is inhibiting fuel from escaping, both petrol and hydrogen, during or after a crash. Hence, the requirement was that none of the crash tests carried out should 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 that do not occur normally even in real accidents, but are hypothetically possible.

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

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

3 DEVELOPMENT OF A SAFETY CONCEPT FOR FUTURE BMW HYDROGEN CARS

3.1 Safety goals for the future

After an adequate transition time with bi-fuelled or alternatively driven cars, which will depend both on infrastructure and on progress in hydrogen technology, BMW will be able to deliver mono-fuel hydrogen cars to its customers. Our integrated concept for developing safe hydrogen cars also includes the infrastructure. For the Hydrogen 7, comprehensive efforts have been undertaken involving testing-, production-, and service locations as well as exclusive public fuel stations worldwide and special hydrogen service stations like the CEP in Berlin. Currently, there are no consistent standards and legislation for H_2-specific systems in the use of hydrogen cars; homologation (permission for operation) and parking in enclosed garages are not uniformly regulated. At present, the Hydrogen 7 is permitted to drive through tunnels, underground garages or car wash plants as well as to stop in enclosed spaces for a limited time. To give our customers a clear message, the BMW Group has therefore stated a policy that the car may not be parked in enclosed areas. Removal of this restriction is clearly a key goal for the future and will require a substantial research effort, including a combination of extensive testing and simulation.

3.1.1 Future Developments for Pure Hydrogen Cars

Mono-fuel operation using 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. If a vehicle is converted from a bi-fuel to a mono-fuel mode, some components become redundant, such as those supplying petrol.

In a mono-fuel car, the option to switch to an alternative fuel operation mode is not available; hence, in case of a potentially safety-relevant malfunction, the system must decide if the drive may be continued. A “graceful degrading” concept in stages would allow the car to continue to operate at a reduced level of demand and subject to an appropriate warning; for instance the vehicle’s speed might be limited in order to decrease temperature and pressure of hydrogen components.

3.1.2 Parking in enclosed areas

Since a certain amount of heat penetrates the tank despite its super insulation, very small amounts of liquefied hydrogen evaporate inside 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 by the boil-off management system. 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. Using realistic figures of 72 m^3 to represent the volume of a domestic garage, and 0.5 ach (air change by hour), it can be calculated that, for 60 grams per hour, the steady state concentration will be less than 2%, i.e. less than half the lower flammable limit and hence a safe level. For the future, BMW aims at reducing boil off-losses to a minimum.

In order to prevent 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 activation, this process can lead to a large amount of released H_2. The severity of a possible accident depends on the following factors: the size of the space, the presence of an ignition source, the presence of ventilation, whether the ignition source acts immediately or is delayed, and whether people are nearby. A large amount of released hydrogen leads to a hazardous event in case of delayed ignition in a small room whether there are people nearby or not. In a large room, persons who detect emission of H_2 (which is accompanied by a crackling sound produced by the safety valve) would have some chance to issue a warning. A large but slow leak which prevails for a prolonged period may also be hazardous, as it may remain undetected before reaching a dangerous concentration. But this could be handled by ventilation, which is able to dilute 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. In case of a fault, the maximum emission of H_2 into the garage has been defined as 200 grams of hydrogen per hour, which would require a ventilation of 110 m^3/h, corresponding to 1.5 ach (air changes per hour) for the same garage, a level that may be achieved by a well designed ventilation system. In other words, in garages approved for H_2 vehicles, safety considerations imply that ventilation must be designed such that no inflammable 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 include research on the following topics:

Sophisticated consideration of enclosed rooms

- Behaviour of customers in everyday 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
- Dilution of H_2-vapour instead of catalytic combustion

Safety of storage system

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

Risk Assessment

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

BMW always demands the highest level safety when designing H_2 vehicle concepts. An important part of the safety concept is a well defined interval of service checks.

4 OUTLOOK

Sustainability plays an essential role in the corporate strategy of a successful and responsible company such as the BMW Group. With its EfficientDynamics and CleanEnergy initiatives, BMW is pursuing the vision of sustainable mobility. BMW Hydrogen 7 represents a first step in the transition to a hydrogen based energy economy, fascinating pioneer customers, and providing impetus for a future hydrogen infrastructure. At the same time, several challenges have been identified that need to be solved to enable market penetration of H_2 powered vehicles.

One of the key challenges remaining is the validation that all H_2 components meet BMW's strict, self-imposed safety standard, a prerequisite for approval of H_2 vehicles for parking in enclosed areas. BMW is addressing this challenge by continuing to develop hydrogen systems with a maximum of available safety. However, the technological progress and effort required to overcome the remaining challenges are quite substantial for a single automobile manufacturer, and in view of the common interest in an environmentally friendly and sustainable energy basis, a cooperative effort of all stakeholders is crucial to success.

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