Safety measures for hydrogen vehicles with liquid storage.
With reference to the BMW H₂ 7 Series as an example.

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ABSTRACT
Clarification of questions of safety represents a decisive contribution to the successful introduction of vehicles fueled by hydrogen. At the moment, the safety of hydrogen is being discussed and investigated by various bodies. The primary focus is on fuel-cell vehicles with hydrogen stored in gaseous form. This paper describes the safety concept of BMW’s hydrogen-fueled vehicles with an internal combustion engine and liquefied hydrogen storage.

The fundamental factor in the fulfillment of the requirements is an intelligent H₂ component layout in the vehicle. The aim of the crash program is primarily to protect the occupants, but also to ensure that the hydrogen system develops no leaks. This provides evidence that a package of a safe LH₂ fuel supply installation that is resistant to crash effects can be implemented.

Theoretical safety observations are complemented by the latest experimental and test results. Finally, reference is made to the topic-areas in the field of hydrogen safety in which cooperative research work could make a valuable contribution to the future of the hydrogen-powered vehicle.

Fig. 1: H₂ 7 Series BMW with LH₂ System
KEYWORDS

INTRODUCTION
BMW has a long tradition in the field of hydrogen-fueled internal combustion engine technology. As long ago as 1979, BMW Research presented the first vehicle powered by an internal combustion engine using hydrogen as a fuel. The goal of BMW CleanEnergy is to assure long-term individual mobility allied to BMW’s proverbial “sheer driving pleasure” independently of fossil energy carriers and without CO2 emissions. Based on the latest 7 Series model, a vehicle with a hydrogen-fueled internal combustion engine is currently being developed. Since the number of hydrogen filling stations is still very low, the hydrogen-fueled ICE engine that is also capable of running on conventional fuels offers the best prospects of satisfying customers’ needs. But before hydrogen vehicles can be supplied to customers, a proven H₂ safety concept must be in place.

H₂-SAFETY MANAGEMENT
In the modern plant and equipment construction area, extensive safety concepts reduce the danger of personal injury or fatality and the risk of damage to the environment. The hazard potential is derived from the extent and frequency of such damage and minimized to a socially acceptable level.

The introduction of hydrogen technology to motor vehicles calls for the development of a specific new safety concept for their operating area. The procedure in the automotive area does not differ greatly from that adopted in plant and equipment construction. There too, situations with safety relevance are evaluated and the possible hazard quantified. All the relevant operating situations must be taken into consideration. Special situations too, for example driving through water, must also be examined, and it is of particular importance to examine and evaluate road accidents.

Hydrogen’s properties differ from those of gasoline (petrol) and diesel oil, and it therefore has to be handled differently. Hydrogen is very light, and rises rapidly. It burns smokelessly with a hot flame that extends upwards. The low ignition energy and extensive range of an ignitable air-hydrogen mixture call for special measures to be taken.

Detailed situation and risk analyses have been carried out on the hydrogen vehicle as part of the systematic development of an H₂ safety concept. This has led to the following primary protection targets being set up:

- The LH₂ tank must not burst.
- An ignitable mixture must not form (especially inside the vehicle or in enclosed spaces)
- No significant (critical) amounts of hydrogen may escape
- There must be no ignition sources in certain areas
- Cold burns must be prevented.
These protective targets result in mechanical requirements (e.g., strength of tanks when pressurized, freedom from leaks from lines conveying hydrogen etc.) and also requirements that the electrical and electronic components must satisfy.

**Situation analysis**

Description of all possible critical safety events

**Risk analysis**

(Hazard-analysis)

**Risk assessment**

Protection targets

Quantitative safety targets

(Concerns about failure rates etc.)

**Measures**

- Error avoidance
- Error mastery

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The current draft of the ECE directive for LH₂ vehicles is used as a basis for the LH₂ system’s ratings. This proposal for a licensing regulation for liquefied hydrogen storage devices in vehicles was drawn up as part of the EIHP (European Integrated Hydrogen Project).

The main basic principles of the EIHP draft include:

- A barrier concept (double-walled construction for non-welded connections on lines carrying H₂ in the interior of the vehicle)
- Redundant provision of shutoff and safety valves
- Mechanical over-dimensioning of components exposed to pressure

The control and regulating system of the LH₂ fuel supply installation consists of the following components:

- Tank control unit as master for the hydrogen system; this controls or regulates all the basic and safety functions
- Electromagnetic valves and sensors (level, temperature, pressure etc.) for the realization of basic, diagnostic and safety functions.
H₂ SAFETY CONCEPT

The focus has been on safety ever since the development of BMW hydrogen-powered vehicles began, starting with the positioning and rating of individual components, for which pre-defined requirements derived from the properties of hydrogen and an analysis of risks in all operating situations were complied with. The principal elements of the safety concept are described below:

- A double containment performs the function of housing potential leakage points on pressurised parts, detecting any specific H₂-leaks that do occur and discharging these from the vehicle. Double-walled components include the noise absorption hood in the engine compartment, the auxiliary-system enclosure on the H₂-fuel tank and the enclosures surrounding all threaded pipe unions.

- The safety lines are intended to purposely discharge H₂ from the inner tank, in order to prevent the tank from bursting, if pressure inside it should rise significantly. In such an event the first safety valve trips. This may occur for example as a result of loss of vacuum resulting from severe crash damage. Since gaseous hydrogen is very light, the outlet aperture to atmosphere has to be at the highest point, in other words on the roof. This is also preferable because it has the advantage that no third parties can come into contact with the cold hydrogen if large quantities of it have to be discharged (see Figure 3). To ensure that even a severely damaged vehicle can always dispose of sufficient line section if H₂ escapes, the safety lines are of redundant design and pass through both the right and the left C-posts of the vehicle’s body.

Fig. 3: H₂ discharge through 1st safety line
• An additional safety line is used for the controlled dispersion of hydrogen if the first safety line is not enough to discharge sufficient hydrogen, for example if the vehicle is lying on its roof. In this event the second safety valve trips and the additional safety line led the boiling volume of gas to a point on the floor pan close to the rear axle.

• Numerous sensors are used to control the hydrogen system (pressure, temperature, content, H₂ sensors) and a central CE control unit restores the vehicle to a safe condition by triggering the safety function if pre-defined limits are exceeded. This means for example that the H₂ supply may be interrupted, but continued operation on petrol remains possible.

• A gas warning system monitors the hydrogen system in case of any leakage in the vehicle. This is important because human beings cannot sense the presence of hydrogen. It consists of H₂ sensors, a warning system and the central CE control unit (see above) that is responsible for triggering specific reactions if the need arises.
  Five H₂ sensors monitor the complete vehicle, especially enclosed spaces such as the engine compartment, the occupant zone, the luggage compartment and the double-wall of the H₂ components. This avoids the undesirable situation in which H₂ could spread through the vehicle without being noticed.
  If a gas alarm should occur, a warning is emitted in the form of light flashes via all four door pins. During the journey the driver is informed additionally by a message displayed on the instrument panel.

• The boil-off management system (BMS) regulates pressure in the hydrogen tank if the vehicle remains at a standstill for some time. It is located under the vehicle, so that the heat and steam, generated when the H₂ boil-off gas is converted into water vapour, can be most effectively disposed of via an exhaust system. To minimize pressure losses in the BMS system, the pipes have to be kept as short as possible. In addition, the apertures at the rear of the vehicle are arranged in such a way that an interruption to the airflow or the catalytic function does not result in any raise of H₂ under the vehicle. This arrangement enables also the BMS to function satisfactorily when the vehicle is at a standstill or at any road speed. The apertures face downwards so that driving through water does not affect their function.

![Fig. 4: functional test, driving through water](image-url)
The refuelling coupling enables the vehicle to be refuelled with hydrogen hermetically and safely at -253°C and approx. 5 bar overpressure. The refuelling coupling is located in the C-post above the rear axle, for greater protection in the event of a side impact (for instance against a pole). This position also has the advantage that the shortest path to the hydrogen tank is obtained.

PASSIVE SAFETY

The fundamental factor in the fulfillment of the requirements is an intelligent H₂ component layout in the vehicle. The primary crash zones are taken into account (see Fig. 5), that is to say the tank is located above the rear axle, which on account of its rigidity provides maximum protection, above all in a side-on crash. The H₂ lines, which are made from stainless steel, are run along the vehicle’s centerline. Where this is not possible, flexible sections of line are used so that changes in length can be accommodated if relative displacement occurs.

![BMW ACCIDENT RESEARCH](image)

Fig. 5: Primary crash zones

In the event of a crash, the crash sensors respond in a few thousandths of a second and transmit a signal to the tank control unit; when the information has been evaluated, power is shut off at the valves of the H₂ storage tank, so that they close and interrupt operation of the engine on H₂. This prevents any significant amount of hydrogen from escaping, for instance if a pipe breaks or splits.

Like automobiles utilizing conventional fossil energy carriers as fuel, BMW’s hydrogen vehicles have to comply with the highest standards. In addition to the ECE requirements, testing proceeds in accordance with those imposed by the US NHTSA authority, which are known to be stringent.
The US-NCAP requirements, in which the vehicle is driven against a rigid barrier at 56 km/h and with 100-percent overlap, have been chosen as the experimental configuration. The resulting accelerative forces are a severe test of the \( \text{H}_2 \) fuel system, in particular the \( \text{H}_2 \) tank and internal tank mounts, which have to withstand high levels of acceleration up to 50 g.

The FMVSS 301 rear-end crash has been selected as a further test; in this, a mobile barrier strikes the stationary vehicle at 80 km/h with 70-percent overlap. The body of the vehicle has to be rigid enough to prevent damage to the tank; its rear end must be capable of the entire deformation energy.

Based on the FMVSS 201 car-to-pole crash test, the behaviour of the LH\(_2\) refuelling coupling was tested in a simulated 30-km/h impact against a tree or lamppost. The most critical configuration, namely a vertical impact against the centre of the refuelling coupling, was chosen. In this type of crash the rear axle absorbs most of the deformation energy, so that the intrusion depth is limited and the tank coupling remains free from leakage inside the vehicle. \( \text{H}_2 \) escape from the tank is prevented by closing the filling/discharge valves; this is triggered by the crash sensors by way of the central CE control unit.

![Car-to-pole crash against the refuelling coupling](image)

**Fig. 6: Car-to-pole crash against the refuelling coupling**

The aim of this demanding crash program is primarily to protect the occupants, but also to ensure that the hydrogen system develops no leaks. This means that no dangerous amounts of \( \text{H}_2 \) should escape from threaded unions, pipes or valves.

In addition, the chosen crash configuration has the task of confirming that the LH\(_2\) storage tank suffers no significant damage. This is to ensure that no potentially dangerous escape of \( \text{H}_2 \) occurs in the vast majority of road accidents. Crash tests so far carried out with BMW’s hydrogen vehicles have yielded thoroughly positive results (see for example Fig. 4 & 3). Both the conventional and \( \text{H}_2 \) fuel systems exhibited no leaks during or after any of the crash configurations that were carried out.
CONCLUSIONS

Many years of experience in the chemical industry and process technology have shown that hydrogen can be handled without technical safety problems arising. However, the people who currently have to handle hydrogen are experts or have received special training. If hydrogen is to be introduced as a motor vehicle fuel, large numbers of the general public will be confronted with this medium. Depending on the chosen storage technology, they will have to refuel their vehicles at filling stations with hydrogen either as a highly compressed gas or as an ultra-low temperature liquid. To prepare the way for handling hydrogen as a fuel, the public must be trained. In general, the risks associated with conventional fuels are underestimated and those associated with hydrogen overestimated. Just as every driver of a motor vehicle is now familiar with the basic rules of handling gasoline (petrol) or diesel oil safely, so the basic knowledge of how to handle hydrogen must be made generally familiar and applied in practice. If the specific properties of hydrogen are examined, it can be seen that a hydrogen-fueled vehicle offers a level of safety comparable with one that uses gasoline or diesel oil as its fuel.

The safety concept developed by BMW creates a basis for hydrogen-fueled vehicles incorporating LH$_2$ storage to be supplied to customers. The safety concept has been confirmed with a validation program. The crash tests that have been performed provide evidence that a package affording safety in a crash and an LH$_2$ fuel supply installation that is resistant to crash effects can be implemented.

With regard to vehicles’ technical features, standards must be compiled that ensure safe and straightforward operation in all normally encountered conditions. In the event of abuse and in extreme situations, a high level of protection must still be available.

All hydrogen vehicles should comply with these standards. The relevant activities have already been commenced all over the world. It is important for the activities currently being undertaken in the USA, Japan and Europe to be coordinated and unified. “Hydrogen safety” must not prove to be a differentiating competitive feature.

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