SAFETY OF HYDROGEN-FUELED MOTOR VEHICLES WITH IC ENGINES

Dr. Fürst, S. [1], Dub, M. [1], Gruber, M. [1], Lechner, W. [1] and Müller, C. [1]
[1] BMW AG, 80788 Munich, Germany

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 looks at the safety of hydrogen-fueled vehicles with an internal combustion engine and liquefied hydrogen storage. The safety concept of BMW's hydrogen vehicles is described and the specific aspects of the propulsion and storage concepts discussed. The main discussion emphasis is on the utilization of boil-off, parking of the vehicles in an enclosed space and their crash behavior. 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.

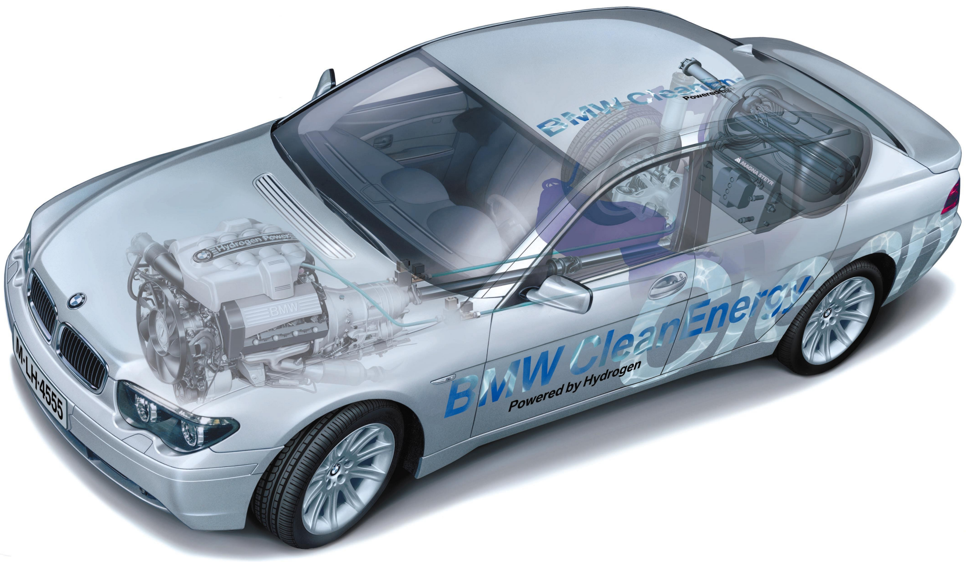

Fig. 1: A 7 Series BMW with hydrogen IC engine and LH_2 storage tank

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.

H_2 SAFETY CONCEPT

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. This includes driving through tunnels, parking the vehicle out of use in an enclosed space, refueling and servicing. 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 LH_2 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.

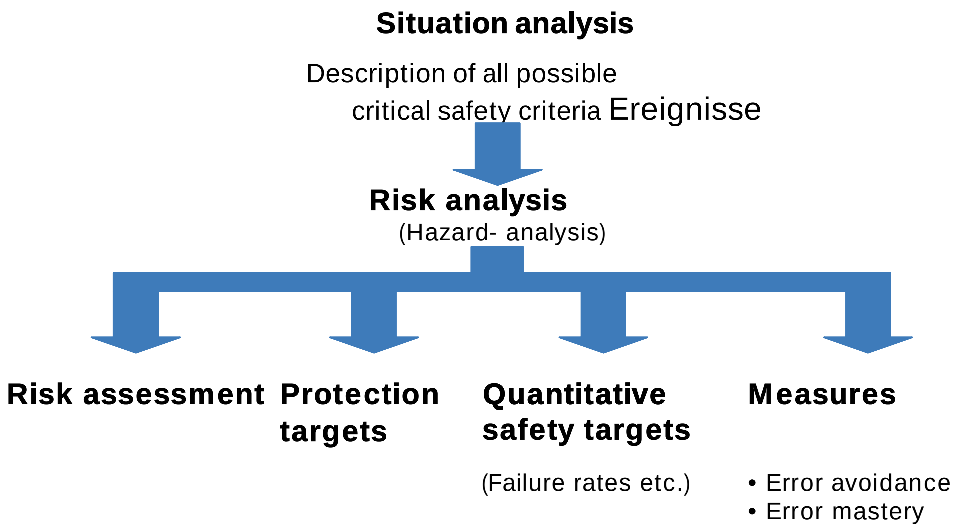

Fig. 2: Systematic derivation of the safety concept

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 H_2 in the interior of the vehicle)
- Redundant provision of shutoff and safety valves
- Mechanical over-dimensioning of components exposed to pressure

Development of specific electrics and electronics for use with hydrogen is based on IEC61508. This is a basic safety standard for the functional safety of electrical, electronic and programmable electronic safety-related systems.

Development based on IEC61508 means that the processes proposed in the standard or derived from it are used for the planning, realization, testing, operation and shutting down out of use of safety-related electrical and electronic equipment.

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

- Gas warning installation for the sensing of escaping hydrogen and the issue of a warning (this is important because human beings cannot sense the presence of hydrogen)

PASSIVE SAFETY

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 H2 fuel system, in particular the H2 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.

Fig. 3: Offset rear crash according to FMVSS 301

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 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 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. 3). Both the conventional and H_2 fuel systems exhibited no leaks during or after the rear-end crash.

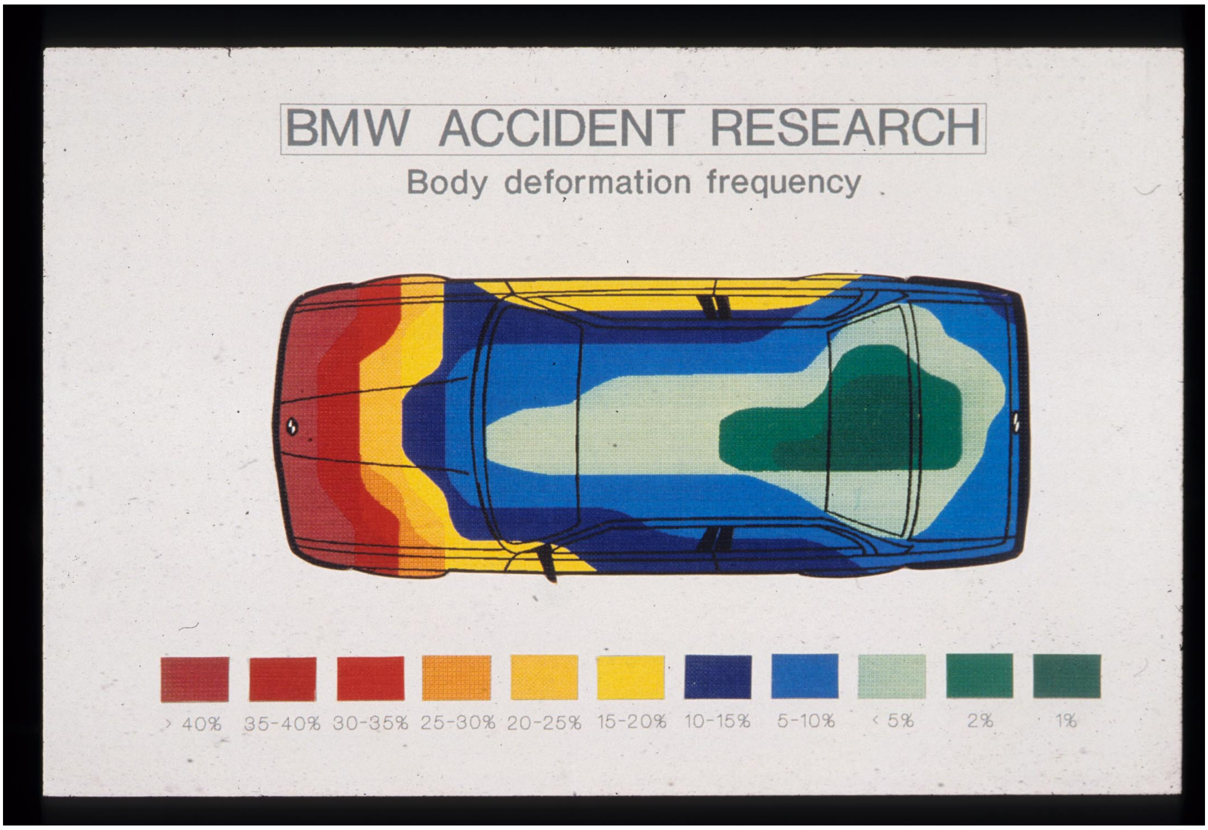

Fig. 4: Primary crash zones

The fundamental factor in the fulfillment of the requirements is an intelligent H_2 component layout in the vehicle. The primary crash zones are taken into account (see Fig. 4), 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 H_2 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.

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 H_2 storage tank, so that they close and interrupt operation of the engine on H_2. This prevents any significant amount of hydrogen from escaping, for instance if a pipe breaks or splits.

SAFETY CONCEPT OF A HYDROGEN-FUELED INTERNAL COMBUSTION ENGINE

BMW is currently developing a series-production hydrogen vehicle. For this purpose a 'bivalent' engine was developed, that is to say one capable of running on either gasoline or hydrogen. This enables H_2 technology to be offered on production vehicles although the H_2 supply infrastructure is still inadequate.

In addition to the one needed for gasoline, the engine requires an additional H_2 mixture formation system. There is a pressure regulator in the feed line from the LH_2 storage tank to the engine's intake system: this reduces the pressure in the tank to the value needed for engine operation, and regulates it. The engine's intake system includes an additional integrated H_2 rail. H_2 injection valves deliver hydrogen from the rail to the individual cylinders' intake pipes. The basic engine differs from a regular gasoline engine only as a result of certain modifications that have to be made:

- A different material for the valve seat rings, since the H_2 fuel has no lubricating effect
- Modified piston, ring assembly and fire land clearances to suit the H_2 combustion process
- Spark plugs and ignition system also suitable for H_2 operation
- Control units to actuate the H_2 components
- Inclusion of the LH_2 storage tank heat exchanger in the engine's cooling circuit

The bivalent engines can be built as an alternative version on the existing production lines for gasoline engines. This enables the manufacturing quality to be high, since the processes are familiar and a large amount of know-how is available. The basic preconditions for a high safety standard are therefore satisfied in the production and assembly areas.

Fig. 5: Hydrogen internal combustion engine

In order to develop a reliable engine concept, a system-FMEA was undertaken to determine the safety-relevant faults of all engine components and error avoidance steps were laid down.

Freedom of the mixture formation system from leaks has high priority. For this purpose, high-quality stainless steel was used for the lines and suitable casting and post-treatment methods for the intake system. Double-walled pipes are used in the vicinity of the threaded unions. Any leaks here are trapped in the double-wall and detected by a gas warning system sensor; if a predetermined threshold is exceeded, H_2 operation is shut down and the LH_2 storage tank's shutoff valves closed. If this occurs while the vehicle is being driven, the bivalent engine offers the advantage of being able to continue the journey on gasoline without loss of performance.

As already implied in the section on passive safety, the H_2 feed line in the engine compartment has to be run in a position that prevents it from being torn off in the event of crash in which the engine is forced back against the body. The intake system has to be designed and the hydrogen injection valves positioned in such a way that in conjunction with a suitable engine operating application the injected hydrogen burns fully in the combustion chambers and no pre-ignition or backfiring into the intake pipe can occur.

Unavoidable blow-by during H_2 combustion leads to H_2 enrichment in the crankcase. The crankcase breather has to be designed to prevent any ignition originating in the intake system from reaching the crankcase. Any increase in the risk of the crankcase breather freezing as a result of the proportion of H_2O must be avoided at all costs. The volume and geometry of the intake air system have to be chosen in such a way that when the vehicle is parked out of use, any leaks at the H_2 injectors cannot lead to hydrogen escaping at the front end of the vehicle.

The efficacy of all the necessary solutions is confirmed by a large number of tests:

- Tests on individual components and assemblies, such as H_2 dissemination tests, ignition tests using worst-case configurations and shaker tests
- Engine rig tests: function and endurance tests to verify safety measures
- Tests on various assemblies in prototype vehicles in order to check the effect of the measures on the complete vehicle

GARAGE TESTS

In view of the differences between the properties of hydrogen and those of conventional fuels, the parking of H_2 vehicles in enclosed spaces has to be specially examined and evaluated. The main characteristics affecting the dissemination of hydrogen are its low density and the speed with which it accordingly rises in air. The formation of pools or puddles, as with liquid fuels or liquefied gas, is therefore ruled out. The high coefficient of hydrogen diffusion in air also leads to rapid horizontal dissemination. Characteristics of hydrogen that must be taken especially into account are its broad ignition range in air and its low ignition energy. This means that special measures hat to be taken, when H_2 vehicles are parked in enclosed spaces, so that the accumulation and ignition of ignitable mixtures of H_2 and air are reliably avoided.

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 60 grams of hydrogen per hour in the event of a fault. In other words the ventilation of a garage approved for H2 vehicles must for safety reasons be designed such 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. The volume of 60 g/h H_2 is also referred to below as the emission limit rate. The components and long-term vehicle tests must confirm that the escape of larger amounts of hydrogen can be prevented with a high degree of reliability.

At BMW the development emphasis is on the storage of ultra-low temperature hydrogen in a superinsulated tank. The main advantage of LH_2 is that the hydrogen's storage density is distinctly higher than if it is stored in other forms, so that the vehicles have a correspondingly greater range before refueling.

Since a certain amount of heat penetrates the tank despite its superinsulation, very small amounts of liquefied hydrogen evaporate ("boil-off"). This boil-off gas causes the pressure in the tank to rise over a period. In order to limit the pressure, the "boil-off" must be discharged in a controlled manner. On BMW vehicles this is taken care of by what is known as a Boil-off Management System (BMS). Above a predetermined overpressure in the tank, the boil-off valve opens and the boil-off gas is allowed to escape to atmosphere via a catalytic converter, in which the gas is converted to water vapor with the aid of atmospheric oxygen, no other source of energy being needed.

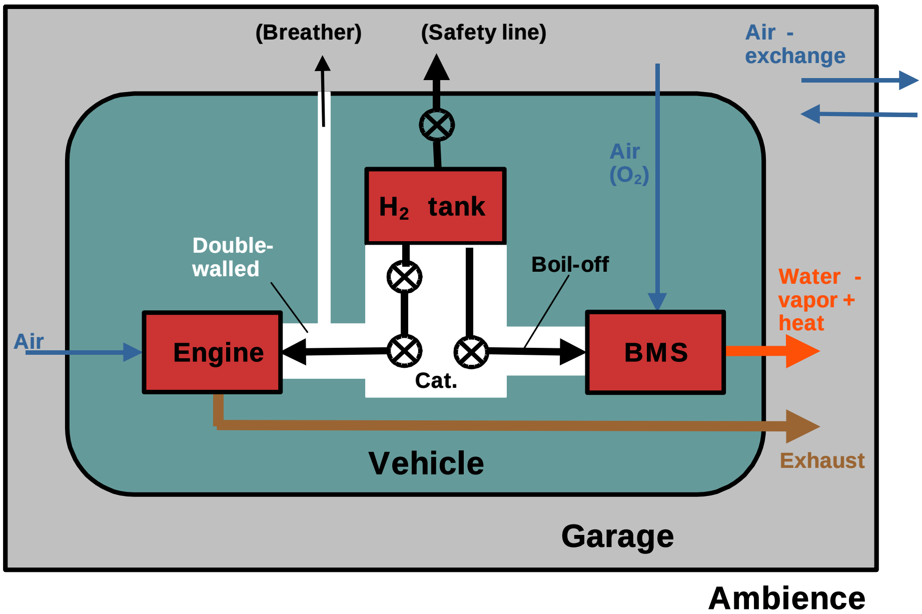

Fig. 4: Vehicle with BMS in a garage (schematic diagram)

Since the oxygen needed for the reaction is taken from the ambient air, minimum ventilation of the areas used to park LH_2 vehicles must be guaranteed. Natural ventilation is normally sufficient to prevent an impermissible level of oxygen depletion. So that the moisture occurring in the catalytic conversion of the oxygen can be dispersed, it may be necessary to provide an active form of air exchange (e.g. with an air exchange rate >2).

When a BMW hydrogen vehicle is parked in a garage, the following changes to the environmental conditions may occur:

- The temperature may rise on account of the heat given off by the catalytic boil-off converter
- Water vapor is emitted

- The oxygen content of the air is reduced, and
- Gaseous H_2 is emitted in the event of a fault (< 60g/h)

It is fundamentally necessary to investigate and evaluate these effects for the many different possible parking areas and garage configurations (single, double and self-built garages etc.). In order to explore the limits, the most critical garage form – on account of its geometrical dimensions – was investigated as an initial step: the prefabricated single garage. This garage is referred to below as the “standard prefabricated garage” (SPG). Since the currently valid garage regulations [1] do not impose any minimum ventilation requirements for this type of garage (small garages with < 100 sq. m parking space), the following experimental series were drawn up:

- Garage fully sealed
- Ventilation through the gap between the garage door and its frame
- Determination of specific ventilation apertures needed in the garage door.

1. German Order on the Construction and Operation of Garages (GaV) dated November 30, 1993 (GVBl. S 593), most recently amended by §5 No. 4 of the Order dated August 3, 2001 (GVBl. p. 593).

For experimental purposes the SPG was equipped with H_2 safety technology, e.g. a gas warning system, an emergency power supply etc. (see Fig. 7).

Fig. 7: Experimental garage for hydrogen-fueled vehicle.

Emission of H2 in the event of a fault

The area close to the BMW endpipe was chosen as the leak point. Since helium and hydrogen have very similar dispersion characteristics, pure helium was used for the dispersion tests as a safety precaution.

a) Fully sealed garage (calibration test)

If gas was allowed to escape at the emission limit rate inside a fully sealed garage, the limit of 4 percent by volume was exceeded within a few minutes.

b) Ventilation through the gap between the garage door and the door frame

For this test, all the ventilation apertures in the garage walls were taped over, leaving only the gap between the corrugated sheet metal door and its frame open for the exchange of air. In this test the H2 concentration always remained below the lower ignition limit.

Since it cannot be assumed that every garage has the air exchange gap utilized in this test, the next test was devoted to determining the ventilation apertures needed in the garage door in order to rule out the risk of ignition in the garage.

c) Determination of specific ventilation apertures needed in the garage door

In order to determine the necessary ventilation cross-sections, two horizontal slits were made across the entire width of the garage door (see Fig. 8). Their areas were made variable for the purposes of the test. For the avoidance of an ignitable concentration in the SPG with gas escaping at the emission limit rate, door ventilation aperture cross-sections of 2x 120 sq. cm were found to be necessary.

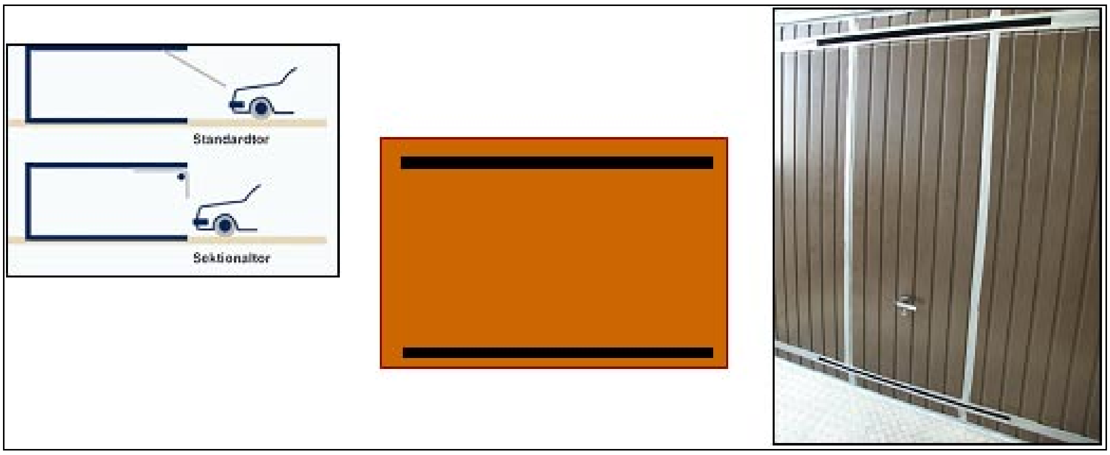

Fig. 8: Variable ventilation positions in the garage door

For the chosen test configuration with hydrogen emerging from the vehicle in the rear bumper area, it was possible to confirm that the standard prefabricated garage guarantees the necessary minimum ventilation.

Reduction of the proportion of oxygen in the ambient air

In further tests, the reduction in the oxygen content of the air was investigated in addition to H_2 dispersion. The results showed that this effect could be avoided in the air inside the garage with much smaller ventilation apertures than were needed in the case of H_2 dispersion.

The increase in temperature and the formation of water vapor inside an SPG have to be evaluated in terms of the customer's reaction, but do not constitute a topic of safety relevance and are therefore not discussed further here.

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 to be confirmed by 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. The physical characteristics of LH_2 storage give rise to requirements that the parking or garage areas for hydrogen vehicles must fulfill. BMW has conducted initial tests on a random basis on standard prefabricated garages. Since there are so many possible garage configurations, it is difficult to make generally valid statements regarding the nature and quality of the required ventilation. It will be necessary to complement the available results with large-scale investigations as a source of information for the formulation of regulations regarding the future design of garages suitable for LH_2.

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.

REFERENCES

Ochmann F.; Gebler B.; Fürst, S.; Müller Chr.: *Industrialization of Automotive Hydrogen Technology*; HYFORUM The International Hydrogen Energy Forum, 25-28 May 2004, Beijing, P.R. China