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Final Research Paper

Challenges of Alternative Fuel Vehicles and their Impact on Safety in Road Tunnels

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This report represents an initial excerpt from the forthcoming PhD thesis of the same title.

Contents

1 Introduction

In many countries all around the world there are strong efforts to reduce dependence from fossil fuels, either for reasons of political independence or to reduce CO_2 emissions. The transport sector is strongly affected by this policy, as vehicles have been powered by conventional fuels (gasoline or diesel) based on hydrocarbons for decades. When they are burned in an internal combustion engine (ICE), they release the greenhouse gas CO_2.

1.1 Alternative Fuel Vehicles

For some years now, efforts to reduce gasoline and diesel vehicles have been showing success and a steady increase of alternative fuel vehicles (AFV) can be observed on the roads. The first term that comes to mind when thinking of an AFV is certainly a battery electric vehicle (BEV), which represents an electrochemical storage. However, there are more types of fuel than this. Hydrogen can also be used as a fuel; its storage takes place liquefied and cryogenic (LH_2), or gaseous and compressed (CGH_2). Even though fuels such as natural gas in gaseous form (CNG) and in liquified form (LNG), or Autogas (LPG) have been used for years, they are also counted as alternative fuels. Alternative fuels also include biofuels and synfuels.

In Fig. 1-1 all fuels for automotive application are classified by their physical conditions stored in the vehicle: liquid, gaseous, liquefied or electrochemical storage.

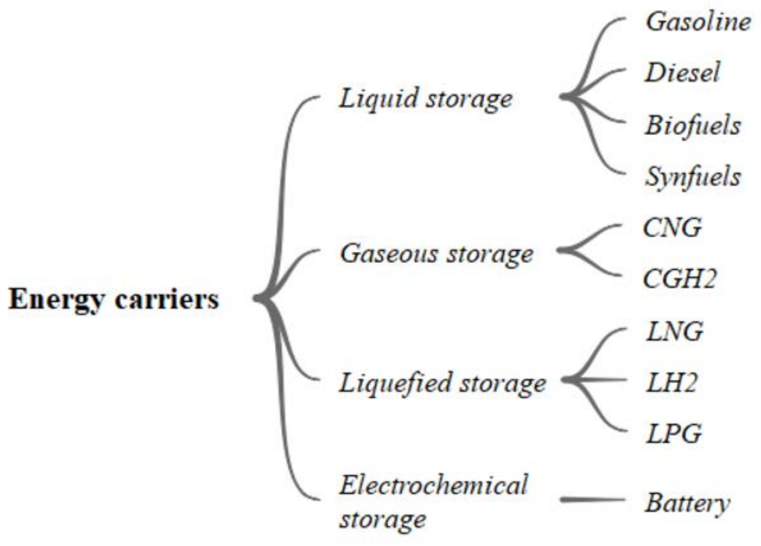


Fig. 1-1 Classification of fuels by physical conditions

Liquid Storage

Storage of fuel in liquid form is the most common, as it is used for conventional fuels. This type of storage is also used for biofuels or synfuels, as they are in a liquid state at ambient conditions. Having a plastic tank as a main component is part of the advantage of this simple storage system.

Gaseous Storage

Storing gases is somewhat more difficult, since their low density means that a large amount has to be stored. Compressed storage is possible for natural gas in pressure tanks up to 200 bar (CNG), and in case of hydrogen (CGH_2) there are pressures up to 700 bar.

Liquefied Storage

If gases are cooled below their boiling point, they change their phase to a liquid form. This type of storage makes it possible to store significantly more fuel than in purely compressed form. It can be applied to natural gas, which is cooled to –162 °C (LNG); while hydrogen must be cooled to –253 °C (LH_2). Since the boiling temperature depends on the pressure, one can also increase the pressure for liquification. This is used for LPG, which liquefies at already 5–10 bar and can thus be stored at standard temperatures.

Electrochemical Storage

An electrochemical storage is used for batteries. A battery is both an energy converter and an energy storage at the same time. The amount of storable energy depends primarily on the cell chemistry.

1.2 Impact of AFVs on Road Tunnel Safety

In the case of fire incidents involving vehicles with conventional fuels, their consequences are well-known. For instance, the tank may have a leak and after ignition, a pool fire occurs under the vehicle. AFVs pose in some cases completely different risks, like explosions, jet fires, thermal runaways, cryogenic burns, etc. Consequently, they also raise new challenges if an accident happens in underground infrastructures, i.e., in a road tunnel or a parking garage. The first step in assessing the hazards posed by alternative fuels is a basic understanding of how they work in vehicles. In this report, the basic technical design of AFVs, their energy storage, and the characteristics when applied in trucks and buses are considered. In addition, implemented safety features are also included.

The impact of AFVs on the safety of road tunnels is not considered in the present report, instead this will be published in the forthcoming PhD thesis. Therefore, the focus of this report lies in the automotive application of new energy carriers.

2 Battery Electric Vehicles

As early as the late 1880s, electric cars were being developed by several companies around the world. Of particular note here is the *Egger-Lohner C2 Phaeton*, one of the first battery electric vehicles to be produced by the Austro-Hungarian car brand in 1898 and with Ferdinand Porsche involved in its development. The range was a respectable 80 km, with a top speed of 35 km/h. A short time later, the *Lohner-Porsche* was presented at the Paris World's Fair in 1900, powered by a patented system [1] of two wheel hub electric motors in the front wheels (Fig. 2-1). The range was about 50 km despite a 420 kg lead-acid battery. [2]

In the USA at the beginning of the 20th century, battery electric vehicles (BEV) and steam carriages were even the most common vehicles on the road; vehicles with gasoline engines were clearly in the minority. Then as now, the range of BEV was the big issue, although its advantages (low noise and locally emission-free) could not change that. Through the further development of the combustion engine (i.e., starter) and the low-priced oil, the combustion engine finally prevailed. The two energy crises in the 1970s did nothing to change this. In response to continued uncertainties about oil supply, it was not until the 1990s that a small number of electric cars were introduced to the market, and then only in small series. [3]

Fig. 2-1 Presentation of a BEV from *Lohner-Porsche* at the Paris World's Fair 1900 (left) and charging BEV (*GM EV1*) around the turn of the millennium (right) [2, 4]

Only during the last 15 years has the automobile industry begun to change significantly, with almost every car manufacturer now launching BEVs on the market. The reason for this development lies in the increasingly stringent legislation on pollutant emissions of PM and NOx to improve air quality, but also in limiting CO_2 regarding global warming.

2.1 Basic Technical Design

The basic layout of the propulsion system of a BEV is illustrated in Fig. 2-2 and consists of an electric motor, the power electronics and the high-voltage traction battery. The battery supplies the DC voltage, which is converted into an AC voltage by the power electronics, as the electric motors in the vehicle are powered by AC (induction motor or synchronous motor). By changing the voltage, the torque in the electric motor is adjusted and the frequency controls its speed.

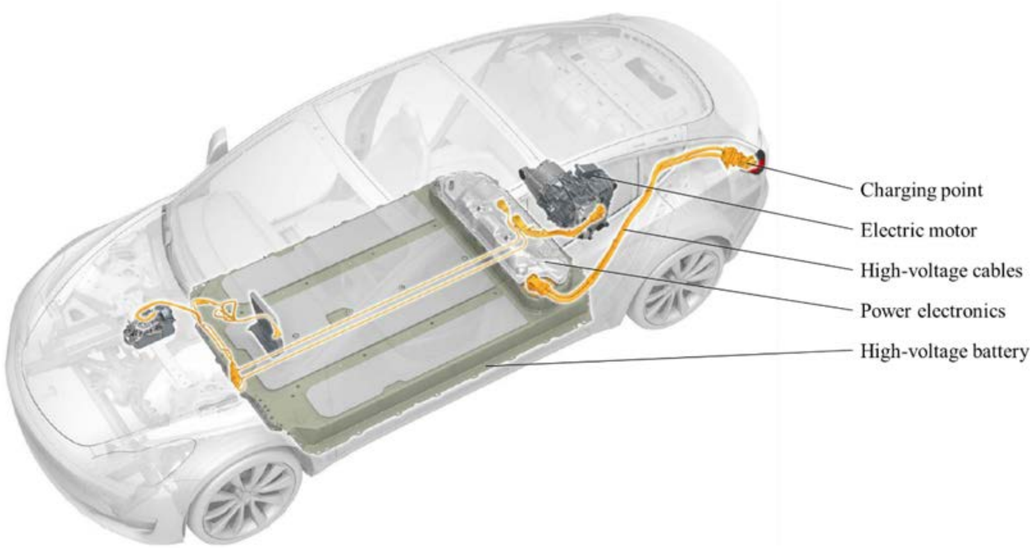


Fig. 2-2 Structure of a battery electric vehicle, adapted from [5]

Automotive batteries are not to be confused with the *traction battery* of an electric vehicle. First ones are implemented in nearly every vehicle, usually even in BEVs, to feed the vehicle with electricity for the on-board power supply which runs at 12 V for passenger cars (HGV and buses run at 24 V) and has an energy capacity of approx. 1 kWh. This power supply is also active for the turned off vehicle, and some important functions (hazard lights, emergency call system, etc.) are even active in case of a crash. For ICEVs, the main function of this battery is to ensure the power supply for the starter. Most commonly lead-acid batteries are used for automotive batteries. An appraisal of costs (acquisition, protective circuit) and benefits (weight savings) entails that Li-ion batteries are still rarely common for this purpose.

Anyway, in the following this report considers just the traction battery, which runs at high-voltage and is used for vehicle propulsion. In addition, only **lithium-ion (Li-ion) batteries** are considered, as these are used almost exclusively for automotive applications.

Fig. 2-3 shows a typical layout of a traction battery. The basic unit of the battery is the *cell*, while an assembly of multiple cells in a frame represents a *battery module*. Several modules in turn make up the final *battery pack* as installed in the vehicle. This usually includes the *battery management system* (BMS) and a metal housing (e.g., made of aluminum) protects the interior from external damage. How the large number of cells are wired together depends on various parameters. A serial connection raises the voltage to reach the nominal voltage of usually 400 V for passenger cars, whereas a parallel connection raises the capacity. For example, the 75 kWh battery of the Polestar 2 (model of 2020) contains 308 individual cells grouped into 27 modules [6]. There are 108 cells connected in series and 3 times they are wired in a parallel configuration, abbreviated by the designation *108s3p*.

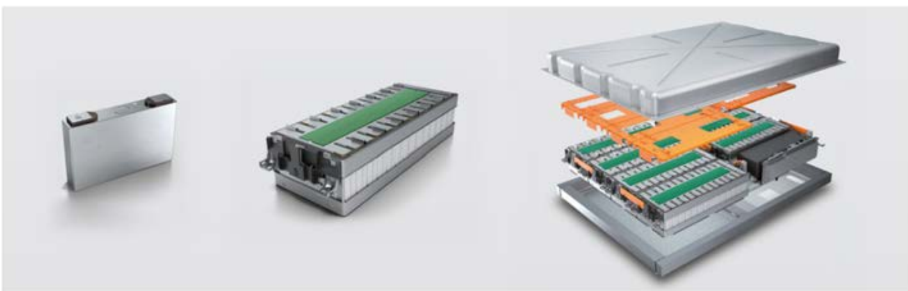


Fig. 2-3 Battery cell, module and pack of a BEV, adapted from [7]

An overview of the cell formats and chemistries of traction batteries used in recent BEV models gives Table 2-1. As one can see, all different cell formats as well as several different cell chemistries are in use, with NMC being the most common.

Table 2-1 Battery characteristics of current BEVs

	Construction year	Cell format [8]	Energy density volumetric (cell) [Wh/kg] [8]	Capacity useable / full [kWh] [6]	Chemistry [6]
Mercedes Benz *EQC*	From 2019	Pouch	123	80 / 85	NMC622
Audi *etron 50*	From 2019	Prismatic	136	65 / 71	NMC622
Tesla *Model 3*	From 2019	Cylindrical	168	58 / 60	NCA and LFP
Jaguar *i-Pace*	From 2018	Pouch	149	85 / 90	NMC622

Basically, two types of developing concepts can be distinguished for designing new vehicles. With the beginning of developing BEVs in recent years, they were often developed from an already existing basic concept (*conversion design*). The underlying concept was provided by a conventional vehicle system in which, in simplified terms, the tank was replaced by a battery and the powertrain was electrified. While this concept limits freedom of design, it is also fast to implement, simplifies the development of hybrid systems and allows manufacturers to save costs. [9, 10]

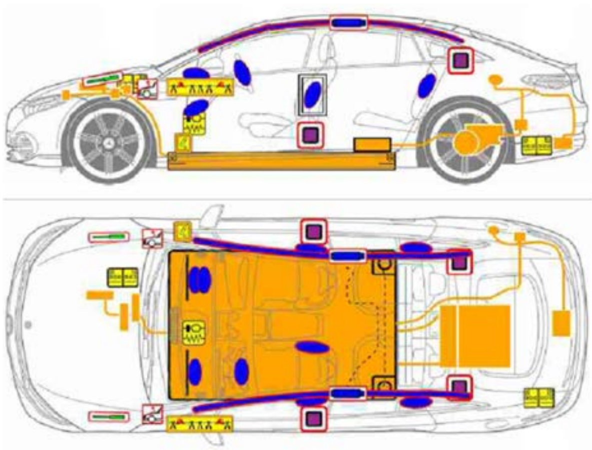
Compared to conventional vehicles, the greatest modification in electric vehicles concerns the traction battery: Even though batteries based on Li-ion technology have good energy densities compared to other battery technologies, there are still large battery capacities required to achieve acceptable ranges. In this type of concept, the batteries can often be located in different places depending on the space available (e.g., see model e-Golf 7 in Fig. 2-4). So, the batteries account for an immense part of the vehicle weight. Table 2-2 lists the technical specifications of vehicles which are offered both as BEV and conventional propulsion; they are developed by conversion design and base on the same platform. It can be seen that the battery-electric version is significantly heavier in both models, but the range is still shorter.

Table 2-2 Comparison of BEV and ICEV based on same platform

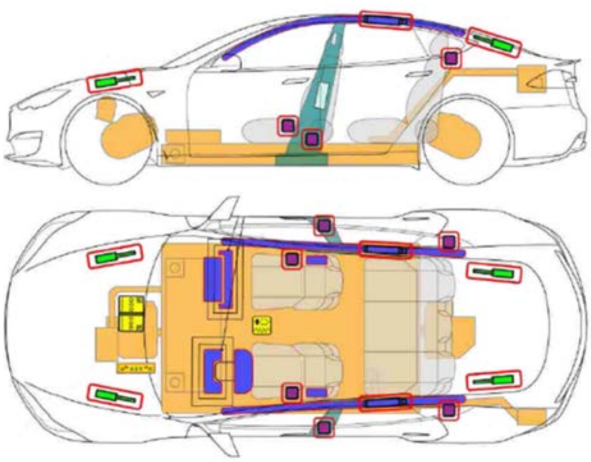
Manufacturer	Mercedes [11]			BMW [12]		
Model	*GLA* (2022)	*EQA* (2022)		*X3* (2021)	*iX3* (2021)	
Energy carrier	ICEV (Gasoline)	BEV		ICEV (Diesel)	BEV	
Curb weight	1570 kg	2045 kg	+30 %	2010 kg	2255 kg	+12 %
Range WLTP	700 km	530 km	-25 %	970 km	460 km	-53 %

The nowadays more and more common *purpose design* represents an entire new development; the vehicle (or platform) is specifically designed and optimized to meet the differing requirements compared to a conventional vehicle. In addition, newly made available space (due to missing ICE, fuel tank, gear box, exhaust system, etc.) can be used for other purposes, e.g., a front trunk instead of the engine compartment.

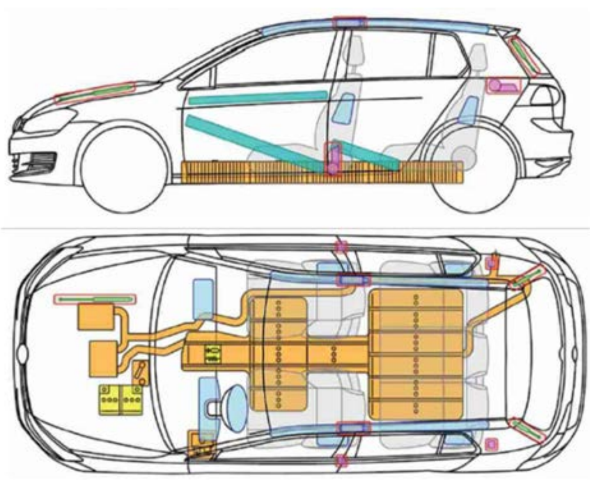
This way of design does not solve the problem of a heavy battery, but one can use this trait to one's own advantage. As can be seen in some rescue sheets in Fig. 2-4, it has become established to install the battery in the vehicle floor and between the vehicle axles. This results in a low barycenter, which has a positive effect on weight distribution and driving stability.



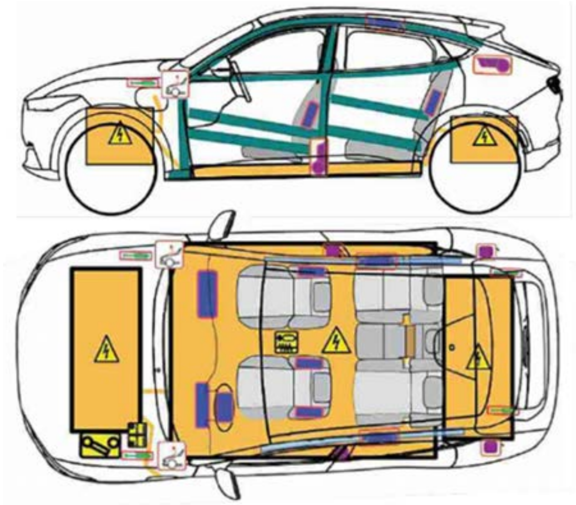
Mercedes *EQE* (2022) [13]



Tesla *Model S* (2021) [14]



Volkswagen *e-Golf 7* (2014) [15]



Ford *Mustang Mach-E* (2021) [16]

Fig. 2-4 Examples of rescue sheets of different BEVs

2.2 Characteristics of Trucks and Busses

The characteristics of trucks and buses in contrast to passenger cars mainly concern the capacity of the battery, which can be many times higher. Differences may also include a higher voltage level and an installation in other locations. While cars currently provide capacities of up to approx. 100 kWh, fully configured buses have capacities of up to 640 kWh [17]. Another distinction is the placement of the battery. In buses, the batteries can usually be arranged in different ways, on the roof of the vehicle (as shown in Fig. 2-5) and/or in the rear area (instead of the ICE in conventionally powered buses). As seen in the technical data sheets of some manufacturers [17–19], the former arrangement is more often used. Although the center of gravity increases and leads to a poorer driving performance, this placement offers some advantages: There is less effort in the modification from conventional buses, and there are no limitations of seating capacity. Due to few surrounding components, there are good conditions for cooling the battery [20]. Finally, a battery mounted on the roof is outside the crash zone, and this does not negatively affect vehicle safety.

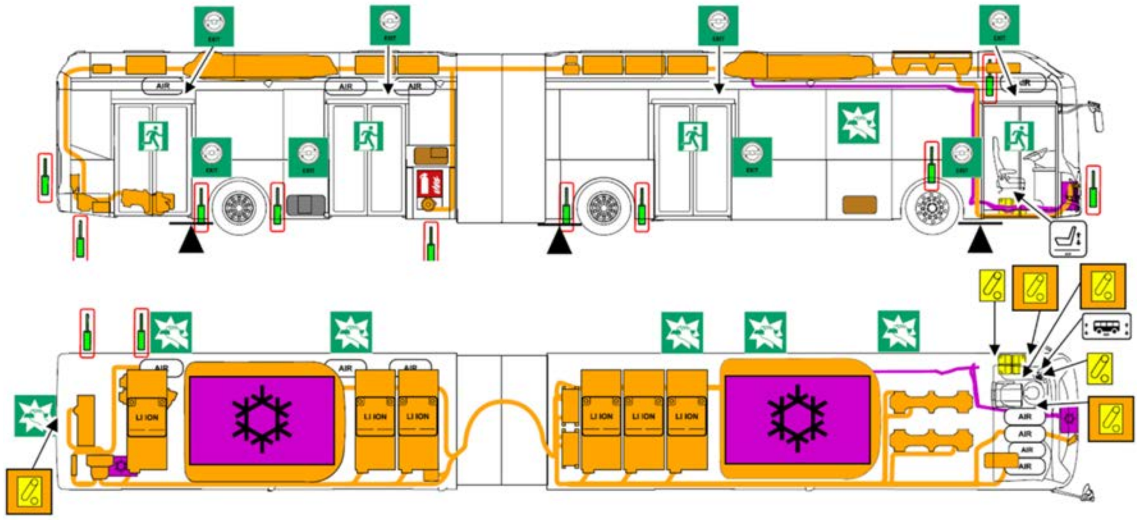
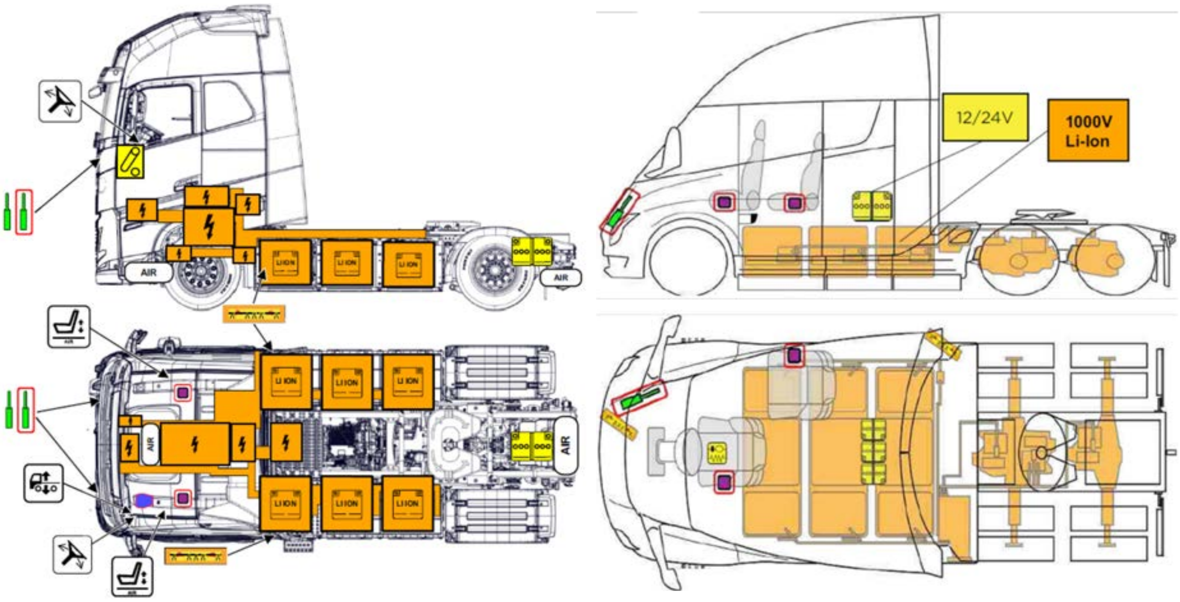


Fig. 2-5 Rescue sheet of a battery electric bus - Volvo *7900 Electric* (2020) [21]

Currently, only a few battery-powered trucks are in operation. The capacities for trucks are up to 300 kWh [20]. Fig. 2-6 illustrates an installation of the battery on the vehicle's floor between the axles or under the driver cab.



Volvo *FH/FM Electric* (2022) [22] Tesla *Semi* (2022) [23]

Fig. 2-6 Examples of rescue sheets of different battery electric trucks

2.3 Safety Measures

The safety measures installed in a BEV mainly concern the battery and other high-voltage components.

2.3.1 Placement of High-Voltage Components

The placement of the high-voltage components in the vehicle has a great influence on safety in the event of a crash. Based on the analysis of about 9000 accidents, Justen and Schöneburg [24] specified areas (Fig. 2-7) where these components are best protected. As deformation already occurs in zone 1 in the event of minor collisions, the placement of high voltage components is strictly avoided here. Zone 2 represents the area of moderately severe frontal collisions, and zone 3 is the intrusion zone in standard crash tests. Areas that deform during crash testing should be avoided for HV components. Otherwise, they are given greater protection.

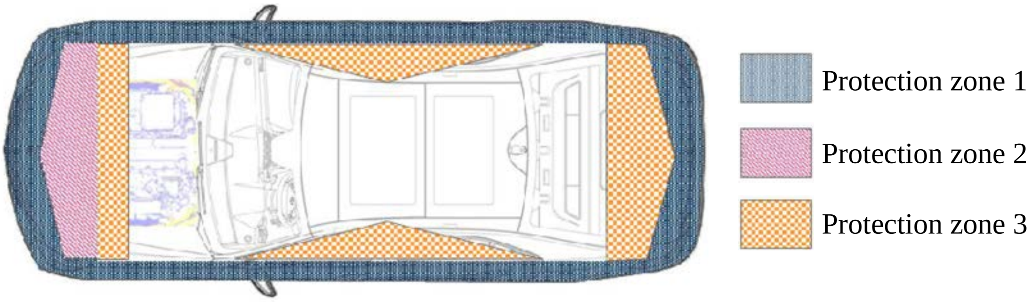


Fig. 2-7 Protection zones of a passenger car [24]

The traction battery in new vehicles is almost exclusively placed in the vehicle floor. How well it is protected there and in its housing is shown by a traffic accident in Tyrol in Austria in 2019. A BEV crashed into a tree, caught fire and burned out completely; the wrecked vehicle is shown in the left picture of Fig. 2-8. However, during a later investigation it turned out that the battery was not involved in the fire at all. The housing was largely undamaged and just a little burnt (right picture of Fig. 2-8).

Fig. 2-8 BEV wreckage after crash against tree (left) and its removed battery (right) [25, 26]

2.3.2 Safety devices on the battery

The safety devices installed directly on the battery are described below. Primarily, their task is to prevent an overcurrent at the cell.

Thermal fuse, PTC, CID and Safety valve

When the temperature at the cell rises above a tolerated value due to excessive currents, a *thermal fuse* is triggered. Its melting point is about 30–50 °C above the operating temperature of the battery. Another safety device is the *positive temperature coefficient* (PTC); it is a ring-shaped fuse that limits the maximum current flow in the cell. Because of the material's properties, the internal resistance increases as the temperature rises. If there is an external short circuit, a high current flows causing the temperature to rise, which in turn increases the resistance and limits the current flow to a bearable value. In contrast, the *current interrupt device* (CID) deforms if the pressure in the cell rises. That happens when gases are generated in the cell. The CID breaks up the physical contact and ends the dangerous flow of current. The *safety valve* works in a similar way and triggers if PTC and CID fail. When the pressure rises too high (e.g., 10 bar), it breaks at predetermined breaking points and the gases are released through the openings (*venting*), preventing the cell housing from uncontrolled bursting. [27–29]

As seen in Fig. 2-9, all these mechanical safety devices are directly attached to the cell housing. Therefore, they depend on the cell format and are usually only applied to cylindrical and prismatic cells.

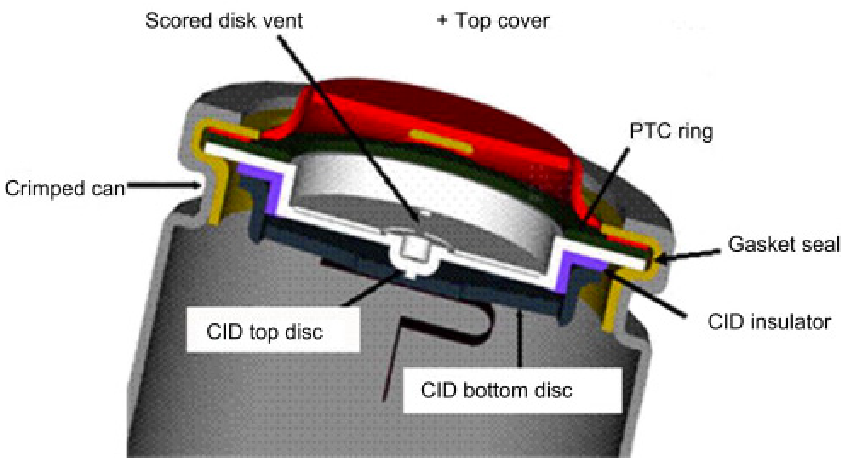


Fig. 2-9 Cylindrical cell showing PTC, CID and safety valve ("scored disk vent") [30]

Separator safety shutdown

The separator is an important safety component, as it electrically separates the two electrodes thus preventing a short circuit. As a more sophisticated safety feature, a melting separator can be used, consisting of two (porous) plastic layers with different melting points (e.g., PE at 135 °C and PP at 165 °C). In the event of a temperature increase, the PE plastic melts first and fills the porous gaps of the PP layer, preventing the flow of ions (*safety shutdown*). [31]

Battery Management System

To provide a long life of Li-ion cells, operation in a tight operating range (depending on cell chemistry and cell design) is required. Therefore, continuous monitoring of the most important parameters in the cell is essential, these are voltage, current and temperature. If this safe operating zone is left, permanent damage to the cell will occur, and in the worst case, venting or a thermal runaway might happen. Fig. 2-10 shows this range in a qualitative way. On the one hand, the voltage must be within a certain range to avoid overcharge and over-discharge (as the nominal voltage of Li-ion cells ranges from 3.3–3.7 V). For example, overcharging can lead to self-ignition, and over-discharging can lead to capacity loss. On the other hand, the temperature must also be in an appropriate temperature band (about 20–40 °C), which is accomplished by heating and cooling. Not only low outside temperatures, but also heat generation during charging and discharging must be considered in the design. [32]

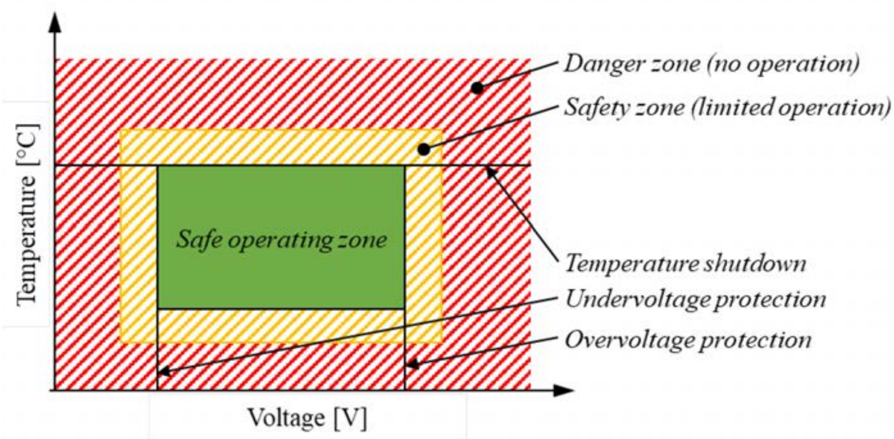


Fig. 2-10 Operating zones of Li-ion cells for temperature and voltage, adapted from [31, 32]

Keeping the cells within this safe operating zone is an important safety function and task of the *battery management system* (BMS). In addition, the BMS disconnects the battery in case of a malfunction and it is responsible for determining SoC and SoH, for balancing the cells, and for communication with the vehicle. [33]

2.3.3 Safety devices on the high-voltage system

The voltage systems 12 V, 24 V, and 48 V operate within voltage class A, and they do not require much protection. For voltage class B (high-voltage), the safety requirements are significantly more challenging and require measures for both basic protection and fault protection. In addition, in automotive engineering both current systems (AC, DC) are relevant: AC often plays a role in charging, whereas the vehicle battery operates with DC voltage. By combining these two systems, it is of particular importance that the protection equipment does not interfere with each other [34]. The following safety measures are applied in electrically propelled vehicles [35–37]:

Galvanic and potential isolation

The entire HV system is isolated and galvanically separated from the vehicle body, and there is no electrically conductive connection between the HV negative pole and the body mass. As illustrated in Fig. 2-11, even a contact between the HV positive potential and the body mass is therefore no danger.

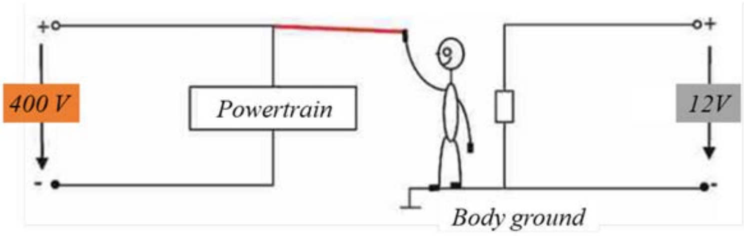


Fig. 2-11 Potential isolation, adapted from [36]

This separation is checked by continuous monitoring of the insulation resistance, which is also done by checking the shielding in the HV cables (Fig. 2-12). If the insulation resistance falls below a certain value, a warning message is sent to the driver and/or the battery is switched off.

Marking of high voltage components

If protective barriers and protective enclosures are removed and hazardous live parts of high voltage are exposed, a yellow warning symbol must be attached. In addition, high-voltage cables located outside the protective enclosures must be sheathed with orange-colored insulation (Fig. 2-12).

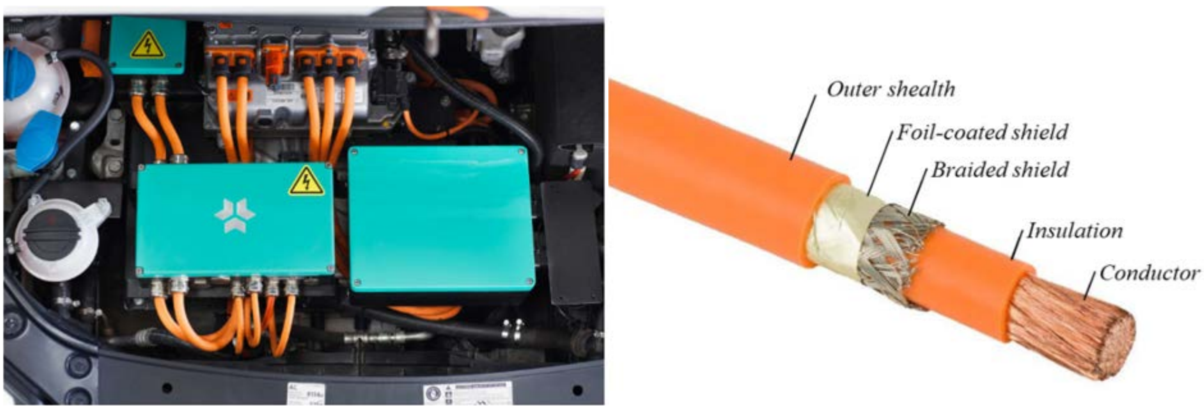


Fig. 2-12 Engine compartment with warning symbols and orange HV wiring (left) and structure of a HV cable (right), adapted from [38, 39]

Equipotential bonding

To avoid dangerous touch current on exposed conductive parts of voltage class B components (e.g., metal housings) in case of a fault, they must be electrically bonded to the body to achieve equipotentiality.

Crash

In the event of an accident, the HV system is automatically disconnected from the HV battery. Each manufacturer has its own specific requirements for triggering the contactors. This can be done by the same sensors that trigger airbags and/or seat belt pretensioners. In addition, the disconnection can be reversible or irreversible, depending on the severity of the accident detected. Furthermore, by opening protective relays, active HV components can be discharged to the non-hazardous voltage class B1. This should happen within a few seconds, e.g., by an intentionally induced short circuit. However, this automatic shutdown is normally not available on trucks and buses [40]. [24, 35, 41]

3 Natural Gas-Powered Vehicles

Starting in the 1930s, a few buses and municipal vehicles were powered by natural gas, mainly to achieve energy independence. Due to the large amount of space required for the storage system, an application for passenger cars was out of the question. Fig. 3-1 shows a city bus in Germany from 1942, where the natural gas was prominently housed in gas-tight bags made of rubber fabric on the roof. This low-pressure system was able to store about 20 m³. However, there were also high-pressure systems with a storage capacity of up to 200 bar, where the cylinders were swapped instead of being refueled. [42]

Fig. 3-1 Natural gas-powered city bus with a low-pressure system from 1942 (left) and CNG vehicle with a changing system from 1945 (right) [43, 44]

After two World Wars, however, natural gas lost importance as a fuel in Europe, with few exceptions. Today, Italy has the highest percentage of natural gas vehicles in Europe. As a result of the events of the 1970s, the focus was once again placed on natural gas, and by the 1990s European car manufacturers were offering a number of natural gas-powered series vehicles. Since they emit less CO_2 than liquid fossil fuels, they are eligible for tax benefits in Germany (until 2025), and in Austria funding is available for the acquisition. [42]

Liquefied natural gas as a vehicle fuel has never had the importance of compressed natural gas since the early days and therefore has a very limited history. In the future, however, it could play a role for an application in trucks and buses.

3.1 Basic Technical Design

The wide ignition limits of methane are advantageous for the combustion process, but methane is inert, that is why spark-ignited engines are usually used. Here, a natural gas-air mixture is injected into the combustion chamber. The chemical stability gives methane a high knock resistance; compared with liquid fuels, natural gas has a converted Research Octane Number (RON) of 130. This has a positive effect on efficiency for the application in gasoline engines. However, it is also possible to burn it in a self-ignition engine, combining natural gas as an ignition-unwilling fuel with diesel as an ignition-willing fuel. Both fuels are burned simultaneously (dual-fuel vehicle). [45]

Although the mass-based calorific value is higher than for conventional liquid fuels, the density of the fuel, which is gaseous under ambient conditions, is naturally low. To achieve acceptable ranges, natural gas is stored compressed (CNG) or liquefied (LNG) in the vehicle. Fig. 3-2 shows a CNG series vehicle with three cylindrical gas containers which are located transverse to the direction of travel in the well-protected area of the rear axle; a small gasoline tank as emergency reserve is also installed. This is because the range of natural gas operation is less than one is used to with conventional liquid fuels and the filling station network is not well developed. Considering this gasoline tank not as an emergency tank but as an independent, second storage system, the vehicle represents a bivalent propulsion system. This type of propulsion in CNG passenger cars is common.

Beginning from the tanks, the stainless-steel gas lines run along the vehicle floor to a gas pressure regulator, which reduces the pressure to about 7–8 bar. The natural gas is then injected into the internal combustion engine.

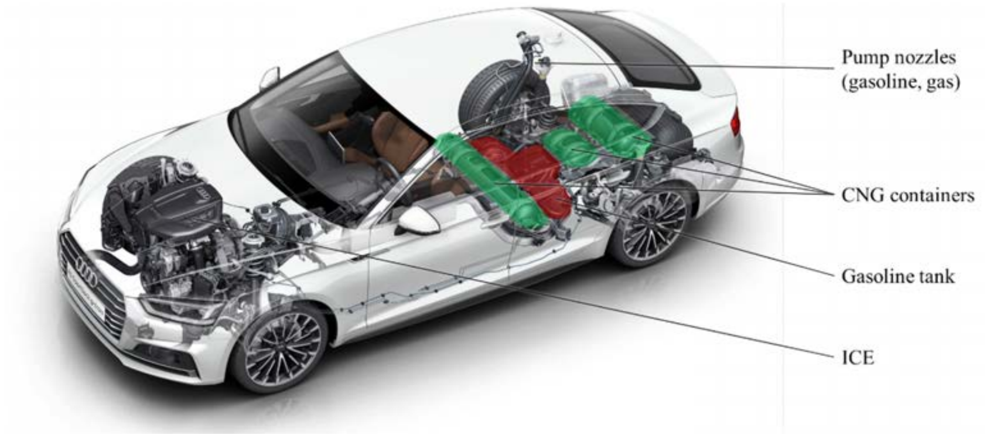


Fig. 3-2 Structure of a natural gas vehicle with compressed gas, adapted from [46]

3.1.1 Storage in CNG Containers

The form of a compressed storage is quite typical for passenger cars. Compressed natural gas is stored in containers up to 200 bar working pressure (15 °C), but during filling, the pressure can reach 260 bar. According to the material properties, UNECE R110 [47] distinguishes between four types of CNG containers:

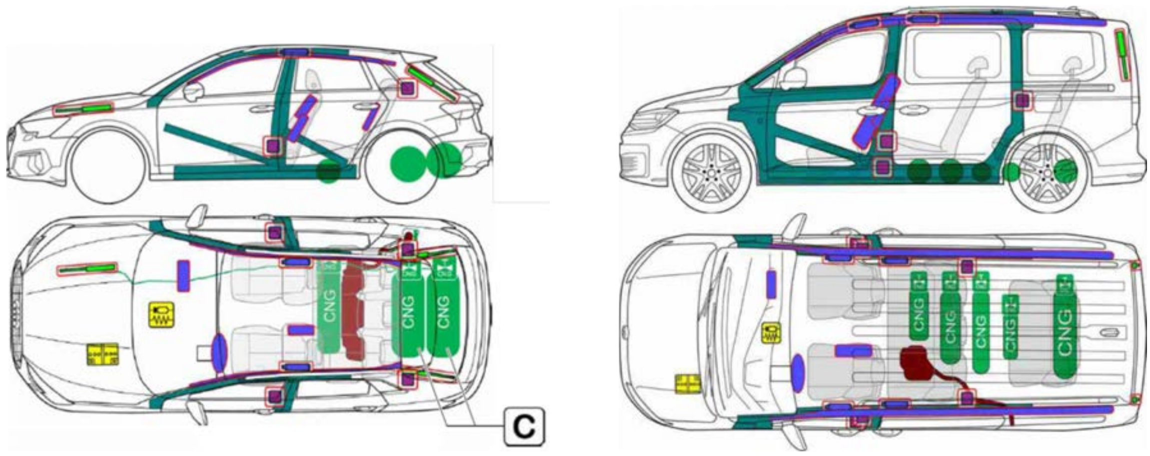
- **Type I, metal:** metal container without wrapping
- **Type II, hoop wrapped:** metal liner reinforced with resin impregnated continuous filament
- **Type III, fully wrapped:** metal liner reinforced with resin impregnated continuous filament
- **Type IV, all composite:** resin impregnated continuous filament with a non-metallic liner

Each type has different provisions on the approval (e.g., burst pressure 470–730 bar) and each type has its advantages and disadvantages. For example, type I containers are heavy due to their metallic construction and are vulnerable to corrosion. However, in the case of quenched and tempered steel, they have a greater energy absorption capacity in a crash than the other types. They also have good thermal conductivity, which is advantageous during refueling because the heat of compression can be quickly dissipated to the environment. Type IV containers contain an inner liner made of plastic which prevents permeation. Strength is provided by wrapped, resin-impregnated fibers made of glass or carbon (*carbon fiber reinforced plastic*, *CFRP*). The low weight of this type reduces fuel consumption, and the mountings can also be designed more simply. However, they are more expensive to manufacture. [42]

The rescue sheets of series vehicles shown in Fig. 3-3 illustrate that both type I and IV are used most frequently. In total, about 20 kg of natural gas are stored in passenger cars (Table 3-1).

Table 3-1 Representative CNG vehicles on the current automotive market

Audi *A3 g-tron* (2020) [48, 49]	200 bar CNG, 17 kg natural gas, 7 l gasoline 2 containers type IV (each 50 l), 1 container type I (30 l)
Volkswagen *Caddy TGI* (2022) [50]	200 bar CNG, 21 kg natural gas, 9 l gasoline 5 containers type I (in total ~140 l)



Audi, A3 g-tron (2020) [48]   Volkswagen, Caddy TGI (2022) [50]

Fig. 3-3 Examples of rescue sheets of different CNG vehicles

3.1.2 Storage in LNG Tanks

Liquefied storage allows a higher range compared to compressed storage due to the higher volumetric energy density; however, it is still below that of a conventional vehicle. To liquefy natural gas, it is cooled to about –162 °C at ambient pressure or –131°C at 7 bar. Despite the storage in double-walled isolated cryogenic tanks made of stainless steel, evaporation losses due to heat input from the environment are unavoidable. Fig. 3-4 shows the pressure losses of a 205 kg LNG tank at different filling levels. According to this, a tank with a 75 % fill level and 14 bar initial pressure has a minimum operating pressure of 5–6 bar after 7 days downtime.

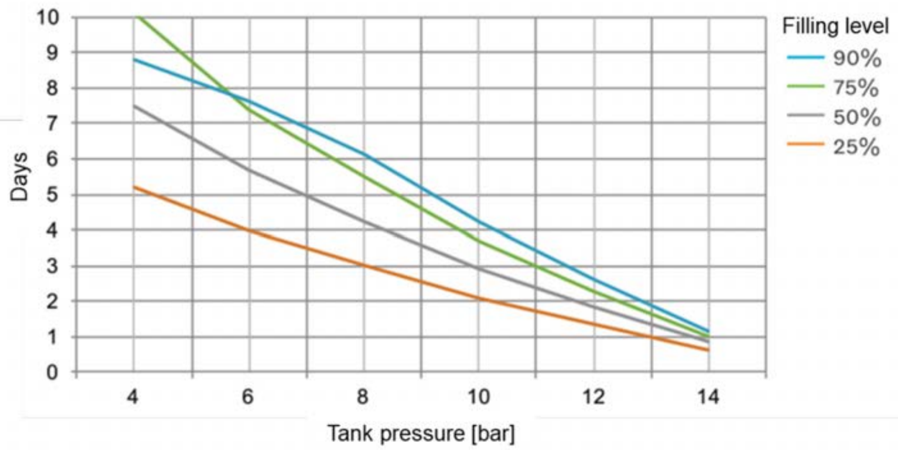


Fig. 3-4 Pressure losses in an LNG tank, adapted from [51]

3.2 Characteristics of Trucks and Busses

As can be seen from Table 3-2, compressed storage is most widely used for buses. They have more and/or larger containers than passenger cars, with a series of reservoirs usually placed on the roof of the bus (Fig. 3-5). In this case, the gas lines between the lateral containers and the engine compartment run along the roof. The amount of on-board natural gas is up to 300 kg. However, a coach powered by LNG has also been presented, where two tanks are mounted in the cargo area.

Table 3-2 Representative natural gas-powered buses on the current automotive market

MAN *Lion's City G* [52, 53]	200 bar CNG, ca. 300 kg natural gas Up to 10 containers type IV (in total 1875 l)
Solaris Urbino CNG [54]	200 bar CNG, ca. 300 kg natural gas Up to 5 containers type IV (each 375 l)
EvoBus *Citaro G NGT*	200 bar CNG Several containers type IV (each 190 l)
Scania *Interlink* [55]	LNG, ca. 300 kg natural gas 2 tanks (each 350 l)

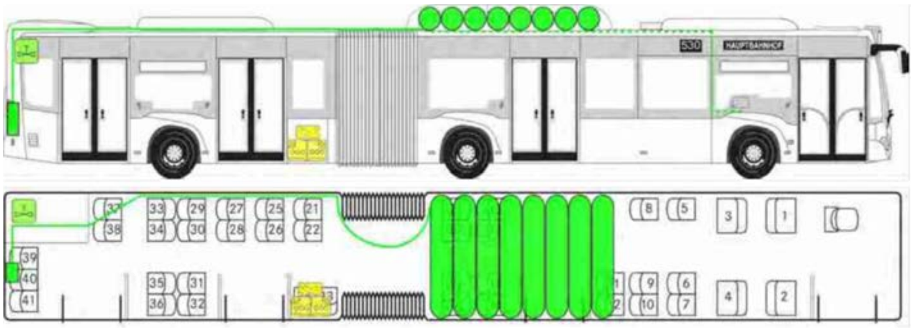


Fig. 3-5 Rescue sheet of a CNG bus, EvoBus *Citaro G NGT* [56]

For application in trucks, both CNG and LNG storage can be found (Table 3-3), with the latter mostly having the tanks located on the side frame. This might make it easier for emergency services to identify, even though they can be behind disguises. All major European truck manufacturers have LNG models in their range. In case of CNG-powered trucks, the containers of are usually situated on the side frame (Fig. 3-6) or behind the driver's cab.

Table 3-3 Representative natural gas-powered trucks on the current automotive market

Scania *P/G LNG* [57]	LNG, 360 kg natural gas 2 tanks (each 550 l)
Volvo *FH LNG* [58]	LNG, 205 kg natural gas 1 tank (495 l)
Mercedes-Benz *Actros NGT* [59]	200 bar CNG, ca. 160 kg natural gas Up to 8 containers (each 100 – 145 l, in total 980 l)

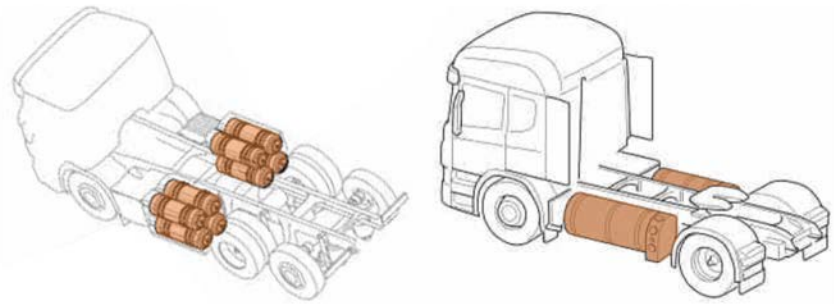


Fig. 3-6 Common locations of CNG containers (left) and LNG tanks (right) on trucks, adapted from [57]

3.3 Safety Measures

Depending on the storage system, CNG and LNG are equipped with different safety devices.

3.3.1 Safety Devices on CNG Containers

In accordance with UNECE R110 [47], the CNG system of vehicles consists of several components (containers, fuel lines, electronic control units, etc.), but in particular it has to contain the following safety devices:

- **Automatic cylinder valve / Electromagnetic shut-off valve:** Controls the flow of gas from the container to the fuel system and cuts off the gas supply if the engine is switched off or an accident is detected. One valve has to be installed directly on each container.
- **Manual valve / Mechanical shut-off valve:** This manually operated valve can be integrated into the automatic cylinder valve. It shuts off the gas line for servicing.
- **Excess flow limiting device:** In the event of a damaged gas line (between container and pressure regulator), the entire content of the container should not escape abruptly to reduce the risk of the formation of an ignitable atmosphere. This valve activates/closes at a pressure difference of 6.5 bar and limits the leakage to a maximum flow of 0.05 Nm^3/min (at 100 bar). Once the leakage (and the pressure difference) is eliminated, the valve opens again.
- **Thermal activated pressure relief device (TPRD):** This one-time use device is installed to prevent a dangerous pressure rise in the container which might cause a tank rupture. If the pressure rise is caused by an external temperature effect, a thermal fuse should trigger at 110 ±10 °C and vents natural gas.

When a localized fire occurs and the TPRD is not exposed to the fire, it might be late in triggering or, in the worst case, will not trigger at all. This is why long containers, such as found on buses or trucks, can be equipped with two TPRDs (one on each side). Nevertheless, for localized fires or if the valve has a malfunction, an additional safety device may be used. This pressure activated device in the form of a burst disc (*pressure activated pressure relief device, PPRD*) is not mandatory according to this directive, but is still often installed. When a certain trigger pressure (340 bar ±10 %) is reached, this device opens and the natural gas flows out of the container. For buses and trucks with containers mounted on the roof, the R110 only permits a vertical upward discharge direction.

Similar specifications are given by the NFPA 52 [60] guideline, which defines that each container shall be protected by one or more PRDs. The PRD shall be vented to the outside of the vehicle; moreover, the valve must not discharge into the following areas:

- Into or toward the passenger or luggage compartment
- Into or toward wheel wells
- Toward CNG storage systems
- Toward the front of the vehicle
- Toward exhaust systems
- Into an engine compartment
- Toward an emergency exit (in case of a bus application)

Thus, for passenger cars, venting in the direction of the roadway is the most appropriate solution. For buses and trucks, on the other hand, it is defined that the vent outlet must be on the roof of the vehicle and directed upwards. It is also important to prevent foreign objects from collecting in PRDs (e.g., snow, ice, mud), but protective devices shall not restrict the flow of the venting gas.

3.3.2 Safety Devices on LNG Tanks

The safety equipment for LNG vehicles required by UNECE R110 [47] is very similar to that for CNG vehicles:

- Automatic valve
- Manual valve
- Excess flow device
- Pressure relief valve (PRV) / Discharge valve

The major difference is that a relief device due to overtemperature (TPRD) is not required for LNG tanks. Instead, the safety mechanism depends on the pressure inside the tank and uses reclosing pressure relief valves (PRV). A primary PRV opens at about 16 bar and reduces the moderate pressure buildup due to evaporation during normal operation or standing time. Natural gas is vented directed upward to the atmosphere through a pipe-away system at the highest level. A secondary PRV is designed to prevent the fuel tank from bursting. It operates independently of the primary PRV and triggers in the event of large heat input (e.g., vehicle fire) or the case of a failure of the primary valve. It discharges the natural gas directly into the environment when the pressure reaches 24 bar. [47, 57, 60, 61]

Fig. 3-7 shows the valve system at an LNG vehicle tank. The primary PRV is connected to the pipe-away system and the secondary PRV can be identified by a red cap. This loose-fitting cap protects the PRV from moisture and dirt and flies away when the PRV is triggered.

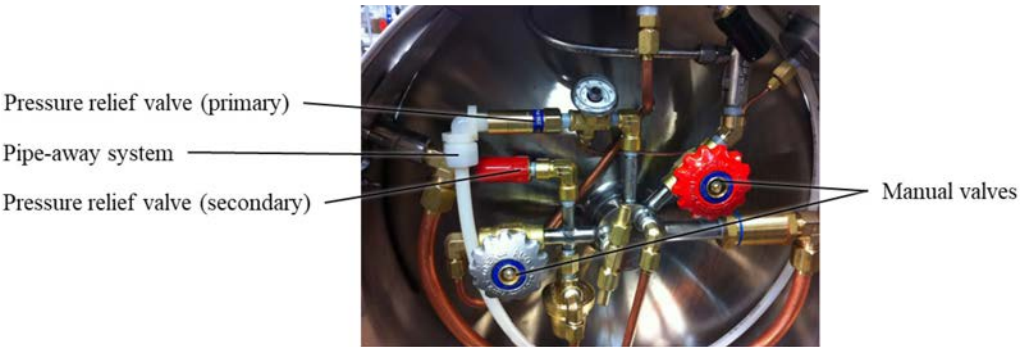


Fig. 3-7 Valve system at a LNG tank, adapted from [61]

Similar to CNG, the directive NFPA 52 [60] specifies that LNG shall not be discharged into the following areas:

- Wheel well
- Engine compartment
- Passenger compartment, or cargo compartment
- Toward the engine exhaust
- Toward components that are normally hot during vehicle use or any other ignition source

For passenger cars it would therefore make sense to direct the opening of the PRD downwards onto the roadway. However, vehicles exceeding 8.8 tons (trucks, buses) are required to have the PRD vents located vertically near the top of the vehicle and orientated to direct the vent gas upward.

In addition, a gas warning system (for example in the engine and driver's compartment) is necessary, operating continuously while the engine is running and even for at least 15 minutes after the engine has been switched off. A visual alarm in the driver's compartment is activated at a maximum gas concentration of 20–30 % LEL; a visual and an audible alarm are activated at 50–60 % LEL. [60]

4 Liquified Petroleum Gas-Powered Vehicles

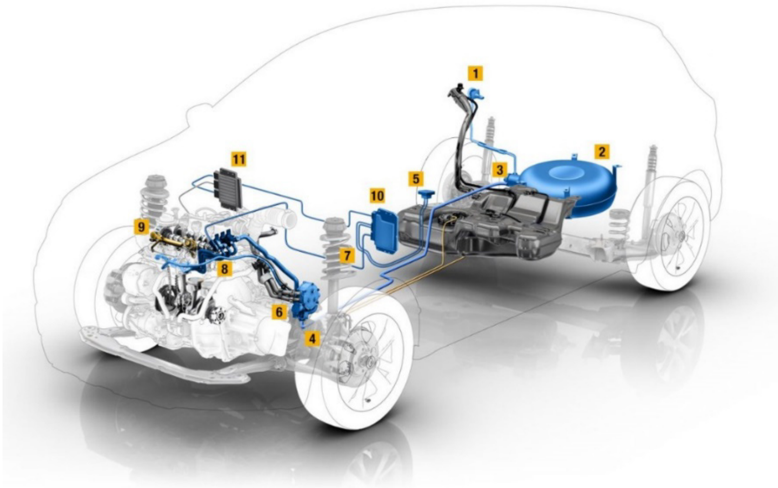
The first car using propane as fuel was already in 1913 [62], but from then on LPG was of little importance as a vehicle fuel for the next decades. Its boom probably began in the 1960s, since LPG was a pioneer in terms of environmental protection compared to the combustion of liquid fossil fuels. Therefore, Vienna’s city bus fleet began to switch to bivalent LPG operation in the 1960s, and as from 1976, only buses with pure LPG operation were acquired. Due to stricter emission standards, however, the conversion back to diesel buses began in the 2010s. [63, 64]

At present, the market share of LPG-fueled vehicles in Austria is still quite low; other European countries (e.g., Poland, Latvia, Italy etc.) have a much better refueling infrastructure and therefore a larger share of vehicles.

4.1 Basic Technical Design

Usually LPG-powered vehicles use a gasoline engine for combustion, as the LPG-air mixture does not self-ignite. Most of them are bivalent, i.e., they have both a gasoline tank and a tank for LPG. However, a retrofit is done quite often due to the low effort required. It should be noted that not every gasoline engine can be converted; for example, the missing lubrication of the cylinder valves and soft valves (or valve seats) must be considered in LPG operation [65].

The gas tanks of LPG vehicles are made of steel and the liquid gas is usually stored in them at an operating pressure of approx. 10 bar. In the principle shown in Fig. 4-1, liquified LPG passes from the tank via the supply line to an evaporator, where it is converted into gaseous phase. The pressure drop decreases the temperature considerably, so the vaporizer is normally heated. The fuel is then injected into the ICE at a specific pressure. However, systems with liquid injection can also be possible, whereby the evaporator can be omitted.



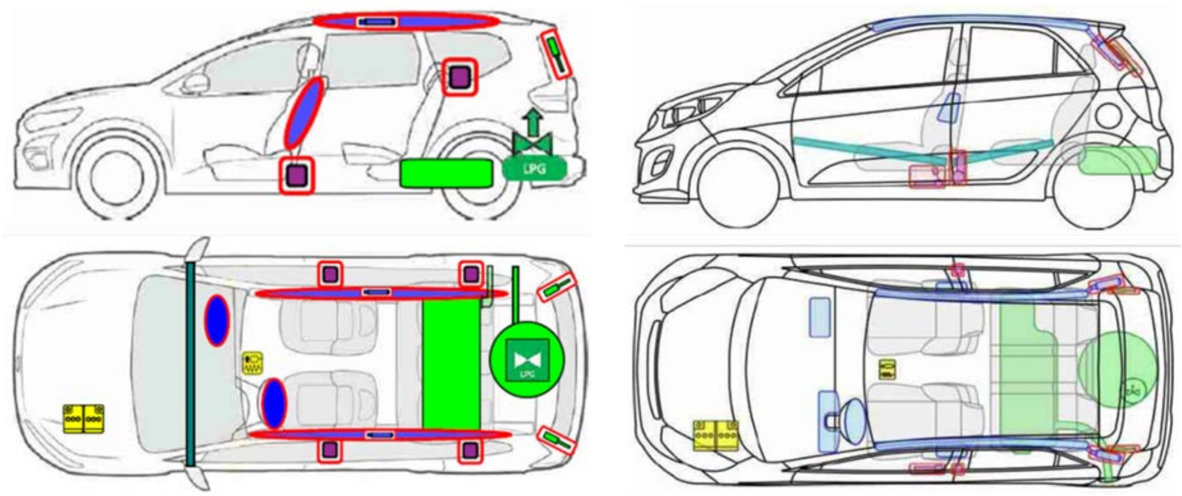
1) *Fillers necks*
2) *LPG tank*
3) *Safety shut-off valve*
4) *LPG pipes*
5) *Selector*
6) *Vaporizer*
7) *Electric wires*
8) *LPG injection*
9) *Gasoline injection*
10) *LPG control unit*
11) *Gasoline control unit*

Fig. 4-1 Structure of a LPG vehicle [66]

Compared to natural gas or hydrogen, the storage is technically much easier here, as LPG already liquefies at a pressure of 5–10 bar. The tank geometry can thus be designed more flexibly, and in most cases a steel tank is installed in the form of a toric, synclinal tank in the trunk (Fig. 4-2). As can be deduced from Table 4-1, there are currently only a few series-produced vehicles on the market.

Table 4-1 Representative LPG vehicles on the current automotive market

Dacia *Jogger* (2022) [67]	40 l LPG, 50 l gasoline
Kia *Picanto LPG* (2017) [68]	27 l LPG, 35 l gasoline



Dacia *Jogger* (2022) [67] Kia *Picanto LPG* (2017) [68]

Fig. 4-2 Examples of rescue sheets of different LPG vehicles

4.2 Characteristics of Trucks and Busses

As already mentioned in the introduction, LPG-powered buses are currently rarely used. Away from Europe, the situation may be different in some countries, such as the USA, where a school bus manufacturer says it has delivered over 18,000 vehicles with LPG to date [69]. There, the containers with a volume of 250–350 l are mounted between the frame beans at the end of the vehicle.

There are also no series-produced trucks, although there are occasional retrofits [70, 71] with LPG-fueled trucks. There, the tanks are attached to the side of the frame, similar to LNG powered trucks.

4.3 Safety Measures

There are two UNECE Regulations for the approval of LPG powered vehicles, R67 [72] for new vehicles and R115 [73] for retrofitted vehicles. The safety requirements for new vehicles are covered by several components, which, however, can also be combined in a multivalve. Following safety relevant tasks have to be fulfilled:

- **80 % stop valve**: Limits the maximum fill level in the tank to 80 %. This ensures that there is sufficient volume available for the gas when it heats up.
- **Pressure relief valve (PRV):** Limits the pressure in the container to prevent bursting. It is spring-loaded and triggers at a tank pressure of about 27 ±1 bar, allowing LPG to flow out until the tank pressure has dropped again.
- **Pressure relief device (PRD):** This function can be implemented as a thermal fuse (TPRD) or in the form of a PRV. In the former case, it opens once at 120 ±10 °C.
- **Remotely controlled service valve with excess flow valve (EFV):** It is the task of the service valve to interrupt the fuel supply to the vaporizer. The EFV is responsible for ensuring that, in the event of a damaged line between tank and vaporizer, the entire

tank contents do not escape abruptly to reduce the formation of an ignitable atmosphere. It is activated at a pressure difference of 0.9 bar and limits the leakage to 8 l/min.

Some functions can also be combined in one device, then it is called a multivalve.

5 Hydrogen-Powered Vehicles

The first worldwide vehicle with a fuel cell was introduced by GMC in 1966. It was a van, equipped with a cryogenic container each for oxygen and hydrogen, and both placed under the back seat (Fig. 5-1, left). Both of these liquefied fuels were expensive at the time and were thought to be unsuitable as an energy source for vehicles, so the van was actually seen as a basis for future fuel cells operated with hydrocarbons [74]. Four years later Karl Kordesch, who also held a professorship at Graz University of Technology for some years, converted his Austin A-40 into a hydrogen-powered vehicle. A 6 kW hydrogen fuel cell was installed in the car trunk (Fig. 5-1, right), combined with a lead acid battery in the hood. Six hydrogen tanks were placed on the roof, containing approx. 2 kg hydrogen at a pressure of 140 bar. The vehicle was in operation on public roads for three years and successfully completed thousands of kilometers. [75, 76]

Fig. 5-1 Hydrogen-powered vehicles in 1966 (left) and 1970 (right) [77, 78]

In the following years, hydrogen-powered vehicles with small fleets were built again and again, for example by Mercedes and BMW. In the end, however, it was not until 2013 that series-production vehicles were step-by-step put on the market, this time by Hyundai, Toyota and Honda.

5.1 Basic Technical Design

On the one hand, hydrogen as a fuel for vehicles can be burned in an internal combustion engine, called H_2-ICEV. On the other hand, hydrogen can also be used as a primary energy carrier in a fuel cell, which generates electricity to power the vehicle (FCEV). To be more precise, it is then by definition a hybrid vehicle due to the additionally installed battery.

Fuel Cell Electric Vehicle (FCEV)

The basic design of a FCEV is similar to a BEV, i.e., the main components of the powertrain include the battery, power electronics and electric motor (Fig. 5-2). Furthermore, one or more hydrogen containers are installed, which feed a stack of fuel cells.

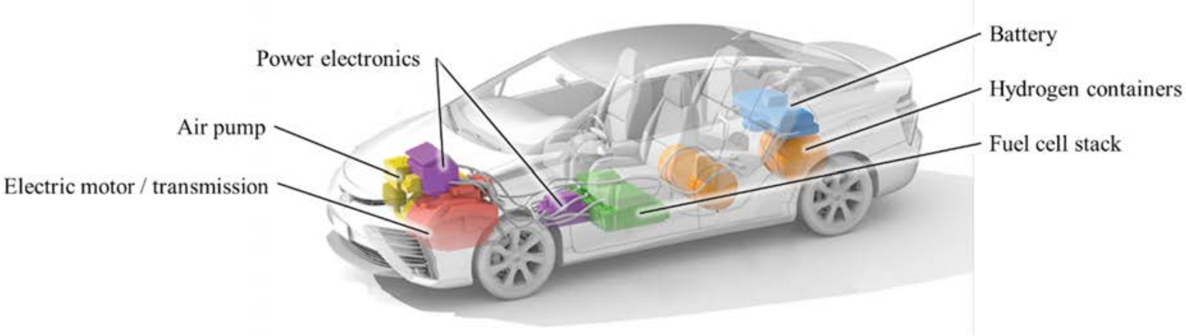


Fig. 5-2 Structure of a fuel cell electric vehicle, adapted from [79]

Klell et al. [75] define two different approaches for dimensioning the fuel cell and the battery of a hydrogen vehicle, a dominant fuel-cell system and a range-extender system. Former principle is designed in such a way that the fuel cell covers the power demand during driving; the battery is used for recuperation or to support acceleration. The hydrogen system is therefore designed using a powerful fuel cell (100–150 kW) and a large amount of stored hydrogen (up to 6 kg) is necessary. On the other hand, the vehicle battery has only a small capacity in about ranges up to 2 kWh. Referring to the range-extender system, a high-capacity battery is installed in the vehicle, which is responsible for driving mode. The battery is charged by the fuel cell during driving, extending the range of the vehicle. The power of the fuel cell can thus be smaller, approximate 20–30 kW. [75]

There are different types of fuel cells, which differ in terms of operating temperature, primary fuel, power range and efficiency. In Table 5-1 it can be seen that their application varies as well. For detailed information, the reader is referred to professional literature.

Table 5-1 Types of fuel cells and their characteristics [75, 80, 81]

Type	Primary fuel	Mobile ion	Operating temperature	Power	Efficiency (system)	Application
PEMFC Proton exchange membrane FC; polymer electrolyte membrane FC	H_2, methanol	H^+	60–120 °C (low temp.) 120–200 °C (high temp.)	< 500 kW	40–50 %	Astronautics, vehicles
AFC Alkaline FC	H_2, ammonia	OH^-	50–200 °C	< 100 kW	50–60 %	Astronautics, vehicles
PAFC Phosphoric acid FC	H_2	H^+	200 °C	< 10 MW	40–50 %	Cogeneration
MCFC Molten carbonate FC	H_2, methane	CO_3^{2-}	650 °C	< 100 MW	60 %	Cogeneration
SOFC Solid oxide FC	H_2, methane	O^{2-}	500–1000 °C	< 100 MW	50–60 %	Cogeneration

Since the low-temperature PEM is widely used for mobile applications and is therefore typically used in vehicles, its principle is explained in more detail. As illustrated in Fig. 5-3, hydrogen is supplied to the cell and diffuses through the gas diffusion layer to the anode. There, the hydrogen molecule catalytically releases 2 electrons (*oxidation*).

$$H_2 \rightarrow 2H^+ + 2e^- \tag{5-1}$$

The electrons flow from the anode via the external circuit to the cathode, generating current. The electrolyte, in that case a polymer membrane, separates the gas spaces and is isolating for electrons. However, it is permeable to ions and the protons travel through the electrolyte to the cathode. As oxygen (from the air) is transported to the cathode and accepts the electrons by means of a catalyst (*reduction*), the reactants combine to form water.

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{5-2}$$

Depending on the fuel, the voltage of a single cells reaches about 1 V (e.g., liquid H_2 generates 1.229 V). This is why several individual cells are combined into fuel cell stacks.

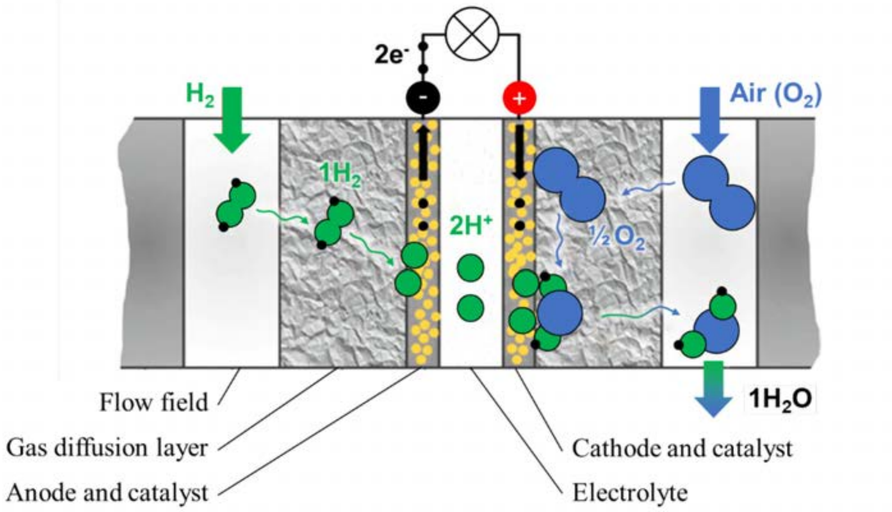


Fig. 5-3 Schematic structure of a fuel cell (PEMFC), adapted from [75]

Besides the stack, the entire fuel cell system consists of several essential auxiliary components, also known as *Balance of Plants* (BoP): [75, 80]

- Pumps, heat exchanger
- Humidifier
- Air processing and air path
- Hydrogen processing and hydrogen path
- Power management system
- Thermal management

In particular the latter component is a key component for good efficiency and high durability of a PEMFC, since a considerable amount of heat is generated during operation. In a PEMFC with an assumed efficiency of 50 %, the energy flow is split as represented in Fig. 5-4. Half of the energy content provided by the H_2 is converted into electrical work (50 %); an excess amount leaves the FC unburnt (5 %); the remaining energy input is converted into heat (45 %). Small portions of this heat energy are used internally for evaporation of the water, or are dissipated by natural convection. However, the majority must be removed by the cooling system (36 %). Due to the low combustion temperature (of a low temperature PEMFC), there is only a low temperature difference to the environment, thus a large cooling surface may be required. The best efficiency of the fuel cell system is realized at low current densities, i.e., at partial load. [75, 82]

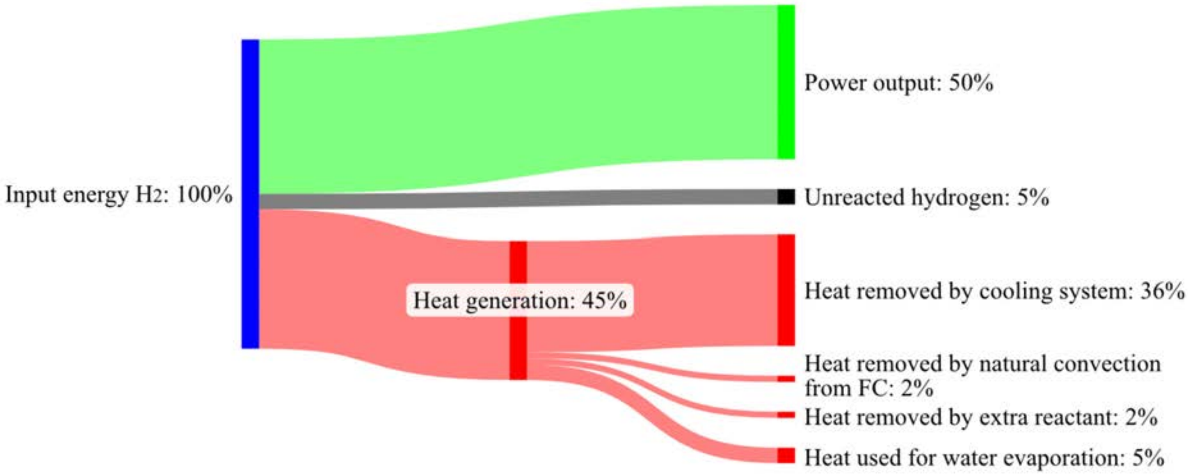


Fig. 5-4 Typical energy flow diagram of a PEMFC [82, 83]

Hydrogen Combustion Engine Vehicle (H_2-ICEV)

The second area of application for hydrogen in automotive engineering is an internal combustion engine, in which hydrogen is combusted (H_2-ICEV). In that case the hydrogen can both be used in a spark-ignited or a self-ignited system, while the former is more appropriate. One reason is that despite the large explosion limits the auto-ignition temperature of hydrogen (560 °C) is significantly higher than that of diesel (225 °C). So far, however, there is no series vehicle utilizing such a system. [75]

However, a prototype with such a system was presented by HyCentA [84] in Graz in 2009. A bivalent gasoline/natural gas vehicle was extended to operate with hydrogen; enabling the combustion of any mixtures of hydrogen and natural gas in the ICE. At the same time, BMW has carried out research on the hydrogen combustion engine, adapting a gasoline powered BMW *7 Series* as shown in Fig. 5-5.and Table 5-2. The bivalent vehicle operates with an external mixture formation system when running on hydrogen, and allows a range of 200 km. The hydrogen is supplied to the engine in gaseous form; no fuel pump is required here because of the pressure gradient. Due to emissions, the engine is always started in hydrogen mode; manual switching is possible after the catalyst has warmed up. Even if carbon-free hydrogen is burned, small amounts of CO, CO_2 and HCs are emitted by flushing the carbon filter of the gasoline tank and by present lube oils. Above a combustion temperature of approx. 1000 °C, the formation of NO_x is also to be expected, which needs to be considered in the engine control system. [85]

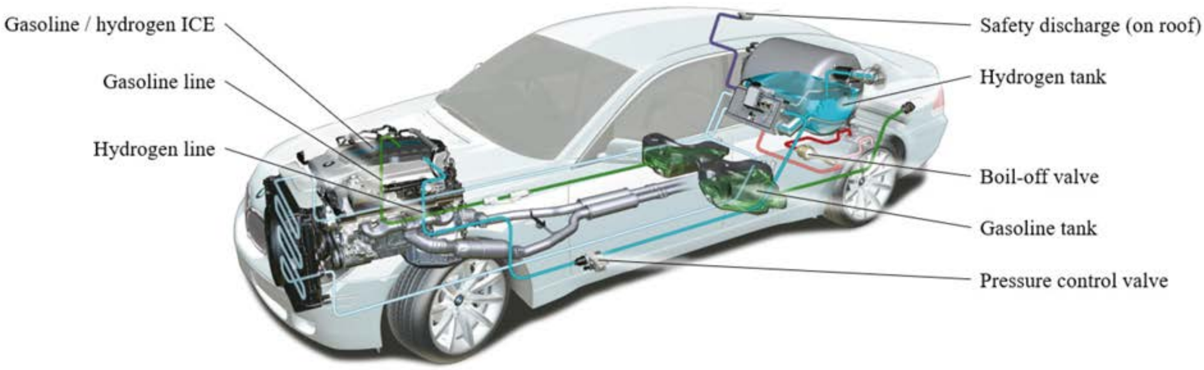


Fig. 5-5 Structure of a hydrogen combustion engine vehicle, adapted from [85]

Table 5-2 Representative H_2-ICEV

BMW *Hydrogen 7* (2006) [85]	LH_2 (–253 °C), 7.8 kg hydrogen, 74 l gasoline 1 tank (170 l)

Different types of hydrogen storage

Due to the low density of hydrogen, its storage is probably the greatest challenge, in both technical and economic terms. Basically, three methods of hydrogen storage are possible:

- Compressed gaseous hydrogen (CGH_2)
- Liquid hydrogen (LH_2)
- Solid-state hydrogen

The storage of CGH_2 and LH_2 are based on physical storage allowing the hydrogen to stay in its molecular form, gaseous at high pressure in a container (Fig. 5-6a), or liquefied at low temperatures in a tank (b), respectively. Solid-state hydrogen is chemically stored at the surface of solids (adsorption), or within solids or liquids (absorption). Examples include storage by adsorption in carbon material (c) and storage in metal hydrides (d). In the latter, hydrogen molecules are dissociated into atomic hydrogen at the metal surface and then diffuse into the metal or alloy structure. Other examples include storage in chemical hydrides (e) or in complex hydrides (f). [86, 87]

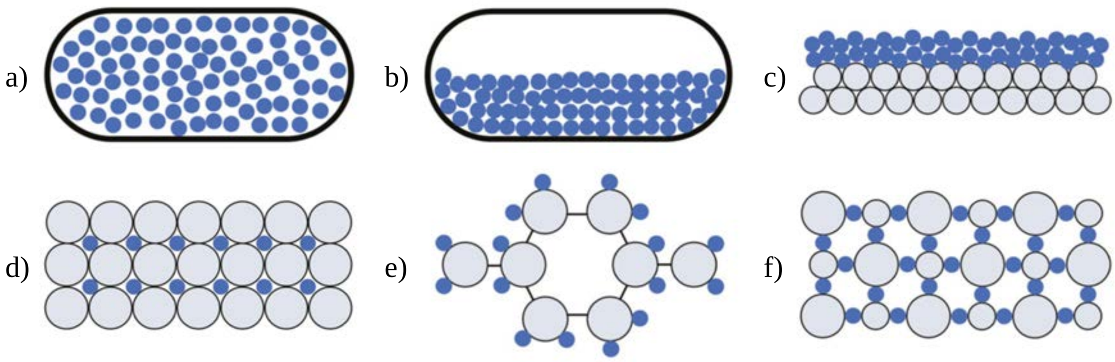


Fig. 5-6 Schematic representation of some hydrogen storage technologies [87]

Some types of solid-state storage theoretically allow high volumetric energy densities (e.g., MgH_2 = 3.6 kWh/dm³ [86]); however, they are currently still under development. Challenges exist in the hydrogenation and dehydrogenation, both in terms of kinetics and temperatures. Nevertheless, the safety aspects are their asset, since hydrogen is bonded in a solid state and will not escape even if the tank is damaged. Furthermore, there are only moderate pressures and no cryogenic temperatures present.

In automotive applications, physical storage is currently the most common system. However, as pictured in Fig. 5-7, it is even here that there are differences in the thermodynamic state of the hydrogen stored in the container or tank. The main characteristics of the technologies are explained in more detail below.

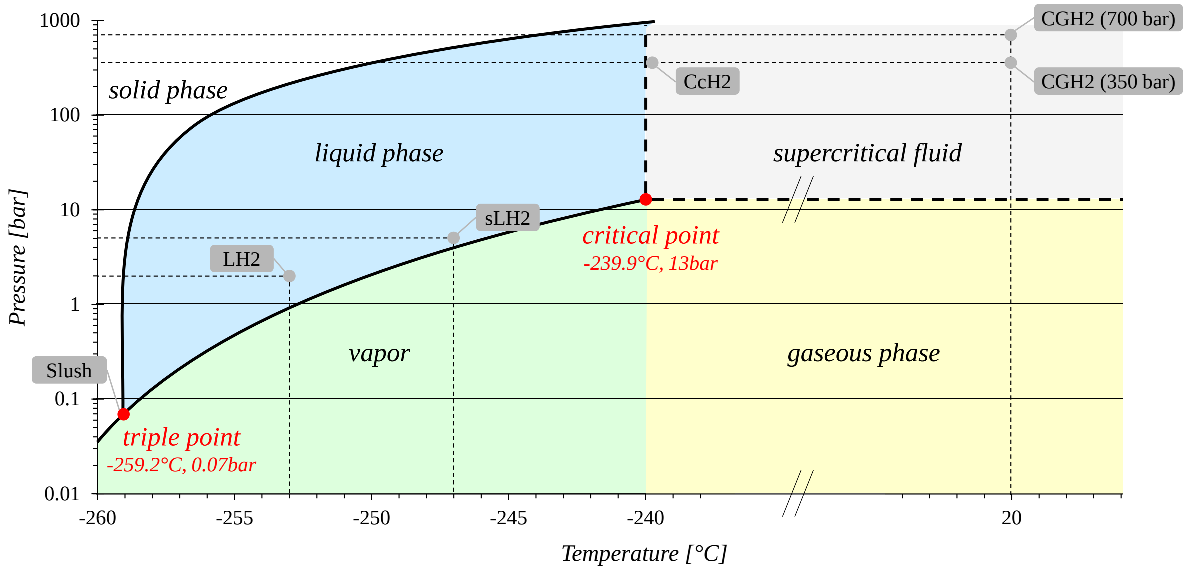


Fig. 5-7 Illustration of different types of hydrogen storage in the phase diagram

At conditions above the critical point, hydrogen is present as a supercritical fluid, but behaves as a real gas with increasing pressure. H_2 has a compressibility factor Z > 1.1 at pressures exceeding about 100 bar. For example, this is the case with CGH_2 at 700 bar; simplified, this form is commonly called gaseous storage.

5.1.1 Storage in CGH_2 Containers

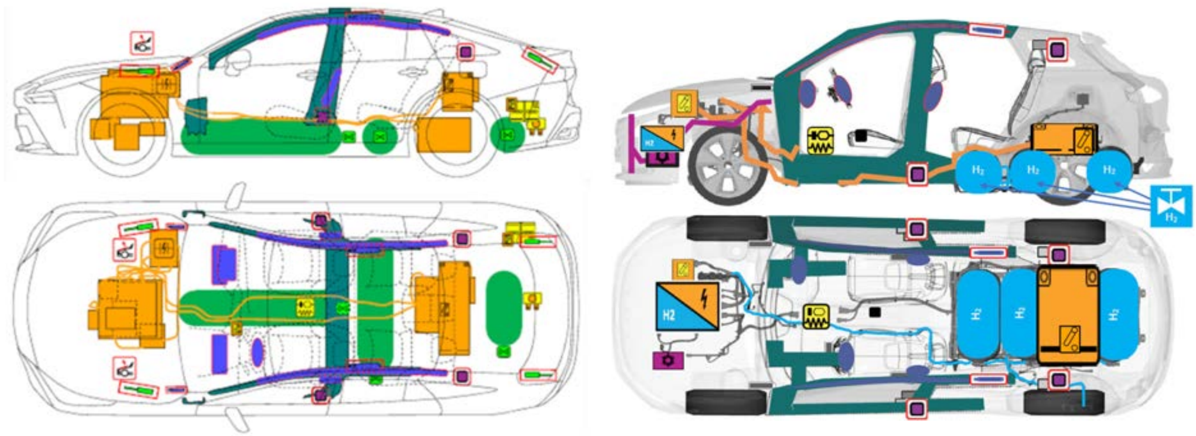
In order to store a large amount of hydrogen in gaseous form, it is compressed under high pressure. Despite these pressures, the energy density of the pure substance (without tank system) is still limited with 0.8 kWh/dm³ at 350 bar or 1.3 kWh/dm³ at 700 bar [75, 86]. However, the advantage compared to liquefied storage is that no fuel is lost even when the vehicle is not in use for a long time.

Analogous to the storage technology of natural gas vehicles, four types of containers are distinguished: type I (metal), type II (hoop wrapped), type III (fully wrapped), and type IV (all composite). Type I containers are the cheapest, as they are widely used in the industry. They have a high weight and are only capable of storing pressures up to about 300 bar. These disadvantages are compensated by the use of type II containers, but they are more expensive and are more commonly used in stationary applications. To increase the energy density, which is important for automotive applications, lower weights and higher pressures are necessary. This can be achieved with type III or IV, capable of storing 350–700 bar. The gravimetric and volumetric energy density is thus more than twice as high as in steel containers [75].

Compressed storage is the preferred method for passenger cars. As can be seen in Fig. 5-8, the fuel is usually packed in several containers. Honda *Clarity FCX* was available only in Asia and the USA, and its production was stopped in 2021. The models listed in Table 5-3 are currently available in Europe.

Table 5-3 Representative FCEVs on the current automotive market

Toyota *Mirai* (2020) [88]	700 bar CGH_2, 5.7 kg hydrogen, 1.2 kWh Li-Ion battery 3 containers type IV (25 + 52 + 65 = 142 l)
Hyundai *Nexo* (2019) [89]	700 bar CGH_2, 6.3 kg hydrogen, 1.6 kWh Li-Ion battery 3 containers type III (52 + 52 + 52 = 156 l)



Toyota, Mirai (2020) [88] Hyundai, Nexo (2019) [90]

Fig. 5-8 Examples of rescue sheets of FCEVs running on CGH_2

5.1.2 Storage in LH_2 Tanks

In cryogenic storage, hydrogen has a significantly higher density of up to 2.3 kWh/dm³ [75, 86]. For this purpose, the hydrogen is cooled to less than –253 °C at near-ambient pressure and is then present in a liquefied state. An unavoidable heat input from the environment causing boil-off losses is influenced by insulation, size and geometric shape of the tank. A large volume with a small surface-to-volume ratio is preferable and leads to a spherical shape (ratio = 3/r) with a large radius. However, due to complex manufacturing, cylindrical tanks are used in vehicle construction. Additional losses due to heat input in pipes, friction in pipes, and return gas during refueling cannot be neglected with this system. In contrast to CGH_2, the system is an open thermodynamic system. The boil-off losses range from 0.3–3 % per day. [75]

The tank system of the previously mentioned BMW (Fig. 5-5) using LH_2 consists of a vacuum insulated tank with two stainless steel sheets (2 mm layer thickness each). The 30 mm insulation between them is equivalent to a 17 m thick Styrofoam layer. The evaporation loss due to natural heat input from a half-filled tank to drain is 9 days. This boil-off valve opens at 5.1 bar and the gaseous H_2 mixes with atmospheric oxygen in a catalyst to form liquid water, which escapes through the vehicle floor. [85]

5.1.3 Other types of hydrogen storage

In order to minimize boil-off losses, ongoing research is being conducted to improve LH_2 storage. With *subcooled liquid hydrogen* (sLH_2), fuel is stored at 5–16 bar and about –247 °C. The increased pressure raises the temperature of the boiling point and more heat input is allowed before vaporization occurs. Nevertheless, boil-off loss is unavoidable during long downtimes. This system is currently being tested in a *GenH2* [91] prototype by Daimler Truck AG, which is expected to be ready for series production by the end of this decade at the latest. The main advantage of this technology is that vacuum-insolated stainless-steel tanks can be used instead of expensive carbon tanks, leading to considerable cost savings. [92]

A special case is *cryo-compressed storage* (CcH2), which allows an increase in energy density to 2.6 kWh/dm³ [86]. Supercritical hydrogen is stored in a vacuum-insulated high-pressure tank above the critical temperature and at 250–350 bar. Boil-off losses are also minimized here, as there is no phase change. However, this storage is still at a very early stage of development; prototypes are not yet known. [75, 93]

Another form of storage is *slush hydrogen*, a mixture of solid and liquid hydrogen. In the two-phase cryogenic mixture, solid hydrogen particles with a diameter of a few millimeters are embedded in liquid hydrogen. The density depends on the mixing ratio of the two phases; the more solid H_2 present, the higher the density. Further on, it is stored at the triple point (18 K), compared to normal boiling LH_2, it has a 15 % higher density with a solid fraction of 50 %. Another advantage is the lower evaporation of the liquid hydrogen, because the heat of fusion of the solid particles absorbs any heat leakage. The production requires a lot of effort, and the application might be more interesting as a fuel for aerospace applications. [94]

5.2 Characteristics of Trucks and Buses

As it is usual for passenger cars, the development of hydrogen for propulsion in buses is focusing on fuel cells combined with a gaseous storage. The example shown in Fig. 5-9 is a CGH_2 system with 350 bar, where the containers (green), the FC stacks (purple) and the HV battery (yellow) are mounted on the roof of the bus.

Fig. 5-9 Rescue sheet of a FCEV bus, EvoBus *Citaro FuelCell Hybrid* [56]

In 2006–2009, the EU project *HyFLEET:CUTE* [95] was carried out investigating the use of hydrogen-powered buses, primarily FC buses. Within this framework, also a small fleet of 14 buses with H_2-ICEVs was developed, constructed and put into operation. This was done in parallel with a newly built hydrogen infrastructure in Berlin's city transport system. At present, the production of FCEV buses is just at the transition between prototype and series production. The technical characteristics of the few buses currently available at demonstration stage are listed in Table 5-4.

Table 5-4 Representative FCEV buses on the current automotive market

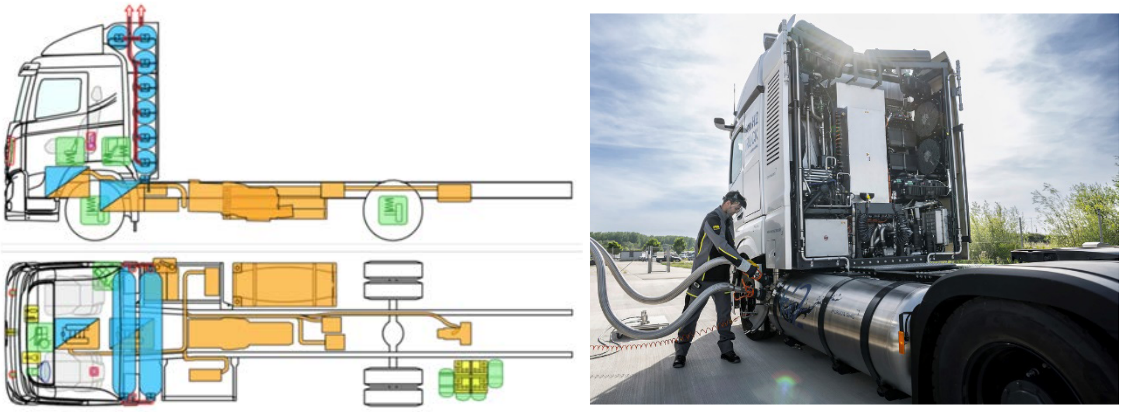
EvoBus *Citaro FuelCell Hybrid* [56, 96]	350 bar CGH_2, 30 kg hydrogen, 392 kWh Li-Ion battery 6 containers, 60 kW FC power
Hyundai *Elec City Fuel Cell* [97]	700 bar CGH_2, 34 kg hydrogen, 78 kWh Li-Ion battery 5 containers, 180 kW FC power
SAFRA *HYCITY* [98]	350 bar CGH_2, 35 kg hydrogen, 130 kWh Li-Ion battery 6 containers, 45 kW FC power

For trucks, no consistent trend in the development of storage technologies can be seen so far (Table 5-5). One of the first series-produced hydrogen-powered truck is from Hyundai and uses CGH_2 at 350 bar. In contrast, two currently available models at the prototype level are running on CGH_2 at 700 bar or sLH_2. Due to the higher energy density of liquefied storage, it is expected for trucks to become more important in future.

Table 5-5 Representative FCEV trucks on the current automotive market

Hyundai *XCIENT* [99]	350 bar CGH_2, 32.1 kg hydrogen, 73 kWh Li-ion battery 7 containers, 190 kW FC power
Nikola *TRE* [100]	700 bar CGH_2, 70 kg hydrogen, 164 kWh Li-ion battery 3 containers type IV, 200 kW FC power
Daimler Truck *GenH2* [91]	5–16 bar sLH_2, 80 kg hydrogen, 70 kWh Li-ion battery 2 tanks, 300 kW FC power

As illustrated in Fig. 5-10, the containers or tanks are located at different positions on the vehicle, depending on the technology. Multiple individual containers, as is common with CGH_2, are located behind the driver's cab; storage methods with fewer but larger tanks are attached to the chassis frame.



Hyundai *XCIENT* with CGH_2 at 350 bar [99] Daimler *GenH2* with sLH_2 (prototype) [91]

Fig. 5-10 Hydrogen trucks with different storage technologies

5.3 Safety Measures

When choosing materials, it is necessary to take some characteristics of hydrogen into account, because interactions can occur. This affects all components in contact with hydrogen and in particular the containers (liner, fiber, matrix). Due to the small atomic or molecular size, hydrogen can be absorbed by some materials. This can lead to leaks or to local deposits of hydrogen. In the latter case, the structure of some metals is distorted, resulting in a hydrogen embrittlement. This damages the material and, in the worst case, leads to structural failure. For cryogenic storage, the material embrittlement can be additionally intensified by the low temperatures.

Regardless of what type of storage system is used, the hydrogen tanks must be placed in a safe position in the vehicle. Investigations concerning the position of hydrogen tanks in passenger cars with liquefied storage have been carried out by Vernier et al. [101]. The frequency of deformations in vehicle crashes is shown in Fig. 5-11; accordingly, an installation of the tank above the rear axle provides the best protection against deformation.

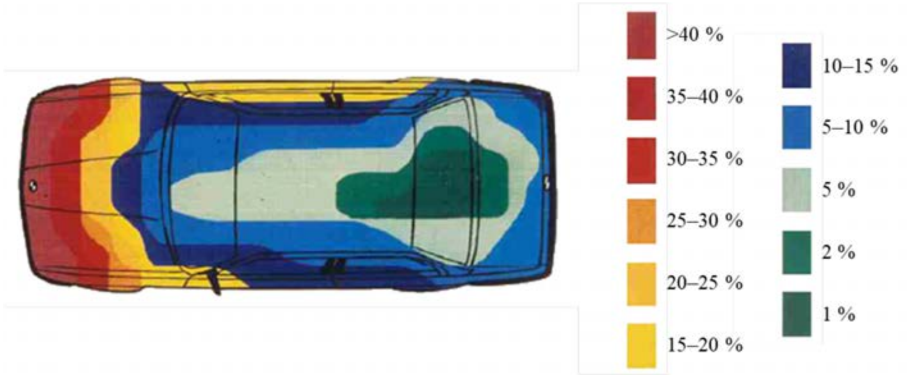


Fig. 5-11 Safe areas of passenger cars [101]

5.3.1 Safety Devices on CGH2 Containers

The requirements for containers depend on its type. For example, ISO 19881 [102] specifies the different requirements for the 4 types of hydrogen containers used in road vehicles in terms of design, testing and material. Due to its comparable technology with CNG, similar safety devices are mounted. UNECE R134 [103] requires the following devices, which, can also be combined:

- Thermal activated pressure relief device (TPRD)
- Check valve to prevent reverse flow to the filler
- Automatic shut-off valve

It also prescribes, that any leaking hydrogen must not reach the passenger compartment. If a concentration of > 3 vol.% is detected due to a system failure during operation, a warning must be given to the driver. At > 4 vol.%, the shut-off valve must be closed. In addition, this valve must be closed in the event of a crash within 5 s.

The temperature that triggers the non-reclosing TPRD is usually set at 110 °C to prevent the container from bursting. In addition, the outlet of the TPRD shall not be directed in any of the following directions: [103]

- Into (semi-) enclosed spaces
- Into a wheel housing
- Towards hydrogen containers
- Out of the front, rear or side of the vehicle, parallel to the roadway

One can conclude that the container mounted in the vehicle underbody of passenger cars is venting towards the road surface. In trucks and buses, a vertical upward venting is usual.

5.3.2 Safety Devices on LH2 Tanks

General construction requirements and testing methods for liquid hydrogen fuel tanks are defined in ISO 13985 [104]. Once again, reference is made to the BMW *Series 7*, where the following considerations in terms of safety are worth mentioning. The fuel lines for hydrogen are made of stainless steel, and they are installed in the well-protected transmission tunnel (Fig. 5-5). Elsewhere, they are designed to be flexible in order to compensate changes in length in the event of a crash. The position of the tank nozzle was chosen to ensure that any damage to it or its feed line is limited, even in the event of a side impact on this critical area. If that occurs, a large part of the energy can be absorbed by the rear axle (Fig. 5-12). In addition, when an accident is detected, a valve on the hydrogen tank closes immediately to minimize gas leakage from a damaged line. [101]

Fig. 5-12 Side impact against a hydrogen tank nozzle [101]

Furthermore, two redundant safety valves mounted on the tank open in the event of a large pressure increase, e.g., in case of a vehicle fire, or if the insulation is damaged and vacuum escapes. The first valve releases gaseous hydrogen on the vehicle roof via discharge lines in the C-pillars. An outlet at this point should prevent people from being cold-burned. The second valve opens at a higher pressure and discharges the hydrogen at the vehicle floor. [85, 101]

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