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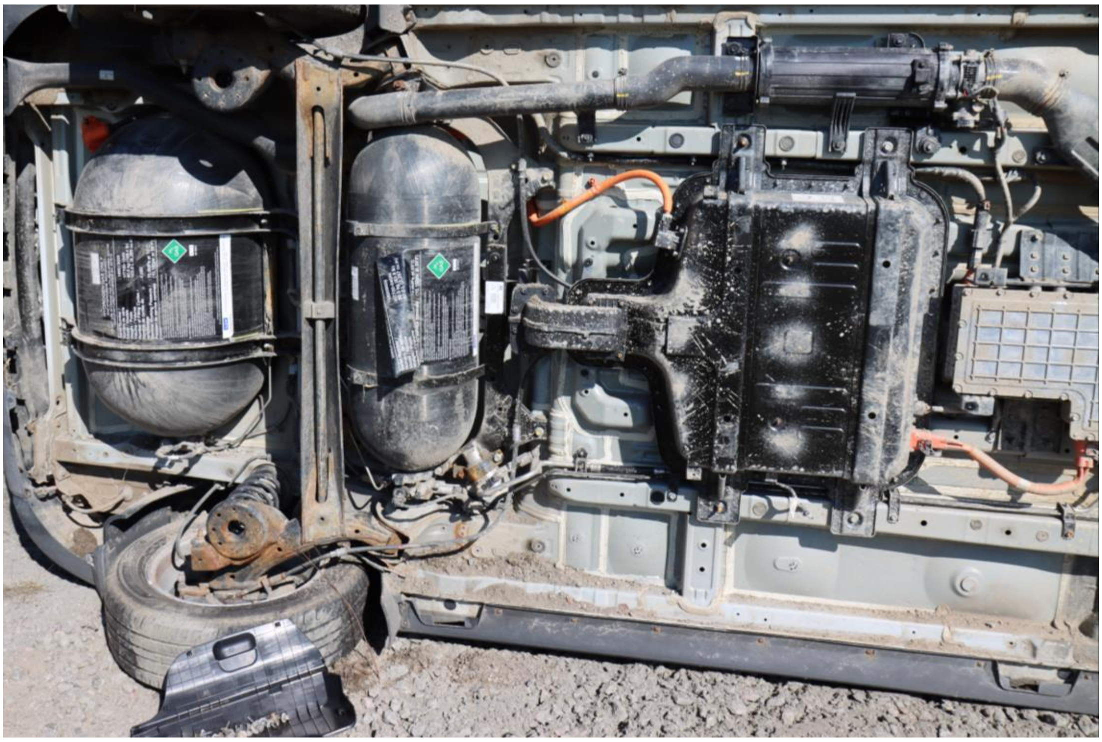

# Risks with hydrogen in underground facilities

Jonatan Gehandler

RISE Report 2023:85

# Risks with hydrogen in underground facilities

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# Abstract

RISE has previously studied alternative fuels, such as batteries and gaseous fuels including liquid and compressed hydrogen (GH2). Each fuel has its unique risks. Liquid hydrogen (LH2) is a cryogenic fluid and is thus stored in cooled liquid form, which entails specific risks. The purpose of this report is to, based on the current state of research, map the risks of hydrogen in underground facilities in relation to conventional fuels and investigate which technical measures can be taken to reduce the risks. Unlike diesel, hydrogen (and for instance methane or gasoline) has such a low flash point that an emission can be ignited at normal temperature by a small ignition source. Hydrogen is also very buoyant, with strong diffusion and dispersion characteristics, accordingly it accumulates at high points in a subsurface environment. Hydrogen requires very low energy to ignite at or near stoichiometric mixing with air at around 30%. The lower flammability limit is, compared to other flammable fuel/air mixtures high at around 4%, which means that many smaller releases in ventilated spaces will be too lean. Explosions would require a higher hydrogen concentration, above 8% or more.

In subsurface environments, containment contributes to a higher increase in pressure, as well as an increased risk of explosion for both GH2 and LH2. The handling of hydrogen underground can therefore be seen as problematic. When it comes to hydrogen as a vehicle fuel, however, there are safety measures to achieve equivalent safety with conventional vehicles. For example, the shut-off valve (mandatory in regulation) on each tank that reduces the risk of leakage, and through the development of explosion-free composite tanks (not mandatory in regulation) in the event of fire that provide a less dangerous fire scenario than a diesel or gasoline tank in case of fire. When it finally comes to transporting hydrogen, pipelines are the long-term sustainable (and safe) alternative. Transport of compressed hydrogen gives a low amount of gas per trailer and entails relatively higher risks than CNG underground, for example in tunnels.

The usage of liquid hydrogen, so far, has an impressive safety record, events like BLEVE or fireballs appear to be rare. The transport of liquid hydrogen provides a larger amount of hydrogen per trailer (than for compressed hydrogen) with a relatively lower risk than, for example, LNG in the open, but a slightly higher risk for explosion of accumulated gas compared to GH2 in enclosed spaces. The safety requirements for transport of compressed hydrogen are less stringent than for road vehicles, e.g., with regard to shut-off valves and melt-fuses and could be improved. Several risk mitigation measures for tunnels and other underground facilities have been identified.

Key words: Hydrogen, road vehicles, tunnel, underground space, risk, hazard

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# Sammanfattning

## Risker med vätgas i undermarksanläggningar

Flera stora fordonstillverkare satsar på flytande vätgas som hållbart drivmedel för tunga transporter från och med 2025. Vätgasen kommer då att användas i bränsleceller som omvandlar vätgasen till el, vilket gör det till ett rent bränslealternativ. Vätgas i komprimerad form har begränsade lagringsmöjligheter, speciellt för energikrävande tyngre transporter. Vätgas i flytande form ger en bra räckvidd, även för tyngre transporter, eller för drivmedelstransporter. RISE har i flera tidigare projekt studerat alternativa drivmedel såsom batteri och gasformiga drivmedel inklusive flytande och komprimerad vätgas. Varje bränsle har sina unika risker och fokus på de senare projekten har varit på risken för tryckkärlsexplosion med komprimerad biogas eller vätgas vid lokal brand eller vattenpåföring. Syftet med rapporten är att utgående från befintligt forskningsläge kartlägga riskerna med vätgas i undermarksanläggningar i relation till konventionella bränslen samt undersöka vilka tekniska åtgärder som kan vidtas för att minska riskerna.

Vätgas har en väldigt låg densitet och lagras antingen under högt tryck på 20 – 70 MPa eller nedkylt till -253 °C och flytande form. Det höga trycket medför risker såsom tryckkärlsexplosion om behållaren brister och den låga temperaturen medför risker med köldskador. Tryckvågen från en behållare för komprimerad vätgas kan vara dödlig ute i det fria i behållarens närhet (inom 5–10 m), men i en inneslutning såsom en tunnel är situationen långt värre eftersom trycket avtar mycket långsamt längs tunneln, samtidigt som bidraget från exempelvis efterföljande deflagrering av vätgas blir än större på grund av omslutningen. Tryckvågen kan leda till dödsfall inom hundratals meter tunnel och hälsoskador skulle kunna uppstå för alla som vistas i tunneln. Därtill finns även hälsorisker med projektiler, vilka dock är än större ovan jord.

Till skillnad från diesel har vätgas (och även metangas eller bensin) en så pass låg flampunkt att ett utsläpp kan antändas vid normal temperatur av en liten antändningskälla. Vätgas är dessutom väldigt flyktigt (buoyant) och ansamlas i höga punkter i en undermarksmiljö och kräver väldigt låg energi för att antända vid eller nära stökiometrisk blandning kring 30%. Den nedre brännbarhetsgränsen är, jämfört med andra brandfarliga bränsle-luftblandningar, hög kring 4 %, vilket gör att många mindre utsläpp i ventilerade utrymmen blir för magra. En explosion kräver en vätekoncentration över 8 % eller mer. Samtidigt bidrar inneslutningen till högre tryckökning, samt en ökad explosionsrisk, jämfört med ovan mark. Sker tryckkärlsexplosionen i ett garage under mark kan ovanliggande våningar riskera att rasa. En väg- eller järnvägstunnel väntas stå emot tryck av den här storleksordningen eftersom den dels har kraftigare konstruktion och den dels inte är sluten utan tryckavlastning kan ske i bägge ändarna.

Hanteringen av vätgas under mark är därmed problematisk. När det kommer till vätgas som fordonsbränsle finns det dock möjligheter att uppnå en ekvivalent säkerhet med konventionella fordon, exempelvis tack vara magnetventilen på varje tank som minskar sannolikheten för läckage och genom explosionsfria komposittankar i händelse av brand som ger ett mindre farligt brandscenario än en diesel- eller bensintank i händelse av brand.

För transport av vätgas så är pipeline det långsiktigt hållbara (och säkra) alternativet. Transport av komprimerad vätgas ger en låg mängd gas per trailer och medför förhållandevis högre risker än transport av metangas under mark, exempelvis i tunnlar. Transport av komprimerad vätgas skulle kunna göras säkrare genom att tillämpa ett eller flera av kraven på fordonssidan såsom avstängningsventil per cylinder eller smältsäkringar. Flytande väte transporteras både med lastbil och på järnväg och ger ca 5 gånger större mängd vätgas per trailer (än för komprimerad vätgas). Flytande vätgas är en kryogas och lagras därmed nedkyld i flytande form, vilket medför specifika risker såsom köldskador. Utsläpp av nedkylt flytande väte utgör ett mycket komplext riskscenario. Vid ett större läckage kommer omgivande gaser i luft att göras flytande; sedan kommer vätet att agera på samma sätt som en tung gas för att slutligen fungera som en mycket lätt gas. Transport av flytande vätgas ger en förhållandevis lägre risk än exempelvis flytande metangas med hänsyn till direkta effekter såsom BLEVE, men en förhöjd risk under mark, där större läckage riskerar leda till en deflagrering eller till och med en detonation.

En annan viktig fråga är räddningstjänstens insatser med hänsyn till de nya faror som kan uppstå med fordon som drivs av nya energibärare. Bränder i tunnlar och parkeringsgarage under mark kan redan idag vara en stor utmaning för räddningstjänst.

Framtida forskning bör fokusera på vidareutveckling av explosionsfria kompositttankar för komprimerad vätgas, och göra detta obligatoriskt i internationella fordonsföreskrifter och standarder. Säkerheten för transport av vätgas kan förbättras utifrån de tuffare kraven för vätgasfordon.

# Content

# Preface

This project is funded by the Tunnel and Underground Safety Center (TUSC), which is greatly acknowledged. TUSC is a joint project which finances research related to fire safety in underground facilities. The partners involved are RISE, Transport Administration in Sweden, The Swedish Fortifications Agency, and GRAMKO (Svemin’s Health and Safety Committee). Special thanks to Paul Adams at RISE for his valuable input in relation to this report.

TUSC

Tunnel and Underground Safety Center

# 1 Introduction

Hydrogen has been used for a considerable amount of time within the process industry, yet is anticipated to play an even more important role as a future energy carrier. Hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water. It can be produced from a variety of domestic resources, such as natural gas, nuclear power, biomass, as well as renewable power like solar and wind. Moreover, hydrogen can either be stored at ambient temperature and high pressure as a compressed gas (GH2), or at cryogenic temperatures and low pressure as a liquid (LH2). GH2 can be stored for a long time without any losses, apart from possible permeation or leakages. Even though LH2 tanks are well insulated, a certain amount of heat transfer will occur. The pressure and temperature in LH2 tanks are kept constant only if the vapor boil-off is removed. If the boil-off is not removed, both temperature and pressure will rise. Accordingly, LH2 storage is best utilized if the boil-off, in the order of 1 % per day is consumed, e.g., as a primary energy source. Hydrogen, either as a compressed gas or a cryogenic liquid, has a comparatively low volumetric energy density. For example on a volume basis, compressed hydrogen gas (GH2) at 70 MPA pressure, contains about one seventh and liquid hydrogen about one quarter the energy of gasoline [1]. As an interim solution, transportation of LH2, and to some extent GH2, is a viable option which means that hydrogen will be transported both by truck and by rail. The long-term sustainable transportation solution, however, is GH2 by pipeline.

Although few hydrogen vehicles exist in Sweden, both storage possibilities (GH2 and LH2) are commercial technologies. For instance, in 2019 there were 2800 and 5500 fuel cell vehicles in Japan and California respectively [2]. GH2 is mainly used for lighter vehicles, while LH2 is an alternative for heavier vehicles. Infrastructure for refueling within Sweden can be foreseen in the near term for GH2 and longer term for LH2. The hydrogen is either used in fuel cells that convert the hydrogen into electricity, or in combustion engines. GH2 and LH2 entail specific risks. GH2 has a very low ignition energy and is most likely ignited if released inside an enclosure or underground. It is also very reactive and is more prone to explode, or even detonate, compared to hydrocarbons. GH2 can, due to the high storage pressures, also result in a powerful pressure vessel explosion, in the event of cylinder rupture. Leakage of LH2 represents a very complex risk scenario. In the event of a major leak, the density of cryogenic hydrogen gas is much denser than at ambient conditions, and just above the boiling point of hydrogen it is denser than air, until sufficient heat is transferred from the surrounding air. Liquefactions of air occurs on surfaces exposed to cryogenic temps, e.g., a cryogenic line with the insulation damaged or around pooled LH2. Besides, in the event of fire, LH2 may result in a BLEVE (Boiling Liquid Expanding Vapor Explosion) in the case of cylinder rupture. However, hydrogen use, storage and transportation in an underground environment will involve additional and specific risks that need to be investigated, evaluated, and mitigated. Molkov [3], a leading researcher within the hydrogen safety field, considers hydrogen to be neither safer nor more dangerous than other fuels. Hydrogen safety fully depends on how professionally it is handled at the design stage and onwards. For instance, standards require that tanks leak before they burst in the event of fire or material fatigue.

RISE has studied alternative fuels such as batteries and gaseous fuels including cryogenic and compressed hydrogen in tunnels and garages [4-8]. In 2010 Lönnermark [7] and Coen [8] started to investigate the particular risk from new energy carriers including hydrogen. Incidents with gas-powered vehicles were investigated. This showed that gaseous energy carriers such as LPG can lead to explosions with catastrophic outcomes. In 2014 Berg [4] concluded that the overall risks with GH2 is in the same order as other gaseous fuels such as CNG. In a tunnel or garage, Berg argues, the risk from an GH2 vehicle will be in the same order or even lower than the risk from a conventional vehicle. However, when it comes to transports of GH2 and LH2, Berg, finds that the risk of explosion must be further studied for road (only allowed in A-tunnels) and railway tunnels. Later projects on gas at RISE in 2019 and 2021 has focused on the risk of pressure vessel explosion with compressed biogas or hydrogen gas in the event of a local fire or extinguishment with water [9, 10].

## 1.1 Purpose

The purpose of this report is to review the risks of hydrogen in underground facilities in relation to conventional fuels and to investigate what technical measures can be taken to reduce the risks, for example techniques for detecting leaking hydrogen, or technical solutions to reduce the consequences of a leakage (for example through inhibition or the like).

## 1.2 Method

This study will build on the earlier studies at RISE about underground hydrogen and CNG safety. In addition, a literature search has been carried out in scientific databases linked to vehicles, liquified and compressed hydrogen, and underground risks in road or railway tunnels. As a complement, one interview was conducted with a hydrogen researcher. The state of knowledge has been compiled. Underground risks with the use and transportation of hydrogen and possible risk-reducing measures have been analyzed. Finally, knowledge gaps and future research needs were identified.

Scientific databases (Scopus and ScienceDirect) and Google were used with the following search phrases; “Hydrogen AND tunnel AND safety”, “liquified AND hydrogen AND safety”, “the risk with liquified hydrogen release underground”, “liquified hydrogen release in road/rail tunnel”, etc.

One Interview was made with Paul Adams, senior researcher at RISE within hydrogen safety who was involved in the development of hydrogen vehicle regulations and standards, referred to as [$I_{PA}$].

## 1.3 Delimitation

Hydrogen powered vehicles in tunnels and garages were included in earlier SP and RISE reports. Berg [4] covered compressed as well as cryogenic, liquified, hydrogen in tunnels in a Swedish SP report from 2014. Gehandler et al. covered compressed methane and hydrogen, and LNG, but not liquified hydrogen in a RISE report [6] (in Swedish) in 2016 which was later translated into English [5] in 2017. The ambition with this report is to continue from earlier works with new studies and information, but without repeating earlier information. In particular there is some new work on pressure vessel explosions in tunnels for compressed hydrogen that will be covered, and the risks with cryogenic hydrogen will be investigated further. Owing to the enclosure, many hydrogen scenarios above ground are even worse below ground, however, one exception is rapid phase transition (RPT) that can only happen for liquid hydrogen unto water such as spillage unto the sea (sprinkler, for instance, is not enough to trigger RPT). Therefore, RPT is not covered.

### 1.3.1 Sub-cooled hydrogen and cryo-compressed hydrogen

In addition to classical liquid hydrogen (LH2) storage systems as used in the BMW Hydrogen 7-Series with a maximum pressure of 1 MPa which was always a 2-phase system, there are two alternative types of cryogenic hydrogen storage systems now being developed commercially; sub-cooled liquid hydrogen and cryo-compressed hydrogen. Both alternatives aim to simplify refueling, reduce boil-off and increase storage density [IPA]. F

Sub-cooled hydrogen (sLH2) storage requires a single refueling hose and has a maximum pressure of 2 MPa. During refueling with sub-cooled hydrogen, the sLH2 storage system will be in a two-phase thermodynamic state, similar to LH2. In this state the storage system can be filled to a pressure exceeding the critical pressure of hydrogen at approx. 1.3 MPa. Once critical pressure is exceeded the hydrogen is in a single-phase state [IPA].

Cryo-compressed hydrogen (CcH2) can be thought of as a combination of LH2 and GH2 storage whereby the insulated tank is designed for 35-40 MPa pressure. Early prototypes were designed to be capable of being refilled by either LH2, cryogenic hydrogen gas or GH2 [IPA]. However, current designs have refueling similar to sLH2 except that much higher pressures are reached resulting in the liquid becoming a supercritical fluid when the hydrogen temperature reaches 33K with a density greater than sLH2 which in turn is greater than LH2 [IPA].

Any special risks associated with sLH2 or CcH2 storage have not been considered in this study.

# 2 Hydrogen

Hydrogen is the chemical element with the symbol 'H' and atomic number 1, it is thus the lightest element. This means that hydrogen has a very high buoyancy (density 0.08 kg/m$^3$ compared to 1.23 kg/m$^3$ for air at normal temperature and pressure (NTP)[1]) and an extremely high diffusivity, it will usually disperse more rapidly than other fuels if released. The main dispersion factor in air at NTP is the high buoyancy. This results in that hydrogen releases often create less risky situations than do the release of hydrocarbons that are far more susceptible of creating large ignitable gas clouds. At standard conditions hydrogen is a gas of diatomic molecules having the formula H2. It is colorless, odorless, tasteless, non-toxic, and highly combustible. To exist as a liquid, hydrogen must be cooled below its critical point of 33 K (−240 °C) and above critical pressure 1.3 MPa. To be in a fully liquid state at atmospheric pressure, hydrogen needs to be cooled to 20 K (−253 °C). The density of liquid hydrogen (LH2) is 70 kg/m$^3$. Cryogenic hydrogen gas above 22 K is lighter than air and below this point it is heavier than air [2].

Hydrogen has a very low viscosity and high diffusivity which means it is very difficult to prevent hydrogen systems from developing leaks. Furthermore, hydrogen is also known to cause embrittlement of carbon metallic alloys [1]. The ideal gas law does not apply for hydrogen stored at high pressures. For example, the hydrogen mass release is overestimated by 45 % at 70 MPa storage pressure.

Hydrogen has a wide flammability range in air. However, the more important lower flammability limit is 4 %, which is better than, e.g., gasoline and diesel at 1 % and propane at 1.7 %, and similar to methane. However, the lower flammability limit during transient conditions, e.g., for releases in ventilated tunnels, is even higher. Above 10 % is required to reach a slow deflagration (i.e., explosion). The explosive limits for hydrogen are in the order of 11 – 60 % [11]. Deflagration of a hydrogen-air cloud in the open generates negligible pressures. Hydrogen burns with a hot but invisible flame. The radiation to other objects will often be in the same order or lower than other hydrocarbons. However, close to stoichiometric mixtures (30 %), hydrogen has a very high burning rate which means it is more prone than most other gases to cause explosions and even transit from deflagration to detonation in confined or congested spaces. Detonation can according to the project HySafe occur above 18 % [11]. The detonation of a hydrogen-air mixture under some conditions generates a shock wave far above fatal pressure.

Hydrogen-air mixtures at around 30 % have a very low ignition energy (0.017 mJ), and high-pressure leakages are even known to "spontaneously" ignite. At low (and high) concentrations, the ignition energy of hydrogen is comparable to that of methane [11]. In most high-pressure incidents hydrogen ignites directly [12] (i.e. resulting in a jet flame and not the more dangerous delayed ignition that results in an explosion). A likely ignition cause is electrostatic charge generation, either by spark discharges, brush discharges or corona discharges [12]. For spark discharges, the voltage required to ignite hydrogen is below 2 kV which can be generated easily on people standing on an insulating surface. Where a potential exists some distance from an earthed surface, an electric field will be present, such a corona discharge can ignite hydrogen without there being a

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[1] A temperature of 20 °C and an absolute pressure of 1 atm (101.325 kPa).

discrete spark or single discharging event. The electric field will be linear between a pair of parallel plates, however, if a small point is placed on one of the plates, it will modify the field and concentrate the lines towards the point. If the local concentrated field strength exceeds the breakdown strength of the air, then a current will pass in the form of a corona. Hydrogen has a Joule-Thomson inversion temperature of about 193 K (-80 °C). This means that released pressurized hydrogen above 193 K will heat up when it expands to ambient pressure. However, the increase in temperature is minor compared to the ignition temperature of hydrogen at above 500 °C which means that this in most situations is not a plausible ignition source on its own, but could be a contributing factor [12].

Liquified hydrogen (LH2) has significantly different properties to other cryogenic gases, see Table 1, therefore, trying to simulate the release behavior based on other more easily handled cryogens is unlikely to yield useful results [13]. LH2 has a very low density and the vapor phase at the boiling temperature has about the same density as air resulting in much slower dispersion than GH2. A release of liquid hydrogen will initially quickly vaporize, but after some time, e.g., 2 min for 60 l/min flow rate [13], the ground is sufficiently cooled resulting in that a pool is being formed. The cloud of hydrogen vapor during the release is visible due to condensation of water within the cloud. The significant cooling of the surroundings causes condensation of nitrogen and oxygen from the air, and even freezing of these gases to produce a vigorously flammable solid (a mixture of solid nitrogen and oxygen and liquid hydrogen).

Table 1 Properties of liquid hydrogen and other common cryogenic gases [13].

| | Hydrogen | Nitrogen | Oxygen | Methane |
|---|---|---|---|---|
| Liquid density (kg/m$^3$) | 71 | 804 | 1142 | 424 |
| Gas density at boiling point (kg/m$^3$) | 1.3 | 4.6 | 4.5 | 1.8 |
| Boiling point (K) | 20 | 77 | 90 | 109 |
| Freezing point (K) | 14 | 63 | 55 | 91 |

## 2.1 GH2 vehicles

Safety of hydrogen fueled vehicles is prescribed in UNECE Regulation 134 (R134) and Global Technical Regulation 13 (GTR13). A new version of GTR13 was adopted in May 2023 with significant changes that will soon be included in R134 [2]. The ambition in GTR13 is that hydrogen and fuel cell vehicles “attains or exceeds the equivalent levels of safety of those for conventional gasoline fueled vehicles”. Road-vehicle hydrogen containers have a nominal working pressure (NWP) of up to 70 MPa. According to the regulation all cylinders should have a burst pressure above 225 % of NWP. Containers having a glass-fibre composite as a primary constituent must have an even higher burst pressure above 350 % of NWP. The hydrogen cylinders are tested in several respects, e.g., fire, refueling cycles, drop test, surface damage test, chemical exposure test and corrosion. Hydrogen cylinders are just like the more common CNG cylinders protected

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[2] UNECE, https://unece.org/sites/default/files/2023-04/ECE-TRANS-WP.29-2023-81e.pdf

with a melt-fuse (TPRD) that should release the gas in the event of fire at around 110 °C [2]. The system should be able to operate at 85 °C without activation. GTR13 includes a bon-fire test that has been developed based on vehicle fire tests in [14]. It includes a local fire exposure for 10 min.

### 2.1.1 Compressed fuel cylinders

There are commonly four different types of GH2 cylinders depending on the material:

- Metal cylinder (metal, Type I).
- Metal container that is, aside from the bottom and neck, wrapped in sheets of composite materials (hoop wrapped, Type II).
- Metal container that is entirely wrapped in sheets of composite materials (fully wrapped, Type III).
- Plastic container that is entirely wrapped in sheets of composite materials (all composite, Type IV).

A composite material is made of a polymer matrix reinforced with fibres. The fibres are usually glass or carbon. A schematic overview of a Type IV GH2 tank is seen in Figure 1.

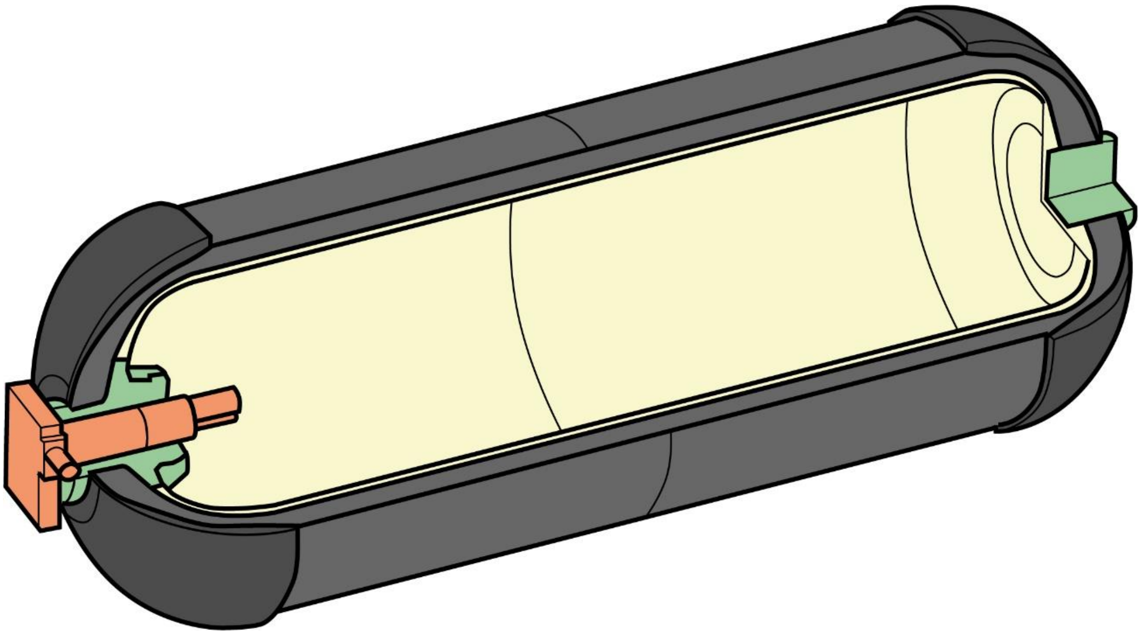

Figure 1 A Type IV compressed hydrogen tank.

When exposed to a fire the steel tank will behave very differently compared to tanks wrapped in composite. Metal has a high heat conductivity and material degradation starts first at around 500 °C. Composites on the other hand are generally a poor heat conductor and the polymer matrix starts to melt already at 100-200 °C [9]. According to Dadashzadeh, Kashkarov, Makarov and Molkov [15] hydrogen vehicles are often equipped with composite cylinders, type III or type IV as in Figure 2, due to their lighter weight and exceptional mechanical strength characteristics, compared to pure steel cylinders.

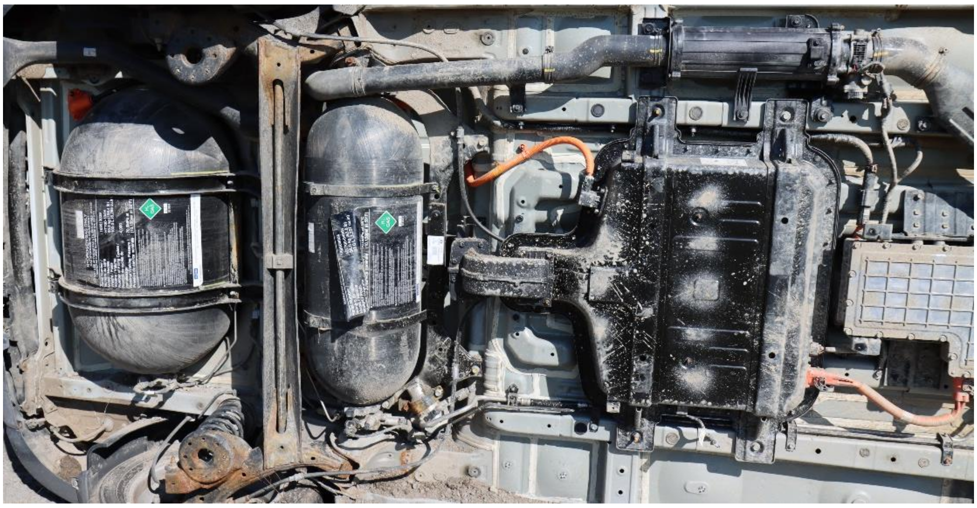

Figure 2 Hydrogen vehicle with two Type IV composite tanks placed at the rear end of the vehicle.

The fire resistance rating, i.e., the time from the start of the fire to tank rupture of thermally unprotected composite tanks is about 6-20 min depending on the heat release rate (HRR). Due to that several CNG cylinders have ruptured in the event of fire, Dadashzadeh, Kashkarov, Makarov and Molkov [15], argue that a pressure vessel explosion in the event of fire is the greatest safety concern of hydrogen vehicles. However, note that there is quite some difference between the old CNG regulations and the new hydrogen regulations that includes an additional 25 years of research. One of the main safety concerns for the unprotected public of a pressure vessel explosion is not the pressure it generates (fatal only in the vicinity of the explosion, serious injury within 13 m in the example with a small hydrogen tank provided by Dadashzadeh et al.), but the fireball that is created once the released hydrogen burns (fatality assumed within the fire ball radius of 35 m in the example with a 62.4 l onboard storage tank at 70 MPa provided by Dadashzadeh et al.). In tunnels, however, the pressure wave from the tank rupture and secondary explosions of hydrogen becomes an even more difficult issue, since much higher pressures are generated by the tunnel confinement.

### 2.1.2 Fire test of GH2 cylinders

The time to tank rupture (starting at nominal working pressure) without TPRD is by Molkov, Dadashzadeh, Kashkarov and Makarov [16] defined as the fire resistance rating (FRR) of the tank. Obviously, this depends on the heat release rate (HRR) of the fire and the incoming heat flux against the tank. For low HRR, e.g., 79 kW it can be 16 – 22 min. For HRR = 165 kW it is 7 – 8 min and for HRR = 370 kW it is 6-7 min. For high HRR (1 – 4 MW) the FRR can be as low as 4 min. Above 350 kW a saturation effect can be seen in the sense that the FFR is only marginally decreased with increased HRR. Therefore, Kashkarov, Makarov and Molkov [17] propose that the bonfire test should be performed with a HRR above 350 kW so that it will be reproducible between different test laboratories. This recommendation is included in the new GTR13 fire test.

Hydrogen cylinders (filled to 100% NWP) may be tested for a generic vehicle installation or for a specific vehicle installation (GTR 13). If tested for a specific vehicle installation, the complete vehicle including all components is tested. The focus here will be the generic vehicle test. The cylinder is then tested for a 250 mm local LPG burner fire (positioned worst case, between 200 and 500 kW/m$^2$) and a 1.65 m long engulfing LPG burner fire between 400 and 1000 kW/$m^2$. The width of the fire source encompasses the entire diameter (width) of the cylinder. The engulfing fire starts at 10 minutes. The test is completed when the contained gas is released in a controlled manner without rupture.

### 2.1.3 Explosion-free tank design

A solution that is being discussed to avoid pressure vessel explosions for Type IV tanks is the so-called explosion-free tanks that, when the plastic in the composite melts, release the gas through the composite fibers, leading to microscopically small jet flames. Such a tank not only eliminates the worst-case scenario of a rupture, but also jet flames and gas cloud explosion because the gas from the microscopic holes is quickly diluted with ambient air. Explosion-free type IV tanks have been developed in the event of fire, both for CNG [18] and hydrogen [19] that lead to a less dramatic fire scenario [20] than conventional fuel tanks. Explosion-free tanks are not required by any regulation.

## 2.2 LH2 vehicles

LH2 is stored in insulated cryogenic tanks. The thermal autonomy or hold time of the tanks is in the order of several days (3 to 7) depending on the design of the tank, which means that boil-off should not be an issue in tunnels. Boil-off management systems are required. However, care should be taken if LH2 vehicles are allowed to park below ground since a boil-off rate in the order of 1 % could occur. The vented gas will initially be cold, but fairly quickly it will be much lighter than air [1].

### 2.2.1 Cryogenic tanks

Cryogenic hydrogen tanks for vehicles are regulated in GTR13 and EU Regulation 2021/535. ISO standard 13985:2022 for cryogenic hydrogen tanks is outdated, and a new version is under development for sLH2 tanks. However, also GTR13 and the EU regulation can be said to be outdated as until recently most work on hydrogen vehicles has been focused on compressed hydrogen, and the cryogenic part has not been updated during the last 10 years or so [IPA].

Typically, the operating pressure is in the order of 0.5-1 MPa. Fuel tanks for LH2 are designed with a multi-layer insulation which yield a small heat absorption and are equipped with two pressure relief devices (PRDs) that release at different thresholds of the maximum allowable working pressure (MAWP). The primary PRD is also used to release boil-off gases and therefore is a reclosing valve. The secondary PRD activates at a higher pressure and could be a non-reclosing burst disc or a reclosing valve. The inner tank should be designed to resist 1.3(MAWP±0.1) MPa, according to Regulation 2021/535. A drawing of a LH2 tank is seen in Figure 3.

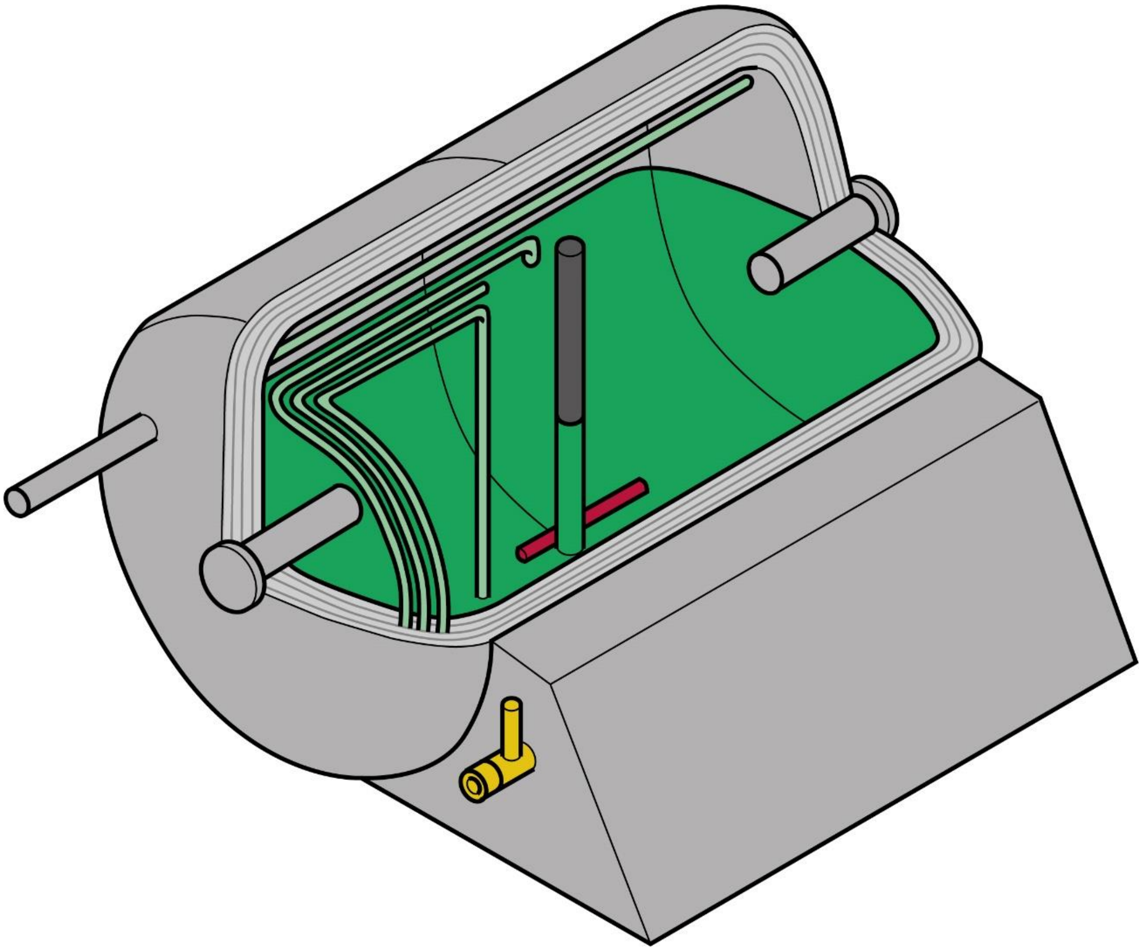

Figure 3 A drawing of a liquid hydrogen tank.

### 2.2.2 Fire test of LH2 tanks

According to GTR13 and Regulation 2021/535, the cryogenic tank should withstand an engulfing fire that is 0.1 m larger than the tank and of a similar fire source that is used for CNG and GH2 bonfire test, i.e., LPG 0.1 m below tank and 590 °C below the tank. The fire test is run until the primary PRD has opened for a second time. The test is passed if: (a) The secondary PRD is not operated below 110 % of the set pressure of the primary PRD; and (b) The container shall not burst and the pressure inside the inner container shall not exceed the permissible fault range of the inner container." The permissible fault range for reclosing PRDs is that the pressure inside the container does not exceed 136 % of the MAWP of the inner container, or 150 % of the MAWP for burst disc PRD.

Since the PRDs may be of a reclosing design, the fire test could go on for a very long time until the container would contain only hydrogen gas. If the vacuum insulation is lost, a similar release rate of hydrogen gas through the PRD would continue also after the fire is extinguished. Since the gas is cold, no water should be allowed to hit the PRD, since it may become blocked by ice formations. Presumably this should not be an issue for water mist systems in garages or road tunnels since the PRD systems ought to be safe during, for instance, heavy rain. However, the rescue service is generally instructed not to cool the tank or the PRD because of the risk of blocking the PRD, but a manual fire hose intervention uses more water per floor area and a different attack angle, very different from rain or water spray systems from above.

## 2.3 Transportation of hydrogen

According to dangerous goods regulations, hydrogen is excluded from tunnels with class B to E, i.e., only allowed in A, for which no tunnel restrictions apply.

As mentioned in the introduction, hydrogen can be transported both as a gas or as a liquid. GH2 tanker trucks operate in EU today. LH2 transportation could be an interim solution for larger quantities, but neither are realistic long-term solutions for large-scale energy transportation due to the low volumetric energy density. Pipelines are a better option in that case.

Transportation of hydrogen is regulated in the TPED EU directive [21]. GH2 can be transported in MEG containers that contain several smaller GH2 cylinders. This means that possible consequences are limited to the rupture of one cylinder at the time. To our best knowledge, it is not mandatory to isolate each cylinder, which means that one leakage point can release gas from all MEG cylinders. There are also GH2 trucks that are not based on MEG.

Large cryogenic vessels (> 100 $m^3$) used for storage and transportation are constructed with a double-walled vacuum and perlite insulation [22]. The amount of LH2 per truck is up to 5000 kg [22] compared to approximately 500 – 1000 kg for GH2, depending on storage pressure.

The transportation of cryogens in railway tank cars started in the 1940s and transportation of LH2 specifically began in the 1960s. The annular space between the inner and outer tanks has a vacuum drawn and use either perlite or multiple layer of foil and paper as insulation [22].

Based on statistics containing 18 incidents with transported LH2, most incidents (72%) occur during loading or offloading with only 28% occur during transit [22].

# 3 Qualitative risk analysis

There have recently been several studies undertaken to investigate the safety of alternative fuel vehicles in underground facilities such as tunnels or car parks. Many of these are summarized in previous work undertaken by RISE such as [5, 23], or others such as [24]. There are also ongoing projects such as the horizon 2020 HyTunnel-CS project "Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces".

## 3.1 Compressed hydrogen

### 3.1.1 Leakage or TPRD release

In the open, released compressed hydrogen at NTP is most likely to either form a jet flame (if ignited upon release), or a gas cloud that may ignite or disperse. The exact behavior is very dependent on the initial release direction. Some (truck) manufactures vent TPRD upwards, at least one car manufacturer vents down at an angle [IPA]. A leak probably results in that the jet would be contained or dispersed to some degree before entering free air.

For a release in enclosures, the buoyant nature of hydrogen eventually forces the hydrogen to move upwards. When the ceiling is reached it then spreads to the sidewalls and then descends (similar to how hot smoke would behave). Depending on the Richardson number (dimensionless number representing the ratio of the buoyancy term to the flow shear term), three different distribution regimes can be identified in a fully closed space; stratified (low release rate, dominated by buoyancy), stratified with a homogenous layer and homogenous mixture (high release rate, dominated by momentum). All three cases can result in ignitable gas clouds. This will also be impacted by the tunnel or enclosure shape, e.g., very low flat roof vs. high horseshoe shape. An example of a hydrogen release through a TPRD and the formation of a hydrogen gas cloud below the tunnel ceiling without any ventilation is seen in Figure 4.

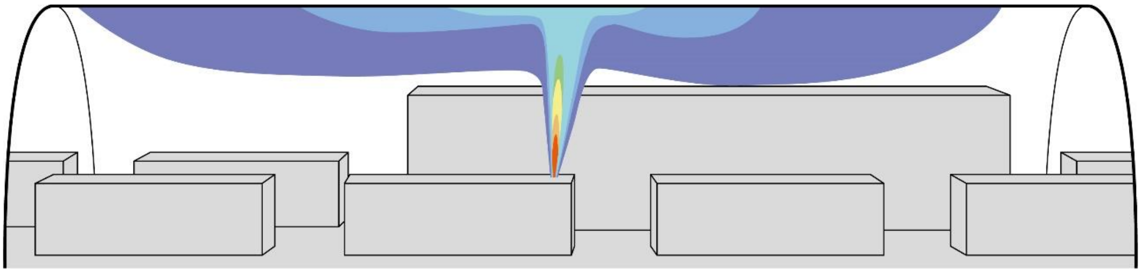

Figure 4 Hydrogen release through a TPRD and the formation of a hydrogen gas cloud below the tunnel ceiling.

Any release of hydrogen in an enclosure would also result in a pressure increase due to the low molecular mass of hydrogen (2 g/mol), called "pressure peaking" [2]. For a given volume and temperature the pressure in an enclosure is dependent on the number of molecules. This means that, for instance, according to simulations in [2], a release of 390 g/s of hydrogen from a TPRD in a 30 m$^3$ garage with a vent size 25 cm x 5 cm, would result in an overpressure above 50 kPa (0.5 bar), which means buildings most likely will fail (typical civil buildings fail at 10 – 20 kPa and 10 kPa is achieved within 1 s). Release of the same amount of helium (4 g/mol) result in 30 kPa, methane (16 g/mol) in 6 kPa and LPG (44 g/mol) almost no pressure increase at all [2]. In order to reach pressures below 10 kPa, the TPRD dimension needs to be below 2 mm (even lower for large GH2 tanks). However, if hydrogen would also ignite, the temperature is increased which would result in even greater pressure increases [2]. To prevent ignitable clouds, ventilation in garages needs to be above 10 air changes per hour and a small TPRD dimension is preferred, e.g. 0.5 mm [25], or even 0.3 mm [2]. For releases in tunnels hydrogen behaves similar to hot smoke, which has been studied extensively [e.g., 26]. However, one important difference is that the release from high pressure storage is dominated by momentum rather than buoyancy, therefore, large ignitable clouds could be formed regardless of the tunnel longitudinal ventilation [27]. However, according to Bie and Hao [28] the gas cloud size is reduced for higher ventilation rate at 6 m/s. Ventilation will also move the cloud downward which can be of importance for trapped vehicles on the upstream side in uni-directional road tunnels. HyTunnel-CS concludes that ventilation in most cases will reduce the risk for vapor cloud explosion [2].In addition transverse tunnel ventilation needs to be considered.

### 3.1.2 Jet flame

Hydrogen jet fire length increases with increasing pressure and nozzle diameter. For example, small nozzle diameters, e.g., 0.1 mm result in an expanded momentum-controlled jet at 50 mm, but a 10 mm nozzle diameter result in a jet at about 5 m length. For high pressure releases the jet will be a momentum controlled jet in the direction of the release, e.g., downward, sidewards, or upwards. With lowered pressure the buoyancy controlled part increases, transferring the jet into an upward plume [2]. A delayed ignition of a turbulent hydrogen jet can result in significant overpressures, up to 20 kPa at 4 m from the ignition point for a 10 mm TPRD diameter and 40 MPa pressure, which is enough to cause eardrum rupture [2]. A comprehensive overview of hydrogen jet flames is presented in [29]. Hydrogen jets from storage tanks and equipment at pressures up to 100 MPa will be mainly in a form of under-expanded jet. The under-expanded jet is defined as a jet with pressure at the nozzle exit is above the atmospheric pressure. Under-expanded hydrogen jet flames can reach tens of meters from the TPRDs of a hydrogen-fuelled vehicle, and up to hundreds of meters for large diameter high pressure industrial hydrogen pipes [29].

### 3.1.3 Vapor cloud explosion

The issue of vapor cloud explosion was reviewed in [5, 6]. It was concluded that a smaller release from a fuel line or safety valve will not be able to yield any larger flammable clouds if the ventilation, e.g., in a road tunnel is above 1 m/s. The worst scenario is larger gas leakages that last for quite some time of a considerable amount of total gas being leaked, which is only possible for DGV transports. For a larger VCE to occur, the total amount of gas, leakage rate, the tunnel cross-section, time of ignition and the ventilation must be combined in a less likely series of events which yields a very low likelihood of occurrence.

Groethe [30] ignited homogenous 37 $m^3$ hydrogen mixtures that were contained in HDPE plastics in a 78.5 m long model tunnel. The cross-sectional areas were 3.74 $m^2$, i.e., a total volume of 294 $m^3$. A homogenous mixture of hydrogen at 9.5% in a model tunnel produced negligible pressure. 20% mixture produced pressure at about 35 kPa throughout the length of the tunnel. A 30% mixture 150 kPa (much higher than an equivalent unconfined experiment where a maximum pressure at 10 kPa was recorded) [30].

Bratland, Bjerketvedt and Vaagsaether [31] performed VCE experiments of inhomogeneous hydrogen-air mixtures in a model scale tunnel. The tunnel was 3 m long, with a cross-section of 100 mm by 100 mm, and open at one end. Hydrogen was released into the channel using nozzles. The gas mixture was ignited at different positions. Strong (e.g., 23 kPa) and relatively prolonged pressure oscillations (e.g., 13 cycles after the fuel were combusted before the peak was reduced to 10% of the maximum pressure) were recorded. Based on the pressure recordings from the explosions, the structural damage potential of the pressure was analyzed using shock response spectra. These revealed frequency-dependent dynamic amplifications of relatively high magnitudes. Bratland, Bjerketvedt and Vaagsaether [31] argues that this must be taken into consideration when designing components and systems that are intended to remain structurally intact and operational in the aftermath of VCE events in confined spaces with high aspect ratios, such as tunnels.

Hydrogen deflagration can transit to a detonation, whereby the flame speed is increased from about 350 m/s to 2200 m/s with a substantial increase in over pressure [22]. For most practical cases the characteristic space dimensions, L, and the detonation cell size, λ needs to fulfill the following condition for detonation [2];

$$L/\lambda > 7$$

The detonation cell size depends on the hydrogen concentration and is very large for lean or fat mixtures. For 30-40 % mixture it is as low as 10 mm[2]. For a tunnel or channel with diameter D and length L, the run-up-distance to detonation, L/D, needs to be between 20 and 40 [2]. For stratified hydrogen clouds in tunnels, the hydrogen layer height needs to fulfill the following condition for detonation [2];

$$h/\lambda > 13.5$$

According to Bjerketvedt et al [32], a transition to detonation inside a tunnel requires a fairly long gas cloud in relation to the tunnel diameter, e.g. a 500 m gas cloud for a 6 m diameter tunnel. Therefore, a detonation in a tunnel requires a large release, e.g. 40 kg of hydrogen at 35 MPa and delayed ignition after 30 s [33]. In addition, congestion induced by vehicles in a tunnel or garage needs to be considered.

Hydrogen is more prone than hydrocarbons to create significant explosions or even detonations in enclosed spaces. According to FM Global [34], the release of hydrogen in enclosures such as underground car parks (not tunnels) lead to explosion in three out of four cases. A leak at a large release rate will become more turbulent and entrain more air into the jet and plume which create a more uniform distribution of hydrogen. Low release rates will be dominated by buoyancy and create more stratified layers with higher concentration near the ceiling [34].

### 3.1.4 Pressure vessel explosion

According to Molkov and Kashkarov [35] there are two groupings in the international safety community around this issue, one group of experts assume that the likelihood of a rupture is so small that the scenario could be removed from the risk analysis due to the rigorous testing of road vehicle hydrogen containers. Another group of experts thinks that the catastrophic tank failure, especially in fire conditions, must be part of risk analysis. The second position is according to Molkov and Kashkarov [35] supported by industry statistics. The catastrophic tank failure may be even greater for hydrogen since experiments show that leaks through crack immediately develop to catastrophic failure, i.e., pressure vessel explosion.

A pressure vessel explosion following a local fire exposure on a 190 l CNG tank was reproduced by Gehandler and Lönnermark [9]. The pressure wave at 5 m distance was above 100 kPa, which is fatal. The tank pressure at rupture after almost 20 min local fire exposure was 22 MPa (raised from 15 MPa). NWP was 20 MPa and the composite container burst pressure without fire was tested to be 61 MPa [9]. However, as stated above, local fire has been considered to some degree in the GH2 vehicle regulations.

Molkov and Kashkarov [35] developed a model for hydrogen pressure vessel explosion that accounts for the mechanical energy (i.e., rapid release of high pressure gas) and the chemical energy from hydrogen-air combustion. For a stand-alone tank explosion, 5% of the stored chemical energy contributes 1.4 times the mechanical energy to the initial overpressure peak for the scenarios investigated. For an under-vehicle tank rupture 9% of the chemical energy contributes 30 times the mechanical energy. The rest of the energy is combusted later and contributes to the fire ball and possibly secondary overpressure peaks. The explosion from the under-vehicle tank is lower in the near field since much energy is used to displace the vehicle. This results in increased turbulence and a slower propagation which results in more time for combustion to contribute to the blast wave strength. The models were validated against experiments.

Molkov and Dery [36] have investigated the blast wave decay correlation for a hydrogen tank rupture in a tunnel fire. Compared to high explosives, a compressed gas tank rupture has lower initial pressure, slower decay with distance, longer positive pressure phase duration, larger negative phase amplitude and stronger secondary shocks. In the far-field, the blast wave from a stand-alone or under-vehicle tank rupture in a fire has a similar strength [37]. The loss of mechanical energy to demolish and translate the vehicle is compensated for by an increase in chemical energy due to higher rate of turbulent combustion under the vehicle. However, in the near field the presence of a vehicle above the tank decreases the blast wave essentially. For tunnel explosions two zones can be defined as follows. Zone 1, near the explosion is dominated by reflections from the tunnel walls [36]. Zone 2 is dominated by a one-dimensional planar blast-wave propagation where the overpressure is mostly dependent on the tunnel height. As an example, a 70 MPa, 62 l tank rupture in a long tunnel with a cross-section area 56.4 m$^2$ (the Laerdal tunnel in Norway), result in fatality (>100 kPa) within 15 m, serious injury (16.5 - 100 kPa) within 190 m, and slight injury (1.35 - 16.5 kPa) within 7 km from the tank rupture ("best fit" values, more "conservative" values were also calculated). In other words, this is a serious and problematic event, would it occur, e.g. during rescue intervention [38]. Real experimental data on hydrogen pressure vessel explosions inside a French road tunnel [39] confirms that many pressure peaks (e.g. from reflections and secondary chemical energy explosions) were recorded, and often the first peak (mechanical energy explosion) was not the highest peak. Contributors to later peaks can be wall reflections or hydrogen combustion (i.e., chemical energy), or both. Since the horseshoe cross-section of the French tunnel was not constant, the pressure wave increased when the cross-section went from 41.3 m$^2$ (zone 1) to 33 m$^2$ (zone 2, planar wave) at 87 m from the explosion. Up to that point the overpressure was diminishing, e.g., from 20 kPa at 30 m to 16 kPa at 80 m for a 78 L Type IV tank filled with 520 MPa hydrogen. When the cross-section was constant again, the pressure wave amplitude was slowly decreasing along the tunnel. The experimental values correlate well with Molkov and Dery's [36] "best fit" estimation, although most experimental measurements are slightly less conservative. The tests confirm that a fraction of the chemical energy contributes to the mechanical blast wave resulting from the pressure drop at rupture [39]. The French tests compare the pressure wave between a rupture of Helium (no chemical energy) and hydrogen (including chemical energy) at similar mechanical energy, i.e. pressure. The pressure wave in a tunnel looks very different compared to the open because of wall reflections. Both impulse and overpressure are larger due to hydrogen deflagrations. Kudriakov, Studer, Bernard-Michel, Bouix, Domergue, Forero, Gueguen, Ledier, Manicardi, Martin and Sauzedde [39] finds that the maximum overpressure in test 7 and test 8 with hydrogen at 52 MPa or 61 MPa, respectively, in a 78 l tank exceed the French limit for significant lethal effects at several positions along the tunnel (which however had a fairly low cross-sectional area). The impulse in test 7 was above 1000 kPa*ms, which is very high, as can be seen in Table 2 below.

Table 2 Limit values for unprotected people outdoors according to NFPA 2 [40].

| Effects on people | Impulse [kPa*ms] |
|---|---|
| 50% blowdown | 60 |
| Lung haemorrhage | 180 |
| Severe lung haemorrhage | 360 |
| 1% serious injury from displacement | 370 |
| 1% fatality probability | 590 |
| 50% fatality probability | 900 |

The fireball diameter for an under-vehicle pressure vessel explosion (35 MPa, 88 l, 1.64 kg hydrogen, respectively) was measured to be 24 m (compared to merely 8 m for stand-alone tank). Heat flux measured at 15 m distance was recorded with spikes in the range 200-300 kW/m$^2$ (can be compared with the limit 35 kW/m$^2$ for 1% lethality in 10 s for unprotected people) [2]. The cylinder was found 40 m from the vehicle and fragments were found up to 107 m from the vehicle. Theoretical worst-case distances for a 165 l, 35 MPa, 79 kg heavy tank are 148 m and 365 m for projection angle 0° and 10° respectively [2]. According to Molkov and Kashkarov [35] models derived for hydrocarbons under-estimate the size of the fire ball, e.g., to 9 m in the 24 m experiment above, and should not be used.

MSB in Sweden have derived safety distances for the rescue service for incidents with alternative vehicles in tunnels [41]. One dimensioning criterion is the level of noise that led to permanent hearing disorder, set to 0.2 kPa without ear protection, 6.3 kPa with earplugs and 11.2 kPa with ear-muffs. Note that the 0.2 kPa limit is well within Molkov & Derry's "no harm" threshold (< 1.35 kPa), while the other two limits are within "slight injury”. Other dimensioning criterias are a temperature of 260 °C or a heat radiation at 20 kW/m$^2$ for the rescue service wearing protective smoke diving equipment. Runefors [41] has calculated risk distances for compressed gas jet flames, fireballs, and pressure vessel explosions in the open and inside road tunnels. The prohibited area, i.e. where not ear-muffs offers sufficient hearing protection, for a 9 m wide and 4.5 m high straight tunnel for a GH2 light vehicle was estimated to 160 m and for a GH2 bus the whole tunnel becomes a prohibited area [41].

## 3.2 Liquified hydrogen

An LH2-tank has a similar construction as an LNG-tank, i.e., similar to a large, insulated thermos with vacuum and insulation between the inner and outer tank. This is an advantage in case of fire since the heat from the fire will take a long time to heat the LH2 inside, as long as the insulation is intact.

One apparent hazard with liquid hydrogen systems is the risk of cryo-burns when human skin or soft tissue comes into contact with cold system surfaces or released cryogenic hydrogen [42]. Other hazards relate to boil-off, slower dispersion, BLEVE, pool fires and potential localized oxygen enrichment [I$_{PA}$].

### 3.2.1 Leakage and release

For LH2-powered vehicles, or LH2-transportation, the initiating leakage-event could be a pipe failure (i.e., continuous release) or the catastrophic failure of a storage tank (i.e., instantaneous release). The processes of release and subsequent distribution of a gas is strongly dependent on its thermodynamic state during storage. LH2 will leak, either as a saturated vapor (single-phase release) or as a liquid which starts to vaporized immediately (multi-phase release), depending on the leak location [22]. The pressure relief from system to atmospheric pressure results in spontaneous vaporization of a certain fraction of the liquid. A two-phase jet is formed, containing vaporized hydrogen and LH2 which may (the release of liquid hydrogen will initially quickly evaporate) eventually reaching the ground and form a pool, after a while, or for larger release amounts. The cold vaporized hydrogen will expand with increasing temperature. The vaporized, but still cold gas will have less buoyant behavior and a tendency of horizontal spreading with strong concentration fluctuations [43]. The pool increases in size when the ground is being cooled. The main heat source for the pool is heat conduction from the ground, even if the pool would be burning, since hydrogen flame radiation is very low. Surface roughness and porosity affect the surface area and thus the heat transfer, e.g., gravel increases the vaporization rate. Thermal interaction between the cryogen and water can lead to a rapid evaporation of hydrogen gas. However, ice formation can reduce the thermal interaction, e.g. for LH2 spillage onto a water surface [44]. Compared with other cryogenic gases of the same energy content, the LH2 pool will be smaller and last for shorter time periods. For instance, the continuous release of 40 m$^3$ LH2 over 40 s at a constant rate, will result in an LH2 maximum radius pool size at 10 m and disappear shortly after the release is terminated, whereas, e.g. the same release of 40 m$^3$ LNG will survive for 54 s [45]. Spills of liquid hydrogen can result in air condensing out in and around the pool of liquid. This can result in in the formation of solid, explosive mixtures of liquid hydrogen and solidified oxygen-enrichened air [1]. Note that asphalt becomes shock sensitive in the presence of liquid oxygen, which could pose a particular hazard for road transport at refueling stations or accident locations.

The spreading and dispersion behavior of a gas is significantly influenced by the density difference to ambient air. In the case of release of a neutral or negatively buoyant gas, mixing with air is poor and slow. Until the source rate equals the removal rate, the vapor cloud grows along the ground [22]. A visible cloud is formed when the cryogenic hydrogen gas condenses the ambient humidity which coincides fairly well with the flammable envelope [42]. Small amounts of LH2 tend to heat up very quickly and become buoyant.

For larger releases of LH2, the vaporized gas will remain near the ground for a longer time as the cryogenic hydrogen is much denser than ambient temperature hydrogen until it heats up becomes less dense and increasingly buoyant. However, even very large instant spills of LH2 do not create lasting hazardous situations that are typical to hydrocarbons spills [22]. Compared with other cryogenic gases of the same energy content, the LH2 pool will be smaller and last for shorter time periods. For instance, a large instantaneous spill of 80 $m^3$ is estimated to spread in a pool with a maximum radius of 27 m (32 m for 30 $m^3$ LNG) and a lifetime of 18 s (60 s for 30 $m^3$ LNG). The pool breaks up at the center already after a few seconds [45]. For rapid spills, thermal and momentum-induced turbulence cause the cloud to disperse to safe concentration levels and become positively buoyant. LH2 vaporization per mass is lower than the vaporization rate for other cryogens such as liquid oxygen, and about the same as LNG [44].

In the open (i.e., above ground) there is no propensity for LH2 vapor to reach detonation, though deflagrations are possible. In enclosures such as underground facilities the risk for secondary deflagration and even detonation needs to be considered. The low temperature slows down the flame propagation and lead to an increase of the flame front area and thus increase the burning rate. This leads to slightly more critical scenarios for LH2 compared to GH2 in enclosed spaces [42]. One of the most hazardous phenomena for LH2 is a potential tank rupture and BLEVE. Damage to insulation on cryogenic components may cause air to liquify, which then becomes preferentially oxygen enriched with localized severe combustion hazards.

From more than 500 tests and various incident databases, Jordan and Saw [42] conclude that a release of LH2 (no ignition in about 60 % of incidents) is much less probable to ignite than release of high pressure GH2 (ignites in above 90 % of all reviewed incidents). However, it should be noted that this depends on the environment and application, perhaps those involving LH2 (space., etc.) are more controlled than GH2 (more common place).

### 3.2.2 Boiling liquid expanding vapor explosion (BLEVE)

If the tank is exposed to an external fire, the LH2 and cryogenic gas inside the tank will eventually heat up, which both expands the liquid and increases evaporation and both increase the pressure inside the tank, which leads to the opening of one or more pressure relief devices (PRD). If the insulation around the tank is designed like a thermos bottle and the vacuum is lost, the insulating ability will be drastically reduced even though the "thermos construction" will function as a flame shield. If the insulation also consists of insulating material such as perlite, the insulating ability will be maintained significantly better and the heat flow will be significantly more limited, which means that the safety valve may have great potential to keep the pressure in the tank at a safe level until the fire is extinguished or the hydrogen has burned out [5].

However, under extreme circumstances with damaged insulation, there is a possibility that the heat effect from the fire will be too strong so that the safety valve does not have time to handle the increase in pressure, which can then lead to the pressure rising further. As the tank's strength most likely decreases at the same time, this may lead to LH2 tank rupture, which can result in a BLEVE, if the liquid gas is heated above its superheat limit (around 30 K for hydrogen) at the time of tank rupture. When the vessel ruptures, the superheated liquid will flash and form a vapor. The explosion pressure primarily results from the physical rapid phase change and expansion when the hydrogen goes from liquid phase to gas phase and warms up to ambient temperature[3]. Firstly, the safety limit to avoid injuries in the open from the pressure wave following a BLEVE of a tank with 5 kg hydrogen in the open is around 50 m [46]. Secondly, the explosion pressure also results in dangerous projectiles being thrown up to one hundred meters. Ustolin, Paltrinieri and Landucci [46] calculated that projectiles could be thrown 65 m from a 5 kg LH2 BLEVE. Thirdly, a fireball is formed if the hydrogen-air mixture ignites which emits dangerous heat radiation for a few seconds. Ustolin, Paltrinieri and Landucci [46] calculated the fireball diameter to be 14 m (20 m according to experiment) and the resulting safety distance to avoid burn injuries to 80 m from the center of the 5 kg tank.

According to PresLhy [47], in case of fire on LNG tanks, the insulation material delays or prevents any BLEVE if the PRDs work. For uninsulated tanks, e.g. LPG a BLEVE can happen even if the PRD work as intended [47]. For well-insulated LH2 tanks, aLH2 BLEVE appears to be even less probable than an LNG BLEVE [22].

## 3.3 Consequences for underground structures

As was presented earlier, several explosions with road vehicle CNG composite tanks have occurred in the event of fire, which may be due to, among other things, a local fire exposure that does not reach the melt-fuse. At the same time, the plastic in the composite melts, which reduces the tank's strength. Although GH2 tanks ought to be safer than CNG tanks since they are designed to handle a local fire exposure for 10 min, they share the same failure modes including a pressure vessel explosion (unless the tank is of an explosion-free design, which, however, is not required) as a CNG tank. Such a pressure wave can be fatal in the open air in the vicinity of the container (within 5–10 m), but in an enclosed underground structure such as a tunnel, the situation is far worse because the pressure decreases very slowly along the tunnel, while the contribution from, for example, the subsequent deflagration of hydrogen gas becomes even greater on due to the enclosure. In addition, there are also health risks with projectiles.

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[3] The ratio of the final specific volume of gaseous hydrogen at NTP conditions to the initial specific volume of LH2 for the phase change from LH2 at NBP is approximately 845:1.

If the explosion occurs in an underground garage, the floors above may be at risk of collapsing. In 2011, there was a gas cloud explosion of LPG in an underground building built in reinforced concrete in Turkey [48]. LPG leaked into the building from a damaged pipeline. The basement level of the building was used as a textile factory but could have been an underground car park. The explosion took place in a limited space of approximately 10 × 30 m. The basement level lacked mechanical ventilation. Outer walls were encased in earth. Above ground there was a filling station for LPG vehicles. The damage to the structure of the building was extensive in the space where the explosion took place. Several columns were flattened as the pressure lifted the roof, so columns were pulled apart. Then the roof fell back down and pushed the pillars together. As a rule, reinforced concrete becomes stronger the higher the load they carry, thus they are sensitive to secondary pressure waves in combination with upward forces that remove load. For a building to withstand internal explosions, the building must have a strong frame structure that holds up the floors and roof. Columns must be well anchored in floors and walls if they are to withstand upward forces well. Afterwards, parts of the roof hung like a hammock inside the building and above ground, large parts of the concrete floor had been broken up. One person died on the basement level and 21 were seriously injured [48]. Thus, a hydrogen explosion inside a car park below ground with floors above could theoretically result in dramatic consequences.

A road tunnel is expected to withstand pressure of this order of magnitude because it partly has a stronger construction and partly because it is not closed, but pressure relief can take place at the portals. This is supported by explosions that have occurred in, for example, Moscow, Madrid, and London, where damage to, for example, trains has been extensive, while damage to the tunnel is limited to lighting and communication equipment. However, to humans the consequences from the resulting pressure wave can, as was reported earlier, e.g., from a pressure vessel explosion, be fatal within hundreds of meters and can cause health implications in a large part of the tunnel.

Another important issue is the risks posed to the rescue services with regard to hydrogen vehicles. Fires in tunnels and underground parking garages with conventional vehicles can already be a major challenge for rescue services. With the introduction of new energy carriers such as hydrogen, the complexity and the number of risks faced by the rescue services increases. For instance, due to the risk of explosion, Sweden have issued stringent safety distances for burning hydrogen vehicles inside road tunnels [49].

# 4 Risk evaluation

Diesel and gasoline are handled and distributed with relatively few incidents. Diesel is a less volatile fuel with a flashpoint of 60°C, such that no flammable mixture is formed at NTP[4], and an open fuel spillage cannot be ignited by a small ignition source. Diesel is however prone to ignite against hot surfaces, while gasoline is a very volatile and flammable fuel even at NTP [50]. Diesel is regarded as an acceptable fuel for underground work, whereas fuels with a lower flashpoint, such as gasoline and gases (e.g., hydrogen), are prohibited. In the case of hydrogen, its high buoyancy, low ignition energy, and high flame speed at higher hydrogen-air concentrations, increase the risks of using it in an underground environment, where the pressure decay is also much slower than aboveground conditions in the event of an explosion.

Hydrogen as an accepted vehicle fuel may require some experience and iteration before its handling and use above ground becomes as natural as the use of conventional fuels. However, some learning has already been made from the use of CNG and LNG. One main issue related to CNG has been the occurrence of explosions in pressure vessels made up of composite in the event of local fire exposure [9]. A local fire test has therefore been included in the standards for hydrogen vehicles (GTR 13 and R134).

Due to the required shut-off valve on both CNG and GH2 vehicle tanks, the likelihood of leaking gas that accumulates inside a an enclosure is reduced, yet a release of combustible gases may accumulate and could ignite inside enclosures. There is a great difference between studies that investigate potential worst-case scenarios and actual release experiments or simulations in a tunnel environment. Due to ventilation and entrainment of air into the gas jet or plume and the subsequent dispersion, the size of ignitable gas clouds is drastically reduced. This is particularly true for smaller hydrogen storages, e.g., road vehicles. It may seem unfair if, for example, the greatest safety benefit of hydrogen being its high dispersion and buoyancy was not included in hazard studies. For example, LaFleur, Glover and al. [24], report of a study where the theoretically worst scenario (a tunnel filled with a stochiometric gas cloud), following a dispersion study reduced the overpressure by two orders of magnitude. A tunnel filled with a stochiometric gas cloud is clearly beyond the worst credible case. A probabilistic study may also reduce the expected risk of a gas explosion. Naturally the most likely event is a hydrogen jet flame due to a fire that is not believed to compromise the strength of concrete tunnels, nor steel structures [24].

Nevertheless, an explosive event, e.g., a pressure vessel explosion, typically results in higher blast wave pressures in tunnels or enclosed car parks compared to open-air. A hydrogen explosion inside an underground infrastructure is thus categorized as a severe event that should be ultimately prevented. For road vehicles, HyTunnel [2] stipulates that the focus should lie on making hydrogen vehicles inherently safe (e.g., through requiring explosion-free composite tanks), rather than changing existing infrastructure or developing novel mitigation measures related to infrastructure.

When it comes to the transportation of hydrogen, GH2 by road or rail is the least economic way to transport hydrogen. Since the TPED requirements are less stringent

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[4] Normal Temperature (20 °C) and Pressure (1 atm or 101.325 kPa).

compared to the UNECE road vehicle regulation, e.g., no fire test or TPRD required in TPED [21], it is also the least safe way, more risky than methane, for instance in the open, and even more risky in underground spaces. A more efficient and safer way to transport hydrogen is as LH2. According to PresLhy [22] that reviewed incident databases, LH2 delivery, transfer, and storage have an impressive overall safety record. Events like BLEVE or fireballs, typical for liquified hydrocarbons (primarily LPG and to a lesser extent LNG), appear to be rare. PresLHy that a smaller flash fire is the more probable outcome of an LH2 container rupture given that most hydrogen is in liquid form and thus cannot ignite at once. However, inside enclosures such as tunnels, secondary explosions of cold H2 vapor could lead to similar or even more severe explosions than for compressed hydrogen. It seems that fire exposed LH2 tanks are fairly robust (through the thermal insulation and at least two independent PRDs) and pose a small risk. The safest and most economical way to transport large amounts of hydrogen is as a gas by pipeline which would reduce hydrogen transportation by road or rail through tunnels.

## 4.1 Risk mitigation

Compressed and cryogenic hydrogen has been used safely for many years in secure and regulated industrial sites. Industrial standards, codes and regulations governing its safe storage and distribution are well established. Its use in populated urban areas presents a new set of problems in relation to security, safety and planning [1], which relate to both hydrogen as a fuel and increased transportation of hydrogen. The transportation risk of GH2 by road or rail could be reduced by mandatory fire testing, TPRD requirements or other UNECE requirements such as shut-off valve on each cylinder [51, 52].

To avoid leakages, it is important to use suitable sealing interfaces and appropriate components when hydrogen systems are designed. Possible leakages or TPRD dimensions should be of limited sizes to avoid large ignitable clouds in underground facilities. According to Molkov and Kashkarov [35], safety strategies should mitigate the effect of fire on storage vessels. To prevent rupture of composite tanks, they could be protected by a fire resistant insulation or paint (thermal protection) [2, 35], or use an explosion-free design. In general, existing ventilation prevents that flammable gas clouds accumulate, reduce gas cloud sizes through dilution and limit the time an explosive atmosphere is present [2, 53]. According to HyTunnel-CS project fixed firefighting systems would be beneficial to break down possible hydrogen stratification and to inert the hydrogen-air mixture [53].

However, burning hydrogen pools or jet flames in underground facilities should not be extinguished as the vapors or gas will continue to accumulate, and subsequent ignition may cause an explosion instead. In most, if not all, circumstances it would be better to let the fire burn until the hydrogen is consumed. Below, a list (without any order of importance) of risk mitigation measures that have been identified for this report follows.

- TPRD and automatic shut-off valve on hydrogen storage tanks (already required for vehicles).
- double walled piping or encapsulated hydrogen equipment (e.g., fuel cells) that ventilate leakage to the open.
- On demand ventilation system that is sensitive to, e.g. hydrogen [5, 6] (to prevent hydrogen concentrations above 1 % according to IEC, ISO or NFPA standards [2],

but as is seen above 10 % or lower significantly reduces the reactivity and the resulting explosion pressure)

- Sensors and detectors for hydrogen gas, leakage (sound), etc.
- Igniters (early ignition is most often better than late, in particular inside enclosures)
- To take advantage of the high buoyancy and diffusivity at the hydrogen system design stage (a challenge below ground, but often utilized outside in the open).
- Explosion-free composite cylinders in the event of fire.
- Fire resistance insulation or intumescent paint for composite cylinders [2].
- Water spray system , e.g. in garages [5, 6, 54] or tunnels [53] for GH2 vehicles.
- Fire extinguishment and cooling of fire-exposed GH2 tanks [18] (However, water can prevent the proper functioning of TPRD and also freeze and block the PRD vents for LH2, which can lead to rupture or a BLEVE, and extinguishment of any burning hydrogen may lead to the accumulation of explosive mixtures in underground environments).
- An increase in tunnel ceiling height results in better dispersion for buoyant releases of hydrogen [2], and lower explosion pressure wave [36].
- An increase in tunnel cross section results in lower explosion pressures along the tunnel [36].
- Lesser hazard associated with horseshoe shaped tunnels than rectangular, due to higher ceiling, which allows further dilution prior to impingement, and also less momentum for the jet to get recirculated back towards the floor [27].

# 5 Conclusions

Each fuel has its unique risks linked to its specific properties and related hazards. Hydrogen in an underground environment entails additional and specific risks that need to be investigated, evaluated, and managed. In this report, the state of knowledge of liquid and compressed hydrogen gas in underground facilities has been compiled.

Unlike diesel, hydrogen (also natural gas and gasoline) has such a low flash point that an emission can be ignited at normal temperature by a small ignition source. Hydrogen is also very light and accumulates at high points in a subsurface environment and requires very low energy to ignite at or near stoichiometric mixing with air at around 30%. In subsurface environments, the containment contributes to a higher increase in explosion pressure wave, as well as an increased likelihood of explosion, compared to above ground. The handling of hydrogen underground is therefore problematic. On the positive side, however, the lower explosion limit is, compared to other flammable air mixtures high, above 8%, which means that many smaller releases in ventilated spaces will be too lean. The use of liquid hydrogen has, so far, an impressive overall safety record. Events like BLEVE or fireballs, typical for cryogenic hydrocarbons, appear to be rare.

For hydrogen as a vehicle fuel, there are possibilities to achieve equivalent safety with conventional vehicles, for example, thanks to the shut-off valve required on each tank that reduces the likelihood of significant leakage (required by international vehicle regulation), and through the use of TPRD (required) and explosion-free composite tanks (not required)  in the event of fire that provides a less dangerous fire scenario than a diesel or gasoline tank in case of fire.

For transporting hydrogen, pipelines are the long-term sustainable (and safe) alternative. Transport of compressed hydrogen gives a low amount of gas per trailer and entails relatively higher risks than CNG underground, for example in tunnels. The transport of liquid hydrogen provides a larger amount of hydrogen per trailer (than for compressed hydrogen) with a relatively lower risk than, for example, LNG for scenarios such as BLEVE, but an increased risk for leakage followed by explosion.

Fires in tunnels and underground parking garages with conventional vehicles can already be a major challenge for rescue services. With the introduction of new energy carriers such as hydrogen, the complexity and the number of risks faced by the rescue services increases.

Future research should focus on further development of explosion-free tanks and consider making this mandatory in international road vehicle standards, as well as investigating if it should be mandatory with hydrogen detection and ventilation in parking garages and road tunnels. The transportation risk of GH2 by road or rail could be reduced by mandatory fire testing, TPRD requirements or other UNECE requirements such as shut-off valve on each cylinder.

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