Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces

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Summary

An assessment has been undertaken to identify the factors that contribute to the extent and severity of an accident involving a FCH transportation system in a tunnel or a similar confined space. The objective of the assessment is to identify accident scenarios that will be used as the basis of the approach undertaken by the HyTunnel-CS project to identify how the consequence of accident in a tunnel or confined space may be different to a comparable accident in an open environment and what should be safety strategies and engineering solutions to underpin inherently safer deployment and use of hydrogen vehicles in tunnels, underground parking, garages, etc.

As an output from the work ten accident scenarios have been identified which align with the HyTunnel-CS research proposal. Each scenario is described in terms of fixed factors and accident variables that combine to describe the scope and range of the scenario. A number of key aspects have been identified through this approach.

The credible transportation modes that should be assessed are cars, buses and trains. These three modes of transport represent those sectors that are likely to see the largest uptake in FCH technology. These modes also encompass a wide range of onboard hydrogen storage quantities (5 to 400 kg hydrogen) which if assessed fully will allow a thorough understanding of the consequences, and allow the project to make robust conclusions and recommendations for stakeholders.

It has also been identified that blowdown volumes following TPRD initiation by fire may, in the worst case, lead to discharge of the full hydrogen inventory simultaneously. Where TPRDs are interconnected then a prolonged discharge through a common vent may occur.

The identification of these two aspects may require some modification to the proposed research programme to take account of larger quantities of release hydrogen and in environments with differing geometries (i.e. to take account of the different designs characteristics of trains and railway tunnels)

These identified scenarios are proposed based on knowledge available at the time of preparation and include processes of release and dispersion of unignited hydrogen, interaction of hydrogen jet fire with structures, pressure and thermal loads from explosions, including tank rupture in a fire in case of TPRD failure to operate or blockage during an accident. Through the progress of the HyTunnel-CS project the focus on particular scenario descriptions may change due to the findings of the research.

Keywords

Hydrogen safety, scenarios, hazards, consequence assessment, unignited release, jet fire, deflagration, detonation, quantitative risk assessment.

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Nomenclature and Abbreviations

ACH	Air Changes per Hour
AFFF	Aqueous film forming foam
CEA	Commissariat a L'Energie Atomique et aux Energies Alternatives
CFD	Computational Fluid Dynamics
CGH2	Compressed gaseous hydrogen
CNG	Compressed natural gas
CS	Confined space
DDT	Deflagration-to-detonation transition
DTU	Danmarks Tekniske Universitet
EMS	Experiment, modelling and simulation
FCEB	Fuel cell electric bus
FCET	Fuel cell electric train
FCEV	Fuel cell electric vehicle
FCH	Fuel cell hydrogen
FCHGV	Fuel cell heavy goods vehicle
FCHGV	Fuel Cell Heavy Goods Vehicle
FCH-JU	Fuel cell hydrogen joint undertaking
FEM	Finite Element Modelling
FRR	Fire resistance rating
HGV	Heavy goods vehicle
HRR	Heat release rate
HSE	Health and Safety Executive
ICE	Internal combustion engine
KIT	Karlsruher Institut Fuer Technologie
LFL	Lower flammability limit
LH2	Liquid hydrogen
MIE	Minimum ignition energy
NCSRD	National Center For Scientific Research "Demokritos"
NTP	Normal temperature and pressure
OEM	Original equipment manufacturer
PIARC	Permanent international association of road congresses
PPP	Pressure peaking phenomena
PRD	Pressure relief device
PS	Pro-Science
QRA	Quantitative risk assessment
RCS	Regulations, Codes and Standards
SSD	Stopping sight distance
TPRD	Thermal pressure relief device
TSI	Technical specification for interoperability
UFL	Upper flammability limit
USN	Universitetet I Sorost-Norge
UU	University of Ulster

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1. Introduction

Fuel Cell Hydrogen (FCH) vehicles represent a valid alternative to replace current internal combustion engines. The use of FCH vehicle coupled with transportation of compressed gaseous hydrogen (CGH2) and liquefied hydrogen (LH2) in tunnels and other confined spaces such as underground car parks, maintenance shops, garages, etc. creates new challenges to provision of life safety, property and environment protection at acceptable level of risk. Several studies have showed that confinement and/or congestion can promote severe accidental consequences compared to accidents in the open atmosphere. There is a strong need to develop validated hazard and risk assessment tools for the behaviour of hydrogen in tunnels, as concluded by the internal HyTunnel project by European Network of Excellence HySafe (NoE HySafe) (HyTunnel-D111, 2009).

1.1 Scope of HyTunnel-CS

HyTunnel-CS will specifically examine the consequences of potential accidents associated with the onboard hydrogen storage system used in FCH transportation. The scope of the project is primarily limited to the high-pressure storage vessel and associated fittings that may operate at high pressure and release large quantities of hydrogen at short time. In assessing the consequence, the project will determine the extent and severity of an accident but will not determine the frequency of a particular accident pathway. The project aims to identify prevention and mitigation strategies and engineering solutions for inherently safer use of hydrogen, including tunnels and similar confined spaces.

Whilst there may be parallels with bulk transportation of compressed hydrogen in tube trailers the project will not examine accidents or consequences that may occur with transportation of compressed hydrogen in this way. Similarly, the project will not consider accidents or consequences with transportation of liquid hydrogen, either as the fuel for vehicles or as transported in bulk unless results of the project are applicable to LH2 applications.

2. Objectives

The present report forms part of the HyTunnel-CS programme of work and undertakes an examination of the factors that will contribute to the initiation of an accident and the development of the resulting consequence. The output from this assessment will be identification of accident scenarios that will be used as the basis for the HyTunnel-CS project, and used to specify research activities including experimental studies, numerical simulations, and the development of engineering tools. Ultimately these scenarios will be used as the basis for assessing the effectiveness of the current Regulations, Codes and Standards (RCS) relevant to FCH transportation. Overall the project will make recommendations for inherently safer use of hydrogen vehicles in underground transportation systems, harmonised recommendations for intervention strategies and tactics for first responders, and recommendations for RCS.

Specifically, this report will:

- Identify the transportation modes that will be the early adopters of FCH technology;
- Assess the key features of transportation infrastructure (tunnels and similar confined spaces) that may contribute to the extent and severity of an accident involving a FCH vehicle;
- Identify factors that lead to initiation of vehicle accidents and the relevance of these factors to accidents with FCH transportation;
- Provide an understanding of fire and explosion safety issues associated with high pressure hydrogen fuel transportation;
- Describe the typical hydrogen storage system design for the different modes of transportation;
- Define the key accident scenarios that will be assessed in the HyTunnel-CS project;
- Identify the variables that should be assessed to allow an understanding of the contributing factors to the extent and severity of an accident;
- Identify mitigation approaches that should be assessed to allow safety recommendations to be made;
- Review the existing knowledge and tools to allow quantification of risk associated with hydrogen in confined spaces; and
- Review knowledge gaps in quantification tools to be addressed in subsequent work packages of HyTunnel-CS project (model development, simulation, experiments, mitigation).

The accident scenarios identified in this report will focus on the consequences of accidents and how design and operation of the physical environment and the FCH transport mode contribute to the quantification of the hazard. As a result of this approach barriers and layers of protection will not be explicitly focused upon; however the experimental, modelling and simulation research may examine how design features and mitigation measures affect the consequence.

2.1 Outcomes

The analysis presented in this report, and in particular the description of accident scenarios will be used to define the key elements of research programme that will be undertaken in:

- Work package 2 – Effect of mitigation system on the hydrogen release and dispersion in confined spaces;
- Work Package 3 – Thermal and pressure effects of hydrogen jet fires and structural integrity; and
- Work package 4 – Explosion prevention and mitigation.

In the first instance a detailed description of the research programme and expected results will be produced by partners for each of these work packages (D2.1, D3.1 and D4.1 respectively) and should be aligned with the accident scenarios described in this report.

3. Approach

3.1 Definition of Accident Scenarios

An accident scenario is defined as the collection of relevant parameters that contribute to the accident outcome. For the purpose of identification and analysis these parameters have been grouped into five categories, which are:

Table 1 Accident scenario parameter categories

Transportation Mode	FCH has been developed or proposed for a number of different modes of transport; however, each mode may have design and operation characteristics.
Infrastructure	Attributes inherent in the design of the tunnel or the confined space.
Accident Initiators	The initiators that lead to an accident occurring that may have an effect on the outcome. The prevalence of these factors will ultimately be dictated by current statistics on accident rates.
Consequence	Outcomes that can arise due to loss of integrity of the FCH storage system or other high-pressure equipment. Generic hazards that may occur in any accident event involving gaseous fuel.
Hazard Variables	The design features of the FCH storage system that contributes to the extent or severity of an accident.

In Section 4, each category is reviewed to identify the parameters that may contribute to the severity of the accident scenario. Where a parameter is deemed to be relevant, then a credible range of values will be identified. In some cases the range may be binary (e.g. present/not present), while for others it may be a range of potential operating values, and where feasible a default/typical value will be given.

3.2 Representative Set of Scenarios and Prioritisation

Arising from this analysis will be a high level representative set of accident scenarios that are described by a number of key parameters, such as release type, transportation mode or confined space type. The representative set will be identified so that the scenarios align with broad descriptions that are relevant to the development of hazard and risk assessment tools.

The scenarios in the representative set will be further defined by a range of scenario variables that will fully describe the particular situation. One of the key objectives of this report is to identify the range and importance of these extended variables. The project as a whole has finite resources to undertake experimental data collection and modelling/simulation assessment of accident scenarios; therefore, the variables for each scenario will be ordered into three broad groups to facilitate research programme design. The variable group, which are described in Table 2, are Baseline, Safety Limit and Mitigation.

Table 2 Variable type used to identify scenario prioritisation

Variable Group	Purpose
Baseline	Standard operation conditions for either the infrastructure or the mode of transport – this will allow baseline assessment of the overall consequences to be characterised.
Safety Limit	Consequence characteristics should be assessed across the full range of foreseeable operations, so that there is confidence in the conclusions and recommendations made by HyTunnel-CS. The safety limits are operating conditions that are beyond typical operation but could occur due to low frequency high consequences events, e.g. as a result of component deterioration or failure.
Mitigation	Where it is expected or identified that accident consequences in confined spaces pose hazards not currently appreciated by prevention and mitigation strategies, then modification to accident factors may be assessed so that the HyTunnel-CS project can make evidence based recommendations.

In assessing each accident scenario the prioritisation approach should be to identify the extent and severity for the consequence under the baseline conditions in the first instance. If the findings from those conditions do not result in a hazardous event e.g. no formation of the flammable atmosphere then the safety limit variables should be explored to determine how the scenario variables can be relaxed or modified before a hazardous consequence occurs. Similarly if the baseline conditions do result in a hazardous consequence then examination of both the safety limit and mitigation variables should be undertaken. The safety limit variable will lead to an understanding of how the consequence may escalate under foreseeable operational conditions, and the mitigation variable will allow an understanding of what recommendations can be made that have the potential to reduce the risk profile of FCH transportation.

4. Description of Accident Factors

The five core elements that make up the complete description of an accident scenario are assessed in this section. For each element, pertinent factors are reviewed and those that are relevant for the accidents occurring in tunnels and confined spaces are identified and proposed to be used in the HyTunnel-CS research programme.

4.1 Transportation Mode

FCH has been developed or proposed for a number of different modes of transport; however, each mode may have design and operational characteristics that may lead to different physical processes dominating the development of the consequences and/or give rise to different scales of event. This section briefly reviews the development of the industry with a view to identifying the prevalent modes of transportation and some of the key design and technology factors that may influence consequence development.

4.1.1 Road

FCEVs have been under development for more than 15 years, with Toyota, Hyundai and Honda being the primary OEMs leading development of technologies. More recently, other car manufacturing groups (e.g. BMW and Daimler) have been promoting their prototype vehicle designs or technological advancements. As of June 2018, there were estimated to be globally 6500 FCEVs on the road. As the vehicle costs become more competitive and the refuelling infrastructure develops, consumer uptake is calculated to increase more quickly. It is projected that by 2030 there will be 1.6m FCEVs in the UK with annual sales of more than 300,000 (H2Mobility, 2019).

Taking the Toyota Mirai vehicle as a reference, the typical dimensions of a FCEV may be taken as 4890 mm length, 1810 mm width and 1535 mm high (Toyota, 2019a).

The development of FCEBs is being promoted through a number of FCH JU projects, such as HyTransit, HighVLOcity, Merlin and Jive. As a result of these subsidies, there are 16 FCEB demonstrations underway across Europe, with a further 23 in development (as of October 2019).

Taking the Toyota Sora hydrogen fuel cell electric bus as a reference, the typical dimensions of a FCEB may be taken as 10 525 mm length, 2490 mm width and 3350 mm high (Toyota, 2019b).

It is expected that FCEVs and FCEBs will become established road users and therefore the hazards that they pose should be assessed in HyTunnel-CS.

Hill et al. (2019) assessed the potential options for decarbonisation of the freight industry. The study identified that FCH transportation is more cost effective than other technologies (battery, range extenders or electrified road); however, due to the mode of operation FCHs may only be relevant to certain sectors. At present, there are a few examples of both small freight vehicles (small to medium rigid body vans) and larger articulated freight vehicles (HGVs). Whilst these designs may be in their infancy, it may be expected that in terms of the design, operation and safety systems of the onboard hydrogen storage there will be similarities between FC-HGVs and FCEBs (n.b. vent orientation may be different - down vs up, storage package design, etc.). For the purposes of the HyTunnel-CS research programme explicitly assessing FC-HGV separately is not required; however, it is noted that the freight cargo and the potential hazardous nature of some freight may provide additional fire loading not seen with a bus.

Other potential FCH road users include motorcycles, which is also an industry in its infancy. The onboard storage size would be considerably less than that found in domestic cars; therefore, consequences identified for cars would be conservative with respect to motorcycles.

4.1.2 Rail

Ruf et al. (2019) assess the use of fuel cell technology and hydrogen in the train sector in the EU. The report identified opportunities of FCH powered rolling stock to be a vital part of a zero carbon rail network. In parallel with hydrogen trains, there are also are battery powered trains and existing electrified infrastructure that will complete the decarbonisation of the rail network.

The implementation of hydrogen fuel cell trains (FC-Train) is only just starting to be realised in Europe. Two prototype trains are in service in Germany, with two fleets totalling 41 trains due to enter service by 2022. The market analysis of the EU rail sector demonstrated that FCH trains could take a market share of up to 41% by 2030 in the high scenario. With this potential development, FCH trains could become a disruptive game changer for the remaining CO2 emissions in the rail sector (Ruf et al., 2019).

In comparison to road vehicles, there are substantial differences with rolling stock and the design of rail tunnels (e.g. size of storage, relative size of trains to tunnel cross-sections, differences in forced ventilation) that make translation of road simulations to rail less reliable. Therefore, it is suggested that trains and train infrastructures are valid accident scenario factors for HyTunnel-CS.

4.1.3 Other

Other uses of fuel cell hydrogen transport include shipping and aerospace. Whilst development in these areas is underway (e.g. FCH drone aircraft and FCH shipping), the level of technology readiness is deemed to be too low to warrant assessment in HyTunnel-CS. However, findings from HyTunnel-CS will be relevant to hazard analysis within aspects of the design of these systems e.g. the confinement within tank connection spaces

In the first instance data, modelling and RCS development obtained from HyTunnel-CS may be applied to analogous environments (e.g. boats/ships in yards, long canal tunnels and aircraft hangers). Additional the output from HyTunnel-CS will be relevant when considering the transport of FCH vehicles (cars, buses, HGV) on ferries, where vehicle will be located in confined space with similarities to underground car parking

4.1.4 Summary

Table 3 presents a summary of the relevant transportation modes.

Table 3 Transportation modes

Transportation mode	Priority
Car	High

Transportation mode	Priority
Bus	High
Train	High
HGV	Medium
Motorcycle	Low
Ship	Low
Aircraft	Low

4.2 Infrastructure

Infrastructure encompasses all structural components, ventilation and other electromechanical equipment, i.e. attributes fixed by the design and/or operation of the confined space facility.

Due to the design and operation of the mode of transportation, tunnel design may be subdivided as road or railway tunnels. Furthermore, there is potential for cars, buses, HGVs and trains to be fuelled with hydrogen; therefore, it becomes relevant to consider both road tunnels and railway tunnels in the selection of accident scenarios. There are fundamental differences between these two types of tunnel which may affect the behaviour of an accident scenario. Background information for the relevant infrastructure parameters is provided below in order to recommend different variables to consider in the project. However, it is acknowledged that for the HyTunnel-CS experiments, the actual parameters would be set by the available test facilities.

4.2.1 Road Tunnels

The EU Directive 2004/54/EC identifies the minimum safety requirements for tunnels in the trans-European road network (European Union, 2004). The directive identifies a wide range of design features and operating regimes for tunnels. Elements of tunnel design that have been identified as relevant to the outcome of an accident involving a FCH vehicle are:

- Tunnel length;
- Number of tubes;
- Number of lanes;
- Lane width;
- Traffic direction;
- Cross-section shape;
- Cross-section diameter/area;
- Vertical alignment; and
- Horizontal alignment.

Other factors included in the EU Directive, which whilst relevant for the occurrence of vehicles accidents, do not directly affect the extent and severity of a consequence of a FCH vehicle are:

- Traffic volume;

- Type of construction (see in Section 4.2.3);
- Risk of congestion (daily or seasonal);
- Access time for the emergency services;
- Presence and percentage of heavy goods vehicles;
- Presence, percentage and type of dangerous goods traffic;
- Characteristics of the access roads;
- Speed considerations; and
- Geographical and meteorological environment.

4.2.1.1 Tunnel Length

EU Directive 2004/54/EC (European Union, 2004) categorises tunnels according to their length; lengths considered in the directive are ≤ 500 m, 500-1000 m, 1000-3000 m and > 3000 m. However, there are a significant number of tunnels that are shorter than 500 m. The Australian standard AS 4825-2011 on Tunnel Fire Safety indicates that any enclosed roadway less than 80 m long is defined as an underpass, a tunnel is 80 – 120 m long and a long tunnel is that one with a length greater than 120 m (Austroads, 2019). Accident frequencies in tunnels with different lengths have been analysed (Norwegian, 1997); tunnel length classification used in the analysis was 0-100 m, 101-500 m, 501-1000 m, 1001-3000 m and > 3000 m. The latter tunnel length ranges are proposed as factor variables. The length of a tunnel has a very substantial influence on relative accident rates and particularly tunnels of less than one kilometre length have higher accident rates relative to longer tunnels (Nussbaumer, 2007).

Tunnel length has the potential to affect the dispersion and/or flame propagation behaviour of a hydrogen release. Furthermore blast wave after tank rupture in a fire could propagate along the entire tunnel length with little decay. Tunnel length also has implications for emergency response times and evacuation from accident locations. Therefore, tunnel length is assigned as high priority in the research programme.

4.2.1.2 Number of Tubes

Typical road tunnels may be single tube or twin-tube, i.e. lanes in both directions are located in a single tube or bore, or the opposing traffic direction is segregated in a dedicated tube. The main criteria in deciding whether to build a single or a twin-tube tunnel should be projected traffic volume and safety: if the projected traffic volume is low, a single tube tunnel can be built, and if the projected traffic volume is high, a twin-tube tunnel is required. However, tunnel length and topographical conditions as well as the percentage of heavy goods vehicles may also influence the decision in favour of one or more tunnel tubes (UNECE, 2001). Where tunnel forecasting for 15 years shows a potential volume of over 10000 vehicles per day per lane, a twin-tube tunnel with unidirectional traffic shall be in place by the time this value is exceeded (European Union, 2004). Compared with single tunnels with bi-directional traffic, twin-tube tunnels have half the risk of accidents and casualties (HyTunnel-D111, 2009).

This factor is considered to be of low priority because it does not have an impact on the sequence of an accident scenario; however, the number of tubes would affect the number of lanes (see below) and consequently the size of the tunnel cross-section, which is a key aspect in relation to development of the accident consequences.

4.2.1.3 Number of Lanes

With the exception of the emergency lane, the same number of lanes shall be maintained inside and outside the tunnel. Any change in the number of lanes shall occur at a sufficient distance in front of the tunnel portal; this distance shall be at least the distance covered in ten seconds by a vehicle travelling at the speed limit. When geographic circumstances prevent this, additional and/or reinforced measures shall be taken to enhance safety (European Union, 2004). In a steeply graded bidirectional tunnel, a climbing lane might be provided by a three-lane carriageway, two lanes up and one down. Where adequate alternative routes can be provided, it may be advantageous to prohibit heavy vehicles from steeply graded tunnels (Highways Agency et al., 1999). The number of lanes in a road tunnel depends on whether the traffic is uni-directional or bi-directional and also on the number of lanes in each direction. To simplify things in this study, consideration of a maximum number of two lanes per direction in a tube is assumed; therefore, the number of lanes could be:

- One (uni-directional traffic – one lane);
- Two (uni-directional traffic – two lanes, or bi-directional traffic – one lane/direction);
- Three (uni-directional traffic – three lanes, or bi-directional traffic – one lane on one direction plus two lanes on the opposite direction); or
- Four (bi-directional traffic – two lanes/direction).

This factor has been given a medium priority; it is considered important because it impacts on the tunnel dimensions which are relevant for the accident scenarios, although it is expected that the cross-section width and height may be more relevant than the number of lanes.

4.2.1.4 Lane Width

European legislation indicates that, where the width of the slow lane is less than 3.5 m and heavy good vehicles are allowed, additional and/or reinforced measures shall be in place (European Union, 2004). The SafeT project report on tunnel safety recommendations (SafeT-D2, 2005) indicates that adequate lane widths could minimise the occurrence of accidents in one-directional and bi-directional road tunnels and offer better access for rescue services in case of an accident. Also, this document includes regular cross-sections for tunnels in Germany; these show that the most common lane widths are 3.5 m and 3.75 m. As the EU Directive indicates that lanes could measure less than 3.5 m, the proposed lane width variables are ≤ 3.5 m and > 3.5 m. Priority for this factor has been assigned as low because there are other factors that better define the tunnel dimensions, such as tunnel length, cross-section shape, cross-section width and height, and number of lanes.

4.2.1.5 Traffic Direction

Traffic can be uni-directional or bi-directional. There is a lower probability of head-on accidents in a one-way tunnel than in a bi-directional tunnel. In unidirectional tunnels with the possibility of daily congestion, similar measures should be taken into account as in bi-directional tunnels (UNECE, 2001). Traffic direction can then have influence on a hydrogen scenario because a vehicle crash can lead to a hydrogen release. Traffic direction can also impact on the consequences that a hydrogen accident scenario may have on people, either on the severity of people affected and also on the evacuation capability. On the other hand, it does not affect the hydrogen cloud development, nor the hydrogen fire/explosion behaviour. Therefore, traffic direction's priority is assigned as medium.

4.2.1.6 Cross-Section

Common cross-sectional designs for road tunnels are either rectangular (box profile) and horseshoe (arch profile). One of the findings of the previous HyTunnel project (Jordan et. al., 2011) was that horseshoe cross-section tunnels indicate lower hazard than equivalent rectangular cross-section tunnels with regards to flammable cloud volume and its longitudinal and lateral spread. The knowledge that cross-section shape is relevant to the outcome and the project's objective of trying the impact of different ventilation arrangements, fire suppression systems and shock wave strength and attenuation techniques, means that this factor is considered to be relevant and therefore it has been given a high priority.

In addition to accommodating the expected range of vehicle designs, road tunnels must enable the installation of equipment like lighting, ventilation, traffic management and safety technology. These elements should be located outside the clearance gauge (Maidl et al., 2014). The recommendations document resulting from the SafeT project (SafeT-D2, 2005) includes information on road tunnel cross-sections. Some of the information provided is detailed below:

1. The vertical clearance requirement in road tunnels is 4.6 m except for pedestrian and cycle tunnels. The vertical clearance specifications apply to the vertical distance measured on the carriageway boundary. Normal cross-sections will be in excess of this to allow for:
   - Extra clearance for subsequent road resurfacing;
   - Normal tolerance for tunnel linings, water and frost protection/concrete linings (total deviation of 0.1 m); and
2. Requirements for vertical clearance including kerbstone.

Normally, the tunnel cross-section will also include space for traffic signs and technical installations. The need for extra width locally must be considered in each individual case. The minimum height for technical equipment must be 4.8 m above the carriageway. For laterally-mounted equipment such as traffic signs etc., the clearance must be individually determined. With consideration to emergency exits, laterally mounted signs should be placed such that the minimum height below the sign is at least 2 m.

Some examples of cross-section tunnels are shown in Figure 1 (Maidl et al., 2014):

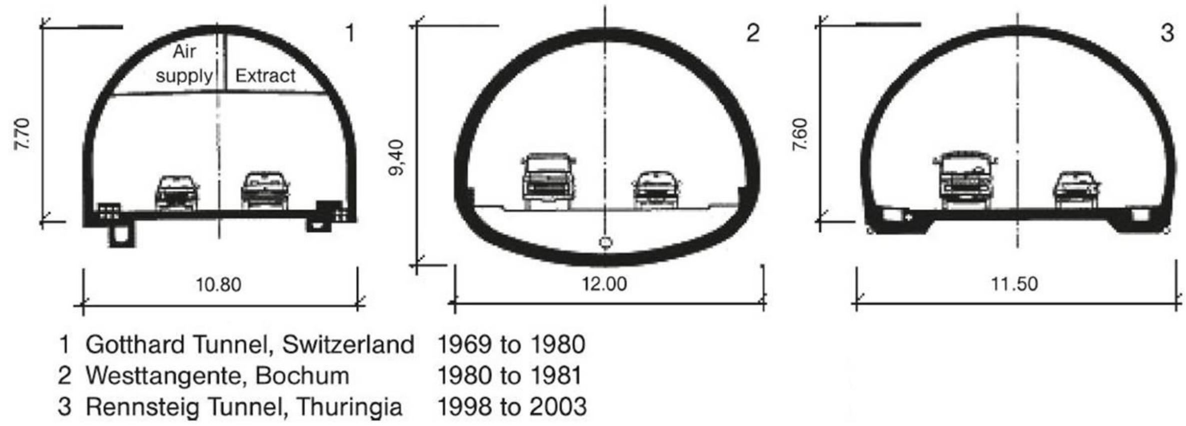

Figure 1 Examples of cross-sections (mined road tunnels)

The height of these tunnels is between 7.60 m and 9.40 m whereas the width measures between 10.80 m and 12.00 m.

Maidl et al. (2014) explain relevant aspects of the standard cross-sections for road tunnels in Germany (Figure 2). In tunnels intended for two-way traffic, the standard cross-section type 10,5 T has a 7.50 m paved width between the kerbs; the whole width of this layout is 9.50 m. The normal layout in tunnels with multi-lane carriageways in one direction should be a reduced standard road section without hard shoulders (26 t or 33 t), although it is justifiable under certain economic or traffic conditions to provide hard shoulders; the whole one direction width of the 26 t layout is 9.50 m and for the 33 t layout is 13.00 m. The reduced form of special cross-section 26 Tr should only be considered for tunnels to be driven with shield machines; in this case, the reduced hard shoulder replaces the breakdown bays along the entire length. Cross-section type 29,5 T is only worth considering for very short tunnels with a very low cost construction method.

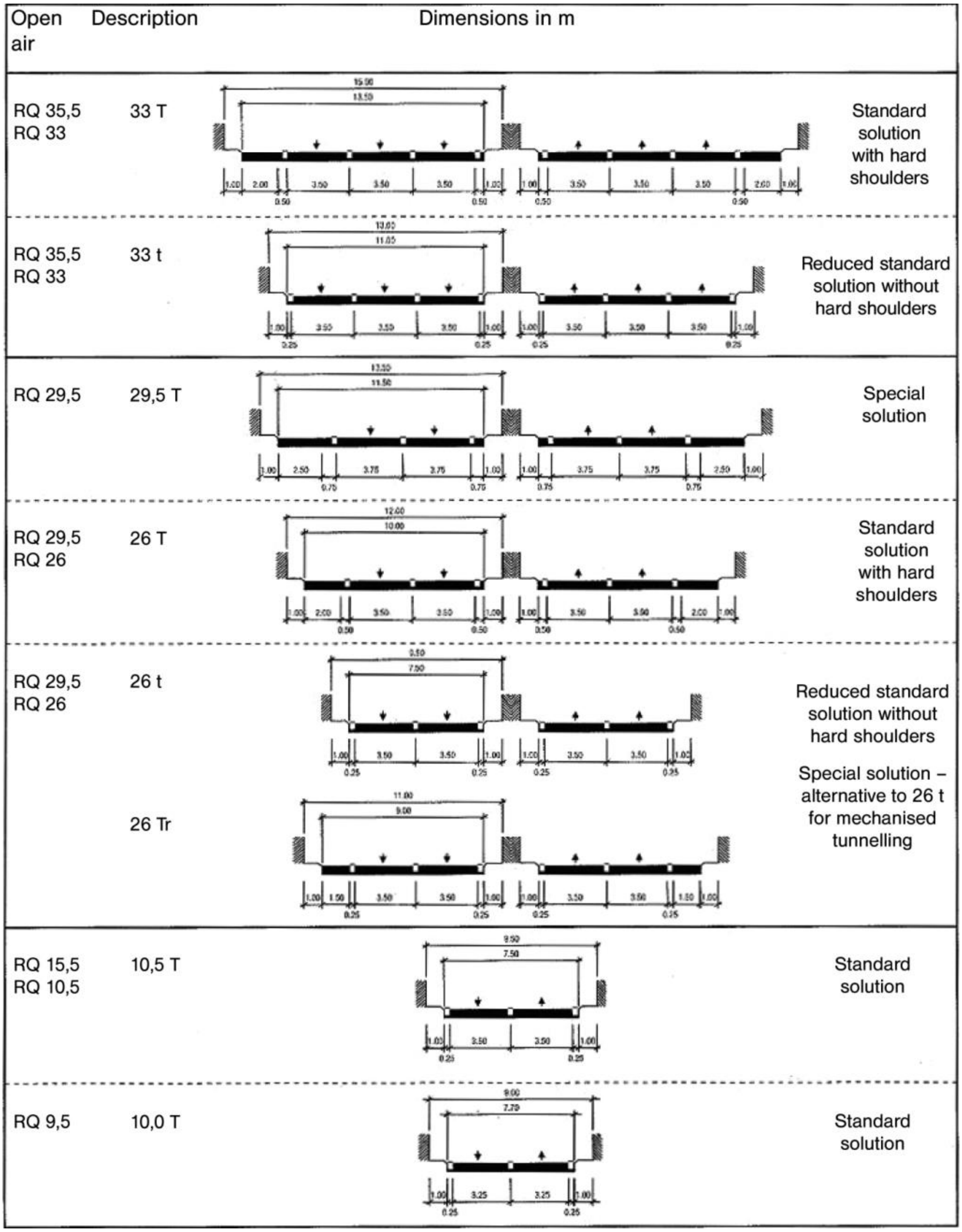

Figure 2 Standard cross-sections for road tunnels in Germany

As previously stated, tunnel dimensions can play a key role in the behaviour of a hydrogen release; for this reason, cross-section width and height are considered as high priority factors.

4.2.1.7 Gradient and Curvature

The road tunnel gradient may depend on the expected traffic density and ventilation. The maximum allowed slope is generally specified by national regulations and typical maximum values are 5% to 6% (HyTunnel-D111, 2009). Annex I of the EU Directive states that new tunnels should not have longitudinal gradients higher that 5%, unless no other solution is geographically possible. Also, it specifies that in tunnels with gradients higher than 3% additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis (European Union, 2004). In Norway, there are examples of older subsea tunnels with a gradient of 12%; Norwegian legislation now limit the gradient to 7%, which is also the maximum gradient in the Rogfast tunnel (Bjelland, 2013). Proposed gradients are ≤ 1%, 1-3%, 3-5%, and > 5%. It may be beneficial to understand whether slopes could have influence on the behaviour of a hydrogen release or a hydrogen fire; therefore, this is considered a high priority factor.

The Design Manual for Roads and Bridges (Highways Agency et al., 1999) indicates that the degree of horizontal curvature in road tunnels is restricted by the need to achieve the minimum Stopping Sight Distance (SSD). It is important to check the SSD for each horizontal curve, as it depends on the length of the curve as well as its radius and the tunnel cross-section. Table 4.4 of the manual shows horizontal curvatures in tunnels to provide SSD standards for a 2 or 3 lane one-way tunnels with 3.65 m lane width, 1 m hard strips and 1 m verges on both sides (Table 4):

Table 4 Horizontal curvature in road tunnels to provide SSD standards

Design speed (km/h)	Radius (m)
120	2850
100	1510
85	840
70	470
60	265

Bassan (2016) states that crash rates in road tunnels are higher when the radius is smaller; the publication presents a relationship between crash rate and horizontal radius. The horizontal radius groups shown are <150 m (0.31 crashes/million vehicles/km), 150-299 m (0.19 crashes/million vehicles/km), 300-599 m (0.12 crashes/million vehicles/km) and ≥600 m (0.08 crashes/million vehicles/km). The latter radius groups are suggested; straight tunnels should also be considered. Although curvature may affect the likelihood of a vehicle crash occurring, and consequently the likelihood of a hydrogen release, it is not relevant for the consequences, e.g. it is unlikely to affect the dispersion of characteristics; therefore, horizontal alignment has been assigned a low priority.

4.2.1.8 Traffic Volume

The EU Directive on road tunnels classifies traffic volume according to annual average daily figures and the categories established are ≤ 2000 vehicles/lane and > 2000 vehicles/lane (European Union, 2004). These could be the variables to use on traffic throughput; an alternative classification could be low, medium or high. Similarly to traffic direction, traffic volume can have influence on the likelihood of a vehicle crash and the possible hydrogen release that could follow, but also on the consequences of a hydrogen accident scenario. However, it does not have impact on the hydrogen release behaviour. Traffic volume is then considered a medium priority factor.

4.2.1.9 Summary

Table 5 presents a summary of the road tunnel geometry parameters, including the variables to consider and the priority of each factor.

Table 5 Road tunnel geometry factors

Factor	Variables	Factor Priority
Tunnel length	0-100 m 101-500 m 501-1000 m 1001-3000 m > 3000 m	High
Cross-section shape	Rectangular (box profile) Horseshoe (arch profile)	High
Cross-section width	9.50 m 11.50 m 13.00 m	High
Cross-section height	7.60 m 9.40 m	High
Vertical alignment - Gradient (slope)	≤ 1% 1-3% 3-5% > 5%	High
Number of lanes	1 - uni-directional traffic – one lane 2 - uni-directional traffic – two lanes 2 - bi-directional traffic – one lane/two directions 3 - uni-directional traffic – three lanes 3 - bi-directional traffic – one lane on one direction plus two lanes on the opposite direction 4 - bi-directional traffic – two lanes/two directions	Medium
Traffic direction	Uni-directional Bi-directional	Medium
Traffic volume	≤ 2000 vehicles/lane > 2000 vehicles/lane	Medium
Number of tubes	Single tube Twin-tube	Low
Lane width	≤ 3.5 m > 3.5 m	Low
Horizontal curvature	Straight tunnel 0-150 m 150-299 m 300-599 m ≥ 600 m	Low

4.2.2 Rail Tunnels

The EU Regulation No 1303/2014 concerns the technical specification for interoperability (TSI) relating to ‘safety in railway tunnels’ of the rail system of the EU (European Union, 2014). It defines a railway tunnel as an excavation or a construction around the track provided to allow the railway to pass for example higher land, buildings or water. Relevant factors that describe the design and operation of a railway tunnel are:

- Tunnel length;
- Number of tubes;
- Number of tracks;
- Track gauge;
- Traffic direction;
- Cross-section shape;
- Cross-section diameter;
- Vertical alignment; and
- Horizontal alignment.

4.2.2.1 Tunnel Length

The length of rail tunnels can vary significantly from one another; they can go from a few meters up to several kilometres. The Eurotunnel system, which connects the UK and France, is approximately 50 km long (CTSA, 1997). The EU TSI (European Union, 2014) states that the length of a tunnel is defined as the length of the fully enclosed section, measured at rail level; a tunnel in the context of this TSI is 0.1 km or longer. This TSI includes specifications for firefighting points, which are different depending on the tunnel length; length ranges are 1-5 km, 5-20 km and >20 km. Based on this classification, the following tunnel length ranges are proposed to be considered: 0-1 km, 1-5 km, 5-20 km, >20 km. Tunnel length is a parameter that could potentially have influence on the behaviour of a hydrogen release; therefore, priority for tunnel length is assigned as high.

4.2.2.2 Number of Tubes and Number of Tracks

Rail tunnels can be single tube double track and double tube single track; both types have their advantages and disadvantages. Double bore single track tunnels might be safer as they avoid accidents caused by derailments obstructing the adjacent track and they provide the second tube as a possible safe haven. On the other hand, double track tunnels have more space for possible rescue operations, but they also have more space for smoke and fire to spread. For high-speed trains, single bore double track tunnels might be preferable and for mixed traffic, taking into account aerodynamics factors, a single bore single track might be more appropriate. The choice should be the result of a thorough evaluation of all parameters (such as, for example, length of the tunnel, type of traffic, etc.) related to safety as well as cost considerations (UNECE, 2003). Number of tubes is considered a low priority factor because it has no effect on an accident scenario; number of tracks is taken as a medium priority factor because it affects the tunnel dimensions, although not as much as cross-section and length.

4.2.2.3 Track Gauge

Rail System (2015) define the gauge of a railway track as the clear minimum perpendicular distance between the inner faces of the two rails and indicates that the different gauges can be divided into four categories:

- Broad gauge – 1676 mm to 1524 mm;

- Standard gauge – 1435 mm and 1451 mm;
- Metre gauge – 1067 mm, 1000 mm and 915 mm; and
- Narrow gauge – 762 mm and 610 mm.

Rail System (2015) also indicates that approximately 55% of the world's railways use standard gauge (1435 mm). Narrow gauge railways are often used in mountainous terrain (some important railways covering thousands of kilometres are laid with a gauge as narrow as 610 mm). It is also used in sparsely populated areas, with low potential demand and for temporary railways that will be removed after short-term use.

For most of the railways in England, Scotland and Wales, the standard track gauge is within the range 1432-1435 mm inclusive. Since 1997, the standard gauge is 1435 mm on new installations of concrete sleepered track (Civil Engineering Conference, 2001).

The standard gauge (1435 mm) is commonly used in Western Europe, except in Spain and Portugal, where a gauge of 1676 mm is used. In Russia, a 1524 mm gauge is used (Encyclopædia Britannica, Inc., 2019). The three track gauges mentioned in this paragraph are proposed for further consideration, although preference would be for the use of the standard gauge, i.e. 1435 mm. This factor has been assigned a low priority because it does not impact on a hydrogen release scenario.

4.2.2.4 Traffic Direction

Although railways are designed to be generally used for trains to run always in the same direction, turnarounds allow traffic in the opposite direction. Therefore, independently of whether it is a single track or a double track tunnel, traffic can be uni-directional or bi-directional. Traffic direction does not impact on a hydrogen release scenario and it is then considered a low priority factor. Although scenarios with traffic in opposite directions could be of interest from the point of view of creation of highly turbulent zone when trains meet (e.g. Ufa accident in Russia).

4.2.2.5 Cross-Section

The cross-section of early tunnels in Germany were mainly based on the clearance gauge for rolling stock (Maidl et al., 2014). The horseshoe (arch) profile was generally used in a higher form for single track tunnels and a flatter form for two-track tunnels. Today, an arch profile with and without invert vault is more commonly used for conventionally driven tunnels and a circular profile for tunnels bored by shield machines. In densely built-up urban areas, in hilly terrain or near stations at intermodal hubs, urban rail lines often run underground. These tunnels can have either round, vaulted or rectangular cross-sections. As explained for road tunnels, cross-section shape is a relevant factor for hydrogen release behaviour and hence this is considered a high priority factor.

In addition to the cross-sectional areas required for the rolling stock and tracks including signal lamps, contact shoes and any other necessary accessories, rail tunnels require a loading gauge that allows for deviations of the wagons through snaking, for example as a result of broken springs. In addition to the loading gauge determined in this way, space also has to be provided for signals, overhead, cables, lighting, pipes and other equipment required for rail operations and escape routes.

Maidl et al. (2014) explain that railway tunnels on new high speed lines in Germany are designed according to the planned use and the resulting design speed; regulations (Ril 853) categorise these into four categories:

- High speed traffic – design speed between 230 km/h and 300 km/h;
- Express traffic – design speed between 160 km/h and 230 km/h;
- Passenger and goods traffic – design speed below 160 km/h; and
- S-Bahn, urban transit – design speed below 120 km/h.

For high speed traffic arch profile tunnels (Figure 3), the standard track spacing should be 4.50 m, with a specified formation width of 12.10 m and a distance of the track centre to edge of formation of 3.80 m. The radius of the cross-sectional area is specified as 6.85 m for two-track tunnels, resulting in a total area above the top rails of 92 m^2.

In double track tunnels on express traffic railways, the standard track spacing should be 4 m, with a specified formation width of 11.60 m and a distance of the track centre to edge of formation of 3.80 m. The radius of the cross-sectional area is specified as 6.10 m, resulting in a total area above the top rails of 79.20 m^2.

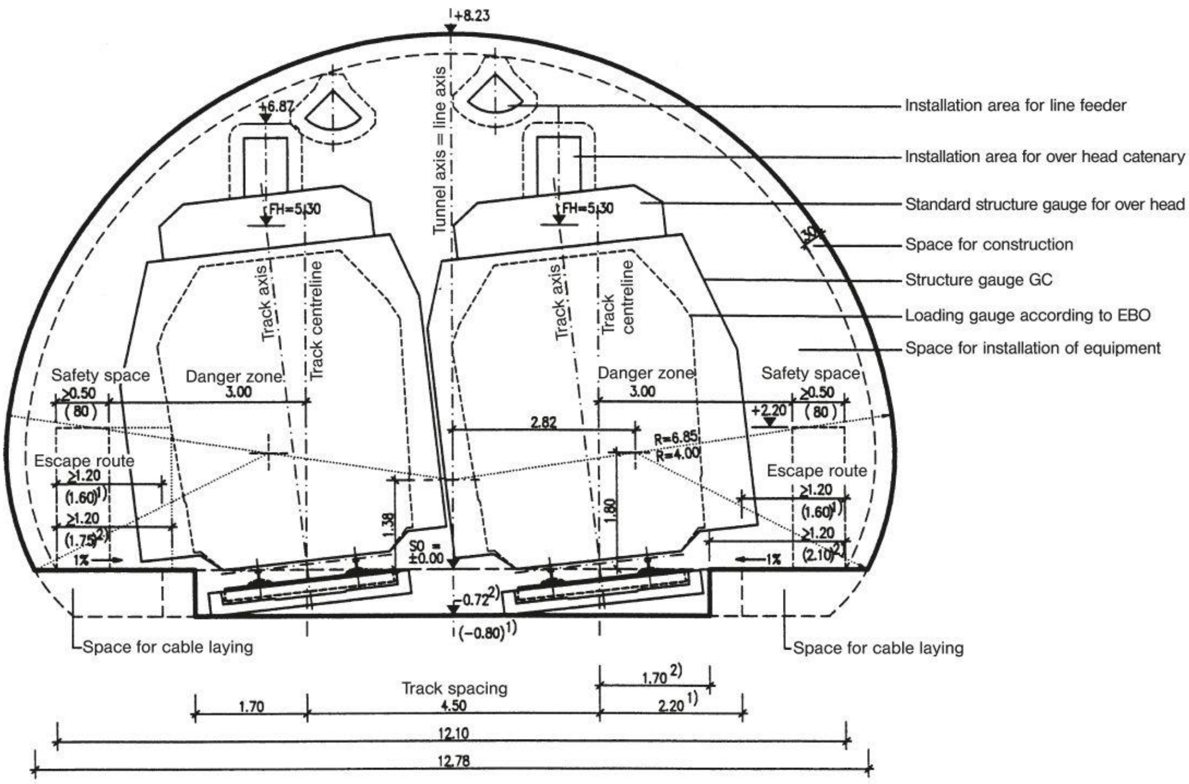

Figure 3 Guideline detail for a two-track high-speed tunnel with arch cross-section according to German regulations (Ril 853)

The Channel Tunnel consists of two single track tunnels with a 7.60 m nominal diameter plus a service tunnel with a 4.80 m nominal diameter (CTSA, 1997). These two diameters are proposed for further consideration, as well as the two formation widths for high speed and express traffic railways. Tunnel dimensions could be relevant factors for hydrogen release behaviour and therefore cross-section diameter is assigned a high priority.

4.2.2.6 Gradient and Curvature

The vertical gradients (slope) on main lines should be limited to 1.25% and on urban side lines to 4%. The permissible gradient should be laid down for each individual case and can sometimes lie outside these values (Maidl et al., 2014). A lower limit should be maintained of 2% for tunnels shorter than 1000 m or 4% for tunnels longer than 1000 m. Ideally, the vertical alignments of tunnels should be ramps with the gradient in one direction for fire protection reasons. Therefore, gradients of 1.25%, 2% and 4% are proposed for further consideration. Given that gradient restrictions are greater in railway tunnels than in road tunnels, gradient is here considered a medium priority factor.

The permissible horizontal curve radii should be limited to the range between 2000 m and 30000 m and determined more precisely from the design speed (Maidl et al., 2014). Both curvature radii are proposed for further consideration, as well as a curvature value in between these limits, i.e. 15000 m. Straight tunnels should also be considered. It is not envisaged that tunnel curvature could affect a hydrogen release scenario and hence it has been taken as a low priority factor.

4.2.2.7 Summary

Table 6 presents a summary of the rail tunnel geometry parameters, including the variables to consider and the priority of each factor.≈

Table 6 Rail tunnel geometry factors

Factor	Variables	Factor Priority
Tunnel length	0-1 km 1-5 km 5-20 km > 20 km	High
Cross-section shape	Horseshoe (arch profile) Circular profile Rectangular (box profile)	High
Cross-section diameter	12.10 m maximum width (double track) 11.60 m maximum width (double track) 7.60 m diameter (single track) 4.80 m diameter (single track)	High
Number of tracks	Single track Double track	Medium
Vertical alignment - Gradient	1.25% 2% 4%	Medium
Number of tubes	Single tube Double tube	Low
Track gauge	1435 mm 1524 mm 1676 mm	Low
Traffic direction	Uni-directional Bi-directional	Low
Horizontal curvature	Straight tunnel 2000 m 15 000 m 30 000 m	Low

4.2.3 Construction

The tunnel construction materials can play a key role to ensure structural integrity. In general, tunnels are built with reinforced concrete, such as the Channel Tunnel which is lined with reinforced concrete or, in some places, cast iron segments (CTSA, 1997). In the UK, there are many railway tunnels from the Victorian era which are built with brickwork; this is an issue of concern that is being progressively addressed to reinforce the structure.

Parameters that may define the integrity of a tunnel structure are:

- Fire resistance (resistance to thermal load, i.e. convective and radiative heat flux):
    - Concrete spalling;
    - Degradation of steel;
    - Decoupling between concrete and steel reinforcement.
- Explosion resistance (resistance to pressure loads, i.e. blast wave pressure and impulse).
- Supports.

The UNECE document in safety on railway tunnels (UNECE, 2003) includes a standard on fire protection for structures. This indicates that this issue should be given careful consideration. The risk study should consider the potential fire size and its thermal impact on the structure (heat transfer, smoke leakage, structural damage, spalling, etc.) and the consequences of structural failure. Appropriate temperature development curves should be chosen for the testing of the materials involved.

Annex I of the EU Directive 2004/54/EC (European Union, 2004) states that the level of fire resistance of all road tunnel equipment shall take into account the technological possibilities and aim at maintaining the necessary safety functions in the event of a fire. The directive also indicates that the main structure of all tunnels where a local collapse of the structure could have catastrophic consequences, e.g. immersed tunnels or tunnels which can cause the collapse of important neighbouring structures, shall ensure a sufficient level of fire resistance.

Fire resistance of the tunnel structure is necessary to reduce the damage caused by the fire and minimise the time and cost of any reinstatement. Damage is dependent on both the fire load and the fire duration, the latter being determined by the capacity of the drainage and ventilation systems within the tunnel, the quantity of combustible material involved in the fire and the firefighting provisions available. For tunnels under rivers the consequences of relatively small areas of structural damage from fire, leading to flood inundation could be very serious (Highways Agency et al., 1999).

Passive fire protection shall safeguard the structural integrity of the tunnel e.g. providing adequate cover to structural reinforcement, spalling resistance etc. including protecting firemen from spalling material and falling equipment; protecting power and communications cabling and ensuring appropriate provision is made for the fire resistance of mechanical components within the tunnel (Highways Agency et al., 1999).

Depending on the design fire to be resisted, additional fire protection layers to structures may not be required e.g. where the structure comprises cast iron segments or where reinforced concrete with adequate cover is used, as these materials are inherently fire resisting. Some damage may occur in the event of a fire without causing failure of the structure. Provision of additional mesh reinforcement may contain spalls of reinforced concrete sections, particularly in more vulnerable upper walls and ceilings (Highways Agency et al, 1999).

Where there is exposed structural steelwork in the tunnel such as at ventilation shafts, two hours fire protection of the steelwork is required to reduce the risk of collapse. This may be obtained by enclosure in suitable fire resisting materials or by coating/spray methods (Highways Agency et al., 1999).

Compared to fire protection less information is available on protection of tunnel structure to explosion loads like those during hydrogen high-pressure storage tank rupture in a fire. The project aims to consider structural response on fire and blast wave using coupled CFD+FEM simulations and relevant validation experiments.

4.2.3.1 Concrete Spalling

Spalling may be a violent effect to fire-exposed concrete destroying the entire cross-sections or reducing the load-bearing capacity of a construction substantially. The public has witnessed a number of cases of severe damage due to spalling of dense concretes (i.e. concrete densified by means of ultra-fine particles smaller than the cement grains) in real fires among which are the fire in the tunnel between Britain and France and that in the Danish tunnel under the Great Belt. All these examples confirm that the dense concretes seem to be more susceptible to spalling than the traditional materials, and that it is difficult to see any recognisable pattern of the risk of spalling. For traditional concretes the effect of explosive spalling is mostly seen within the first 20 minutes of a fire. Significant spalling cannot be expected if the concrete is not densified by particles smaller than the cement grains such as micro silica and if the moisture content is less than 3% by weight. If the moisture content is between 3% and 4% the risk can be considered to be small (Hertz, 2003).

Spalling is most likely to happen when the concrete is exposed to high temperatures for a long period of time. Research has demonstrated contradicting results for the mechanisms that drive concrete spalling. Recent research has shown that concrete with low permeability or low tensile strength has higher probability of explosive spalling (LaFleur et al., 2017).

One of the conclusions of a recent study on hydrogen vehicle safety in tunnels (LaFleur et al., 2017) is that the thermal conditions may result in localised concrete spalling in the area where the hydrogen jet flame impinges the ceiling. However, if ventilation is operating the maximum temperature is significantly lower, and spalling is not expected to occur.

A rapid heating leads to a faster loss of strength, this is because under heating water vapour in the pores and crystal water in the cement are released resulting in shrinking of this cement phase. Above 300 °C concrete will start forming micro cracks and the strength is lost permanently; this needs to be investigated more in relation to hydrogen jet flames impinging tunnel walls (HyTunnel-CS D1.2, 2019).

An experimental study on fires affecting tunnel concrete lining concluded that adding polypropylene fibres into the high strength concrete mix with low permeability exhibits a reduced risk of explosive spalling when exposed to severe hydrocarbon fires (HyTunnel-CS D1.1, 2019). This can be considered as solution to exclude spalling in tunnels if this would be considered as cost-efficient construction approach.

Therefore, the consequence of hydrogen jet fire on concrete lining and additives is identified as a high priority for assessment in the accident scenarios.

4.2.3.2 Degradation of Steel

Metal reinforcement in concrete may be effected by thermal loads that occur during exposure to fires. The higher temperatures that occur during fire exposure promotes thermal expansion of metal which can significantly reduce the load-bearing capacity, e.g. at 700 °C, the load-bearing capacity of steel decreases to 20% of the value at normal temperature. The low carbon steel has a blue brittleness issue at a temperature of 200–300 °C (HyTunnel-CS D1.1, 2019). Therefore, the evaluation of whether the steel structure could support the concrete panels in the event of a hydrogen jet fire becomes relevant.

Decoupling between concrete and steel reinforcement can occur. Both steel and concrete expand with increasing temperature. However, the two expansion ratios become remarkably different if the temperature is over 400 °C. The difference causes decoupling and then damaging stresses in the mix (HyTunnel-CS D1.1, 2019). Another experimental study confirmed the conclusion that the load-bearing tunnel structure can be protected against extreme fire effects by adding plastic fibres into the mix, also by optimising the concrete composition and selecting the aggregates (HyTunnel-CS D1.1, 2019). The heating of steel in concrete to about 500 °C (depends on steel) is often considered in numerical simulations as loss of reinforced concrete load-bearing ability. The consequence of hydrogen jet fire on steel supports coupled with concreate lining should be a high priority for assessment in the accident scenarios.

4.2.3.3 Explosion Resistance

Reported in HyTunnel-CS D1.1 (2019), several studies have been carried out to evaluate different blast wave attenuation methods: low-density foam, compressive protective barriers made of polyurethane foam, rigid barriers made of concrete, water filled plastic wall and perforated plates. For the low-density foam, it was concluded that the optimal foam thickness depends on the length of the tunnel and the level of shock wave attenuation required. Test results for the water filled plastic wall and the perforated plates do provide significant blast mitigation effect. Also, small scale tests were performed on a water bag inside the tube; the results showed that the overpressure was mitigated using this method and the research concluded that it could be scaled-up to tunnels.

Other methods found in the literature include: wrapping the tunnel with flexible and compressible barrier consisting of a layer of polyurethane foam, introducing energy absorbing flexible honeycomb elements between radial joints of the tunnel, etc. As for the mitigation of the blast strength on the people this could be archived for limited amount of hydrogen released, e.g. during tank rupture in a tunnel, by compressible porous foams, ventilation openings and presence of evacuation lanes to route the blast away, use of perforated plates for blast shielding, etc. (HyTunnel-CS D1.1, 2019). However, details are not known yet and the project aims to address this knowledge gap.

The capability of explosion resistant materials in tunnel structure and blast prevention/mitigation technologies should be a high priority for assessment in the accident scenarios.

4.2.3.4 Supports

European Commission (2018) explains that in railway tunnels, supports are necessary both temporarily during the excavation process and permanently during the operational phase of the tunnel. The type and thickness of supports employed depend on the geological context, on the excavation method and the construction requirements (e.g. design life) as well on the designer choice. Supports are traditionally classified as:

- Temporary support, defined as any system designed and installed to support the perimeter of an underground opening between the time it is first excavated up to the time that a permanent lining is in place. Typical temporary supports are shotcrete, rock bolts and/or steel ribs; and
- Permanent support, defined as the support that is designed and installed to guarantee the long term stability of the underground structure. Additionally, the definitive support insulates the tunnel from humidity, water infiltrations and reduces the turbulences within the tunnel. Typical permanent supports are cast in-situ concrete lining, precast concrete segments, cast iron, coated steel segments, shotcrete and steel ribs.

The consequences of hydrogen jet fires and blast wave on rail tunnel supports should be a high priority for assessment in the accident scenarios.

4.2.3.5 Summary

Table 7 provides a summary of the tunnel structure integrity considerations, as well as the priority of these.

Table 7 Tunnel structure integrity

Factor	Priority
Concrete spalling	High
Degradation of steel	High
Explosion resistance	High
Supports	High

4.2.4 Confined Spaces

A confined space is identified as any enclosed volume that forms part of the infrastructure of FCH transportation, where a vehicle or train may transit or reside for a prolonged period. The following confined spaces have been identified as being applicable to the transportation modes prioritised in section 4.1 (e.g. cars, buses, HGV, trains) along tunnels:

- Residential garage;
- Maintenance shop;
- Multi-storey car park;
- Underground parking;
- Bus depot;
- Bus station;
- Train depot; and
- Train station.

The main differences between these spaces are the size of confined volume, the ventilation (vent size, passive or forced ventilation, etc.) arrangements, the mitigation strategies used and the population expected to be present.

Residential garages would largely have one car parked inside, maybe two. In this case, the amount of hydrogen released would not be significant (within 5 kg), but the dynamics of release and the effect of TPRD diameter is very important to prevent the structure from collapse. On the other hand, natural (passive) ventilation would probably be limited and the inhabitants could be relatively close to the release point. However, this type of confined space has been identified as being susceptible to the pressure peaking phenomena (Makarov et al., 2018); therefore, residential garages are considered a high priority confined space.

As a reference, minimum single garage dimensions are taken here as 3 m wide by 6 m long; for double car garages, the minimum dimensions are taken here as 5.5 m wide and 6 m long (Monmouthshire County Council, 2013). In both cases, it is considered a minimum height of 1.90 m (ESPA, 2015). Therefore, the volume of a single garage is 3 x 6 x 1.90 m = 34.2 m^3 and for a double garage is 5.5 x 6 x 1.90 m = 62.7 m^3.

To discuss about maintenance shops, it may be beneficial to differentiate between during working hours and outside working hours. During normal working hours, there could be several hydrogen fuelled cars inside and outside the shop, which will be open and therefore there would be adequate ventilation, so that if hydrogen is released from a vehicle it would be rapidly diluted below the flammability levels if release diameter would be small enough to allow decay of hydrogen concentration under the maintenance shop ceiling below 4% by volume (LFL) to exclude the formation of flammable layer. Outside working hours, vehicles could be locked inside and ventilation would be lower than during daytime so, in case of an accident, there could be damage to the property if no proper design to account for the pressure peaking phenomenon is carried out. The possibility of damage to people would depend on the location of the shop; if it is close to any housing or passing pedestrians, there would be potential for people being affected. It is considered a medium priority space.

In multi-storey car parks, the amount of hydrogen fuelled vehicles could be higher than in a maintenance shop. The level of confinement would depend on the design of the car park and there would be a choice or combination of natural ventilation and mechanical ventilation. It could be possible for a fire to spread to different storeys. Effect of pressure loads for such constructions should be assessed. This is considered a medium to high priority confined space.

There could be several hydrogen fuelled vehicles in an underground car park. Due to the level of confinement in this space, forced ventilation requirements should be in place; even so, a release of hydrogen could result in very severe consequences. This is considered a high priority space.

The Northern Ireland parking standards (Planning Portal, 2019) recommend the minimum dimensions for a car space in a car park to be 4.80 m by 2.40 m and 2.40 m by 5.50 m for a light van. These dimensions do not take account of access, manoeuvring space or space required for loading/unloading. On the conservative side, a minimum height can be taken as 1.90 m (ESPA, 2015).

The number of vehicles inside a bus or a train depot can be significant and the level of congestion could be an issue, although generally they are fairly open and natural and mechanical ventilation may be ensured. It is not expected to encounter significant populations nearby depots. It is considered a medium priority space.

Generally, the level of congestion in bus and train stations is lower than in depots, although the amount of people likely to be in the area is a factor that could significantly affect the severity of an accident involving hydrogen. It is considered a medium priority space.

In light of all the above comments about confined spaces (beyond tunnels), it is believed that all of them may be relevant for hydrogen release, fire and blast scenarios and therefore it is suggested to keep all these confined spaces in consideration. Assigned priorities for confined spaces are summarised in Table 8.

Table 8 Prioritisation of confined spaces

Confined space	Priority
Residential garage	High
Underground parking	High
Multi-storey car park	Medium to High
Maintenance shop	Medium
Bus depot	Medium
Bus station	Medium
Train depot	Medium
Train station	Medium

4.2.5 Ventilation

Ventilation requirements are not the same for road tunnels, railway tunnels and confined spaces. The main factors to consider in relation to ventilation arrangements are ventilation system design and the operational ventilation rate.

4.2.5.1 Road Tunnels

There are three core designs of ventilation systems used in road tunnels: natural (passive) ventilation, longitudinal ventilation and transverse ventilation (HyTunnel-CS D1.1, 2019).

Other variants are semi-transverse ventilation or longitudinal ventilation by Saccardo nozzle system.

EU Directive 2004/54/EC (European Union, 2004) requires that:

- Mechanical (forced) ventilation shall be installed in all tunnels longer than 1000 m with a traffic volume higher than 2000 vehicles/lane;
- In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis is acceptable and/or specific measures are taken; and
- Transverse or semi-transverse ventilation systems shall be used in tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed.

HyTunnel-CS D1.1 (2019) reviewed the application of ventilation in tunnels and concluded that:

- Every road tunnel is unique due to many factors, like local meteorological and geological conditions, engineering feasibility for construction, capital budget, etc. Thus, the determination of ventilation mode choice must depend on specific case study;
- Natural (passive) ventilation is suitable only for relatively short tunnels, e.g. 1 km depending on the local traffic density;
- Semi-transverse ventilation mode shows merits in air and smoke controls by using its hybrid features from both longitudinal and full transverse ventilation. As an important auxiliary design, a Saccardo nozzle system can be incorporated in the tunnel design to obtain an optimum ventilation effect due to many advantages of the system; and
- A critical ventilation flow velocity in the longitudinal direction of a tunnel is recommended as 3.5 m/s. It is sufficient to extract gaseous contaminations and toxic smoke of fire, while it is not too large to impede the personal evacuation and rescue operation.

Ventilation arrangements in road tunnels can play a key role on the consequences of a hydrogen release and therefore all ventilation systems should be considered and given high priority.

4.2.5.2 Rail Tunnels

HyTunnel-CS D1.1 (2019) indicates that natural (passive) ventilation in railway tunnels can be longitudinal or semi-transverse (ventilation shafts). In general, mechanical (forced) ventilation is required only for those tunnels that are longer than 20 km if no specific requirements are prescribed for the thermal-dynamic condition of the air in tunnels. Shorter railway tunnels can be ventilated by natural winds and by fast moving trains due to the piston effects created by them.

Emergency ventilation system is indispensable for a railway tunnel in order to supply safe evacuation of people and a suitable condition for fire-fighting in case of tunnel fires. If it is either impossible or commercially unacceptable to construct transverse ventilation shafts, longitudinal ventilation by using jet fans is appropriate for a railway tunnel, to satisfy the requirements for both normal operation mode and emergency ventilation mode. Nevertheless, transverse ventilation shafts are built, where possible, especially for extremely long modern rail tunnels to realize air injection or air removal from the traffic tunnel.

The conclusions obtained in HyTunnel-CS D1.1 (2019) on railway tunnels are:

- Rail tunnels have relatively small cross-section area; thus, the piston effect generated by moving trains are not ignorable particularly in single track tunnels;
- Impulse jet fans for longitudinal ventilation must be positioned with care about the rather limited height of the rail tunnel and with attention to the power lines normally on the tunnel roof for electric locomotives; and
- The solutions of an integral momentum equation for tunnel ventilation flow by modelling of piston effects of moving trains are discussed, which supplies a theoretical tool for hydrogen transport estimations.

The assessment of the air flow in a tunnel should consider tunnel and train aerodynamics, the fresh air supply (for physiological needs), the control of heat and smoke from a fire and the control of pollution (diesel). Ventilation design should take into account the associated risks and costs. Ventilation systems must be designed to keep emergency exits, cross passages and safety tunnels free of smoke (UNECE, 2003).

Ventilation arrangements in railway tunnels can significantly impact on the behaviour of a hydrogen release and therefore all railway ventilation systems (natural, longitudinal and semi-transverse) should be considered and a high priority assigned.

4.2.5.3 Confined Spaces

HyTunnel-CS D1.1 (2019) provides information on ventilation systems in confined spaces, focusing on underground parking. Ventilation systems described in the report are passive/natural and active/forced/mechanical.

Mechanical systems are present in those spaces where adequate natural ventilation cannot be provided; this circumstance can be found in underground car parks or enclosed car park storeys. In normal working conditions, the mechanical ventilation systems shall ensure at least 6 air changes per hour (ACH) in the main parking area (BS 7346-7:2013).. In the zones where vehicles may stop with running engines, local ventilation shall ensure at least 10 ACH.

Ventilation strategies in confined spaces may be able to influence the development of a hydrogen cloud; consequently, all ventilation types should be considered. At the same time the diameter of release and height of the enclosure are other factors defining the safety strategy. Ventilation in confined spaces is considered a high priority factor.

4.2.5.4 Ventilation Velocity in Tunnel

The internal HyTunnel project of NoE HySafe evaluated the effect of ventilation velocity (HyTunnel-D111, 2009). The WUT Computational Fluid Dynamics (CFD) study suggests that the introduction of even a low level of ventilation (1 m/s) causes a dramatic change in the flammable cloud size and its associated hazard. The introduction of a minimum ventilation level of 3 m/s is identified as a requirement for hydrogen vehicles to be inherently safer accommodated in road tunnels for considered scenarios.

Another part of the NoE HySafe internal project HyTunnel involved hydrogen release deflagration experiments and CFD simulations inside a reduced-scale tunnel geometry

(HyTunnel-D111, 2009). The tunnel ventilation was shown to reduce the hazard dramatically, and suggested that suitable ventilation of a tunnel can significantly reduce the chance of a strong explosion, i.e. with injuries of people and property losses. It was underlined that further work is required, however, to examine higher release rates of hydrogen than those studies so far. There may be the possibility that even in a well ventilated tunnel a high release rate of hydrogen could produce a near homogeneous mixture at close to stoichiometric conditions, with a correspondingly increased explosion hazard. The project aims to avoid such scenarios in practice by formulation requirements to the system vehicle (train) – tunnel (confined space) that would exclude formation of hazardous flammable cloud with unacceptable pressure and thermal load as much as possible.

HyTunnel-CS D1.2 (2019) suggests that the ventilation velocity value of 3.5 m/s seems to be sufficient for most tunnel fires to prevent the "back-layering" effect, including large fires of more than 100 MW. This aligns with HyTunnel-CS D1.1 (2019) which concludes that this ventilation rate is sufficient to extract gaseous contaminations and toxic smoke of fire, while it is not too large to impede the personal evacuation and rescue operation. It is assumed at the moment, based on preliminary analysis, that properly engineered release of hydrogen with limited hydrogen flow rate, e.g. by reducing TPRD release diameter and increase of fire resistance rating of onboard storage, will not change seriously heat release rate (HRR) in a fire.

HyTunnel-CS D1.2 (2019) also mentions that one study showed how in certain conditions ventilation may transport the cloud of flammable gas and contribute to further extend it. The cloud may thus move towards other vehicles or along ventilation ducts and shafts. The same is valid for hot combustion products in case of hydrogen jet fire.

Minimum proposed ventilation rates for further study are 1 m/s, 2 m/s, 3.5 m/s and 5 m/s. The evaluation of higher ventilation rates would allow determination of a velocity that could lead to a situation in which a near homogeneous turbulent mixture is formed that still will decay along the tunnel length due to air entrainment. It is really important to demonstrate what ventilation rates can ensure an acceptable level of risk but it is equally important, if not more important, to evaluate what rates are not safe enough. For this reason, ventilation rate is taken as a high priority factor.

4.2.5.5 Summary

Table 9 presents a summary of the ventilation parameters, including the variables to consider and the priority assigned to each factor.

Table 9 Ventilation factors, variables and prioritisation

Factor	Variables	Factor Priority
Ventilation systems. Road tunnels	Natural ventilation Longitudinal Transverse ventilation Semi-transverse Longitudinal (Saccardo nozzle)	High
Ventilation systems. Railway tunnels	Natural Longitudinal Semi-transverse (ventilation shafts)	High
Ventilation systems. Confined spaces (underground parking)	Natural (Passive) Mechanical (Active)	High

Ventilation rate (Tunnel)	1 m/s 2 m/s 3.5 m/s 5 m/s	High
Ventilation rate (Car Park)	6 ACH 10 ACH	High

4.2.6 Fire Suppression Systems

Fire suppression systems should be considered for both tunnels and confined spaces, especially the interaction of these measures with the ventilation arrangements. Fire suppressions systems taken into account are:

- Water sprays; and
- Water mists.

UNECE recommendations on safety in road tunnels (UNECE, 2001) indicated the need for further investigation on automatic fire extinguishing systems in order to verify their efficiency and to determine in what conditions they could be used. For railway tunnels, an active fire suppression system is not generally practical and is not recommended (UNECE, 2003).

As already explained in HyTunnel-CS D1.1 (2019), water extinguishing systems may bring benefits only it these are applied properly with integration to other conventional safety measures. Fixed fire-fighting systems can mitigate fires, but in certain circumstances new risks may arise as well. HyTunnel-CS D1.1 (2019), reviewed the efficiency of different fire extinguishing agents for different types of fires, it appears that water and foam are not good agents to extinguish a hydrogen fire; however, the report also mentions that water mists with a droplet size up to 200 µm, i.e. Class I mists, could work due to its large surface-to-volume ratio and dispersion character in the whole gas volume. However, it is known that high ventilation flows can reduce the efficiency of mist system.

Water injection (HyTunnel-CS D1.1, 2019) can have some advantages, such as breaking down possible hydrogen stratification (thus reducing amount of fast burning flammable mixture), making the hydrogen-air mixture inert to combustion and potentially mitigating a blast wave strength. Nonetheless, the turbulence brought by water injection can intensify hydrogen combustion and increase potential hazard. Disadvantages of water injection into tunnels include loss of visibility, loss of smoke stratification if it is formed, decrease of tenability of temperature limit due to increased humidity, which influence adversely evacuation, rescue and fire-fighting activities. Water injection systems are not widely accepted in traffic tunnels worldwide except in Japan and Australia, where such installations are prescriptive.

The HyTunnel-CS D1.1 (2019) report refers to previous tunnel fire experiments concluding that the addition of an aqueous film forming foam (AFFF) to the water can strengthen the extinguishing effect; this has been tested for gasoline fires, which could be a reason for a tank rupture in a fire in case of TPRD failure or blockage in a car crash.

The use of Class I water mists and water mists with an added AFFF should be considered for the selection of accident scenarios. The interaction of these suppression systems with ventilation in tunnel fires should be taken into account. Priority of these factors is assigned as high.

Table 10 presents a summary of the considered fire suppression systems.

Table 10 Fire suppression systems

Factor	Priority
Water mist (Class I mist)	High
Water mist with AFFF	High
Water spray	Low
Foam	Low

4.3 Accident Initiators

Accident factors encompass those initiators that could lead to a hydrogen release scenario, as well as other circumstances of an accident which could impact on the scenario outcome. The prevalence of these factors will be dictated by statistical analysis of current accident rates.

4.3.1 Initiating Events

Initiating events to be considered for a hydrogen release scenario from a hydrogen fuel cell vehicle are:

- Mechanical failure;
- Failure of safety functions;
- External fire; and
- Driver error (traffic accident).

4.3.1.1 Mechanical Failure

Fires due to mechanical or electrical defects now occur less frequently and carrying out periodical checks on vehicles can minimize the risk (UNECE, 2001). Tretsiakova-McNally (2016b) explains that due to the small size of hydrogen molecules, hydrogen is prone to leak easily through some materials, cracks, or poor joints of the storage tanks, as opposed to other common gases at equivalent pressures. The major concerns related to compressed hydrogen are: the large amount of energy needed for the compression, the potential fatigue of the containers' materials caused by repeated cycling from low to high pressures, the inherent safety issues for the use of such high pressures in pressurised vessels, the high weight of the vessels, and additional costs to design such vessels. Thus, the containers used to store compressed hydrogen must be made of robust materials and must withstand high pressures without a loss of containment following tests required by UN GTR#13 and other RCS.

4.3.1.1.1 Corrosion

Hydrogen is generally non-corrosive and does not react with the materials used for storage containers (Tretsiakova-McNally, 2016b). Tretsiakova-McNally (2016b) explains that the compatibility of hydrogen with metals is affected by chemical interactions and physical effects, including dry corrosion: a chemical reaction between a dry gas and a metal, which eventually may lead a reduction of a cylinder wall thickness. Dry corrosion is not very common, because its rate is very low at ambient temperature. However, at high temperatures hydrogen can react with some metals, forming hydrides for example.

4.3.1.1.2 Hydrogen Embrittlement

Hydrogen embrittlement is a process by which various metals, mainly high-strength steels, become brittle (i.e. lose their ductility) and crack after being exposed to hydrogen (Tretsiakova-McNally, 2016b). It is caused by ingress of either molecular or atomic hydrogen into a metal lattice. It occurs at relatively low temperatures (e.g. at ambient). Hydrogen attack is another degradation process that typically occurs at higher temperatures, above 200 °C. Also, hydrogen can form compounds within a metal lattice such as metal hydrides or methane. Hydrogen embrittlement is categorised as follows:

- Environmental embrittlement. This occurs when a material is being exposed to a hydrogen atmosphere, e.g. in storage tanks;
- Internal reversible embrittlement. This occurs when hydrogen enters a metal during its processing; this may lead to a structural failure of a material that has never been exposed to hydrogen before; and
- Hydrogen reaction embrittlement. This occurs at higher temperatures, when hydrogen chemically reacts with a constituent of a metal, forming a new microstructural element or phase such as a hydride or to generate gas bubbles also known as blistering.

4.3.1.1.3 Permeation

Permeation is an inherent phenomenon for all gases which are in contact with polymers, and is the result of the hydrogen gas dissolution and diffusion in the polymer matrix (Tretsiakova-McNally, 2016b). Due to a small size of its molecules, hydrogen diffusion and permeation are enhanced.

Hydrogen permeation through the polymeric liner can lead to its accumulation in the space between the liner and the carbon fibre reinforced plastic forming a ‘blister’. This may cause a partial or full collapse of the liner, when the pressure of the accumulated hydrogen becomes higher than the internal pressure of the liner (e.g. during tank depressurisation).

The permeation rate increases when the storage pressure increases, but also when the wall thickness is reduced.

Permeation may be categorised as a long-term slow hydrogen release from a compressed gas hydrogen system. The permeation from onboard hydrogen tanks is a safety issue for enclosures as hydrogen can accumulate over a period of time to create a flammable mixture with air. In sealed enclosures without ventilation the hydrogen LFL in air (4% by volume) can be reached as a result of permeation over quite a long time. Analytical analysis and numerical simulations have demonstrated that the levels hydrogen of permeation rate from a composite storage cylinder in a typical garage would not lead to formation of a flammable atmosphere (HyTunnel D1.2, 2019).

4.3.1.2 Failure of Safety Functions

Laumann et al., (2015) described the core safety devices included in a compressed hydrogen storage system:

- A check valve;
- A shut-off valve;
- A thermally-activated pressure relief device (TPRD); and
- Gas detector.

Check Valve: During fuelling, hydrogen enters the storage system through a check valve. The check valve prevents back-flow of hydrogen into the fuelling line.

Shut-off Valve: An automated hydrogen shut-off valve prevents the outflow of stored hydrogen when the car is not operating or when a fault is detected that requires isolation of the hydrogen storage system.

TPRD: Pressure relief device designed to open when the temperature reaches a certain limit, usually 110 ^{o}C, and to vent the entire contents of the container safely. They do not reseal or allow repressurisation of the container for hydrogen systems. The controlled release may result in an intense flame for a short time (until pressure in the tank is relieved), but the overall risk is likely to be reduced. TPRDs may fail in two different modes: either by a premature activation or by failing to vent properly (Tretsiakova-McNally, 2016b). TPRDs can be blocked by dirt, stones or ice and thus fail to act when necessary. They can become corroded or otherwise damaged such that they relieve pressure when they should not be. They can be as well blocked from a fire by other vehicle parts in case of a crash. Localised fire is another challenge for TPRD initiation, however trigger lines are provided to sense the fire in multiple locations around the tank.

Gas Detector: In addition to the safety devices mentioned above, a number of hydrogen sensors are located in fuel cell vehicles. When a potentially hazardous hydrogen leak is detected, the system controller will automatically stop the flow of hydrogen from the tank.

It has been recognised that the failure of key components in the onboard storage system is a realistic concern. A study by Burgess et al. (2017) reviewed instances of Pressure Relief Device (PRD) failure on hydrogen storage systems. It was identified that there are five common failure modes:

- Valve fails to open;
- Valve opens prematurely;
- Mechanical failure;
- Valve fails to reseat after actuation; and
- Leakage past valve seat.

Of particular concern to the HyTunnel-CS project are the first three modes that can lead to the consequences of vessel rupture (first mode) or unignited blowdown (modes two and three). PRDs that are stuck closed are a serious safety concern because the system can potentially experience an unprotected overpressure condition e.g. when exposed to fire. Similarly, when the valve operates prematurely then the vessel contents will be discharged, and it would be reasonable to assume that in a tunnel environment accumulation and ignition of the discharged hydrogen could occur.

Burgess et al. (2017) identified that value failure can be related to a range of contributing factors, those that are particularly relevant to the FCH transportation include; maintenance, cyclic temperature/pressure, material degradation, fouling and vibration. Engineering and administrative controls should be used as part of a preventive maintenance plan to assure PRD reliability. While these engineering and administrative controls are a generally accepted practice in the process gas industry, in the transportation sector, and particularly those owned domestically, there may be variable degree of maintenance competence (e.g. home repairs). This aspect can be addressed through vehicle leasing which is the current approach for the FCEV market in California, USA.

The application of TPRDs in a FCH transport system is a relatively immature technology (although they have been applied in CNG vehicles) so direct identification of the failure frequency is not possible. PRD failure rates in the offshore sector (where high pressures and harsh conditions are prevalent) show that failure frequencies are of the order 1E-06 to 5E-06 dependant on the failure mode (OREDA, 2009). Therefore, it should be accepted that TRPD failure will occur in FCH transportation. Addressing and controlling some contributing factors will help to reduce the frequency, in particular regular inspection and maintenance is essential, but nonetheless understanding the consequence is required.

Failure of safety functions, especially failure of a TPRD, is a credible accident initiator and hence this factor must be taken into consideration in the accident scenario assessment with special emphasis on the effect of TPRD diameter on accident consequences.

4.3.1.3 External Fire

In the case of fire (it may be an external fire or a fire originated as a result of a car crash), the composite materials (resin) used for storage vessels may degrade in high temperature and a loss of hydrogen containment may occur. In the worst-case scenario, this may lead to a catastrophic rupture of a hydrogen storage tank, generating a blast wave along with a fireball and flying projectiles/missiles (Tretsiakova-McNally, 2016b).

TPRDs provide a controlled release of the gas from the compressed hydrogen storage containers before the high temperatures in the fire weaken the walls of the containers and cause their hazardous rupture (Tretsiakova-McNally, 2016a).

In relation to fires in car parks, DCLG (2010) reviewed UK car park fires occurring during a period of 12 years; approximately half of the fires reported did not start in a vehicle. Small fires (less than 1 m^2) are mostly accidental and mostly due to non-vehicle sources of ignition. UK statistics say that most fires in car parks do not spread to a vehicle (from non-vehicle sources of ignition) or to another car (from vehicle sources of ignition). However, there are many instances where vehicle to vehicle propagation does occur. An extreme example is the Liverpool Echo Arena car park incident which involved over 1000 vehicles, and demonstrates that fire can spread between cars and that, in extreme cases, very many cars can burn out with a very high heat release rate (and substantial structural damage).

External fires are a valid factor that can lead to escalation of a FCH vehicle accident. The contribution of external fires to the consequences of an accident is an important area that requires further investigation.

4.3.1.4 Driver Error (Traffic Accident)

The SafeT-D4.5 Part II (2005) document provides information on tunnel accident data (road, rail and metro tunnels). The identified causes of road tunnel accidents are technical failure, human error, intentional act and natural/environmental event. Technical failures were mainly due to a brake failure leading to collision and engine failure leading to spontaneous fire. Human error was mainly due to careless driving. In most cases, the concrete cause could not be identified.

The United Nations recommendations on safety in road tunnels (UNECE, 2001) highlight that the principal factor in road accidents is human error, so efforts to increase the level of road safety have to be primarily aimed at preventing these human errors. Various ways to influence the way people act may include education, driving instruction and provision of information, as well as regulations, police enforcement and penalties for traffic violations. The second step to increase road safety would be to ensure that errors that may still be made by drivers do not give rise to grave consequences.

Caliendo (2012) stated that the behaviour of drivers changes in tunnels. Drivers approaching the tunnel portal change their driving style both by increasing the distance from the side wall, which interferences with the traffic flow in the adjacent lane, and by reducing their speed. Another effect before entering a tunnel is that the driver's attention focuses on the tunnel entrance in such a way as to cause a loss of information provided through road signals. In addition, in the first part inside the tunnel, the darkness causes poor visibility and slow adaptation of one's eyes to the reduced level of illumination. Furthermore, driving within the tunnel generates anxiety as these structures are dark, narrow, and monotonous when compared to open road sections. Besides, drivers in tunnels generally modify both their lateral position and speed in order to avoid the disturbing effects due to the tunnel wall being too close to the traffic lane. At the tunnel exit, different lighting at the threshold close/open road section and/or unexpected weather conditions (e.g. rain, snow, lateral wind, etc.) also might surprise drivers negatively.

Nussbaumer (2007) analysed accident data in tunnels. The study concluded that the most frequent cause of accidents in tunnels is lacking vigilance (over-fatigue, distraction, inattentiveness). In second place are wrong driving behaviour such as the failure to maintain a safe distance to the vehicle in front, wrong overtaking and the failure to remain within the marked lane. The third most frequent cause is misinterpretation of road design and layout, meteorological conditions and other vehicles. The rate of accidents caused by speeding is particularly high in tunnels with uni-directional traffic. Other causes of accidents, such as unpredictable events and technical defects (motor, tyres and brakes) were negligible.

The SafeT accident analysis (SafeT-D4.5 Part II, 2005) evaluated whether the day of the week or the season of the year could be factors affecting to the number of road tunnel accidents. In relation to the day of the week, figures show that the spread is quite even, except for a significant reduction at the weekend, which could be due to the elimination of commuter traffic or perhaps due to tunnels' controlled usage at weekends, such as the prohibition of trucks or HGVs. Expectations on the analysis of the season of the year were for accidents occurring in winter because of snow or ice on the road outside the tunnels or on the wheels of vehicles. However, more accidents seem to happen in the spring and summer; therefore, it seems like the weather does not appear to influence the number of accidents, and it must therefore be other factors such as the volume of traffic that may be using the tunnels in these periods possibly due to vacation travel.

The circumstances that can initiate rail tunnel accidents are much more limited than with road tunnel accidents, i.e. trains run according to timetables determined by scheduling software, and can only travel where the rail-track allows them to without the ability to overtake etc. On the causes that were identified, technical failures were prevalent, probably due to the considerable amount of automation of the rail industry. These technical failures have resulted in spontaneous fires or possible collisions. Human error was also identified as an accident cause.

Metro vehicles also run according to timetables determined by scheduling software, and can only travel where the rail-track allows them. The main basis for any accident to be able to occur is either a technical failure or human and organisational error. What can be seen is that technical failures contribute far more than human errors, again due to the highly automated nature of the underground metro systems. However, there seems to be a relatively large number of intentional acts in comparison to road or rail tunnel accidents.

Although there is evidence that driver error can lead to a vehicle crash, which could consequently originate a hydrogen release in a FCH vehicle, it is considered that a vehicle crash as a potential accident initiator would be better represented by analysing the influence of a vehicle fire (Section 4.3.1.3). Therefore, driver error will not be incorporated into the accident scenarios in HyTunnel-CS.

4.3.2 Accident location

The final report for the previous HyTunnel project (HyTunnel-D111, 2009) provided information referring to the variation of accident frequency in different parts of tunnels (Table 11):

Table 11 Accident rate in different tunnel zones

Tunnel zone	Description	Accident rate (accidents per million veh.km)
1	*50 m in front of tunnel openings*	0.3
2	First 50 m inside the tunnel openings	0.23
3	Next 100 m inside the tunnel	0.16
4	Mid-zone (remainder of the tunnel)	0.10

Tunnels shorter than 100 m only have zones 1 and 2, while tunnels shorter than 300 m do not include zone 4. Table 11 shows that accident rates are higher in the entrance of tunnels and that these accident rates diminish as one proceeds inside the tunnel.

The study findings indicate that accidents close to the portal are more prevalent. The location of the accident will have a bearing on the emergency response action, and may also influence the escalation parameters such and airflow velocity (dispersion) and direction (blast propagation and harm criteria). Therefore, some consideration should be given to assessing the effect of accident location in the accident scenarios.

4.3.3 Summary

Table 12 presents a summary of the relevant accident factors for a FCH vehicle, indicating their priority for being studied in the project.

Table 12 Accident factors

Factor	Priority
Mechanical failure	High
Failure of safety functions	High
External fire	High
Accident location in tunnel	High
Driver error	Low

4.4 Consequences

The consequences may be identified through hazard assessment and risk analysis approaches such and bow tie diagrams, fault/event trees, etc. Examples of where this has been undertaken for FCEVs or high-pressure hydrogen storage included: LaFleur et al. (2017), Li (2018), and EHSP (2019). From these types of assessments, it has been identified that there are four accident consequences which are relevant to FCH transportation systems, which are:

- Vessel rupture - unignited;
- Vessel rupture - ignited;
- Pressurised release - unignited; and
- Pressurised release - ignited.

4.4.1 Unignited Vessel Rupture

Vessel rupture without ignition may occur due to material fatigue or damage to the vessel during severe real accident. The design regulations, codes and standards (RCS) relating to the production of high-pressure storage vessels ensure that the likelihood of material induced failure is very low. Similarly, the testing regimes described for these vessels (e.g. UN GTR#13, FMVSS304) ensure that they have mechanical integrity to resist foreseeable accident scenarios. Therefore, the occurrence of unignited vessel rupture is deemed to have a low probability of occurrence and will not be assessed further.

4.4.2 Ignited Vessel Rupture

Hydrogen storage vessels in FCH transportation are fitted with a TPRD that is designed to prevent over pressurisation of the vessel as a result of exposure to fire and avoid degradation of composite wall materials (resin) causing tank’s rupture (e.g. hydrocarbon pool fire from a conventional internal combustion engine ICE vehicle accident). When the TPRD fails to operate as intended then the vessel may be pressurised to the point of failure ("assisted" by wall degradation in a fire and thus decreasing its load-bearing capability), and due to the presence of fire the resulting vessel rupture will lead to instantaneous release of hydrogen, ignition and expansion of vessel contents, which will be coupled with the mechanical stored energy. The part of released chemical energy (5-10% depending on storage pressure) will contribute to the blast wave strength as well. The consequence include devastating blast wave, large fireball and projectiles (the largest being a vehicle).

A review of PRD performance for use on compressed hydrogen vessels was undertaken by NREL (Burgess et al., 2017), which identified examples of valve failure modes (failure to open and premature/unintended opening). The likelihood of TPRD failure to operate has been assessed as non-zero (HyTunnel D1.2, 2019), which therefore makes this a credible consequence.

Another route to achieving this accident consequence will be via an onboard fuel leak resulting in a localised jet fire that impinges on the vessel wall away from the TPRD. In this situation, the TPRD may not reach the temperature (≈110 °C) required to initiate its opening before the vessel wall fails to bare high internal pressure due to composite degradation in a fire.

Therefore, vessel rupture in a fire is a credible accident scenario for study in HyTunnel-CS.

4.4.3 Unignited Pressurised Release

As discussed in the previous section, hydrogen compressed gas cylinders are fitted with TPRDs to prevent over pressurisation during exposure to fire. An identified failure mode for TPRDs is unintended activation at pressures below the device set point (Burgess et al., 2017). There are numerous causes of premature release including dirt ingress, thermal cycling or vibration, which are all conceivable in FCH transportation.

Unintended activation of the TPRD will lead to a continuous jet release of hydrogen from the high-pressure storage vessel, and as the operation of a TPRD is typically irreversible this will result in complete blowdown of the vessel to atmospheric pressure. Where the vehicle is stationary, as may result from an accident, then a flammable atmosphere will develop in the vicinity of the vehicle. The extent and location of the flammable atmosphere will be influenced first of all by the storage pressure and TPRD diameter and by other accident factors such as ventilation rates, tunnel geometry and internal design features. Additionally, a unique consequence of a hydrogen vessel blowdown in a confined space with limited ventilation (e.g. a domestic garage) is a rapid rise in pressure that may be in excess of building strength due to the pressure peaking phenomenon (Makarov, 2018).

In many transportation environments ignition sources are present, and in particular in a confined space there may be light fittings or ventilation fans that are not ATEX rated. Furthermore, if a vehicle crash initiated the unintended operation of the TPRD then it is conceivably that the naked flames or hot surfaces will be present in the local environment.

It is foreseeable that a consequence of an unignited hydrogen release is the formation and accumulation of a flammable atmosphere that will subsequently be ignited leading to a flash fire, deflagration or even transition to detonation.

Therefore, unignited pressurised release and pressurised release with delayed ignition are credible accident consequences for assessment by HyTunnel-CS.

4.4.4 Ignited Pressurised Release

Where a FCH vehicle is involved in an accident and subject to fire in the region of the hydrogen storage vessels then under normal operation the TPRD will activate to prevent over pressurisation of the vessel. As described in the preceding section this activation is irreversible and will lead to complete vessel blowdown to atmospheric pressure. Due to the locality of fire it is reasonable to assume that such a release will ignite and result in a hydrogen jet fire.

Therefore, ignited pressurised release is a credible accident consequence for assessment by HyTunnel-CS.

4.4.5 Summary

Accident consequences that should be assessed by the HyTunnel-CS research programme are as shown in Table 13.

Table 13 Consequences

Consequence	Priority
Ignited vessel rupture	High
Pressurised release with delayed ignition	High
Ignited pressurised release	High
Unignited pressurised release	Medium
Unignited vessel rupture	Low

4.5 Hazard Variables

4.5.1 Hydrogen Storage System

The hydrogen storage system on a FCH vehicle comprises one or more high pressure cylinders that are interconnected to supply hydrogen to the fuel cell stack. A schematic of the conceptual design of the hydrogen circuit in the Toyota Mirai is shown in Figure 4. In a typical system the storage cylinders are interconnected via manifolds and valve system that allow parallel refuelling and supply of hydrogen so that both cylinders are maintained at approximately the same pressure.

As the fuel passes through the circuit from the supply vessel to the fuel cell stack, the gas is expanded and the pressure reduced in stages from high pressure (70 MPa) in the storage cylinders and the immediate inlet/outlet pipework; to medium pressure (1 - 1.5 MPa) in the supply lines that pass through the vehicle; and to low pressure (40 - 200 kPa) in the fuel cell stack. To mitigate the potential of a hydrogen leak and subsequent fire, each stage in the hydrogen circuit contains pressure sensors that monitor the flow and determine if a leak is occurring. Shut-off valves are incorporated into the intra-stage regulators to allow line isolation.

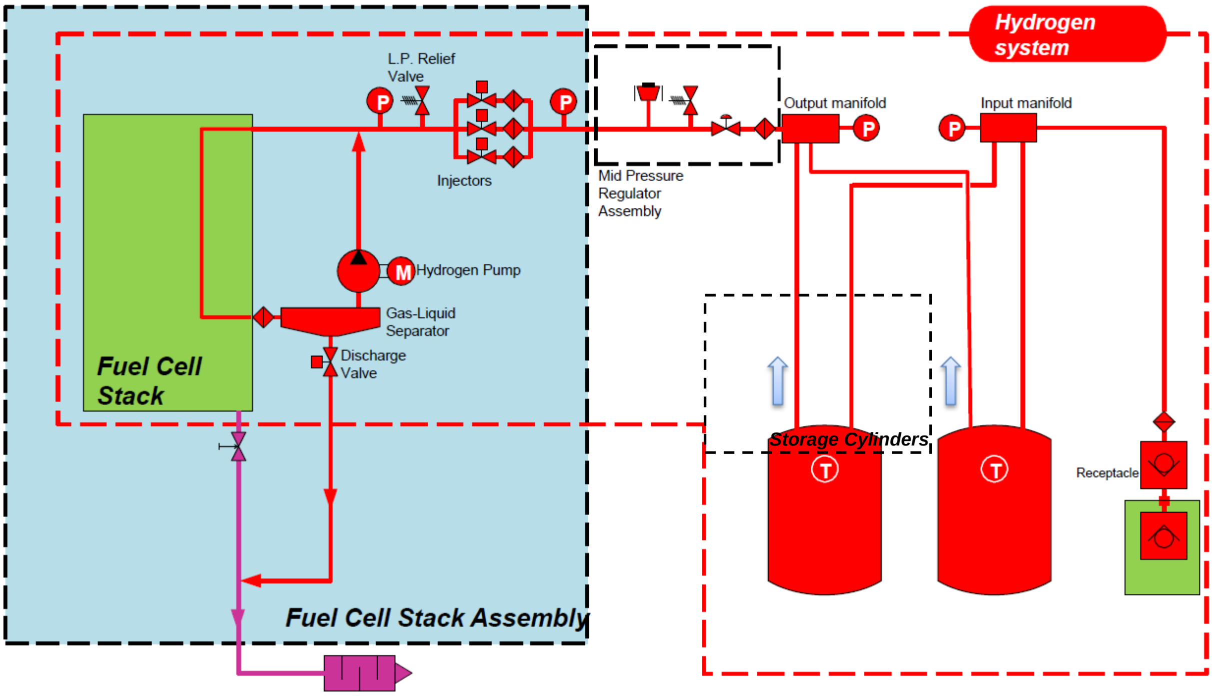

Figure 4 Schematic of the hydrogen storage and supply on a hydrogen fuel cell vehicle (Mattelaer, 2019)

Figure 5 shows a picture of a hydrogen storage cylinder located in the undercarriage of a vehicle with the integrated on-tank valve positioned on the end of the cylinder. A schematic diagram of the internal components of the integrated valve is also shown in Figure 5. The integrated valve contains five components, which are:

- A check valve that prevents back flow during filling;
- A manual shut-off valve that will isolate the cylinder contents from all flow lines (except the cylinder thermal pressure relief valve);
- A thermal pressure relief device (TPRD) that protects the cylinder from over pressurisation in the event of fire;
- A depressurization valve to facilitate manual vessel blowdown; and
- An automatic tank shut-off to isolate the cylinder in the event of an onboard leak.

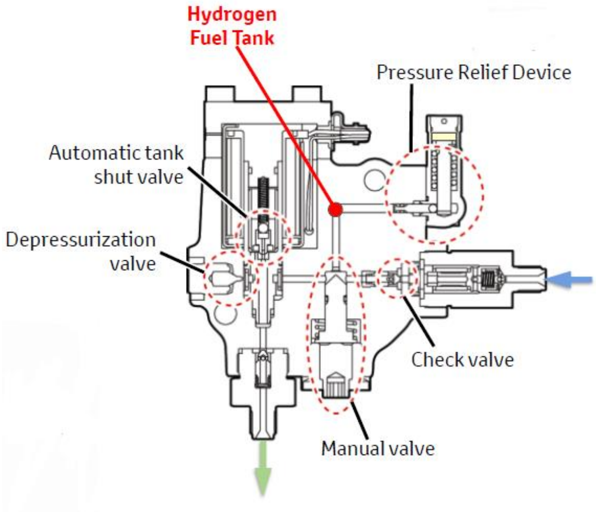

Figure 5 Hydrogen storage cylinder and integrated valve –attached to cylinder in vehicle (left) and schematic of the integrated valve (right) (Mattelaer, 2019)

In many designs of vehicle there are multiple high-pressure cylinders each with a dedicated integrated valve, and in the case of longer cylinders a second TPRD is required.

In the event of fire and subsequent TPRD operation the outflow is directed to a suitable location directly from TPRD or through a vent line where the direction of the release is controlled to ensure that accumulation within the vehicle does not occur and driver/passengers could leave vehicle safely. Where multiple cylinders are present then multiple vessels may release through own TPRDs or all vent though a common vent line; therefore, a single exit orifice will be fed by the full combined storage volume.

The TPRD flow rate is dictated by the storage system fire test requirement, i.e. that the system should vent prior to vessel rupture (time duration in 10 minute of localised fire exposure and until full blowdown) (GTR#13, 2013 and working draft). TPRD should be designed to exclude the pressure peaking phenomenon in accordance with requirement of international standard ISO 19882 "Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers". The standard states:): "The adequacy of flow capacity of pressure relief devices for a given application is to be demonstrated by bonfire testing in accordance with ISO 19881, ANSI HGV 2, CSA B51 Part 2, EC79/EU406, SAE J2579, or the UN GTR No. 13 for fuel cell vehicles and by the minimization of the hazardous effects of the pressure peaking phenomenon which could take place during high flow rate releases from small diameter vents in enclosed spaces".

To facilitate fast filling an overpressure allowance of up to 87.5 MPa is available in the pressure rating of the vessel (GTR#13). Increased pressure occurs during refuelling due to adiabatic heating of gas during transfer. Therefore, an accident involving a FCH car may occur at up to 87.5 MPa when the vehicle has recently refuelled prior to an accident occurring. This increased pressure condition is most likely only relevant to cars which refuel more frequently around the road network compared to other vehicle types. This specific scenario condition would only be relevant to road tunnels and not to confined spaces such as car parks, where it is expected that there will be sufficient cooling time after accessing the confined space prior to an accident occurring.

Relevant Scenario Variables

- In the event of a large vehicle fire the operation of all TPRD valves on all storage vessels should be assessed. This event will result in a larger reservoir volume of hydrogen, e.g. full onboard inventory should be assessed leading to longer release / blowdown duration.
- Maximum pressure of stored hydrogen – it is estimated that the maximum allowable pressure after fast refuelling is 87.5 MPa.

4.5.2 Transportation Design

4.5.2.1 FCEV

A Fuel Cell Electric Vehicle (FCEV) comprises a number of core components that can be subdivided into the high voltage components side or the hydrogen components. Figure 6 shows an overview of these core components on a plan view of the 2018 Honda Clarity. In other vehicle makes/models the components may be located elsewhere, e.g. the battery in the rear and the fuel cell stack under the passenger compartment in the Hyundai Tucson FCEV. However, in most models of FCEV the hydrogen cylinders are located to the rear of the vehicle above the rear wheel axle.

Table 14 summarises the key parameters in the storage system design for FCEVs that have entered the market over the past five years. In all cases the storage pressure on a FCEV is 70 MPa; however, storage vessel pressure can increase up to 87.5 MPa during refuelling. A median value for the total storage volume is in the range of 130 l which equates to a hydrogen mass of approximately 5.5 kg. This volume is typically split between two storage cylinders, with each vessel having a dedicated integrated valve i.e. one TRPD per vessel. For FCEVs, the cylinders are mostly located in the rear of the vehicle, either under the rear passenger's seats and/or close to the luggage space. In recently produced vehicles the hydrogen vent line orientation is downwards towards the road surface at a 45 ° angle (towards the rear of the vehicle). The TPRD vent diameters are of the order 2 mm.

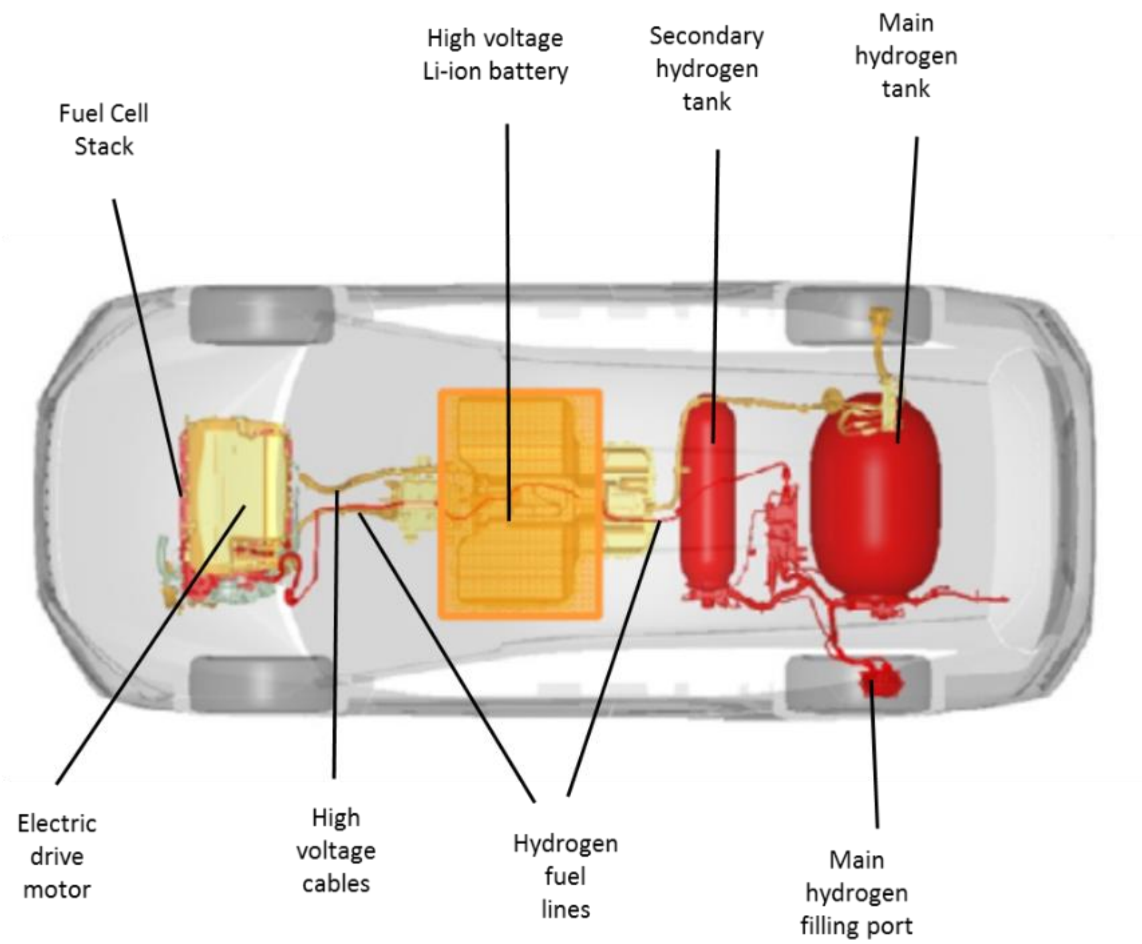

Figure 6 Core power train components on the Honda Clarity FCEV (Honda, 2019)

Table 14 FCEV hydrogen storage specifications

Make/Model	Year	No tanks	Vessel pressure (MPa)	Mass (kg) per tank / total	Volume (litres) per tank / total	Vent Size (mm)	Vent* Angle
Mercedes-Benz GLC F-CELL.	2018	2 (different shape / equal size)	70	2.2 [A] x 2 / 4.4 [D]	57.5 [A] / 115*	2 [A]	
Hyundai NEXO Fuel Cell	2018	3	70	2 [C] /6 [C]	52 [C] / 156 [D]		
Honda Clarity Fuel Cell	2016	2 (not equal size)	70	? /5.46 [D]	144*		
Toyota Mirai	2015	2	70	2.3 [A] / 4.6 [A]	60 [D], 62.4 [D] / 122.4 [D]	2 [A]	135°
Hyundai Tucson/ix35 FCEV	2013	2 (not equal size)	70	? / 5. 6 [D]	/ 133 [C]		

[D] = Manufacture Data
[A] = Assumption
[C] = Calculated ($\rho_{H2,700bar}$ = 38kg/m^3)
* 0° = vertically up

A typical FCEV scenario should use the following values to define the storage system parameters:

- Pressure: 70 MPa and 87.5 MPa;
- Total volume and mass hydrogen: 120 l and 5 kg;
- Number of vessels: 2;
- Volume and mass per vessel: 60 l and 2.5 kg;
- Vent line diameter: 2 mm;
- Vent line discharge: downwards, 135°;
- Simultaneous vessel discharge during fire induced blowdown; and
- Single vessel discharge following unintended TPRD activation.

4.5.2.2 FCEB

The roll out of fuel cell electric buses (FCEB) in Europe is being driven by funding provided primarily by FCH JU through initiatives such as HyTransit, HighVLOcity, Merhlin and Jive. FCEB are currently being developed by a number of bus manufactures including Van Hool, Solaris and WrightBus.

Functionally, there are many parallels in the design of FCEB and FCEV albeit at a different scale. A notable difference is that the maximum operating pressure for storage vessels on a bus is 35 MPa. Due to the lower pressure and the different driving style and load requirements the number of vessels is greater (6 to 10), which results in a greater mass of stored hydrogen of about 40 kg.

Some key demonstration projects that are utilising the latest vehicle designs are:

- Aberdeen, UK – fleet of 10 Van Hool A330;

- California, USA – fleet of 20 New Flyer Xcelsior Charge H2.

Table 15 FCEB hydrogen storage specifications

Make/Model	Year	No tanks	Vessel pressure (MPa)	Mass (kg) per tank / total	Volume (litres) per tank / total	Vent Size (mm)	Vent* Angle
Van Hool A330		8 D	35	5 D / 40 D	220 each / 1750	5A	0A
New Flyer Xcelsior XHE40 Fuel Cell Bus		8 D	35	4.7 D / 37.5 D	200 l each	5A	0A
Solaris Urbino 12 hydrogen		5 D	35		312 D each	5A	0A
D = Manufacture Data A = Assumption C = Calculated ($\rho_{H2,350bar}$ = 23kg/m^3) * 0° = vertically up							

Typical values of the key scenario parameters for buses are:

- Pressure: 35 MPa and 44 MPa;
- Total volume and mass of hydrogen: 1.8 m^3 and 40 kg;
- Number of vessels: 8;
- Volume and mass per vessel: 220 l and 5 kg;
- Vent line diameter: 5 mm;
- Vent line discharge: vertically upwards (no offset angle);
- Combined vessel discharge during fire induced blowdown; and
- Single vessel discharge following unintended TPRD activation.

4.5.3 Trains

The design and development of fuel cell trains is currently in its infancy in terms of maturing towards a final design with only a few Fuel Cell Electric Trains (FCET) in operation. However, based on the data available some general design points can be identified that will provide a basis for designing HyTunnel-CS accident scenarios.

There are currently two prototype design trains in service in Germany. These are fuel cell modifications of the Coradia iLink manufactured by Alstom. Following on from this trial a further 41 full production versions of this train are due to enter service in 2021-2022 in Lower Saxony and Rhine-Main districts of Germany. It is expected that the full production version will have a larger hydrogen storage capacity. The prototype trains comprise two carriages each with 96 kg of hydrogen in 24 cylinders at 350 bar, e.g. 4 kg per cylinder ca. 175 l each. Storage cylinders are located in the roof space above the carriage (http://www.railvolution.net/news/fuel-cell-coradia-ilint-on-test).

In the UK a demonstration joint venture between Potterbrook and Birmingham University has produced the HydroFLEX train which has 20 kg of hydrogen storage across four vessels at 350 bar. In early 2019, Alstom announced a UK prototype design of a fuel cell hydrogen train called ‘Breeze’; however, no full production versions have been announced yet.

From the marketing information it is possible to make an estimate of the full scale production trains that may enter the market in Germany and the UK:

Storage Volume:

- Coradia iLink. Two carriages each with 96 kg hydrogen in 24 cylinders at 350 bar – 4kg per cylinders ca 175 l each. Located in roof space above carriage. (http://www.railvolution.net/news/fuel-cell-coradia-ilint-on-test); or

- Full scale design estimate: 440 kg total hydrogen at 35 MPa, total volume of 19 m^3.

Number of Tanks:

Full scale design estimate:

- 72 tanks each 265 l;
- 36 tanks per carriage = max discharge in a fire;
- 1 vessel discharge during valve failure or tank rupture in fire.

Tank Type – Type IV

Location: options include

- On roof – may lead to issues with train roll stability, particularly relevant for tunnels where there is limited gauging tolerance.
- Underside of the carriage – exposed to track debris and dirt, potential vulnerable locations.
- Dedicated section on a carriage – reduces seating area, internal to the carriage – leak concerns into included space.

Vent orientation: Dependant on storage location. Vertically upward limits the exposure of public and workers in the event of an ignited release – similar approach to buses, however directs release towards the overhead electrification line which will be a high probability ignition source.

4.6 Summary of accident scenario factors

Table 16 to Table 20 below present a summary of all factors and variables to be considered for the selection of the representative set of scenarios to be studied in the HyTunnel-CS project.

Table 16 Transportation mode factors and variables

Factor	Variables	
Road	Car	Bus
Rail	Train	

Table 17 Infrastructure factors and variables

Factor	Variables				
Space	Tunnel	Car Park	Garage		
Design	Cross-section (WxH)	Length / Area	Slope		
Ventilation	Restricted/None	Natural	Forced		
Internal Features	Bulkhead	Gantries	Ventilation ducts	Wiring	
Construction material	Concrete	Steel	Brick		
Mitigation	Ventilation	Water mist	Attenuation	Others	

Table 18 Accident initiator factors and variables

Factor	Variables	
Mechanical failure	Component Failure	
Vehicle fire	Single vehicle	Multiple vehicle
Driver error	Single vehicle	Multiple vehicle
Location	Near portal	Central zone

Table 19 Consequence factors and variables

Factor	Variables	
Rupture	Ignited	
Blowdown	Unignited	Ignited
Ignition	Instantaneous	Delayed

Table 20 Hazard variable factors and variables

Factor	Variables			
Volume/Mass	Single vessel	Full inventory		
Pressure	35 MPa	70 MPa	Fuelling overpressure	Jet fire overpressure

Vent Diameter	1 mm	3 mm	5 mm	0.5 mm
Vent Orientation	0°	135°	180°	
Vehicle Present	Yes	No		
Mitigation	Vent diameter	Vent Orientation	Vessel size	Vessel design

0° = vertical up

5. Accident Scenarios

The identification of the accident scenarios has been achieved in two ways. Firstly, through review of the HyTunnel-CS Description of Actions (DoA) of the Grant Agreement and the HyTunnel-CS Deliverables D1.1 and D1.2, which reviewed underground safety provisions and hydrogen hazards, respectively. The second approach has been to use the accident factors identified in section 4 to design scenarios based on the logical options and permutations of the accident factors.

The headline title for each scenario is listed below and, in the subsequent sections each scenario is described using the accident factors from Section 4. The accident factors are subdivided into those that are fixed for the scenario and those which are variable that could be assessed during the experimental and simulation work. The fixed factors describe the core of the scenarios that are invariant while assessing the scenario; secondly, the scenario variables that should be modified to understand the influence of these variables on the extent of the accident consequence. The scenario variables are also subdivided into the prioritisation categories, i.e. baseline, safety limit and mitigation (as discussed in Section 3.2). In the first instance, baseline and safety limit variables should be assessed to allow a full understanding of the factors that contribute to the consequences; thereafter, and as required, the mitigation variables may be assessed to allow recommendations for the safe operation of FCH transportation in tunnels and confined spaces to be made.

List of Scenarios:

1. Unignited hydrogen release and dispersion in a confined space with mechanical ventilation
2. Unignited hydrogen release in confined spaces with limited ventilation
3. Unignited hydrogen release in a tunnel with natural/mechanical ventilation
4. Hydrogen jet fire in confined spaces with limited ventilation
5. Hydrogen jet fire and vehicle fire in a mechanically ventilated confined space (maintenance shop/ underground parking)
6. Hydrogen jet fire impingement on a tunnel
7. Hydrogen jet fire and vehicle fire in a tunnel
8. Fire spread in underground parking
9. Hydrogen storage vessel rupture in a tunnel
10. Hydrogen storage vessel blowdown with delayed ignition in a tunnel

5.1 Unignited hydrogen jet release and dispersion in a confined space with mechanical ventilation

5.1.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Space – Car Park Design - Fixed dimensions
Accident Initiator	Mechanical failure - Component failure
Consequence	Blowdown - Unignited
Hazard Variable	Single Vessel, 70 MPa

Scenario Variables

Baseline	Vent diameter: 0.5 mm, 2 mm* *calculate/model output to determine diameter to provide no flammable cloud under the ceiling Ventilation rate - 6 ACH Vent direction**: 135 °
Safety limit	Vent diameter: > 2 mm, e.g. 5 mm
Mitigation	Ventilation rate: 10 ACH Vent direction - 180° Vessel volume / Reduce hydrogen storage quantity

(**Vent Direction: 0° = vertically upward)

5.1.2 Research Programme

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 21 HyTunnel-CS work activities (Scenario 1)

Work Package	Work Type	Summary
2.2. Analytical studies and development of engineering tools (UU, CEA, NCRSD)	Engineering Models and Tools	Develop an engineering tool for mechanical ventilation in an underground parking (UU, CEA). Develop non-adiabatic blowdown model for under-expanded jets from the onboard storage tank to assess effectiveness of underground facility ventilation systems at different stages of accident and to underpin accuracy of numerical simulations of release and dispersion in realistic scenarios (UU).

Work Package	Work Type	Summary
		Develop further the pre-existing choked flow and tank blowdown models with Helmholtz free-energy-based hydrogen equation of state to account for non-adiabatic conditions and frictional effects during release of hydrogen (NCRSD).
2.3.1. Pre-test and validation simulations (NCSRD, CEA)	Simulation	Pre-test simulations for the experiments in 2.4.1. "Mechanical ventilation in underground parking with hydrogen-powered vehicles" with subsequent validation of CFD model following the experimental programme.
2.4.1. Mechanical ventilation in underground parking with hydrogen vehicle (USN)	Experimental	Obtain concentration profiles after under-expanded hydrogen jet dispersion in a mock-up of underground parking with mechanical ventilation.
2.4.4. Efficiency of mechanical ventilation on dispersion of hydrogen release (PS)	Experimental	Investigate the hydrogen jet structure and its dispersion in presence of co-, cross- and counter-flow. Determine the hazard distances as a function of the ratio of hydrogen mass flow rate and air flow velocity; provide data for model development and validation.

5.1.3 Knowledge Gaps

This accident scenario will address the following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Effectiveness of regulated ventilation systems in case of hydrogen release accident;
- Hazard distances of unignited release, i.e. location of flammable hydrogen-air mixture for releases and dispersion in realistic scenarios at storage pressures up to 700 bar;
- The upper limit of hydrogen release rate that will not require change in ventilation systems;
- Engineering tool for the assessment of ventilation system parameters to prevent and mitigate flammable mixture formation in tunnels and especially its ventilation systems;
- Engineering tool for mechanical ventilation in underground parking;
- Experimental data and tools for hydrogen release in enclosure with more than one vent;
- Mechanical ventilation in underground parking with hydrogen-powered vehicle;
- The effect of using fans in confined spaces;
- Predictive tool for the design of tunnel ventilation systems and corresponding ventilation protocols; and
- Impinging hydrogen unignited jets.
- Requirements to inherently safer design of vehicle-underground parking system.

5.2 Unignited hydrogen release in confined spaces with limited ventilation

5.2.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Space - Garage Design - Fixed dimensions – (1 or 2 cars garage)
Accident Initiator	Mechanical failure - Component failure
Consequence	Blowdown - Unignited
Hazard Variable	Single vessel, 70 MPa, vent direction

Scenario Variables

Baseline	Vent diameter – 2 mm Ventilation area - A
Safety limit	Vent diameter - > 2 mm, e.g. 5 mm (if possible) Ventilation Area - < A (if possible)
Mitigation	Vent diameter - < 2 mm, e.g. 0.5 mm* *calculate/model output to determine diameter to provide no flammable cloud under the ceiling

5.2.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 22 HyTunnel-CS work activities (Scenario 2)

Work Package	Work Type	Summary
2.2 Analytical studies and development of engineering tools (UU, CEA, NCRSD)	Engineering Models and Tools	The existing tool on unignited release of hydrogen in confined space developed by UU will be used to plan validation experiments that would expand the validation domain of the model for unignited releases to larger enclosures.
2.3. Pre-test and validation simulations (NCSRD)	Simulation	Release and dispersion simulation of experiments conducted in 2.4.2. to assess pressure peaking phenomenon for unignited releases in confined spaces.
2.4.2. Pressure peaking phenomenon for unignited releases in confined spaces (USN)	Experimental	Series of experiments aimed to provide unique experimental data in real-scale garage-like enclosure for development and validation of engineering and CFD models of the pressure peaking phenomenon (PPP) for unignited releases.

5.2.3 Knowledge Gaps

The accident scenario will address the following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Hazard distances of unignited releases, i.e. location of flammable hydrogen-air mixtures for releases and dispersion in realistic scenarios at storage pressures up to 700 bar;
- Experimental data and tools for hydrogen release in enclosures with more than one vent;
- The effect of using fans in confined spaces;
- The pressure peaking phenomenon validation for garage-like enclosures for unignited releases; and
- Impinging hydrogen unignited jets.

5.3 Unignited hydrogen release in a tunnel with natural/mechanical ventilation

5.3.1 Accident Scenario Design

Fixed Factors

Transportation Type	*see baseline below*
Infrastructure	Space – Tunnel
Accident Initiator	Mechanical failure - Component failure
Consequence	Blowdown - Unignited
Hazard Variable	Single vessel, 35 MPa and 70 MPa (as per transportation type)

Scenario Variables

Baseline	Transportation type: -Car (P=70 MPa) -Bus (P=35 MPa) -Train (P=35 MPa) Cross section design: -Road tunnel -Rail tunnel Tunnel slope Ventilation rate (air velocity) Internal features Accident location Vent diameter Vent orientation
Safety limit	Vent diameter Vessel size Ventilation rate (air velocity)
Mitigation	Vent diameter

Vent orientation
Vessel size

5.3.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 23 HyTunnel-CS work activities (Scenario 3)

Work Package	Work Type	Summary
2.2. Analytical studies and development of engineering tools (UU, CEA, NCRSD)	Engineering Model / Tool	Develop an engineering tool for the assessment of ventilation system parameters to prevent and mitigate flammable mixture formation in tunnels and especially its ventilation systems (CEA). Develop non-adiabatic blowdown model for under-expanded jets from the onboard storage tank to assess effectiveness of underground facility ventilation system at different stages of accident (UU). Develop further the pre-existing choked flow and tank blowdown model with Helmholtz free-energy-based hydrogen equation of state to account for non-adiabatic conditions and frictional effects during release of hydrogen (NCRSD).
2.3.1. Pre-test and validation simulations (NCSRD, CEA)	Simulation	Pre-test simulations for the experiments in 2.4.3. “Dynamics of release and dispersion of hydrogen in a tunnel” with subsequent validation of CFD model following the experimental programme.
2.4.3. Dynamics of release and dispersion of hydrogen in a tunnel (HSE)	Experimental	Investigate the dynamics of hydrogen dispersion in tunnels; measuring the characteristics of downstream flow developed by normal tunnel ventilation with a view to determining whether the resultant hydrogen layer (i) is flammable and (ii) depending on the degree of mixing may extend a substantial distance from the source; study the effects of obstructions in the tunnel on near field dispersion; and provision of unique experimental data for development and validation of models for unignited hydrogen behaviour in tunnels.
2.4.4. Efficiency of mechanical ventilation on dispersion of hydrogen release (PS)	Experimental	Investigate the hydrogen jet structure and its dispersion in presence of co-, cross- and counter-flow. Determine the hazard distances as a function of the ratio of hydrogen mass flow rate and air flow velocity; provide data for model development and validation.

5.3.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Effectiveness of regulated ventilation systems in case of hydrogen release accident;
- Hazard distances of unignited releases, i.e. location of flammable hydrogen-air mixture for releases and dispersion in realistic scenarios at storage pressures up to 700 bar;
- The upper limit of hydrogen release rate that will not require change in ventilation system;
- Engineering tool for the assessment of ventilation system parameters to prevent and mitigate flammable mixture formation in tunnels and especially its ventilation systems;
- Dynamics of release and dispersion of hydrogen in a tunnel, including hydrogen release and dispersion in a tunnel with forced ventilation;
- Difference between hydrogen dispersion in tunnels with regulated slope, below 5%, and without slope in sense of hazard distance;
- The effect of ventilation and its interaction with other mitigation systems, e.g. water spray and mist, bulkheads, etc.;
- Predictive tool for the design of tunnel ventilation systems and corresponding ventilation protocols; and
- Impinging hydrogen unignited jets.

5.4 Hydrogen jet fire in confined spaces with limited ventilation

5.4.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Space – Garage Design - Fixed dimensions – 1 or 2 cars garage Passive ventilation
Accident Initiator	Vehicle fire
Consequence	Blowdown – Instantaneous ignition
Hazard Variable	Full Inventory, 70 MPa, vent direction

Scenario Variables

Baseline	Vent diameter 2 mm Ventilation area A
Safety limit	Vent diameter > 2 mm, e.g. 4 mm or 5 mm (if possible) Ventilation Area < A (if possible)

Mitigation	Vent diameter < 2 mm, e.g. 0.5 mm

5.4.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 24 HyTunnel-CS work activities (Scenario 4)

Work Package	Work Type	Summary
3.2.1. Correlation for pressure peaking phenomenon for jet fires in enclosures (UU)	Engineering Model / Tool	Models will be further developed and validated that describe the pressure peaking phenomenon model for ignited releases of hydrogen (jet fire) in confined space with limited ventilation.
3.3.1. CFD model for predictive simulation of pressure peaking phenomenon for hydrogen jet fire in confined space (UU)	Simulation	A three-dimensional CFD model of pressure peaking phenomenon will be developed that allow distribution of hazardous parameters like temperature in space and time to assess the evacuation and rescue strategies after the release. Model validation against experiments in (3.4.1) will allow its use as a verification tool to expand applicability domain for the engineering correlation.
3.4.1. Pressure peaking phenomenon for hydrogen jet fires in confined spaces (USN)	Experimental	Undertake tests to quantify pressure and thermal loads on structures during the pressure peaking phenomena in an enclosure with limited ventilation for ignited jet release (fire) of hydrogen.

5.4.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al, 2019):

- The pressure peaking phenomenon validation for garage-like enclosures for jet fires from TPRD; and
- Fire dynamics of hydrogen vehicles with understanding that standard curves cannot be applied.

5.5 Hydrogen jet fire and vehicle fire in a mechanically ventilated maintenance shop/underground parking

5.5.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Forced ventilation

Accident Initiator	Vehicle fire
Consequence	Blowdown – Instantaneous ignition
Hazard Variable	Full Inventory, 70 MPa, release under vehicle

Scenario Variables

Baseline	Space - Underground car park - Maintenance shop Ventilation rate: 10 ACH Vent diameter: 2 mm Vent orientation: 0 °, 135 °, 180°
Safety limit	Vent diameter > 2 mm, e.g. 5 mm Ventilation rate > 10 ACH
Mitigation	Vent diameter < 2 mm, e.g. 0.5 mm Ventilation rate: 10 ACH Vessel size

5.5.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 25 HyTunnel-CS work activities (Scenario 5)

Work Package	Work Type	Summary
3.2.3. Mechanical ventilation of hydrogen non-premixed turbulent combustion in underground parking (UU)	Engineering Model / Tool	An engineering tool will be developed that will help to assess if the current ventilation standards for underground parking in case of a vehicle fire is still applicable in the event of hydrogen jet fire from a vehicle TPRD, or the hydrogen jet fire will aggravate the vehicle fire hazards.
3.3.2. CFD model of hydrogen non-premixed turbulent combustion in scaled underground parking with mechanical ventilation (NCSRD)	Simulation	Develop and validate CFD model of hydrogen non-premixed turbulent combustion in scaled underground parking with mechanical ventilation.

3.4.2. Thermal effects of hydrogen non-premixed turbulent combustion on a vehicle fire behaviour, structure and evacuation conditions in underground parking (USN)	Experimental	The effect of turbulent non-premixed hydrogen combustion on fire behaviour in mechanically ventilated facility will be assessed. The tests will investigate how the heat/combustion released from hydrogen via TPRD jet fire will affect the primary vehicle fire behaviour which has activated the TPRD. The fire dynamics without and with TPRD initiation, including effect on heat release rate, heat flux and temperature distribution will be compared and analysed.

5.5.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Fire dynamics of hydrogen vehicles;
- Effect of water vapour generated by hydrogen combustion from TPRD on the visibility and the choice of "cross passage" distance;
- Hydrogen non-premixed turbulent combustion in scaled underground parking;
- Thermal effects of hydrogen non-premixed turbulent combustion on a vehicle fire behaviour, structure and evacuation conditions in underground parking;
- Dynamics of total and radiative heat flux on under-vehicle hydrogen storage and surroundings from the “conventional” car fire before and after TPRD initiation; and
- Effect of water generation during hydrogen combustion from TPRD on soot density from car fire.

5.6 Hydrogen jet fire impingement on a tunnel

5.6.1 Accident Scenario Design

Fixed Factors

Transportation Type	*see baseline below*
Infrastructure	Space – Tunnel Design - Fixed dimensions Ventilation rate
Accident Initiator	Vehicle fire
Consequence	Blowdown – Instantaneous ignition
Hazard Variable	Full inventory

Scenario Variables

Baseline	Transportation type: - Car (70 MPa) - Bus (35 MPa)

	- Train (35 MPa) Cross section design: - Road tunnel - Rail tunnel Construction material - Concrete - Steel - Brick Accident location Vent diameter 2-5 mm - dependant on transportation type
Safety limit	Vent diameter Storage volume Ventilation rate
Mitigation	Vent diameter < Baseline e.g. 0.5 mm Vent orientation

5.6.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 26 HyTunnel-CS work activities (Scenario 6)

Work Package	**Work Type**	**Summary**
	Engineering Model / Tool	
3.3.3. Coupled CFD/FEM modelling of the structures reaction to fire (DTU)	Simulation	The combined effect of pressure and thermal loads on the structural integrity of steel in tunnel will be investigated. Finite Element Modelling (FEM) modelling will be implemented in a multi-physics commercial software, where mechanical action of the explosion and thermal action of the fire will be considered in the form of pressure and temperature time-histories.
3.4.3. Effect of hydrogen jet fire on structure integrity and concrete spalling (DTU)	Experimental	Investigate effect of hydrogen fire on the structural integrity and concrete spalling caused by hydrogen jet fires in a tunnel.
3.4.4. Effect of hydrogen jet fires on the erosion of tunnel road materials and lining materials (HSE)	Experimental	Investigate if a burning hydrogen jet will pose new hazards and associated risks to the integrity of tunnels through a series of materials tests. The work will characterise a representative hydrogen jet that might occur from a hydrogen vehicle through the activation of a PRV/TPRD. It will then perform up to five materials tests to evaluate erosive properties of hydrogen jet fires on the various substrates and materials used in tunnel constructions.

5.6.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Relation between concrete spalling and a way structural elements and linings are fixed;
- Impact of impinging hydrogen jet fires on high strength concrete types, which may lead to concrete degradation;
- Coupled CFD-FEM modelling of the structure's reaction to fire;
- Effect of hydrogen jet fire on structure integrity and concrete spalling;
- Effect of hydrogen jet fires on the erosion of tunnel road materials and lining materials; and
- Impinging hydrogen jet fires.

5.7 Hydrogen jet fire vehicle fire in a tunnel

5.7.1 Accident Scenario Design

Fixed Factors

Transportation Type	*see baseline below*
Infrastructure	Space – Tunnel Design - Fixed dimensions Passive / Forced ventilation
Accident Initiator	Vehicle fire
Consequence	Blowdown – Instantaneous ignition
Hazard Variable	Full inventory

Scenario Variables

Baseline	Transportation Type: - Car (70 MPa) - Bus (35 MPa) - Train (35 MPa) Cross section design: - Road tunnel - Rail tunnel Ventilation rate Vent diameter 2-5 mm - dependant on transportation type Vent orientation
Safety limit	Vent diameter > Baseline
Mitigation	Vent diameter < Baseline e.g. 0.5 mm Ventilation rate Water sprays

5.7.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 27 HyTunnel-CS work activities (Scenario 7)

Work Package	Work Type	Summary
	Engineering Model / Tool	
	Simulation	
3.4.5. Effect of hydrogen combustion from TPRD on vehicle fire dynamics in tunnel (CEA)	Experimental	Understand and quantify the effect of hydrogen combustion on the combined heat release rate (HRR) and fire behaviour, including smoke layer development and propagation, during a real vehicle fire in real tunnel.
3.4.6. Effect of water sprays on mitigation of hydrogen jet fires (PS)	Experimental	The efficiency of water spray to suppress combustion of and radiation from hydrogen jet fire and finally to reach an extinction of the jet fire will be investigated.

5.7.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al, 2019):

- Fire dynamics of hydrogen vehicles;
- Effect of water vapour generated by hydrogen combustion from TPRD on the visibility and the choice of "cross passage" distance;
- Effect of hydrogen combustion on smoke back-layering;
- Effect of hydrogen combustion from TPRD on vehicle fire dynamics in tunnel;
- Dynamics of total and radiative heat flux on under-vehicle hydrogen storage and surroundings from the “conventional” car fire before and after TPRD initiation;
- Effect of water generation during hydrogen combustion from TPRD on soot density from car fire;
- Efficiency of hydrogen fire suppression systems by water sprays and oxygen depletion;
- Effect of water sprays on mitigation of hydrogen jet fires;
- Effect of TPRD diameter on hazard distance from burning car (fire hazard distances); and
- Performance of leak-no-burst tank in real car fire conditions (with measurement of heat flux to the tank located under- and above a vehicle).

5.8 Fire behaviour in underground parking

5.8.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Space – Underground car park Design - Fixed dimensions Forced ventilation Multiple vehicles
Accident Initiator	Vehicle fire
Consequence	Blowdown – Instantaneous ignition
Hazard Variable	Full Inventory, 70 MPa

Scenario Variables

Baseline	Vent diameter - 2 mm Ventilation rate: 10 ACH
Safety limit	Vent diameter - > 2 mm, e.g. 5 mm Ventilation Area > 10 ACH
Mitigation	Vent diameter - < 2 mm, e.g. 0.5 mm

5.8.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 28 HyTunnel-CS work activities (Scenario 8)

Work Package	Work Type	Summary
3.3.4. CFD model on influence of hydrogen releases to fire spread scenarios in underground transportation systems (DTU)	Simulation	Will assess the shortcomings of design practice for underground car parks hosting hydrogen and fuel cell vehicles. As a part of this sub-task, a numerical study of fire spread from a hydrogen car to adjacent cars in an underground parking will be carried out using CFD model. The influence of mechanical ventilation, type and geometry of parking, spacing between cars, ceiling height and structure will be analysed in the parametric study.

5.8.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Effect of hydrogen releases on fire spread scenarios in underground transportation systems.

5.9 Hydrogen storage tank rupture in a tunnel

5.9.1 Accident Scenario Design

Fixed Factors

Transportation Type	Road - Car
Infrastructure	Space – Tunnel Forced ventilation
Accident Initiator	Vehicle fire and component failure
Consequence	Tank rupture - ignited
Hazard Variable	Full inventory, 70 MPa, vent direction

Scenario Variables

Baseline	Transportation Type: - Car (70 MPa) - Bus (35 MPa) - Train (35 MPa) Vessel pressure: nominal and fire overpressure Cross section design: - Road tunnel - Rail tunnel Internal design - None - Bulkhead - Gantries - Ventilation ducts - Cable trays Vehicle present (yes/no)
Safety limit	Vessel volume
Mitigation	Attenuation material Vessel design, including LNB tank preventing explosion in a fire

5.9.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 29 HyTunnel-CS work activities (Scenario 9)

Work Package	Work Type	Summary
4.2. Engineering models for assessment of blast wave and fireball of hydrogen tank rupture	Engineering Model / Tool	Develop engineering models for assessment of blast wave and fireball of hydrogen tank rupture in a tunnel using parameters of a storage vessel and of a tunnel.

Work Package	Work Type	Summary
4.2. Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire (UU)	Engineering Model / Tool	Create an engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire.
4.3. Simulation of water injection effect on shock wave attenuation (KIT)	Simulation	Water injection effect will be studied numerically using a reduced spray model that will simulate the water spray introduction into the channel. The interaction between the water droplets and gases in the channel will be modelled too. The simulation will be carried out for different initial hydrogen concentration gradients, hydrogen inventory and two different cross-sections of the channels.
4.3. Analysis of the interaction between absorbing materials and systems and shock wave (UU)	Simulation	Effect of different absorbing materials of varying thickness will be studied numerically. The mitigation capacity of different engineering solutions will be compared.
4.3. Pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball	Simulation	Parametric study to find out the maximum allowable hydrogen inventory to mitigate the effect of blast wave and fireball after hydrogen tank rupture in a fire in a tunnel on people and structure. The established harm criteria for humans and damage criteria for structures will be applied to find out the parameters of inherently safer onboard storage tank.
4.3. Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast	Simulation	Modelling and simulation of a tunnel structure reaction to the blast produced by hydrogen storage tank rupture in a fire.
4.4.1. Blast wave and fireball of hydrogen tank rupture in a tunnel (HSE, CEA)	Experimental	Experimental studies to measure blast wave and fireball parameters to characterise consequences of hydrogen storage tank failure as a result of fire in tunnels of different size.
4.4.5. Shock wave attenuation (PS, HSE)	Experimental	Evaluate shock wave attenuation by: water and mist systems, absorbing materials, soft bulkheads, sacrificial pre-evacuated volumes with respect to their mitigating capacities.
4.4.6. Innovative safety technology for prevention of tank rupture (UU, HSE, CEA)	Experimental	Develop and manufacture four prototypes of leak-no-burst composite type 4 tanks for testing in a tunnel fire at CEA and HSE tunnels.

5.9.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al, 2019):

- Prediction of blast wave from deflagrations of hydrogen-air mixtures in tunnels;
- Behaviour of high-pressure storage tanks in a tunnel fire;
- Coupling blast wave pressure load CFD simulations and structural FEM simulations;
- Physical modelling and CFD-FEM simulations of tank rupture under-vehicle accounting for losses on vehicle demolition and translation in space;
- Hydrogen combustion and pressure dynamics in presence of vehicles and other obstacles in a tunnel;
- Prediction of blast wave and fireball dynamics after hydrogen tank rupture in a tunnel fire;
- Engineering models for assessment of blast wave and fireball of tank rupture in a tunnel using parameters of a storage vessel and of a tunnel;
- Dependence of inherently safer hydrogen inventory on tunnel parameters;
- Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast produced by hydrogen storage tank rupture in a fire;
- Experimental data and engineering tools for the assessment of a fireball and blast wave dynamics in a tunnel;
- Prevention and mitigation techniques eliminating hydrogen tank rupture in a tunnel and its devastating consequences: blast wave, fireball, projectiles, e.g. leak-no-burst safety technology for prevention of tank rupture in a fire;
- Shock wave attenuation by water and mist systems, absorbing materials, soft bulkheads, sacrificial pre-evacuated volumes; and
- Protection of humans and critical equipment against pressure effects.

5.10 Hydrogen storage vessel blowdown with delayed ignition in a tunnel

5.10.1 Accident Scenario Design

Fixed Factors

Transportation Type	*see baseline below*
Infrastructure	Space – Tunnel Forced ventilation
Accident Initiator	Component failure
Consequence	Blowdown – Delayed ignition
Hazard Variable	Single vessel

Scenario Variables

Baseline	Transportation Type: -Car (P=70 MPa) -Bus (P=35 MPa)

	-Train (P=35 MPa) Vessel pressure: nominal and fuelling overpressure Cross section design: -Road tunnel -Rail tunnel Internal design -None -Bulkhead -Gantries -Ventilation ducts -Cable trays Vehicle present (yes/no) Accident location (near portal / central zone) Vent diameter: 2 - 5 mm (dependant on vehicle type) Ventilation rate: 0 - 3 m/s Vent orientation
Safety limit	Vent diameter > baseline Ventilation area > 3 m/s (if possible)
Mitigation	Vent diameter < 2 mm (e.g. 1 mm or 0.5 mm) Vessel size Water sprays Attenuation material

5.10.2 Work Package

This accident scenario will be assessed in the following work activities in HyTunnel-CS:

Table 30 HyTunnel-CS work activities (Scenario 10)

Work Package	Work Type	Summary
4.2. Engineering model for assessment of overpressure during spurious hydrogen release (UU)	Engineering Model / Tool	Develop a reduced model to assess overpressure from delayed ignition of turbulent hydrogen jets.
4.2. Correlation for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles (KIT)	Engineering Model / Tool	Using experimental data on DDT tests in stratified hydrogen-air mixture develop the criteria for DDT in homogeneous hydrogen-air mixture and a new correlation for non-uniform explosive mixtures.
4.2. Analytical model for water spray/mist system effect on hydrogen combustion and a shock wave attenuation (KIT)	Engineering Model / Tool	Analytical correlation will be developed based on the existing experimental data of thermal-dynamic properties and hydrogen flame measurements with water spray influence.
4.3. Deflagration of non-uniform hydrogen-air	Simulation	CFD simulation of non-uniform hydrogen-air mixture. Deflagration will be developed by three

Work Package	Work Type	Summary
cloud created by release in tunnel experiments (NCRSD, CEA, KIT)		partners. These simulations will allow a better understanding of the physics of the phenomenon by evaluating the strength of the different factors that contribute to the overpressure development.
4.3. Simulation of water injection effect on hydrogen combustion (NCSRD, KIT)	Simulation	CFD simulations that are capable of simulating both combustion and dispersion of two phase flows will be used to investigate premixed combustion. Two-phase dispersion (e.g. with presence of water droplets in air) will be modelled using the homogeneous mixture approach assuming thermal equilibrium, with and without hydrodynamic equilibrium.
4.3. Simulation of water injection effect on shock wave attenuation (KIT)	Simulation	The mitigation potential of water droplets will be assessed to analyse the strength of shock attenuation of water. Simulations are performed using the KIT in-house computer code COM3D. The attenuation performance is determined as a function of parameters such as droplet size, density of the droplets and Mach number of the shockwave. The results of the numerical calculation will be validated against experimental data.
4.3. Analysis of the interaction between absorbing materials and systems and shock wave (KIT)	Simulation	Effect of different absorbing materials of varying thickness will be studied numerically. The mitigation capacity of different engineering solutions will be compared.
4.3. Simulations to validate multi-phenomena turbulent burning velocity deflagration model (UU)	Simulation	A CFD model will be developed and validated to assess the pressure and thermal hazards from delayed ignition of hydrogen jets. The model will allow more accurate predictions of overpressure and assess scenarios that cannot be represented by the engineering tool.
4.3. Simulations of flame acceleration and transition to detonation in tunnel structures (USN)	Simulation	Simulations will be developed using existing data from experiments done on flame acceleration and DDT in inhomogeneous gas clouds in ducts for validation. The work will develop methods for simulating similar problems related to tunnel structures.
4.4.2. Overpressure during spurious operation of TPRD (HSE)	Experimental	Experimental programme examining hydrogen discharge through a TPRD to simulate vessel blowdown and ignition within a 70 m tunnel. The test data will support the development of engineering models and CFD models of vessel blowdown and subsequent ignition – measurements to include overpressure, heat flux and flame speed, together with imaging and visualisation.

Work Package	Work Type	Summary
4.4.3. Deflagration of non-uniform cloud in a tunnel (HSE)	Experimental	Building on the test programme in 4.4.2. the occurrence of stratified hydrogen layers will be investigated with the effect of internal tunnel features included.
4.4.4. Tests on flame propagation through a layer of fire extinguishing foam filled in by flammable hydrogen-air mixtures (PS)	Experimental	Small-scale tests on flame propagation through a layer of fire extinguishing foam of different properties filled in by flammable hydrogen-air mixtures.
4.4.4. Tests on effect of water sprays and mist systems on combustion and DDT (PS)	Experimental	Experiments will be performed in a rectangular geometry of HYKA A1 vessel (with a box 3x0.6x9 m). Tests on effect of water spray/mist systems on combustion and DDT of uniform layer of hydrogen–air mixture.
4.4.4. Effect of droplet size on mitigation of combustion and DDT (USN)	Experimental	The droplet sizes will be measured using a high-speed microscopic imaging system with laser lighting for shadowgraphy. The nozzle will be tested at USN and results will be correlated with explosion tests by PS.

5.10.3 Knowledge Gaps

The accident scenario will address following knowledge gaps that were identified in HyTunnel-CS Deliverable 1.2 (Cirrone et al., 2019):

- Gas cloud deflagrations near low flammability limit;
- Conditions for DDT in ventilation system of tunnels, including horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles;
- Maximum pressure of turbulent LFL mixture deflagration in closed space;
- Deflagration of non-uniform hydrogen-air cloud in a tunnel, including effect of cross-section geometry;
- Foam and water spray/mist system effect on premixed combustion and DDT;
- Prediction of blast wave from deflagrations of hydrogen-air mixtures in tunnels;
- Thermal and pressure effects of turbulent hydrogen jet delayed ignition in confined space;
- Engineering model for assessment of overpressure during spurious hydrogen release, e.g. during operation of TPRD;
- Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire;
- Validated CFD model for deflagration of non-uniform hydrogen-air cloud created by release in a tunnel;
- CFD model accounting for effect of water spray/mist system effect on deflagration;

- Flame acceleration and transition to detonation in tunnel structures, including bulkheads smoke mitigation systems and ventilation channels; and
- Influence of heat transfer to structure on pressure and temperature decays for deflagration strength.

6. Conclusions

An assessment has been undertaken to identify the factors that contribute to the extent and severity of an accident involving a FCH transportation system in a tunnel or a similar confined space. The objective of the assessment is to identify accident scenarios that will be used as the basis of the approach undertaken by the HyTunnel-CS project to identify how the consequence of accident in a tunnel or confined space may be different to a comparable accident in an open environment and what should be safety strategies and engineering solutions to underpin inherently safer deployment and use of hydrogen vehicles in tunnels, underground parking, garages, etc.

As an output from the work ten typical accident scenarios have been identified which align with the HyTunnel-CS research proposal. Each scenario is described in terms of fixed factors and accident variables that combine to describe the scope and range of the scenario. A number of key aspects have been identified through this approach.

The credible transportation modes that should be assessed are cars, buses and trains. These three modes of transport represent those sectors that are likely to see the largest uptake in FCH technology. These modes also encompass a wide range of onboard hydrogen storage quantities (5 to 400 kg hydrogen) which if assessed fully will allow a thorough understanding of the consequences, and allow the project to make robust conclusions and recommendations for stakeholders.

It has also been identified that blowdown volumes following TPRD initiation by fire may, in the worst case, lead to discharge of the full hydrogen inventory simultaneously. Where TPRDs are interconnected then a prolonged discharge through a common vent may occur.

The identification of these two aspects may require some modification to the proposed research programme to take account of larger quantities of release hydrogen and in environments with differing geometries (i.e. to take account of the different designs characteristics of trains and railway tunnels)

These identified scenarios are proposed based on knowledge available to at the time of preparation and include processes of release and dispersion of unignited hydrogen, interaction of hydrogen jet fire with structures, pressure and thermal loads from explosions, including tank rupture in a fire in case of TPRD failure to operate or blockage during an accident. Through the progress of the HyTunnel-CS project the focus on particular scenario descriptions may change due to the findings of the research.

References

Austroads (2019), Dangerous Goods in Tunnels: Application and methodology, AP-R590-19, Austroads.

Bassan, S. (2016), Overview of traffic safety aspects and design in road tunnels, International Association of Traffic and Safety Sciences Research 40, 35-46.

Bjelland, H., Aven, T. (2013), Treatment of uncertainty in risk assessments in the Rogfast road tunnel project, Safety Science 55, 34-44.

BS 7346-7:2013 - Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks, BSI

Burgess, R., Post, M., Buttner, W., and Rivkin C., (2017). High Pressure Hydrogen Pressure Relief Devices: Accelerated Life Testing and Application Best Practices. NREL Technical Report NREL/TP-5400-67381.

Caliendo, C., De Guglielmo, M.L. (2012), Accident rates in road tunnels and social cost evaluation, SIIV – 5th nternational Congress – Sustainability of road infrastructures, Procedia – Social and behavioural sciences 53, 166-177.

Channel Tunnel Safety Authority - CTSA (1997), Inquiry into the fire on Heavy Goods Vehicle shuttle 7539 on 18 November 1996. Available from: http://www.railwaysarchive.co.uk/doclisting.php?sortKey=date&sortDirection=ASC&showSearch=true&text=&startYear=1996&endYear=1997&development=all&category=4&author=all&publisher=all&published=all&submit=Go [Accessed 02/10/2019].

Civil Engineering Conference (2001), Maintenance of track gauge guidelines, CEC/DG/001, Issue I, January 2001.

Department for Communities and Local Government – DCLG (2010), Fire spread in car parks, BD2552, BRE, December 2010.

EHSP (2019). Safety planning for hydrogen and fuel cell projects. European Hydrogen Safety Panel Report for FCH 2 JU. Available from: https://www.fch.europa.eu/page/european-hydrogen-safety-panel. [Accessed 15/10/2019]

Encyclopædia Britannica, Inc. (2019), The railroad in continental Europe, available from: https://www.britannica.com/technology/railroad/The-Liverpool-and-Manchester-Railway#ref64365 [Accessed 03/10/2019].

European Commission (2018), Assessment of unit costs (standard prices) of rail projects (CAPital EXpenditure) – Annex 13: Case study on tunnels. Available from: https://ec.europa.eu/regional_policy/en/information/publications/reports/2018/assessment-of-unit-costs-standard-prices-of-rail-projects-capital-expenditure [Accessed 02/10/2019].

European Standard Parking Award (ESPA) (2015), Manual for the ESPA checklist. Available from: https://www.europeanparking.eu/en/awards/espa-off-street/ [Accessed 25/10/2019].

European Union (2004), Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

European Union (2014), Commission Regulation No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union.

GTR13 (2013). United Nations Economic Commission for Europe (2013) Global technical regulation on hydrogen and fuel cell vehicles, Addendum 13: Global technical regulation No. 13. Global Registry. (Global Registry). UNECE.

H2Mobility (2019). Customer Demand. Available from:

Hertz, K.D. (2003), Limits of spalling of fire-exposed concrete, Fire Safety Journal 38, 103-116.

Highways Agency et al (1999), Design Manual for Roads and Bridges, Volume 2, Section 2, Part 9, BD 78/99: Design of Road Tunnels, The Stationary Office Ltd, UK.

Hill, N., Hilton, G., Morgan-Price, S., Weldon, P., (2019). Zero Emission HGV Infrastructure Requirements. Report for Committee on Climate Change, Ricardo Energy ED12387.

http://www.hysafe.net/download/1763/Hyunnel_Final%20ReportDraft_20Feb09_final.pdf [Accessed on 30.06.2019].

http://www.ukh2mobility.co.uk/the-project/consumer-demand [Accessed 29/10/2019].

https://www.monmouthshire.gov.uk/planning-policy2/supplementary-planning-guidance/adopted-supplementary-planning-guidance/domestic-garage-spg-jan-2013/ [Accessed 25/10/2019].

https://www.planningni.gov.uk/index/policy/planning_statements_and_supplementary_planning_guidance/spg_other/parking-standards.htm [Accessed 25/10/2019].

https://www.toyota-europe.com/new-cars/mirai/index/specs [Accessed 25/10/2019].

Hua T., Ahluwalia R., Peng J.K., Kromer M., Lasher S., (2010). Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications, Report Number ANL-10/24, Argonne National Laboratory.

HyTunnel-CS D1.1 (2019), Report on assessment of effectiveness of conventional safety measures in underground transportation systems and similar confined spaces, Report of the HyTunnel-CS project. Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Grant Agreement Number 826193.

HyTunnel-CS D1.2 (2019), Report on hydrogen hazards and risks in tunnels and similar confined spaces, Report of the HyTunnel-CS project. Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Grant Agreement Number 826193.

HyTunnel-D111 (2009), Internal project on investigating the use of hydrogen vehicles in road tunnels, Deliverable D111, 15 April 2009. Accessible from:

Jordan, T., et al (2011), Achievements of the EC network of excellence HySafe, International Journal of Hydrogen Energy 36, 2656-2665.

Lafleur, C., Bran-Anleu, G., Muna, A.B., Ehrhart, B.D., Blaylock, M. and Houf, W.G. (2017) Hydrogen fuel cell electric vehicle tunnel safety study. Sandia National Laboratories Report SAND2017-11157.

LaFleur, C., et al (2017), Hydrogen fuel cell electric vehicle tunnel safety study, Sandia

National Laboratories, Report number SAND2017-11157, October 2017.

Laumann, F., Verbecke, F., Duclos, A., Zanoto, A., and Zhiyong, L. (2015). HyResponse-D2.1: Description of selected FCH systems and infrastructure, relevant safety features and concepts. Accessible from: http://www.hyresponse.eu/deliverables.php. [Accessed on 01/08/2019]

Li, Y.Z. (2018). Fire and explosion hazards of alternative fuel vehicles in tunnels. Brandfrosk 2018:1

Maidl, B., Thewes, M., Maidl, U. (2014), Handbook of Tunnel Engineering II: Basics and Additional Services for Design and Construction, Wiley.

Makarov, D. et al. (2018) Pressure peaking phenomenon: Model validation against unignited release and jet fire experiments. International Journal of Hydrogen Energy. Pergamon, 43(19), pp. 9454–9469.

Mattelaer, V. (2019a). Safety when handling FCV's. Presentation to XXXX, Sept 2019.

Monmouthshire County Council (2013), Supplementary Planning Guidance - Domestic Garages. Available from:

Norwegian (1997), Studies on Norwegian Road Tunnels, TTS 15 1997, Norwegian Public Roads Administration.

Nussbaumer, C. (2007), Comparative analysis of safety in tunnels, Young Researchers Seminar, Brno.

OREDA – Offshore Reliability Data, Volume I – Topside Equipment, 5th Edition, 2009.

Planning Portal (2019). Available from:

Rail System (2015), Rail gauges. Available from: http://www.railsystem.net/rail-gauges/ [Accessed 02/10/2019].

Ruf, Y., Zorn, T., Akcayoz De Neve, P., Andrae, P., Erofeeva, S., Garrison, F., Schwilling, A., (2019). Study on the use of fuel cells and hydrogen in the railway environment'. Report for Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking.

SafeT-D2 (2005), Recommendations for the enhancement of preventing tunnel safety.

SafeT-D4.5 Part II (2005), Analysis of tunnel-accident data and recommendations for data collection and accident investigation.

Toyota (2019a), Compare Specifications. Available from:

Toyota (2019b), Toyota equips Sora hydrogen fuel cell electric bus with preventive safety features. Available from: https://media.toyota.co.uk/2019/08/toyota-equips-sora-hydrogen-fuel-cell-electric-bus-with-preventive-safety-features/ [Accessed 25/10/2019].

Tretsiakova-McNally, S. (2016a), HyResponse Lecture Notes: Introduction to FCH applications and hydrogen safety. Accessible from: http://www.hyresponse.eu/training-mat-1.php [Accessed on 01/08/2019]

Tretsiakova-McNally, S. (2016b), HyResponse Lecture Notes: Safety of hydrogen storage.

Accessible from: http://www.hyresponse.eu/training-mat-1.php [Accessed on 01/08/2019]

United Nations Economic Commission for Europe - Inland Transport Committee, UNECE, (2001), Recommendations of the group of experts on safety in road tunnels: final report, TRANS/AC.7/9.

United Nations Economic Commission for Europe - Inland Transport Committee, UNECE, (2003), Recommendations of the multidisciplinary group of experts on safety in tunnels (rail), TRANS/AC.9/9.