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

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Harmonised recommendations on response to hydrogen incidents

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Summary

The main target group for the "Harmonised recommendations on response to hydrogen incidents" are the emergency services. This document intends to be a good practice in the field of intervention strategies and tactics for hydrogen incidents in tunnels and confined spaces. Based on the thorough analysis of experimental, numerical and theoretical studies performed within the HyTunnel-CS project (https://hytunnel.net), the development and validation of new models and tools for quantitative assessment of hazards and associated risks specific for use of hydrogen vehicles in confined spaces such as tunnels, underground parking, garages etc., the document can serve as a basis for the further development of intervention strategies and tactics, evacuation and rescue procedures, standard operating procedures (SOP) and guidelines (SOG).

The recommendations have been developed, taking into account:

- The knowledge generated by the HyTunnel-CS project on pressure and thermal hazards associated with hydrogen-powered vehicle incidents in tunnels and similar confined spaces.
- The hazards and associated risks characteristic for use of operating today hydrogen-powered vehicles in tunnels and other underground transportation infrastructure.
- The possibilities and limitations of intervention by fire and rescue services (FRS) today.

The major conclusions drawn from complementarities and synergies of experimental, numerical and theoretical studies and quantitative risk assessment (QRA) performed in the HyTunnel-CS project are:

- The potential of high-pressure onboard hydrogen storage tank rupture in a fire should be eliminated or substantially reduced. This would eradicate the most severe hazards (blast wave, fireball, projectiles) and associated risks facing FRS personnel during the intervention as described in this document. Fire risks would be reduced to the level which may be managed well by FRS.
- It should be ensured that FRS staff have access to all relevant information about the type of propulsion of vehicles involved in an incident as early as possible. Without this information and relevant training, e.g. training being developed by the HyResponder training (www.hyresponder.eu), they have little to no chance to react properly to such incidents or would be exposed to unnecessary hazards and risks during the intervention.

Keywords

Hydrogen safety, hazards and associated risks, hydrogen release and dispersion, hydrogen combustion, hydrogen storage tank rupture in a fire, blast wave and fireball, incident prevention and mitigation strategies and engineering solutions, ventilation, first response, standard operation procedures, intervention tactics and strategies, HyResponse training, VIN, telemetry, rescue information, fire fighting,

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Nomenclature and abbreviation

CNG	Compressed Natural Gas
CTIF	International Association of Fire and Rescue Services
EERG	European Emergency Response Guide
FIA	Fédération Internationale de l'Automobile
FRR	Fire Resistance Rating, i.e. time to tank rupture in a fire in the case of blocked during an incident TPRD or failed to operate TPRD, e.g. in a localised fire not affecting TPRD.
FRS	Fire and Rescue Services
HRR/A	Specific Heat Release Rate, i.e. Heat Release Rate (HRR) divided by the area of combustion (A)
HRS	Hydrogen Refuelling Station
LFL/LEL	Lower Flammability Linit (equivalent to Lower Explosive Limit)
LPG	Liquefied Petroleum Gas
NWP	Nominal Working Pressure
OEM	Original Equipment Manufacturer
PPE	Personal Protective Equipment
SoC	State of Charge of hydrogen storage tank
SOG	Standard Operating Guidelines
SOP	Standard Operating Procedure
TPRD	Thermally activated Pressure Relief Device
UN	Unites Nations
VIN	Vehicle Identification Number

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1. Introduction and scope

In an event of an incident, it is generally the task of emergency services to protect people, property, the natural and built environment. In most incidents involving hydrogen-powered vehicles in tunnels and similar confined spaces, this protection will be provided by the FRS. The first responders will consider operating or not in what can be a very hazardous environment requiring technical abilities and knowledge.

From point of view of FRS, hydrogen is a flammable gas that can cause fires, deflagrations and detonations, and its storage in high-pressure storage tanks can potentially lead to tank rupture in a fire followed by the destructive blast wave, fireball and projectiles. For the sake of brevity, the document will use the term "explosion" for either deflagration, detonation or tank rupture in a fire. Firefighters have effective personal protective equipment (PPE) to face thermal hazards from a fire. Using the correct PPE will offer some protection for a period of time against a given heat flux with self-contained breathing apparatus providing an autonomous circuit of fresh air (see Figure 1). Against explosion hazards, there are no effective protection measures other than moving to a safe distance away from the thermal and pressure effects produced by an explosion.

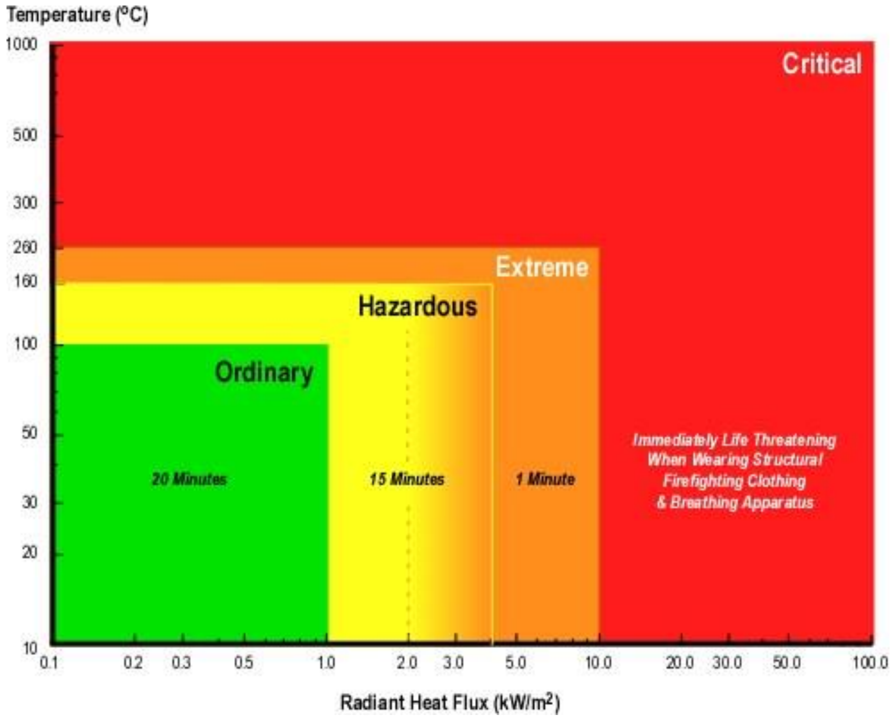

Figure 1. The turnout gear of firefighters protects against heat for a period of time against a given heat flux (Hartin, 1994)

Therefore, the first step in many local and existing procedures of FRS is based on the principle of cordoning off a wide area and keeping a safe distance that would exclude or essentially reduce the potential of harm to people. If people must be rescued out of the hazardous area of the incident scene, only the absolutely necessary number of operational personnel will be deployed to limit the number of affected resources in a case of an explosion.

In general, FRS are aware of possible intervention tactics to deal with an incident regarding flammable gas. In the case of a gaseous fire, they can choose to try to extinguish it or to let combustion continue in a controlled manner until supply ceases or has been stopped.

Extinguishing the flames allows the reduction and removal of the heat flux towards surrounding objects. The removal of this heat is important to prevent fire propagation to other items or a pressure rise in any closed gas or liquid vessels. However, because extinguishing the gas flame does not stop the gas flow, a flammable cloud remaining may reignite. Unignited gas release in a confined space can form a flammable mixture that can undergo explosive deflagration or even detonation if ignited, a situation which in turn may be more dangerous than a jet fire.

Another way to treat a gaseous jet flame is to allow it to burn in a controlled manner. While the gas continues to burn, the risk of creating an explosive atmosphere is minimised, and cooling surrounding objects can drastically reduce heat transfer to prevent further fire spread, structural collapse, etc.

The FRS can also attend to a gas leak that has not yet ignited. In confined spaces, one option is to dilute the flammable gas by incombustible gases, e.g. nitrogen or carbon dioxide (measures to exclude asphyxiation should be undertaken). Sometimes FRS recommend accelerating this process with tactical ventilation. This can be done either by natural (passive) ventilation, creating a flow path due to the buoyancy and atmospheric conditions, or by forced (mechanical) ventilation, e.g. by using positive pressure fans. In the latter method, careful positioning of the fans is important to prevent potential ignition sources, e.g. from the equipment itself, to ignite a flammable hydrogen-air cloud.

Choosing which option to use for a hydrogen incident crucially depends upon the probability of explosion in the specific circumstances of the case. The outcomes of the HyTunnel-CS's "Internal seminar on research conclusions for use by emergency services" (HyTunnel-CS M5.3, 2021), which was dedicated to setting up a specific consideration of hazards and associated risks in confined spaces where an incident with hydrogen takes place, are used to shape practically usable rules of thumb to the FRS implemented in this document.

The HyTunnel-CS developed the QRA methodology and applied it to examples of road and rail tunnels. These studies have shown that risk for users of hydrogen-powered vehicles and FRS in tunnels is a complex issue affected by the uncertainty of different parameters and conditions which are difficult to record or measure during FRS's operations. These parameters include but are not limited to the following: location and response time of TPRD to fire; fire intensity characterised by specific heat release rate (affects FRR); FRR of onboard storage tanks in standardised fire test; the potential of TPRD blockage from a fire during an incident; the fact that hydrogen was released or not at the moment of the FRS arrival at the scene; type of hydrogen storage tank; pressure in the tank (one of the HyTunnel-CS results is the establishing of the fact that tank rupture in a fire is not possible if the SoC is below 50% of SoC at NWP); further risk factors like tunnel branch frequency, etc.

These parameters cannot be changed or influenced by FRS. At any time, FRS cannot clearly rule out the risk of explosion or tank rupture if they are aware that hydrogen is involved (irrespective of whether an onboard hydrogen tank is affected by fire or not and whether there is a release of non-ignited hydrogen in the tunnel or not yet).

In the event of an incident involving hydrogen in confined spaces, the FRS must therefore always assume the presence of an acute explosion risk and tactically must first locate their command position at a safe distance from the hazard, which is a challenging task in confined spaces like tunnels and underground parking where the decay of blast wave, initiated by tank rupture in fire, is “prevented” by the confining geometry and dispersion of fireball by buoyancy in the atmosphere is not possible due to the confinement (instead the velocity of fireball in the horizontal direction with a speed of the order of 20-25 m/s can be observed). If they do decide to deploy firefighters into the hazardous zones of underground transportation structures, where a hydrogen-powered vehicle is involved, they should only do so to save others’ lives (unless the safety technology that excludes tank rupture in any fire, e.g. self-venting TPRD-less tanks, is used in the vehicle).

According to the current level of knowledge on deployed hydrogen vehicles, experience and training, many FRS have questions on how to deal effectively and efficiently with incidents involving hydrogen-powered vehicles of today. FRS skills, knowledge and experience are generally based on incidents involving fossil fuel vehicles, which present a rather low risk of explosion, and are therefore usually attacked immediately at close range.

FRS will therefore need to learn more about emerging safety technologies for hydrogen vehicles and have access to case studies and statistics on incidents with hydrogen-powered vehicles. This would underpin the development of new intervention tactics and strategies, which ultimately should not be different from current applicable to fossil fuel vehicles, i.e. the immediate attack on fire to reduce hazards for life, property and environment from fire smoke in tunnels, fire spread, etc. For outdoor fires, the appropriate procedures are readily available, for example, in the European Emergency Response Guide (HyResponse D6.3, 2016) (to be updated in HyResponder project). For incidents in confined spaces, procedures other than the general defensive approach mentioned above are not currently available.

2. Definitions and Terms

2.1 Emergency Services

Land-based emergency services are generally understood to be primarily the police, FRS and medical/paramedical rescue services, and in some cases designated and trained personnel from product supply and transport operators. In the case of incidents involving hydrogen-powered vehicles, vehicle recovery services can also play a significant role.

2.2 Prevention, Intervention and Post-intervention

Prevention means avoiding emergencies by taking all possible measures before the incident occurs, which serve to either avoid the incident or to manage its consequences as well as possible. Therefore, fire and rescue services should "continually strategically assess the risks, in terms of the foreseeable likelihood and severity, of incidents involving tunnels and underground structures occurring within their areas” (TSO, 2012).

Another focus of the FRS is **intervention**: dealing with incidents. As a result, an important task is to prepare comprehensively by training and education. Intervention includes taking all possible measures after the occurrence of an incident which are aiming to eliminate the acute danger.

If there is no longer an acute danger, the **post-intervention** phase follows: for example, the medical rehabilitation of injured persons, the repair of property damage, the settlement of claims for compensation.

2.3 Emergency response

Emergency response is defined in different ways. An appropriate definition can be found in the operational guidance for tunnels and underground structures for fire and rescue services in the UK (TSO, 2012): "Emergency response can be defined as the actions taken to deal with the immediate effects of an emergency. It encompasses the resources and effort to deal not only with the direct effects of the emergency itself (e.g., fighting a fire, rescuing individuals) but also the indirect effects (e.g., disruption, media interest)".

The following definitions and distinctions are made for the present recommendations:

2.3.1 Immediate action

Immediate actions are understood to be all measures taken by affected persons, lay helpers or operators at the incident scene until the arrival of the FRS. One target group is the operators of tunnels or underground car parks. They have to take initial measures, even if it is only to alert the fire service. Other actions are often decided in consultation with the fire service. However, since these tunnel operators are liable, a comprehensive hazards and associated risks analysis is essential.

Immediate action also includes measures taken by other emergency services. For them, the same instructions apply to all types of fires or incidents involving dangerous goods. The most important rule is to keep a safe distance from the incident site and/or cordon off the scene.

2.3.2 First Response

In case of hydrogen incidents, the first response is provided by the respective FRS in charge. The priority goal is to prevent a further spread of the danger and to save human lives.

2.3.3 Second Response

Due to the limitation of specialisations, FRS may have to call in specialists for further measures and assistance (Fischer, 2012). The term "second responder" is used here to make clear that specialists may be required to deal with hydrogen incidents who are only available on-site minutes later than the responsible fire service: in the second phase. Local fire service provides the first response and bridges the time until their arrival. These specialists may be members of a fire service or operators of a company that manufactures hydrogen vehicle or distributes hydrogen.

It is also becoming apparent that in the future, vehicle recovery services will need specialists who are trained to deal with damaged hydrogen-powered vehicles (e.g. familiar with vehicle manufacturers' emergency response guides, etc.). The recovery of hydrogen-powered vehicles is to be counted as part of the second response phase since according to the current state of knowledge and experience, the danger is eliminated at the earliest when the hydrogen-powered vehicles are in the care of specialists. This also applies to electric batteries vehicles.

3. Actors

The actors, as appear in the usual sequence of an incident development that leads to the deployment to an emergency, are:

- Persons present at the incident scene;
- Users of hydrogen-powered vehicles;
- Operators of tunnels, underground car parks, vehicle workshops, etc;
- Members of emergency response services.

3.1 Persons present at the incident scene

The European Emergency Response Guide (HyResponse D6.3, 2016) states that incidents involving hydrogen-powered vehicles or hydrogen-carrying equipment should be handled in a fundamentally different manner than incidents involving fossil fuel vehicles.

Therefore, it would be helpful that all persons who may be involved in immediate action can recognise that hydrogen is involved in the incident so as not to endanger themselves (e.g. trying to extinguish a hydrogen flame with a fire extinguisher). "Secondly, the emergency services should have information (from involved persons or obtained by any technical means) that hydrogen may be involved as this will impact on their choice of emergency response tactics".

3.2 Users

Users of hydrogen-powered vehicles are expected to be informed on how to behave in case of malfunctions or emergencies through the vehicle manufacturer manual.

3.3 Operators

Operators of transportation systems, e.g. tunnels, underground car parks etc., where hydrogen vehicle incidents may occur should be trained to control their systems correctly in case of malfunctions. In the simplest case, a correct response would be, for example, to prevent further vehicles from entering a tunnel in the event of an incident.

3.4 Members of emergency services

Two fundamentally different functions can be distinguished among the members of emergency services:

- The personnel who are deployed to deal with the incident; below they are referred to as operational personnel;
- Experts who are involved in approval processes, e.g. approval of the construction and operation of a hydrogen station or a general approval process of hydrogen-powered vehicles; below they are referred to as technical experts.

Approval procedures may be very different from country to country. In some countries, FRS are licensing authorities themselves. In other countries, transport or building authorities or environmental protection authorities are responsible for the approval procedures. In such cases, the FRS is merely consulted sometimes without any right of veto.

4. Lack of knowledge and experience

The work of the FRS is based on scientific and technical knowledge and experience. There is a shortage in both areas. Many questions remain unanswered, for example, whether and how the hazardous consequences (blast wave, fireball, projectiles) and risk of explosion originated from hydrogen vehicle incident can be influenced with the means of the FRS. The FRS lacks practical experience with hydrogen incidents and no case studies and statistics are available due to the emerging nature of hydrogen-driven transport.

For a long time, the practical work of FRS was highly experienced-based although in the last decades a complementing academic approach has been witnessed in several countries. Fire services in particular are increasingly learning to investigate their issues scientifically and to systematically use findings from fire research and fire engineering, see for example (Fire Engineering, 2006; IAFC, 2014; Kerber, 2014).

The importance of pre-normative research such as HyTunnel-CS for FRS is huge. For example, the tools developed in the project allow assessing how long it takes for hydrogen to be released from a hydrogen-powered vehicle in an underground car park, how to exclude the formation of the flammable hydrogen-air layer under the ceiling of underground facility and thus to eliminate the risk of a strong large-scale explosion (deflagration of a turbulent jet from TPRD cannot be excluded unless novel safety technologies like self-venting TPRD-less tanks are used), etc. From this knowledge, FRS could deduce intervention strategies, e.g. how long they should wait before entering the building, and form confidence in the safety level and performance of hydrogen-powered vehicles in a fire with more knowledge on the correspondence of hydrogen vehicles design to the "Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems" (HyTunnel-CS D6.9, 2022)

So far, only very few incidents with hydrogen-powered vehicles are known. Consequently, the FRS have very little experience with this type of operation. To a certain extent, the experience can also be gained with simulation facilities, such as those maintained by the École Nationale Supérieure des Officiers de Sapeurs-Pompiers (a French firefighting academy) and others to be created following the completion of the HyResponder project in 2023.

Ultimately, however, it is only in real operations that it becomes clear which incident intervention tactics and techniques are both effective and practicable. Here, real-life operations have a function similar to experiments in the natural sciences. They serve to verify or falsify knowledge and assumptions. The essential difference is that scientific experiments take place under definable, measurable, and mostly controllable laboratory conditions. The operational conditions under which firefighters work, on the other hand, are usually neither measurable nor reliably controllable, and often cannot be captured entirely, let alone be repeated.

Consequently, gaining experience can be very painful and, in the worst case, can involve the loss of human life. This makes it all the more important to expand scientific knowledge from the perspective of FRS and to use it systematically for operations. Sharing information on innovative safety strategies and engineering solutions used in new models of hydrogen-powered vehicles that would make them inherently safer is of huge importance for the increase of efficiency of the FRS operations at an incident involving hydrogen vehicles in underground structures like tunnels and underground car parking.

5. Risks for emergency services

This section discusses how emergency response services can use the results of quantitative risk analysis performed in HyTunnel-CS. It is shown that emergency services need to prepare for all types of events, regardless of their estimated probability and/or frequency which are hardly available for emerging technologies like hydrogen-powered transport and especially in confined spaces. However, the intensity of preparation depends on the frequency of the event that will be available as the deployment of the technology will be continued in different countries around the globe to better inform FRS.

5.1 Consequences

HyTunnel-CS deliverable D1.3 (HyTunnel-CS D1.3, 2019) considered as the first step the four generic scenarios of hydrogen incidents selected for the detailed combined theoretical, numerical and experimental studies of incident consequences and development of innovative prevention/mitigation strategies and engineering solutions for tunnels and similar confined spaces:

- Hydrogen storage tank rupture – unignited;
- Hydrogen storage tank rupture – ignited;
- Pressurised release of hydrogen – unignited;
- Pressurised release of hydrogen - ignited.

These conclusions of the critical analysis of the phenomena related to these four scenarios are described in (HyTunnel-CS D1.3, 2019) as follows:

- An unignited tank rupture is considered unlikely and is therefore not considered in detail here;
- The consequences of an ignited tank rupture (rupture in a fire) are a “devastating blast wave, large fireball and projectiles”;
- The possible consequences of an unignited pressurised release are “the formation and accumulation of a flammable atmosphere that will subsequently be ignited leading to a flash fire, deflagration or even transition to detonation.” It is worth mentioning that HyTunnel-CS developed safety strategies related to safety systems of a vehicle that excludes formation of hazardous flammable hydrogen-air mixtures under the ceiling of underground structure;
- The consequences of an ignited pressurised release are described as “a hydrogen jet-fire” with associated thermal and pressure loads in confined spaces.

Operational personnel can effectively protect themselves against the thermal stress of a hydrogen jet fire, which is known to be extremely difficult to extinguish. They can protect themselves against the pressure and thermal effects of an explosion only by keeping a sufficiently large separation distance, which increases drastically in tunnels due to its quasi-one-dimensional geometry that prevents a quick decay of the blast wave similarly to decay in the open atmosphere. The HyTunnel-CS revealed a “new” hazard from fireball propagation in a tunnel, which is fireball propagation along a tunnel with a velocity of the order of 20-25 m/s behind the blast wave. This is essentially different from a fireball rising vertically in the open atmosphere. If the distance is too short from the location of the incident, there is a risk of fatality and serious injuries from the heat of fast-moving combustion products, blast waves or projectiles following an explosion.

5.2 Probabilities

As shown in the previous section, incidents involving hydrogen-powered vehicles can lead to an explosion. At least in the initial phase of their operations, FRS cannot reliably assess how great the probability of an explosion is in a specific case. For one thing, this would require a lot of information that cannot be obtained immediately, for example about the filling level and condition of the tank of a damaged vehicle. On the other hand, we are dealing with dynamic, rapidly changing situations. Hydrogen may have already escaped, or it may have just escaped, or it may be released in the next moment.

For the FRS, therefore, it is not the size of the probability of an explosion that is decisive, but the fact that they cannot exclude an explosion. So they will follow the Standard Operation Procedures provided for an acute explosion danger - completely independent of how great the probability of an explosion is.

This means that in the initial phase of their operations, FRS can neither rule out a risk of explosion nor assume that an explosion will certainly occur. Therefore, they will initially assume that there is a risk of explosion. They will then act according to the procedures provided for this purpose, which are discussed in the following section.

6. Standard procedures for dealing with explosion hazards

The general procedures for the first response of the FRS in case of incidents with flammable gases or explosion hazards can be summarised as follows, c.f. e.g. (LeSage, 1995):

- Keep distance;
- Identify hazards from a safe distance;
- Delay the rescue until hazards are identified;
- Call in specialists.

In detail, however, the procedures of the FRS are very different, which is why the possibilities and limits of intervention are discussed here using the example of the Standard Operating Procedures (SOP) commonly used in German-speaking countries.

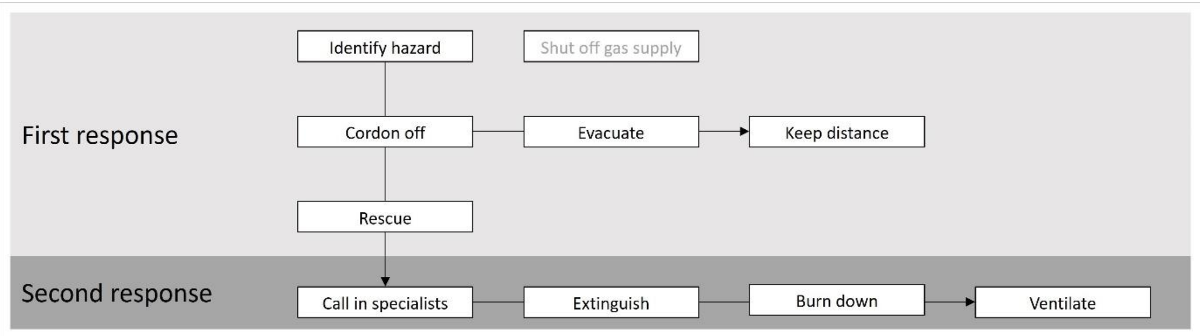

Figure 2. Standard operating procedures (SOP) for incidents with dangerous goods in German-speaking counutries.

The principle of this SOP is illustrated in Figure 2. The main steps of the SOP are: Identify hazards, Cordon off, Rescue and Call in specialists. The option shut off gas supply is shown as greyed text here because it is rarely used for vehicles. However, this is often one of the most important measures for events at hydrogen refuelling stations (HRS), for example.

To be able to consider the SOP in a differentiated manner, the terms "first response" and "second response" are used here as defined in section 2.

6.1 First response

The first response includes all measures that, in principle, can be carried out by any FRS, because all firefighters have learned this capability. Depending on the situation, however, they may need personnel support for this, which may be provided by neighbouring FRS or by police, who e.g. can provide the cordoning off.

6.1.1 Hazards identification

An indispensable prerequisite for the correct handling of hydrogen incidents is that the hazards and associated risks are correctly recognised and then addressed. This would currently be quite possible in practice because hydrogen-powered vehicles are marked with appropriate labels or logos. However, in the case of burning or demolished vehicles, these features may not be visible. And if hydrogen-powered vehicles become widespread, they will no longer be a special feature. It is to be expected that hydrogen-powered vehicles will then be marked as such less and less often. In addition, different hydrogen technologies will be used in the future, and FRS will have to deal with them differently.

Therefore, it must be ensured that the emergency services receive the rescue relevant information at the earliest possible time, including on innovations in vehicles safety provisions. The requirement of availability of this information is also embedded into the recommendations to the next generation of Regulations, Codes and Standards (RCS) formulated in the HyTunnel-CS deliverable D6.10 "Recommendations for RCS" (HyTunnel-CS D6.10, 2022-2).

Without information about the type of propulsion, parameters of safety systems and information on the performance of a vehicle type in fire, a correct action tailored to the incident cannot be expected of the first responders. However, this applies not only to hydrogen-powered vehicles but also to all types of propulsion, for example, to electric batteries vehicles.

The CTIF Commission for Extrication & New Technology[1] accomplished very important work that is beneficial to all relief workers worldwide. Here the "UN Decade of Action for Road Safety" is at the centre, with the most important goal of shortening the intervention time, to increase the survival chances of the victims, as well as striving for optimal security for both the victims and the relief workers at the place of the incident.

The CTIF ISO 17840 project defines the minimum required information that industry and vehicle manufacturers should make available for the first and second responders. The CTIF Commission for Extrication & New Technology worked on determining standardised structure in the *Rescue Sheets* (ISO 17840-1, 2015; ISO 17840-2, 2019) and in the *Emergency Response Guides* (ISO 17840-3, 2019) that are drawn up by the manufacturers for new models. The

[1] CTIF is the 'International Association of Fire and Rescue Services' and has as its main goal supporting and stimulating the cooperation between the fire departments and other emergency services from all over the world. CTIF ensures scientific research, the publication of articles and reports, the organization of different commissions and working groups and the cooperation with other bodies than the rescue services that are also working in the field of prevention and security.

rescue information is directly linked to recognisable pictograms defined in the "Propulsion energy identification" part of the same standard (ISO 17840-4, 2018).

In case of an incident in a tunnel, this crucial information regarding the type of propulsion may not be easily available with the current state of the art because logos and labels on the vehicles could be unrecognisable due to crash effects, fire or a smoke obstruction. Therefore, there is a strong opinion among fire & rescue professionals and experts that some sort of automated call technology may be the way to implement the standard and to convey information to the FRS. For example, details of the vehicle involved in the incident (VIN, fuel type, propulsion etc.) can be sent out via E-call to emergency services at the moment of the incident providing the FRS with crucial information.

Another example is technological tools already being used in Formula 1 by FIA for transmitting telemetry and information from accidents data recorders. The technology is a further developed and improved version of the E-call system and operates even in absence of a mobile network (3G/4G/5G). It would work as a source of important information and help FRS to make critical life, property and environment saving decisions. The information can also be sent out directly to the fire engine and crew, their dispatching station or even collected by the tunnel infrastructure itself and forwarded in case of emergency. In these cases, extremely important 'Vehicle-to-Vehicle' or 'Vehicle-to-Infrastructure' communication lines should be provided. All information in case of emergencies could be made available by scanning the VIN of all vehicles when they enter an underground infrastructure. This shortens the intervention time by facilitating and optimizing the reconnaissance phase. As a result, response strategy and technique can be determined proactively without having to enter the underground space or tunnel.

6.1.2 Cordon off

The most important standard procedure in the event of explosion hazards is to cordon off the scene of the incident. Various safety distances are currently recommended for this purpose for incidents in the open atmosphere. The recommended radii range from 50 metres for hydrogen-fuelled passenger vehicles to several kilometres for liquid hydrogen tankers, to name just one example from the technical literature (Thorns, 2012). The information on hazard distances (fatality, injury and no-harm distances) for hydrogen vehicle incidents in confined spaces like tunnels was not available before the HyTunnel-CS project. The project developed not only tools for assessment of hazard distances for hydrogen unigited releases, jet fires, blast waves and fireballs but developed and validated breakthrough safety strategies and engineering solutions, e.g. to prevent tank rupture in any fire, including localised fires, using self-venting (microleak-no-burst) tank technology that excludes blast waves, fireballs and projectiles.

In practice, two serious problems will arise here. Firstly, in many cases, it will hardly be possible to reliably estimate the actual current explosion hazards and thus also the hazard distances required at the incident location. Secondly, the establishment of large safety zones is extremely time-consuming and personnel-intensive and is itself associated with considerable risks, for example, if a building above an underground car park has to be evacuated very quickly, etc. Thus, the engineering solutions excluding onboard hydrogen storage tank rupture in any realistic fire conditions (not only regulated fire test, e.g. GTR#13 fire test with fire intensity below the characteristic for gasoline/diesel spill fires of HRR/A=1-2 MW/m^2).

It should be noted here that textbooks and instruction sheets of emergency response services also set the required safety radii generously because acute explosion hazards in urban areas are comparatively rare. Unfortunately, due to the slow decay of the blast wave in a tunnel would it be generated in an incident involving a hydrogen vehicle, the distance to no-harm could be not available throughout the whole length of the tunnel in many cases. While hydrogen-powered vehicles of today's common technology become widespread, then incidents involving such vehicles will also occur more frequently. This does not necessarily mean an increase in serious incidents. However, with the usual safety rules of today's emergency services, evacuations of the entire tunnel would occur much more frequently.

The hazard distances also apply to emergency forces, as they cannot protect themselves against the pressure effects of explosions (except by keeping a sufficient distance that is hard or not possible at all in confined spaces like tunnels and underground parking). Therefore, the following applies. At the latest when their explosimeters indicate an acute danger of explosion or there are other indications of explosion hazards, the emergency forces must retreat to the safe area. In the case of the tank rupture scenario, the use of explosimeters doesn’t work well because the TPRD is not activated. Probably the recognition of the presence of a fire close to the hydrogen tank using a thermal imaging camera or other techniques is a better system to recognise the explosion hazards.

In the case of TPRD activation, the noise of the gas released can be used as an indication of hydrogen release from storage tanks. This, in most cases, would indicate that the probability of tank rupture is reduced. The self-venting (TPRD-less) storage tanks, when initiated to leak by fire, also produce a characteristic acoustic noise when hydrogen is released through the tank wall as observed in the HyTunnel-CS experiments. The use of self-venting tanks does not require any change in intervention tactics and FRS can start to extinguish the fire as soon as possible without “being afraid” to cool down the TPRD. The prolonged cooling of the self-venting tank surface by water jets in the scenario when the hydrogen release was not yet initiated by a fire, would stop combustion and degradation of the composite resin and reduce pressure inside the tank to the original value thus excluding its rupture.

The technical challenges such as the cooling of tanks from a great distance are more pronounced in confined spaces like tunnels where hazard distances are much longer compared to the open atmosphere scenarios. The corresponding tactics and techniques of using pumps to increase safety distance are known to the FRS, which is why they will not be discussed here.

6.1.3 Rescue

Rescuing people from hazardous areas is the primary task of all FRS. Therefore, many recommendations, such as those in the European Emergency Response Guide (HyResponse D6.3, 2016), require firefighters to rescue people from hazardous areas, even if this means putting their own lives in danger. The basic rule for such actions is to deploy only as much operational personnel as is absolutely necessary for the rescue. This implicitly means that it is not possible to protect the emergency forces and it is only possible to limit the number of potentially injured or killed operational personnel (unless innovative safety solutions for hydrogen-powered vehicles, e.g. explosion free in fire self-venting tanks, are implemented by OEMs).

Whether it is responsible to deploy first responders into the area of possible explosions is an ethical question. There is no systematic research on the positions of firefighters from different countries and cultures on this question. The position of OEMs would essentially affect the risk of responders dealing with incidents involving hydrogen vehicles.

A survey conducted by the International Fire Academy in December 2021 can serve as orientation. The survey asked how incident commanders should decide in certain situations. One considered situation was as follows: a goods train loaded with butadiene is on fire in a railway tunnel. There is an acute danger of explosion. The locomotive driver is missing. The participants could choose between two options:

A. Search for the locomotive driver despite the danger of an explosion.
B. Search for the driver only after the danger of explosion has been eliminated.

Out of 298 participants, 11% chose option A and 89% chose option B.

This survey result can be understood to mean that many leaders tend not to expose their operational personnel to too high a level of risk, even if this leads to a possible rescue not being attempted.

6.2 Second response

The second response includes measures that may not be carried out by every FRS because not all firefighters are suitably trained. The second response begins with advice requested from the specialists. This advice can be given by radio or telephone. Mostly, however, the specialists are requested to attend the scene of the incident to directly assess the situation and offer advice and guidance.

6.2.1 Call in specialists

The necessity to call in specialists correlates directly with the frequency of occurrence of the respective hazard or type of incident.

Incidents involving hydrogen, as previously outlined, are currently infrequent and therefore require specialists specifically trained and equipped to respond to hydrogen incidents.

One of the critical issues that may require specialist support is the question of firefighting tactics. Today, as a rule of thumb, burning hydrogen-powered vehicles should not be extinguished but allowed to burn down in a controlled manner, see e.g. (Blasczyk and Himmelreich, 2012). This is also recommended by vehicle manufacturers, e.g. (Hyundai Motor Company, 2014). The reasoning for this “rule of thumb” is in many cases the need to initiate TPRD and start release from the storage tanks as soon as possible. While this approach could be accepted as reasonable for fires in the open atmosphere, it is hardly possible to allow the continuation of fire and smoke propagation with all bad consequences for life in underground structures like tunnels. The HyTunnel-CS demonstrated and recommends the use of explosion free in fire TPRD-less tanks that do not require any change in intervention tactics and would support the attack on a fire ASAP without explosion hazard (the tested self-venting tank prototypes demonstrated the continuation of leakage through the wall when the fire around the tank was suppressed and the tank was affected by water sprays).

So far, the tactics to “not extinguish the vehicle fire but allow to burn down in a controlled manner” has been explicitly intended for vehicles powered by hydrogen, natural gas or LPG outdoors. Whether it is also suitable for vehicle fires in underground car parks or tunnels is the subject of a technical discussion that is just beginning among the FRS. It is worth mentioning that this issue is related only to hydrogen storage systems using TPRDs. It would be worth mentioning that alternative TPRD-less safety systems would allow dropping this restricting freedom and established for centuries intervention strategy of FRS to extinguish the vehicle fire, especially in confined spaces like tunnels to stop smoke propagation from vehicle fire and further fire propagation to nearby vehicles, as soon as possible.

It is also being discussed whether, in the event of a release of hydrogen without ignition in confined spaces, an attempt should be made to ventilate the affected structure (e.g., underground car park or tunnel) with special large fans. Again, the solution suggested and demonstrated by HyTunnel-CS is to design a vehicle in a way to exclude the formation of a flammable hydrogen-air mixture under the underground structure ceiling that can potentially explode (deflagrate or even detonate). This would require actions from regulators and OEMs that are informed through expert groups like GTR#13 IWG SGS (Phase 2) on the availability of solutions to provide better protection of FRS in case of incidents with fire and underpin public acceptance of hydrogen-powered vehicles.

These questions were discussed in the HyTunnel-CS "Internal seminar on research conclusions for use by emergency services" (HyTunnel-CS M5.3, 2021) with the invitation of stakeholders, including OEMs. No conclusive answers were derived from the seminar on difficult questions thus indicating the need for further discussions with stakeholders. There is an intention of OEMs to consider self-venting tanks as a subject of Phase 3 of the development of GTR#13 expected to be started in 2023.

7. Performance limits of the FRS

As previously outlined, the roles and tasks of an FRS depend on dynamically changing hazards and associated risk assessment of the situation at the incident scene that involves hydrogen vehicle(s). This is especially so in the case of incidents in traffic tunnels and other underground transportation structures. The rescue is particularly difficult with the generally accepted tactic of "extinguishing to save lives" given priority as success decreases - and eventually stops – as smoke formation occurs reducing opportunities to find people (Brauner, 2016).

8. Concluding remarks

Without sufficient information on the specific incident and limited knowledge on design and performance in a fire of current hydrogen-powered vehicles, it is very difficult for FRS to manage incidents with such vehicles and hazards and associated risk assessment by themselves.

With sufficient information on vehicle design and performance in confined space fires, FRS can protect the surroundings of the incident site and themselves against the effects of a possible explosion. This statement can be considered as a request to OEMs on the release of more detailed information on their vehicles, including fire-resistance rating (FRR) at fires of different intensity, i.e. time to high-pressure hydrogen storage tank rupture in a fire in conditions of failed to be initiated TPRD (either being blocked from fire during an incident, being not affected by localised fire, e.g. smouldering fire in garbage trucks resulted in few explosions of CNG tanks equipped by TPRD in the USA, etc.).

Under operational conditions, it is difficult to almost impossible for FRS to estimate how likely an explosion is to occur, as they usually cannot have the data required for a situational risk assessment.

Penetrating underground structures to deal with fires involving hydrogen-powered vehicles fires can be so risky that many FRS are likely to attempt it only when absolutely necessary to save lives, if at all. To protect property alone, many FRS are unlikely to take these risks.

Most FRS will call in specialists for hydrogen incidents. This will be the case at least until the FRS have sufficient experience with hydrogen incidents and can derive generally applicable SOP from this experience. This results in a need for such specialists, who are currently not easily available, to say the least.

So, the FRS are not in a position to deal with incidents involving hydrogen-powered vehicles of conventional design in the same way as they can deal with incidents involving vehicles powered by fossil fuels like petrol or diesel, for example. Either the FRS are limited in their possibilities of rescuing people and limiting property damage - or they must take extraordinarily high risks of their own. Dealing with vehicles powered by natural gas or LPG is difficult as well, yet higher pressure of hydrogen storage and a higher reaction rate can generate higher pressure loads for hydrogen-powered vehicles.

The prevention of devastating consequences of incidents involving hydrogen vehicles relies on the level of technological safety available to OEMs rather than the bravery of FRS personnel. FRS may develop more effective and safer intervention strategies for dealing with incidents involving hydrogen-powered vehicles in confined spaces if the OEMs will demonstrate the trend in constant improvement of the safety performance of hydrogen vehicles rather than waiting for gathering statistics of incidents and their consequences to invest more in safety solutions which are already available for the implementation.

In addition, there is an immense training and education needs for millions of firefighters, as the risks of conventional hydrogen-powered vehicles will be ubiquitous when they become commonplace. The consequence would be that these events could occur everywhere and therefore all FRS, without exception, would have to be adequately trained to be able to protect others and themselves adequately.

With the current level of information from OEMs, e.g. on FRR of onboard storage, little experience in tackling incidents, knowledge and training of responders, the FRS are not able to manage efficiently and safely incidents with hydrogen-powered vehicles in confined spaces and with calculable risks of their own. The success or failure of the operation depends on numerous factors that the FRS can neither precisely measure nor specifically influence under operational conditions. The role of technological safety of hydrogen vehicles provided by OEMs is seen as the most important factor for the deployment of the technology and efficient dealing with incidents involving hydrogen vehicles by FRS.

9. Recommendations

9.1 The general recommendation for stakeholders

Based on currently available information and knowledge on the safety performance and parameters of hydrogen-powered vehicles, experience in tackling incidents and specific training, FRS are not able to handle efficiently and safely incidents with hydrogen-powered vehicles as with fossil fuels vehicles.

Therefore, it is recommended to develop and/or use hydrogen vehicle technologies that exclude explosion hazards, e.g. explosion free in a fire microleak-no-burst (μLNB) self-venting TPRD-less technology validated and described in the HyTunnel-CS project deliverable D6.9 "Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems" (HyTunnel-CS D6.9, 2022). This would eliminate most of the concerns of the FRS intervention strategies and tactics described in this document. Risks of hydrogen vehicles would be reduced with the use of such safety technologies to a level equal to or even below the risk of today's fossil fuel vehicles that FRS can manage well.

9.2 Recommendation for authorities

It is recommended to the respective national or regional authorities to ensure that all relevant legislative, technological, and organisational information is available to emergency services such as police, medical and FRS. Provision of information relevant for intervention about the vehicles involved in an incident in an automated way and without delay should be the primary goal for the authorities. In particular, it must be ensured that the FRS receive the information that hydrogen, LPG or natural gas fuels are involved in an incident as early as possible.

It is recommended to also register, through the information management systems used for this purpose, how many vehicles of which type of propulsion are located, e.g. in underground car parking, tunnel, maintenance workshop, etc. In the event of incidents, this information should then also be made available to the emergency services automatically and without delay.

For the reasons mentioned below, these information systems would also be necessary if vehicle technologies without explosion hazards are predominantly used in the future:

- Hydrogen-powered vehicles of conventional design may continue to be in operation. Their risks of incident could increase over time due to ageing, wear and tear and insufficient maintenance;
- Information systems such as E-call can already provide information on, for example, the nature and severity of an incident. Emergency services can use such information to optimise their intervention strategy, tactics and assistance;
- Hydrogen tanks of any design can be misused, for example, as a weapon for attacks. Therefore, the information that hydrogen or similar gases are present in a structure can be very important for security authorities.

9.3 Recommendation for operators of confined spaces

Owners and operators of confined spaces such as tunnels, underground and multistore parking, etc. are advised to analyse the risks that may arise from the use of their facilities by hydrogen-powered vehicles. This is because these risks can vary depending on the facility (dimensions, structure, ventilation, purpose of use, frequency of use, etc.).

It is recommended to consciously decide whether the respective facility is approved for use by hydrogen-powered vehicles where explosion risks cannot be excluded. It is recommended to consider allowing the use of such facilities only for hydrogen-powered vehicles with technologies that do not pose an explosion hazard and associated risk is at an acceptable level.

It is noted that the use of facilities by a large number of hydrogen-powered vehicles of conventional design could result in the need to equip these facilities with elaborate safety devices, e.g. special hydrogen and hydrogen fire detection systems and/or ventilation systems.

9.4 Recommendations for all emergency services

It is recommended that all emergency response services ensure that their response teams can recognise the hazards and associated risks related to hydrogen-powered vehicles and act appropriately. Typically, their proper behaviour will consist of maintaining a safe distance and cordoning off the scene that is especially challenging in confined spaces like tunnels.

In particular, it is recommended that police officers, emergency physicians and paramedics be trained to recognise at an early stage whether hydrogen-powered vehicles are involved in a traffic incident.

9.5 Recommendations for FRS

9.5.1 The general recommendation for all FRS

As more and more hydrogen-powered vehicles are registered, the likelihood of FRS being confronted with incidents involving hydrogen-powered vehicles will increase. Therefore, all FRS are advised to immediately prepare for incidents that are already possible in their area of responsibility.

It is recommended to adapt the existing Standard Operation Procedures to the current state of information and knowledge. It is recommended to use all available information, e.g. the European Emergency Response Guide (HyResponse D6.3, 2016) that has to be expanded based on the outcomes of the HyTunnel-CS project.

It is recommended that all FRS ensure that they are informed by the relevant authorities in which facilities in their area of responsibility hydrogen-powered vehicles are permitted, should it be tunnels, garages, depots, underground parking, maintenance shops or similar confined spaces.

9.5.2 Recommendations for higher-level FRS institutions

Higher fire services institutions (ministries, supervisory authorities, state fire service schools, etc.) are recommended to immediately address the hazards and associated risks of hydrogen-powered vehicles. In detail, it is recommended that:

- Communication centres should specifically ask callers during the emergency call for indications of the involvement of hydrogen vehicles in the incident. These can be, for example, conspicuously loud whistling noises, vehicle lettering such as "fuel cell", logos for hydrogen technology or specific vehicle types.

- Where such procedures are used, look specifically for indications of hydrogen (or LPG or CNG) when requesting vehicle data via the vehicle registration number or license plate or the vehicle identification number (VIN).
- The specific regional and local risks that can arise from the operation of hydrogen-powered vehicles should be analysed and evaluated individually. For this purpose, the extensive scientific knowledge and results of the HyTunnel-CS (www.hytunnel.net), HyResponse (www.hyresponse.eu) and HyResponder (www.hyresponder.eu) projects can be used.
- Based on hazards and associated risks analyses and assessments, a position should be taken at an early stage on general and individual approval procedures. The aim should be to limit the explosion hazards and risks of hydrogen-powered vehicles inherent in the system.
- The hazard distances for incidents with hydrogen-powered vehicles in tunnels that can be assessed using tools and models created in the HyTunnel-CS project should be used to update and standardise safety radii/distances based on the current state of research on hydrogen-powered vehicles. In the future, this should be differentiated more strongly than before according to the type of incident, size of the vehicles involved, type, size and use of the affected structure, location of the incident in the underground transportation structure such as tunnel, etc.
- Build up a sufficiently dense network of specialists who can advise the local FRS both in preparation and in intervention. It is recommended that modern telecommunication systems be used for this purpose so that specialists can also advise the FRS from a distance and thus more quickly than if they always had to go to the scene first.
- Quickly establish an international network for the exchange of knowledge and experiences of FRS from interventions in connection to incidents involving hydrogen-powered vehicles.
- Operational tactics and techniques should be continuously developed in line with current experience and knowledge.
- Investigate how tactical ventilation of buildings such as tunnels and underground car parks can be used to dilute non-flammable hydrogen. The risks involved and the possible positive effects should be investigated. Monitor the application in practice of the novel safety strategies developed in HyTunnel-CS deliverable D6.9 “Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems”.
- Develop rules of thumb for the assessment of situational risks based on empirical values from concrete operations.

9.6 Recommendation for general prevention

It is recommended that all services involved in general prevention should examine whether and how they can inform their respective target groups about the particular hazards and associated risks of hydrogen-powered vehicles, and especially their use in underground transportation facilities and similar confined spaces.

9.7 Recommendations for insurers

If facilities that were previously only used by fossil fuel vehicles are used by hydrogen-powered vehicles in the future, the fire and explosion hazards and associated risks, and possibly also the liability risks, will change and possibly increase if no opposite is demonstrated or no safety innovations are further developed and introduced. In particular, the probability of a total loss of structure due to an explosion could increase. Fire and (motor vehicle) liability insurers are advised to analyse these risk changes to react with appropriate premium adjustments or even coverage exclusions, if necessary.

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