QRA OF HYDROGEN VEHICLES IN A ROAD TUNNEL

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ABSTRACT
Hydrogen energy is recognized by many European governments as an important part of the development to achieve a more sustainable energy infrastructure. Great efforts are spent to build up a hydrogen supply chain to support the increasing number of hydrogen-powered vehicles. Naturally, these vehicles will use the common traffic infrastructure. Thus, it has to be ensured these infrastructures are capable to withstand the hazards and associated risks that may arise from these new technologies. In order to have an appropriate assessment tool for hydrogen vehicles transport through tunnels a new QRA methodology is developed and presented here. In Europe, the PIARC is a very common approach. It is therefore chosen as a starting point for the new methodology. It provides data on traffic statistics, accident frequencies, tunnel geometries including certain prevention and protection measures. This approach is enhanced by allowing better identification of hazards and their respective sources for hydrogen vehicles. A detailed analysis of the accident scenarios that are unique for hydrogen vehicles hereunder the initiating events, severity of collision types that may result in a release of hydrogen gas in a tunnel and the location of such an accident are included. QRA enables the assessment and evaluation of scenarios involving external fires or vehicles that burst into fire because of an accident or other fire sources. Event Tree Analysis is the technique used to estimate the event frequencies. The consequence analysis includes the hazards from blast waves, hydrogen jet fires, DDT.

1.0 INTRODUCTION

Due to sustainability and environmental aspects, more tunnels are being established worldwide, as they potentially reduce travelling distances and protect neighbours from traffic emissions and noise. New hydrogen vehicles such as cars, busses and heavy goods trucks will also use this underground traffic infrastructure and therefore the risks in case of a serious accident must be estimated to ensure the safety of the tunnel users and the tunnel structure.
To have an appropriate assessment tool for hydrogen vehicles transport through tunnels a new quantitative risk assessment (QRA) methodology is developed and presented here. A QRA is a logical and systematic approach to estimate the risk level associated with certain hazardous events scenarios. It is an assessment that uses special quantitative tools and techniques to establish the risk to people from defined scenarios with a given set of parameters. It involves estimating the likelihood and consequences of hazardous events and expressing the findings as risk to people.
A prior literature review revealed several risk assessment models and tools, as e.g. QRAM [1], TUNRIM RWS, IRAM, QRAFT, BASt and the PIARC [2,3]. These models and tools are evaluated, but either they do not include hydrogen as a dangerous substance (i.e., the QRA from PIARC [2], or the “low frequency – high consequence” events are not analysed (i.e., QRA developed by SANDIA) [4].

In Europe, the PIARC is a very common approach. The PIARC methodology provides already mean data such as traffic statistics, accident frequencies, tunnel geometries including certain prevention and protection measures, as e.g. various means of traffic control, monitoring, ventilation systems, protection of escape routes, and emergency procedures. The present QRA methodology is an enhancement of the PIARC to allow for a better identification of hydrogen related hazards and their respective sources. Thereby, the proposed QRA methodology is developed to improve the assessment and evaluation of scenarios involving external fires close to a hydrogen vehicle or hydrogen vehicles that burst into fire because of an accident or other fire sources. Such scenarios are of great concern, as the heat impact on the hydrogen storage system may potentially develop into gas cloud explosion and very severe tank rupture scenarios.

The former scenario could happen when the mandatory safety device, a thermally activated pressure relief device (TPRD) is opening due to a malfunctioning (TPRD activation without demand) and hydrogen is released without immediate ignition into a tunnel. Of course, other scenarios may lead to gas cloud explosions as well, as e.g., flame blow-off happens due to decrease pressure in the storage tank. Flammable hydrogen-air cloud may deflagrate or even detonate. The latter scenario (tank rupture) could happen when the same TPRD does not activate in case of a thermal exposure (TPRD failure of activation on demand). This may be caused by e.g., faulty TPRD's or in case of localized fires due to large temperature gradients caused by the low heat conductivity of the vessel material. In that case the thermal exposure may lead to a tank rupture followed by a fireball and blast wave. The initiating event could be a strong heat source like a fire of the hydrogen vehicle itself, another burning vehicle nearby the hydrogen vehicle, or any other close distance external fire source. The consequence analysis must therefore include the hazards from blast waves, fireball, hydrogen jet fires, deflagration-to-detonation transition (DDT).
In particular, the QRA methodology proposed enables the calculation of the individual risk (IR), i.e. annual fatality probability, risk of structural failure and hazard distance associated with a hydrogen powered vehicle accident in a confined space like a tunnel. As an example, it has been applied to accident scenario in a road tunnel in this paper, but further applications are made for railway tunnel, underground parking and other confined spaces like ship's hold, etc.

2.0 QRA METHODOLOGY

The first step of the QRA proposed methodology is the definition of the system through the key elements concerning the type of structure, type of traffic environment, safety measures, characteristics of the access roads. They comprise accident and fire frequencies, traffic statistics, tunnel geometries including certain prevention and protection measures, as e.g., means of traffic control, monitoring, ventilation and emergency procedures that are able to control and extinguish the fire.

Then QRA methodology combines event tree analysis for probabilistic assessment with engineering correlations for consequence analysis, i.e., for hydrogen jet flames [5] and for the blast wave decay in a tunnel [6], and DDT model developed by Kuznetsov [7].

2.1 Event tree analysis

Event Tree Analysis (ETA) is the technique used to describe the scenarios and to estimate the event frequencies. It depicts the chronological sequence of events that could occur following the initiating accident, including escalations and mitigation measures, e.g. first responders' intervention at the site of the incident. The difficulties in assessing emerging technologies is the still incomplete knowledge about the possible accident scenarios, as e.g., a lack of robust data from statistics, equipment failure rates and scenario probabilities that contribute to the QRA uncertainty. Therefore, caution should be taken in using general frequency data, the QRA is best served as a comparative/sensitivity analysis for various risk scenarios.

A detailed analysis of the incident scenarios that are unique to hydrogen vehicles, such as consequences of the initiating events, is included in the QRA methodology. The collision types that may result in a release of hydrogen in a tunnel and the location of such an incident are also considered. The worst-case incident scenario in a road tunnel is assumed to be a collision of a large vehicle at high speed into the last vehicle in a queue. The rear–end crashes category is estimated as 70-80% of all crashes and tunnel crashes are often caused by drivers' aggressive lane changes and high speed, which leads to rear–end crashes [8].

Then both hydrogen release from the hydrogen fuel system and TPRD are considered. The compressed hydrogen storage system (CHSS) consists of a high-pressure storage container and primary closure devices for openings into the storage container. The closure devices shall include the function of TPRD [9]. TPRDs are used to blowdown hydrogen from a storage tank in the case of fire "to prevent its catastrophic failure". Unfortunately, the TPRD activation on demand could be prone to malfunctioning in some fire scenarios, e.g. in the case of a fire affecting only localized area of a tank (i.e. tank IV with low heat conductivity) far from TPRD. Another malfunctioning may occur when the TPRD sensing element gets by jammed by parts of car(s) during a road accident, without a chance to be initiated. In these cases, TPRD response time to a low intensity fire could be too long to be able to prevent tank rupture. In these cases, a tank can experience a strong and rapid thermal load from a fire and thus a progressive degradation of the composite tank wall.

Therefore, the proposed methodology enables the assessment and evaluation of scenarios involving external fires or vehicles that burst into fire because of an incident. The heat impact on the hydrogen storage system is of great importance as it implies the storage tank rupture and gas cloud explosion scenarios. To distinguish between those scenarios, both engulfing fire and localised fire scenarios are considered by application of different probabilities of TPRD failure "Not open" on demand in a fire taken from publicly available sources.

2.2 Consequence analysis

The consequence analysis includes the hazard from unignited release, hydrogen jet deflagration and fire, deflagrations/DDT/detonations of flammable cloud under a ceiling if it is created, blast wave and fireball after hydrogen storage tank rupture in a fire, etc.

For jet fire, the flame length, which depends on the storage pressure and release orifice diameter, is calculated using the dimensionless correlation for hydrogen jet flames [5] that is available on the free access online e-Laboratory of Hydrogen Safety (https://elab.hysafer.ulster.ac.uk/). The correlation is for free jets. There are no engineering tools for impinging jets available at the moment. In the case of TPRD releases impinging jet will be shorter than free jet and therefore the free jet can be considered as a conservative estimation of hazard distances.

For the blast wave after hydrogen tank rupture in tunnels, the universal dimensionless correlation for the decay of blast wave in a tunnel [6] is used for the consequence analysis and assessment of hazard distances.

For the fireball after high-pressure hydrogen tank rupture in a fire, the engineering correlations for assessment of hazard distance (defined by the fireball size) are available both for stand-alone and under-vehicle tanks rupture in the open atmosphere, but not in confined spaces [10, 11]. Therefore, the consequences of the fireball could not be properly estimated.

Predicting the consequences of hydrogen detonation is important for hydrogen safety assessment in confined spaces. Li et al. [12] calculated the hydrogen dispersion in the tunnel to evaluate the risk of flame acceleration and the DDT. The detonation in the tunnel is calculated by assuming a strong ignition at the top of the tunnel at an unfavorable time and location. The pressure loads are calculated to evaluate the consequence of the hazard. The correlation developed for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles is used [7,12].

Concerning delayed ignition scenarios such as deflagration of flammable cloud, more advanced methods, i.e. CFD, are required for evaluate the consequences in a confined space such as a tunnel [7, 10, 12].

2.3 Individual risk

The QRA outputs for hydrogen-powered vehicles in tunnels are hazard distance and individual risk in terms of human fatality per year, for a selected scenario. Individual risk (location-based risk) is defined as the probability of fatality of an average, unprotected person that is continually present at a given location. The individual risk is evaluated by multiplying the frequency of a chain event, e.g., tank rupture, and the probability of fatality along the tunnel length. The individual risk obtained by QRA is then compared against established risk acceptance criteria. Finally, hazard distance is evaluated assuming a threshold probability of individual risk.

2.4 Harm criteria

Jet Fire

Temperature is here used to determine harm from jet fires [13]. For the evaluation of separation distances from a leak source, the following harm criteria for people are considered:

- Temperature 70ºC is taken as "no harm" criterion.
- Temperature 115ºC is assumed as the acceptance criteria for "pain limit" in hot air when considering an escape from an elevated temperature gas flow generated by a hydrogen jet fire.
- Temperature 309ºC is assumed as the acceptance criteria for "fatality limit", causing the third degree burns by a 20 seconds exposure, causing burns to larynx after a few minutes, escape improbable.

Explosion

In the case of an explosion, possible consequences on humans and structures or equipment include blast wave overpressure effects, impact effects, impact from fragments generated by the tank rupture, the potential collapse of equipment or structural elements, and the thermal effects from subsequent fireballs.

The fatality rate for explosions depends on many indirect effects (e.g., impact of projectiles, collapse of buildings, people thrown against hard surfaces, etc.) in addition to the direct effects on people of overpressure that cannot be easily determined. These indirect effects of an explosion can result in fatalities for much lower overpressures than the effects that lead to fatalities directly. The local conditions with regards to projectiles, collapse of buildings, hard surfaces etc. vary greatly, which means that it is extremely difficult to establish comprehensive fatality probit functions for explosions that account for these indirect effects.

For estimating the fatalities due to overpressure (for example, injuries to lungs, head impacts) are well-established cause consequence models are available in form of probit functions. The direct effect of explosion over pressure is normally displayed in the form of lethality as a function of overpressure and duration of the blast wave. Persons who are exposed to explosion overpressures have no time to react or take shelter; thus, time does not enter into the relationship. The HSE report into the transportation of dangerous goods by road & rail suggests a probit relationship for blast over pressure fatality [13]. Among the models available, the HSE model provides the most conservative results for low peak overpressures even if it provides lower probabilities than other model at higher overpressures [13]. Regarding the structural failure, the Eisenberg model is chosen as it provides results that agree reasonably well with the data reported in [14].

Finally, hazard distance is evaluated assuming a threshold probability of individual risk. The threshold probability is the *de minimis* risk defining the acceptable risk level (10^{-6}) below which society normally does not impose any regulatory guidance. For hydrogen safety applications, several groups have adopted different criteria. The fatality risk criterion proposed by EIHP [15] and EIGA [16] are 2 x 10^{-6}/yr and 3.5 x 10^{-5}/yr, respectively. In the following case study, both values 10^{-5} and 10^{-6} fatality per year will be used and results compared.

3.0 CASE STUDY

As an example of the QRA methodology application to road tunnel, an Italian tunnel was considered. The investigated tunnel is a bi-directional road tunnel, 1.2 km long, 10.5 m wide and 5.5 m high, with an almost uniform upward slope of 2%. The tunnel has a rectangular cross section with two lanes. The annual average daily traffic (AADT) is more than 10,000 vehicles per day in each traffic direction, with a percentage of heavy vehicles slightly less than 5%. The speed limit for vehicles is 50 km/h.

The tunnel is equipped with a longitudinal ventilation system. In ordinary traffic conditions a minimum level of ventilation with air average velocity of 2–2.5 m/s is provided, while in the case of fire emergency an air flow at the velocity of 9 m/s is assured to remove and control smoke and toxic gases generated by fire. The emergency ventilation system is activated by a linear heat detection system when the temperature is above 68°C [17,18].

3.1 Accident scenario

The scenario under congested traffic is assumed as follows: an HGV collides at high speed into the last vehicle, a hydrogen fuel cell electric vehicle (HFCEV) in a queuing situation, at the tunnel center (600 m from the exit), blocking both lanes of the tubes (Fig.1). This is assumed to lead to mechanical damage of HFCEV and a potential fire scenario.

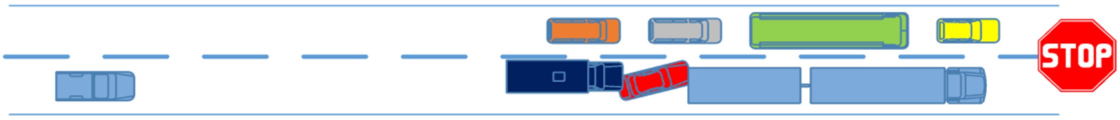

Figure 1. Worst-case situation like front rear crash of a large vehicle in case of a traffic jam situation.

In each lane of the tube, cars are supposed to queue up and stop, maintaining a minimum distance from the vehicle in front of about 2 m, up to the tunnel downstream portal. People caught up in the traffic jam downstream the HGV can be considered as being unable to leave the tunnel by car. From the center of the tunnel the distance to reach the portal is 600 m. It is assumed that the car has two onboard storage tanks, but only the rupture of the larger tank of 62.4 L volume and nominal working pressure of NWP=70 MPa [19]. Considering the onboard hydrogen tank's state of charge (SoC) will normally not be 100% (immediately after fueling), but rather up to 40% on average after driving (before refueling), the value of SoC=40% (giving pressure 24.4 MPa at 20°C, as calculated using Abel-Noble real gas equation) is selected for the consequence analysis, while the value of SoC=100% is considered for a conservative estimate. Type IV tanks with such SoC has a high probability of leaking not rupture [20]. This is not valid for Type III tanks.

4.0 RESULTS OF QRA

4.1 Event Tree

Figure 2 shows the event tree analysis for the case study.

Initiating event

The initiating event is a collision. An average collision rate of 0.12 per 10^6 vehicle-km is used, corresponding to the average of tunnel accident for Italian tunnels [20].

Probability of a fire post-crash

As average fire rate is used the value of 5.64 per 10^9 vehicle-km reported for tunnels in Italy [20]. This value is based on the recording of 147 fires in 349 Italian tunnels (404 km) in the period 2006–2012, where the cumulated traffic has been 26.1 billion vehicle-km. Correspondingly, the probability that an accident in tunnel results in a fire is calculated as 0.046.

Probability of hydrogen release

As consequence of a crash, hydrogen may be released from all the components of the hydrogen system. To characterize this probability, Ehrhart et al. [4] have analysed published crash test data, concluding that in all (five) tests there was not enough damage to the system for it to leak or release hydrogen. A Jeffrey's Beta prior distribution (0.5, 5.5) was assumed and updated with the zero failures out of five tests.

In agreement with [4], the Beta (0.5, 5.5) uncertainty distribution is considered that is parametrized in terms of its mean (0.08) and standard deviation (0.10). This is shown in the event sequence diagram where it is used a 0.08 probability of hydrogen release after crash and 0.92 probability of not releasing hydrogen.

Probability of extinguishing the fire

If the HFCEV catches fire after the crash, the consequence will depend on whether the fire reaches the fuel tank and affects the TPRD to initiate it. If the fire is extinguished before it reaches the tank, hydrogen is not released. If the fire reaches the tank, hydrogen may be released by the TPRD. If the TPRD fails to open on demand the tank rupture may occur.

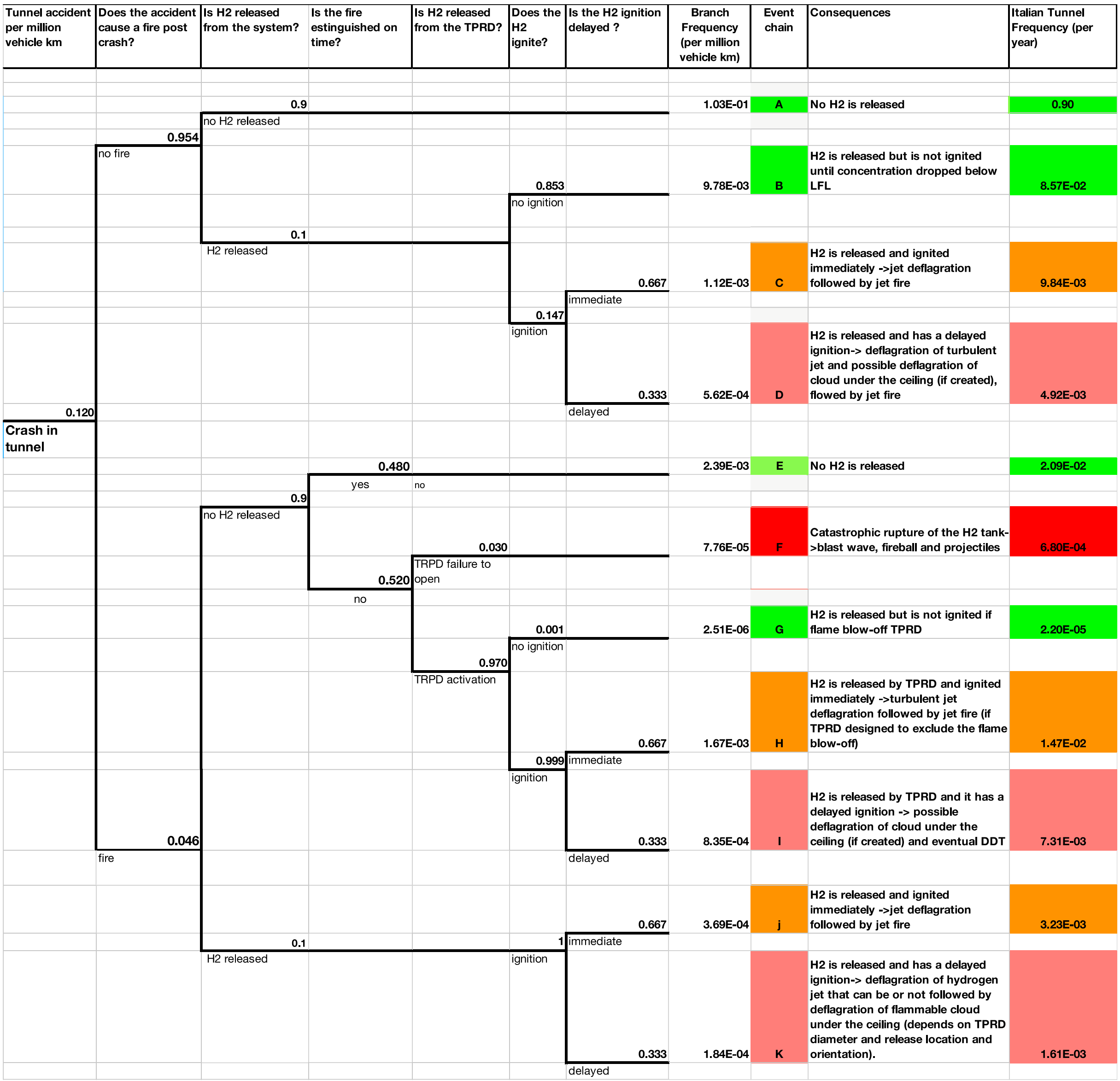

Figure 2. Event tree for crash scenario involving a HFCEV in Italian tunnel

To distinguish between those cases, the probability that a fire can be extinguished before tank failure is considered. It is obtained by comparing the time required to fire extinguishment with the fire resistance rating (FRR) of a hydrogen tank. According to the CFD simulation carried out by Ulster University, for a 62.4 L tank exposed to a fire of specific heat release rate HRR/A=1 MW/m^2, the FRR ranges between 7.5 min and 13.5 min, respectively for a SoC of 100% and 40%. The safety feature of tank leakage at SoC<50% is not valid for the tanks with PA liners, which is the drawback. In case of the HDPE liner, the tank would not rupture at all.

It is assumed here that time from fire detected to fire declared extinguished is shorter than 10 min. According to the literature the probability that a fire is extinguished in a time <10 min is 48% [22]. This provides a complementary 52% chance of not extinguishing.

Probability of failure to open of the TPRD

When the fire is not extinguished in time, the tank is exposed to the fire and the TPRD may activate or not. Regarding the reliability of the TPRD, it is not reported sufficiently. HyRAM+ reports the default failure to open probabilities of PRV (pressure relief valve) as estimated from generic data from the offshore oil, process chemical, and nuclear power industries [23, 24]. For the mobility sector limited literature data are available, e.g. those reported in the FireCOMP risk assessment study [25] and the SANDIA publication [4].

In this work the probability of failure to open TPRD is assumed to be 0.03 obtained as average of the beta distribution (0.5, 16.5) reported in [4]. This value is assumed for a localized fire. While for engulfing fire a probability of TPRD failure of 6.04×10^{-3} can be considered [25].

Hydrogen ignition probability

Once hydrogen is released it may ignite or not. The hydrogen ignition probabilities considered are those used in HyRAM+ software [23] as function of H_2 release rate.

Immediate ignition occurs if the leak is ignited within the first few fractions of a second after the leak occurs and delayed ignition allows the hydrogen to accumulate and mix with ambient air before being ignited. The total probability of ignition is the sum of the averaged probabilities for immediate and delayed ignition and is estimated to be on average 0.147. Then, if hydrogen ignites immediately (with a probability of 0.667), generates a jet fire, while if its ignition is delayed (with a probability of 0.333) an explosion occurs.

One exception to these probabilities is the case when a crash leads to a post-crash fire, with hydrogen released from the TPRD. If the fire is large enough to activate the TPRD which releases hydrogen from the tank, it is assumed to ignite the released hydrogen. Thus, it is assumed that for such case the ignition probability is close to 1 (0.999). Conversely, if TPRD is not activated a catastrophic tank rupture may occur with fireball and outwards propagating blast wave are the consequences. These two hazards are also considered in the event tree analysis.

Event's frequency

The branch frequency (events per 10^6 vehicle-km) of each event chain is obtained by the combination of all the probabilities along a branch leading to that event chain multiplied by the frequency of the initiating event (event per 10^6 vehicle-km). Then the likelihood of each event chain (events per year) is obtained by multiplying the branch frequency (events per 10^6 vehicle-km) by the annual average daily traffic AADT (10^6 vehicle per day) by the number of days in a year (days per year) and the length of tunnel (km).

The results of the analysis show that the most likely consequence includes scenarios (A and E) with no release of hydrogen (0.92 events per year) or hydrogen release without ignition (B and G) (8.6×10^{-2} events per year). When the hydrogen does ignite, a jet fire from the hydrogen system (C and J) (1.31×10^{-2} events per year) or more likely from a TPRD (H) (1.47×10^{-2} events per year) may occur. If hydrogen released by the TPRD is not immediately ignited, a hydrogen-air flammable cloud is accumulated under the ceiling. In this case it is more likely the scenario (I) of deflagration of the cloud or DDT (7.3×10^{-3} events per year).

In the presence of a localised fire, if the TPRD is likely not activated by the fire, and fails to open, or is accidentally being "heat-shielded" from a fire caused by an incident, the catastrophic hydrogen tank rupture is a most likely scenario (6.8×10^{-4} events per year).

4.2 Jet Fire

A jet fire from a TPRD has a frequency of 1.47×10^{-2} events per year (Figure 2 2). For a jet fire from a TPRD, flame length and hazard distances are calculated as reported in Table 1 where the input data and the results for SoC=100% and 40% are shown.

The flame length is evaluated in the range 4.4-6.6 m, while no-harm distance ranges between 15.3-23.1 m for the SoCs under analysis. It should be noted that the exact location of the vent lines connected to TPRD depends on the vehicle manufacturer and its model, but it is usually near the hydrogen tank and direct downward. Therefore, the jet flame impinges on the floor. Unfortunately, there are no engineering tools for the assessment of hazards of attached or impinging jets now. In the case of TPRD releases, the impinging jet will be shorter due to loss of momentum and follow-up effect of buoyancy compared to a free jet and therefore the correlation used (assuming a horizontal free jet) can be considered as a conservative estimate.

Table 1. Input data and results for jet fire from TPRD of 2 mm orifice diameter.

Input Data					
SoC (%)	H_2 pressure in reservoir (MPa)	H_2 temperature in reservoir (°C)	Orifice diameter (mm)	Ambient pressure (atm)	Ambient temperature (°C)
40	22.5	15	2	1	15
100	70.0	15	2	1	15
Results					
Initial Mass flow rate (kg/s)	Flame length (m)	No harm (70°C) separation distance (m)	Pain limit (5 min, 115°C) separation distance (m)	Third degree burns (20 s, 309°C) separation distance (m)	
0.0407	4.4	15.30	13.12	8.74	
0.1077	6.6	23.07	19.77	13.18	

4.3 Tank rupture

For this worst-case tunnel scenario, the overpressures along the tunnel at different distances from the tunnel centre, are calculated using the universal correlation for the blast wave decay after a hydrogen tank rupture in a tunnel fire [6] (Fig. 3).

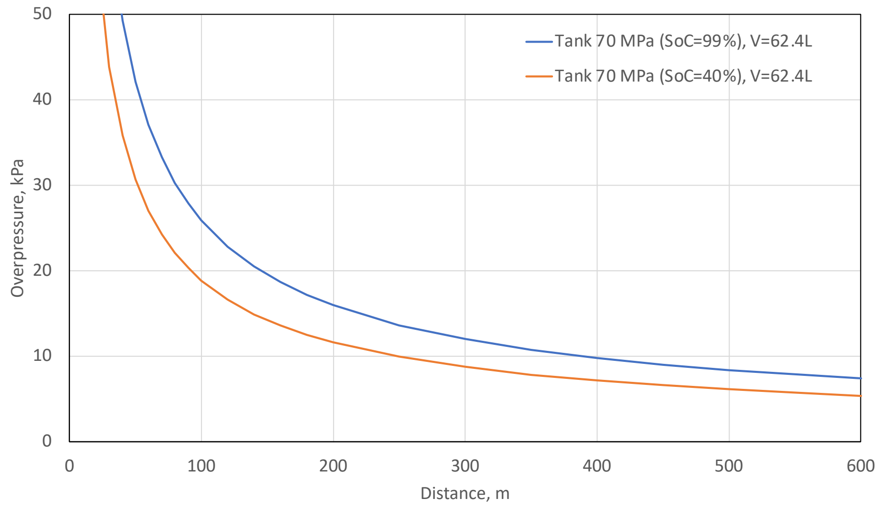

Figure 3. Blast wave decay vs distance from the hydrogen-powered vehicle located at the centre of the tunnel (H_2 tank of 62.4 L, SoC=100% and SoC=40%)

By means of the overpressure values and the probit function [13], the probability of fatality at different distances from the tunnel center is predicted. The individual risk is then calculated by multiplying the frequency of the tank rupture and the probability of fatality along the tunnel length (Fig.4).

The individual risk is in the range of 6.8×10^{-4} to 1.0×10^{-5} fatality per year up to a distance from the tunnel centre of 160 m for SoC=100% and of 100 m for SoC=40%.

Assuming a risk acceptance criterion of 10^{-6} fatality per year, a fatality hazard distance of 375 m and 240 m is evaluated for SoC=100% and SoC=40%, respectively. These distances correspond respectively to a queue of 52 and 33 cars for each lane [26], and assuming an occupancy of 2 people per car, respectively, to 208 and 132 fatalities.

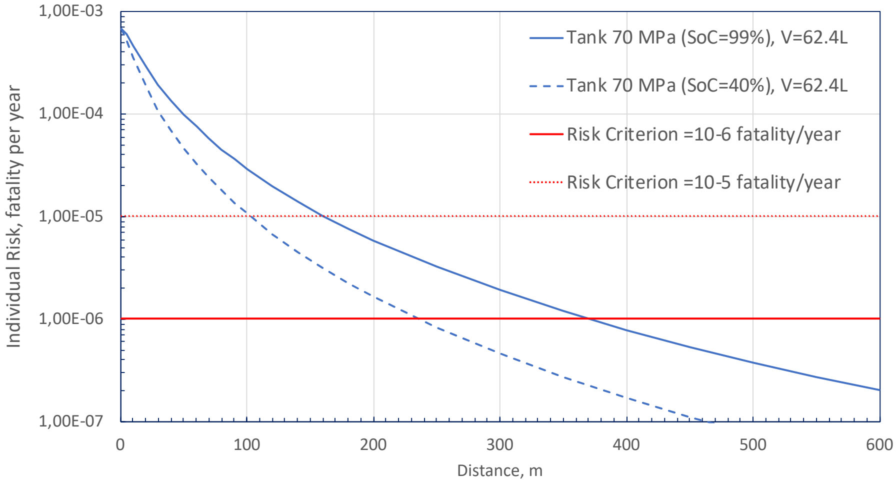

Figure 4. Individual risk vs distance from the hydrogen-powered vehicle in the case of H_2 tank rupture at the center of the tunnel (tank of 62.4 L: SoC=100% and SoC=40%)

On the other hand, using as risk acceptance criterion of 10^{-5} fatality per year, the hazard distances reduce to 160 m and 100 m for SoC=100% and SoC=40%, respectively. Correspondingly, the number of cars in the queue for each lane is 22 and 14, and the fatalities 88 and 56, respectively.

These hazard distances are significantly higher than the no-harm distance calculated in the case of a hydrogen jet fire from TPRD of 15.3-23.1 m for SoC=40-100%.

With respect to damage to the equipment and cars in the tunnel, the overpressure reached in the accident location is higher (657 kPa) than the threshold value of 200 kPa to crush cars up to 5 m from the tunnel centre (SoC=99%). The probability of failure of the tunnel structure is evaluated at different distances from the tunnel centre using the Eisenberg model [14]. The Eisenberg probit provides as result a probability of tunnel failure of 100% up to 50 m (30 m) from the tunnel center for SoC=100% (40%), which decreases to 50% probability of failure at a distance of 154 m (98 m).

4.4 DDT

In hydrogen release accident scenarios in confined spaces like tunnels, the released hydrogen could not have sufficient time to mix with the ambient air below the lower flammability limit of 4% by volume before ignition. Thus, the hydrogen combustion occurs mostly in a non-uniform mixed state, e.g., in stratified layers under the ceiling of the tunnel.
In the case of hydrogen release and accumulation under the ceiling, four cases of hydrogen cloud formation in a tunnel cross-section were analysed, as shown in Fig.5:

- Case 1: Uniform hydrogen concentration distributed over the entire tunnel cross-section for the given hydrogen inventory;
- Case 2: Uniform hydrogen concentration distributed inside a layer of hydrogen-air mixture for the given hydrogen inventory;
- Case 3: Stratified layer of hydrogen-air mixture for the given hydrogen inventory;

- Case 4: Stratified hydrogen-air mixture filled the entire tunnel cross-section for the given hydrogen inventory.

If a hydrogen cloud is ignited, a deflagration or DDT may occur. The evaluation of flame propagation and eventual DDT is performed by the method of flame propagation regime evaluation developed by KIT which is based on the so-called sigma-criterion for flame acceleration, lambda criterion and run-up distance criterion for detonability evaluation. A detailed description of the method is reported in [7].

Case 1 (uniform full filled)

X_H H

Case 2 (uniform layer)

X_H h

Case 4 (stratified full filled)

X_H H

Case 3 (stratified layer)

X_H h

Figure 5. Hydrogen distribution profiles in a tunnel (H= tunnel height; h=height of hydrogen layer; X_H=hydrogen concentration)

The traffic and hydrogen cloud characteristics considered in the model are reported in the following Table 2 and Table 3 for car accidents.

Table 2.Traffic characterisation for car accident.

Title	**Value**	**Units**
Cars in queue lane 1	125	-
Cars in queue lane 2	125	-
Car density	10000	vehicles/day
Car height	1.7	m
Car width	1.8	m
Car cross-section area	3.06	m^2
Car length	6	m
Parking distance	2	m
Distance between cars (front to front)	8	m
Blockage ratio BR (single lane)	0.052987	-
Blockage ratio BR (double lane)	0.105974	-

Table 3. Hydrogen cloud characterisation for car accidents.

Title	**Value**	**Units**
Tank pressure	700	bar
Hydrogen inventory cars	62.4	L
Mass of hydrogen	2.48	kg
Volume of hydrogen (STP conditions)	30.0	m^3

Table 4. Calculated hydrogen release time for tank NWP=70 MPa, 62.4 L.

TPRD orifice diameter, mm	**1**	**2**	**3**	**5**
Characteristic release time, t_{ch}, s	41.6	10.4	4.6	1.7
Total release time, t, s	166	42	18	6.7

Table 4 shows the calculated release time for the car accident in a tunnel depending on TPRD orifice diameter from 1 mm to 5 mm in the case of accident (speed of sound is 983 m/s). The model allows the evaluation of the possible flame propagation regimes of the hydrogen-air cloud formed by the release of 2.48 kg of hydrogen in the four defined cases of hydrogen release and distribution profile in the tunnel.

The results of the flame propagation and DDT modelling are summarised as follows:

- The two scenarios (case 1 and case 4) for fully filled tunnel cross-section with a hydrogen-air mixture are more likely for a very short release time. In both cases the length of the flammable cloud is not enough for flame acceleration to the speed of sound and transition to detonation. The flame propagates comparatively slow, with maximum combustion overpressure not higher than 0.1-0.2 MPa. Note that this was a preliminary simulation case that assumed a very large TPRD diameter and 0 m/s tunnel air velocity, which may not be representative of reality.
- The two scenarios (case 2 and case 3) for formation of a layer of hydrogen-air mixture are more likely for relatively longer release time of the order of 10 s. In both cases the length of the flammable cloud is much longer and can be enough for flame acceleration to the speed of sound.
- For all car accidents, there is no scenario of hydrogen release with formation of detonable cloud. The flame propagates comparatively slow with a maximum deflagration overpressure not higher than 0.1-0.2 MPa.

5.0 CONCLUSIONS

The proposed methodology enables the assessment and evaluation of scenarios involving external fires or vehicles that burst into fire because of an incident or other initiating event. The heat impact on the hydrogen storage system is of great importance as it implies the storage tank rupture and gas cloud explosion scenarios. To demonstrate the application of the suggested QRA methodology, an example has been provided for the selected road tunnel accident scenario.

For jet fire, higher event frequency is calculated than tank rupture and deflagration/DDT scenarios. In contrast, no-harm hazard distances are found to be significantly longer for the tank rupture scenario than jet fire. As for delayed ignition scenarios such as deflagration of flammable cloud eventually accumulated under the ceiling, more complex software (i.e. CFD) is needed to evaluate the consequences in a confined space such as a tunnel. But it is estimated that there is no hydrogen release scenario with detonable cloud formation.

For delayed ignition scenarios, ventilation can facilitate cloud dispersion, as assessed in the HyTunnel-CS project: when the 3 m/s ventilation was set in the tunnel, almost all hydrogen clouds were blown downstream. The deflagration overpressure is effectively reduced by the ventilation.

The probability of occurence of the described worst case scenario needs to be as low as possible. Therefore, the tunnels safety measures and traffic guidance systems are essential to avoid traffic accidents. Further measures should also be considered to ensure an acceptable level of risk for the tank rupture scenario. An option could be the emerging safety technology of self-venting TPRD-less tanks working on the microleaks-no-burst concept [27] in case of a heat impact. Other more conventional options could be measures to increase the fire resistance of the tanks, and the reliability of the TPRD's to activate on demand, e.g. by ensuring the functioning of the TPRD's heat sensors.

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