QRA of hydrogen vehicles in a road tunnel

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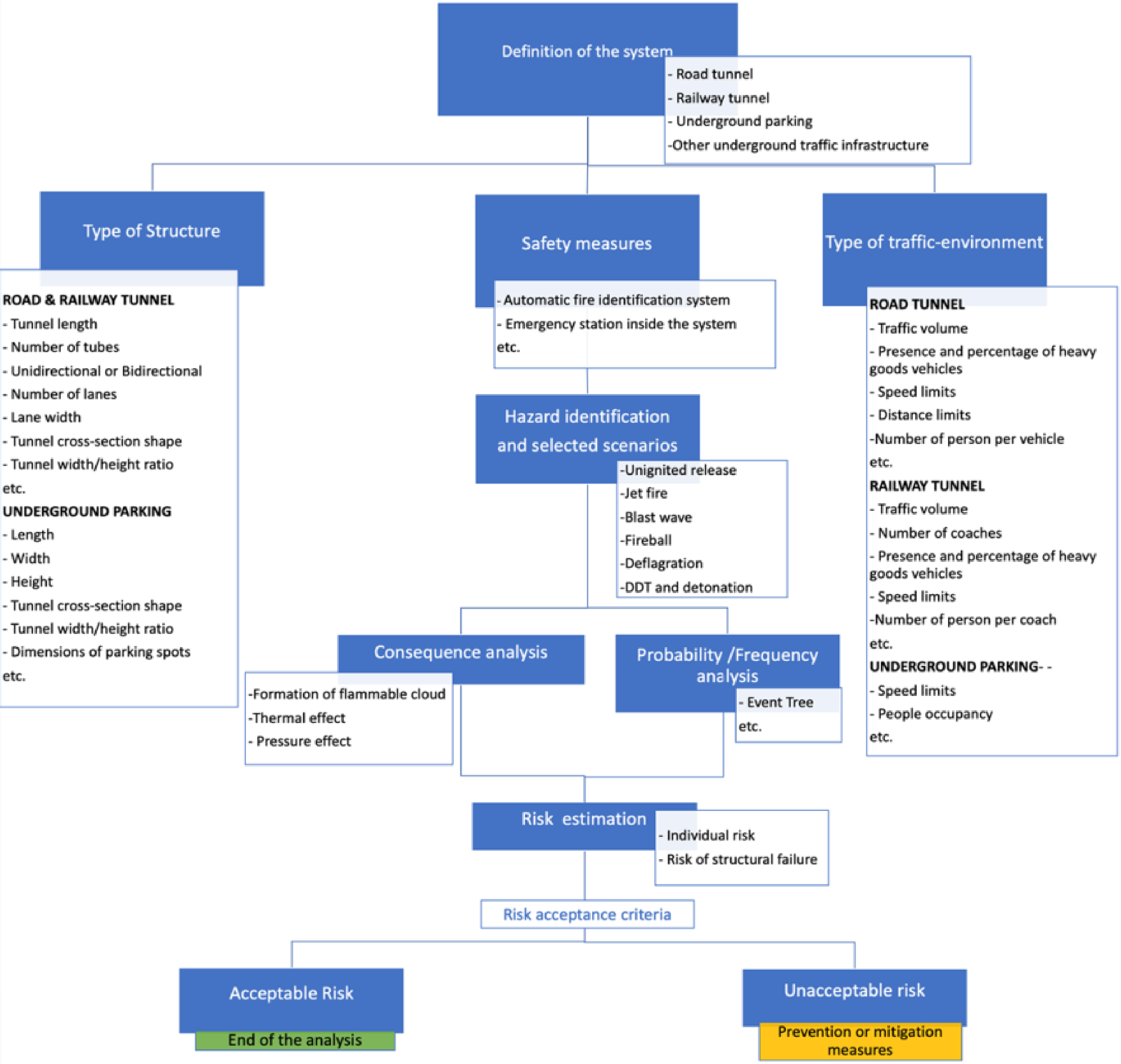
Motivation

- 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.**

QRA methodology

- Literature review revealed a few risk assessment models and tools e.g. QRAM, TUNRIM RWS, IRAM, QRAFT, BASt, but either they do not include hydrogen as a dangerous substance (i.e., the QRA from PIARC), or the “low frequency – high consequence” events are not analysed (i.e., QRA developed by SANDIA).
- In Europe, the PIARC approach is widespread and chosen as a starting point for the new methodology.
- This approach is enhanced by enabling better implementation of hazards identification and respective sources for hydrogen vehicles.

QRA flow diagram



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Case study

Varano tunnel

- Rural road (S.S.145)
- Bi-directional road tunnel
- **1.2 km long**
- Longitudinal slope of +2% from Portal A to Portal B.
- Rectangular cross section: width = 10.5 m, height = 5.5 m.
- Two lanes (3.75 m wide) one for each traffic direction.

Traffic

- **Annual Average Daily Traffic (AADT) >10,000 vehicles per day for each traffic direction,**
- Heavy vehicles : 5%.
- Limit speed: 50 km/h.
- Vehicles are also forbidden to overtake.

Ventilation system

- Longitudinal ventilation (air velocity 2–2.5 m/s)
- Emergency ventilation (air velocity of 9 m/s)
- A linear heat detection system is assumed to activate the emergency
- ventilation system when the temperature is above 68 C.

Selected Scenarios

Unignited scenarios:

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

Immediate ignition scenarios:

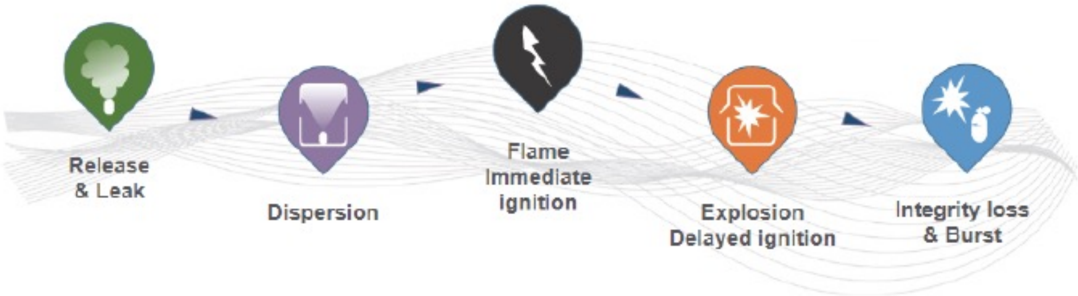
- Hydrogen jet fire in a tunnel

Burst scenario

- Hydrogen storage vessel rupture in a tunnel

Delayed ignition scenario

- Hydrogen storage vessel blowdown with delayed ignition in a tunnel



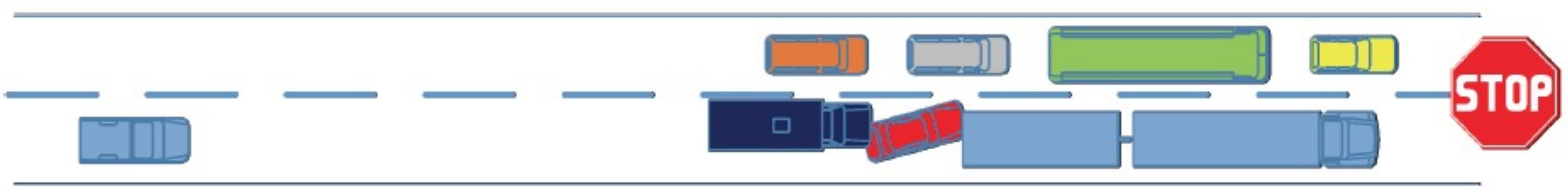
Accident Scenario

Scenario under congested traffic:

- a vehicle collides into the last vehicle (a FCEV) in a queue, **at the center of the tunnel (600 m from the exit);**
- both lanes of the tube are blocked,
- in each lane of the tube, 83 cars queue up and stop (11 min)

The FCEV has two onboard storage tanks but

- only one tank of **62.4 L** is involved in the accident
- **TPRD 2 mm-orifice size (jet directed downward)**
- State of charge (**SoC**)**: 100%** (immediately after fuelling) and **40% (24.4 MPa, 20 C)**



Event tree

Frequency= Branch frequency x AADT x L_{tunnel}

Tunnel accident per million vehicle km	Does the accident cause a fire post crash?	Is H2 released from the system?	Is the fire estinguished on time?	Is H2 released from the TPRD?	Does the H2 ignite?	Is the H2 ignition delayed ?	Branch Frequency (per million vehicle km)	Event chain	Consequences	Italian Tunnel Frequency (per year)
Crash in tunnel 0.120	no fire 0.954	no H2 released 0.9					1.03E-01	A	No H2 is released	0.90
		H2 released 0.1			no ignition 0.853		9.78E-03	B	H2 is released but is not ignited until concentration dropped below LFL	8.57E-02
					ignition 0.147	immediate 0.667	1.12E-03	C	H2 is released and ignited immediately ->jet deflagration followed by jet fire	9.84E-03
						delayed 0.333	5.62E-04	D	H2 is released and has a delayed ignition-> deflagration of turbulent jet and possible deflagration of cloud under the ceiling (if created), flowed by jet fire	4.92E-03
	fire 0.046	no H2 released 0.9	yes 0.480	no			2.39E-03	E	No H2 is released	2.09E-02
			no 0.520	TRPD failure to open 0.030			7.76E-05	F	Catastrophic rupture of the H2 tank->blast wave, fireball and projectiles	6.80E-04
				TRPD activation 0.970	no ignition 0.001		2.51E-06	G	H2 is released but is not ignited if flame blow-off TPRD	2.20E-05
					ignition 0.999	immediate 0.667	1.67E-03	H	H2 is released by TPRD and ignited immediately ->turbulent jet deflagration followed by jet fire (if TPRD designed to exclude the flame blow-off)	1.47E-02
						delayed 0.333	8.35E-04	I	H2 is released by TPRD and it has a delayed ignition -> possible deflagration of cloud under the ceiling (if created) and eventual DDT	7.31E-03
		H2 released 0.1			ignition 1	immediate 0.667	3.69E-04	j	H2 is released and ignited immediately ->jet deflagration followed by jet fire	3.23E-03
						delayed 0.333	1.84E-04	K	H2 is released and has a delayed ignition-> deflagration of hydrogen jet that can be or not followed by deflagration of flammable cloud under the ceiling (depends on TPRD diameter and release location and orientation).	1.61E-03

TPRD scenarios

6.8×10^{-4} Catastrophic tank rupture

1.47×10^{-2} Jet fire

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Collision Rate & Vehicle Fire Rate in tunnels

P =0.046

Tunnel Collision Rate (PIARC, 2016)

Country	Type of traffic	Collision rate (C_a) (per 10^8 veh. km)	
Austria	bidirectional	3.60	*
Argentina	bidirectional	5.74	**
France	bidirectional	5.30	***
Norway	bidirectional	11.72	****
Spain	bidirectional	9.30	*****
Vietnam	bidirectional	71.98 (18.00)	******
		Collision rate (C_u) (per 10^8 veh. Km)	
Austria	unidirectional	9.80	*
Denmark	unidirectional	3.97	
France	unidirectional	8.72	***
Italy	unidirectional	12.02	
Netherlands	unidirectional	5.35	
Norway	unidirectional	11.60	****
South Korea	unidirectional	2.10	
Spain	unidirectional	6.30	*****
Switzerland	unidirectional	7,58	*******

* Figures not calculated in this report but obtained from the report Safety of Road Tunnels - Traffic Safety in Highway and Expressway Tunnels (1999 to 2009) [34]
** The collision rate reported for Argentina covers only one tunnel (Túnel Subfluvial Uranga-Sylvestre Begnis) [50]
*** Figures not calculated in this report but obtained from the report [47]
**** Figures are derived from the report "*Studies on Norwegian road tunnels II. An analysis on traffic incidents in road tunnels 2001-2006*" [29]
***** Figures not calculated in this report but obtained from the report [53]
****** The collision rate reported for Vietnam covers only one tunnel (Hai Van tunnel), the collision rate includes all collisions – also those without casualties; the number in brackets gives an estimation of the rate for collision with casualties (reduction by a factor 4 – based on expert judgement); this number is included in illustration 6
******* The rate covers all Swiss tunnels (mainly unidirectional tunnels) as given in [42]
Background data concerning collision rates see appendix 5.2, table 11 and table 12.

0.1202 crashes per million vehicle-km

Fire rates for road tunnels (PIARC, 2016)

Country	Fire rate all vehicles (per 10^9 veh. Km)
Norway	15.0
Netherlands	3.2
Austria	6.5
Germany°	25.7
Italy	5.6
Spain	3.5
France	10.6
United Kingdom#	Insufficient data (10 – 20)
Czech Republic	17 - 25
Japan^	(38)
South Korea	6.4
Vietnam*	560

Notes : # Value from the UKs in parenthesis is a rough estimate.
^ The tunnels cover four tunnels with fire events only – the rate is an upper value for Japan.
* The statistics only cover one single tunnel.
° The available data covers only the 28 German TERN tunnels – also small fires are included

0.0056 fires per million vehicle-km

Probability of H_2 release

P =0.08

- Scarce published crash test data on H_2 vehicles: 5 tests.
- In all 5 tests there was not enough damage to the system for it to leak or release hydrogen.
- A gamma distribution conjugate (Jeffreys) prior was used to account for a half of an event (0.5).

- The Beta (0.5, 5.5) uncertainty distribution is parametrized in terms of its mean (0.08) and standard deviation (0.10).

SANDIA REPORT - SAND2017-11157

B.D. Ehrhart, D. M. Brooks, A. B. Muna and C. B. LaFleur
Fire Technology 2020 https://doi.org/10.1007/s10694-019-00910-z

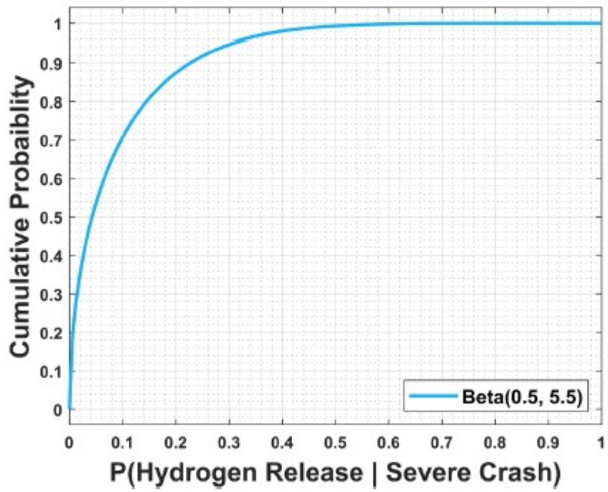
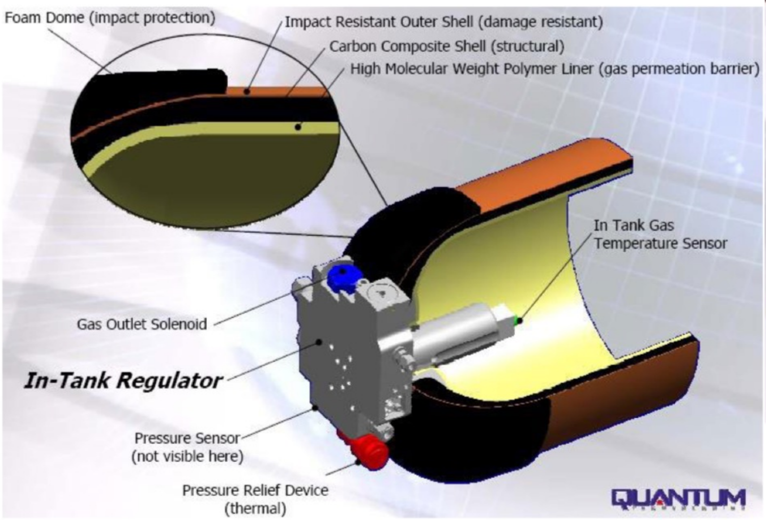
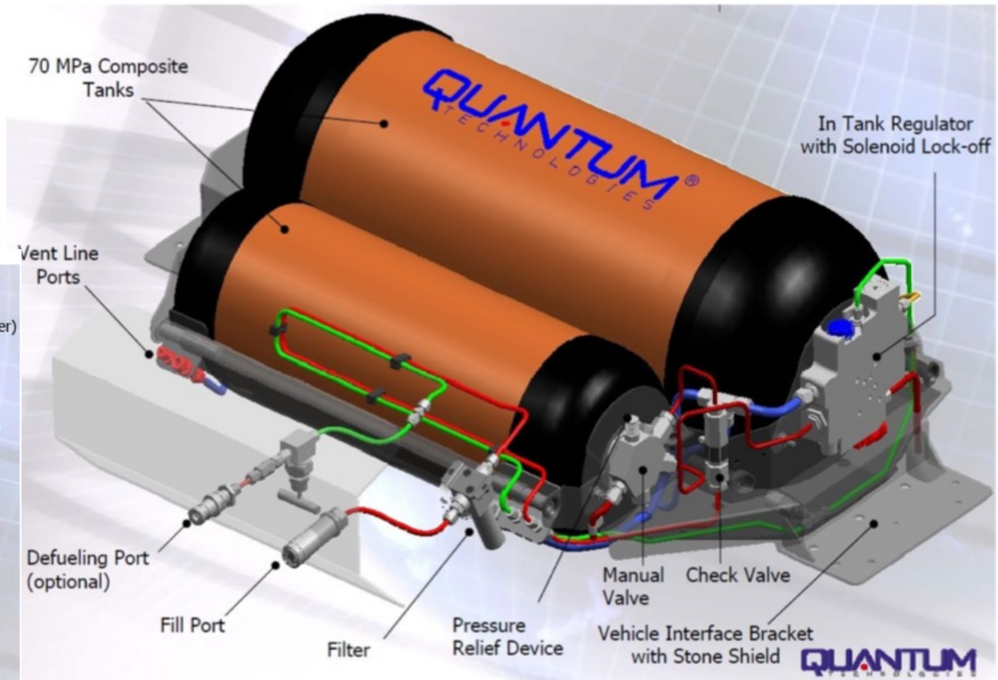


Figure 6. Uncertainty distribution on the probability that a crash results in hydrogen release.

H_2 TANK IV





- Thermally Activated Pressure Relief Device (TPRD) provides a controlled release of the gaseous hydrogen GH2 from a high pressure storage container before its walls are weakened by high temperatures, leading to a catastrophic rupture.

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Probability of extinguishing the fire

P =0.48

Table 10
Recorded time from fire detected to fire declared extinguished.

Duration (mins)	<5	<10	<20	<30	<40	<50	<60	>60
No. of Fires	15	34	54	66	69	70	70	71
By Percentage	21%	48%	76%	93%	97.2%	98.5%	98.5%	100%

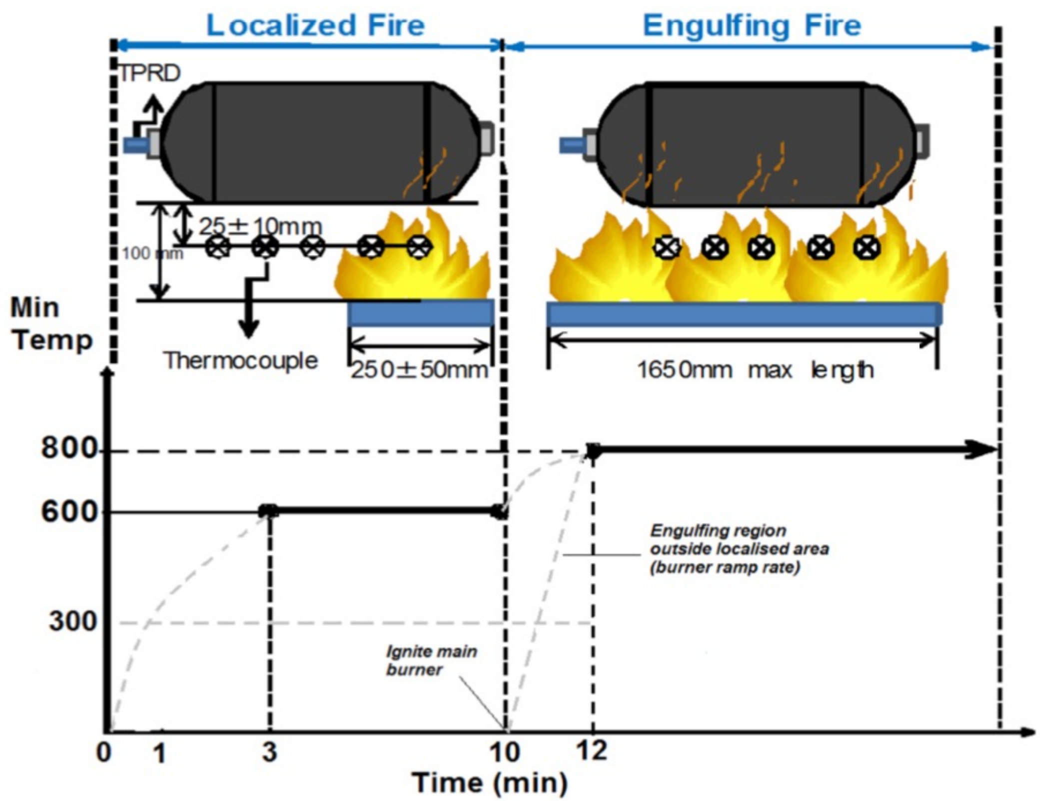
- It is obtained by comparing the time required to fire extinguishment with the fire resistance rating (FRR) of a hydrogen tank.
- According to the CFD simulation carried out by Ulster University, for a 62.4 L tank exposed to a fire of specific heat release rate HRR/A=1 MW/m^2,

FRR= 7.5-13.5 min for H2 tank @ 100%-40% SoC

Casey,N. 2020, Fire incident data for Australian road tunnels, Fire Safety Journal 111, 102909

Probability of TPRD failure to open

Localised and Engulfing fire



- The probability of failure to open TPRD is assumed to be **0.03** for a localized fire (SANDIA, assuming a Jeffrey's beta prior distribution)
- For engulfing fire a probability of TPRD failure of **6.04 x 10^{-3}** can be considered (FireComp project).

Probability of ignition

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
>6.25	0.23	0.12
Average	0.098	0.049

P = 0.147

- In the case of post-crash fire, with hydrogen released from the TPRD the ignition probability is close to **1** (0.999).

P = 0.999

- The probability of an **immediate ignition** (given that an ignition will occur) is 66.67%, and the complimentary probability of delayed ignition is 33.33%.

P = 0.667

Groth, K. M., Hecht, E. S, 2017. HyRAM: A methodology and toolkit for Quantitative Risk Assessment of hydrogen systems, International Journal of Hydrogen Energy, 42, 7485-7493.
Tchouvelev, A., Hay, R., Benard, P., 2007.Comparative Risk Estimation of Compressed Hydrogen and CNG Refuelling Options. In Proceedings of National Hydrogen AssociationConference, San Antonio, Texas, March 19-22, 2007.

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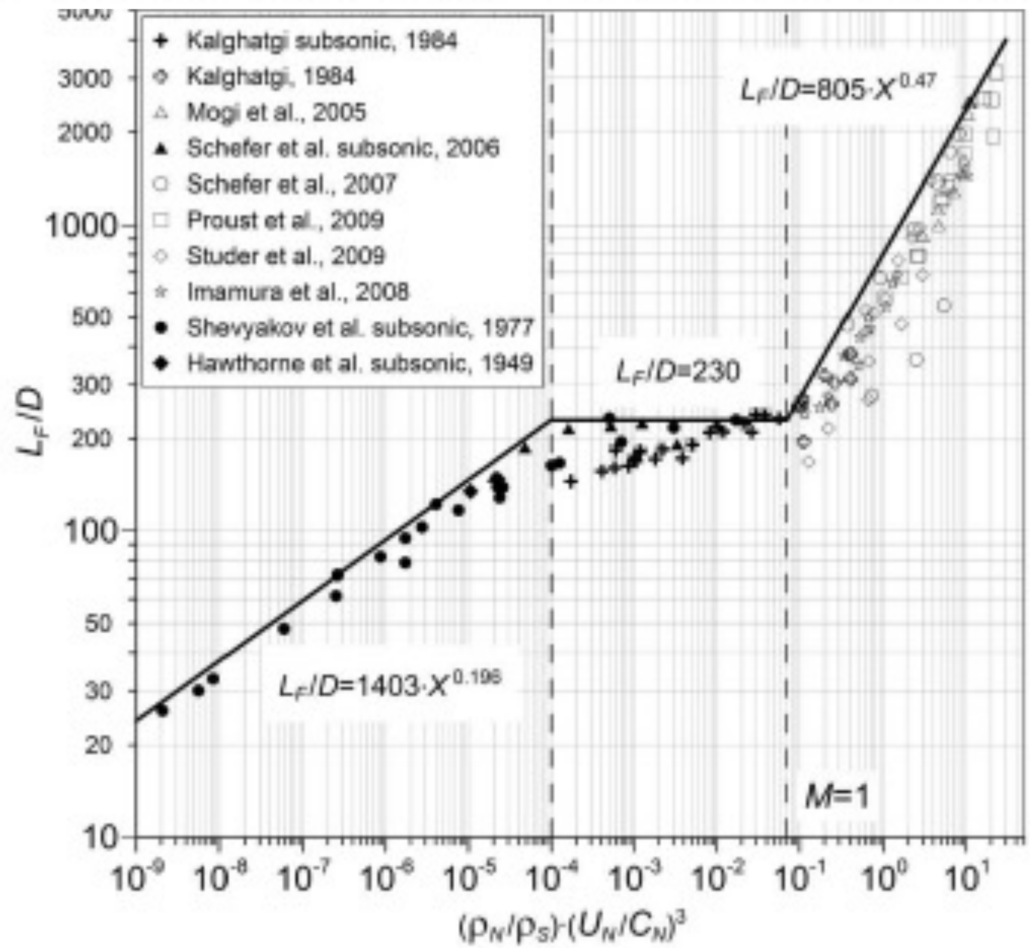
Event's frequency

Event chain	Consequences	Varano Tunnel Frequency (per year)
A	No H_2 is released	0.9
B	H_2 is released but is not ignited	$8.6\text{x}10^{-2}$
C	H_2 is released and ignited immediately -> jet fire	$9.8\text{x}10^{-3}$
D	H_2 is released and has a delayed ignition-> deflagration of cloud under the ceiling (if created)	$4.9\ \text{x}10^{-3}$
E	No H_2 is released	$2.1\text{x}10^{-2}$
F	Catastrophic rupture of the H_2 tank->blast wave, fireball and projectiles	$6.8\text{x}\backslash 10^{-4}$
G	H_2 is released but is not ignited	$2.2\text{x}10^{-5}$
H	H_2 is released by TPRD and ignited immediately -> jet fire	$1.5\text{x}10^{-2}$
I	H_2 is released by TPRD ignited with a delay -> flammable cloud deflagration under the ceiling (if created) and DDT	$7.3\text{x}10^{-3}$
J	H_2 is released and ignited immediately ->jet fire	$3.2\text{x}10^{-3}$
K	H_2 is released and has a delayed ignition-> deflagration of flammable cloud under the ceiling	$1.6\text{x}10^{-3}$

Jet fire **Consequence analysis**

Under expanded jet of H_2

The dimensionless correlation for hydrogen jet flames (in formulas "X" denotes the similarity group $(\rho_N/\rho_S)(U_N/C_N)^3$).



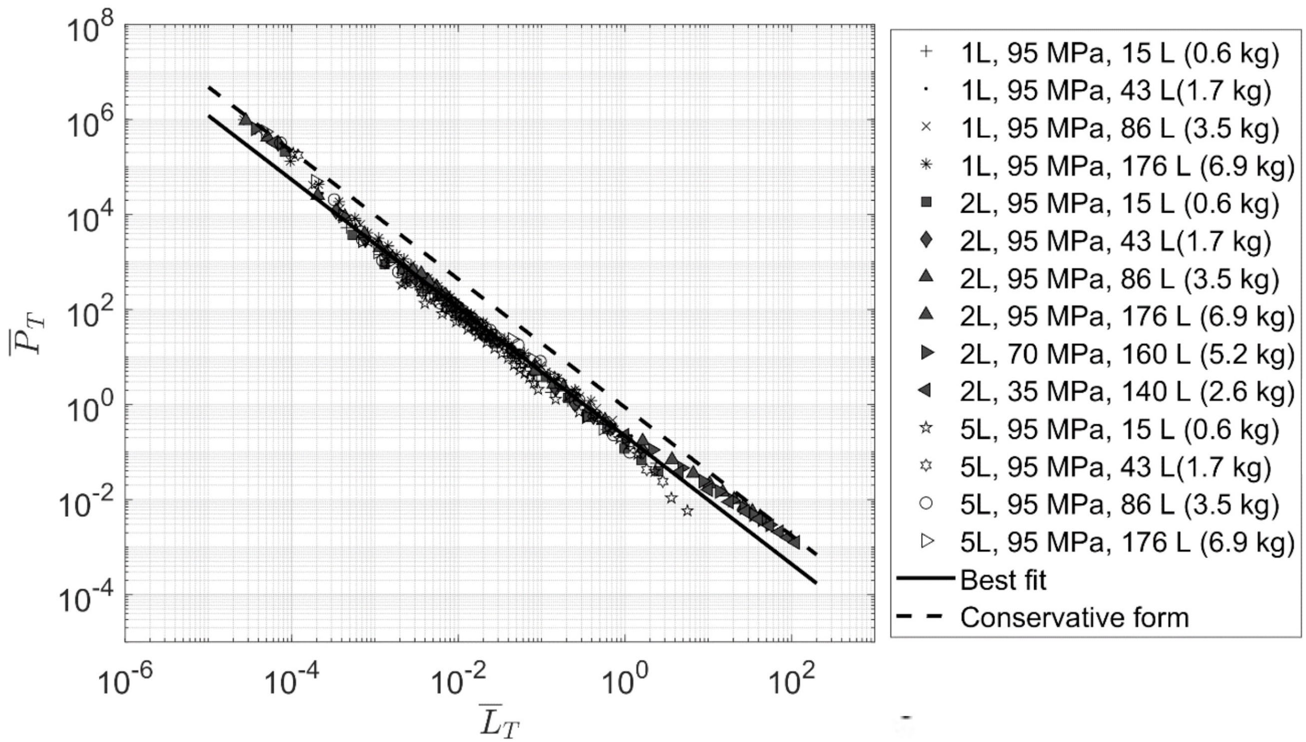
- Flame length by the tool available in hydrogen e-laboratory (https://hyresponder.eu/e-platform/e-laboratory)

Molkov, V., Saffers, J.-B. 2013.Hydrogen jet flames, International Journal of Hydrogen Energy, 38(19), pp. 8141–8158.

Consequence analysis

Tank rupture

- Universal correlation for the blast wave decay after a hydrogen tank rupture in a tunnel fire, by V. Molkov and W. Dery. (2020)



$$\overline{P_T} = 0.22 \cdot \overline{L_T}^{-1.35}$$

$$\overline{L_T} = \frac{P_0 L A_T}{E \cdot AR^{0.5}} \left(\frac{fL}{D_T}\right).$$

$$\overline{P} = \overline{P_T} * \overline{L_T} =$$

$$E = \alpha \cdot E_m + \beta \cdot E_{ch},$$

$$\Delta P = P0 * \overline{P} = P0 * 0{,}22 * \left(\frac{P0\ L\ P}{4\ E\ AR^{0.5}} * f\ L\right) \wedge -0{,}35$$

Consequence analysis

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DDT potential

- A tool for the assesment of a detonation case is here taken into account (developed by M. Kuznetsov, KIT) to evaluate the consequence of the hydrogen detonation in the tunnel.
- It is assumed to be the consequence of the release of hydrogen from TPRD, when TPRD is activated by a fire, and a strong ignition at the top of the tunnel at an unfavourable time and location.
- The pressure loads are calculated to evaluate the consequence of the hazard.

Rattigan, W., Moodie, K. et al. HyTunnel-CS. Deliverable D4.3 Final report on analytical, numerical and experimental studies on explosions, including innovative prevention and mitigation strategies, 2022.

Consequence analysis

DDT potential

- Case 1: Uniform hydrogen concentration distributed over the full 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 whole tunnel cross-section for the given hydrogen inventory.

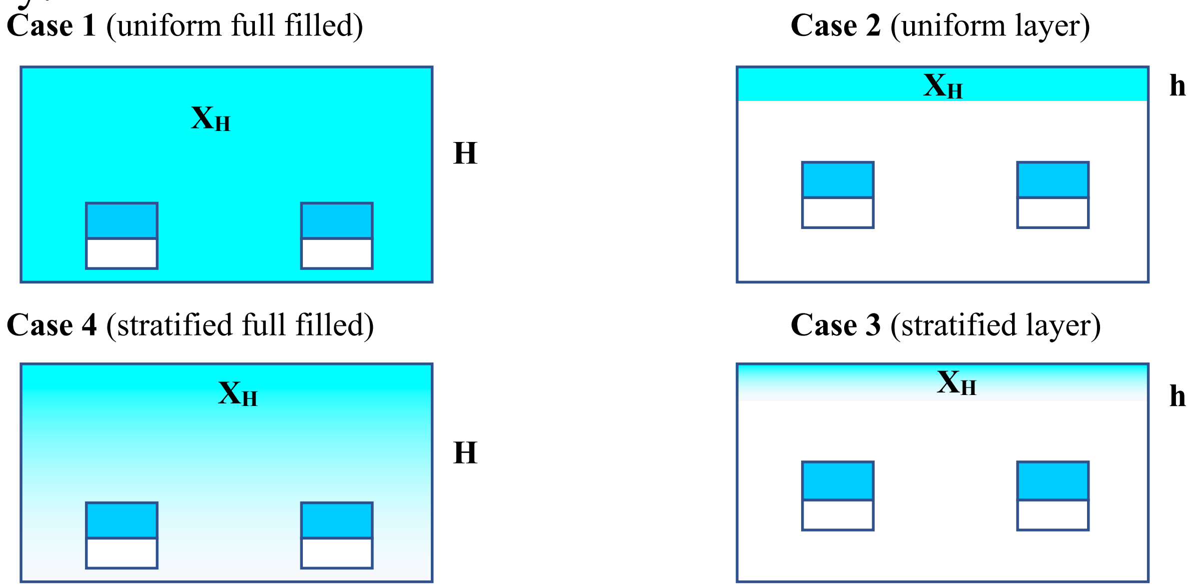

Figure 1`. Hydrogen distribution profiles in a tunnel.

Harm criteria

Jet fires:

- 70^{o}C is taken as “no harm” criterion.
- 115^{o}C 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.
- 309^{o}C 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.

Overpressure Hazard

Probit function for harm to people and structural damage

Death due to lung hemorrhage

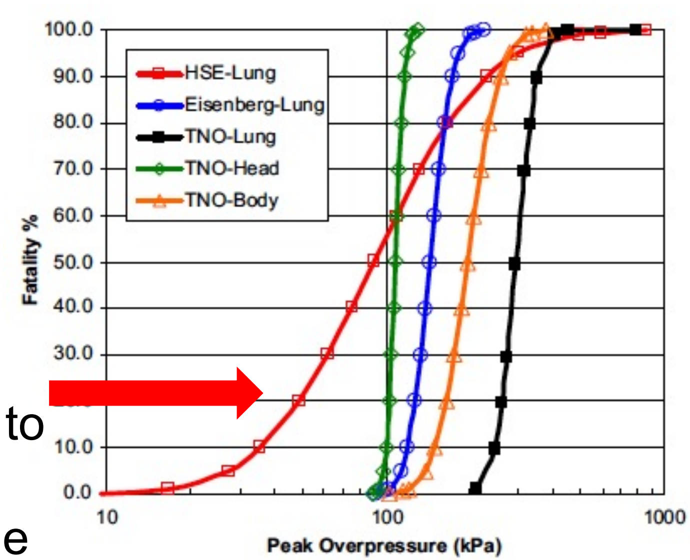

Fig. 2 – Comparison of overpressure probit functions for harm to people.

Structural damage

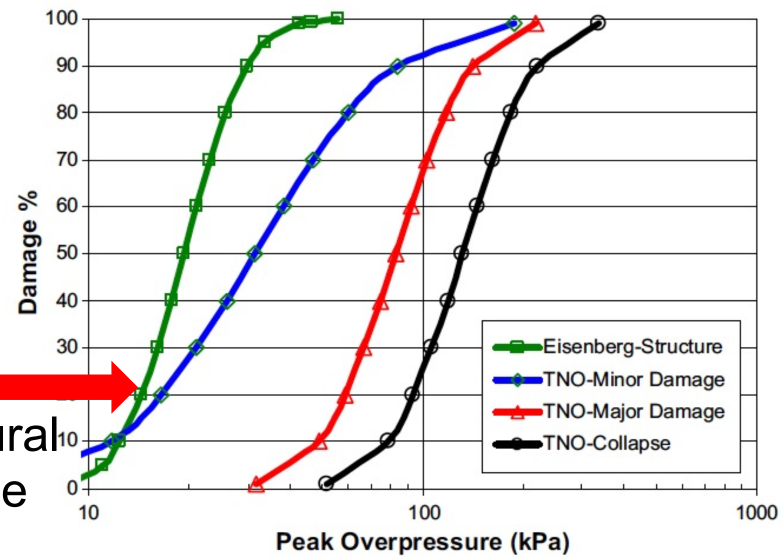

Fig. 4 – Comparison of structural damage probit functions.

La Chance et al. International journal of hydrogen energy 36 (2011) 2381-2388

Risk criteria

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- Both values 10^{-5} and 10^{-6} fatality per year are used and results compared.
- 10^{-6} per year is an acceptable risk level below which society normally does not impose any regulatory guidance.
- For hydrogen safety applications, the fatality risk criterion proposed by EIHP [15] and EIGA [16] are 2×10^{-6}/yr and 3.5×10^{-5}/yr, respectively.

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Flame length and hazard distance

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

- Impinging jet on the road pavement

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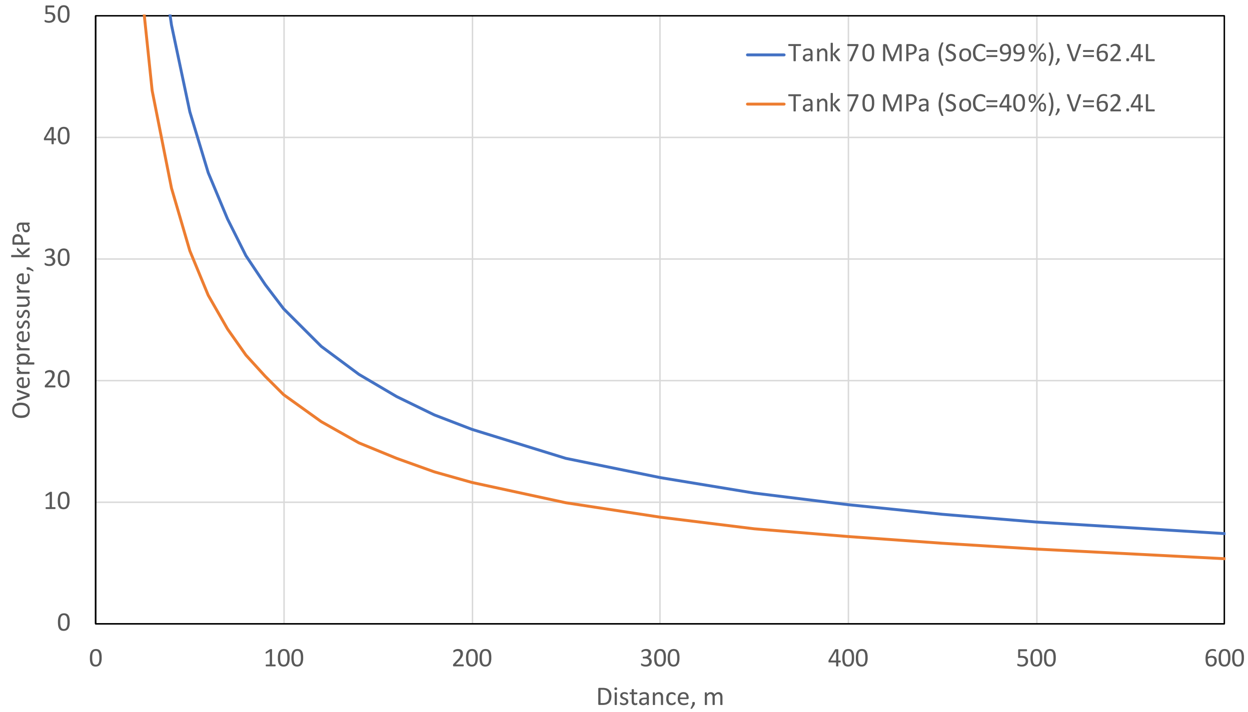
Blast wave decay vs distance from vehicle

vehicle located at the centre of the tunnel



- The overpressure decreases rapidly along the tunnel, especially within the first 50 m.
- Probability of structural damage of 100% up to 50 m (30 m) for SoC=100% (40%), which decreases to 50 at a distance of 154 m (98 m).

Tank rupture

Individual Risk

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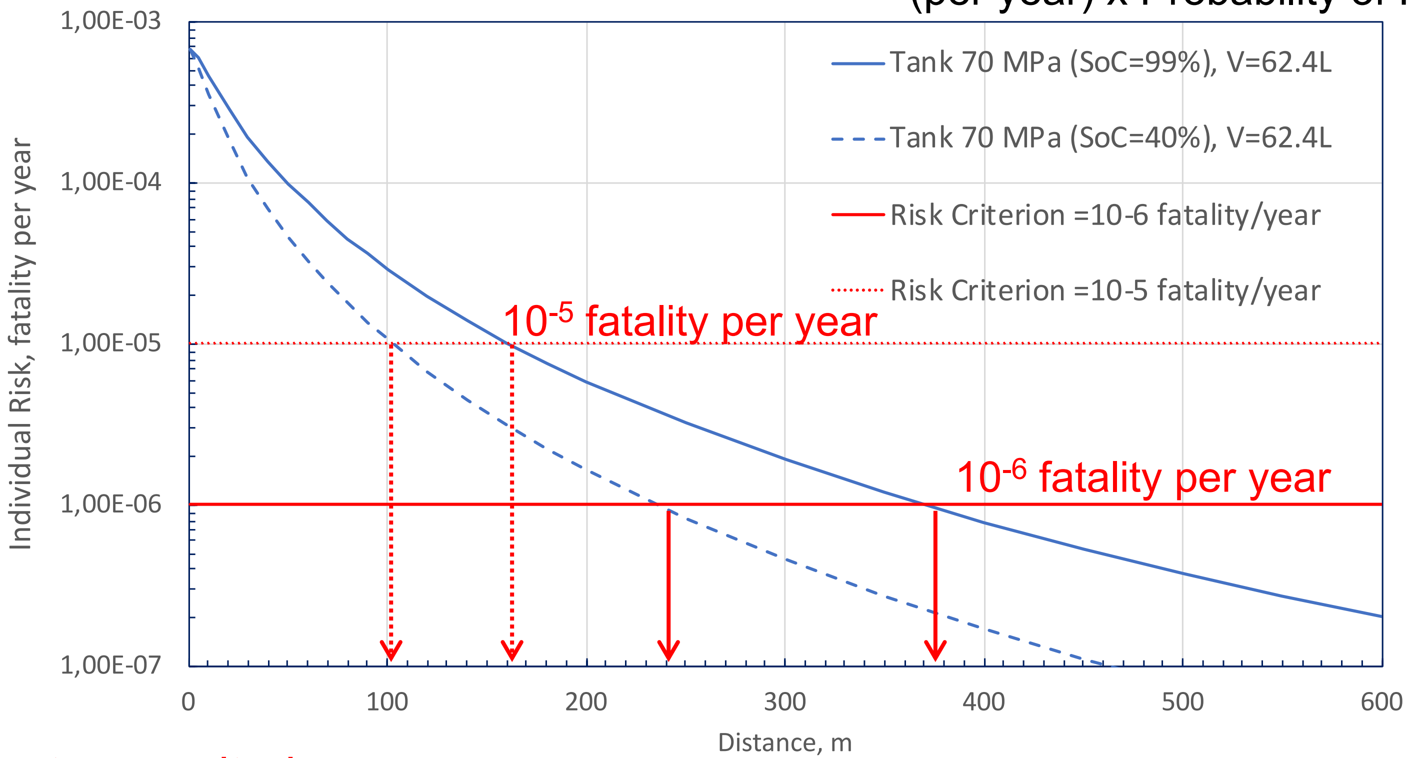
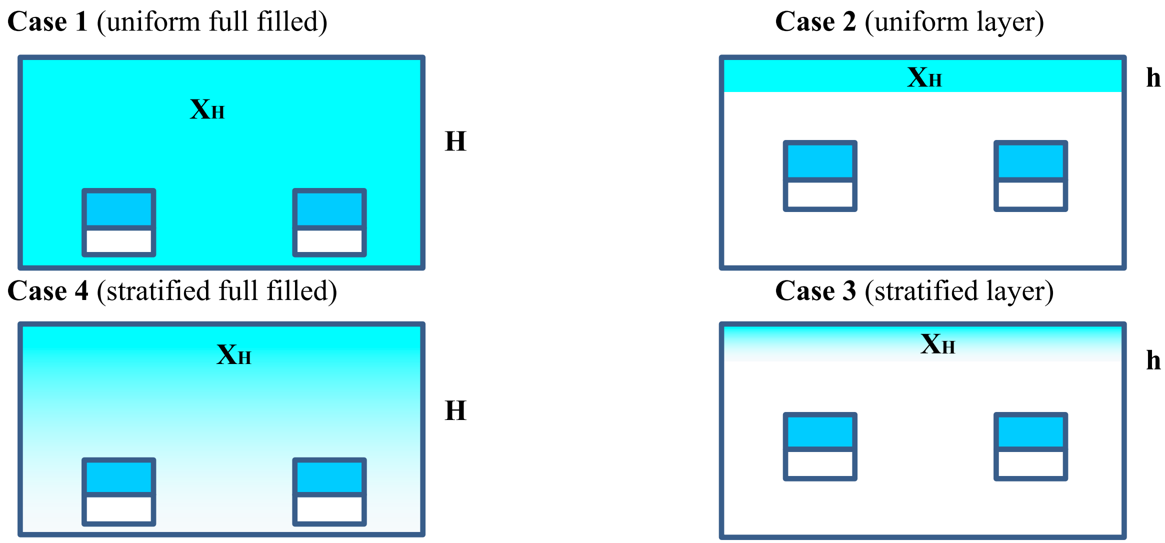
IR = Frequency of tank Rupture (per year) x Probability of Fatality



Risk acceptance criterion

10^{-6} fatality per year	• 375 m for SoC=100% • 240 m for SoC=40%	• 52 cars for each lane ->208 fatalities • 33 cars for each lane -> 132 fatalities
10^{-5} fatality per year	• 160 m for SoC=100% • 100 m for SoC=40%	• 22 cars for each lane ->88 fatalities • 14 cars for each lane -> 56 fatalities

DDT modeling results



Short release time

Longer release time

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

- 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

Conclusions

- The new QRA methodology is based on a detailed analysis of the incident scenarios that are unique for hydrogen vehicles.
- Catastrophic tank rupture and deflagration of flammable cloud under the ceiling and eventual DDT are considered in terms of both frequency of such events and their consequences.
- The difficulties in ETA for emerging technologies is a lack of statistics, failure rates and probabilities that make QRA uncertainty very high.
- Thus, the priority at the initial stages of technology implementation should be given to the development of inherently safer engineering solutions that are rather supported than substituted by risk analysis.
- An option could be the emerging safety technology of self-venting TPRD-less tanks working on the microleaks-no-burst concept 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.

tunnel HP

Clean Hydrogen Partnership

Acknowledgements

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Ulster University · KIT Karlsruher Institut für Technologie · USN Universitetet i Sørøst-Norge · HSE Health & Safety Executive · DTU Technical University of Denmark · Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón · ifa International Fire Academy · Sapienza Università di Roma · NEN · ibz · cea · Pro-Science

Probability of TPRD failure to open

P = 0.03

- Failure rates of TPRD statistics are not available.
- Assuming a Jeffrey's beta prior distribution, the data in Table 2 results in a Beta (0.5, 16.5) distribution
- TPRD failure probability (0.03) is obtained as mean of the beta distribution (0.5, 16.5)

Table 2
Summary of TPRD Operations in Hydrogen Tank Fire Experiments [20-24]

Source	TPRD demands	TPRD operation
Yamazaki	2	2
Suzuki	4	4
Zheng	1	1
Wyandt	6	6
Sekine	3	3

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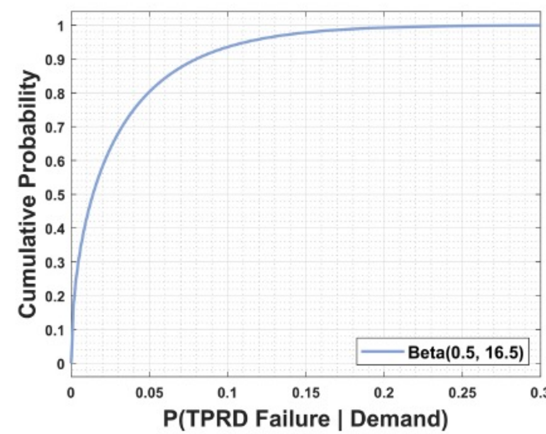

Figure 8. Uncertainty distribution on the probability that a TPRD will fail to operate on demand.

B.D. Ehrhart, D. M. Brooks, A. B. Muna and C. B. LaFleur
Fire Technology 2020 https://doi.org/10.1007/s10694-019-00910-z

Tank rupture

Blast wave effects

- 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).

DDT modeling

Simulation conditions

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	-

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

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

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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.
- 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