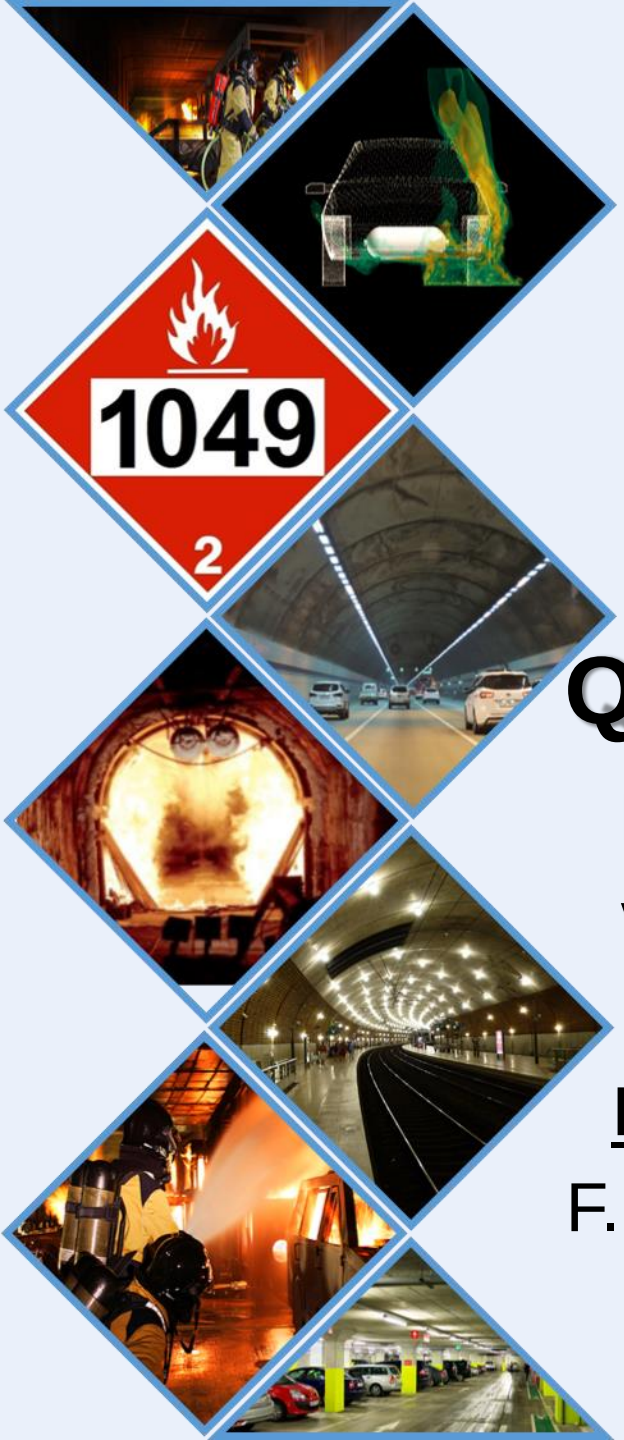

HyTunnel-CS dissemination conference
14-15 July 2022, Brussels, Belgium

Quantitative risk assessment methodology for hydrogen vehicles in confined space

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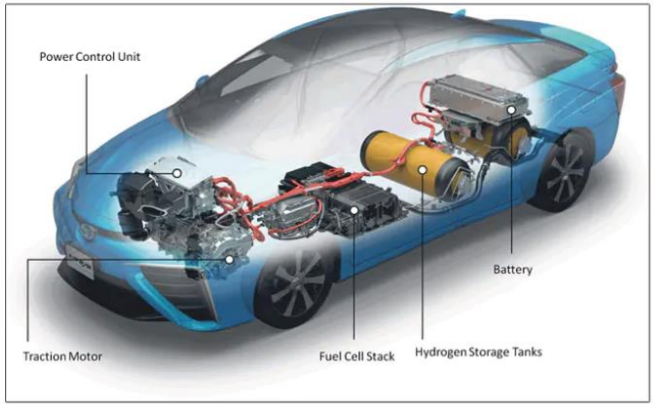
F. Markert (Danmarks Tekniske Universitet)

Clean Hydrogen Partnership
Co-funded by the European Union

Quantitive risk assessment

Objective

- It is necessary to ensure that the traffic infrastructures are able to withstand the specific risks that may arise from these new technologies.
- A quantitative risk assessment is developed to estimate the risk level associated with hazardous events scenarios related to H_2 vehicles.
- The likelihood and consequences of hazardous events in confined spaces is evaluated and the findings are expressed as risk to people and structures.



QRA

Literature review

- Literature review revealed a few risk assessment models and tools, but either :

➢ they do not include hydrogen as a dangerous substance

➢ or the “low frequency – high consequence” events are not analysed

- In Europe, the PIARC approach is widespread, and it has been 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.

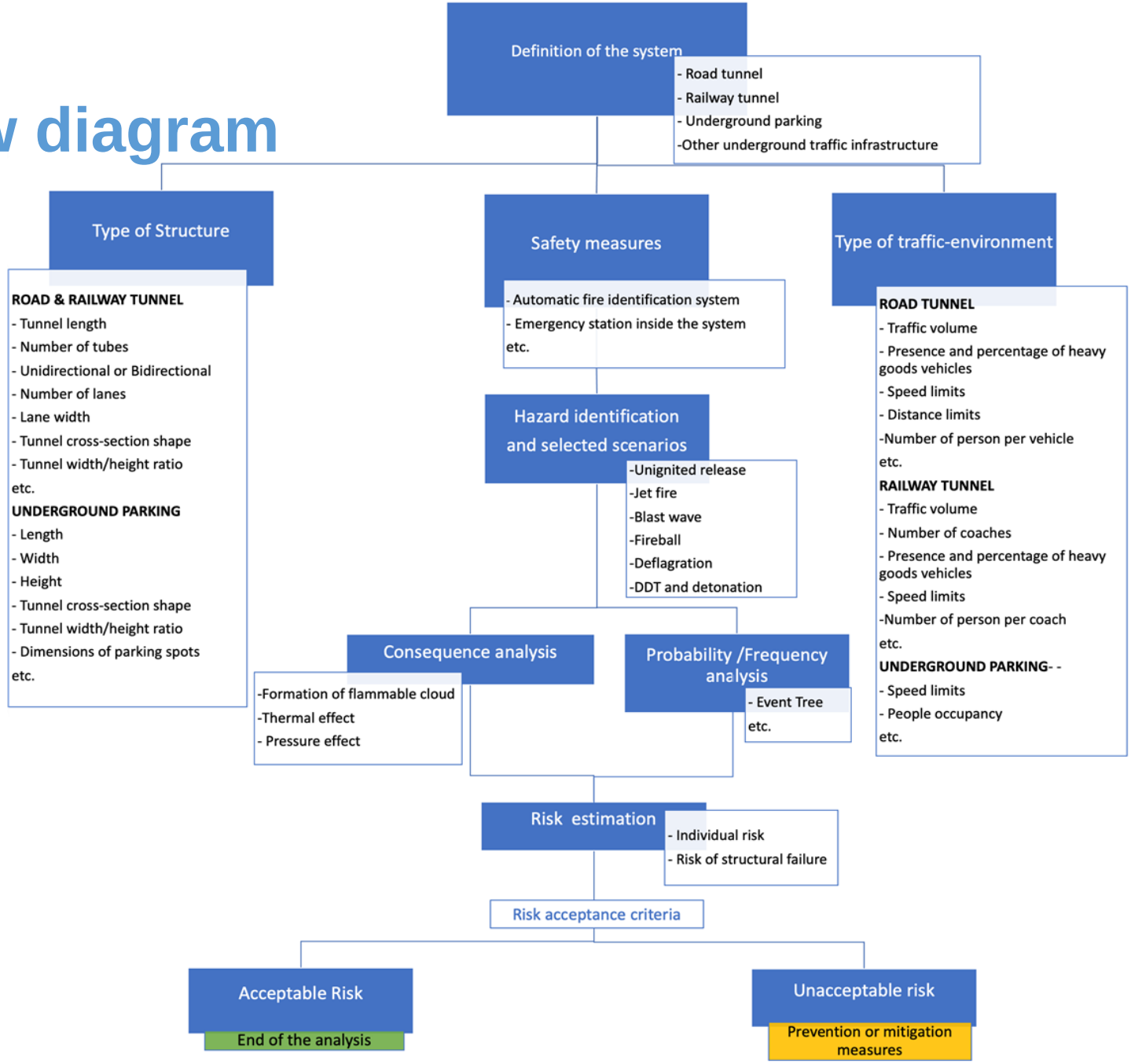
QRA

The new methodology for H_2 vehicles

- The QRA methodology for “quantitative tunnel and car park risk analysis” is an analytic method that fundamentally is facilitating to find the answers to the following main questions:

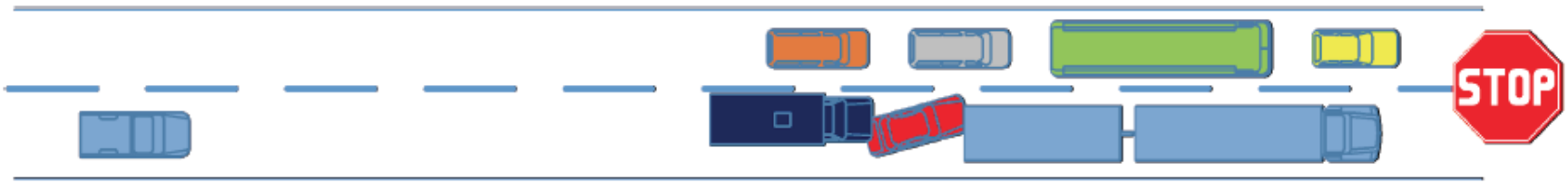
- What could happen inside the system?
- What is the probability of occurrence of the event?
- Having established that the event occurs, what are its possible consequences?

QRA
The flow diagram



Hazard Identification

Initiating event



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

Selected Scenarios

Event chain in the Event tree

Unignited scenarios:

- 1. Unignited hydrogen release and dispersion in a confined space with mechanical ventilation
- 2. Unignited hydrogen release in confined spaces with limited ventilation
- 3. Unignited hydrogen release in a tunnel with natural/mechanical ventilation

B G

Immediate ignition scenarios:

- 4. Hydrogen jet fire in confined spaces with limited ventilation -> garages are not considered
- 5. Hydrogen jet fire and vehicle fire in a mechanically ventilated confined space (maintenance shop/ underground parking)
- 6. Hydrogen jet fire impingement on a tunnel
- 7. Hydrogen jet fire and vehicle fire in a tunnel
- 8. Fire spread in underground parking

C H J

Burst scenario

- 9. Hydrogen storage vessel rupture in a tunnel

F

Delayed ignition scenario

- 10. Hydrogen storage vessel blowdown with delayed ignition in a tunnel

I

Probability analysis

Event tree

- Does the accident cause a post-crash fire?
- Is H_2 released from the system?
- Is H_2 released by the TPRD?
- Is the fire extinguished on time?
- Is the H_2 ignited?
- Is the H_2 ignition delayed?

Event tree

Initiating Event								
Tunnel accident per million vehicle km	**Does the accident cause a fire post crash?**	**Is H2 released from the system?**	**Is the fire extinguished on time?**	**Is H2 released from the TPRD?**	**Does the H2 ignite?**	**Does the H2 ignition is delayed ?**	**Event chain**	**Consequences**
							A	**No H2 is released**
		no H2 released						
	no fire						**B**	**H2 is released but is not ignited**
					no ignition			
		H2 released					**C**	**Jet fire**
						immediate		
					ignition		**D**	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
						delayed		
Crash in tunnel								
							E	**No H2 is released**
			yes					
		no H2 released					**F**	**Catastrophic rupture of the H2 tank->blast wave, fireball and projectiles**
				TRPD failure to open				
			no					
							G	**H2 is released but is not ignited**
					no ignition			
				TRPD activation			**H**	**Jet fire**
						immediate		
					ignition		**I**	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
	fire					delayed		
							j	**Jet fire**
						immediate		
		H2 released			ignition		**K**	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
						delayed		

Probability analysis

Tunnel crash rate

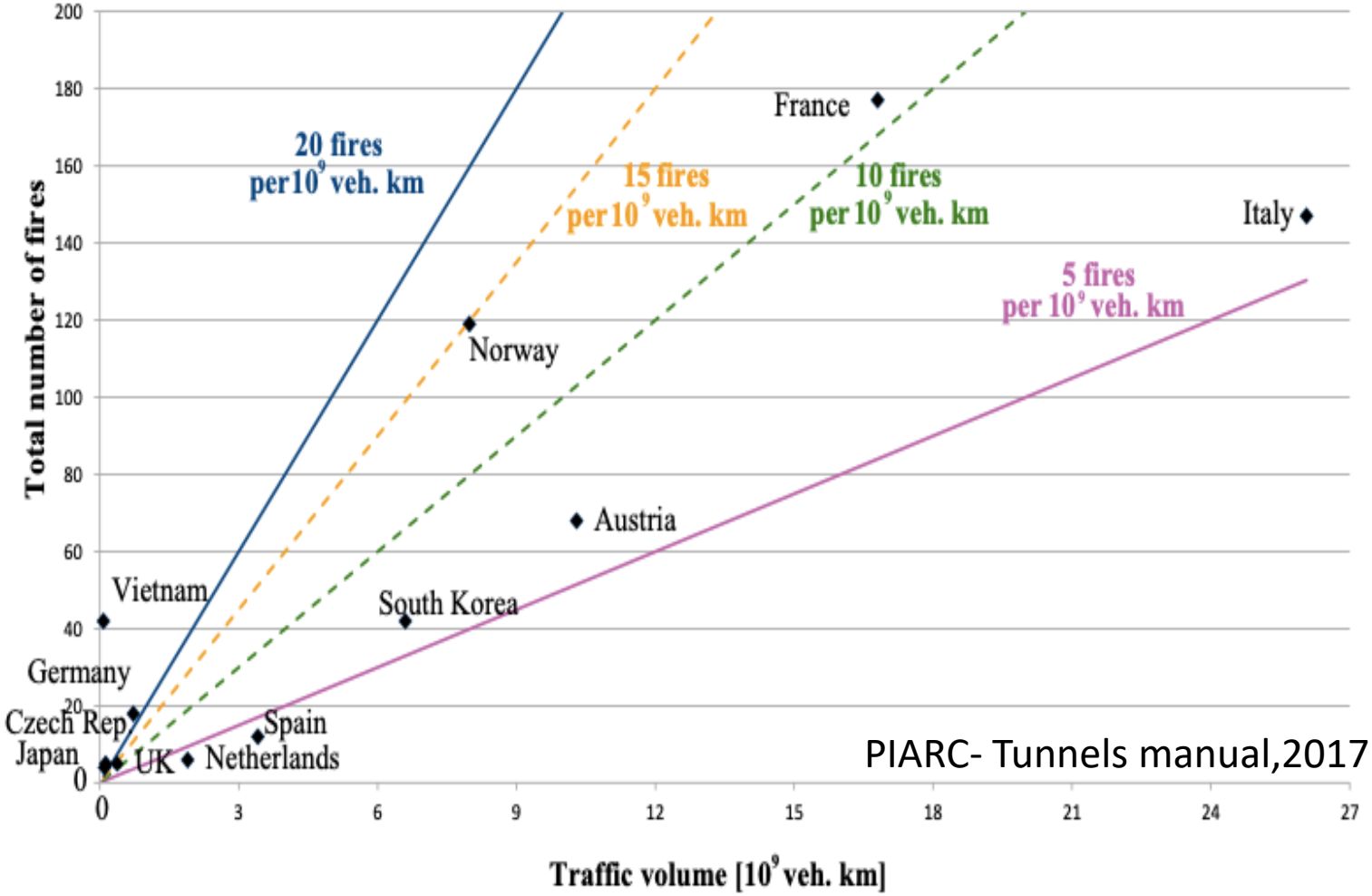
ANAS, 2009

Accidents with material damage only	Rate per million vehicles-km
Urban Tunnels	from 0.40 to 1.50
Motorway Tunnels	from 0.30 to 0.80
Accidents with people damage	
Urban Tunnels	from 0.10 to 0.50
Motorway Tunnels	from 0 to 0.15

Italy: 0.46 crashes per million vehicle-km

Probability analysis

Vehicle Fire Rate in tunnels



PIARC- Tunnels manual,2017

Italy: 0.005 fires per million vehicle-km

Probability analysis

Probability of H_2 release post-crash

P =0.10

- 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.
- Sandia used a gamma distribution conjugate (Jeffreys) prior to account for a half of an event (0.5).
- 10% probability of a release

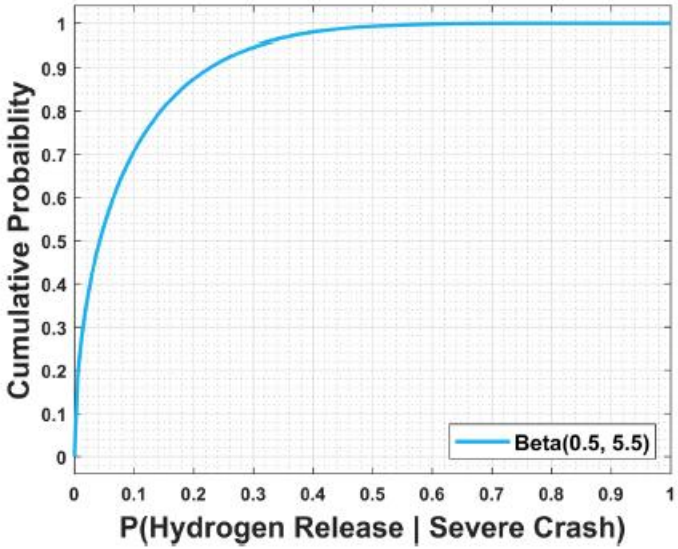
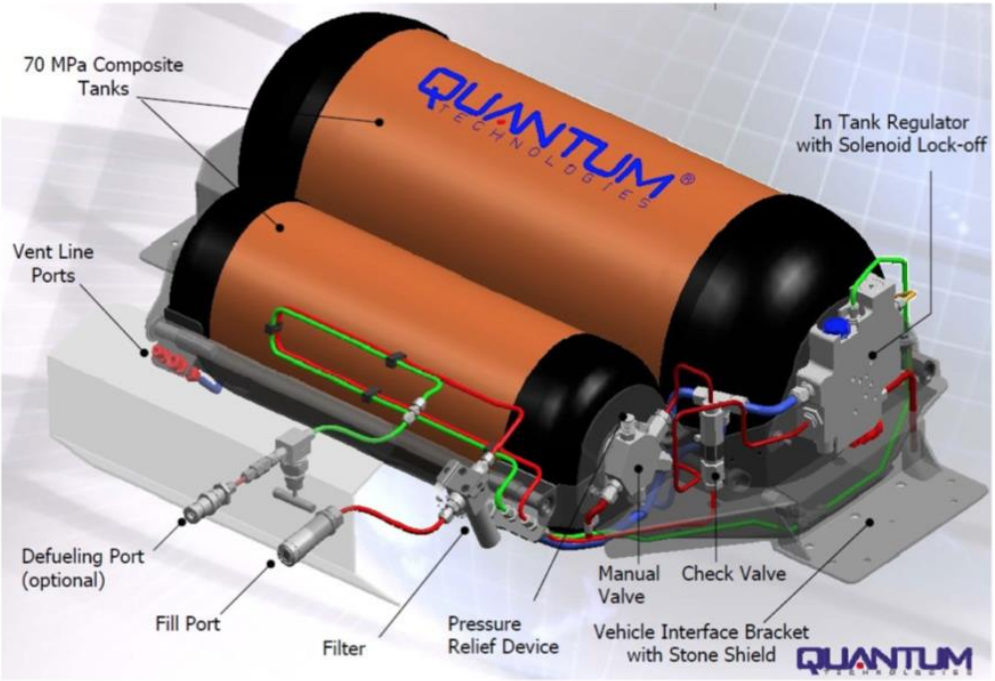
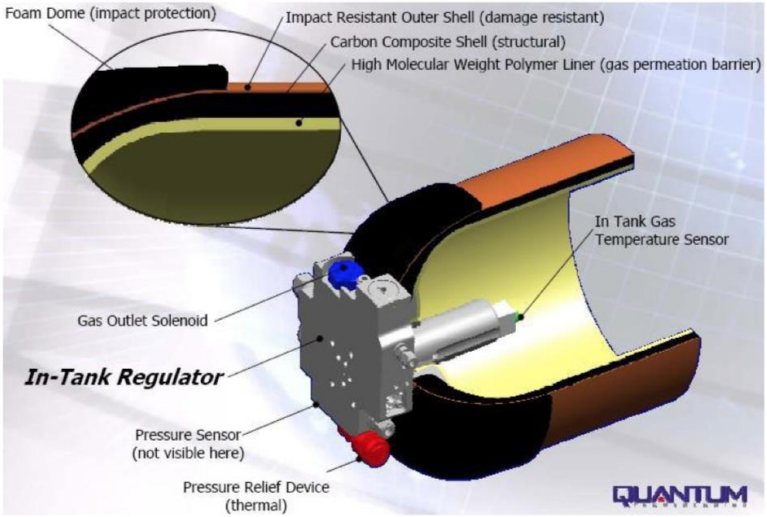


Figure 6. Uncertainty distribution on the probability that a crash results in hydrogen release.

Sandia Report - Sand2017-11157

H_2 TANK IV

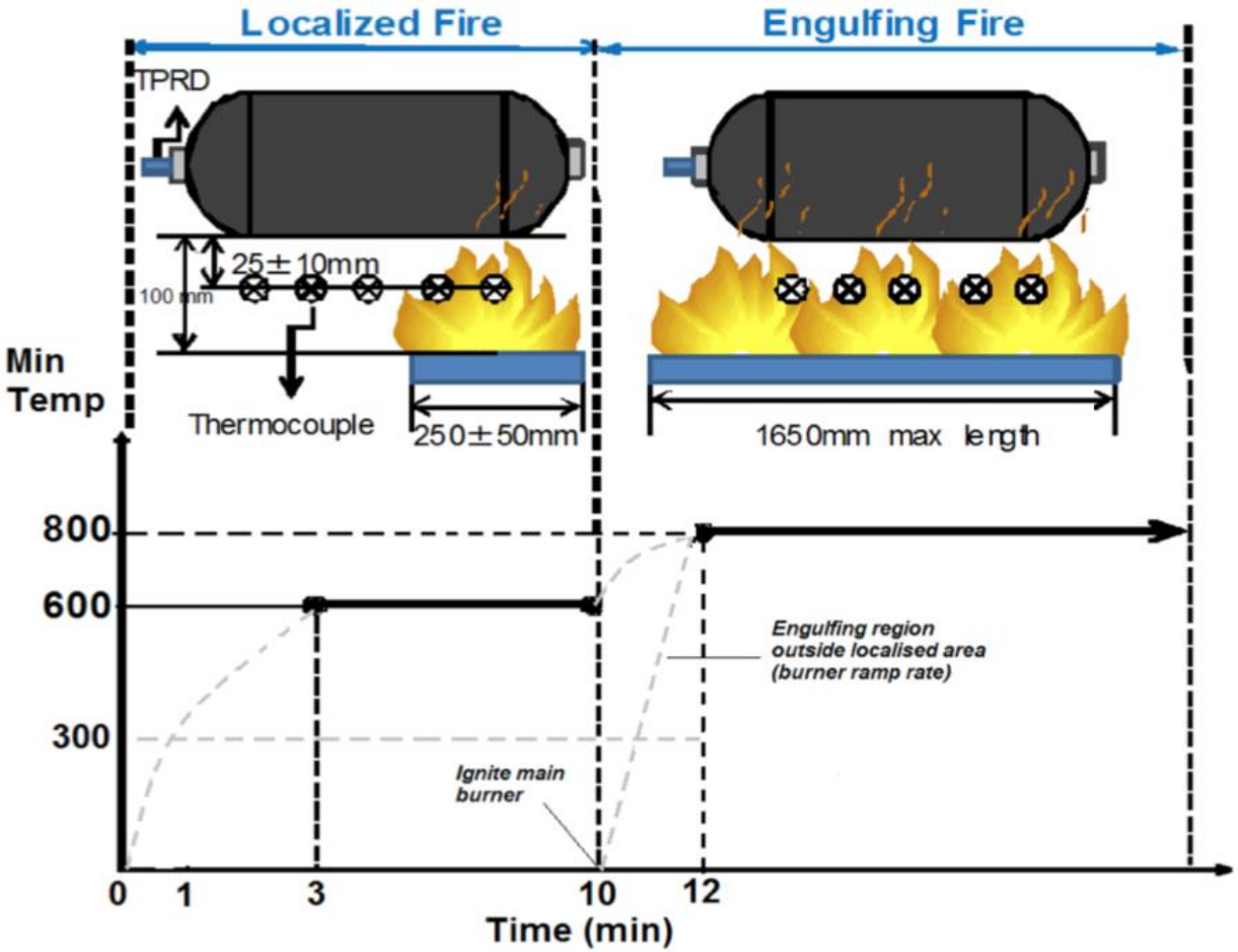




- *Thermally Activated Pressure Relief Device (TPRD)* provides a controlled release of the gaseous hydrogen GH2 from a high pressure storage container before its walls are weakened by high temperatures, leading to a *catastrophic rupture*.

Localised and Engulfing fire

BONFIRE TEST



Probability of TPRD failure

Engulfing fire

$P = 6.04 \times 10^{-3}$

- Failure rate of TPRD statistics are not available.
- Value for the random mechanical failure probability of pressure relief device (PRD) are proposed in the literature.
- FireComp project considered a failure probability of TPRD of 6.04×10^{-3}.

Probability of TPRD failure

Localised fire

P = 0.03

- Failure rate of TPRD statistics are not available.
- Sandia suggested a value for TPRD failure probability (0.03) obtained as average 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

Assuming a Jeffrey's beta prior distribution, the data in Table 2 results in a Beta(0.5, 16.5) distribution

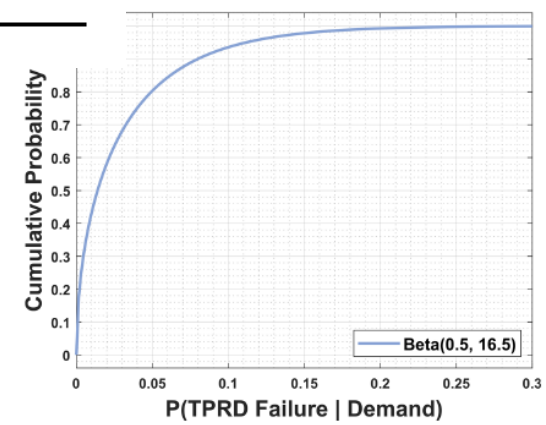


Figure 8. Uncertainty distribution on the probability that a TPRD will fail to operate on demand.

B.D. Ehrhart, D. M. Brooks, A. B. Muna and C. B. LaFleur
Fire Technology 2019 https://doi.org/10.1007/s10694-019-00910-z

Probability of TPRD failure

Reviews of accidents

- *"Reviews of the accident literature on the CNG and H_2 composite cylinder showed that the cause of accidental burst of cylinders was mainly a localized fire or a wrong design of the size of the TPRD orifice.*
- *Then, overpressure and fragments from the burst cylinder could have catastrophic consequences."*

Ruban et al., 2012

Probability analysis

Probability of fire extinguishment

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%

Fire resistane rating = 8min

Nigel Casey - - Fire incident data for Australian road tunnels - Fire Safety Journal 111 (2020) 102909

Probability analysis

Probability of H_2 ignition

P = 0.08 for car
P=0.2 for bus/train

TPRD diameter (mm)	Initial mass flow rates (kg/s), for:	
	Car (700 bar tank)	Bus/train (350 bar tank)
0.5	0.0067	0.0038
1	0.0268	0.0150
2	0.1072	0.0601
3	0.2412	0.1353
4	0.4289	0.2405
5	0.6701	0.3757
6	0.9649	0.5410

car

Bus/train

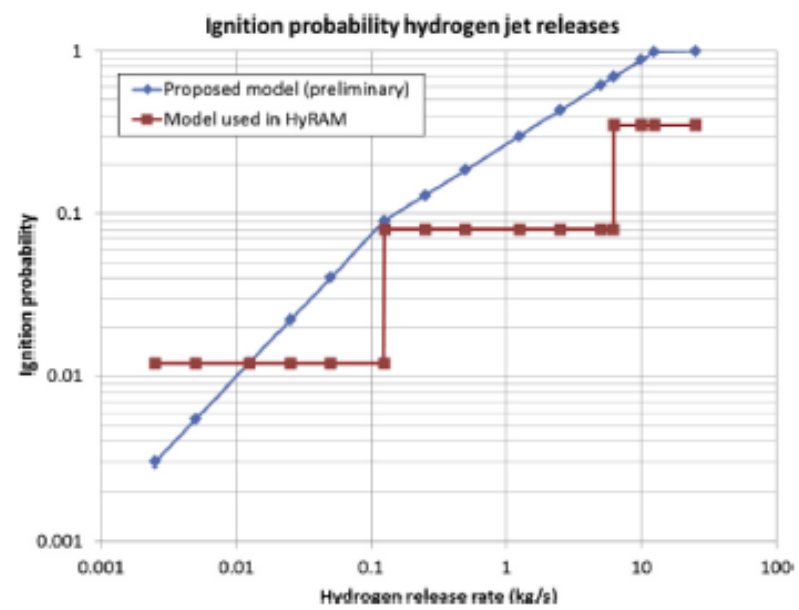


Fig. 3 – Proposed ignition probability for hydrogen jet releases, compared to HyRAM model proposed in [19].

F. G. Aarskog , O.R. Hansen, T. Strømgren, Ø. Ulleberg, IJHE 45(2020) 1359-1372

Probability analysis

Probability of immediate ignition

P = 0.667

- 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%.

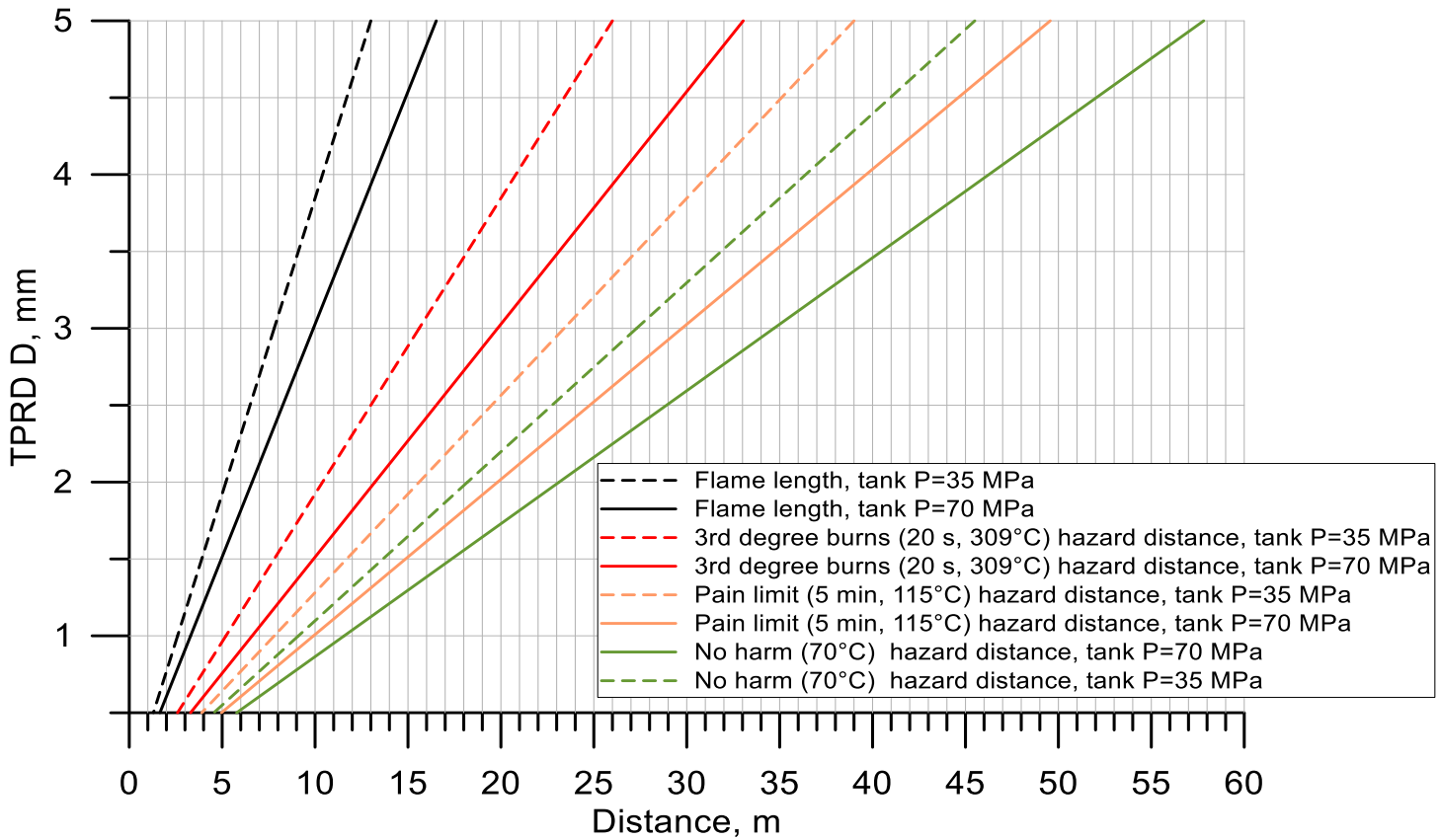
Table 2: Hydrogen ignition probabilities.

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

Sandia Report - Sand2017-11157

Consequence analysis

Jet fire



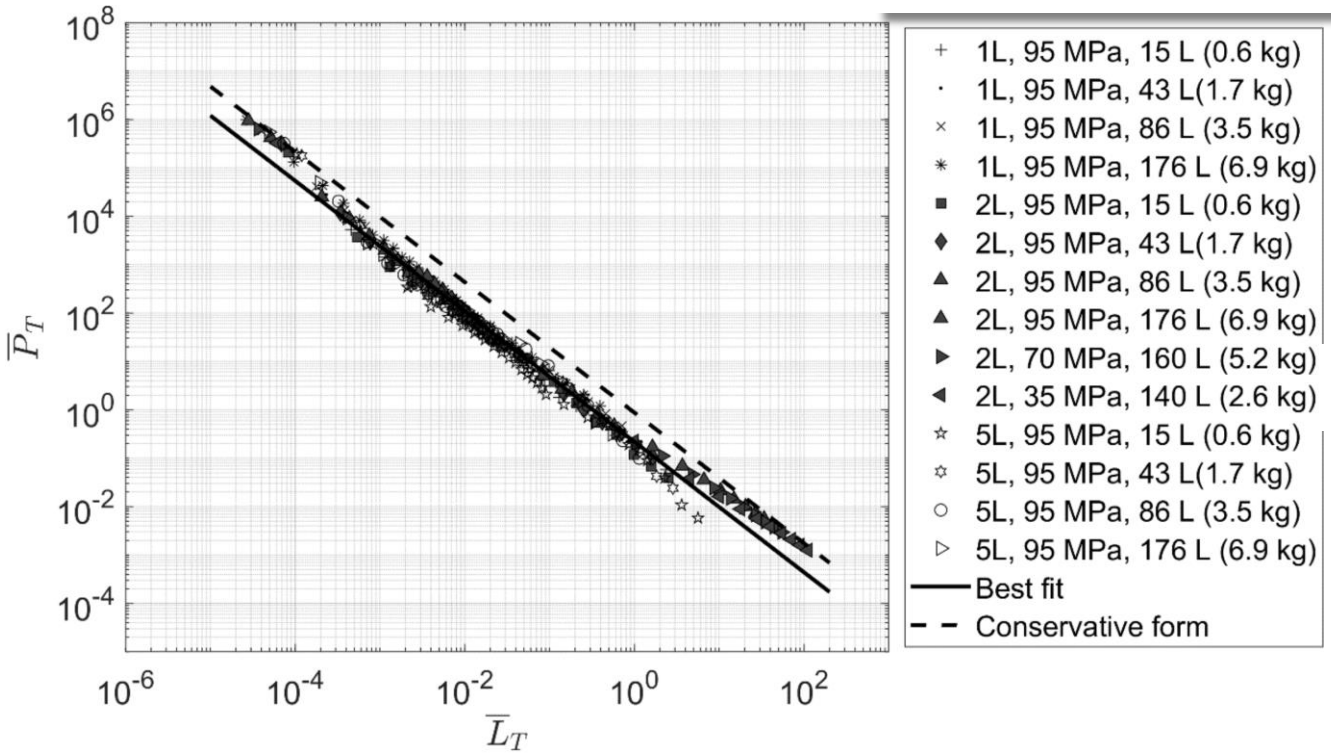
- Calculations of flame lengths and three hazard distances for free hydrogen jet fires, (“E-Laboratory”; Molkov, 2012)

Consequence analysis

Blast wave decay in a tunnel

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

$$\Delta P = P0 * \overline{P} = P0 * 0{,}22 * \left(\frac{P0\ L\ P}{4\ E\ AR^{0{,}5}} * f\ L\right) \wedge -0{,}35$$



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

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

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

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

Consequence analysis

DDT potential

- A tool for the assesment of a detonation case is here taken into account (developed by 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.

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.

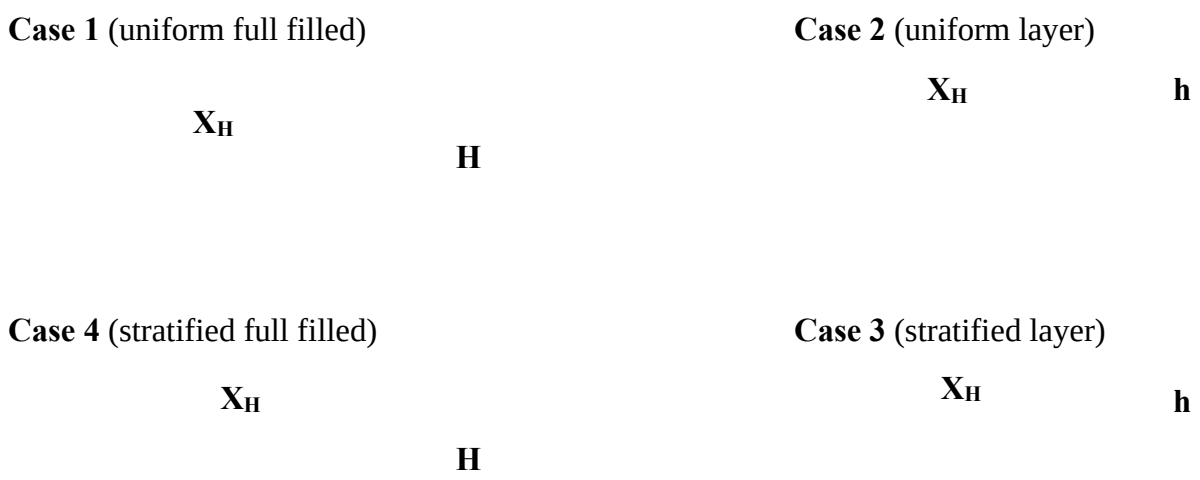


Figure 1`. Hydrogen distribution profiles in a tunnel.

Overpressure Hazard

Probit function for harm to people and structural damage

Death due to lung hemorrhage

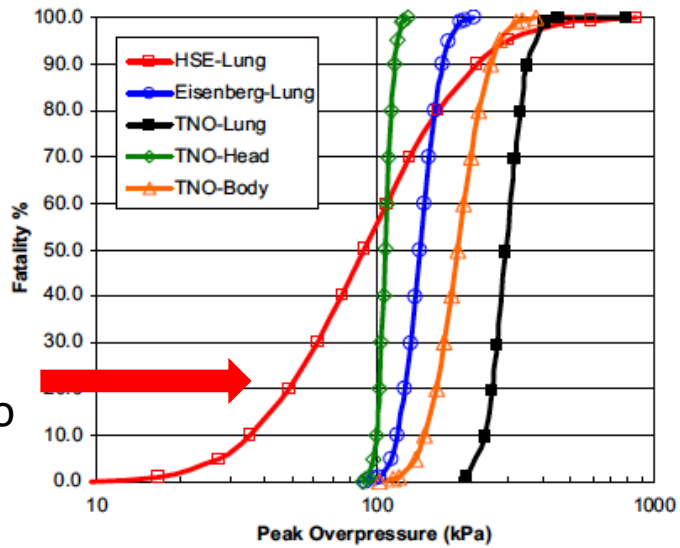


Fig. 2 – Comparison of overpressure probit functions for harm to people.

Structural damage

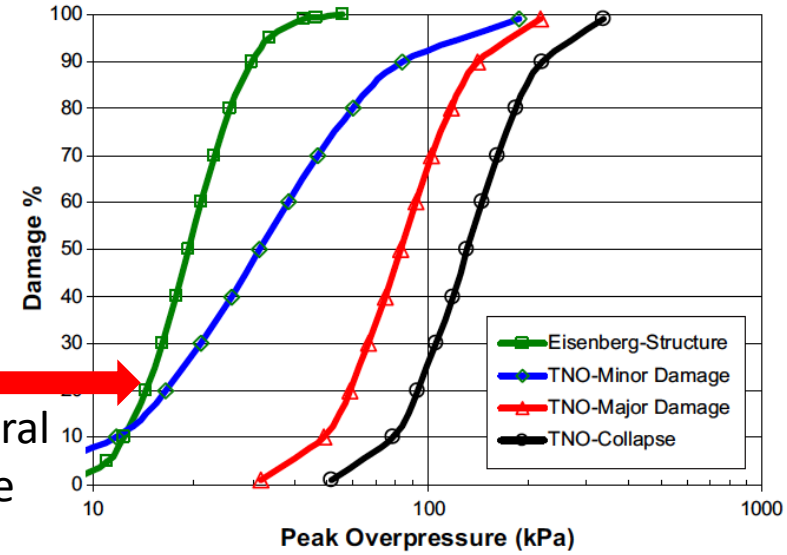


Fig. 4 – Comparison of structural damage probit functions.

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

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.

Case study

Road tunnel: Varano (IT)

- L=1.2 km
- Bi-directional road tunnel
- Two lanes (3.75 m wide) one for each traffic direction.
- Rectangular cross section: W=10.5 m, H=5.5 m

Case study

Rail tunnel : Severn (UK)

- L=7.012 km
- Double bore, 2 tracks
- W=7.9 m, H=6.1 m

References:

M. Lipscomb, Northern Trains Ltd., Private communication, 2021.

https://en.wikipedia.org/wiki/Severn_Tunnel

https://www.networkrailmediacentre.co.uk/news/the-130-year-old-severn-tunnel-to-close-for-six-weeks-for-essential-railway-upgrade

Case study

Underground car park: Århus (DK)

- Underground Danish car park prismet in the town Århus
- area of 2144 m^2
- 58 parking slots
- parking efficiency P = 37 m^2/car

Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 826193. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.