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

QRA of hydrogen trains in rail tunnels

P. Russo (Sapienza University)

Clean Hydrogen Partnership

Co-funded by the European Union

Case study

Rail tunnel : Severn (UK)

- L=7.012 km
- Double bore, 2 tracks
- Horse cross section: 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

Rail tunnel: Severn (UK)

- The annual average daily traffic (AADT) is 350 trains per day for each traffic direction
- train length three cars
- 64 m long
- passenger occupancy is around 148 passengers per train
- at peak times the maximum passenger load is 304 passengers

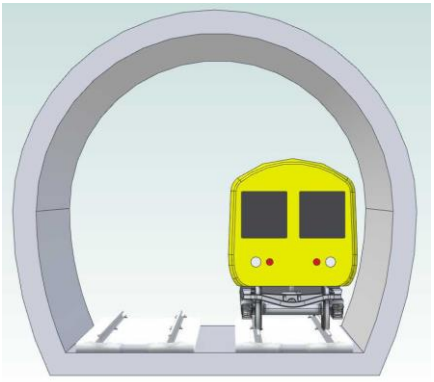
References:
M. Lipscomb, Northern Trains Ltd., Private communication, 2021.

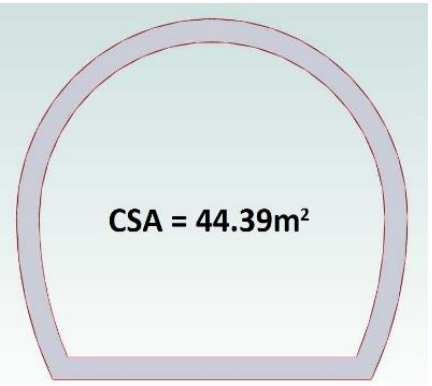
Case study

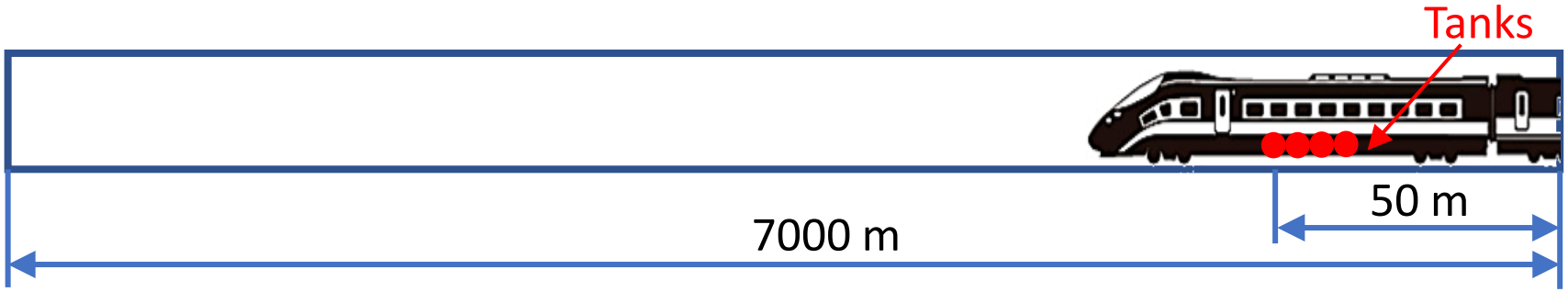
Rail tunnel scenario

Assumptions:

- Tank V=160 L NWP=35 MPa
- 1 tank explodes
- FCEV is located 50 m from the tunnel entrance







References: *M. Lipscomb, Northern Trains Ltd., Private communication, 2021.*
S. Ring, Alstom, Private communication, 2021.

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**
Crash in tunnel	no fire	no H2 released					A	**No H2 is released**
		H2 released			no ignition		B	**H2 is released but is not ignited**
					ignition	immediate	C	**Jet fire**
						delayed	D	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
	fire	no H2 released	yes				E	**No H2 is released**
			no	TRPD failure to open			F	**Catastrophic rupture of the H2 tank->blast wave, fireball and projectiles**
		H2 released		TRPD activation	no ignition		G	**H2 is released but is not ignited**
					ignition	immediate	H	**Jet fire**
						delayed	I	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
							j	**Jet fire**
						immediate	K	**Deflagration of turbulent jet and possible deflagration of cloud under the ceiling**
						delayed		

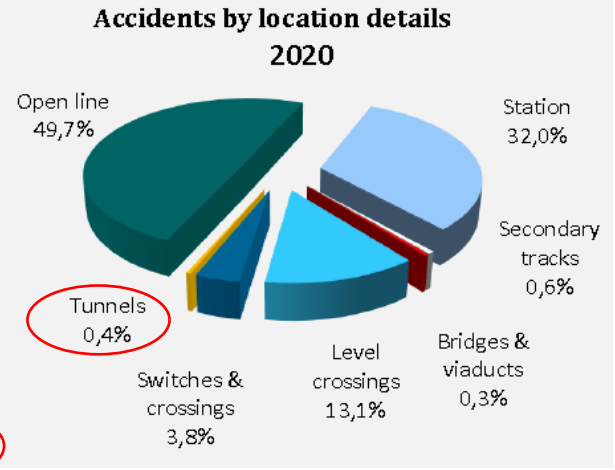
Probability analysis

Statics for railway tunnels from International Union of Railways (UIC)

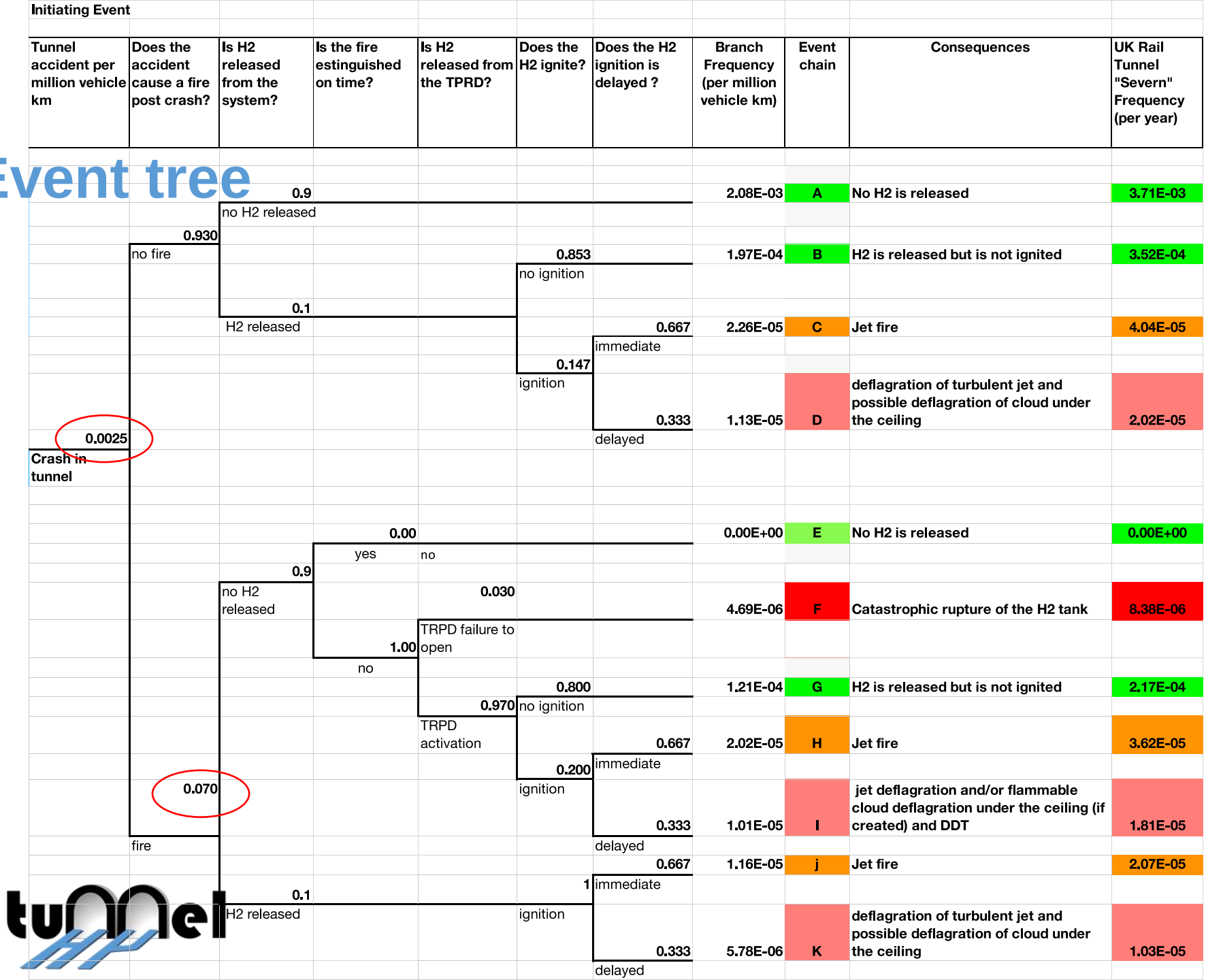
- In 2020 an average accident rate of 0.62 per million train-km is reported for a total number of 6122 per million train-km, but only 0.4% of the accident occurred in tunnels, hence a tunnel accident rate of **2.5×10^{-3} per million train-km** is calculated.

- The probability that an accident in tunnels results in a **fire** is **7%**, i.e. 1 fire in 14 incidents in tunnels (UIC, 2021).

ALL RAILWAYS	2015	2016	2017	2018	2019	2020
Number of significant accidents	1926	2006	1971	4 246	4 187	3 781
Significant accidents per million train-km	0,42	0,43	0,42	0,66	0,63	0,62
Number of accidents with victims	1584	1718	1 688	3 920	3 851	3 435
Accidents with victims per million train-km	0,35	0,37	0,36	0,61	0,58	0,56
Number of victims	1803	2119	1919	4 319	4 137	3 670
Victims per million train-km	0,39	0,46	0,41	0,67	0,62	0,60
Number of fatalities	1029	1181	1086	2 687	2 608	2 329
Fatalities per million train-km	0,22	0,26	0,23	0,42	0,39	0,38
Number of million train-kilometres	4580	4 617	4731	6 399	6 631	6122



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 estinguished on time?
Is H2 released from the TPRD?
Does the H2 ignite?
Does the H2 ignition is delayed ?
Branch Frequency (per million vehicle km)
Event chain
Consequences
UK Rail Tunnel "Severn" Frequency (per year)
0.0025
Crash in tunnel
0.930
no fire
0.070
fire
0.9
no H2 released
0.1
H2 released
0.9
no H2 released
0.1
H2 released
0.00
yes
1.00
no
no
0.030
TRPD failure to open
0.970
TRPD activation
0.853
no ignition
0.147
ignition
0.800
no ignition
0.200
ignition
1
ignition
0.667
immediate
0.333
delayed
0.667
immediate
0.333
delayed
0.667
immediate
0.333
delayed
2.08E-03
A
No H2 is released
3.71E-03
1.97E-04
B
H2 is released but is not ignited
3.52E-04
2.26E-05
C
Jet fire
4.04E-05
1.13E-05
D
deflagration of turbulent jet and possible deflagration of cloud under the ceiling
2.02E-05
0.00E+00
E
No H2 is released
0.00E+00
4.69E-06
F
Catastrophic rupture of the H2 tank
8.38E-06
1.21E-04
G
H2 is released but is not ignited
2.17E-04
2.02E-05
H
Jet fire
3.62E-05
1.01E-05
I
jet deflagration and/or flammable cloud deflagration under the ceiling (if created) and DDT
1.81E-05
1.16E-05
j
Jet fire
2.07E-05
5.78E-06
K
deflagration of turbulent jet and possible deflagration of cloud under the ceiling
1.03E-05

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

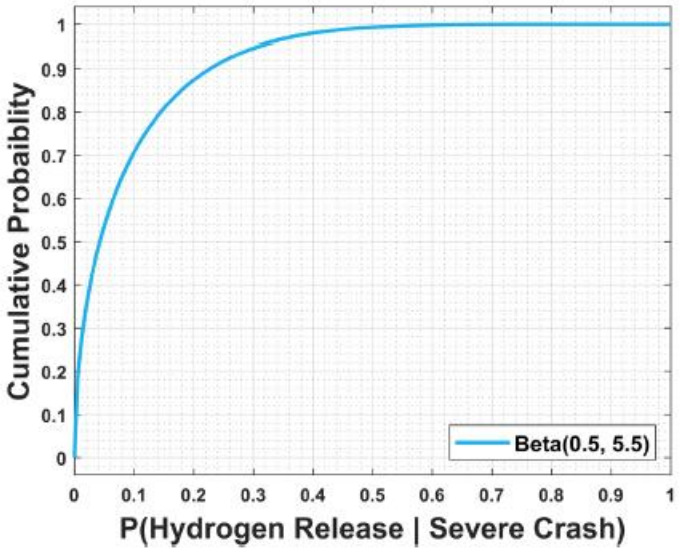


Figure 6. Uncertainty distribution on the probability that a crash results in hydrogen release.

Sandia Report - Sand2017-11157

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

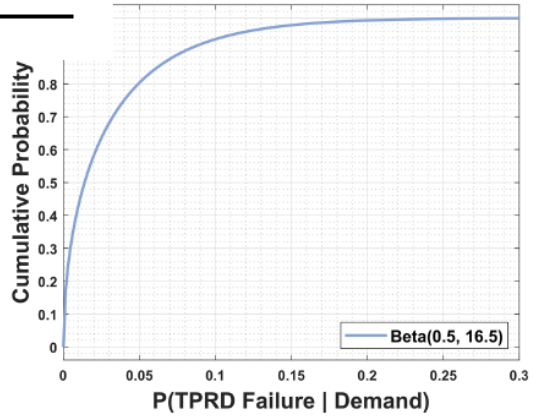


Figure 8. Uncertainty distribution on the probability that a TPRD will fail to operate on demand.

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 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

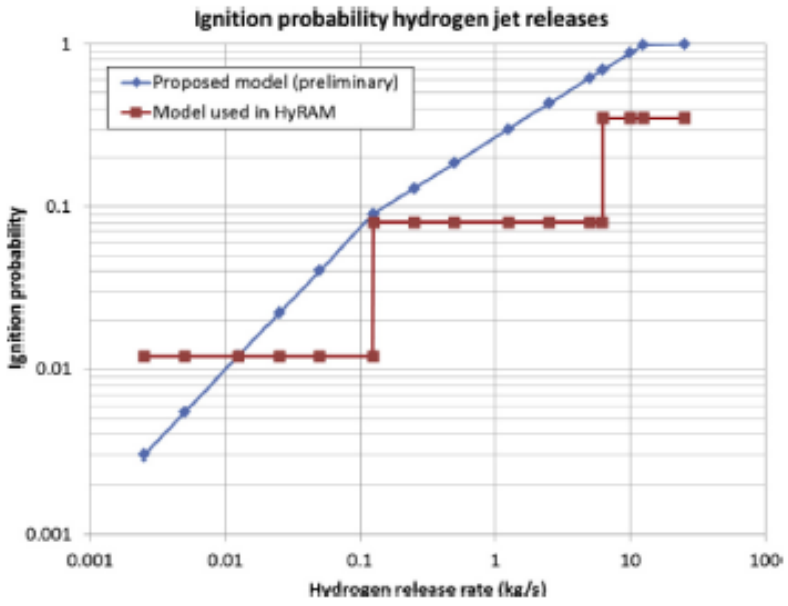


Fig. 3 – Proposed ignition probability for hydrogen jet releases, compared to HyRAM model proposed in [19].

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

Probability analysis

Probability of immediate ignition

P = 0.667

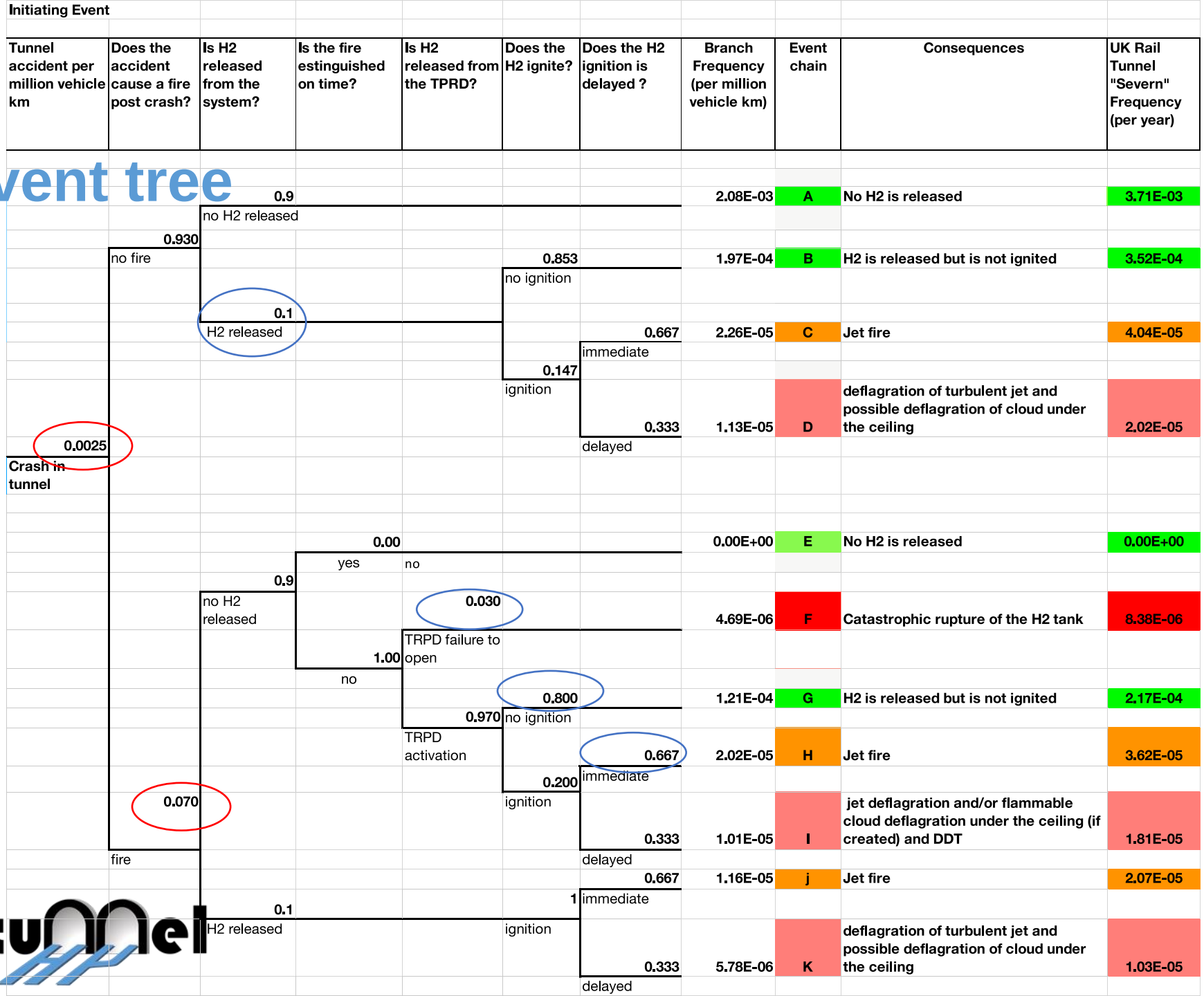
- The probability of an **immediate ignition** (given that an ignition will occur) is 66.67%, and the complimentary probability of delayed ignition is 33.33%.

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

Event tree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5.78E-06
K
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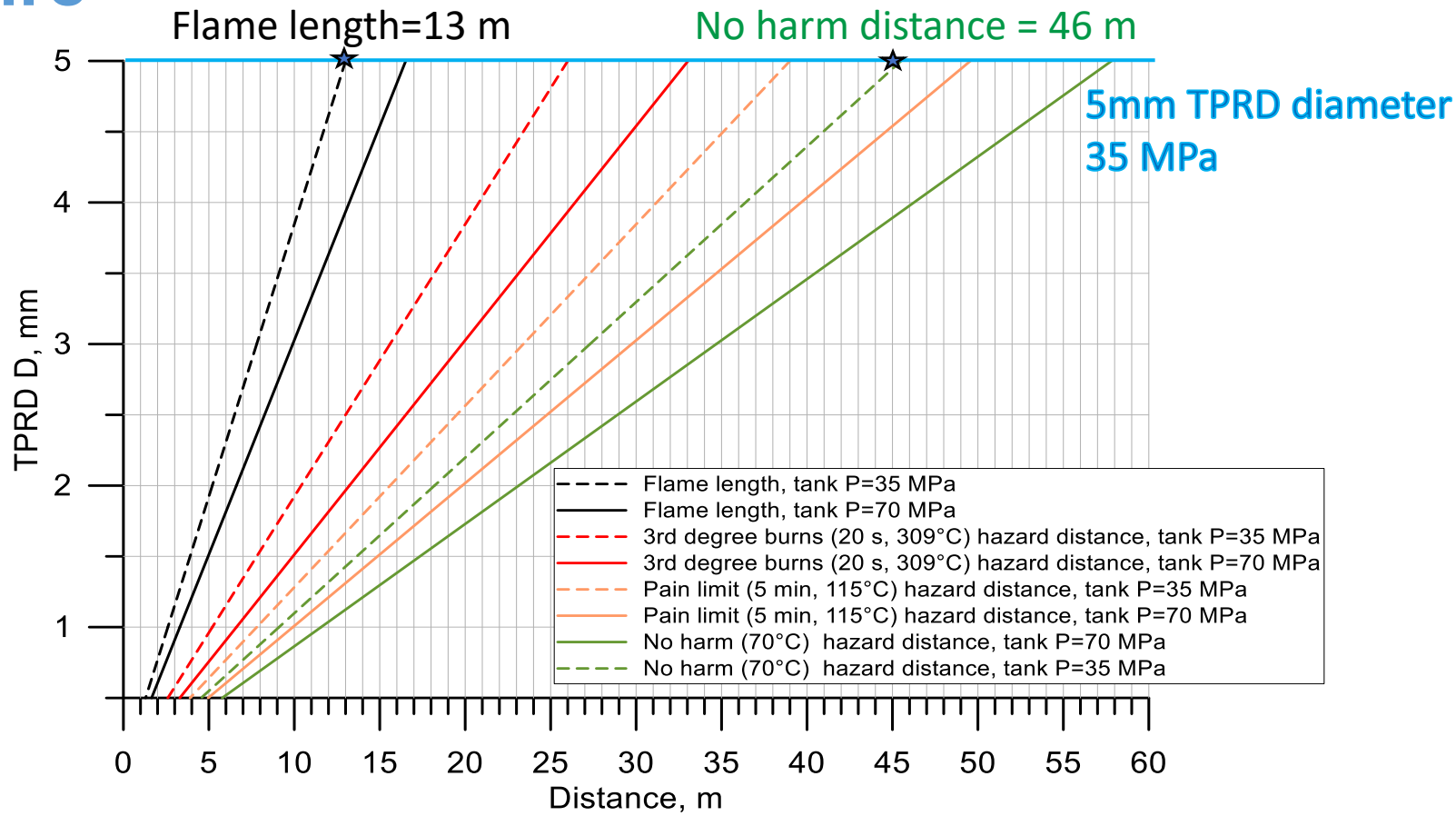
Example of Railway tunnel

Jet fire



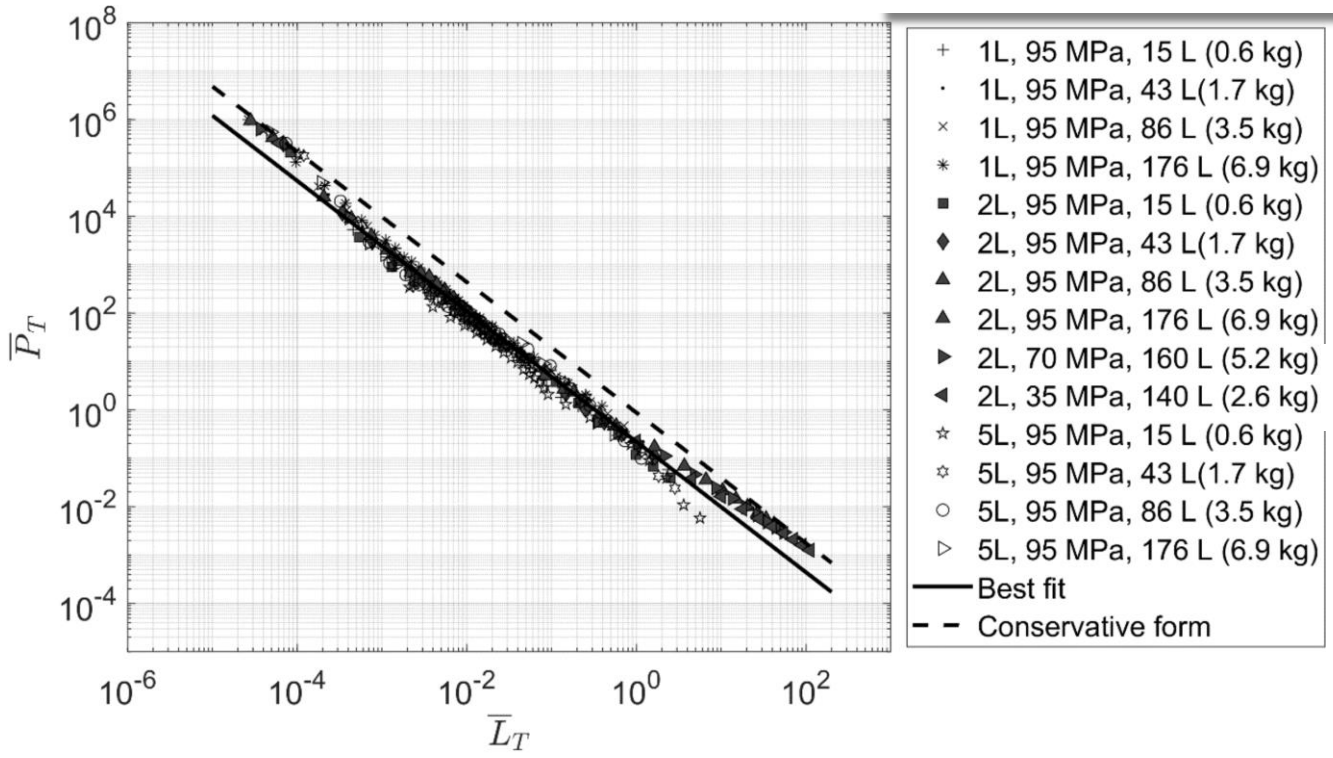
- Calculations of flame lengths and three hazard distances for free hydrogen jet fires, (“E-Laboratory”; Molkov, 2012)

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).

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



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

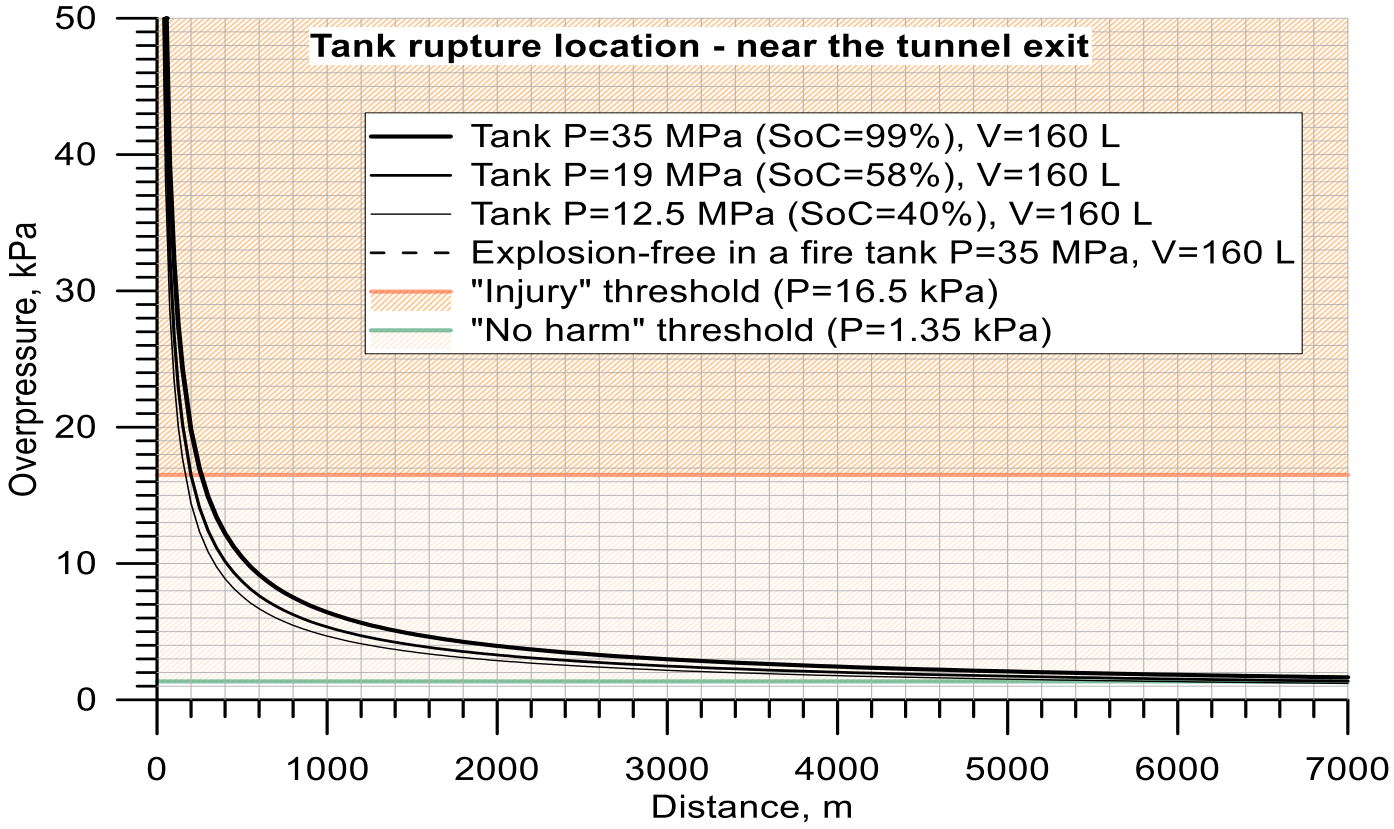
$$\overline{L_T} = \frac{P_0 L A_T}{E \cdot AR^{0.5}} \left(\frac{fL}{D_T}\right).$$

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

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

Example of Railway tunnel

Blast wave decay



Tank rupture near the end of the 7 km road tunnel: blast waves after rupture of 160 L tanks with different SoCs

Overpressure Hazard

Probit function for harm to people and structural damage

Death due to lung hemorrhage

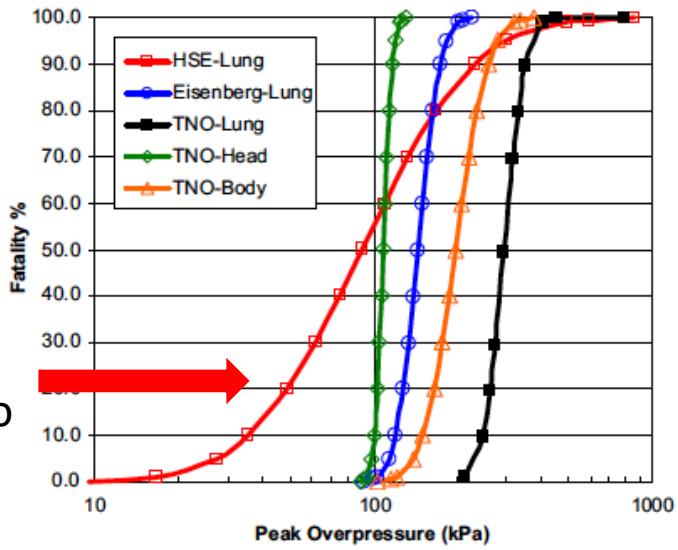


Fig. 2 – Comparison of overpressure probit functions for harm to people.

Structural damage

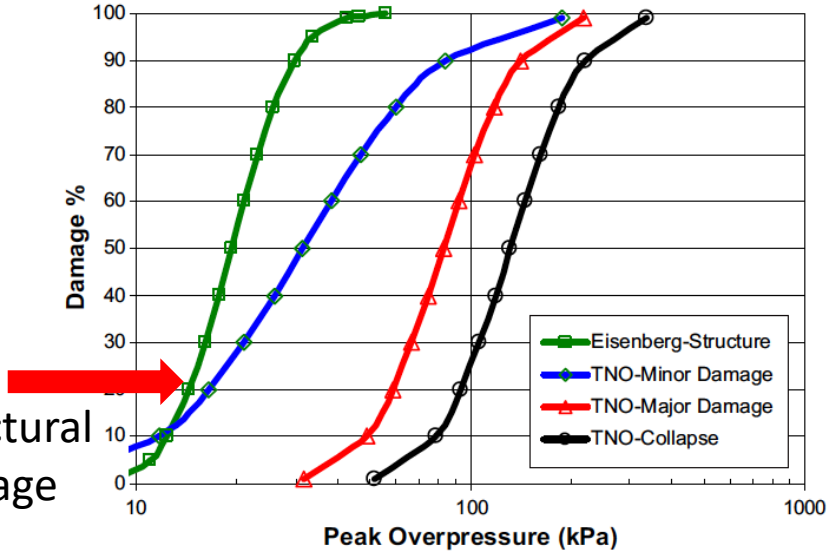
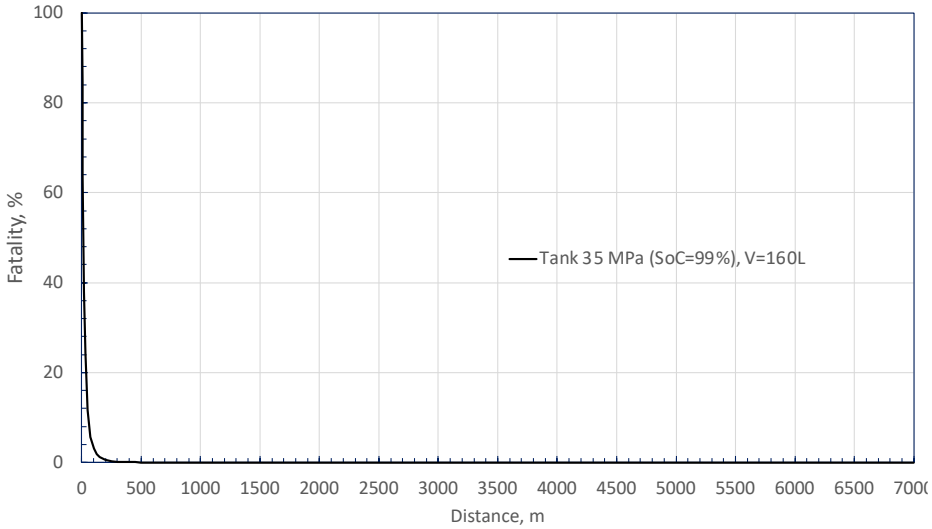


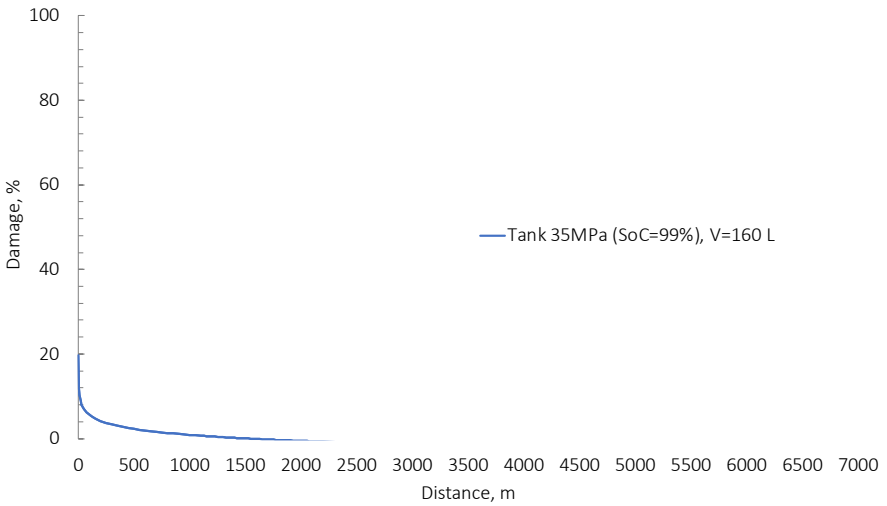
Fig. 4 – Comparison of structural damage probit functions.

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

Example of Railway tunnel

Percentage of Fatality and Damage





Probability of Fatality < 1% at 200 m

Probability of damage = 20% at tunnel entrance
Probability of damge < 1% at 900 m

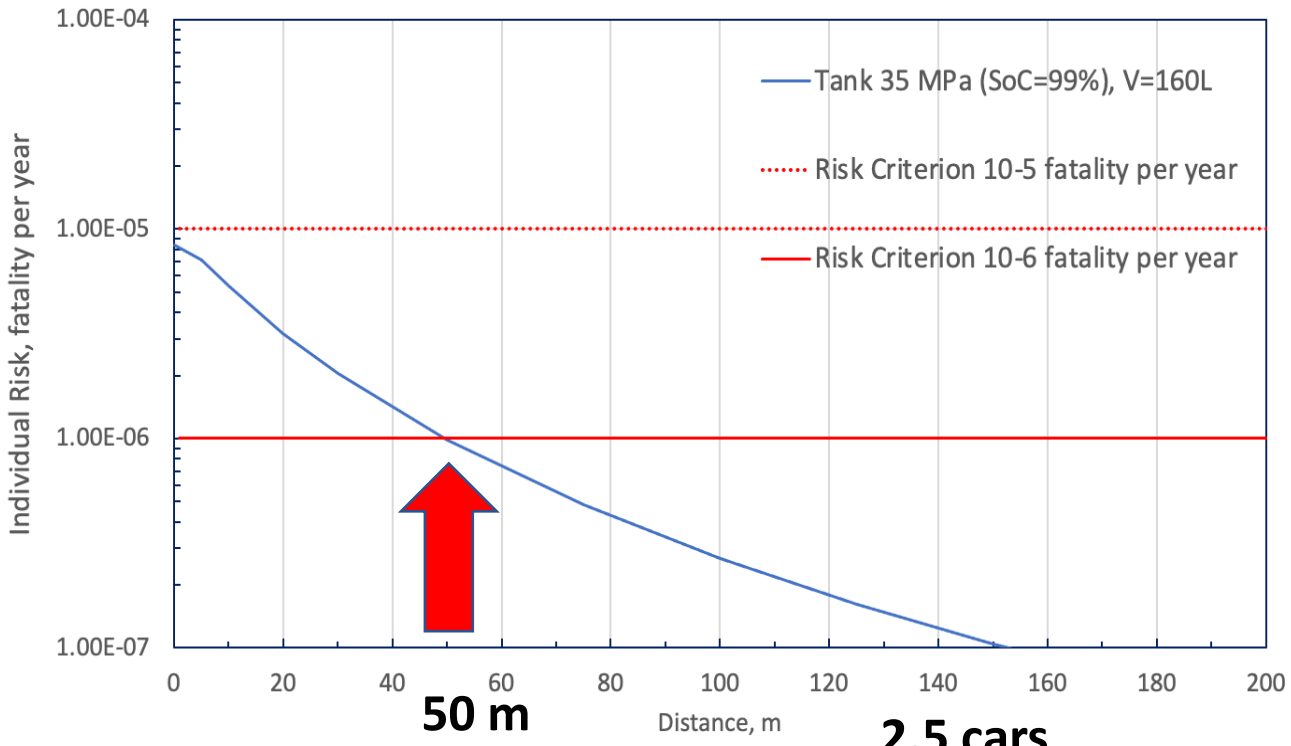
Example of Railway tunnel

Individual risk

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

Localised fire

Tank rupture location: near the tunnel exit



50 m

- train length: three cars
- 64 m long
- passenger occupancy :148 passengers per train

2.5 cars
116 fatalities x one train /
232 for 2 trains

Consequence analysis

DDT potential (KIT)

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

Example of Railway tunnel

DDT potential

Case (I):

- Single rail tunnel of two-tubes tunnel with a circular cross-section 64.3 m^2
- Equivalent diameter Deq=8.98 m
- Tunnel roughness equivalent to BR = 1% which is equal to 2.2 cm of roughness.
- Hydrogen inventory 5.8 kg due to the accident, then cloud formation with a late ignition.

Uniform hydrogen-air mixture of 10 to 30%H_2 in air filled a layer of h=0.6 m thick above the train. The cloud is formed in a gap between the roof of the train and the ceiling

Case (II):

- Single rail tunnel of two-tubes tunnel with a circular cross-section 64.3 m^2
- Equivalent diameter Deq=8.98 m
- Tunnel blockage by the train is equivalent to BR = 40%.
- Hydrogen inventory 5.8 kg due to the accident, then cloud formation with a late ignition.
- Stratified hydrogen-air mixture filled the whole tunnel cross-section

A linear hydrogen concentration gradient with maximum concentration 10, 15, 20, 25, 30% H_2 at the ceiling and 0% H_2 at the bottom of the tunnel is assumed

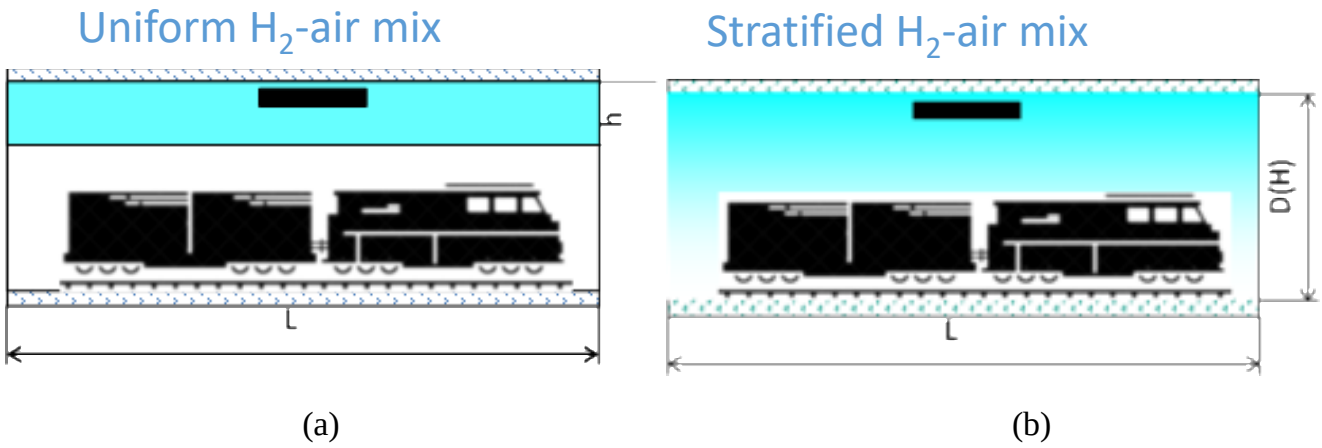


Figure 1. Hydrogen cloud geometry: a layer of uniform hydrogen-air mixture (a); fully filled tunnel cross- section with a stratified hydrogen-air mixture (b).

Example of Railway tunnel

DDT potential

Initial hydrogen inventory, mass flow rate and discharge time for train

Vehicle	Total Vehicle Inventory (kg)	Single Tank Inventory (kg)	Initial mass flow rate (kg/s)	Discharge time (sec)	Cross-section area (m^2)
Train 1 (350 bar)	96.0	4.14	7.85	67	10.7
Train 2 (350 bar)	105.0	5.80	5.89	97	13.9

Example of Railway tunnel

Results of Flame propagation and DDT

- Independent of hydrogen inventory, for maximum hydrogen concentration of 10 and 11% H_2 the flame cannot accelerate to the speed of sound. It will propagate as a slow subsonic flame with a maximum combustion over-pressure 1-2 bar.
- Independent of maximum hydrogen concentration at the ceiling, for hydrogen inventories 5.8 and 10 kg the only slow subsonic flame with a maximum combustion over-pressure 1-2 bar may develop because too small size of the cloud.
- Only in the case **IV** for 100 kg of hydrogen inventory the size of the cloud will be enough for flame acceleration and detonation onset at maximum hydrogen concentration above 15%. Then, it needs the ventilation to keep hydrogen concentration below 15% to prevent the detonation.

Conclusions

- The results of the frequency analysis showed that the most likely consequence includes scenarios with no release of hydrogen or hydrogen release without ignition.
- When the hydrogen does ignite, it is most likely a jet fire from the hydrogen system or a TPRD.
- In the presence of a localised fire, if the TPRD fails to open, the catastrophic H_2 tank rupture is the most likely scenario.
- The risks with the largest consequences are shown to be scenarios leading to hydrogen flammable mixture deflagration (could be eliminated by proper TPRD design) and tank rupture in a fire (could be eliminated by using innovative explosion free in a fire tanks, i.e. micro LNB safety technology).

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Europe Research.