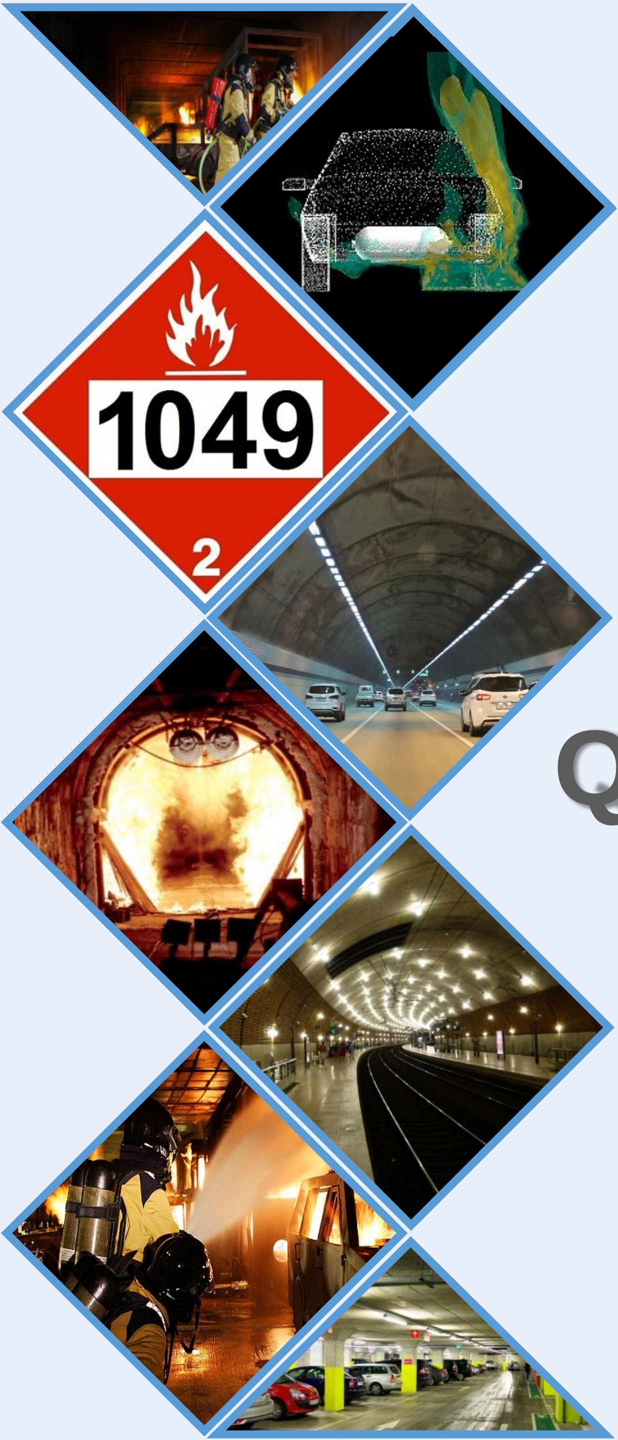

Dissemination Conference of HyTunnel-CS project
“PNR for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces”
14-15 July 2022, Brussels

QRA of hydrogen vehicles in road tunnels

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Overview

- QRA methodology
- Consequence Analysis
- Frequency Analysis
- Risk Results
- Concluding remarks
- Acknowledgments

Abbreviations and definitions

HFCV - Hydrogen Fuel Cell Vehicle

EP - Escalation probability

FRR - Fire resistance rating: time from burner ignition until tank's rupture in a fire (without TPRD or failed TPRD or localised fire far from TPRD, e.g. in a smouldering fire)

LNB - Leak-no-burst safety technology, producing hydrogen micro-leaks from the tank in the event of a fire and releasing hydrogen safely

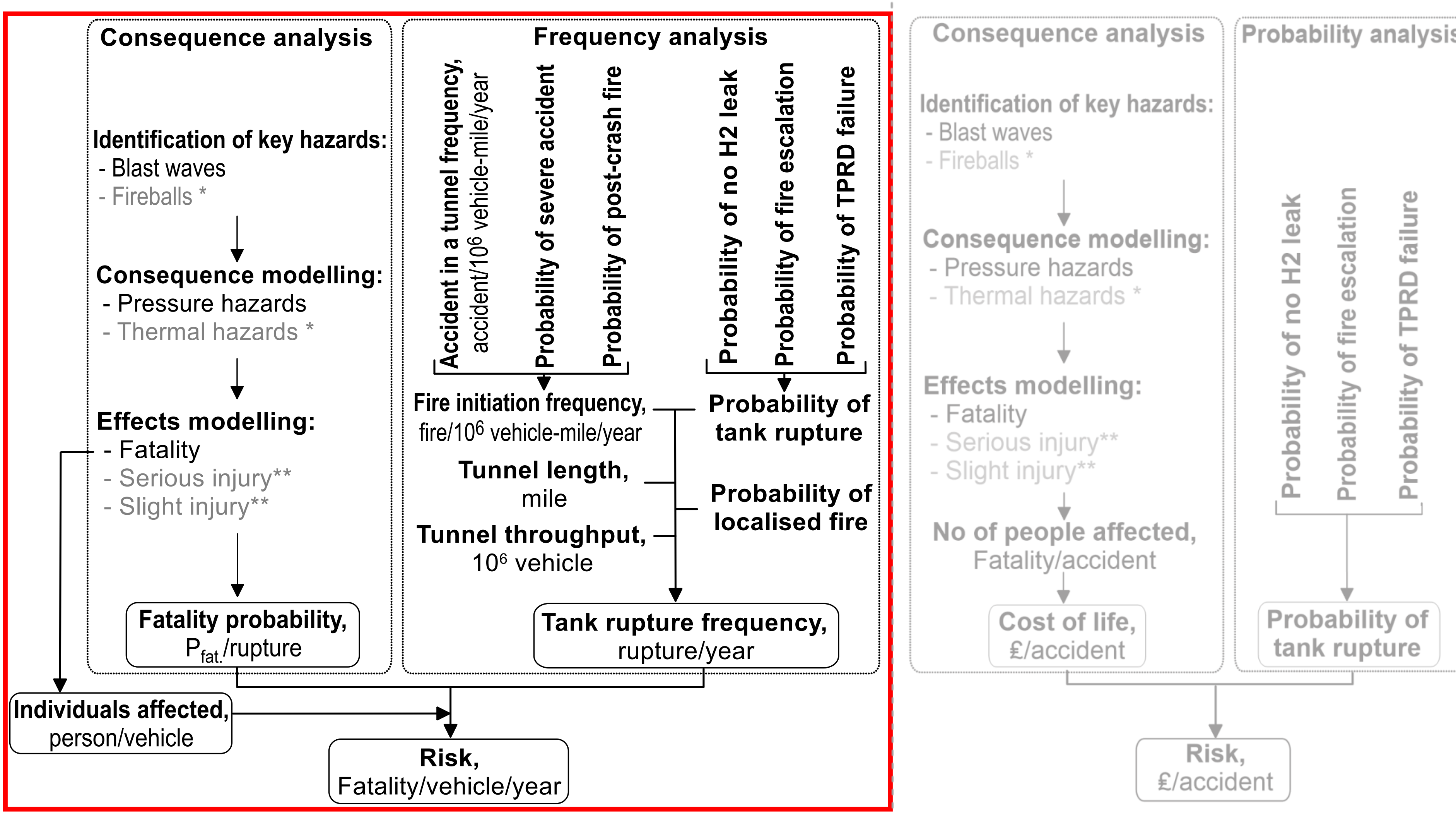
NWP - Nominal Working Pressure

SoC - State of Charge; SAE J2601: "ratio of CHSS hydrogen density to the density at NWP rated at the standard temperature 15 ºC"

TPRD - Thermally activated pressure relief device

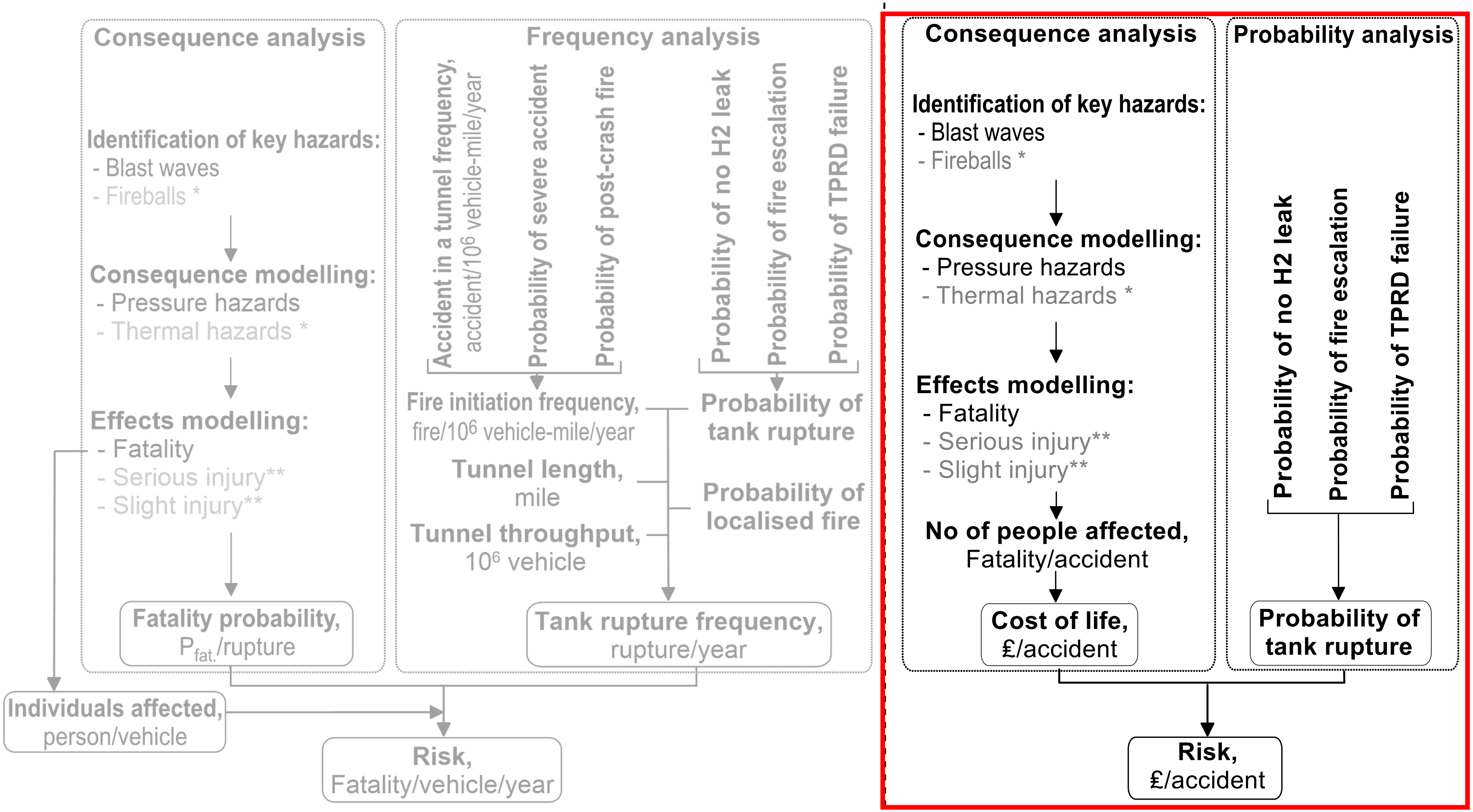
UU QRA Methodology

Risk (Fatality/vehicle/year)



UU QRA Methodology

Risk (Monetary Losses)

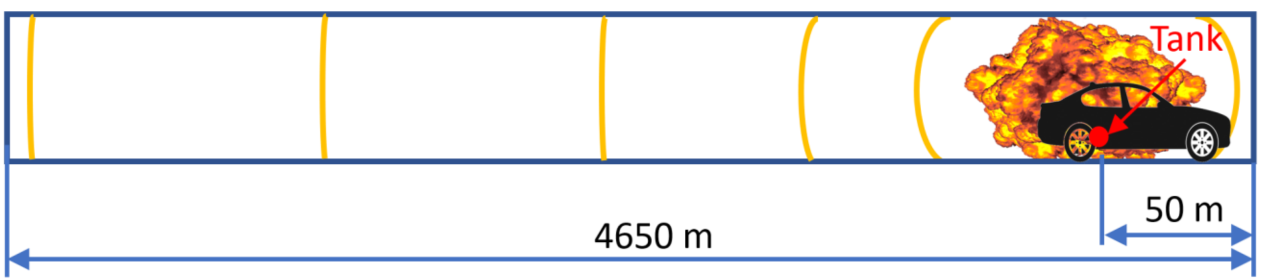


Consequence analysis

Road tunnel example: Dublin tunnel

Assumptions for QRA:

- Tank V=62.4 L, NWP=70 MPa
- HFCV is located 50 m from the tunnel entrance
- Only blast wave overpressure is considered in consequence analysis at the moment
- L=4.65 km
- Throughput $5.5 \cdot 10^6$ vehicle
- 2 tubes, 2 lanes each



References:

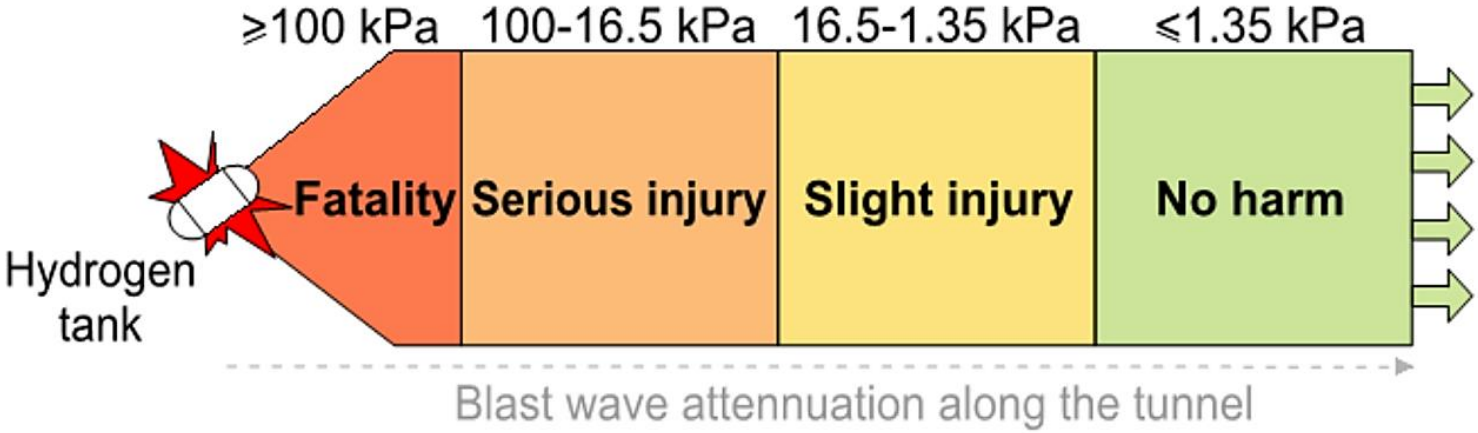
1. Road Tunnel Association (RTA) UK & Eire Road Tunnel Directory. UK & Eire Road Tunnel Directory, 2019. https://dublintunnel.ie/about-dublin-tunnel/

2. Yamashita, A., Kondo, M., Goto, S., Ogami, N., 2015. Development of High-Pressure Hydrogen Storage System for the Toyota "Mirai." SAE Tech. Pap., SAE International. https://doi.org/10.4271/2015-01-1169

Consequence analysis: blast waves

Harm criteria & fatality probability

- **“Fatality” -** 100 kPa (1% fatality prob., lung haemorrhage)
- **“Injury” -** 16.5 kPa (eardrum rupture threshold)
- **“No harm” -** 1.35 kPa (temporary threshold shift)



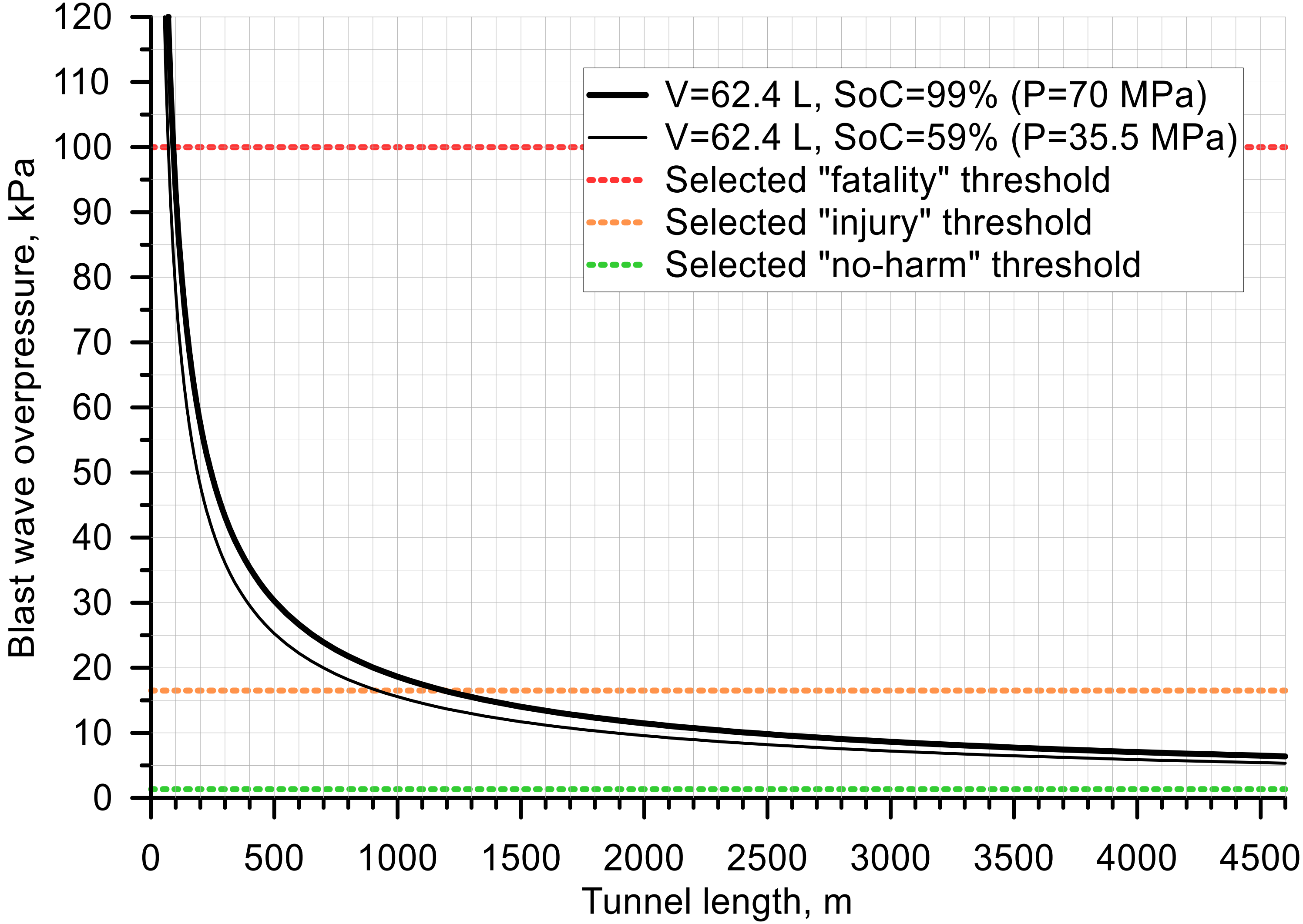
References:

1. Lees' loss prevention in the process industries, vol. 1, 2005.

2. R.M. Jeffries et al. Derivation of fatality probability function for occupants buildings subject to blast loads WS Atkins Sci Technol, 1997.

Consequence analysis: blast waves

Harm criteria & fatality probability



References:

Molkov V., Dery W. The blast wave decay correlation for hydrogen tank rupture in a tunnel fire, IJHE, 2020.

Consequence analysis: blast waves

No of people, parameters of tunnel and vehicles

- Tunnel length used in calculation – 4600 m
- Average car length = 4.5 m
- Assumed gap between two cars = 5 m
- Average number of passengers per vehicle = 1.55
- Number of vehicles in two lanes within fatality zone (SoC 59%) = 70 m/(4.5 m+5 m)]×2 = 15
- Hence, average number of people affected (*fatality) = =15 *1.55 = 23.25
- Calculated risk in terms of monetary losses = 31,080,600 £/accident (based on HSE accident cost of £1,336,800)

References:

- *What Are The Average Dimensions Of A Car In The UK? 2021. https://www.nimblefins.co.uk/cheap-car-insurance/average-car-dimensions*
- *Average car and van occupancy England 2002-2018 Statistic. https://www.statista.com/statistics/314719/average-car-and-van-occupancy-in-england/*

Consequence analysis: blast waves

Hazard zones and people affected

Harm to people	Blast wave hazard zone for tank rupture at different SoC	
	For tank SoC=99% (70 MPa)	For tank SoC=59% (35.5 MPa)
Fatality	0-90 m	0-70 m
Serious Injury	90-1150 m	70-900 m
Slight Injury	1150-4600 m (end of the tunnel)	900-4600 m (end of the tunnel)
No harm	Does not exist	Does not exist

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Frequency Analysis

Fire initiation freq. & TPRD failure probability

- **Fire initiation frequency** = $5.84.10^{-3}$ fire/10^6 vehicle-mile/year
- **TPRD Failure Probability:**
  - *There is no published data and data on the failure rate of TPRD for hydrogen-powered vehicles.*
  - Characteristic failure probability for pressure relief devices of $6.04.10^{-3}$ was used in this QRA
  - With suggestions from FireCOMP project, TPRD failure probability for engulfing and localized fire conditions was found to be $6.04.10^{-3}$ and 0.503, respectively.
  - **Past QRA study at UU** demonstrated that the highest risk for a hydrogen-powered vehicle on London roads is due to localised fire.

References:

1. *C. Lafleur, G. Bran-Anleu, A. Muna, B. Ehrhart, M. Blaylock, W. Houf, Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study, United States: 2017*
2. *S. Bassan, Overview of traffic safety aspects and design in road tunnels. 2016*
3. *U.S. DOT National Highway Traffic Safety Administration (NHTSA). Traffic safety facts 2015*

Frequency Analysis

Fire escalation prob. & tank rupture prob.

- **Fire escalation Probability**:
  - EP was calculated using probit function
  - Probit equation as a function of FRR was written considering 90% failure probability for 5 min brigade response time and 10% for 20 min brigade response time.

$$Y = 9.25 - 1.85 * ln\,(FRR) \qquad EP = \frac{1}{2}\left[1 + erf\left(\frac{Y-5}{\sqrt{2}}\right)\right]$$

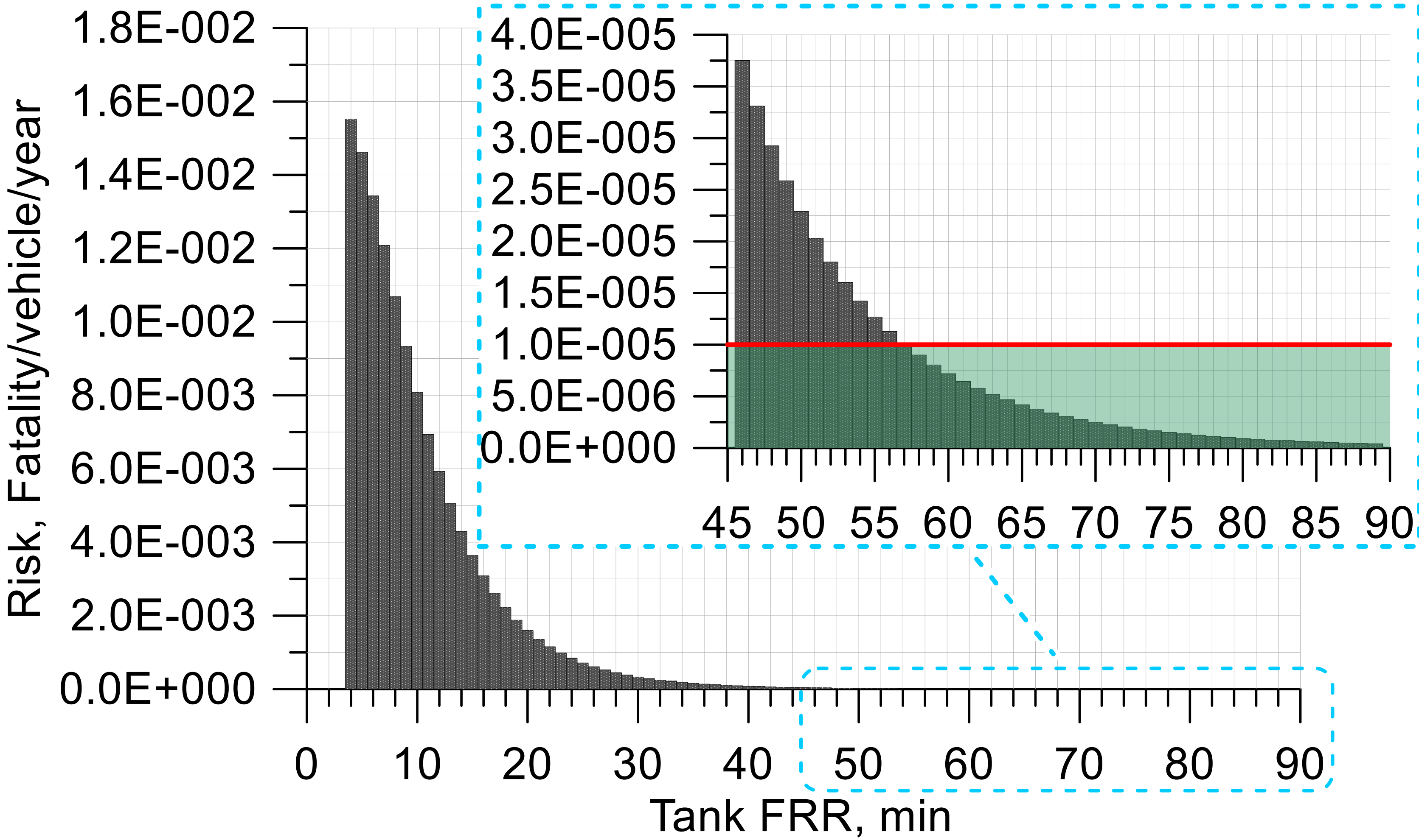
- **Tank rupture probability** = $P_{no\text{-}H2\text{-}leak} \times P_{EP} \times P_{TPRD\ failure}$ = =$6.89.10^{-3}$ ruptures/year.
- Each fire could be both a localized fire, e.g., when an edge of a liquid spill is affecting a tank, or a fire engulfing the tank;
- Hence, we assume $\boldsymbol{P_{loc.fire}}$ **as 0.5**.

References:

1. *C. Lafleur, G. Bran-Anleu, A. Muna, B. Ehrhart, M. Blaylock, W. Houf, Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study, United States: 2017*
2. *S. Bassan, Overview of traffic safety aspects and design in road tunnels. 2016*
3. *U.S. DOT National Highway Traffic Safety Administration (NHTSA). Traffic safety facts 2015*

Risk results

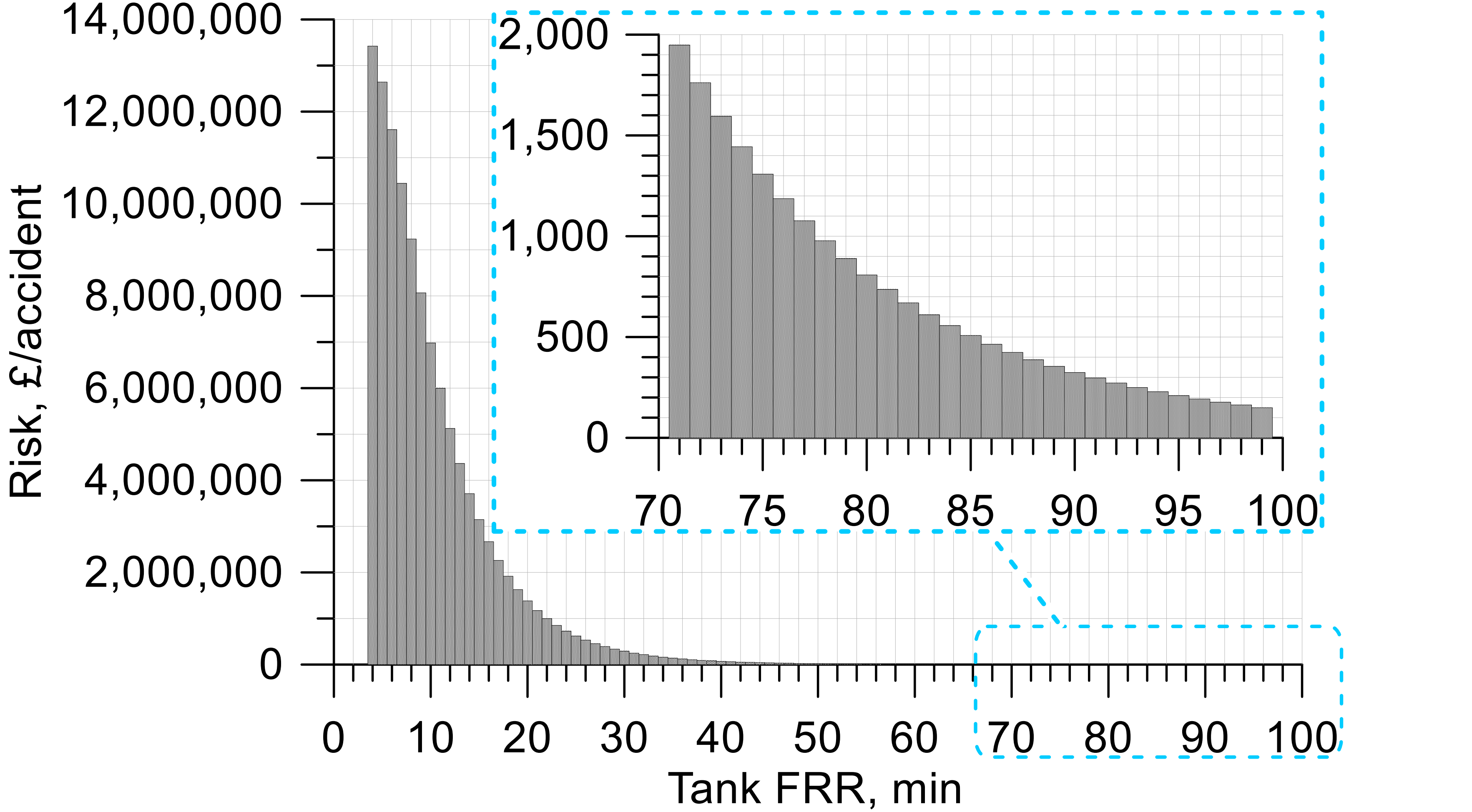
Fatality/Vehicle/Year



To reduce the risk in terms of Fatality/vehicle/year to the acceptable level, the tank FRR should be increased to 58 min

Risk results

Monetary Losses



To reduce the risk (£/accident) to about £300,the tank FRR should be **increased to 91 min**

Conclusions

- Universally applicable QRA methodology was proposed for hydrogen tank ruptures in road tunnels
- The increase of FRR to 91 min reduces both risks to acceptable levels below 10^{-5} fatality/vehicle/year and 300 £/accident
- To fully exclude the risk, the use of the explosion-free in a fire self-venting (TPRD-less) tank is recommended.

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