Case Study – Lessons Learnt from Road Transportation Quantitative Risk Assessment (QRA) Study of High-Pressure Hydrogen Tube Trailer in Singapore

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2025 Center for Hydrogen Safety Asia-Pacific Conference
August 14, 2025
Sydney, Australia

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Arjun Mulloth possesses 9 years of local and international experiences comprising of process safety, commercial, business development and project management experience for facilities storing & handling hazardous chemicals. His expertise includes Quantitative Risk Assessment (QRA), Safety Case development for onshore facilities, qualitative and semi-quantitative process safety studies, EH&S consulting, commercial/business management, and business development.

He is knowledgeable in QRAs (e.g. facility siting study, OBRAs) and has executed over forty (40) QRAs for various brownfield & greenfield facilities in Singapore including for the pipeline and transport of hazardous chemicals. He is well versed with the widely used commercially available risk and consequence modelling software such as DNV PHAST and Gexcon Effects/RiskCurves.

Agenda

- QRA & tQRA in Singapore
- Singapore tQRA Case Study
- Scenarios Considered & Modelled
- Mitigation Measures as part of ALARP Demonstration
- Challenges and Opportunities for Improvement
- Conclusion

Background –QRA/tQRA in Singapore

- Singapore established the revised QRA guidelines (RGL) in 2016 April through collaboration between various local regulatory agencies, UK HSE, and local industry partners
- Aim to standardize QRAs, and add on ALARP demonstration
  - Specified hole sizes to be modelled (10mm, 25mm 75mm, catastrophic rupture)
  - UK HSE FRED/BEVI RIVM, for failure rates and IOGP for ignition probabilities
  - Clearly defined harm levels
  - Standardized assumptions for consequence modelling
- RGL is risk based* and customized for fixed installations, pipelines and bulk transport

QRA Criteria Guidelines
[Revision No: 2]
[Date of Revision: 11 July 2024]

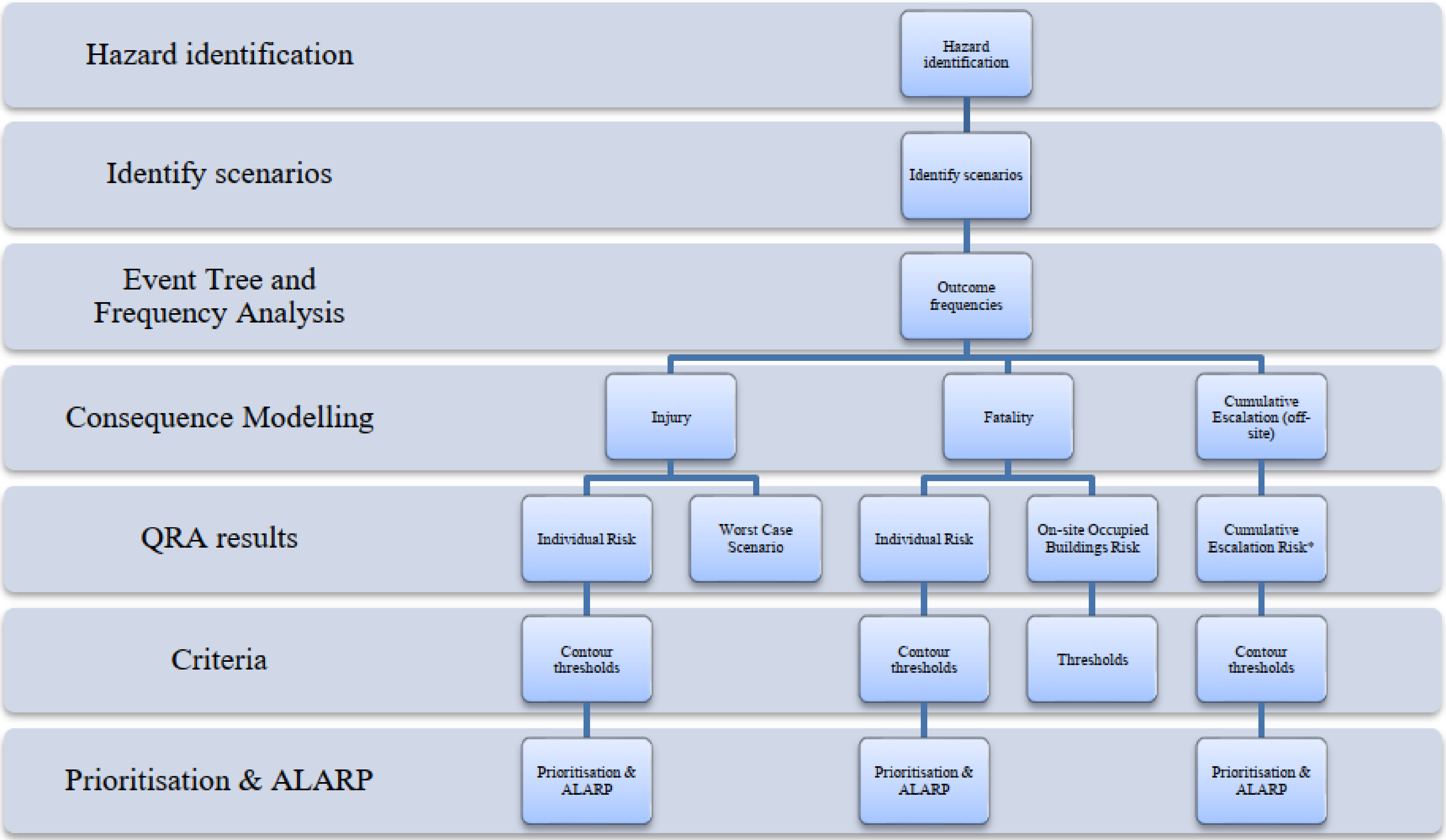
QRA Submission Format
[Revision No: 2]
[Date of Revision: 17 May 2018]

QRA Technical Guidance
[Revision No: 4]
[Date of Revision: 11 July 2024]

Measure	Criteria	Frequency per year		
		Fixed	Pipeline	Transport
Injury	Industrial/commercial only	3E-07	3E-08	3E-08
Fatality	Within boundary	5E-05	5E-06	5E-06
	Industrial only	5E-06	5E-07	5E-07
Escalation	Within boundary	1E-04	1E-05	1E-05
Onsite occupied Buildings	Not exceeded	1E-03	N/A	N/A
Injury hazard range	Industrial/commercial only	N/A	N/A	applies

Ref: Singapore QRA risk criteria, taken from IChemE Hazards 27 presentation on development of QRA guidelines

Singapore QRA Methodology[1]



SDS (inherent chemical hazards)

Leak/rupture, HAZOP for process specific scenarios

Failure rate databases, LOPA, FTA, RTA failure rates

2D: Gexcon Effects
DNV PHAST
3D: DNV KFX,
Gexcon FLACS

Gexcon RiskCurves
DNV Safeti

Risk or consequence based

Qualitative or Quantitative

1. Required/recommended approach: Singapore QRA Technical Guidance, published July 2024

Road Transportation QRA (tQRA)

tQRA is required when either conditions are fulfilled:

- Road transport of HazMat in a larger container size than existing approved routes; OR
- Road transport of HazMat via non-approved routes.
  - Pre-2016, no tQRA required for HazMat transport approval

- tQRAs in Singapore are rare, and almost impossible to meet the consequence-based criteria.
- Since 2016 AcuTech personnel have only done 3 (including this one) and all have not met the criteria
  - Transport approval was eventually granted with conditions (to demonstrate ALARP)

Definition of Consequence-based criteria for tQRA

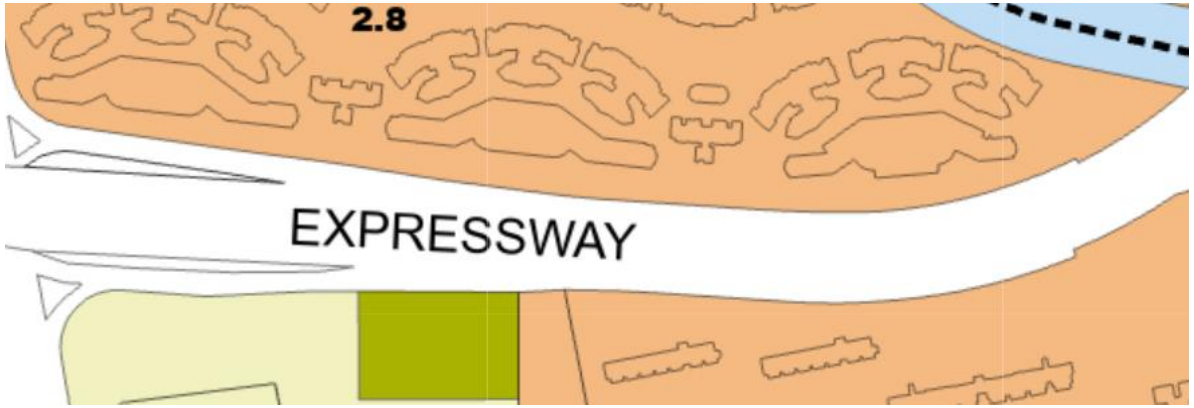
Worst Case Scenario-Offsite[1]	Criteria
Hazard zone for the outcome which gives the largest injury harm distance relative to the Boundary (toxic release, fire and explosion)[2]	Confined to industrial and commercial developments only and shall not reach sensitive receptors

Bulk Transport: The boundary shall be taken to be the nearest adjacent premises boundary along the transport route.

'Injury' harm levels to be modelled

QRA criteria	Toxic	Thermal	Flash fire	VCE
Injury	AEGL-3	4 kW/m²	LFL	1 psi

Singapore URA Masterplan for typical expressway (areas in orange are residential developments)



Singapore tQRA Case Study

Inception

Client intends to transport pressurized (200 barg) Hydrogen (H2) tube trailers (30 tubes per trailer with a payload of 215.8 kg of hydrogen per trailer) from the West to the East of Singapore (route length is ~ 50 km)

Purpose

tQRA is required as there is nor prior approved road transport route for H2 tube trailer between the start and end point. AcuTech was engaged to perform the tQRA study.

Results

tQRA meets risk criteria, but does not meet the consequence-based criteria as the identified Worst Case Scenario-Offsite (WCS-O) scenario extends beyond the road boundary by 172m and encroaches into sensitive receptors[Note]

Note: Land parcels containing developments with vulnerable population (e.g. hospitals, schools, residential Ports/airports)

Scenarios Modelled and Selection of WCS-O

- Leak (hole diameter of 10mm, 25mm and 75mm) and catastrophic rupture (instantaneous release) scenarios were considered for entire tube trailer inventory.

RTA LoC Scenarios

- Jet Fire, Flash Fire and Gas Fireball were considered credible and modelled[Note]
- Modelled using Gexcon Effects/RiskCurves (v 12.3) for 3 wind conditions (1F, 2B and 3C)

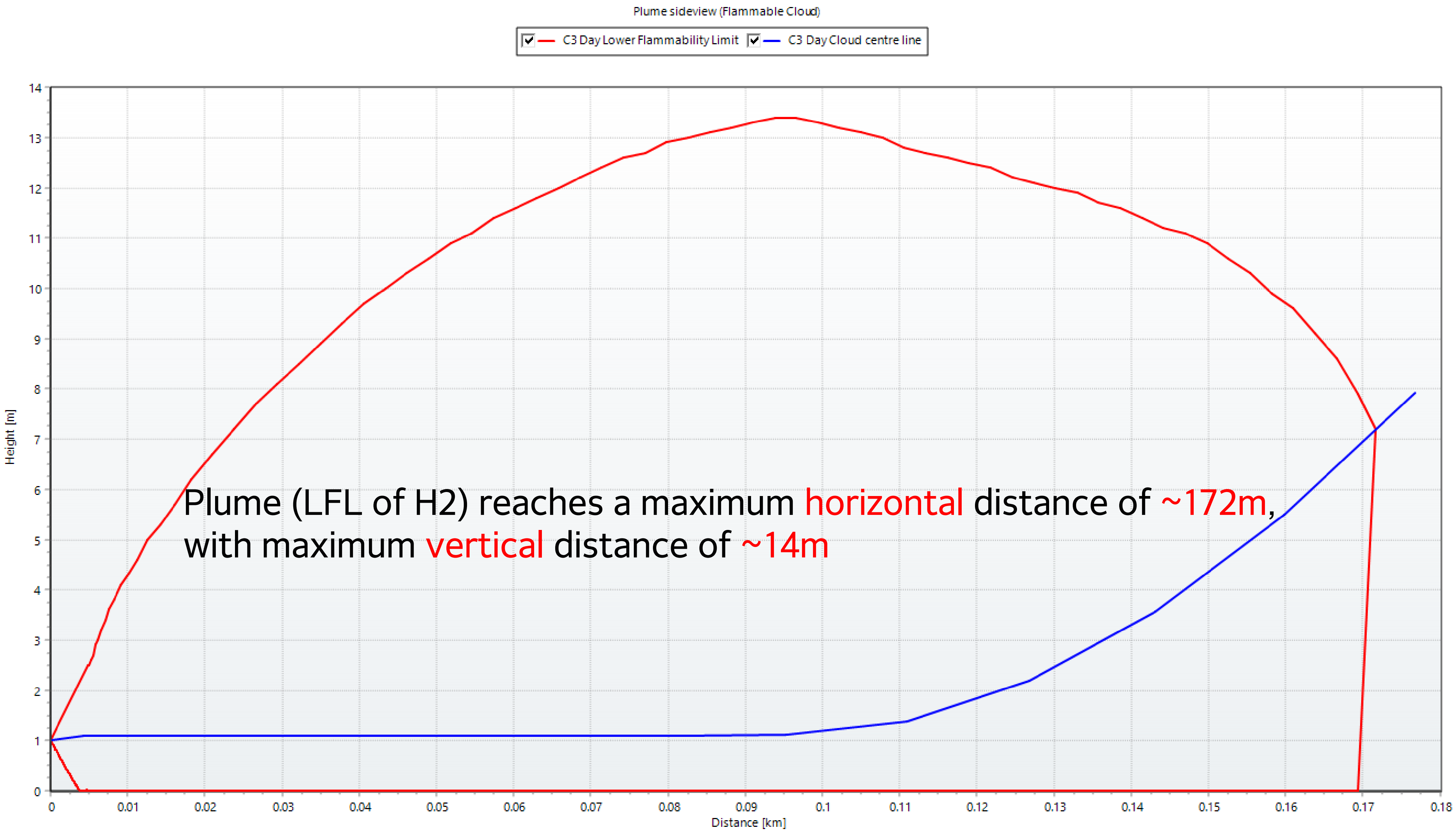
Credible Outcomes

- WCS-O identified is flash fire due to a 75mm leak (horizontal orientation) in 3C wind condition. Scenario is modelled as a plume (horizontal distance of 172m) with concentration above LFL (4 vol% of H2)

WCS-O

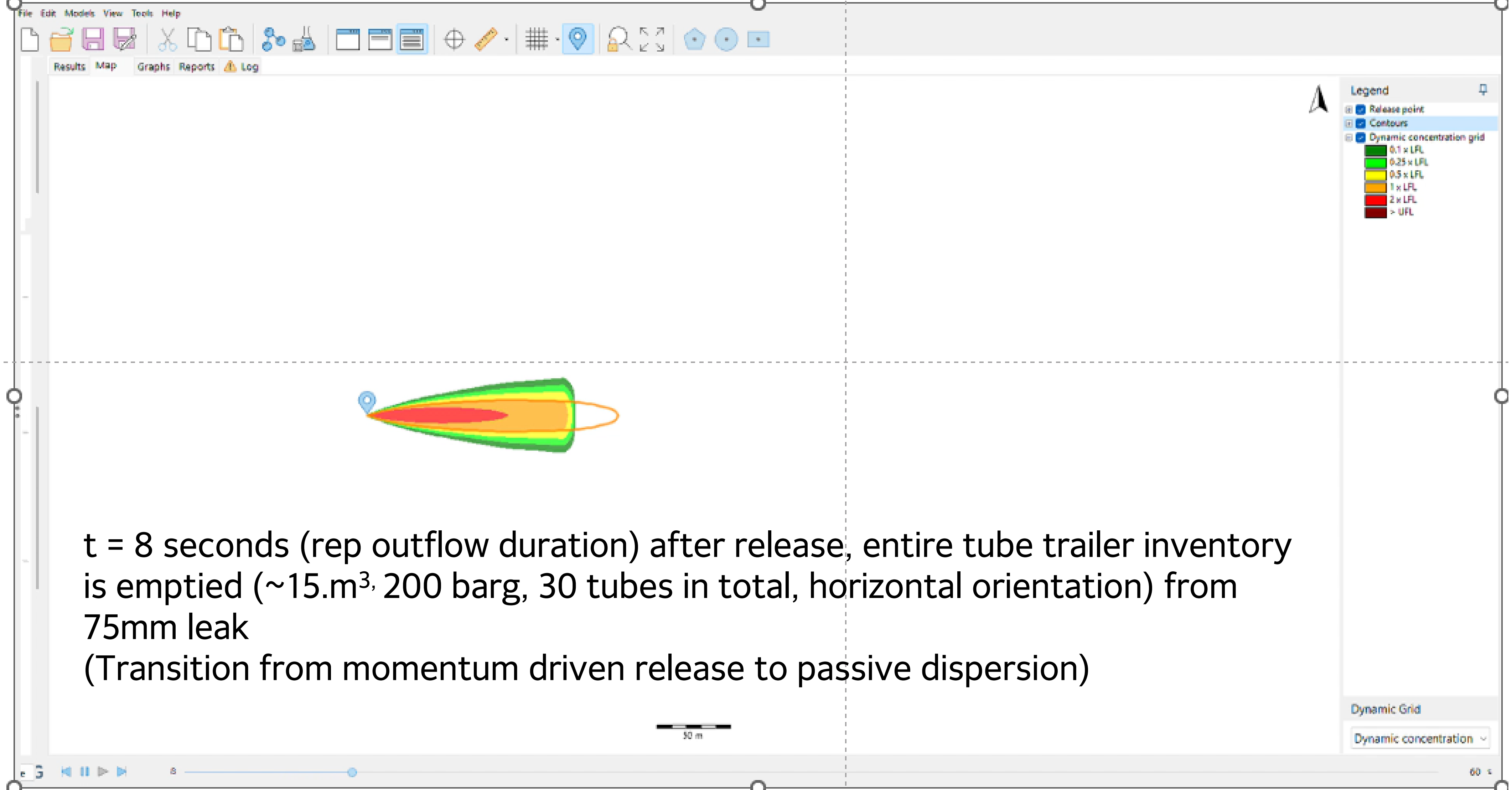
Note: Vapor Cloud Explosion (VCE) scenarios were considered non-credible as 1) Delayed ignition was agreed with regulators to be non-credible/unlikely as H2 would be released in a public road (no ignition source control) and 2) Confinement is unlikely as HazMat vehicles in Singapore are not allowed to travel in tunnels

Side view of WCS-O Plume



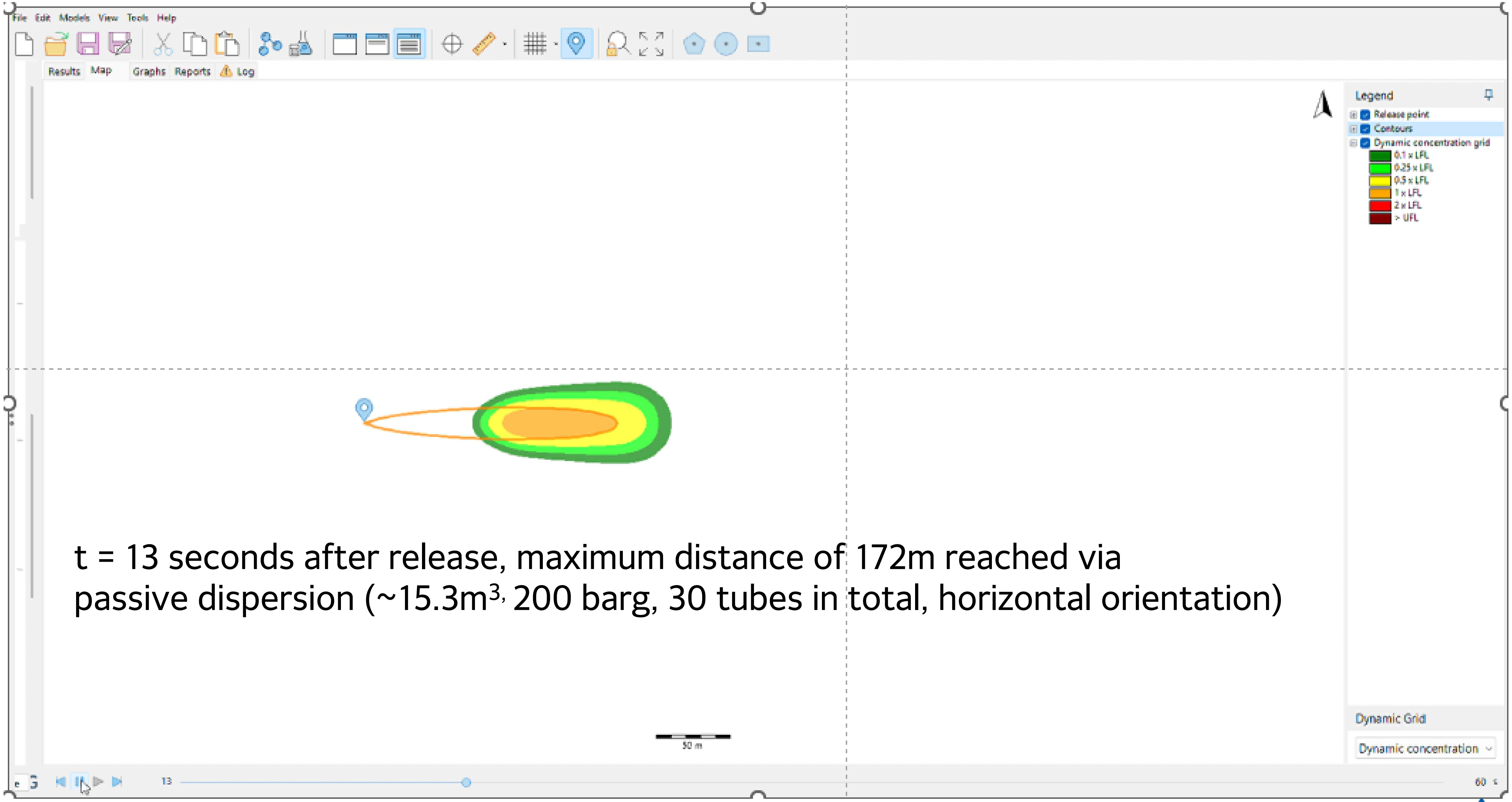
Plume (LFL of H_2) reaches a maximum horizontal distance of ~172m, with maximum vertical distance of ~14m

Plan View of Development of WCS-O Plume [1 of 3]



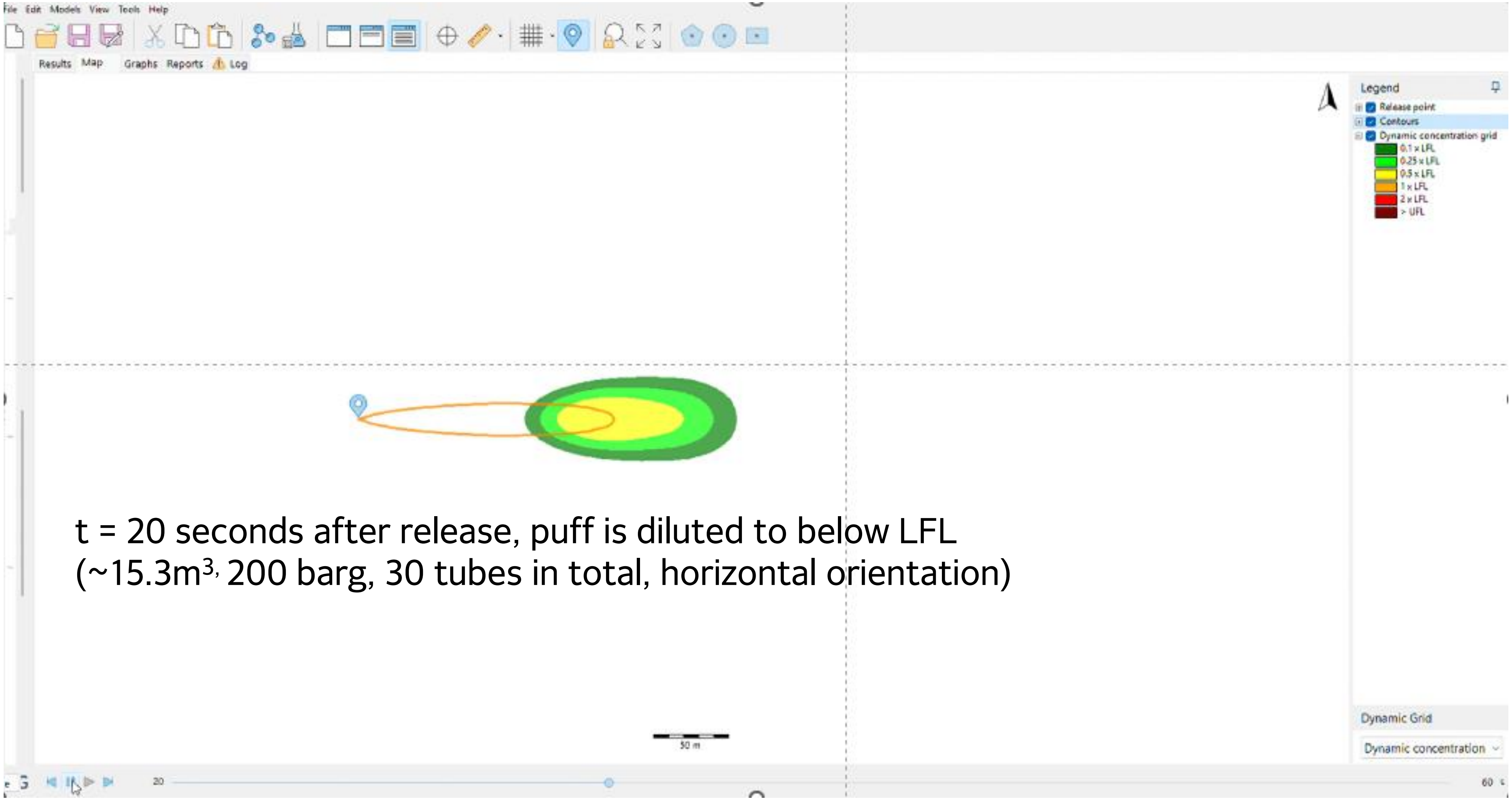
t = 8 seconds (rep outflow duration) after release, entire tube trailer inventory is emptied (~15.m^3, 200 barg, 30 tubes in total, horizontal orientation) from 75mm leak
(Transition from momentum driven release to passive dispersion)

Plan View of Development of WCS-O Plume [2 of 3]



t = 13 seconds after release, maximum distance of 172m reached via passive dispersion (~15.3m^3, 200 barg, 30 tubes in total, horizontal orientation)

Plan View of Development of WCS-O Plume [3 of 3]



t = 20 seconds after release, puff is diluted to below LFL
(~15.3m^3, 200 barg, 30 tubes in total, horizontal orientation)

Mitigation Measures as part of ALARP Demonstration (for transport approval)

Training & Certification for HazMat Drivers, and roadworthiness certification for prime movers

Robust Preventive Maintenance Programs, leak check/close manifold valves before transport, good crash protection design for the tube trailer

Restricted travel hours, speed limits (50 km/hr), HazMat approved restricted roads, use of vehicle escorts, and transponders to track vehicles

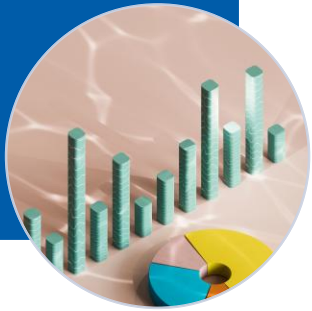
Communication plan for emergency response with key stakeholders (e.g. local fire service, gas transporter, end user & other land parcels affected)

Long Term: Transportation of Hydrogen tube trailers via sea route (barge)

Challenges and Opportunities for improvement [1 of 2]

- Challenge: Currently no publicly available statistical database for expected leak hole sizes for tube trailers, even for failures at storage conditions. A 75mm hole leak might be overly conservative.

Better initiating failure rate/leak hole size definition for tube trailer scenarios?

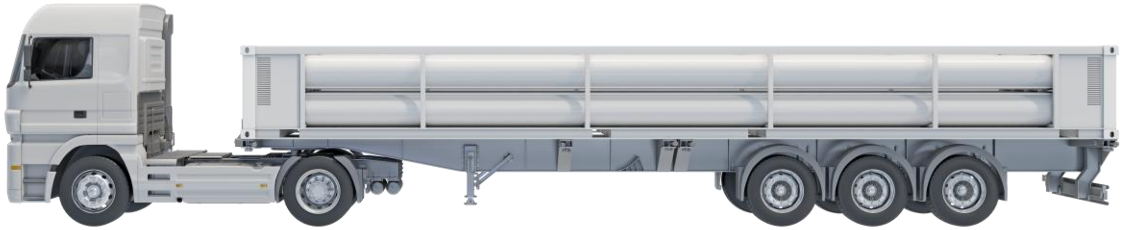


- Delayed ignition for hydrogen releases will have a lower probability due to high reactivity of H2 and the number of ignition sources on a road.

Probability of delayed ignition of H2 for releases on a road?

Uncertainties in Tube Trailer Releases

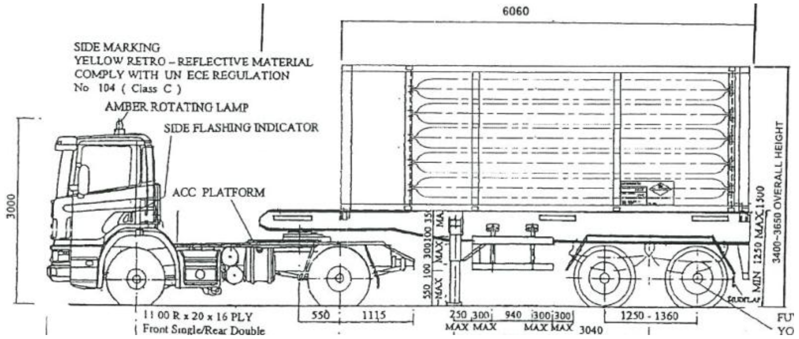
- Tube trailers come in different Shapes and Sizes!



- 40ft, 9 tubes tube trailer
- 40ft, 12 tubes tube trailer
- 20ft, 56 tubes tube trailer
- 20ft, 30 tubes tube trailer

Credible scenarios:

1. Single tube leak (hole size?)
2. Single tube rupture
3. PRD release? (Non-RTA)
4. Multiple tubes leak?
5. Multiple tubes rupture?



20 ft, 30 tubes tube trailer

Crash protection for trailer

Challenges and Opportunities for improvement [2 of 2]

- Results for consequences of fires (e.g. Jet Fire, Gas Fireball, Flash Fire) from consequence modelling software are provided in thermal radiation flux (kW/m^2). Difficult for stakeholders to gauge damage to equipment or buildings.

Better understanding of physical damage caused by fire scenarios?

- Challenge: Road traffic is a complex and dynamic 3D geometry due to the uncertainty in the number of vehicles and varied road user behaviours which makes accurate CFD modelling difficult.

CFD modelling for more accurate consequence results?

Conclusion

- tQRA methodology for hydrogen is not different from other gases, but is challenging to meet consequence-based criteria for transportation through urban and densely populated areas
- Limited approval (5-year duration) granted, contingent on the switch to the sea route as a permanent transportation solution
- Key opportunities for improvement include:
  - Defining credible leak hole sizes and initiating failure frequencies for tube trailers based on statistical/historical incident data on tube trailer loss of containment scenarios
  - Better estimates for delayed ignition probability from a loss of containment of a hydrogen tube trailer along a public road
  - Further assumptions/simplifications that can allow for CFD to be used for dispersion along a transportation route (e.g. used of 2D models with integrated CFD functionality?)
  - Visualization of temperature profile vs distance for hydrogen fires?

Questions?

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