A MODEL FOR ASSESSING THE RISK OF LIQUID HYDROGEN TRANSPORT THROUGH ROAD TUNNELS

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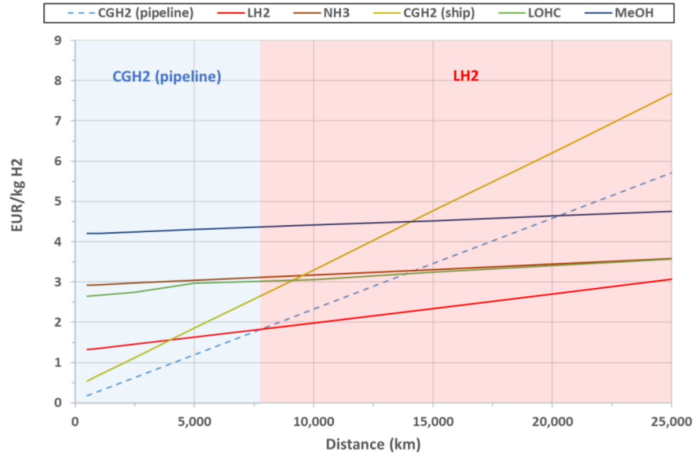
INTRODUCTION

Hydrogen has the potential to help mitigate the current rapid climate change and achieve the goals of the European Green Deal:

- To reduce greenhouse gas emissions by at least 50% by 2030 compared to the ’90;
- To achieve climate neutrality in Europe by 2050.



Source: European Commission, JRC Technical Report, Assessment of Hydrogen Delivery Options (2022).

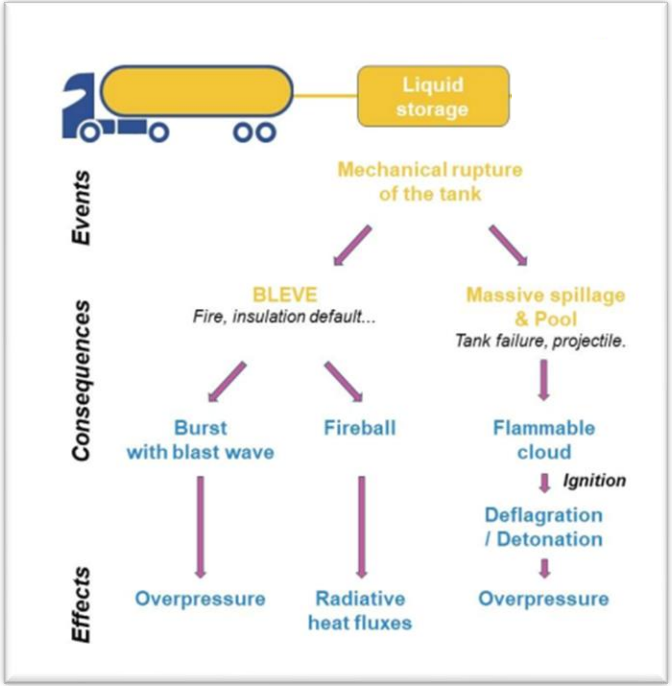
In the short-term perspective **delivery of hydrogen by road transport as liquid** might represent the optimal solution, especially for long distances.

INTRODUCTION

- Liquid hydrogen (LH$_2$) presents different hazards and risks compared to those related to the more commonly known compressed gaseous hydrogen [1]

- After an accidental release of LH$_2$, in fact, the flammable cloud might be significantly larger than that induced by a gaseous hydrogen release due to the high density and vaporization [2]

- The consequences of a LH$_2$ leakage might be much more severe **in a road tunnel**, since the hydrogen mixture can be trapped by the tunnel ceiling increasing the risk of explosion [3]



Feared events associated with the trasport of liquid hydrogen.

Source: PRESLHY Project Deliverable D6.3 Recommendations for RCS

[1] Jordan, T., Jallais, S., Bernard, L., Venetsanos, A., Coldrick, S., Kuznetsov, M. and Cirrone, D., Status of the pre-normative research project PRESLHY for the safe use of liquid hydrogen, Proceedings of the International Conference on Hydrogen Safety, 24-26 September 2019.

[2] Bernard, L., Houssin, D., Jallais, S., Jordan, T. and Cirrone, D., Novel guidelines for safe design and operation of LH$_2$ systems and infrastructure, Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY), Deliverable Number: D6.2, Work Package: WP6, 2021.

[3] Kožuh, M., Preventing hydrogen detonations in road tunnels hydrogen trap concept, *International Journal of Hydrogen Energy*, 39, No. 30, 2014, pp. 17434–17439.

STATE OF THE ART

Statharas, J.C., Venetsanos, A.G., Bartzis, J.G., Würtz, J. and Schmidtchen, U., Analysis of data from spilling experiments performed with liquid hydrogen, *Journal of Hazardous Material*, 77, No. 1, **2000**, pp. 57–75;

Hall, J., Ignited releases of liquid hydrogen, RR987 Research Report, Health and Safety Laboratory, **2014**;

Sklavounos, S. and Rigas, F., Fuel gas dispersion under cryogenic release conditions, *Energy & Fuels*, 19, No. 6, **2005**, pp. 2535–2544;

Unno, S., Takaoka, Y., Kamiya, S., Oyama, S., Kishimoto, A., Miida, A. and Suga, H., A study on dispersion resulting from liquefied hydrogen spilling, Proceedings of the International Conference on Hydrogen Safety, 19-21 October **2015**;

Jin, T., Wu, M., Liu, Y., Lei, G., Chen, H. and Lan, Y., CFD modeling and analysis of the influence factors of liquid hydrogen spills in open environment, *International Journal of Hydrogen Energy*, 42, No. 1, **2017**, pp. 732–739;

Liu, Y., Wei, J., Lei, G., Lan, Y., Chen, H. and Jin, T., Dilution of hazardous vapor cloud in liquid hydrogen spill process under different source conditions, *International Journal of Hydrogen Energy*, 43, No. 15, **2018**, pp. 7643–7651;

Giannissi, S.G. and Venetsanos, A.G., A comparative CFD assessment study of cryogenic hydrogen and LNG dispersion, *International Journal of Hydrogen Energy*, 44, **2019**, pp. 9018–9030;

Liu Y., Wei, J., Lei, G., Chen, H., Lan, Y., Gao, X., Wang, T. and Jin, T., Spread of hydrogen vapor cloud during continuous liquid hydrogen spills, *Cryogenics*, 103, 2019, 102975;

Pu, L., Shao, X., Zhang, S., Lei, G. and Li, Y., Plume dispersion behaviour and hazard identification for large quantities of liquid hydrogen leakage, *Asia-Pacific Journal of Chemical Engineering*, 14, No. 2, **2019**, e2299;

Hansen, O.R., Liquid hydrogen releases show dense gas behavior, *International Journal of Hydrogen Energy*, 45, No. 2, 2020, pp. 1343–1358;

Ustolin, F. and Paltrinieri, N., Hydrogen fireball consequence analysis, *Chemical Engineering Transactions*, 82, **2020**, pp. 211–216.

Liu, Y., Liu, Z., Wei, J., Lan, Y., Yang, S. and Jin, T. Evaluation and prediction of the safe distance in liquid hydrogen spill accident, *Process Safety and Environmental Protection*, 146, **2021**, pp. 1–8.

Cirrone, D., Makarov, D., Molkov, V., Venetsanos, A., Coldrick, S., Atkinson, G., Proust, C., Friedrich, A. and Kuznetsov, M., Detailed description of novel engineering correlations and tools for LH2 safety, version 2, Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY), Deliverable Number: D6.5, Work Package: WP6, **2021**.

Experiments and/or simulations of LH_2 release **in the open**

Middha, P. and Hansen, O.R., CFD simulation study to investigate the risk from hydrogen vehicles in tunnels, *International Journal of Hydrogen Energy*, 34, No. 14, **2009**, pp. 5875–5886.

Tang, X., Pu, L., Shao, X., Lei, G., Li, Y. and Wang, X., Dispersion behavior and safety study of liquid hydrogen leakage under different application situations, *International Journal of Hydrogen Energy*, 45, No. 55, **2020**, pp. 31278–31288.

Simulations of LH_2 release **in road tunnels**

STATE OF THE ART

KNOWLEDGE GAP

- Most of the studies have prevalently focused on the consequences of LH_2 releases in open spaces, but very few authors have dealt with their effects in confined spaces, such as tunnels.

SCOPE

- To develop a **3D CFD model of LH_2 release and dispersion in a road tunnel** for assessing the potential negative effects on users (e.g., in the event of deflagration).

METHODOLOGY

- The results of the CFD simulations (e.g., the amount of hydrogen contained within the flammable cloud) have been combined with established simplified consequence methods to estimate the overpressures generated from a potential hydrogen deflagration.

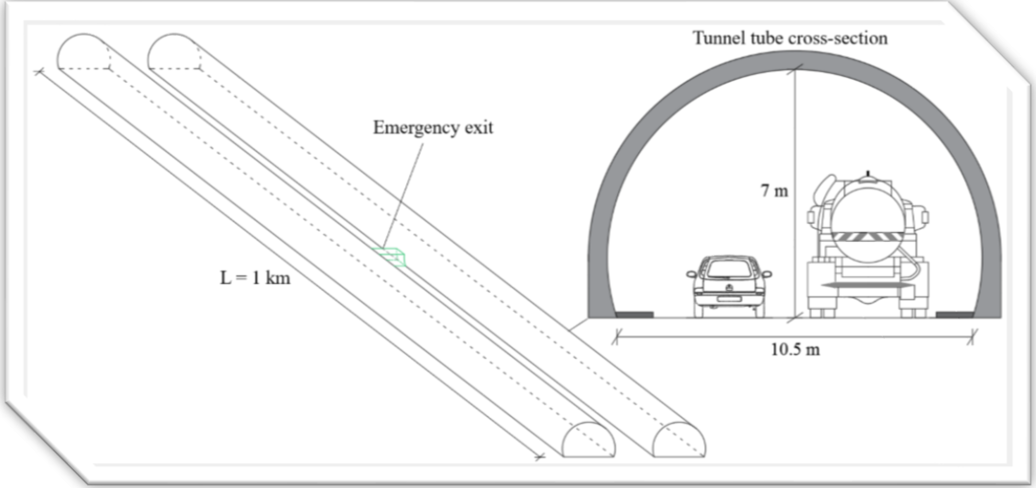
ROAD TUNNEL DESCRIPTION

GEOMETRIC AND FUNCTIONAL CHARACTERISTICS

- 1 km-long unidirectional road tunnel, straight, flat, with an emergency exit located in the middle of the tunnel length;
- Cross-section: 63 m^2 (2 lanes of 3.75 m, two sidewalks of 1 m, and two shoulders of 0.5 m);
- Only natural ventilation due to the piston effect of vehicles in motion [1].

MATERIAL PROPERTIES

	Tunnel walls (concrete)	Road pavement (asphalt mixture)
Thickness	0.5 m	0.4 m
Density	2585 kg/m^3	2275 kg/m^3
Thermal conductivily	1.67 W/m/K	0.56 W/m/K
Specific heat	0.94 kJ/kg/K	0.88 kJ/kg/K



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[1] Directive 2004/54/EC, European Parliament and Council, Official Journal of the European Union, 2004.

ROAD TUNNEL DESCRIPTION

ACCIDENT SCENARIOS

- Accidental release of LH_2 from a road tanker as a consequence of a traffic accident that generates a hole at the bottom rear side of the road tanker, the diameter of which was assumed to be 50 mm;
- Five different locations equally spaced along the tunnel have been simulated (i.e., 165, 335, 500, 670, and 835 m from the entrance portal of the tube).

Road tanker characteristics [1]

$$Tank\ volume = 45\ m^3$$

$$Tank\ capacity = 2500\ kg$$

$$Tank\ working\ pressure = 4\ bar$$

$$Storage\ temperature = 20\ K$$

Mass flow rate

$$\dot{m} = 7.7\ \mathrm{kg/s}$$

Duration of the release

$$t = 5.4\ \mathrm{min}$$

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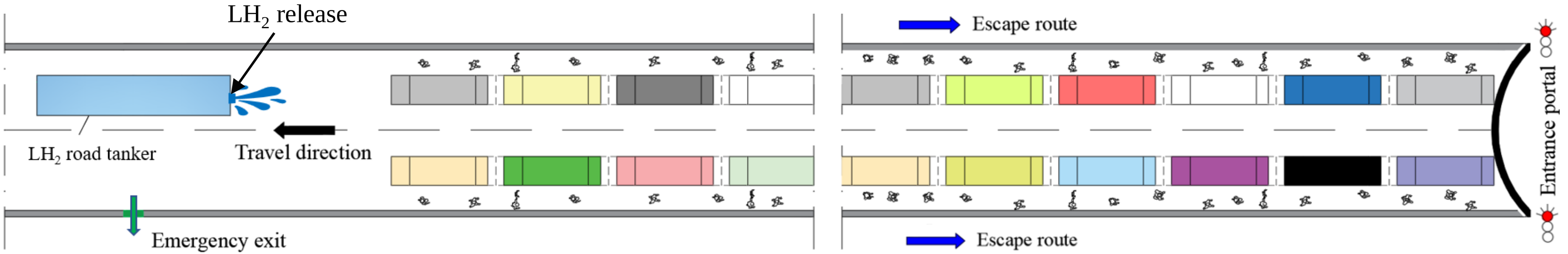
[1] Hall, J.E., Hooker, P. and Willoughby, D., Ignited releases of liquid hydrogen: Safety considerations of thermal and overpressure effects, *International Journal of Hydrogen Energy*, 39, No. 35, 2014, pp. 20547–20553.

ROAD TUNNEL DESCRIPTION

SCHEMATIZION OF QUEUED VEHICLES AND PEOPLE EVACUATION PROCESS

- Vehicles are schematized as parallelepipeds with dimension: **6 m (length) × 1.8 m (width) × 1.5 m (height)**;
- Safety distance between the vehicles upstream of the LH_2 road tanker: **2 m**;
- Traffic composition: **75% cars, 25% heavy vehicles (including 2% buses)**;
- Average occupancy rate: **2 people per vehicle**;
- Pre-movement time (detection + reaction time): → **90 s** → **150 s**
- People movement speed: **0.5 m/s**.



NUMERICAL MODELING

CFD SIMULATION CODE

- Simulations have been carried out using **ANSYS Fluent, version 2022 R1**

<u>Multiphase model</u> → The transient two-phase flow was simulated by the ***mixture model*** [1]

- Liquid phase → Liquid hydrogen;
- Gas phase → Hydrogen-air mixture;
- All gases are assumed to be incompressible (Mach number ≤ 1.0).

The mass transfer from the liquid phase to the gas phase and vice versa is governed by the **evaporation-condensation Lee model** with saturation temperature set to 20.27 K.

Turbulence model → Turbulence closure solved by the ***k-ε model*** because found as the most appropriate when dealing with gas dispersion in the presence of obstacles [2], as well as to account for any buoyancy effect [3]

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[1] Shao, X., Pu, L., Li, Q. and Li, Y. Numerical investigation of flammable cloud on liquid hydrogen spill under various weather conditions, *International Journal of Hydrogen Energy*, 43, No. 10, 2018, pp. 5249–5260.

[2] Sun, R., Pu, L., Yu, H., Dai, M. and Li, Y., Investigation of the hazardous area in a liquid hydrogen release with or without fence, *International Journal of Hydrogen Energy*, 46, No. 73, 2021, pp. 36598–36609

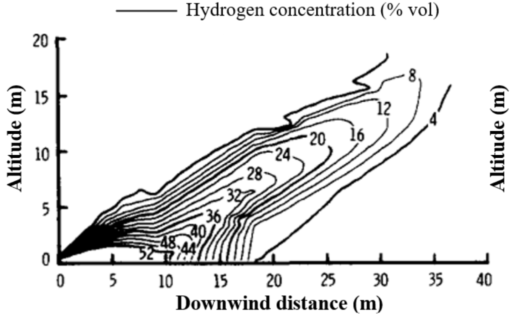
[3] Xie, Y., Lv, N., Wang, X., Wu, D. and Wang, S., Thermal and fire characteristics of hydrogen jet flames in the tunnel at longitudinal ventilation strategies, *Fuel*, 306, 2021, 121659.

NUMERICAL MODELING

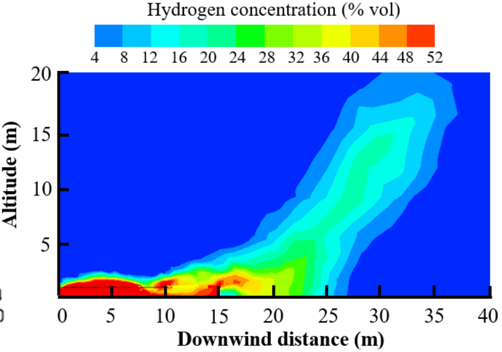
CODE VALIDATION

Comparison with the experimental test performed by NASA [1] of LH_2 release in the open

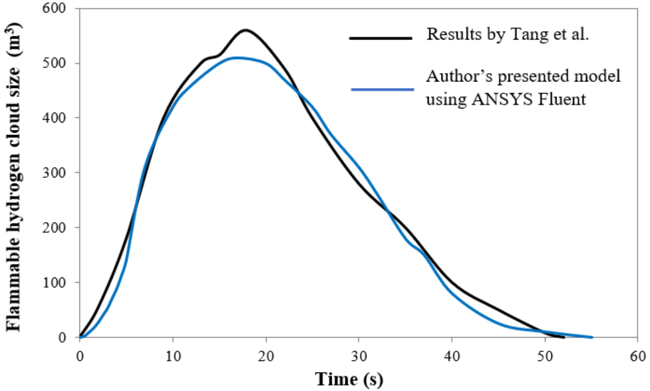
*Experimental results by **NASA***



*Simulated results by **ANSYS Fluent***



Comparison with the numerical study by Tang et al. [2] of LH_2 release in a road tunnel



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[1] Witcofski, R.D. and Chirivella, J.E., Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills, *International Journal of Hydrogen Energy*, 9, No. 5, 1984, pp. 425–435.

[2] Tang, X., Pu, L., Shao, X., Lei, G., Li, Y. and Wang, X., Dispersion behavior and safety study of liquid hydrogen leakage under different application situations, *International Journal of Hydrogen Energy*, 45, No. 55, 2020, pp. 31278–31288.

NUMERICAL MODELING

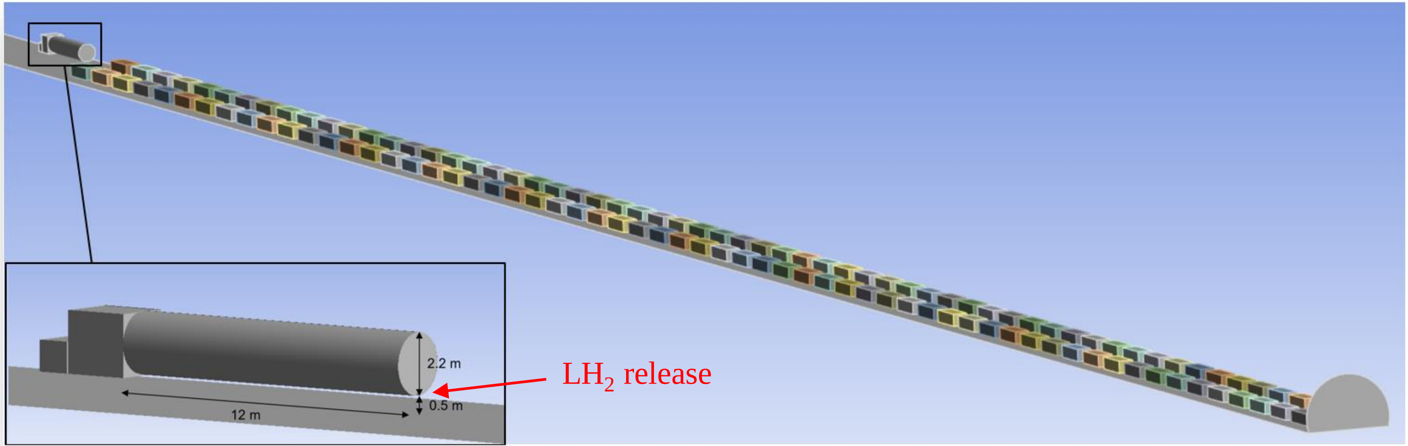
COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

Atmospheric initial conditions →

- P = 101,325 Pa;
- T = 288 K;

Boundary conditions →

- Entrance portal: Pressure inlet (5 Pa [1] to account for the natural ventilation);
- Exit portal: Pressure outlet;
- Tunnel walls and road pavement: No-slip conditions;
- Source: Mass flow inlet (7.7 kg/s LH_2 constant release for 5.4 min);



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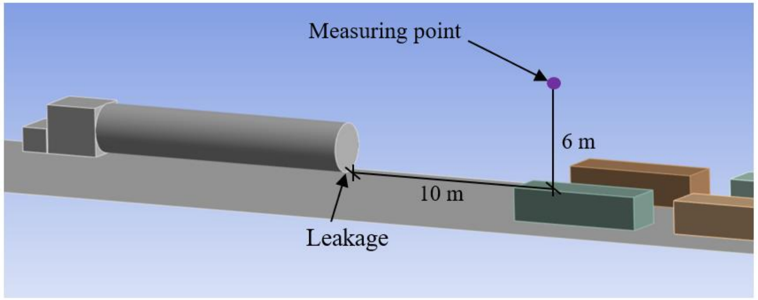
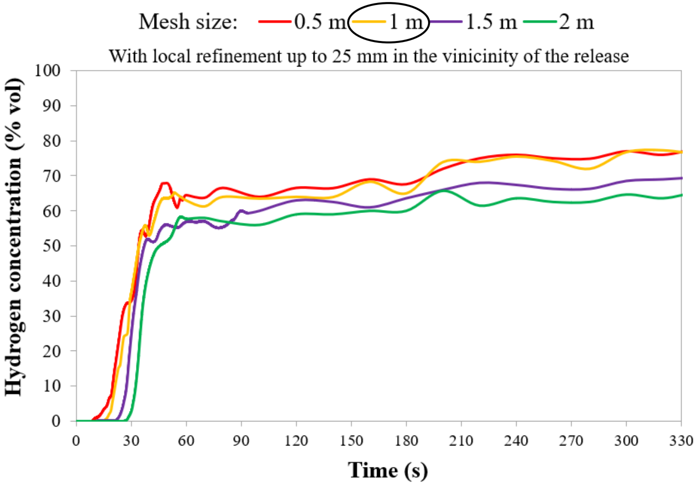
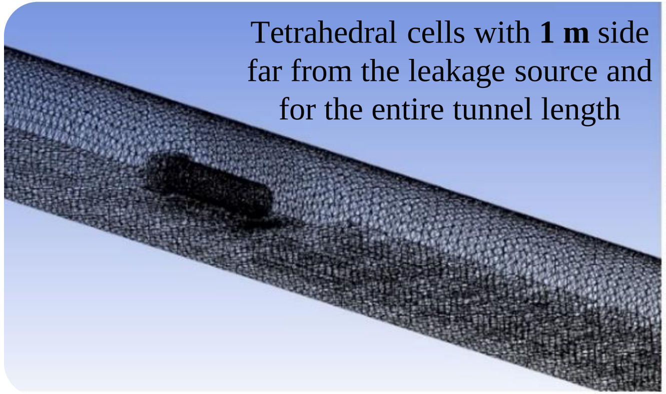
[1] Ciambelli, P., Meo, M.G., Russo, P. and Vaccaro, S., Natural Vs Forced Ventilation During Fires In Relatively Short Road Tunnels, Proceedings of 29th Meeting of the Italian Section of the Combustion Institute, Pisa, Italy, 14-17 January 2006.

NUMERICAL MODELING

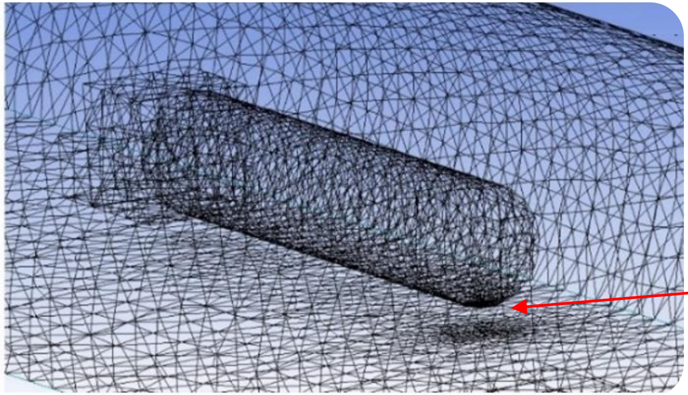
GRID SENSITIVITY ANALYSIS





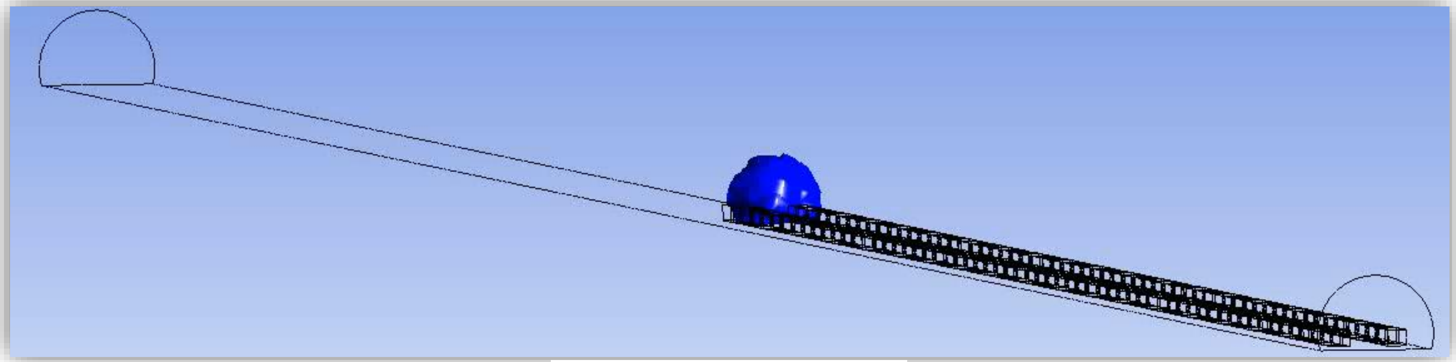


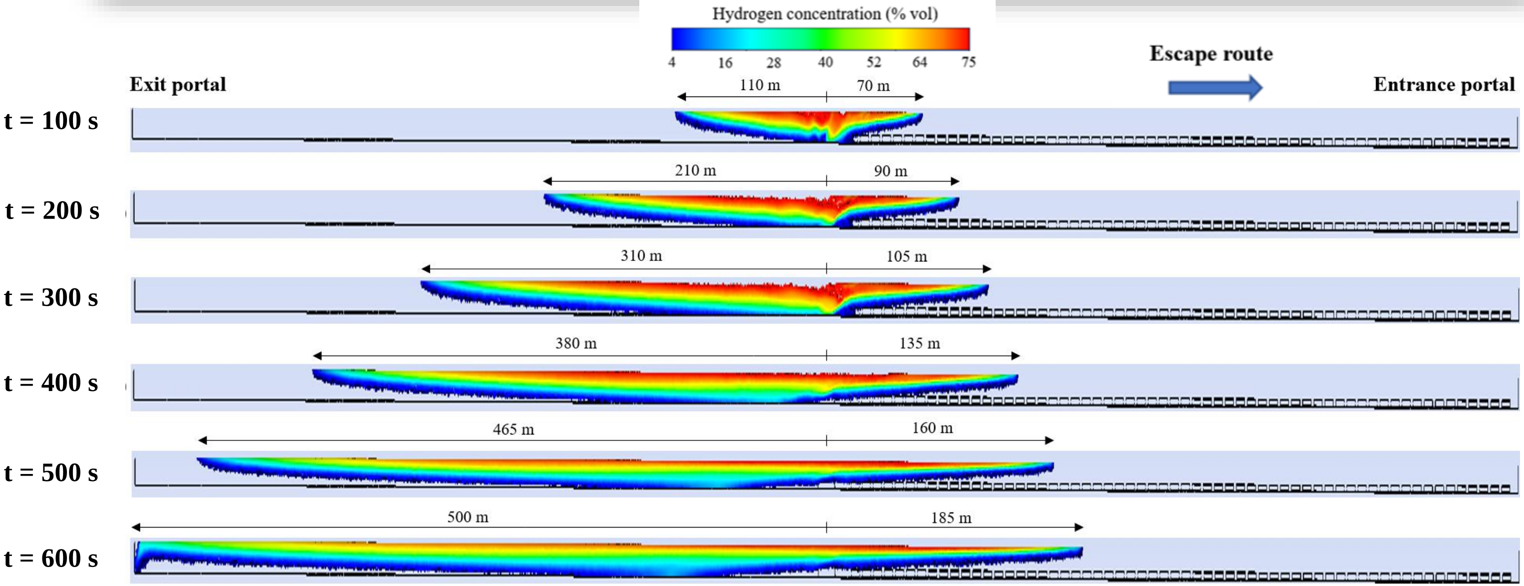
Tetrahedral cells with **1 m** side far from the leakage source and for the entire tunnel length



Local refinement up to **25 mm** near the source location

RESULTS

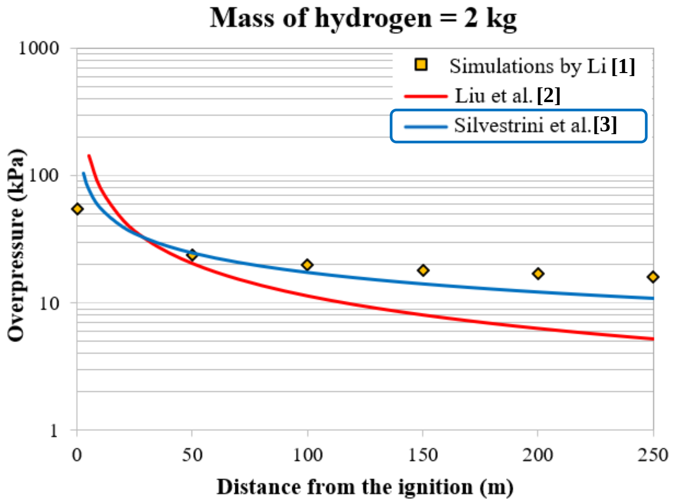


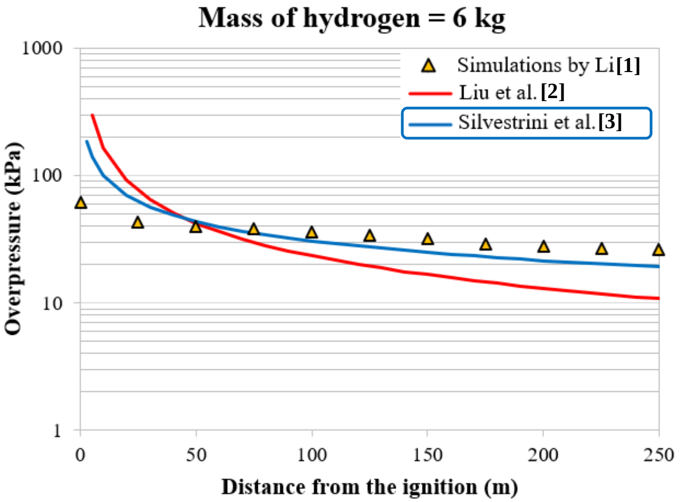

Hydrogen concentration (% vol)
4
16
28
40
52
64
75
Escape route
Exit portal
Entrance portal
110 m
70 m
t = 100 s
210 m
90 m
t = 200 s
310 m
105 m
t = 300 s
380 m
135 m
t = 400 s
465 m
160 m
t = 500 s
500 m
185 m
t = 600 s

RESULTS

EVALUATION OF CONSEQUENCES OF A POTENTIAL DEFLAGRATION

- To predict the overpressure generated from a potential deflagration, two simplified engineering correlations have been examined, based on the mass of hydrogen contained within the cloud.





[1] Li, Y.Z., Fire and explosion hazards of alternative fuel vehicles in tunnels, Research Institutes of Sweden, Rapport 2018:20, 2018.

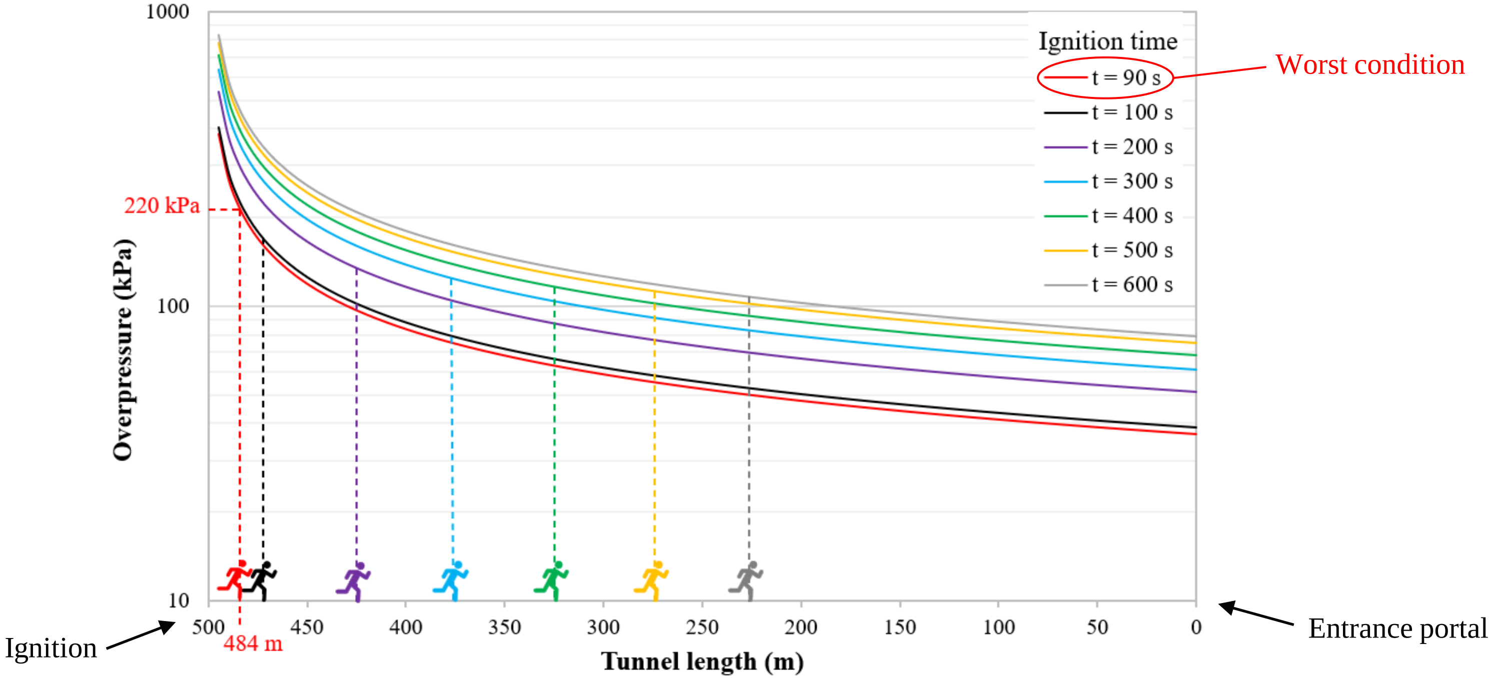
[2] Liu, J., Yan, Q. and Wu, J., Analysis of blast wave propagation inside tunnel, *Transactions of Tianjin University*, 14, No. 5, 2008, pp. 358–362.

[3] Silvestrini, M., Genova, B. and Trujillo, F.J.L., Energy concentration factor. A simple concept for the prediction of blast propagation in partially confined geometries, *Journal of Loss Prevention Process in the Process Industries*, 22, No. 4, 2009, pp. 449–454.

RESULTS

OVERPRESSURE ESTIMATED WITH THE SIMPLIFIED METHOD

- Overpressures over distance as a consequence of the hydrogen deflagration within the investigated tunnel tube for different ignition times when the leakage occurs in the middle of the tunnel length.

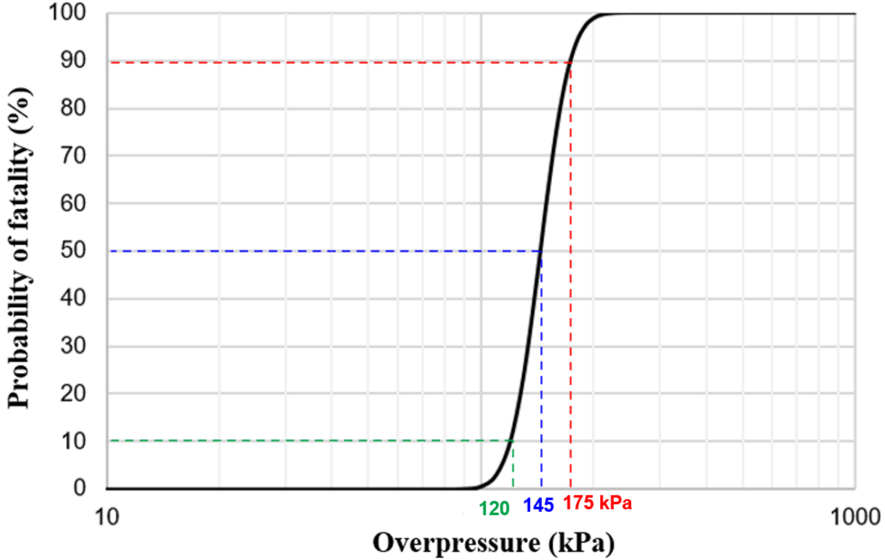


RESULTS

- The Eisenberg probit function [1] was used to correlate the overpressure (P_s) with the probability of human falatity (P_r) due to lung hemorrhage ⟶ $Y = -77.1 + 6.91 \cdot \ln(P_s)$

Y	P_r(%)
0,00	0
3,72	10
4,16	20
4,48	30
4,75	40
5,00	50
5,25	60
5,52	70
5,84	80
6,28	90
8,09	100

Distribution function



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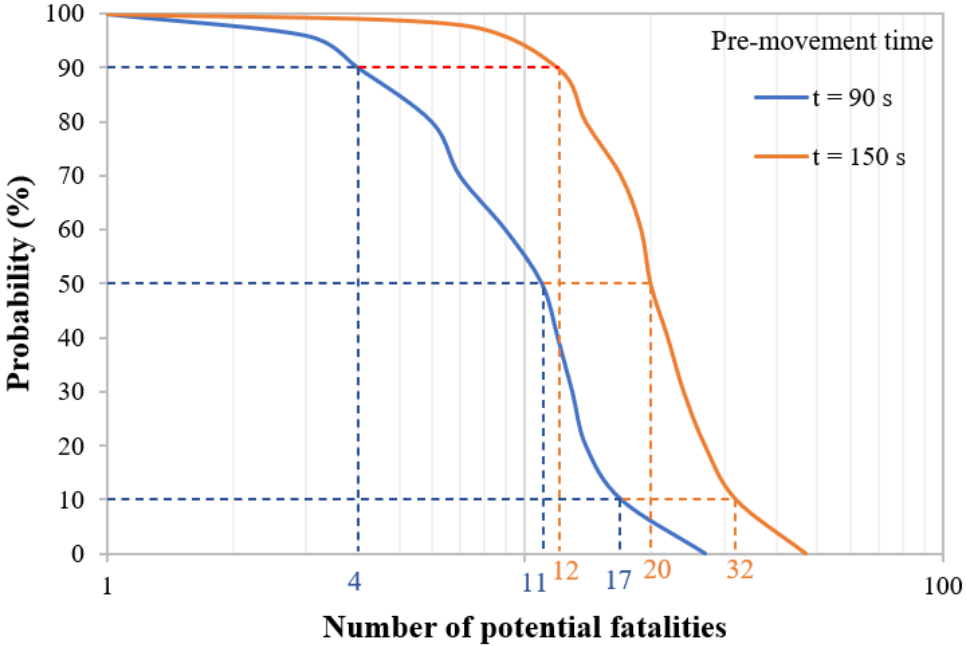
[1] LaChance, J., Tchouvelev, A. and Engebo, A., Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure, *International Journal of Hydrogen Energy*, 36, No. 3, 2011, pp. 2381–2388.

RESULTS

- By knowing the position of each user within the tunnel tube during the evacuation process it was possible to estimate the number of people exposed to a given overpressure and their probability of fatality.



CONCLUSIONS

- A **3D CFD model of liquid hydrogen release** from a tanker within a road tunnel was developed and validated against experimental tests and numerical simulations;

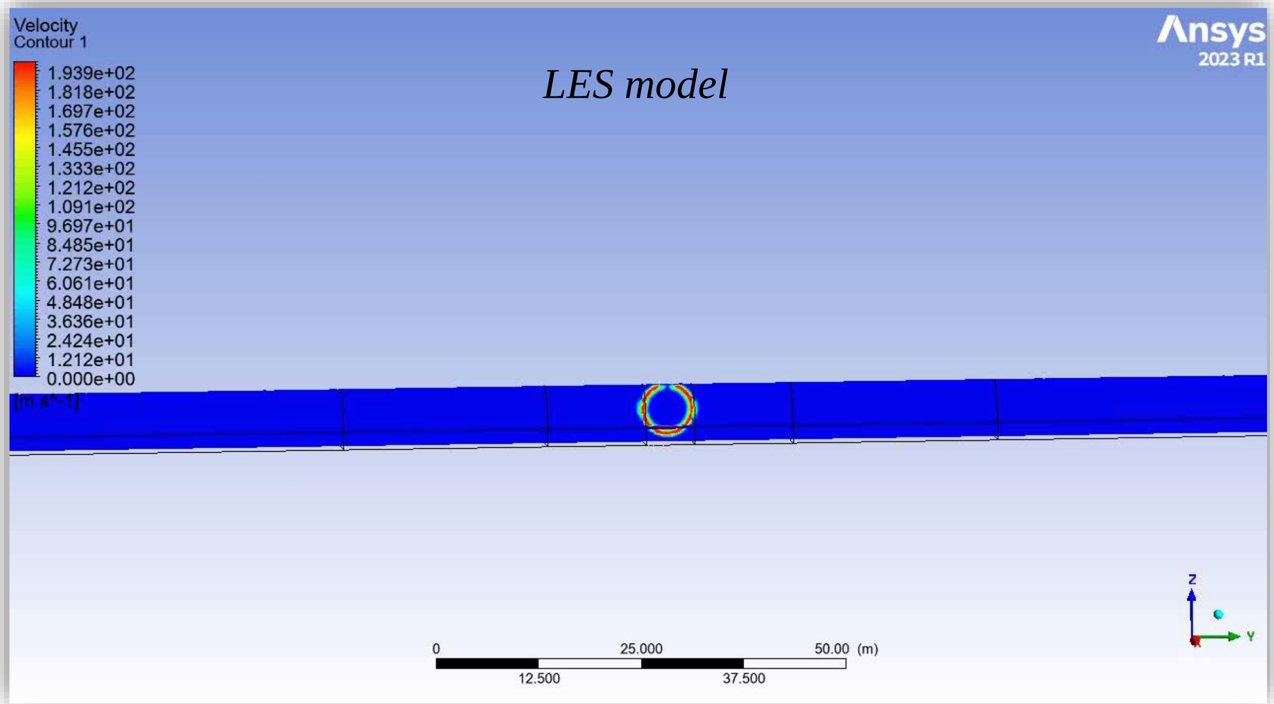
- The results showed that the worst-case scenario is when the release occurs in the middle of the tunnel length, and the potential ignition of the flammable hydrogen cloud after 90 s from the release.

- The **number of potential fatalities** due to lung hemorrage as a consequence of the deflagration **significantly increases** with the pre-movement time of the escaping users. This means that the evacuation process should start as soon as possible when an accidental release of LH_2 occurs in a road tunnel.

CONCLUSIONS

FURTHER STUDIES

- Development of a **CFD model to estimate the overpressures** due to hydrogen deflagration



THANK YOU

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