HyTunnel-CS
Dissemination Conference
Hotel, Brussels
14-15 Jul 2022

Drastic difference between fireball dynamics in the open space and in a tunnel

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Blast wave in a tunnel
Outline

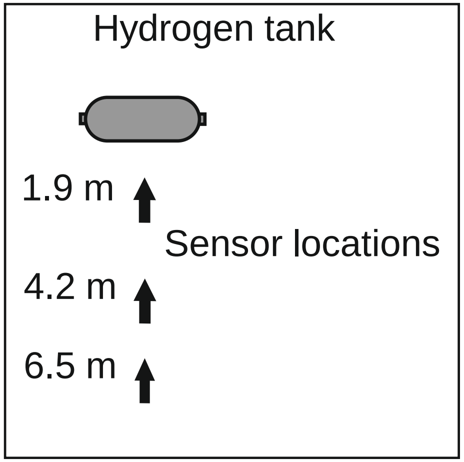
- Fireball in open space
  - Numerical details
  - Model validation
  - Simulation results
- Fireball in a tunnel
  - Numerical details
  - Model validation
  - Simulation results
- Conclusions

FB in open space

CFD model
Description

- The Reynolds averaged Navier-Stokes (RANS) equations.
- The renormalization group k-ε turbulence model (Yakhot & Orszag).
- The eddy dissipation concept (EDC) combustion model (Magnussen et al.).
- The 37-step chemical reaction mechanism of hydrogen combustion in air with 13 species (Peters & Rogg).
- The in-situ adaptive tabulation (ISAT) algorithm accelerating chemistry calculations by 2-3 orders of magnitude (Pope).
- The discrete ordinates (DO) radiation model.

Bonfire test
Experimental set up



- Heat release rate 370 kW
- Stand-alone type 4 tank volume 72.4 L
- Pressure 34.5 MPa
- Three pressure sensors **@ 1.9 m, 4.2 m and 6.5 m**

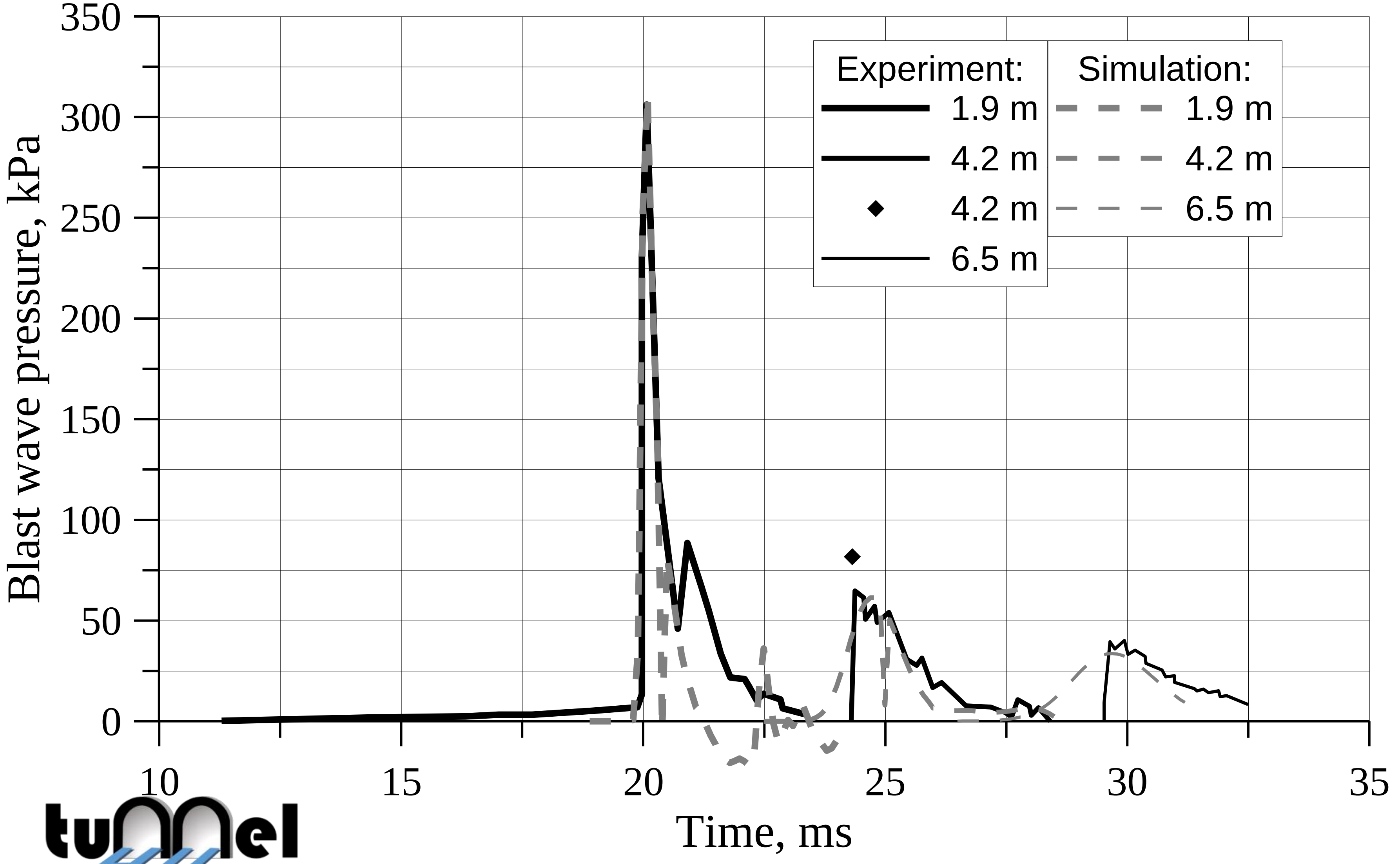
Weyandt N. Analysis of Induced catastrophic failure of a 5000 psig type IV hydrogen cylinder. Southwest Research Institute Report for the Motor Vehicle Fire Research Institute; 2005. 01.06939.01.001.

Bonfire test
Results

- Tank rupture (fire resistance) after **6 m 27 s**
- Peak pressures varied from: **300 kPa** at 1.9 m to **41 kPa** at **6.5 m**
- Fireball diameter at 45 ms **7.7 m** (Weyandt, 2005)
- Tank fragment projectiles were found at distances of **34 m to 82 m.**

Model validation

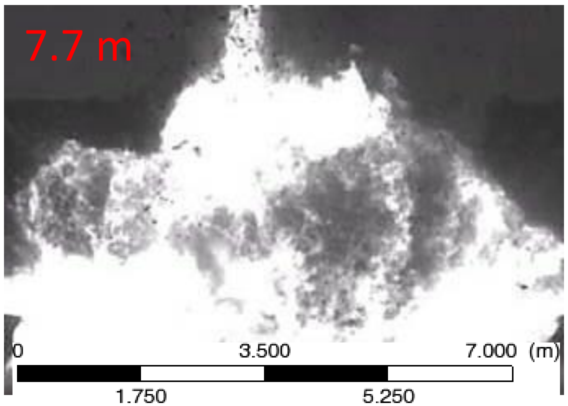
Overpressure transients



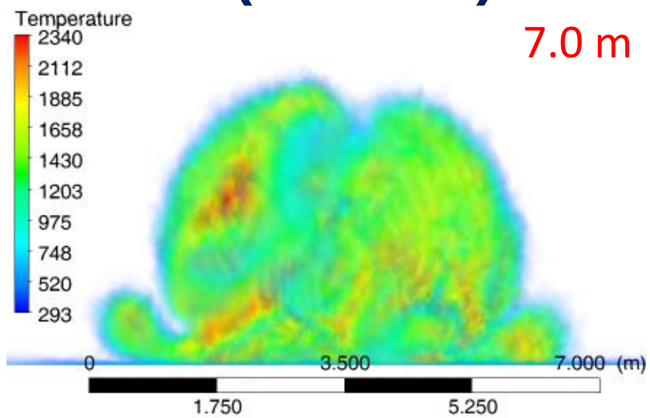
Model validation

Fireball size at 45 ms

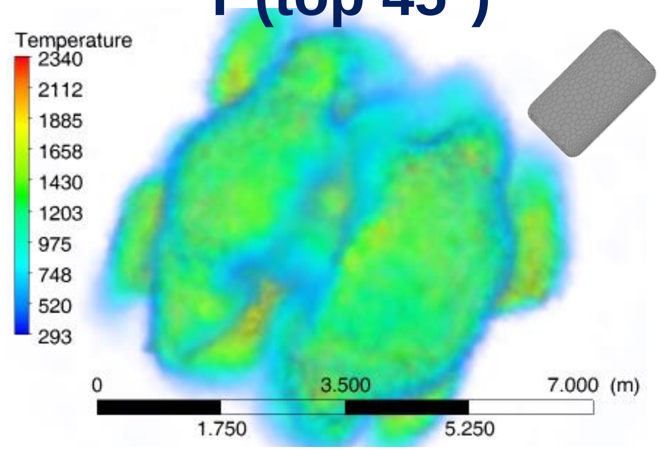
Experiment



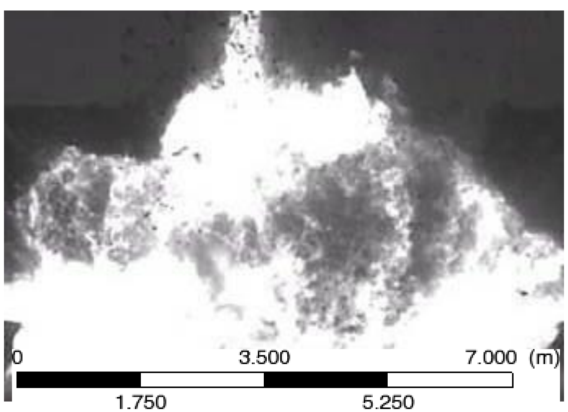
T (side 45º)



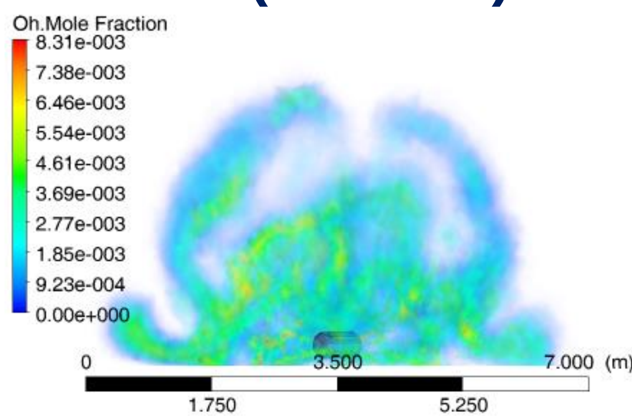
T (top 45º)



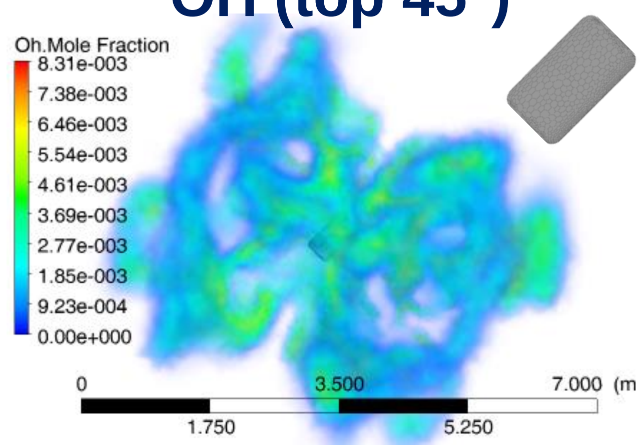
Experiment



OH (side 45º)

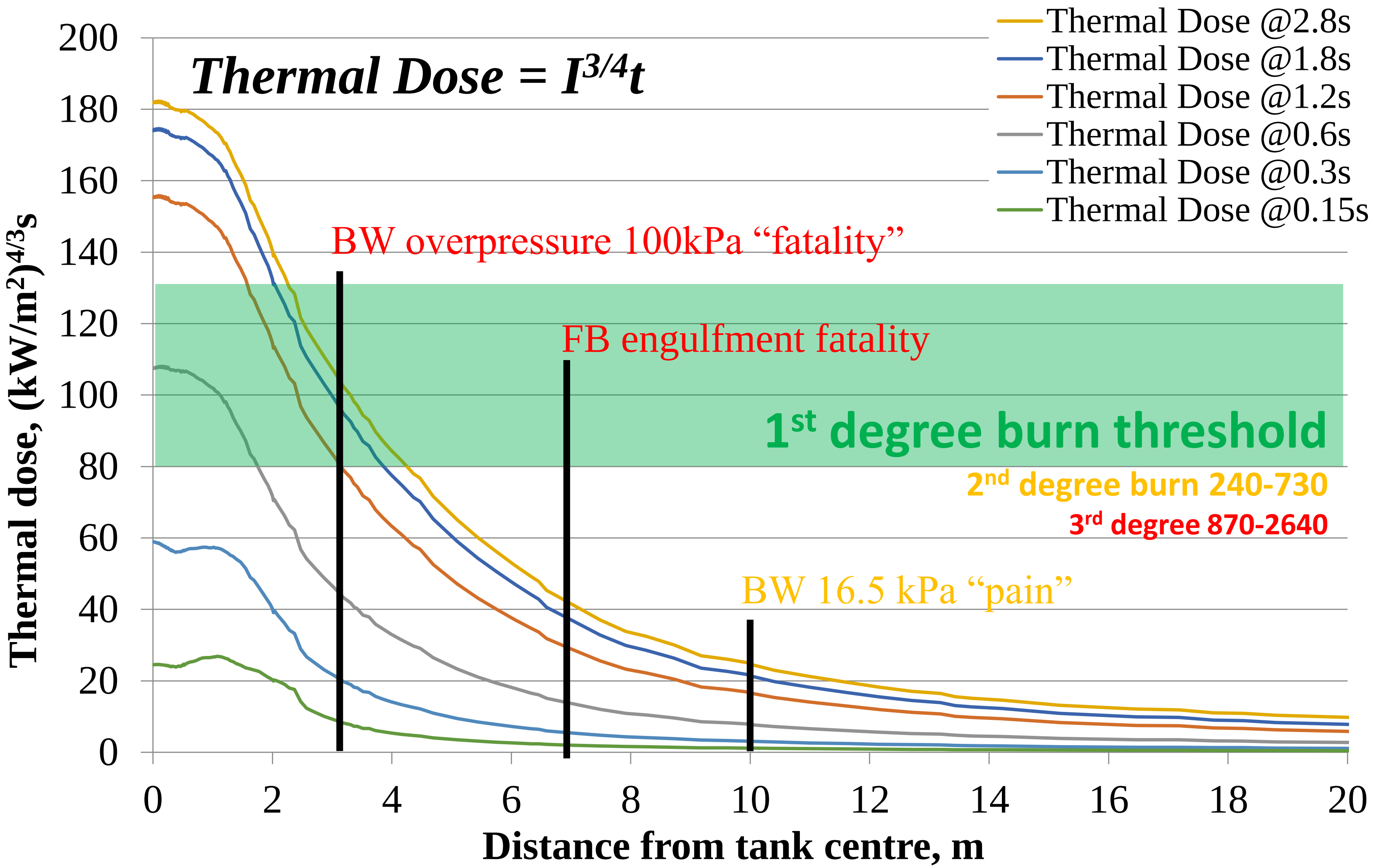


OH (top 45º)



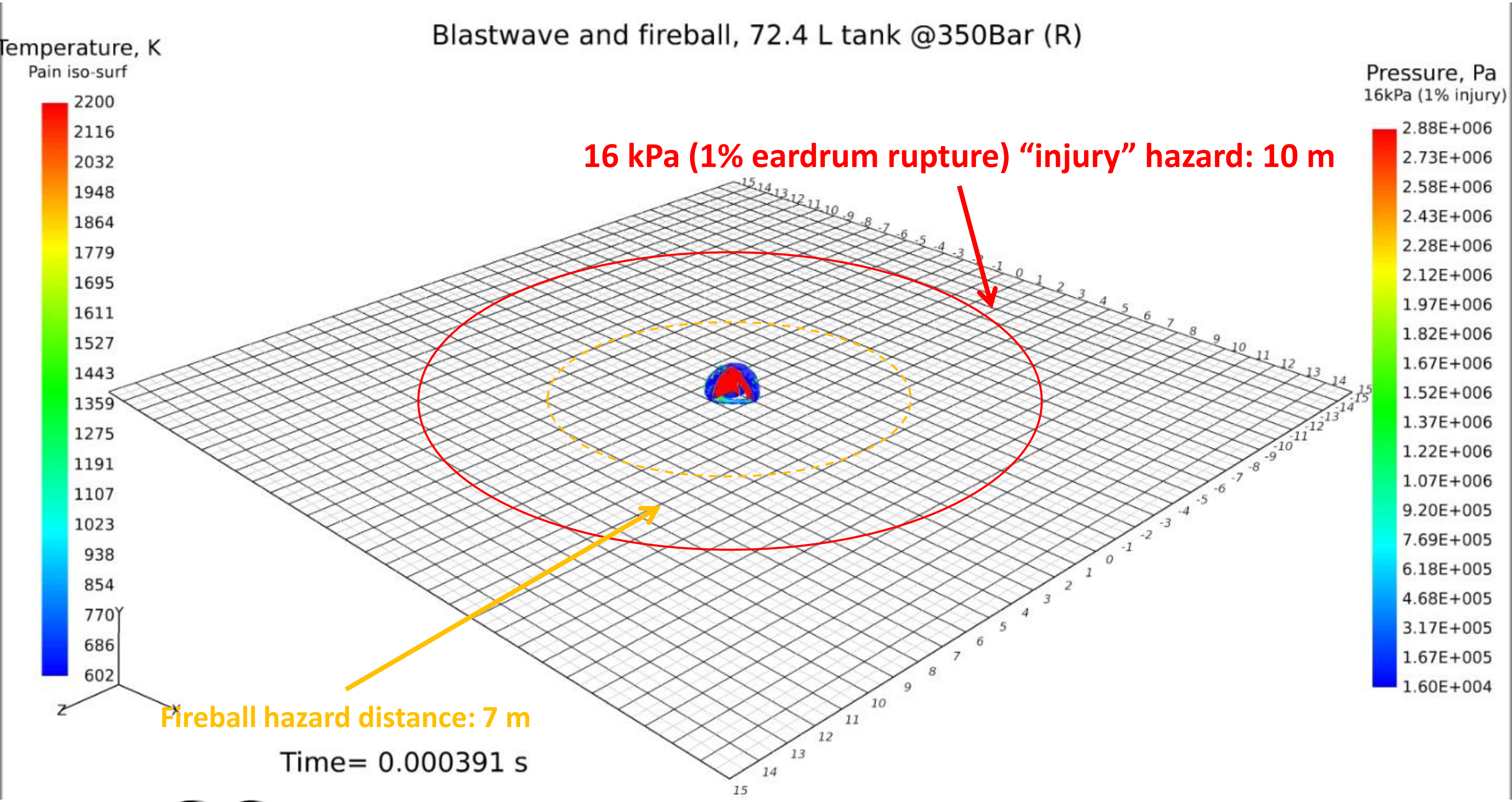
Hazard distance

Fireball vs Blast Wave vs Thermal Dose



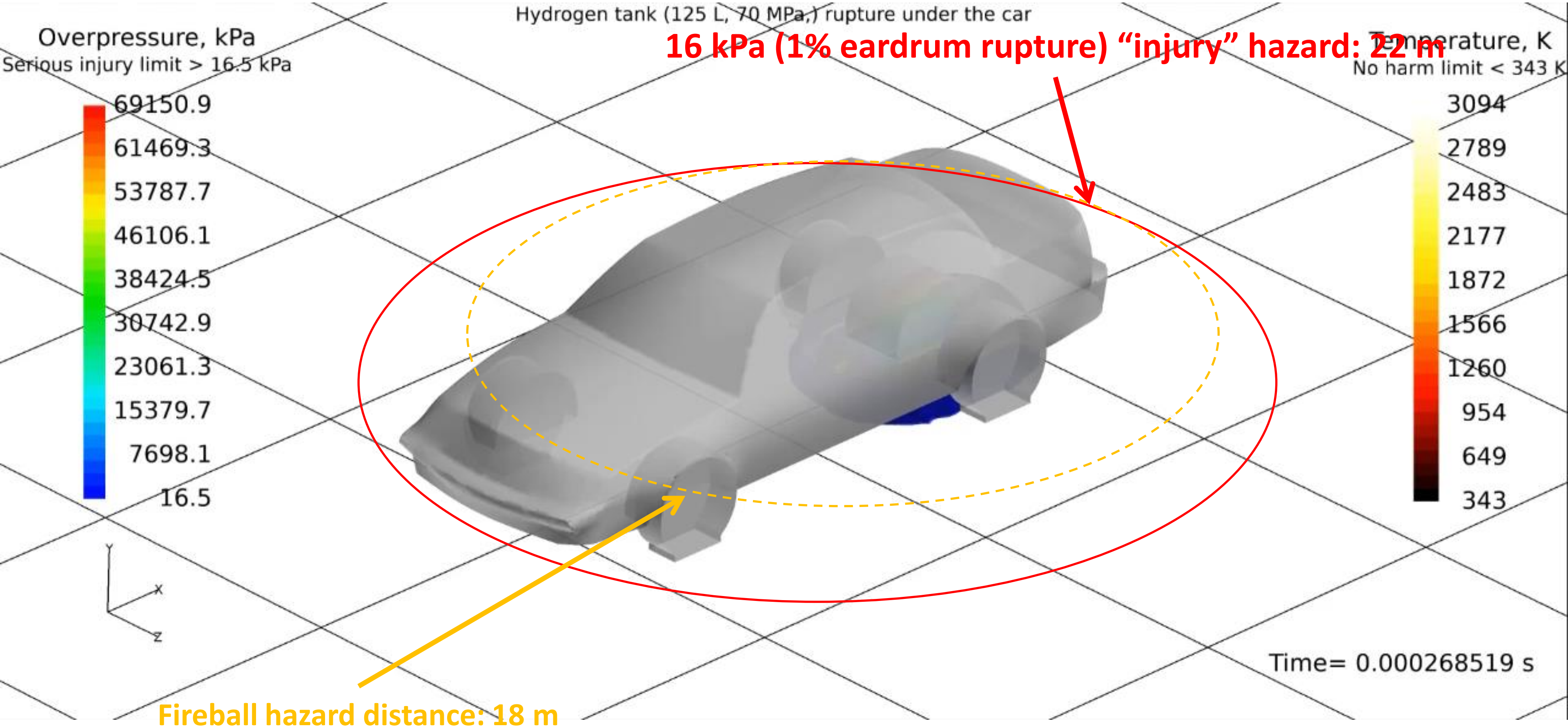
Thermal dose outside the fireball is at "no harm" level during fireball existence

Hazard distances
Blast versus fireball stand alone tank



Hazard distances

Blast versus fireball: under-vehicle tank



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FB in Tunnel

LES model of blast wave and fireball

Numerical details 1/2

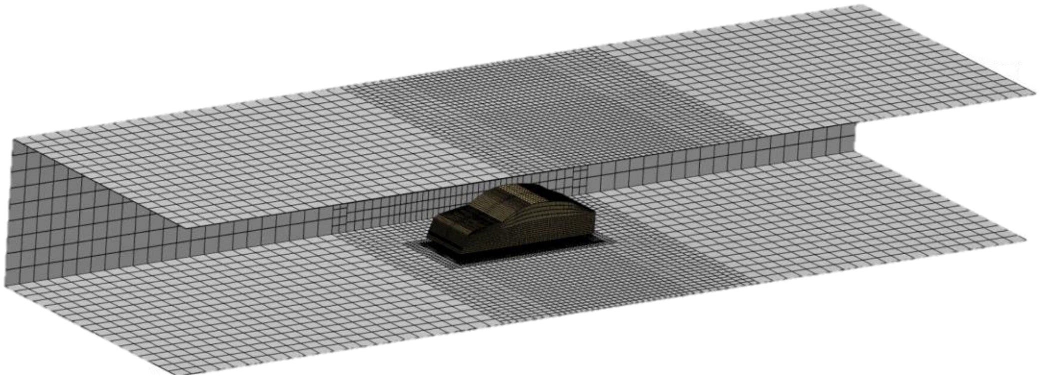
- LES of shock and reacting compressible flow using Fluent 2021R2 as an engine
- The density-based solver
- The tunnel walls and floor are specified as non-adiabatic to allow heat transfer from the combustion, the ground is no-slip wall
- The external non-reflecting boundary is defined as pressure outlet
- The governing equations are based on the filtered conservation equations for mass, momentum, and energy in their compressible form with Redlich-Kwong real gas EoS

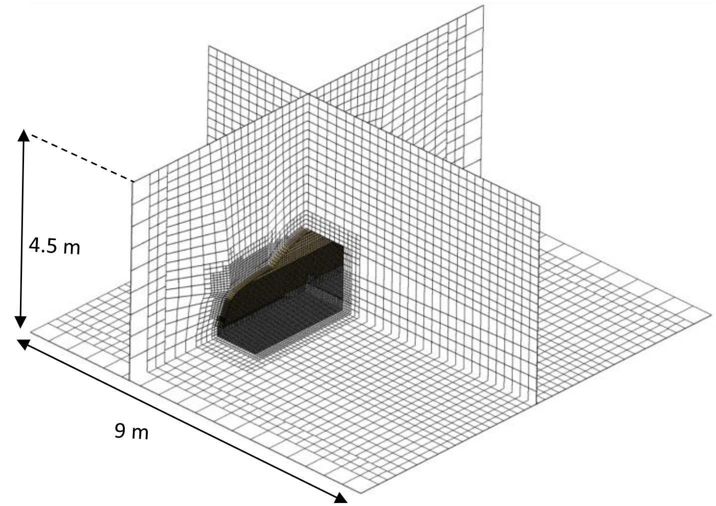
LES model of blast wave and fireball

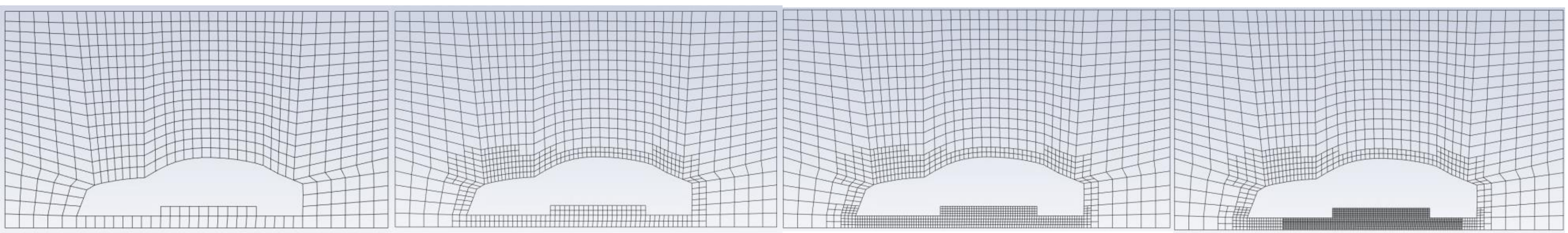
Numerical details 2/2

- The Least Square Cell-Based and second-order upwind scheme were used for convective terms.
- The time step adapting technique was employed to maintain a constant Courant-Friedrichs-Lewy (CFL) number at the value of 0.2 until the blast wave left the tunnel at 1 s and gradually increased up to the value of 2 during 100 time steps to speed up the simulation of a fireball
- The Smagorinsky-Lilly model for the SGS turbulence modelling
- Turbulence-chemistry interaction by FRC model with one-step Arrhenius chemistry

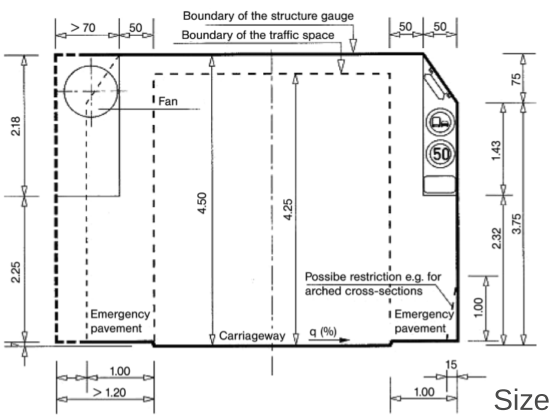
Numerical model
Grid







Original | Refined 2x (+6.7k CV) | Refined 4x (+24.7k CV) | Refined 8x (73.2k CV)



Size of the tunnel lanes according to Maidl, 2014

- Refinement-derefinement applied
- Dynamic CFL increase

Numerical details

Tunnel and tank parameters

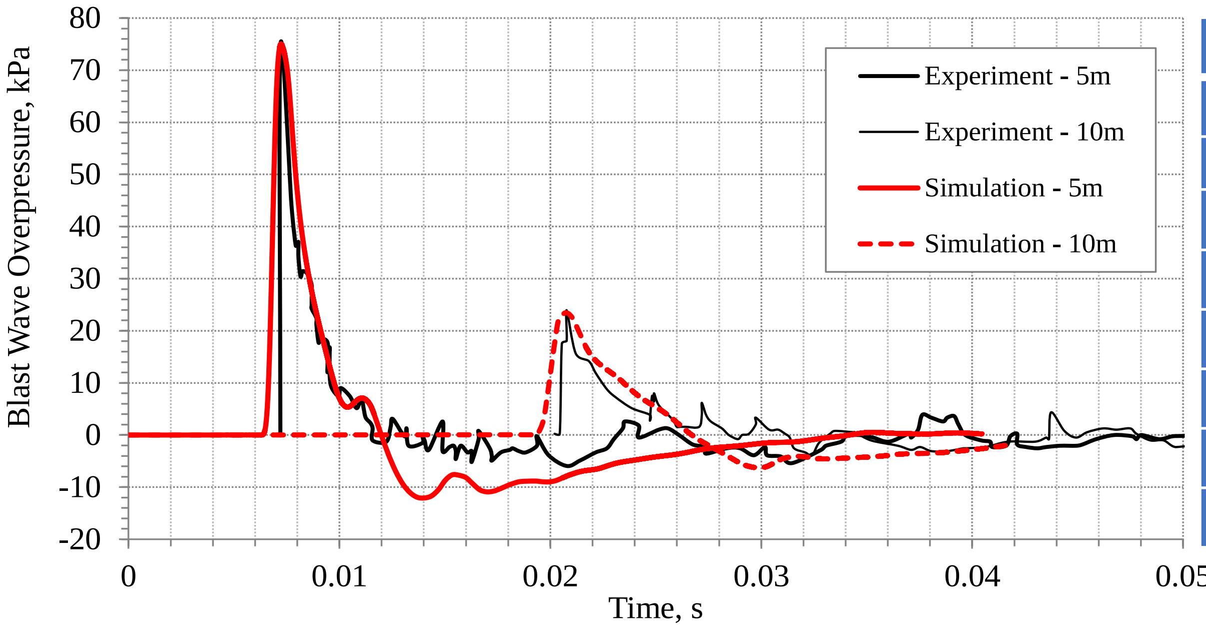
Tunnel cross section, m^2	Tunnel length, m	Tank volume, L	Tank mass, kg	Tank pressure, MPa	Grid CV number
24 (SL) 40 (DL) 139 (FL)	750 m 1500 m (DL, mid)	15	0.61	95	SL 457.4k DL 460.2k FL 876k
		30	1.22		
		60	2.45		
		120	4.9		

Tank volume, L	Pressure, MPa	E_m, MJ		E_{ch}, MJ		E_{tot}, MJ
		E_m	αE_m	E_{ch}	βE_{ch}	$\alpha E_m + \beta E_m$
15	95	2.43	4.38	73.45	8.81	13.19
30		4.86	8.75	146.90	17.63	26.38
60		9.72	17.50	293.81	35.26	52.76
120		19.45	35.01	587.62	70.51	105.52

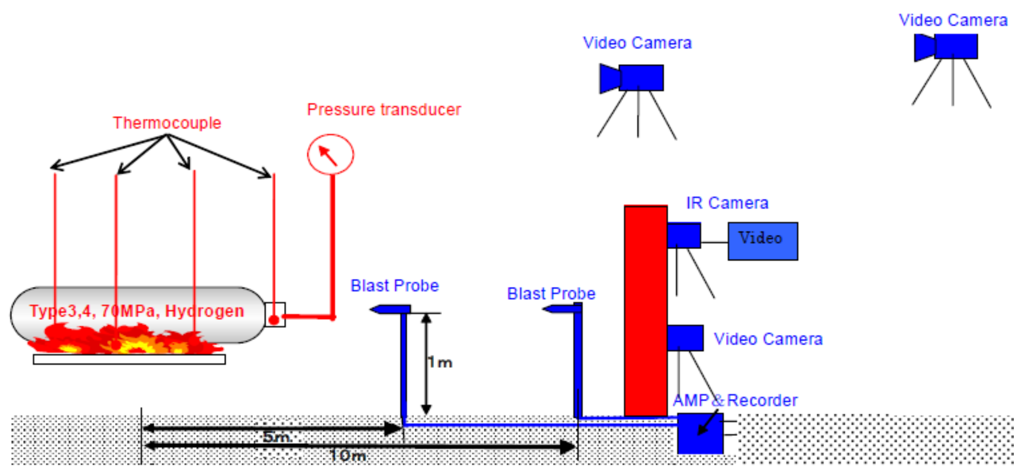
Note:
- SL – single lane, DL – double lane, FL – five lane
- Mechanical energy contribution $\alpha=1.8$
- Chemical energy contribution $\beta=0.12$
- 70 MPa tank ruptures at 95MPa

Model validation

Japanese experiment – open space

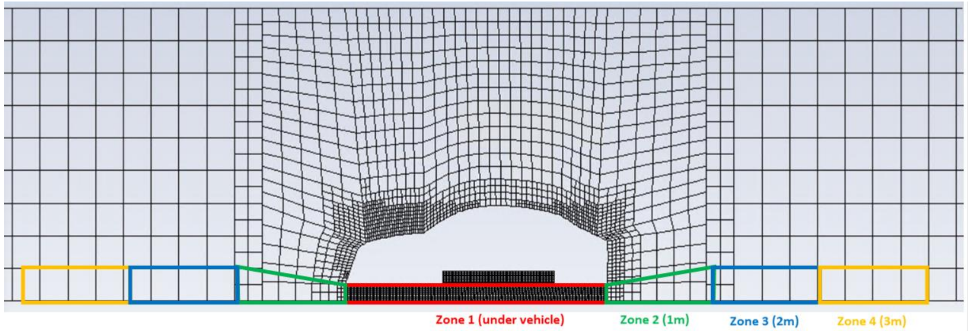


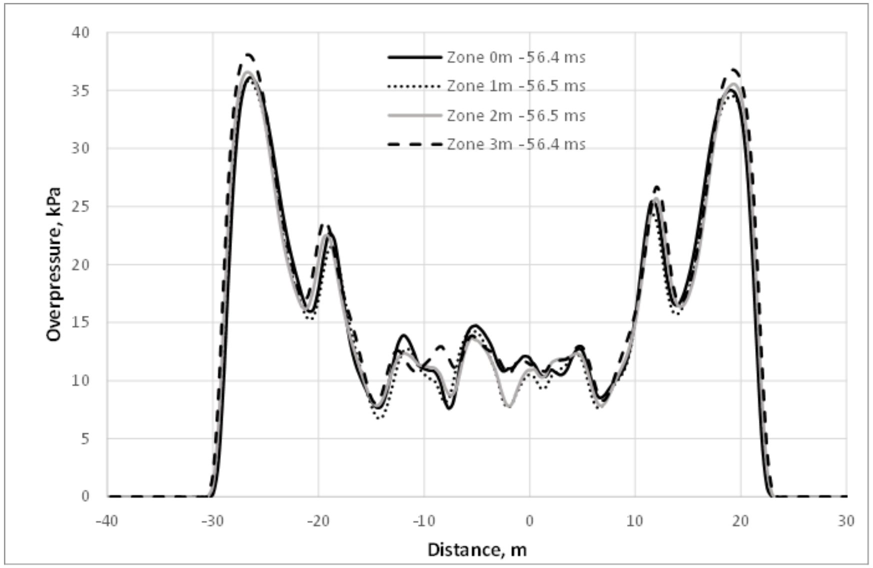
Pressure initial	70.69MPa
Temperature initial	282 K
Pressure before burst	95 MPa
Temperature before burst	398K
Tank Volume	36L
Rupture time	654sec
Blast wave (5m)	74.3kPa
Blast wave (10m)	23.4kPa
Fireball diameter	About 20m

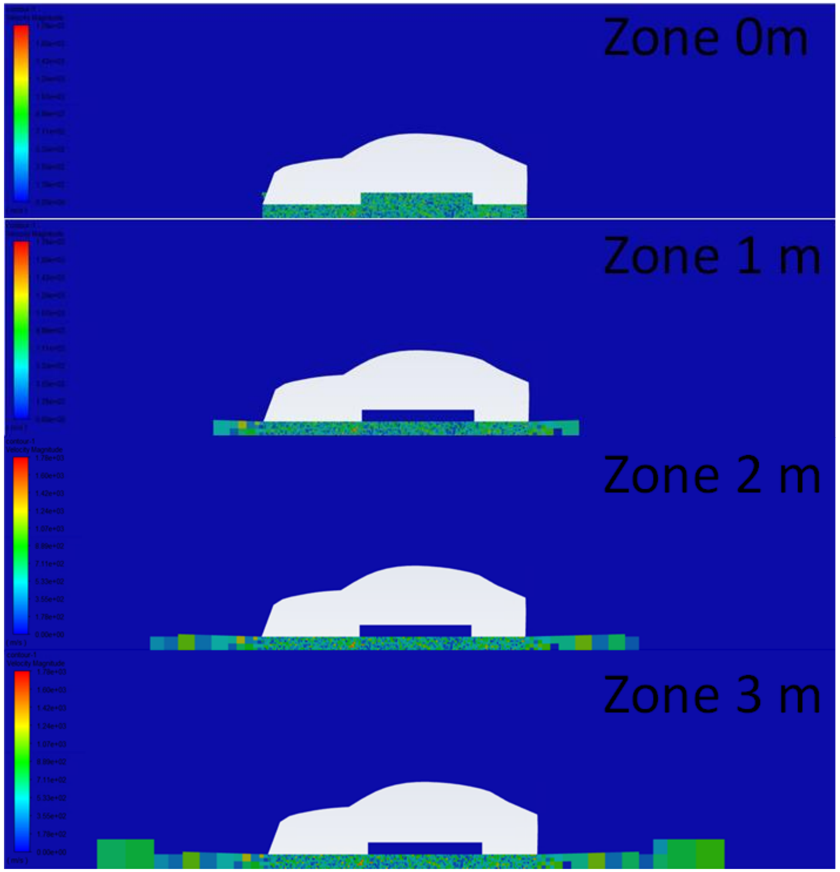


Y. Tamura, M. Takahashi, Y. Maeda, H. Mitsuishi, J. Suzuki, and S. Watanabe, “Fire Exposure Burst Test of 70MPa Automobile High-pressure Hydrogen Cylinders,” The Society of Automotive Engineers of Japan Annual Autum Congress 2006, Sapporo, 2006.

Model with car in a tunnel
Initial turbulence

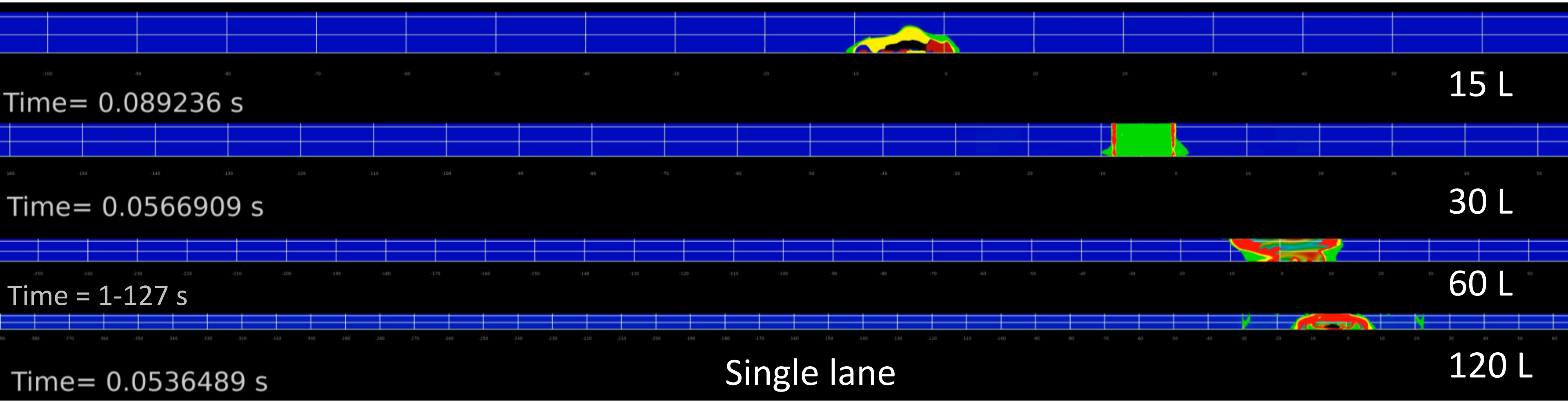


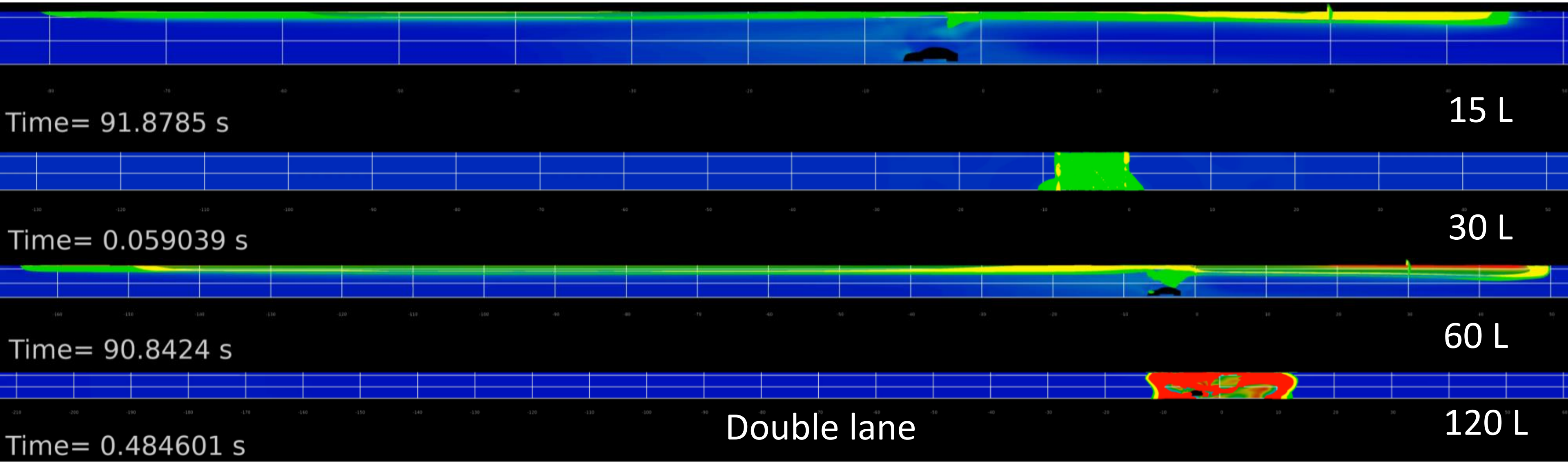




Simulation results

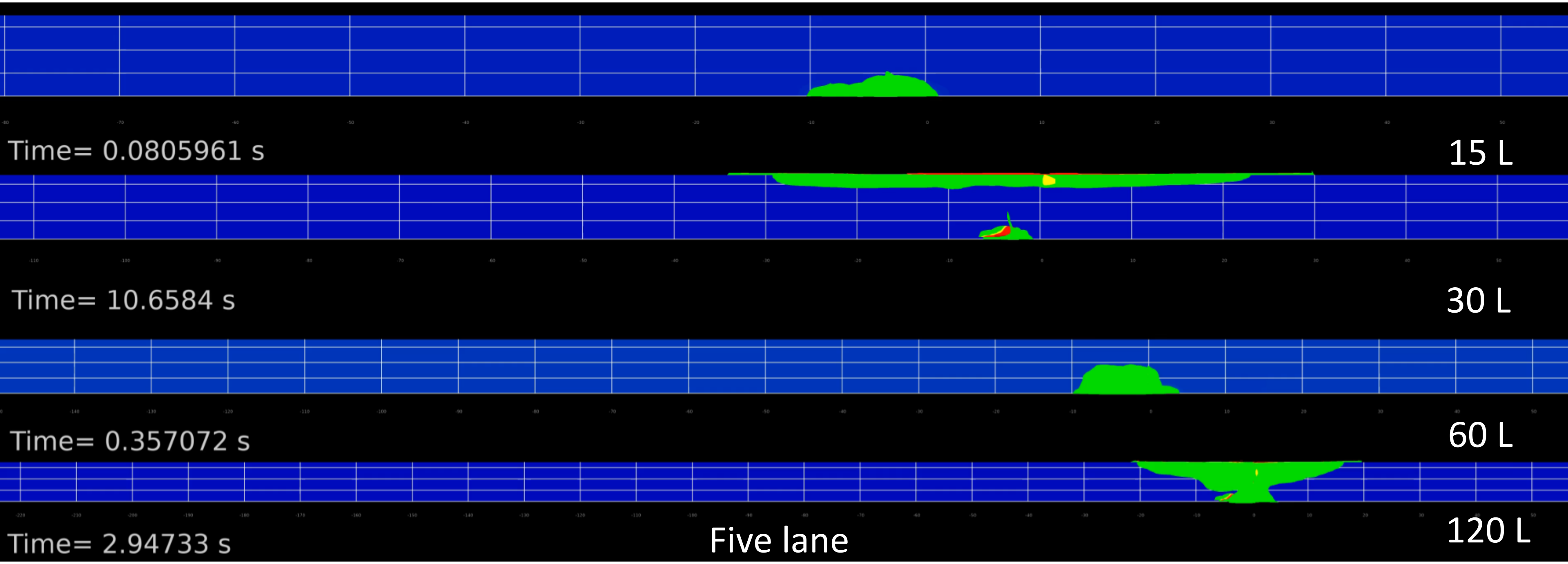
Fireball dynamics in SL and DL tunnel





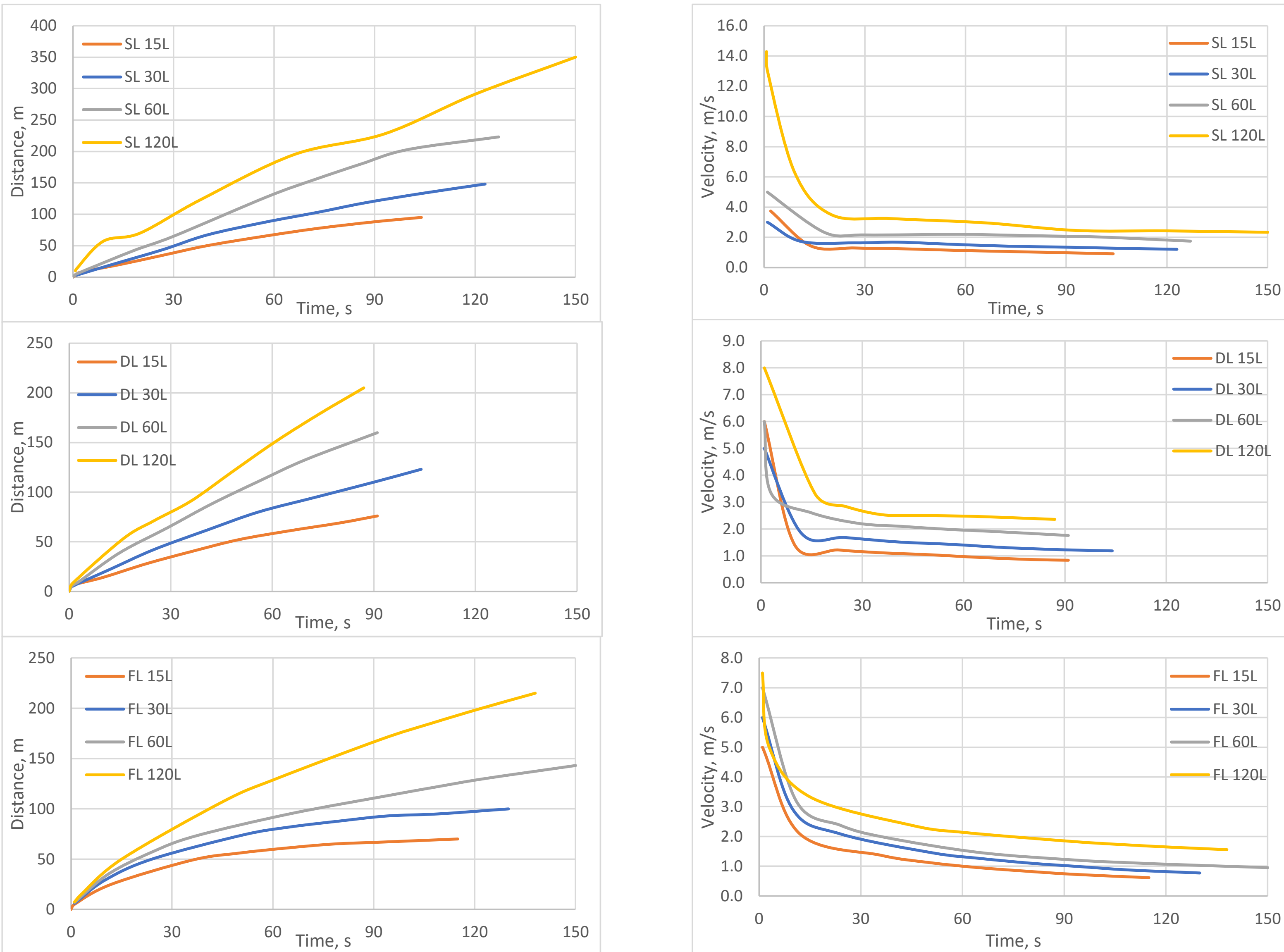
Simulation results

Fireball dynamics in FL tunnel



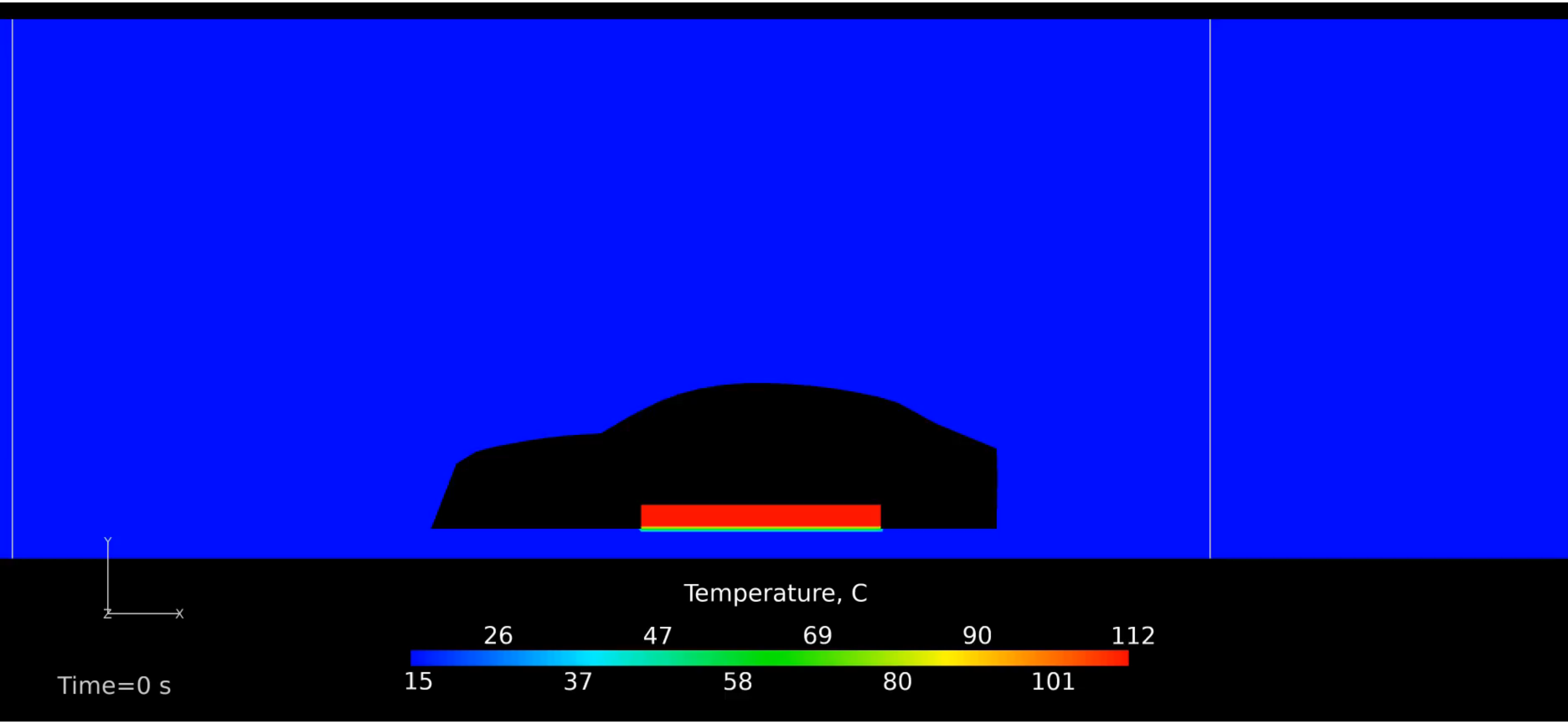
Simulation results

FB no harm hazard distance and velocity decay



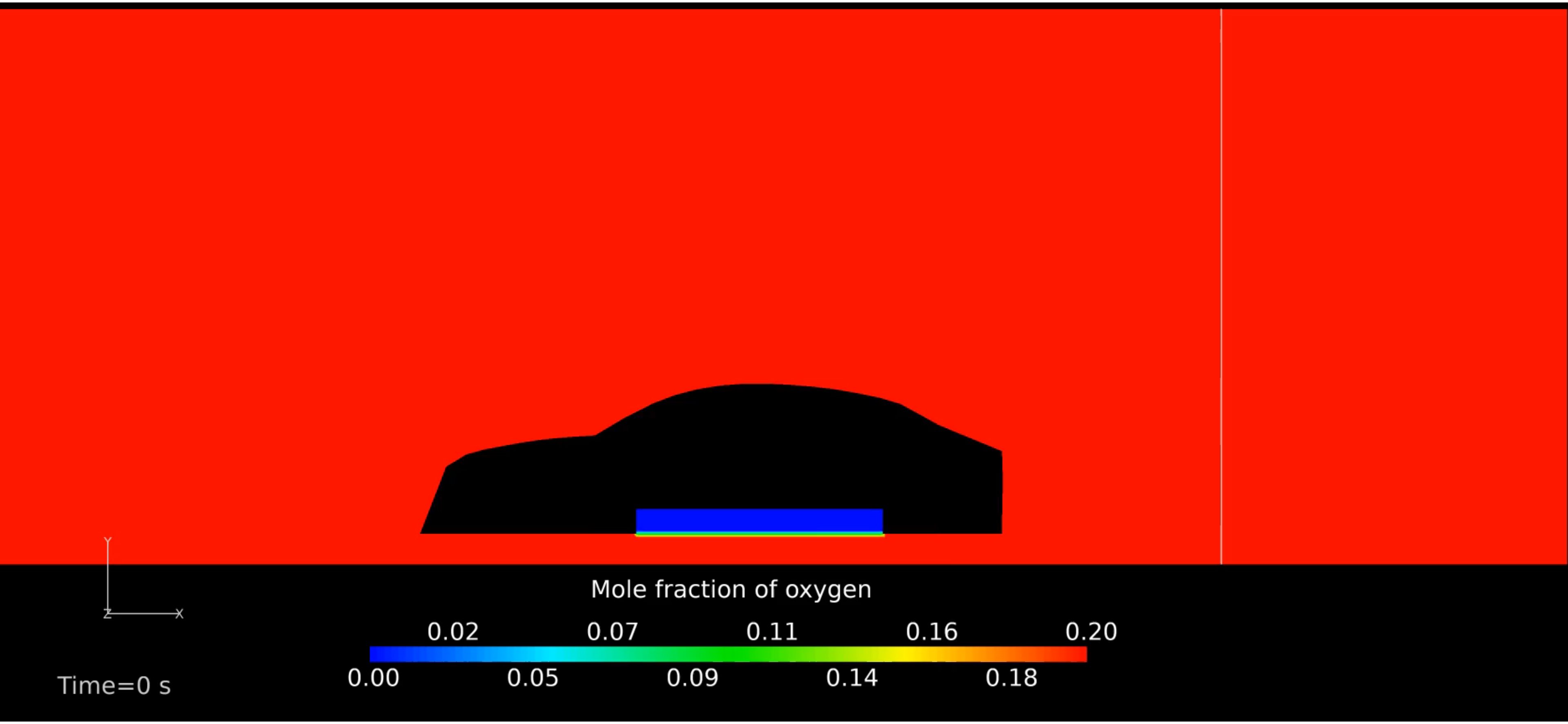
Fireball dynamics

Temperature 120L middle, double lane tunnel



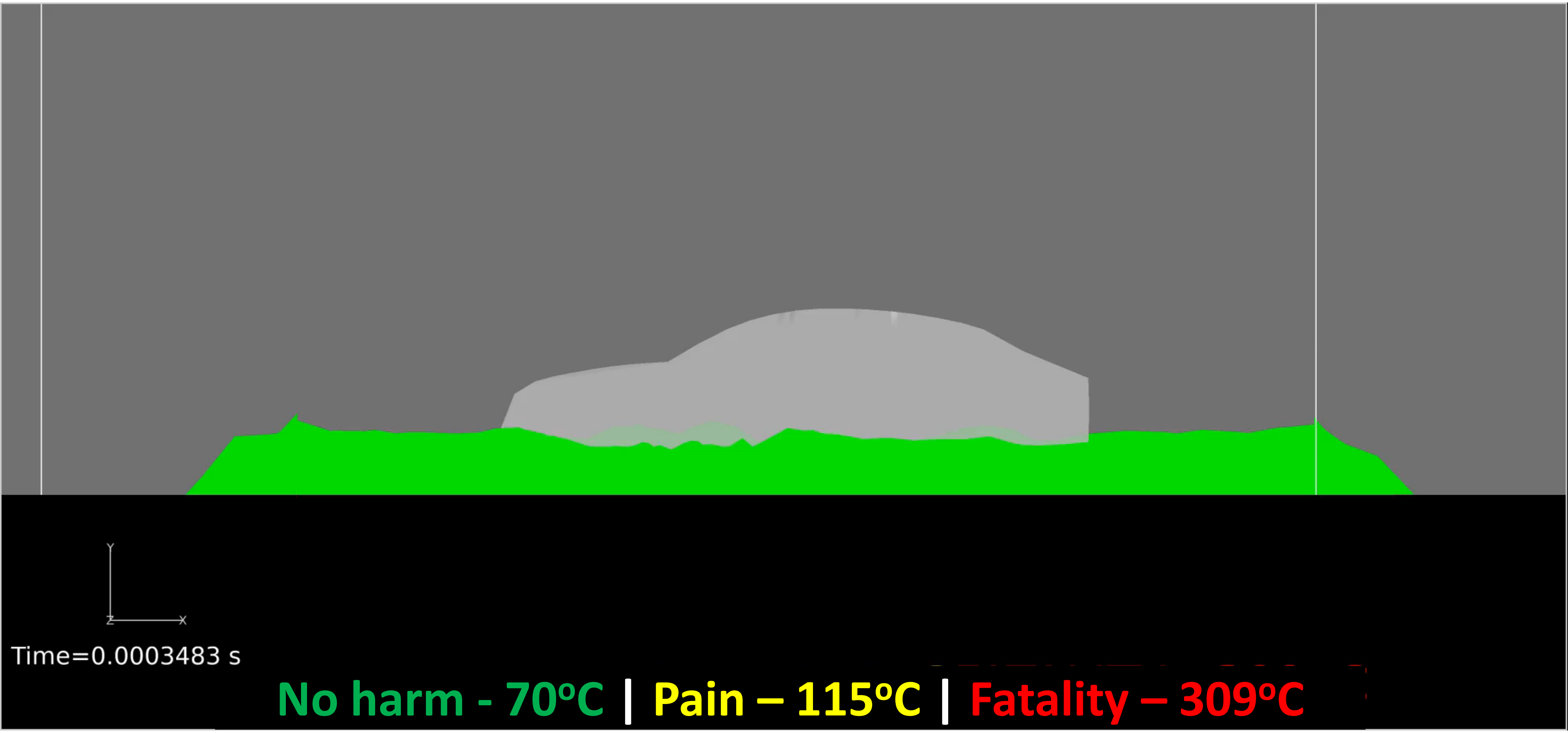
Hazards

Oxygen, 120L middle, double lane tunnel



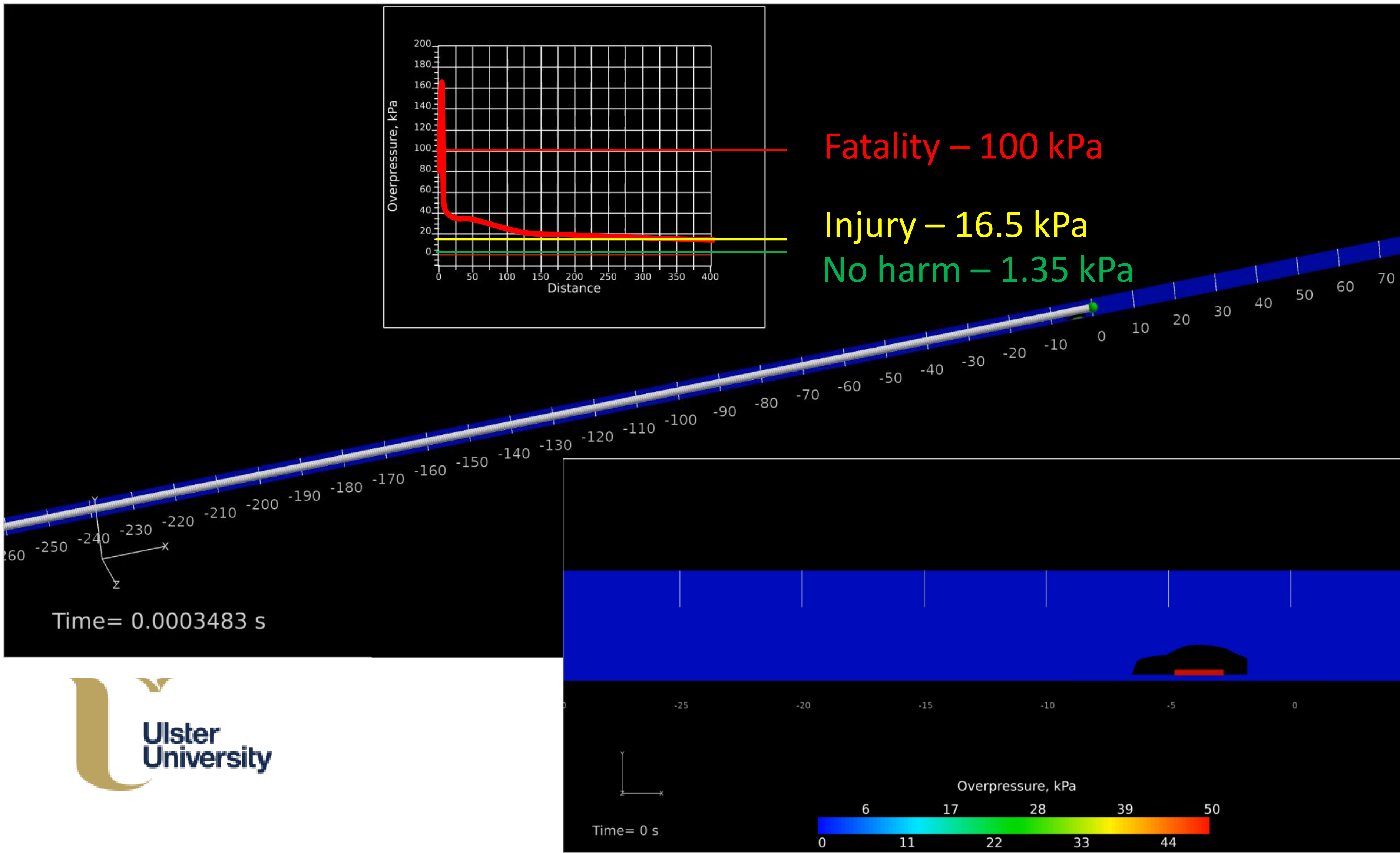
Hazards

Temperature, 120L middle, double lane tunnel



Overpressure

Maximum + dynamics



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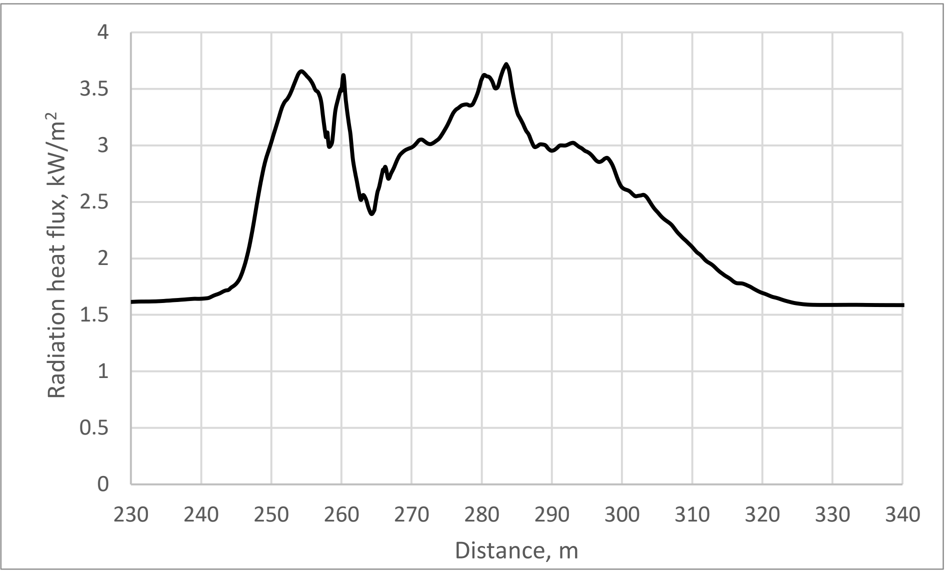
Hazards

Heat flux and thermal dose, 120 L, middle, DL



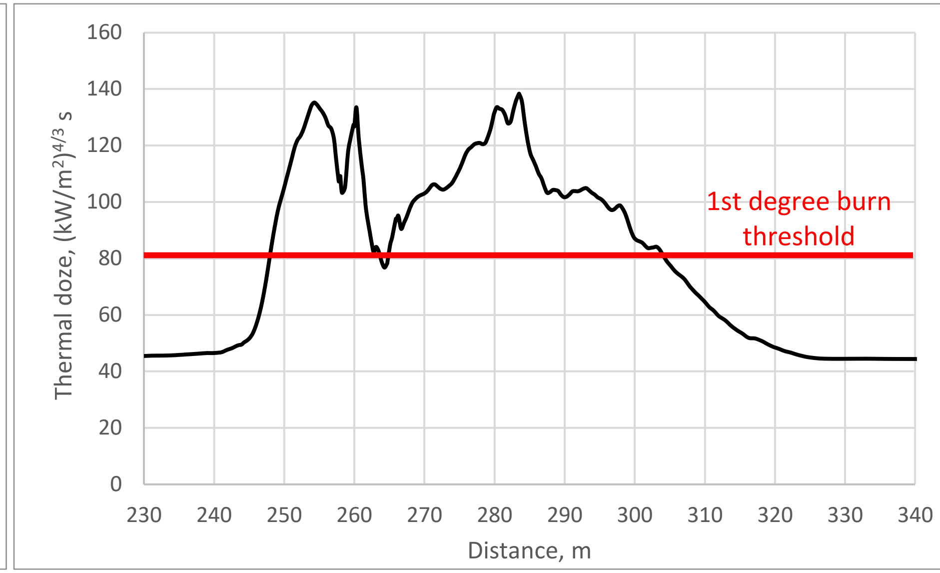


Table 1 – Example radiant heat flux harm criteria for people [2].

Thermal radiation intensity (kW/m^2)	Type of damage
1.6	No harm for long exposures
4–5	Pain for 20 s exposure; first degree burn
9.5	Second degree burn after 20 s
12.5–15	First degree burn after 10 s; 1% lethality in 1 min
25	Significant injury in 10 s; 100% lethality in 1 min
35–37.5	1% lethality in 10 s

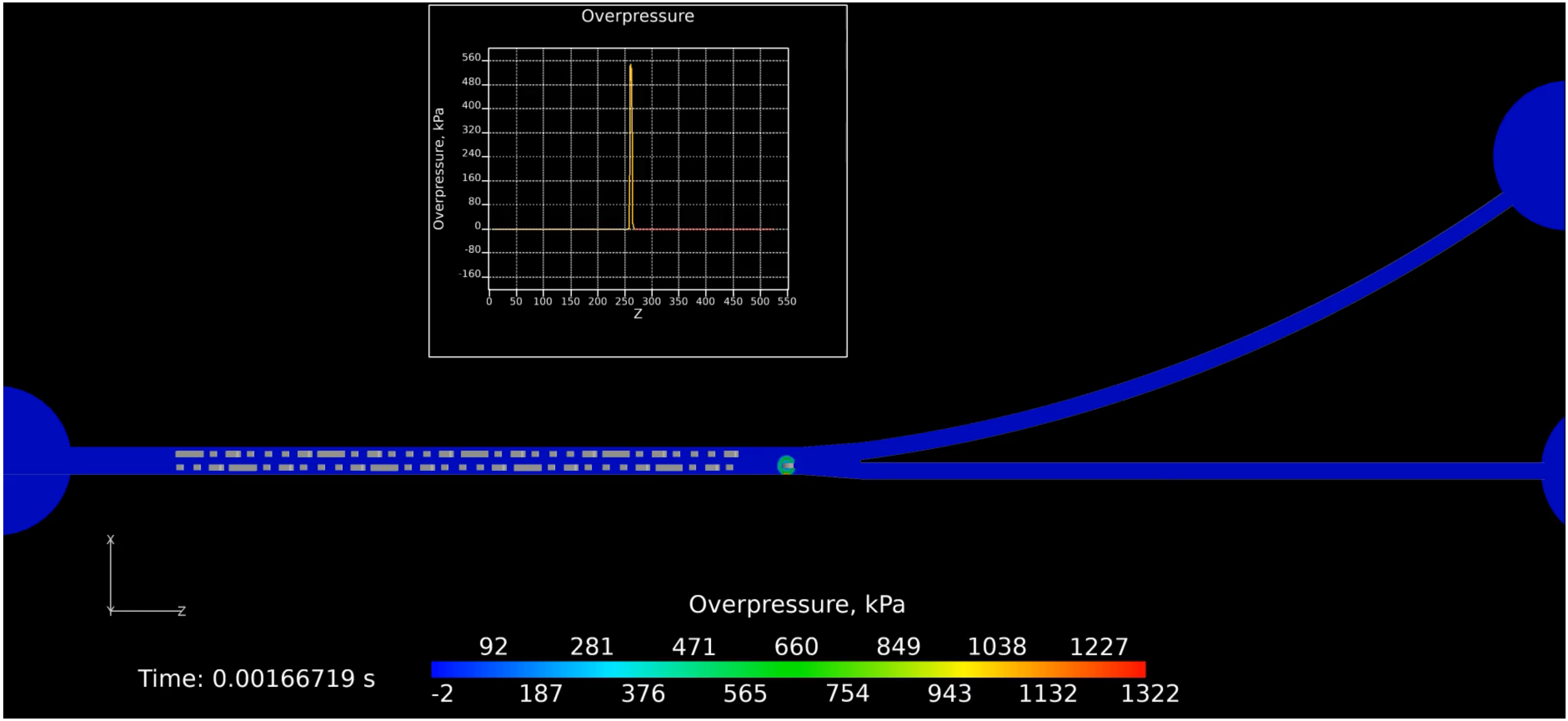
doi:10.1016/j.ijhydene.2010.03.139

Burn Severity	Threshold Burn Severity dose $(kW/m^2)^{4/3}s$	
	Ultraviolet	Infrared (mean)
First Degree	260-440	80-130 (105)
Second Degree	670-1100	240-730 (290)
Third Degree	1220-3100	870-2640 (1000)

The 1st degree burn threshold is exceeded only at the fireball spread distance.

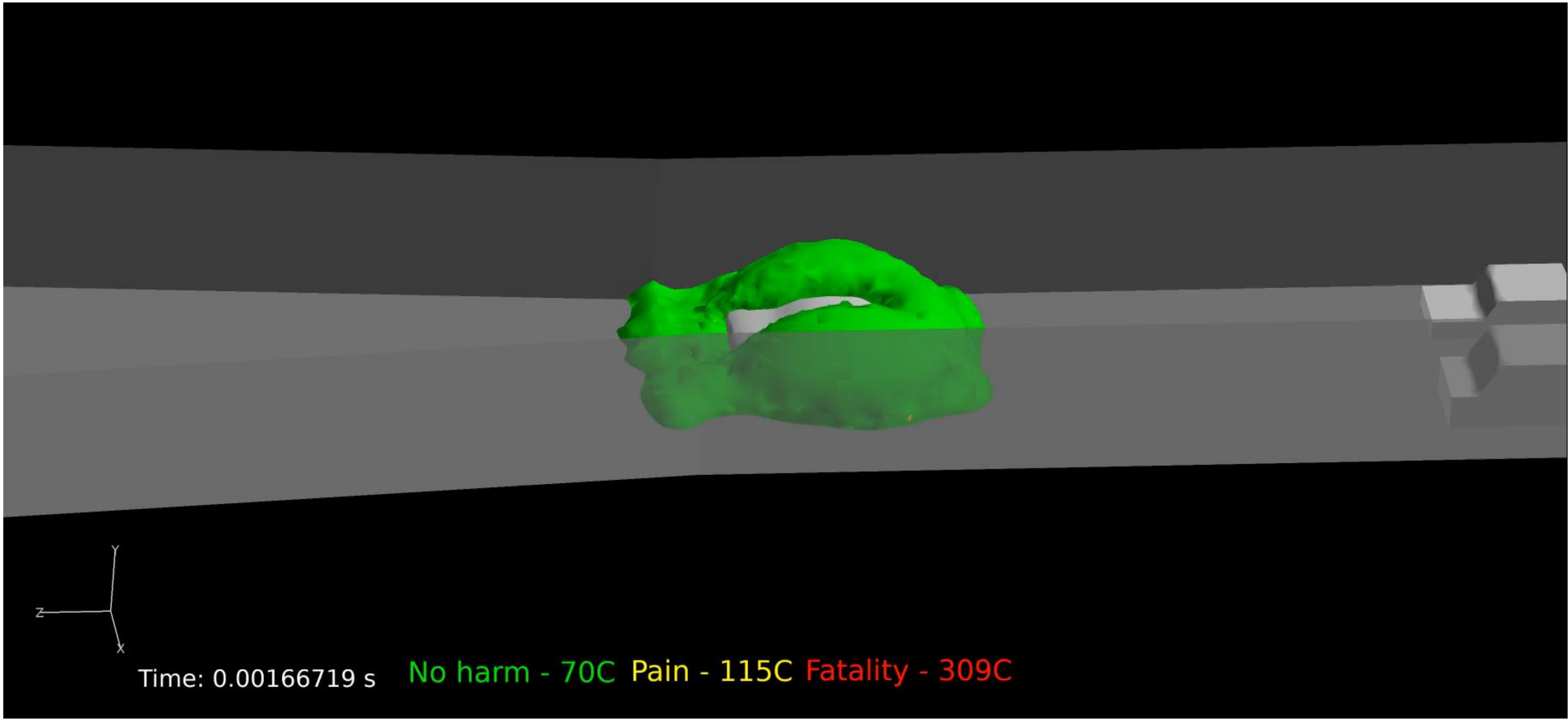
Simulation results

BW&FB in split tunnel with congestion



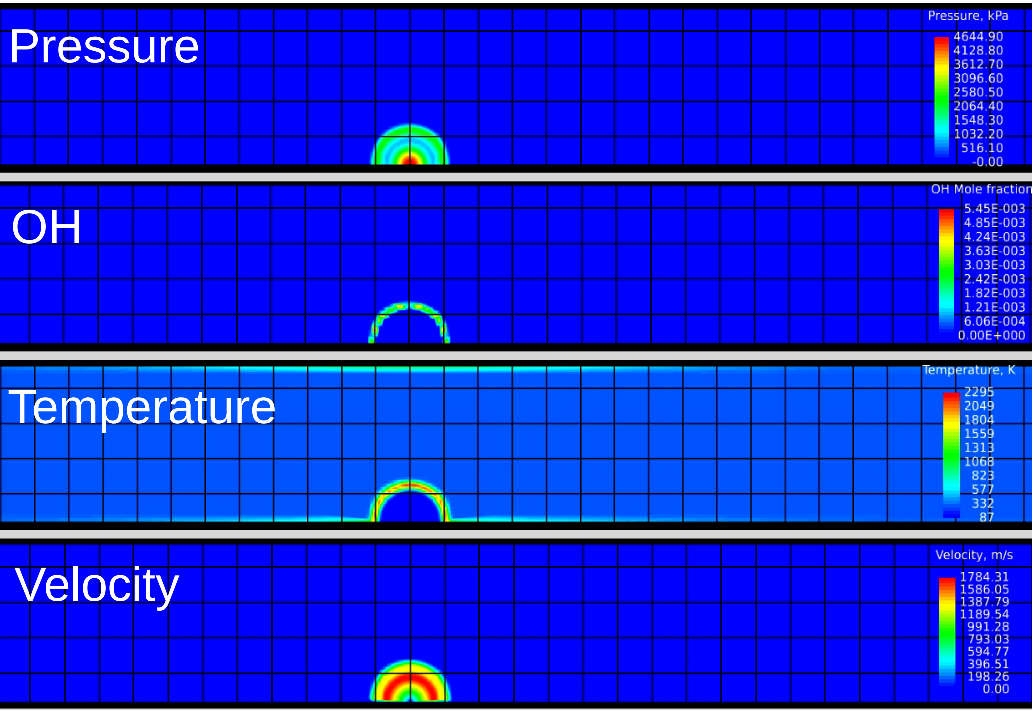
Simulation results

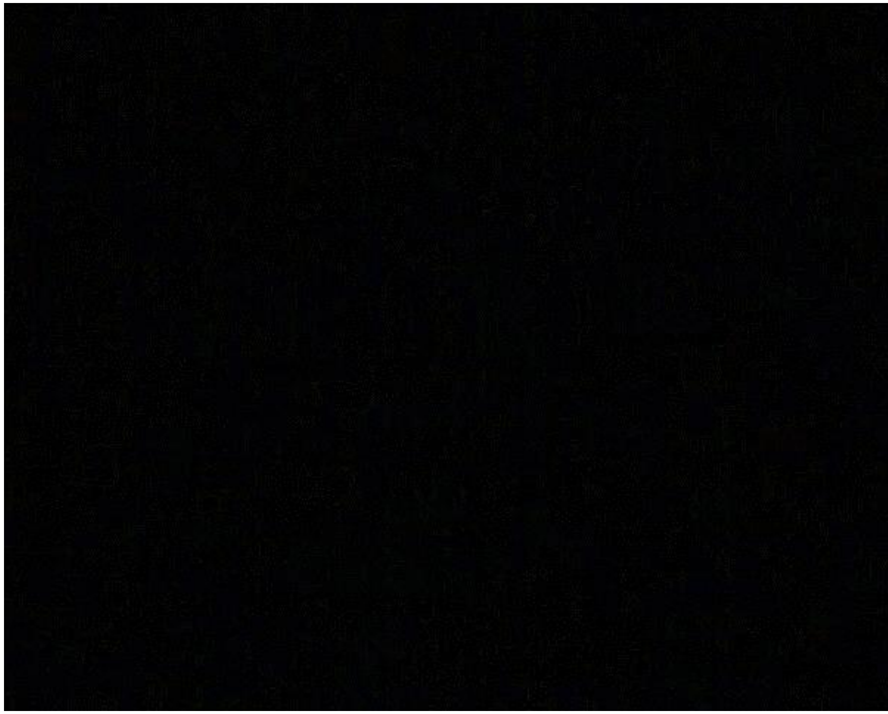
FB in split tunnel with congestion



Tank rupture in a tunnel

Real test (CEA) vs simulations (UU)





Conclusions

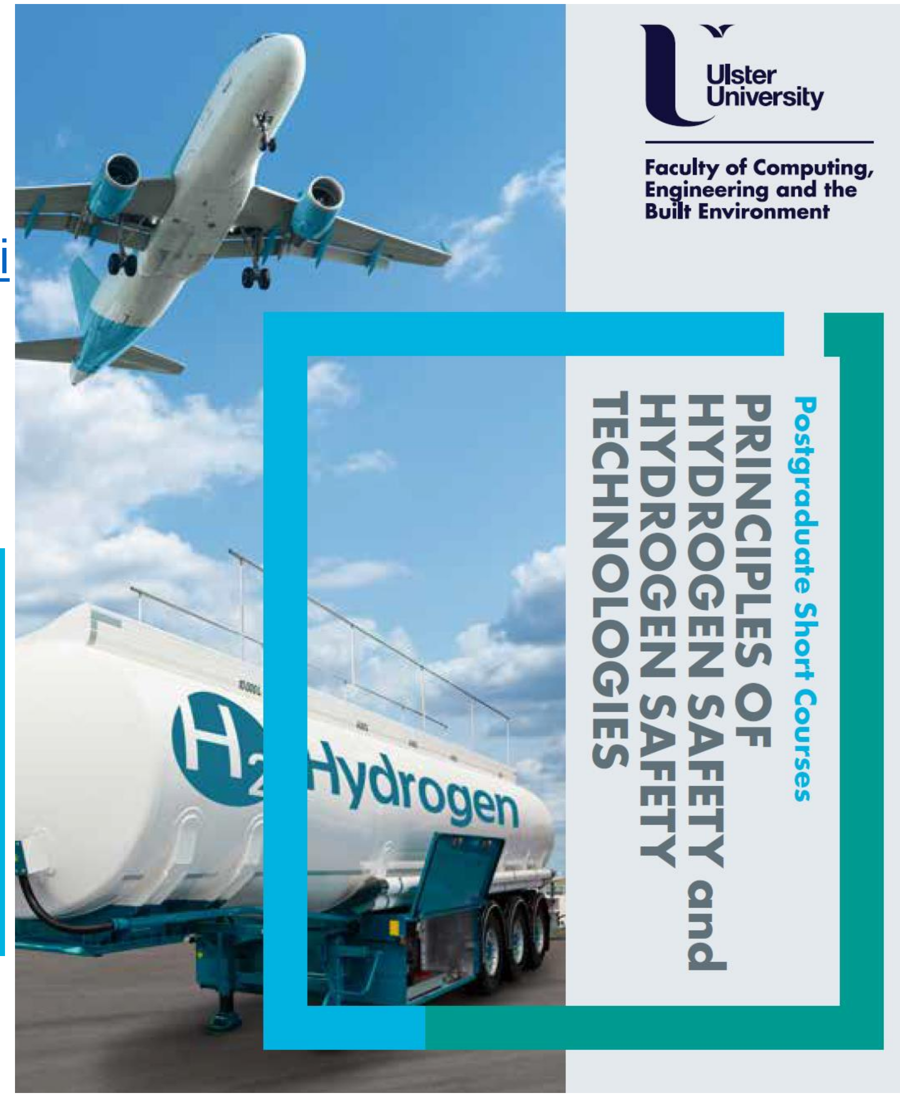
- The study of fireball after stand alone in open space and under vehicle tank rupture in a fire in a tunnel performed for various cases
- If tank ruptures in a middle FB propagates to both sides of tunnel equally, if at the entrance the it goes to the longer side of the tunnel
- Oxygen depletion is similar to the BF hazard and not as pronounced compared to high temperature and blast wave
- Simulation reproduced experimental fireball behaviour
- Hazard distance by blast wave is shown to be longest compared to the hazard distance by the fireball size (temperature) and radiation thermal dose.
- Hazard distance in tunnel longer compared to open space both for BW&FB
- Effect of ventilation is not studied and need to be addressed
- Full CFD-FEM coupling simulation required to be delivered in the new projects

HyTunnel-CS in education

Postgraduate Certificate in Hydrogen Safety

Distance learning course (will be updated by HyTunnel-CS outcomes), more information at:

https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering/study



Get in touch

If you would like to speak to our course team, please get in touch by email or call us directly at the number below. We will be happy to answer your questions:

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Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 826193. The JU receives support from the European Union’s Horizon 2020 research and innovation programme.

FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

The EU Framework Programme for Research and Innovation HORIZON 2020

Ulster University

KIT Karlsruher Institut für Technologie

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Ha FUNDACIÓN PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGÍAS DEL HIDRÓGENO EN ARAGÓN

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