Digital Stakeholders Workshop
HyTunnel-CS project
4-5 May 2020

The critical analysis of the state-of-the-art

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(on behalf of WP1 partners)

The state-of-the-art in safety provisions for underground transportation systems …

- Report on assessment of effectiveness of conventional safety measures in underground transportation systems and similar confined spaces (D1.1)
  Lead KIT (Germany), 82 pages, 83 references
- Report on hydrogen hazards and risks in tunnels and similar confined spaces (D1.2)
  Lead Ulster University (UK), 154 pages, 368 references
- Report on selection and prioritisation of scenarios (D1.3)
  Lead HSE (UK), 81 pages, 52 references
- Report on critical analysis of RCS for tunnels and similar confined spaces (D1.4)
  Lead: NEN (the Netherlands), 34 pages, 8 references, 32 standards

The state-of-the-art in safety provisions for underground transportation systems …

All reports are available at https://hytunnel.net/?page_id=71:

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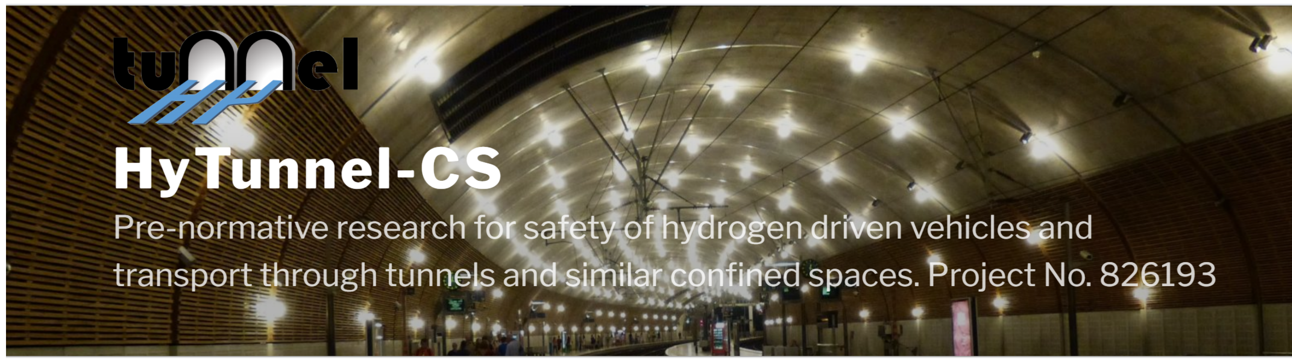

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Deliverables

No.	Title	Lead	PU/CO	Due date
D1.1 (D1)	Report on assessment of effectiveness of conventional saf ety measures in underground transportation systems and s imilar confined spaces	KIT	PU	31 Aug 2019 (M6)
D1.2 (D2)	Report on hydrogen hazards and risks in tunnels and similar confined spaces	Ulster	PU	31 Aug 2019 (M6)
D1.3 (D3)	Report on selection and prioritisation of scenarios	HSE	PU	30 Nov 2019 (M9)
D1.4 (D4)	Report on critical analysis of RCS for tunnels and similar co nfined spaces	NEN	PU	29 Feb 2020 (M12)

Pre-existing knowledge

HyTunnel-CS builds on and exploits:

- FP6 Network of Excellence for Hydrogen Safety (NoE HySafe, www.hysafe.org), 2004-2009.
- NoE HySafe internal project on use of hydrogen vehicles in road tunnels (D111), 2009.
- FP6 project "Installation permitting guidance for hydrogen and fuel cells stationary applications" (HYPER), 2006-2009.
- FP7 project "PNR on safe indoor use of fuel cells and hydrogen systems" (HyIndoor), 2012-2015.
- European Hydrogen Emergency Response training for First Responders (HyResponse, www.hyresponse.eu), 2013-2016.
- Expertise of partners, members of SAB and NN, etc.

Hydrogen fire mitigation (1/2)

Ventilation systems

- Natural ventilation:
  Suitable for (relatively) short tunnels (<1 km)
- Mechanical ventilation:
  longitudinal, transverse, semi-transverse, Saccardo nozzle
- Velocity
  - Critical 3.5 m/s (to control smoke movement)
  - Upper limit 11 m/s (to ease rescue and evacuation)
- Smoke extraction
  - No flow direction reversal
  - Retaining stratification
- Hydrogen “update”: control of flammable cloud, effect of combustion products on people and structures

Hydrogen fire mitigation (2/2)

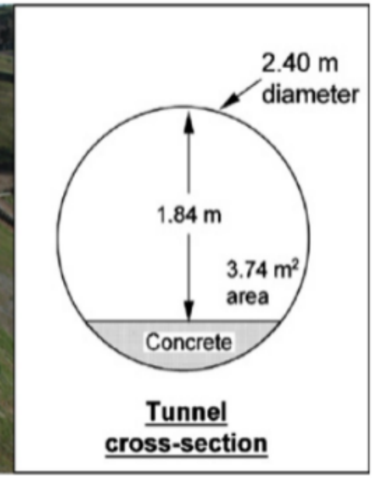
Water sprinklers, spray, mist systems

- \+ Destroys hydrogen stratification
- \+ Decreases temperature and radiation heat flux
- \- Fails to extinguish hydrogen under-expanded jet fires
- \- Destroys smoke layer stratification
- \- Decreases tenability limit due to high humidity
- \- Creates turbulence intensifying combustion
- \- Changes to hydrogen flammability limits, DDT and shock attenuation need to be clarified

Hydrogen pressure hazards

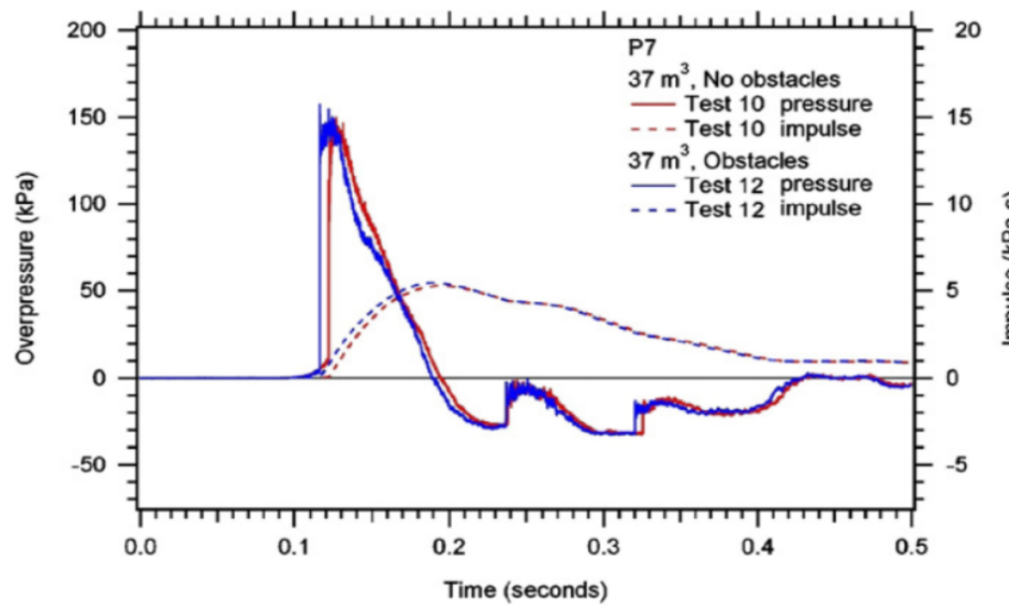
- Hydrogen deflagration, deflagration-to-detonation transition (DDT) and detonations could present large pressure loads in tunnels.
- Tunnel installations (jet fans, lighting system etc.) provide conditions for hydrogen flame acceleration.
- “New” hazard: high-pressure hydrogen tank rupture in a fire.
- Tunnel design (geometry, ventilation, etc.) and design of hydrogen vehicles are the key variables to determine hydrogen pressure hazards and associated risk levels.

Deflagration pressure hazards (1/2)



Ref: Groethe et al., 2007
1/5th scaled real tunnel
Length×Height = 1.84×79.5m
9.5%-30% vol. H_2 experiments
0.32 – 1.0 kg H_2

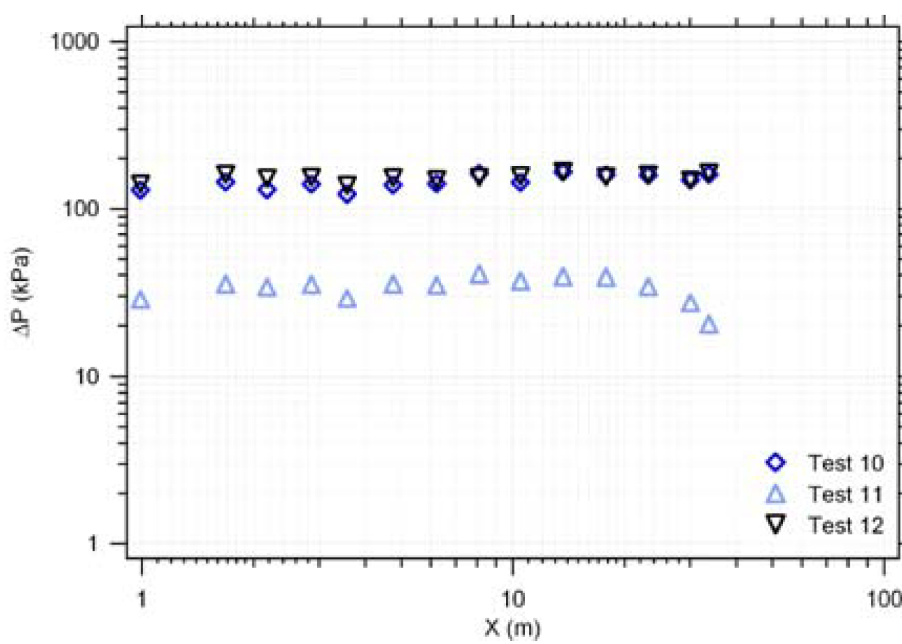
Experimental overpressure	~140 kPa
"No harm" threshold	1.35 kPa
Death threshold	100 kPa



Deflagration pressure hazards (2/2)

Ref: Groethe et al., 2007
1/5th scaled real tunnel
Length×Height = 1.84×79.5m
9.5-30% vol. H_2 experiments
0.32 – 1.0 kg H_2

- Constant overpressure along the tunnel ~140 kPa
- Max overpressure decreased to 5 kPa in less than 1 m from the tunnel exit



Quantitative Risk Assessment

- Low frequency high consequence events, e.g. hydrogen tank rupture in a tunnel fire.
- QRA analysis tools of DTU with potential for hydrogen accidents analysis:
  - Dynamics models (better predict worst case scenarios)
  - Bayesian Belief Networks (increasingly used for structural reliability and industrial safety), etc.
- QRA methodology published by Ulster University

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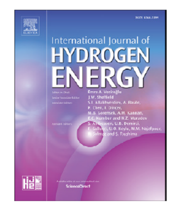

Risk assessment methodology for onboard hydrogen storage

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Some of safety knowledge gaps (1/2)

Hydrogen releases and dispersion:

- Hydrogen flows in tunnels with slope
- Hydrogen effect on back-layering in tunnels
- Dispersion in underground parking with mechanical ventilation, etc.

Hydrogen jet fires:

- Hydrogen combustion contribution to a vehicle fire (HRR)
- Pressure peaking phenomenon in large enclosures
- Fire resistance of hydrogen onboard storage
- Mechanical ventilation in underground parking
- Impinging jets
- Structural response to hydrogen jet fires, etc.

Some of safety knowledge gaps (2/2)

Explosions:

- Deflagrations and DDT in non-uniform mixtures in tunnels.
- Use of jet fans and possibility of DDT.
- Blast wave and fireball after hydrogen tank rupture in a fire.

Structural response to hydrogen accident (CFD+FEM):

- Response to hydrogen fire: concrete spalling, etc.
- Response to blast loads of weakened by fire structure.

Emergency response:

- Emergency preparedness, firefighting, rescue and evacuation (collaboration with the HyResponder project)
- Safety management and operator’s actions as responder.

Relevant RCS (1/3)

- **Directive 2004/54/EC** of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network
- Minimum Safety Requirements For Tunnels In The Trans-European Road network, Proposal for a directive of the European Parliament and of the Council, COM(2002) 769 Final, **EC Communities**, Brussels, 30.12.2002
- **PIARC** (1999), Fire and smoke control in road tunnels. World Road Association.
- **PIARC** (2001 & 2004), Report 05.11&12.B. Cross Section Design for Uni- and Bi-Directional Road Tunnels. World Road Association.
- **PIARC** (2008), Road Tunnels: Operational Strategies for Emergency Ventilation, Technical Committee C3.3 Tunnel Operations, Working Group No. 6 Ventilation and Fire Control, World Road Association.
- **PIARC** C3.3 (2008), Technical Committee C3.3 – Road Tunnel Operation. Road Tunnels: An Assessment of Fixed Firefighting Systems. Technical document, World Road Association.
- **NFPA** (2008), NFPA 502 – Standard for Road Tunnels, Bridges, and other Limited Access Highways, 2008 ed. National Fire Protection Association, Quincy, Massachusetts.
- **NFPA** 2 (2011), National fire protection association, Hydrogen technologies code, 2011.
- **NFPA** 502 on Standard for Road Tunnels, Bridges, and other Limited Access Highways (NFPA, 2004, 2008).
- Design Manual for Roads and Bridges, Volume 2, Section 2, Part 9, **BD 78/99**: Design of Road Tunnels, The Highways Agency et al (1999), The (UK) Stationary Office Ltd. (Highways Agency, 1999).
- **Commission Regulation (EU)** No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union
- **Directive (EU) 2016/798** of the European Parliament and of the Council of 11 May 2016 on railway safety

Relevant RCS (2/3)

- **ISO/TR 15916:2004** Basic considerations for the safety of hydrogen systems;
- **ISO/TS 20100:2008** Gaseous hydrogen-Fuelling stations;
- ISO 26142:2010 Hydrogen detection-Stationary applications;
- **ISO 19882:2018** Gaseous hydrogen-Thermally activated pressure relief devices
- **ISO 23273-2:2006** Protection against hydrogen hazards for vehicles fuelled with GH2
- **ISO 17840** Road Vehicles-Information for first and second responders
- **ISO 22899:2007** Determination of the resistance to jet fires of passive fire protection
- **ISO 6944-1:2008** Fire containment-Elements of building construction-Ventilation ducts
- **ISO 21925-1:2018** Fire resistance -Fire dampers for air distribution systems
- **ISO/DIS 23693** Determination of the resistance to gas explosions of passive fire protection
- **ISO/TR 16576:2017** Examples of fire safety objectives, functional requirements and safety criteria
- **ISO 16732-1:2012** Fire risk assessment
- **ISO/CD TR 17886** Design of evacuation experiments
- **ISO/CD 20710** Active fire protection systems
- **ISO 10961:2019** Gas cylinders-Cylinder bundles-Design, manufacture, testing and inspection
- **ISO 11625:2007** Gas cylinders-Safe handling

Relevant RCS (3/3)

- **IEC 62282-5-1 (2007-02) Ed. 1.0** Fuel cell technologies-Portable FC power systems-Safety
- **EN 1846-2:2009+A1:2013** Firefighting and rescue service vehicles-Common requirements
- **EN 1846-3:2013** Firefighting and rescue service vehicles-Permanently installed equipment
- **EN 1366-1:2014** Fire resistance tests for service installations-Ventilation ducts
- **pNWI** Hydrogen in confined spaces
- **EN ISO 11439:2013/prA1** Gas cylinders-High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles;
- **FprEN ISO 19884** Gaseous hydrogen-Cylinders and tubes for stationary storage;
- **prEN ISO 11114-2** Gas cylinders-Compatibility … with gas contents-Non-metallic materials
- **EN 1797:2001** Cryogenic vessels-Gas/material compatibility
- **EN 1990:2002** Eurocode-Basis of structural design;
- **Eurocode 3** Design of steel structures- General rules - Structural fire design
- **BS 7346-7:2013** Components for smoke and heat control systems. Code of practice … for covered car parks
- **NPR 6095-1:2012** Smoke and heat control systems-Guidelines on design … in car parks
- **NEN 2443:2013** Design standards and recommendations on parking facilities …
- **NEN 6098:2012** Smoke control systems for powered smoke exhaust ventilators in car parks

Critical analysis of RCS (NEN)

- Major RCS analysis, e.g.
  - PIARC Committee on Road Tunnels "Fire and smoke control in road tunnels" (1999)
  - NFPA 502 "Standard for Road Tunnels, Bridges, and Other Limited Access Highways"
  - NFPA 130 "Standard for Fixed Guideway Transit and Passenger Rail Systems"
- Appropriateness of conventional mitigation technologies (ventilation, water sprays/fog/foams, etc., safety management and first responders' intervention strategies) in the case of hydrogen-powered vehicle accident
- Analysis of SDO activities for alternative fuels (LPG, CNG, batteries) to exploit similarities
- Aimed at provision of "Recommendations for RCS" relevant to use of hydrogen in tunnels and similar confined spaces

Scenarios selection and prioritisation (HSL)

- Five elements to analyse scenarios.
- High/Medium/Low priorities approach to select 10 high-priority scenarios from the variety presented below (see next slide).

Transportation Mode → **Infrastructure** → **Accident Initiators** → **Consequence** → **Hazard Variables**

Transportation mode	Factor	Initiator	Consequence	Variables defining H_2 discharge and consequences
Car	Space	Mechanical failure	Ignited vessel rupture	Vehicle type
Bus	Design	Failure of safety system	Pressurised release with delayed ignition	Storage design
Train	Ventilation	Driver error/ vehicle collision	Ignited pressurised release	TPRD diameter
HGV	Internal Features	Hydrocarbon pool fire	Unignited pressurised release	Release
Motorcycle	Construction material	Other vehicles involved	Unignited vessel rupture	Ignition delay
Ship	Mitigation	Other fire loading		
Aircraft				

Selected scenarios (1/2)

No.	Scenario	Car	Bus	Train
1	Unignited hydrogen release and dispersion in a confined space with mechanical ventilation	✓		
2	Unignited hydrogen release in confined spaces with limited ventilation	✓		
3	Unignited hydrogen release in a tunnel with natural/mechanical ventilation	✓	✓	✓
4	Hydrogen jet fire in confined spaces with limited ventilation	✓		
5	Hydrogen jet fire and vehicle fire in a mechanically ventilated garage/underground parking	✓		
6	Hydrogen jet fire impingement on a tunnel	✓	✓	✓
7	Hydrogen jet fire and vehicle fire in a tunnel	✓	✓	✓
8	Fire spread in underground parking	✓		
9	Hydrogen storage vessel failure in a tunnel	✓	✓	✓
10	Hydrogen storage vessel blowdown with delayed ignition in a tunnel	✓	✓	✓

Selected scenarios (2/2)

TPRD diameter for theoretical, numerical and experimental release and fire scenarios:

- ∅ **5 mm:** previously used for cars, currently considered for trains, HGV, busses
- ∅ **2 mm:** currently used in passenger cars
- ∅ **0.5 mm:** drastic reduction of
  - Thermal and pressure loads of releases,
  - Eliminates the pressure peaking phenomenon,
  - Facilitates evacuation and rescue operations
  - Requires improved fire resistance of storage

tunnel HP

Acknowledgements

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