Research Institutes of Sweden (RISE)

FIRE AND EXPLOSION HAZARDS OF NEW ENERGY CARRIERS IN ROAD TUNNELS

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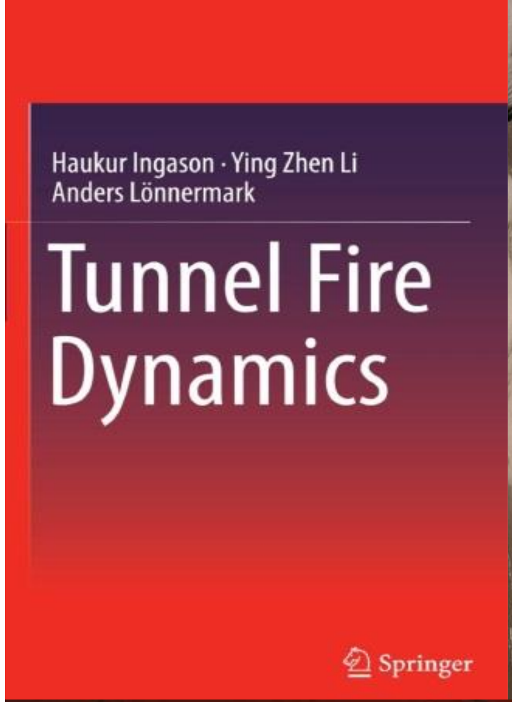
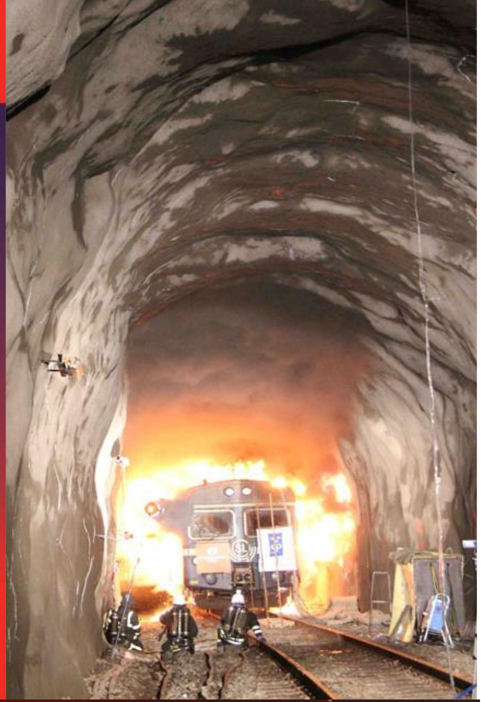




Introduction

- **Biofuels?**
- **Decarbonization 2050?**
- **Electric battery vehicles?**
- **Or hydrogen - Internal combustion engine or Fuel cell?**
- **Reality:**
  - **Liquid fuels**: Traditional fuels, Ethanol, Methanol
  - **Liquefied fuels**: LNG, LPG, LH2
  - **Compressed gas**: CNG, GH2 (fuel cell)
  - **Electricity**: Electric battery, fuel cell
- **Research questions:**

  (1) Parameters for existing vehicles

  (2) Fire hazards

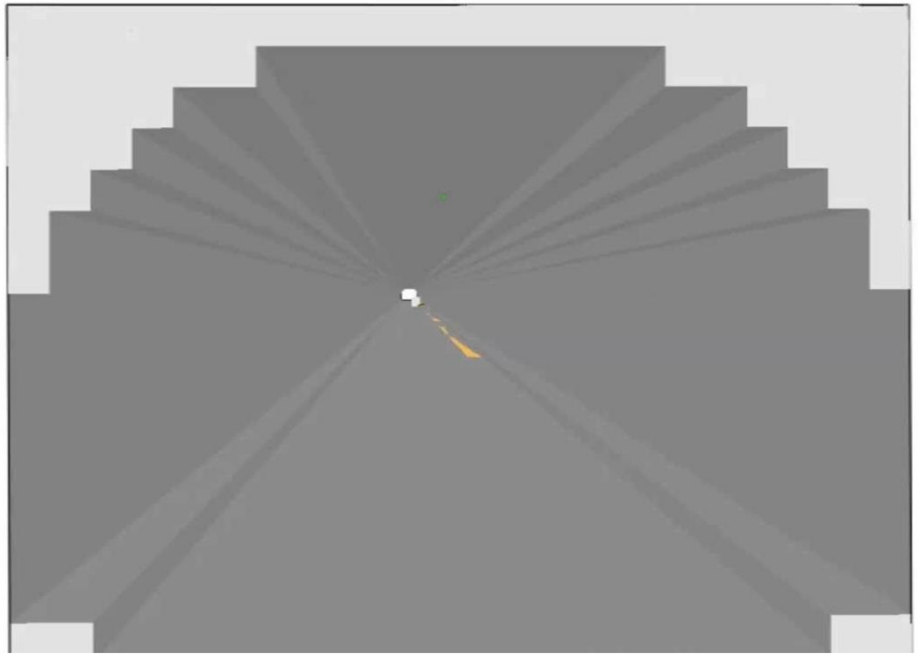
  (3) Explosion hazards

Qualitative analysis of fire and explosion hazards

- **Fire hazards:** Spilled Pool fires; Jet fires; fireballs and flash fires.
- **Explosion hazards**: Gas tank rupture, BLEVE, and gas cloud explosion.

Tank failure may cause fragment projections

Spilled LNG pool (100 m)



Spilled pool fire in tunnel

Jet, BLEVE and fireball

(*Superheat temperature*)

Boiling liquid expanding vapor explosion

Qualitative analysis of fire and explosion hazards

- **Most probable Scenarios:**
  - Liquid fuel vehicles: pool fires
  - Liquefied fuel vehicles: Jet fires with pool fires; BLEVE with fireballs; Gas cloud explosion
  - Compressed gas vehicles: Jet fires; Gas tank rupture with fireballs; Gas cloud explosion
  - Electric battery vehicles: Normal fires with small jet flames; Gas cloud explosion.

Note: Even without ignition (fire), Liquefied fuel vehicles and compressed gas vehicles pose **explosion hazards**, and battery vehicles pose **toxicity** problems in case of a thermal runaway.

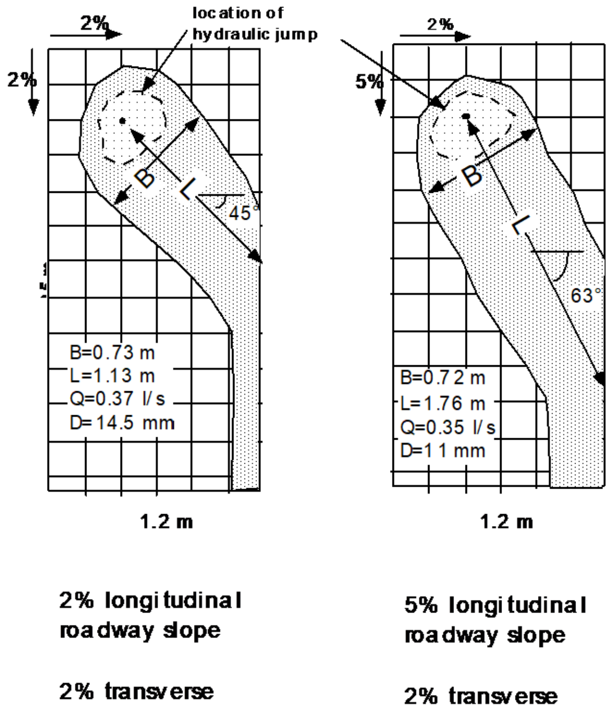
Fire hazards – Spilled liquid pool fires

- Leakge rate through a hole: $\dot{V} = C_d A_d \sqrt{\dfrac{2(P_{tank} - P_o)}{\rho} + 2gh}$
- Tunnel spillage area: $A = 2\dot{V}^{0.46} \dfrac{W}{\cos(\arctan(y\% / x\%))}$

For a tunnel with transverse slope of 1 %.

Fuel	HRRPUA (MW/m^2)	Spillage rate (l/s)	Spill area (m^2)		Peak HRR** (MW)	
			2 % slope*	10 % slope*	2 % slope*	10 % slope*
Ethanol	0.15	0.11	15	65	2	10
Methanol	0.17	0.11	15	65	2	11
Diesel	0.56	0.11	15	65	8	37
Gasoline	0.89	0.11	15	65	13	58
LPG	1.7	1.6			43	43
LNG	1.4	2.3			49	49
LH2	8.9	4.5			45	45

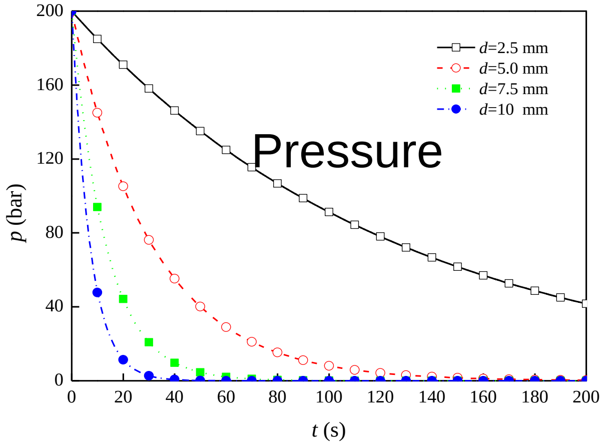
* Longitudinal tunnel slope

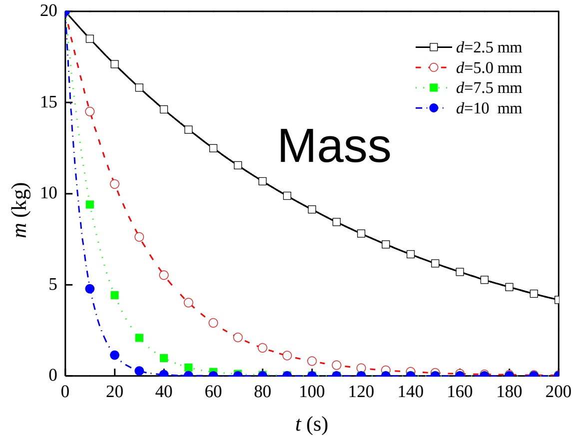


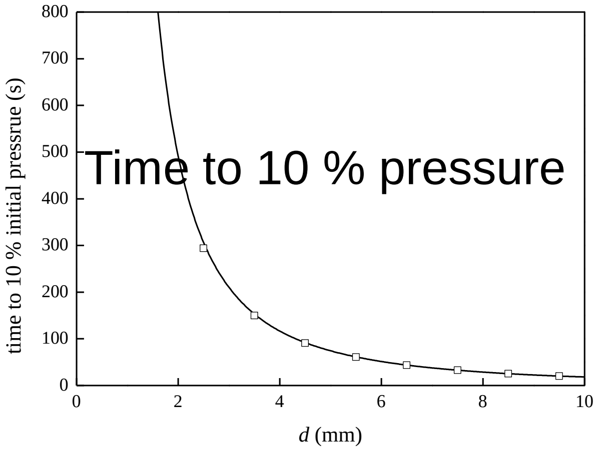
Regarding fire size, the liquid fuels pose equivalent or even lower fire hazards compared to the traditional fuels (gasoline and diesel)

Fire hazards – Jet fires

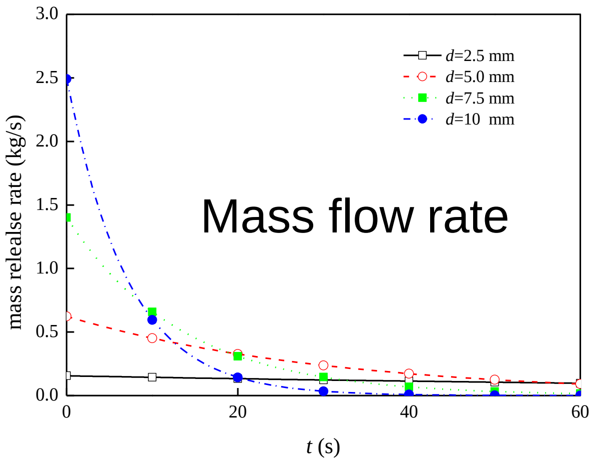
- Critical flow through a PRD.

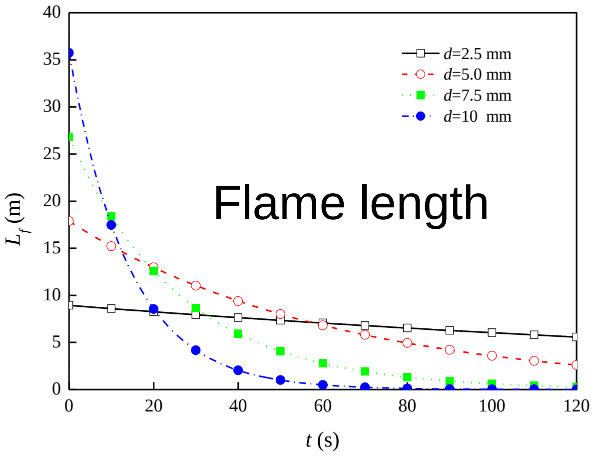






20 kg CNG tank 200 bar





- ❑ Critical flow (chocked flow)
- ❑ Importance of PRD diameter
- ❑ Rapid decrease in parameters
- ❑ Short duration

Fire hazards – Jet fires(Max values)

Compressed gas tanks

Fuel	Diameter of PRD/hole	Release rate	HRR	Lf, Delichatsios	Lf, Lowesmith	Heat flux*
	mm	kg/s	MW	m	m	kW/m²
CNG 200 bar	2.5	0.13	7	7.3	6.0	1
	5	0.62	34	18	10.8	4
	10	2.49	137	35.7	18.1	14
GH2 350 bar	2.5	0.10	14	8.0	7.6	1
	5	0.38	54	16.1	12.8	6
	10	1.53	217	32.1	21.5	22
GH2 700 bar	2.5	0.19	27	11.4	9.9	3
	5	0.76	108	22.7	16.6	11
	10	3.06	434	45.4	27.8	45

Liquefied fuel tanks (Hole on gas side)

Fuel	Diameter of PRD/hole	Release rate	HRR	Lf, Delichatsios	Lf, Lowesmith	Heat flux*
	mm	kg/s	MW	m	m	kW/m²
LPG 32 bar	2.5	0.041	1.9	5.4	3.7	0.36
	5	0.165	7.6	11	6.2	1.45
	10	0.661	30	21.7	10.3	5.81
LNG 25 bar	2.5	0.019	1.0	3.1	2.9	0.11
	5	0.076	4	6	4.9	0.43
	10	0.305	16.8	12.5	8.3	1.74
LH2 10 bar	2.5	0.003	0.4	1.4	2.0	0.04
	5	0.011	1.5	2.7	3.4	0.16
	10	0.044	6.2	5.4	5.7	0.64

Hole on liquid side:

Fuel	Diameter of PRD/hole	Release rate	HRR	Lf, Lowesmith	Heat flux*
	mm	kg/s	MW	m	kW/m²
LPG 32 bar	2.5	0.10	4.5	5.1	0.9
	5	0.40	18.2	8.5	3.5
	10	1.58	72.8	14.3	13.9
LNG 25 bar	2.5	0.055	3.0	4.4	0.3
	5	0.22	12	7	1.3
	10	0.88	48.5	12.3	5.0
LH2 10 bar	2.5	0.009	1.3	3.2	0.1
	5	0.036	5.1	5.3	0.5
	10	0.14	20.2	8.9	2.1

- Large HRR for gas tanks (also for Liquefied fuels)
- Very long flame length → Impingement and extension
- Lf more sensitive to flow rate instead of HRR
- High risk for fire spread

Liquefied fuel tanks pose lower hazards than gas tanks concerning jet fires but meanwhile it can cause pool fires.

Fire hazards – Fireball

- Gas tanks and liquefied tanks: *Rupture +Ignition*
- Fireball diameter on open roads:

  Constant flame spread rate

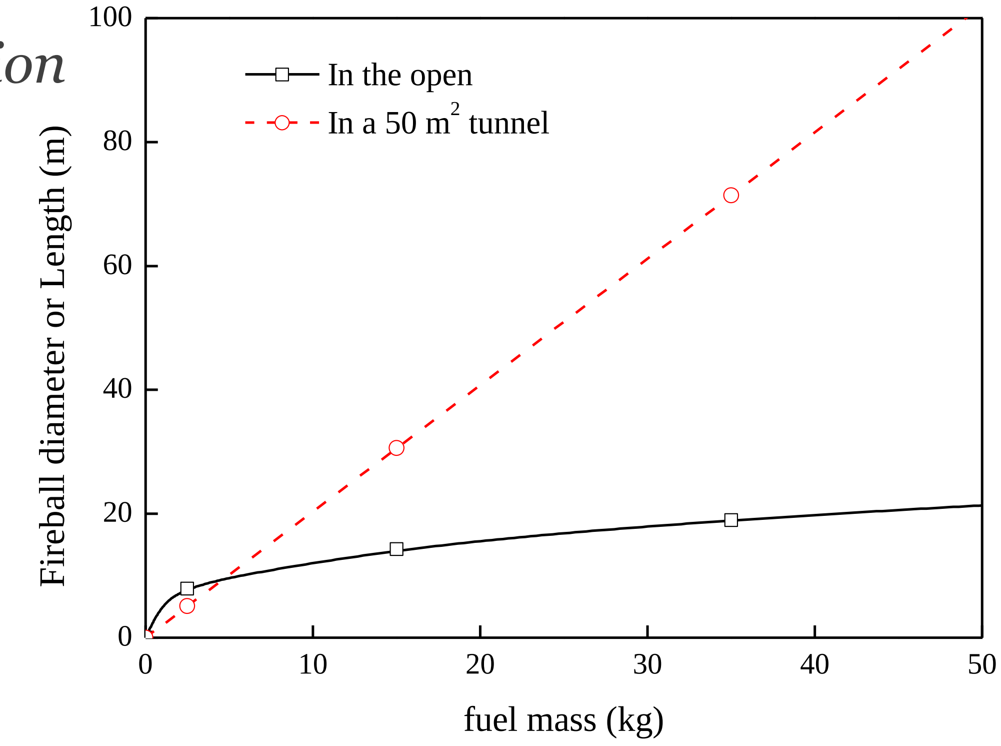
$$D_{\max} = 5.8 m_f^{1/3} \qquad t_{\max} = 0.45 m_f^{1/3}$$

- Fireball length in tunnels:

  assuming similar mixing and spread rate as in the open

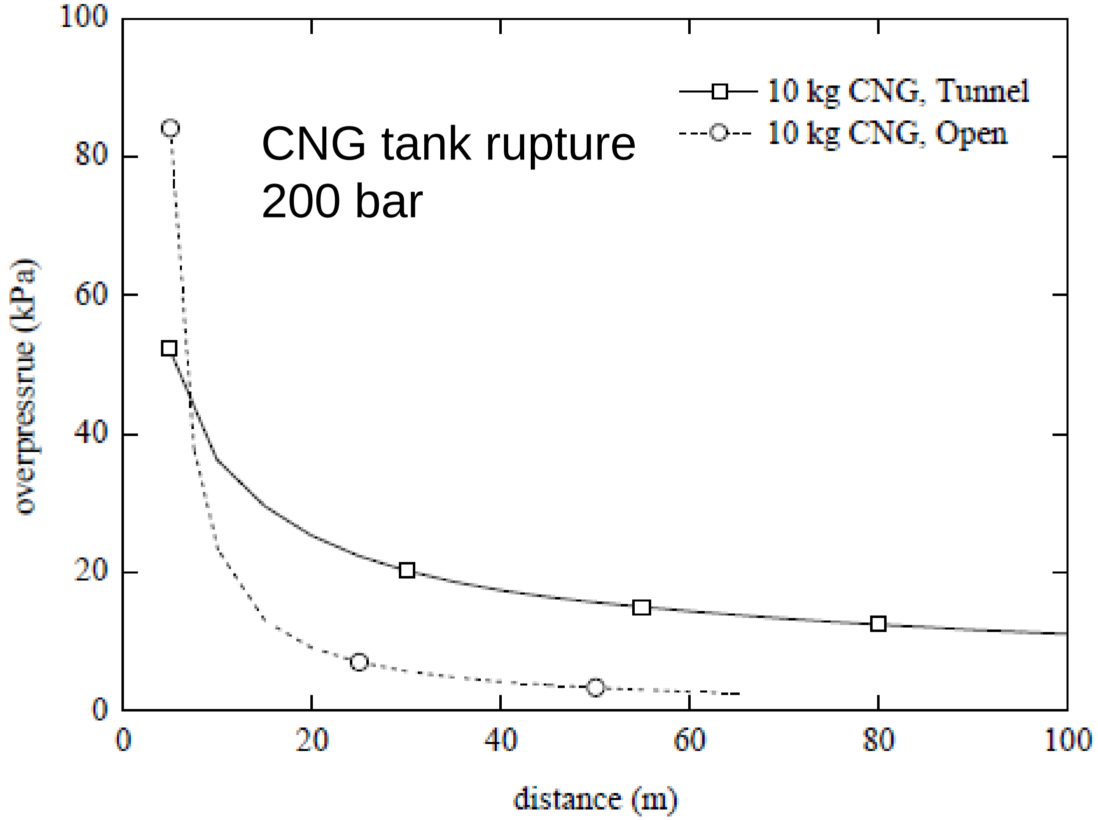
$$L_{\max} = 100 \frac{m_f}{A}$$

Duration is hard to estimate.



Significantly longer fireball lengths in tunnels

Explosion hazards – Gas tank rupture in tunnels



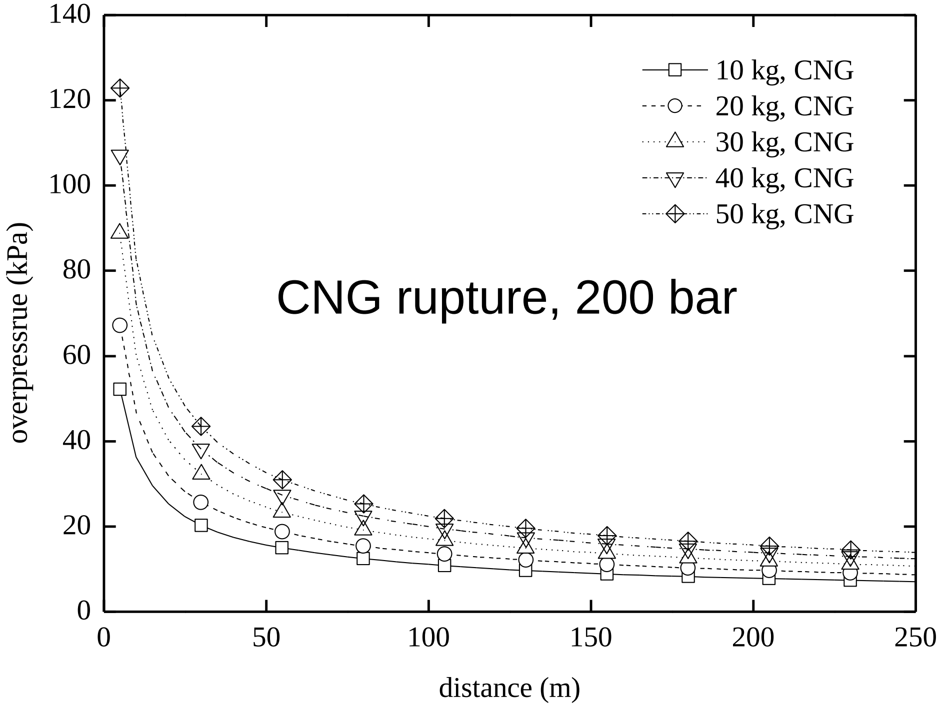
Difference in pressure distribution between tunnel and open

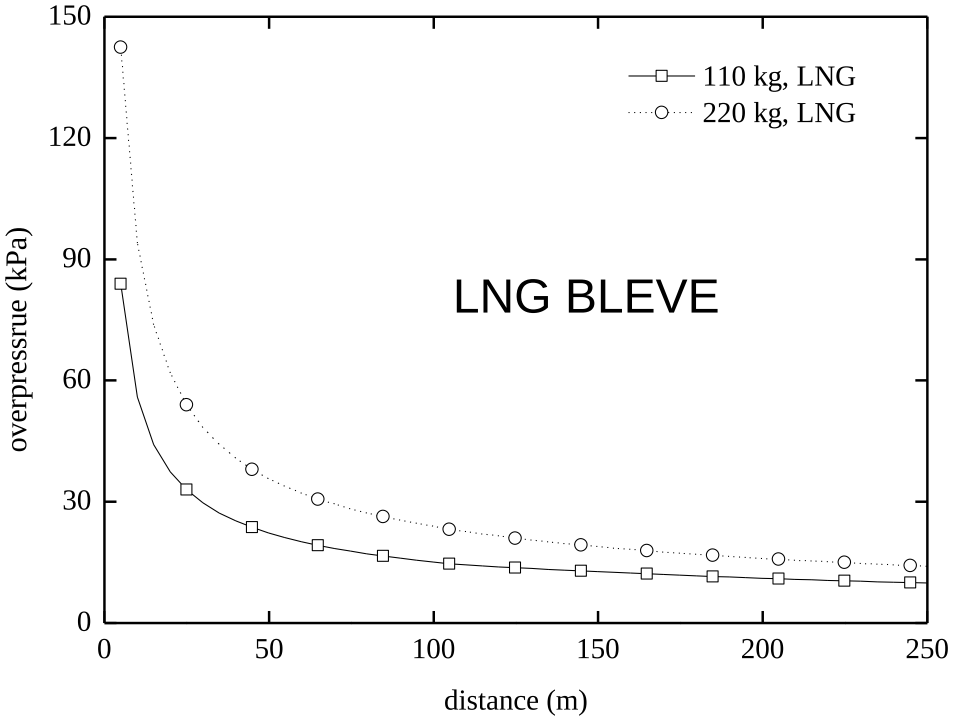
10 -20 kPa:

- Eardrum rupture
- Personnel knocked down
- Window breakage(secondary fragments).

Explosion hazards – Tank rupture in tunnels

Natural Gas

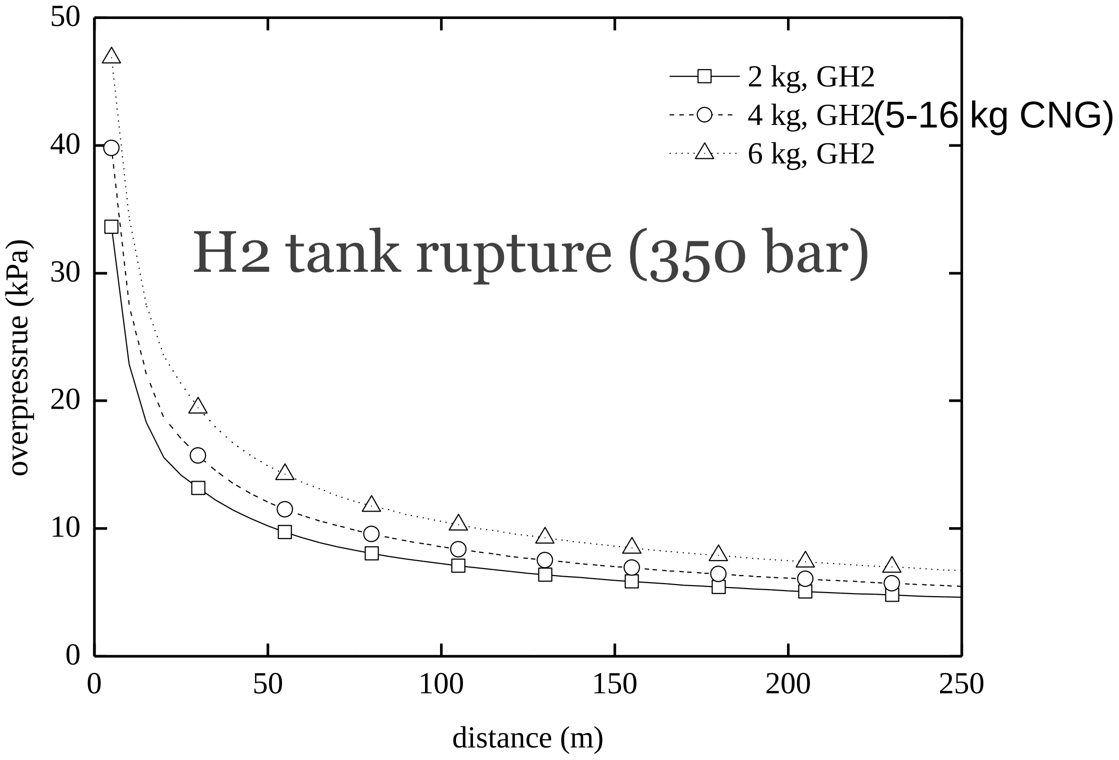


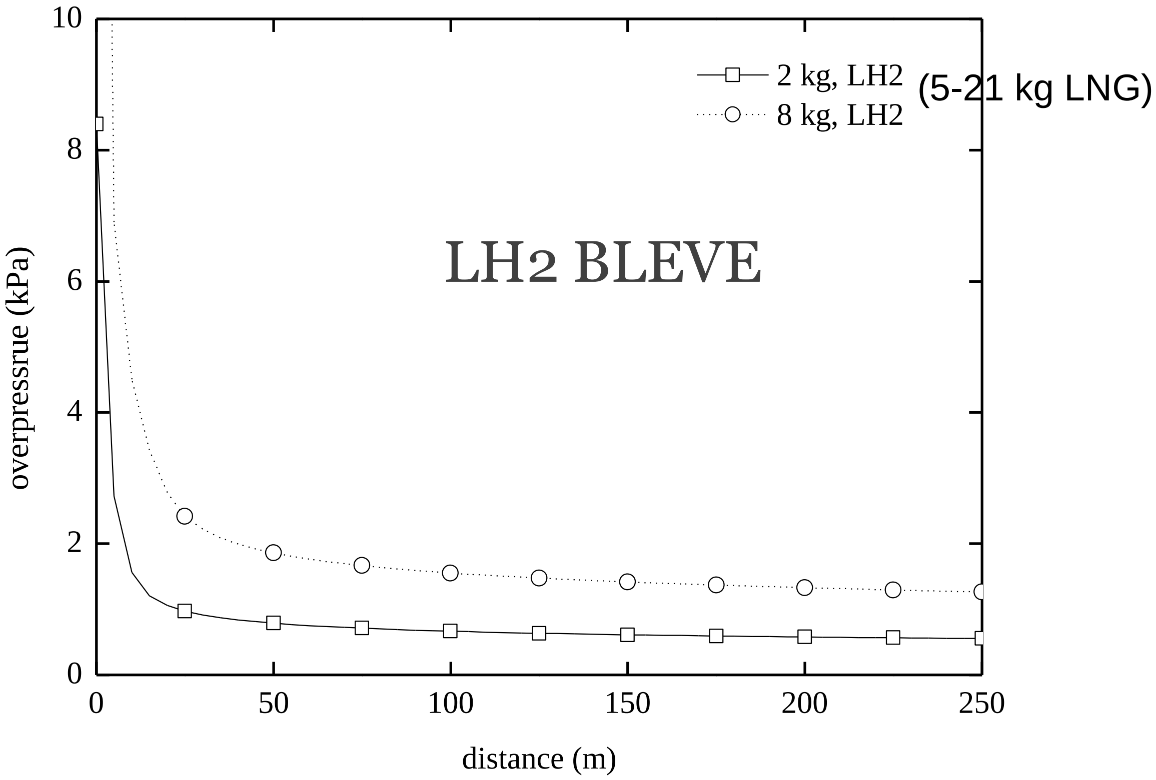


10 -20 kPa: Eardrum rupture/Personnel knocked down/Window breakage(secondary fragments).

Explosion hazards – Tank rupture in tunnels

Hydrogen





Explosion hazards – Comparison 1

- Comparison of Gas tank rupture and BLEVE

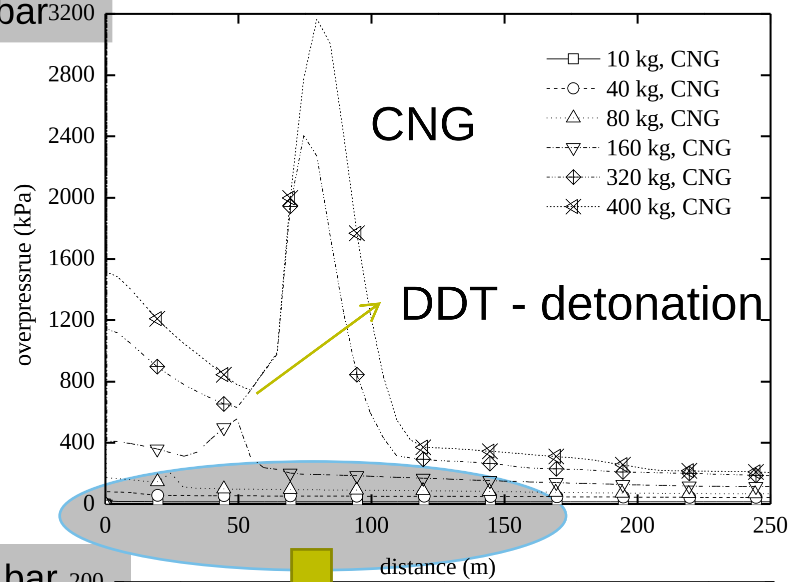
Vehicle type	Energy	Overpressure at 50 m	Overpressure at 100 m
	MJ	kPa	kPa
CNG	5 - 26	15 - 29	10 - 20
GH2	5 - 18	10 - 15	7 - 11
LNG	7 - 30	22 - 36	15 - 24
LH2	0.08 – 0.8	1 - 2	0.7 - 1.5
LPG	2 - 14	10 - 16	7 - 11
LDME	3 - 20	11 - 19	7 - 13

For vehicles available on market

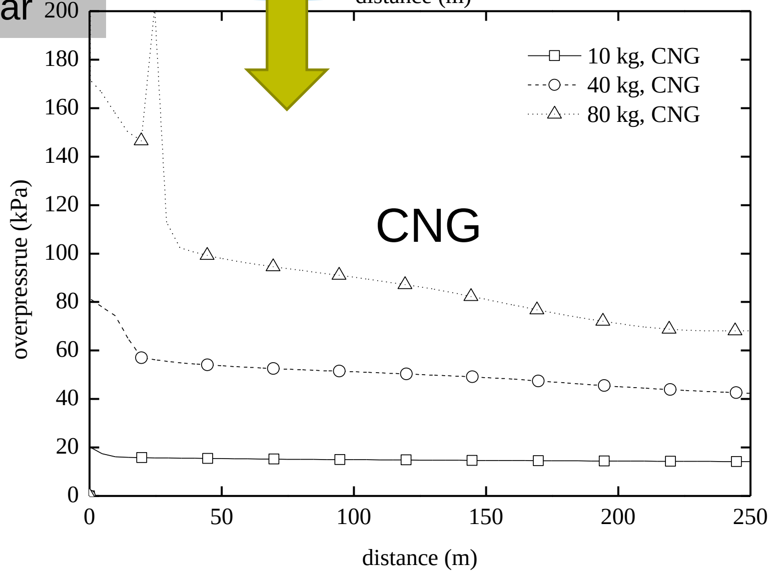
- Explosion energy: mostly **2 – 30 MJ**.
- Peak overpressure: mostly **0.1 –0.36** bar at 50 m, and 0.07-0.24 bar at 100 m.
- Duration of 1st positive overpressure: **0.1 s – 0.5 s**, mostly **0.1 – 0.25 s**.
- Consequences of such incidents: relatively tolerable/marginal for locations over 50 – 100 m.
- Reducing the amount of fuels are needed in some cases.

Explosion hazards – Gas cloud explosion in tunnels

32 bar

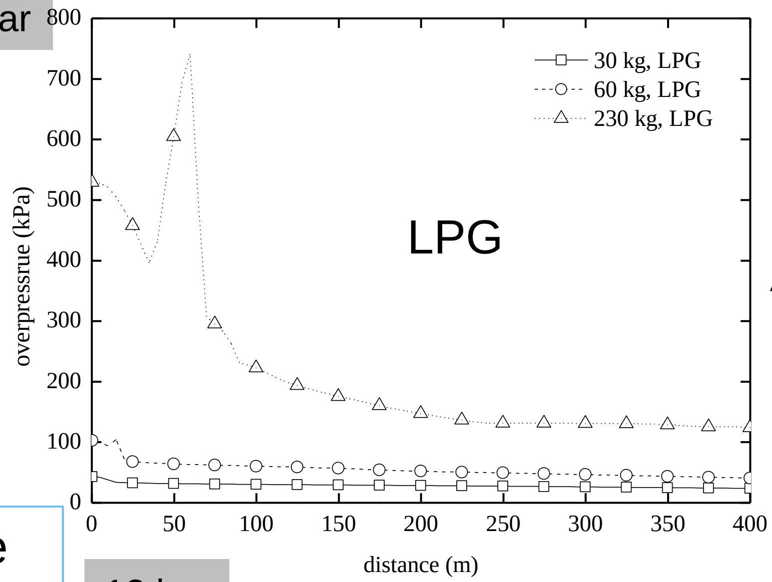


2 bar



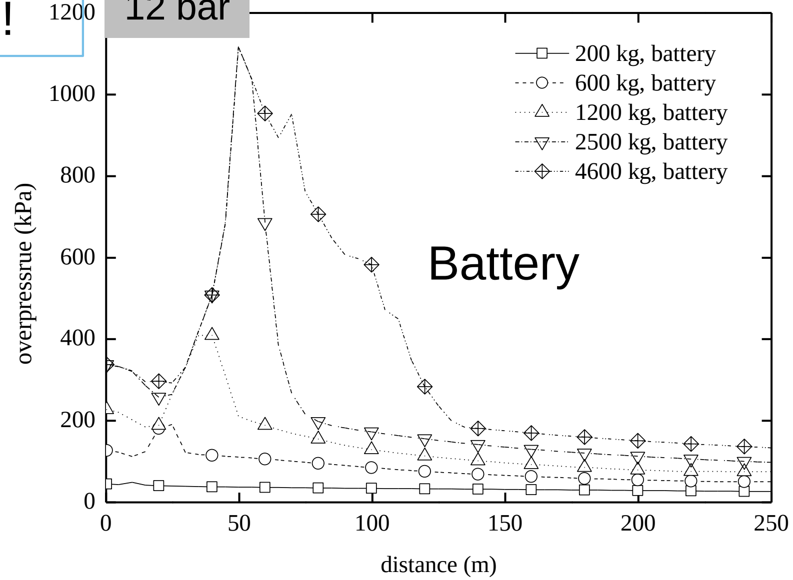
Scenarios are conservative!

8 bar



Flashed fuels + Aerosols/Sprays

12 bar



All solvents

Explosion hazards – Comparison 2

- Comparison of Gas cloud explosion

Vehicle type	Energy	Overpressure at 50 m	Overpressure at 100 m
	GJ	kPa	kPa
CNG	0.5 - 20	15-780	15-830
GH2	0.2 - 0.7	19-38	18-36
LNG	5.5 - 23	136-850	120-1850
LH2	0.2 - 1	19-84	18-73
LPG	1.4 - 11	30-600	30-223
LDME	1.4 - 11	23-300	22-200
Battery	0.4 - 9	37-1120	34-582

- Explosion energy: mostly **0.2 – 23 GJ**.
- Peak overpressure: mostly **0.15 –11.2** bar at 50 m, and **0.15-18.5 bar** at 100 m.
- Duration of 1^{st} positive overpressure: **0.1 s – 0.5 s**.
- Consequences of such incidents: **not tolerable** over 50 – 100 m and even for the whole tunnel.
- **Reducing the amount of fuels** are extremely needed by:

  (1) increase number of tanks; (2) strictly prevent fire spread to other battery modules.

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Explosion hazards – for same energy at wheel

- Comparison of Gas cloud explosion energy between battery vehicles and others

Type	Mass of battery	Energy at wheel (MJ)	Energy contained in fuels (MJ) [a]		Explosion energy (MJ) [b]		Equivalent mass (kg) [c]	
			Battery	Internal combustion engine	**Battery**	**Internal combustion engine**	CNG	H2
Car	200	54	90	270	**384**	**270**	8	3
	600	162	270	810	**1152**	**810**	23	9
Bus	1200	324	540	1620	**2304**	**1620**	46	18
	2500	675	1125	3375	**4800**	**3375**	96	38
Truck	600	162	270	810	**1152**	**810**	23	9
	4600	1242	2070	6210	**8832**	**6210**	177	71

❖ Explosion energies are approximately the same, while values for batteries are slightly greater than others.

Summary

- Different types of new energy carriers in vehicles are investigated and detailed parameters are obtained.
- Qualitatively and quantitative analysis of the risks and consequences for each type of alternative fuel vehicles in tunnels are presented.
- **Gas cloud explosion energies are approximately the same for all fuels**, but they have **various fire hazards**.
- Consequences of gas tank rupture and BLEVE are relatively low/marginal 50-100 m away, but the situations in case of **cloud explosion are mostly very severe and intolerable** for tunnel users (based on the well-mixed assumption).

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THANK YOU!

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In Munich, 11-13 March 2020
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Abstract submission: **5 May 2019 (**2-page**)**
Full paper submission: **29 Sep 2019**