QRA of hydrogen vehicles in underground parking

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Co-funded by the European Union

Case study

underground car park (DK)

Scenario:
- longer term parking of the cars as it could be typical for company car park,
- each slot is thought of being used by 583 different cars during a year.
- 33841 cars using this car park during a year
- vehicle fire frequency F is 0.006 fires year^{-1}.

Fire statistics

Denmark 2013 - 2020

[number of fires]	2013	2014	2015	2016	2017	2018	2019	2020
underground carpark	6	5	12	23	12	15	6	5
Outhouse / carport / garage	0	0	79	131	110	90	352	382
All fires	14392	13086	12027	12381	11520	13420	11224	10946

Number of fires in carparks compared with outhouse /carport /garage fires and all fire incidents in Denmark during the period 2013 – 2020.
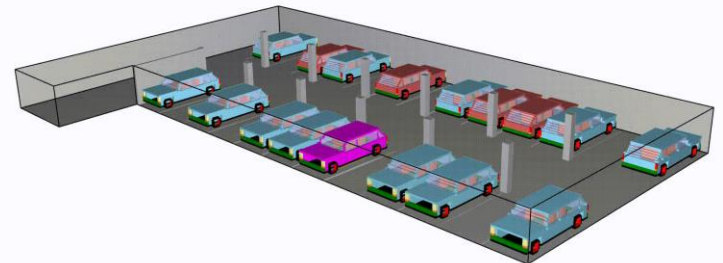
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Danish legislative requirements

Mitigation measures

- Fire compartments smaller than 1000 m^2,
  - require no active fire protection measures.

- Fire compartments smaller than 2000 m^2
  - require only mechanical fire ventilation.

Legislation presently under revision

Observed construction strategy:
Minimize the active fire
protection measures

tunnel

Underground parking

- Only cars and small vans are expected to use ordinary underground parking.

- While accident scenarios involve severe collisions in road tunnels, the situation in underground parking is different due to the very low speeds of the vehicles in such an infrastructure.

- Fires in car parks are not very frequent and the vast majority is extinguished within a short time.

- The mitigation systems that are required for underground parking are very different from country to country depending on the size of the parking.

- Possible mitigation measures are well established and include, e.g. fire compartments, fire ventilation, sprinkling, etc.

Case study

underground car park (DK)

- underground Danish car park 'prismet' in the town Århus
- area of 2144 m^2
- 58 parking slots
- parking efficiency P = 37 m^2/car,

$$F = f \cdot R \cdot \frac{A}{P}$$

f = 1.71 10^{-7} vehicle fire frequency per vehicle visit
R = annual usage ratio or turn over ratio
A = total floor area [m^2]
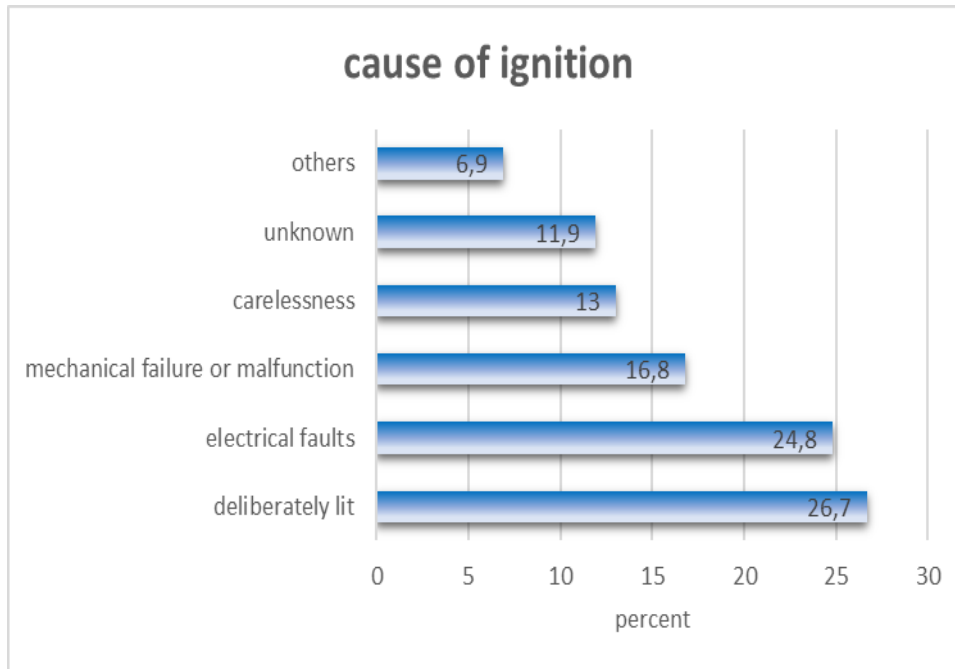*P = efficiency of parking (assumed 29 m^2 /space)*
F = vehicle fire frequency per year

National fire statistics in New Zealand

(Lit.: Tohir and Spearpoint, 2014)

QRA underground car parks

Initiation of possible accidents

cause of ignition

Category	Percent
others	6,9
unknown	11,9
carelessness	13
mechanical failure or malfunction	16,8
electrical faults	24,8
deliberately lit	26,7

percent

Causes of car ignition in New Zealand car parks 1995 – 2003 (Li and Spearpoint, 2007).

Initiation of car related fires in an underground car park may be caused by ignition of nabor cars.

➢ Fire spread scenarios

Fire statistics

New Zealand

No. of involved vehicles	No. incidents	Incident probability P
1	344	0.858
2	27	0.067
3	21	0.052
4	4	0.01
5	3	0.007
6	0	0
7	2	0.005
Total incidents / incident probability for 2-7 vehicles ignited	401	0.142

Number of vehicles involved in a fire scenario (Mohd Tohir and Spearpoint, 2014).

Underground parking

- The vehicles are having a certain distance to the neighbouring vehicles and only the burning vehicles heat radiation is exposing the potential hydrogen vehicles body, while the pressure vessel is shielded due to the vehicle body unless the fire of a spill of combustible liquid is involved.

- It may be realistic to assume that the fire spreads to the (hydrogen) vehicle after a certain duration (20 min)

- Here an insufficient distance between vehicles may be an important factor and may increase the likelihood of fire spread from car to car.

Underground parking

Fire Spread scenarios

Hydrogen car is ignited:

Fire spreads internally inside the car

Hydrogen tanks are after a delay exposed to heat

Activation of TPRD →jet release, delayed gas explosion or jet flame

No activation of TPRD → tank rupture → fire ball

Other car is ignited:

Fire from that car evt spreads to nabor cars

(geometry of car park, parking distances between cars)

Hydrogen car scenarios

Gasoline outflow

→ pool fire close to hydrogen car

→ Engulfed and localized fires

Event tree

Initiating Event								
Fires per 33841 cars per year in car park	Fire spreads to neighboring cars	Is the fire extinguished in time?	Is H2 released from the TPRD?	Does the H2 ignite?	Is the H2 ignition delayed ?	Frequency	Event chain	Consequences
		0,48				3,94E-04	E	No H2 is released
		yes	no					
	0,142							
	2 to 7 cars on fire							
					0,333	8,99E-06	I*	H2 from 1 - 7 cars is released by TPRD ignited with a delay -> possible turbulent jet deflagration and/or flammable cloud deflagration under the ceiling (if created) and DDT
				0,08	delayed			
				ignition	0,667	1,80E-05	H*	H2 from 1 -7 cars is released by TPRD and ignited immediately ->turbulent jet deflagration followed by jet fire (if TPRD designed to exclude the flame blow-off)
			0,79		immediate			
			TPRD activation of a single car out of 7 cars					
				0,92	yes	3,11E-04	G*	H2 from 1 - 7 cars is released but is not ignited
		0,52		no ignition				
		no						
0,006								
Fires			0,21			8,97E-05	F*	Catastrophic rupture of 1 - 7 H2 tanks->blast wave, fireball and projectiles
			TPRD failure to open of a single car out of seven cars OR gate --> sum of P(1) for 7 cars = 0.03 *7					
		0,48				2,38E-03	E	No H2 is released
		yes	no					
	0,858							
	1 car on fire							
					0,333	6,67E-05	I	H2 is released by TPRD ignited with a delay -> possible turbulent jet deflagration and/or flammable cloud deflagration under the ceiling (if created) and DDT
				0,08	delayed			
				ignition	0,667	1,34E-04	H	H2 is released by TPRD and ignited immediately ->turbulent jet deflagration followed by jet fire (if TPRD designed to exclude the flame blow-off)
			0,97		immediate			
			TPRD activation	0,92		2,30E-03	G	H2 is released but is not ignited
		0,52		no ignition				
		no						
			0,03			7,75E-05	F	Catastrophic rupture of the H2 tank->blast wave, fireball and projectiles
			TPRD failure to open					

Fires per 33841 cars per year in car park

Localised fire

7 x 10⁻⁵ Deflagration/DDT

10⁻⁴ Jet fire

8 x 10⁻⁵ Catastrophic rupture

Underground parking

Most severe scenarious

Frequency [year^{-1}]	Scenario	Consequence
2.38 x 10^{-03}	E	No H2 is released
2.30 x 10^{-03}	G	H2 is released but is not ignited
3.11 x 10^{-04}	G*	H2 from 1 – 7 cars is released but is not ignited
1.34 x 10^{-04}	H	H2 is released by TPRD and ignited immediately ->turbulent jet deflagration followed by jet fire (if TPRD designed to exclude the flame blow-off)
1.80 x 10^{-05}	H*	H2 from 1 -7 cars is released by TPRD and ignited immediately ->turbulent jet deflagration followed by jet fire (if TPRD designed to exclude the flame blow-off)
8.97 x 10^{-05}	F*	Catastrophic rupture of 1 – 7 H2 tanks->blast wave, fireball and projectiles
7.75 x 10^{-05}	F	Catastrophic rupture of the H2 tank->blast wave, fireball and projectiles
6.67 x 10^{-05}	I	H2 is released by TPRD ignited with a delay -> possible turbulent jet deflagration and/or flammable cloud deflagration under the ceiling (if created) and DDT
8.99 x 10^{-06}	I*	H2 from 1 – 7 cars is released by TPRD ignited with a delay -> possible turbulent jet deflagration and/or flammable cloud deflagration under the ceiling (if created) and DDT

underground car park

Consequence analysis

- The scenarios with the potential catastrophic rupture and deflagration need more detailed consideration as these may develop in very short time leaving only very little time for safe egress time of people in the car park.

- It should also be assessed in more detail whether the consequences of such explosions and the resulting blast waves may impact on the carparks structural integrity and possibly could affect the floor separations etc..

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Consequences of hydrogen releases

Engineering tool for mechanical ventilation in an underground parking (UU)

Table 2-5. Hydrogen mole fraction: two reduced models versus maximum CFD simulation results (excluding jet zone).

TPRD, mm	Pressure, bar	Hydrogen mole fraction @10 ACH, %		
		"Perfect mixing"	"HyIndoor" method	CFD_{max}
0.5	700	0.85	1.4	4
1	700	4.02	6.56	20
2	700	14.29	21.8	45
5	350	37.07	49.1	70

Releases from TPRD with diameter 0.5 and 0.75 mm don't result in a flammable layer formation under the car park ceiling for the considered range of ceiling heights (2.1-3.0 m) and ventilation rates – ACH=0 (no ventilation) and ACH=10 (required mechanical ventilation rate in case of fire).

Consequences of large releases

Pressure Peaking Phenomena: unignited
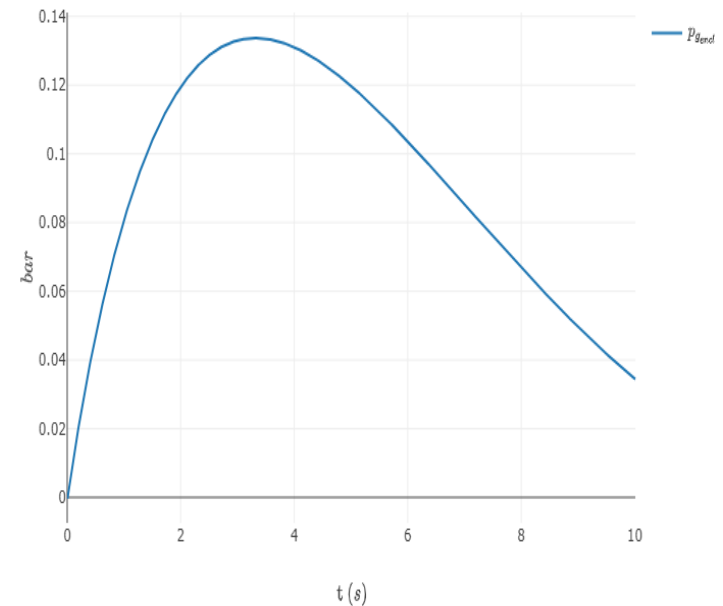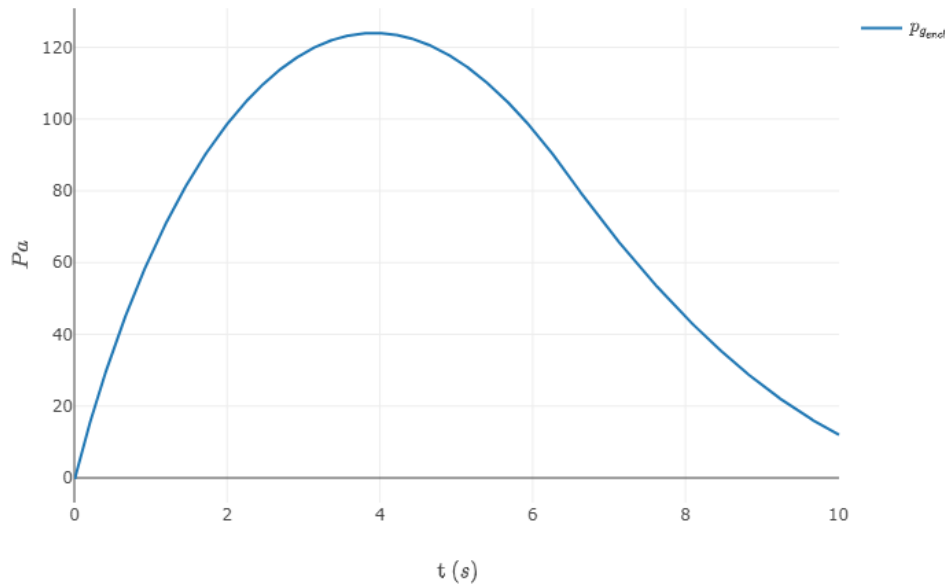
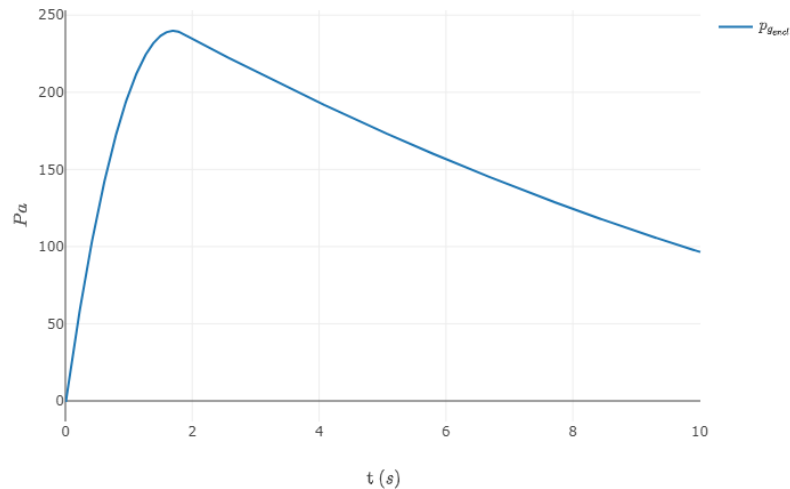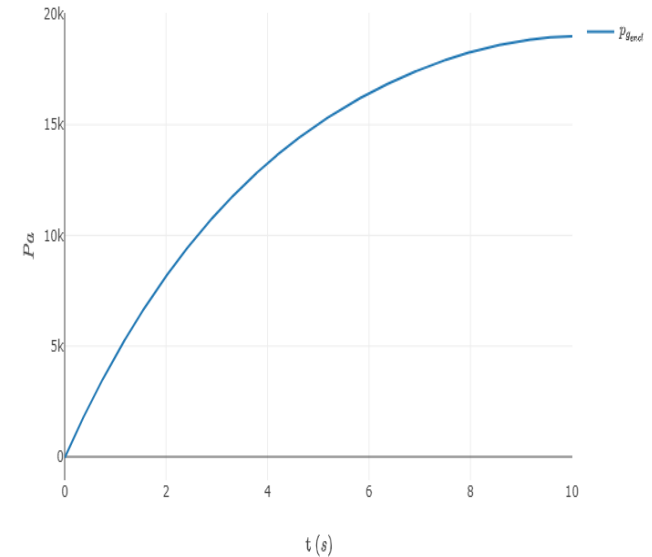Tank blow out scenarious are identical- differences the volume of encloser.
Left: 30 m3 right 300 m3
Car parks much larger than 300 m3 → no consequences on structure

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Consequences of large releases

Pressure Peaking Phenomena: ignited

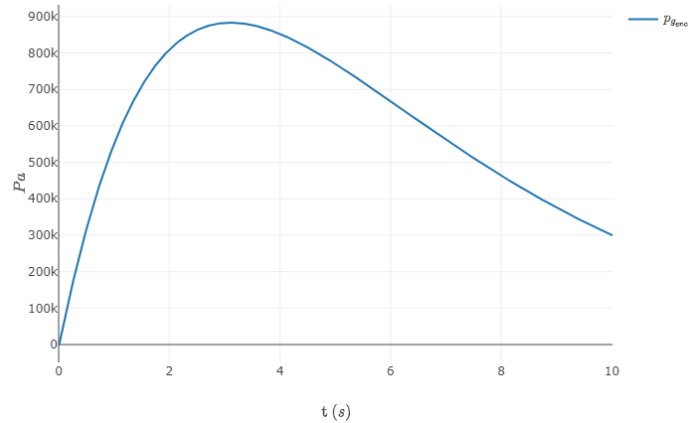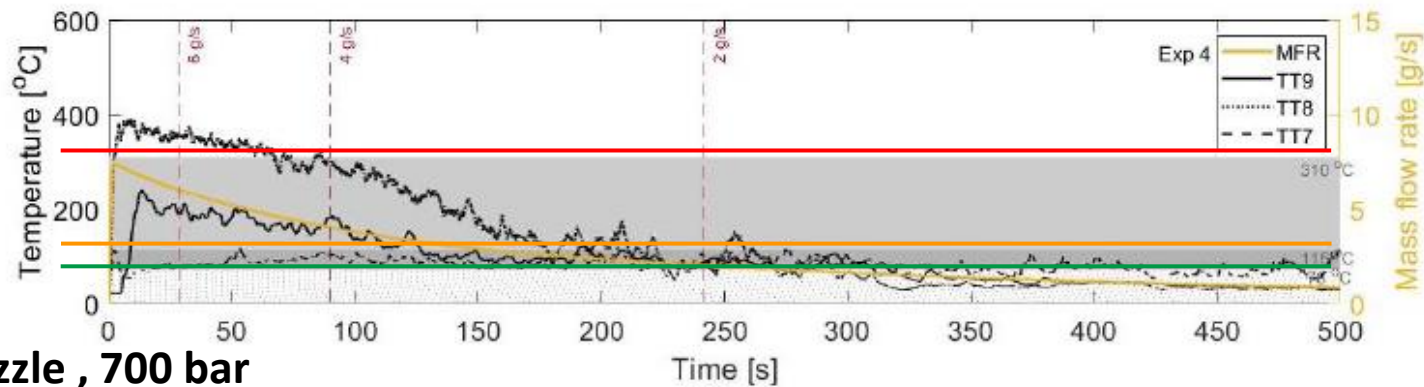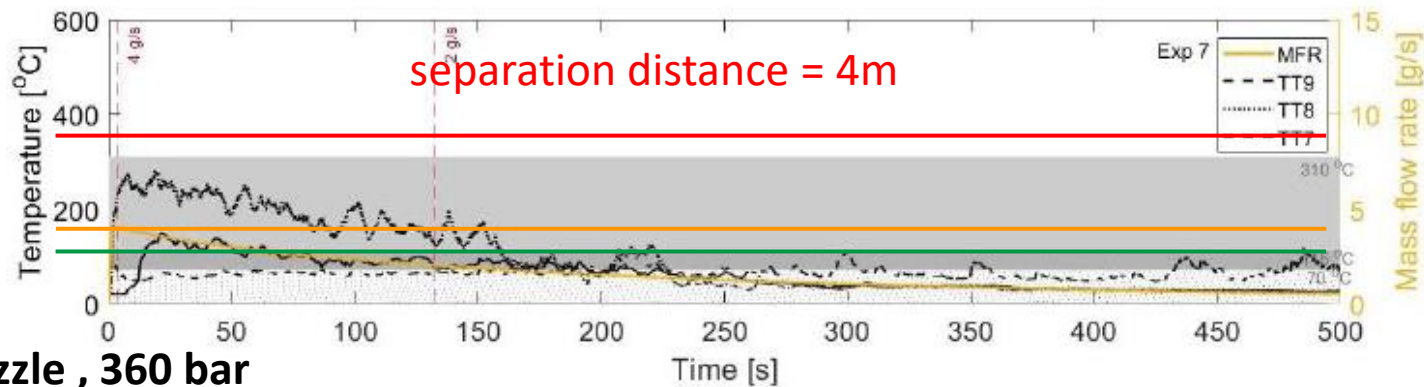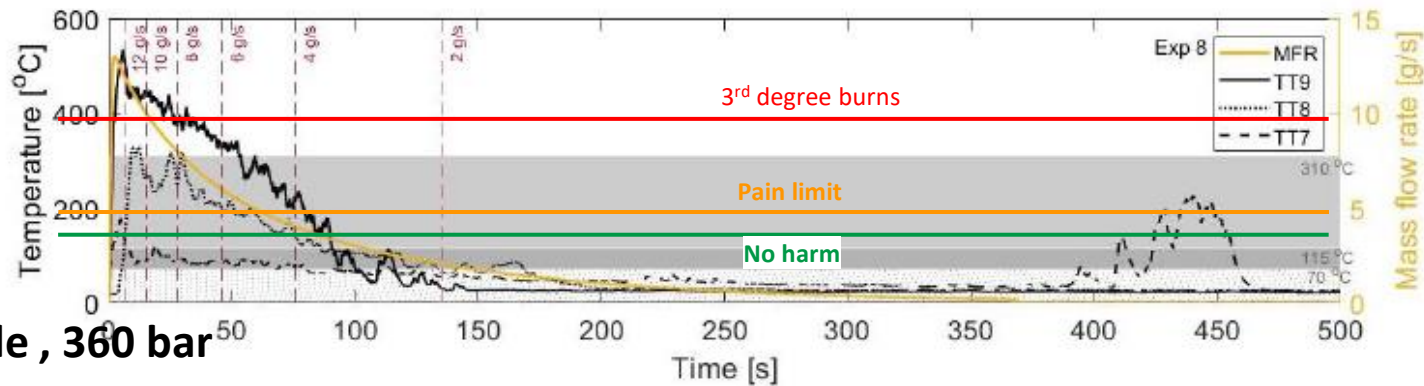Tank blow out scenarious are identical-differences the volume of encloser.
Left: 30 m3, right 300 m3, bottom 600 m3

Car parks much larger than 600 m3

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1 mm nozzle , 360 bar

0.5 mm nozzle , 360 bar

0.5 mm nozzle , 700 bar

Temperature behind the TPRD vs time,**0.38 m. 1.68 m and 3.95 m** behind the TPRD – **TT7, TT8, and TT9** respectively.

Outsite fire balls

Fire ball diameters

Calculation of fireball diameter for rupture in a fire of a stand-alone and an under-vehicle hydrogen storage tanks

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Pressure in tank (Pa)	30500000
Temperature in tank (K)	312
Tank volume (m³)	0.0724
Fireball diameter stand-alone (m)	11.25882527
Fireball diameter on-board (m)	29.27294569

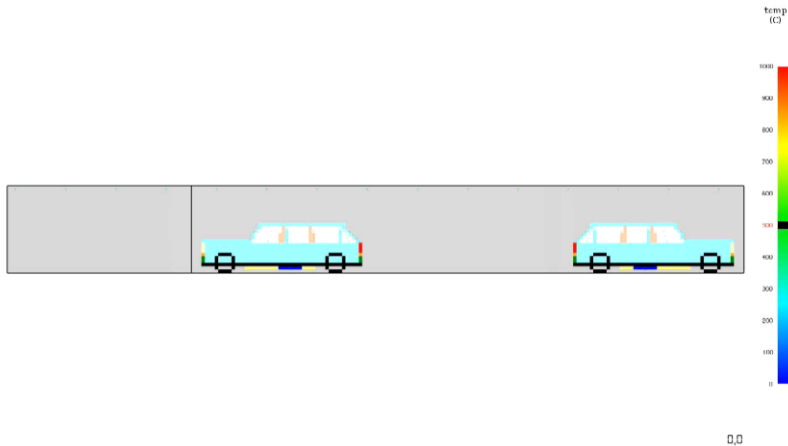More severe scenario for an underground carpark , normally few people exposed

→ exposed area of carpark will be much larger as ceiling height is much lower than 11 m

→ All people inside this area assumed lethalities

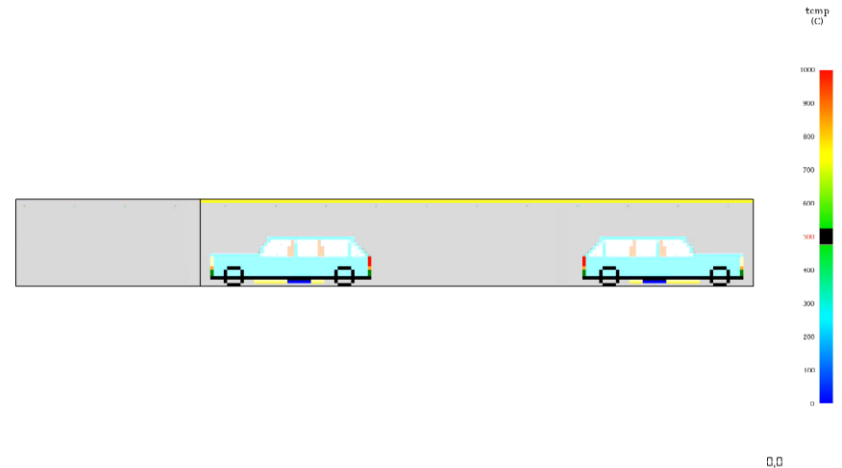# Carpark consequence modelling
fire spread domain dependency

Temperature slice: anticipated vehicle load. Ceiling height 2.6 m

Temperature slice: anticipated vehicle load. Ceiling height 2.5 m

- Spread rate to adjacent row dependent on ceiling height.
- 10 cm decreased ceiling height was found to be sufficient to cause spread to row two in the base layout with anticipated vehicle load.

Carpark consequence modelling
Fire spread → Sprinkler effect

Table 5.2: *Scenario group 1: Sprinkler scenarios. Primary thermal effects and simulated consequences.*

Scenario	THR [GJ]	tPHRR [s]	PHRR [kW]	Concrete area destroyed [m²]	No. of vehicles involved [-]
0A	42.7	851	24,818	18.6	5
0B	≥151.5	829	27,846	≥ 351.8	≥ 21
1AI	5.2	275	6,364	0	2
1AII	7.9	923	8,407	0	2
1AIII	6.1	317	6,600	0	2
1CI	8.8	1,115	13,075	0	2
1CII	11.1	745	20,584	0	2
1CIII	10.4	804	20,678	0	2
1EI	5.7	279	6,148	0	3
1EII	9.6	1,606	10,868	0	3
1EIII	6.4	291	7,179	0	3

Key findings:

- Fire contained to 3 vehicles.
- No concrete damage.
- Only flame spread to adjacent vehicles.

Scenario 1EII

Scenario 0B

Very large fire accidents in car parks

Larger fires

- Some recent fires involved a significant amount of vehicles.

- High temperatures, long duration.
  - Plastic content of vehicles increased from 6% to 18% from 1970 to 2020 [Rouiloux and Znojek, 2012].
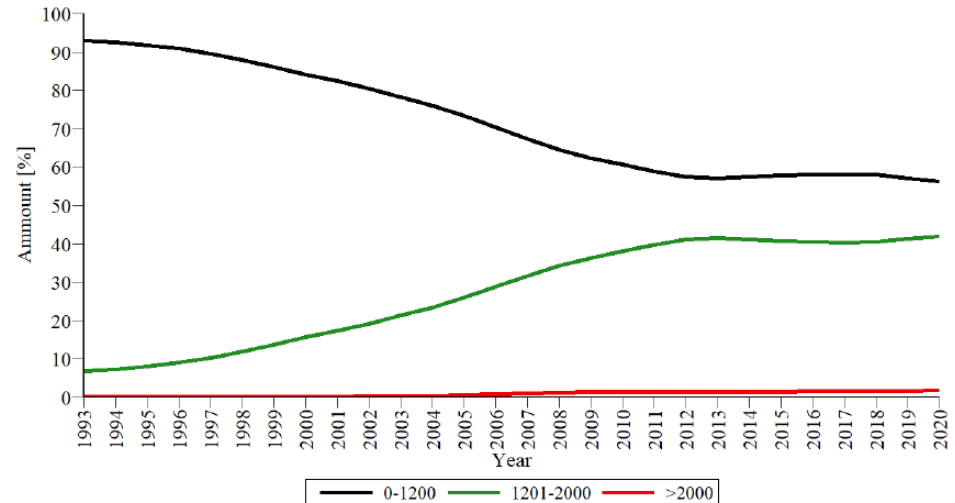 - Vehicle weight increased in the same period.

Figure 2.5: *Distribution of sold passenger vehicles by weight per year in Denmark. Legend values are weight ranges in kg. Data from www.dst.dk (Retrieved on 16/07/2021). Note: From 2006, the input value is changed from self weight of vehicle to curb weight of vehicle. Therefore, the self weight of the vehicle is added 125 kg, representing fuel and driver.*

(a) Damages to concrete slab, with obvious concrete spalling [Nair, 2018]

(b) Multiple vehicles engulfed in flames [Nair, 2018]

Figure 2.1: *Photos of damages from and magnitude of fire at Kings Docks Liverpool 2017, [Nair, 2018].*

(a) Damages on structure. Obvious evidence of concrete spalling and severe deformation of steel components, [Roche, 2019].

(b) Damages on structure. Obvious evidence of concrete spalling and severe deformation of steel components, [Roche, 2019].

Figure 2.2: *Extent of damages at Douglas Village Shopping Centre, Cork 2019 [Roche, 2019].*

Large car park fires

Possibly many cars involved

Fire spread reaches cars at longer distances

→ Liverpool , Stavanger car park fires

Consequences:

Possibility to trigger several TPRD's simultaneously also form more remote placed cars

- Gas dispersion → high probalility of delayed ignition

- TPRD does not open for engulfing fires → multiple tank ruptures

Recommendations

Overall measures for car parks

- In carparks mitigation measures should be more strictly required, e.g. fire compartments, fire ventilation, water sprinklers, etc.

- The reduction of distance between vehicles may be an important factor and may increase the likelihood of fire spread from car to **car.**

Measures for hydrogen cars

- Increase of the reliability of TPRD activation in case of localised fires by improved technological means

- Hereunder, important developments are the reduction of the TPRD release diameter and its proper location and direction of release

- Increase of the pressure tanks fire resistance rating to possibly beyond 90 min

- To use the LNB safety technology for explosion-free in a fire tanks, i.e. "self-venting" containers.

- In the case of a big fire (i.e. bus , multiple H2 cars) the TPRD can be activated simultaneously -> consequences should be assessed

Acknowledgements

This project has received
funding from the Fuel Cells
and Hydrogen 2 Joint Undertaking
(now Clean Hydrogen Partnership)
under Grant Agreement No 826193.
This Joint Undertaking receives support
from the European Union's Horizon 2020 Research
and Innovation program, Hydrogen Europe and Hydrogen
Europe Research.

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Clean Hydrogen Partnership

Co-funded by
the European Union

Ulster University

KIT Karlsruher Institut für Technologie

USN Universitetet i Sørøst-Norge

HSE Health & Safety Executive

DTU Technical University of Denmark

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

ifa International Fire Academy

SAPIENZA Università di Roma

NEN ibz

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Pro-Science