HYDROGEN-FUELED CAR FIRE SPREAD TO ADJACENT VEHICLES IN CAR PARKS

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ABSTRACT

Car park fires are known to be dangerous due to the risk of fast fire spread from one car to another. In general, no fatalities are recorded in such fires, but they may have a great cost in relation to damaged cars and structural repair. A very recent example is the Liverpool multi-storey car park fire from December 31, 2017. It destroyed 1400 cars, and parts of the building structure collapsed. This questions the validity of current design praxis of car parks. Literature studies assumes a 12 minutes period for the fire spread from one gasoline fuelled car to another. Statistical research and test from the European commission of steel structures states that in an open car park at most 3-4 vehicles are expected to be on fire at the same time.

A number of investigations have been made concerning vehicles performance in car park fires, but only a few are concerned with hydrogen-fuelled vehicles (HFV). It is therefore important to investigate how these new vehicles may contribute to potential fire spread scenario. The aim of the paper is to report the outcome of car park fire spread simulations involving common fuelled and hydrogen fuelled cars. The case study is based on a typical car park found in Denmark. The simulation applied numerical models implemented in the Fire Dynamic Simulator (FDS). In particular, the focus of the study is on the influence of the parking distance to fire spread to adjacent vehicles in case a TPRD is activated during a car fire. The results help understanding whether different design rules should be envisaged for such structures or how a sufficient safety level can be obtained by ensuring specific parking condition for the hydrogen-fuelled cars.

1 NOMENCLATURE

Symbol	**Parameter**	**Unit**
k	Thermal conductivity	W/(m K)
C	Heat capacity	kJ/ kg K
ρ	Density	kg/m^3
H_c	Heat of combustion	kJ/kg
T_{ig}	Ignition temperature	^oC
$HRRPUA_{peak}$	Peak heat release rate per unit area	kW/m^2
HRR	Heat release rate	kW
Q_{total}	Total released energy	MJ/m^2
l	Thickness	m
m_{total}	Total mass	kg

2 INTRODUCTION

Car park fires are known to be dangerous due to the risk of fast fire spread from one car to another. In general, no fatalities are recorded in such fires, but they may have a great cost in relation to damaged cars and structural repair of the multi-storey car park. Hereunder, it has to be distinguished between three different categories of car parks:

1) Closed car park, which is a closed off building, e.g. with no natural ventilation. Such are often found being in the underground, e.g. under large shopping centers.

2) Open car park, which is typically an open-air natural ventilated parking area. It can also be a carport with no walls.

3) Semi-open car parks are a mix of the two above described types. It has large openings in the walls to allow for natural ventilation. The enveloping walls maybe 1 meter high, while the remaining sides are open. Semi-open car parks are often found in multi-storey buildings.

Several fires in open car parks have been found to damage unexpected many cars. A very recent example is the Liverpool multi-storey car park fire from December 31, 2017 [1]. It destroyed 1400 cars, and parts of the building structure collapsed. Other fires are recorded as the October 2002 car park fire at Schiphol airport burning 30 cars [2] or the October 2013 fire adjacent to the Aquatic Centre of the Sydney Olympic Park [3]. This fire damaged about 100 cars, while 47 were destroyed. Many other fast spreading fires are reported e.g. from the UK [4]–[6] and Denmark [7], [8].

This questions the validity of current design praxis of open and semi-open car parks, assuming mitigation of the fire severity by the high ventilation rate of the premises. Literature studies find a period of 12 minutes for the fire spread from one gasoline fueled car to another. Statistical research and test from the European commission of steel structures [9] states that in an open car park at most 3-4 vehicles are expected to be on fire at the same time. One of the contributing factors to the much severer fire spread observed in the above mentioned open car park fires may be the increased use of combustible light-weight materials [10], as shown in Figure 1. This is assumed being valid for hydrogen-fueled vehicles (HFC) as well and therefore it is important to gain appropriate knowledge about the fire spread in car parks that involves vehicles driven with modern sustainable fuels as hydrogen.

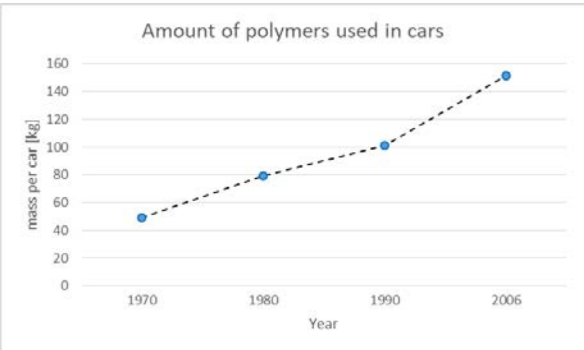

Figure 1 Development of the average amount of polymers in cars *[10]*

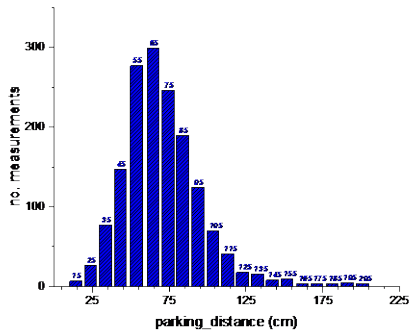

Figure 2 Statistics on parking distances [11]

Several vehicle fire test and assessments are reported, as e.g. compiled in [9], [11]–[15]. Being a new approaching technology, presently, only a limited number of studies have been done being concerned with the fire spread behaviour of hydrogen fuelled vehicles (HFV) [13], [16]–[18]. It is therefore important to investigate whether HFV's may lead to severer car park fires in relation to the structural elements and fire spread.

Marton et.al. [19] used a very simplified model and car materials, e.g. the car surface is made of rubber (tires), to simulated worst-case situations for gasoline driven cars. It was possible to estimate the flame spread and get good indications on the fire spread between cars, hereunder the influence of parking distance (see Figure 2) and geometrical relations in a semi open car park.

Tamura et.al. [16] evaluated test scenarios valid for an outdoor parking lot and also for marine transportation of HFVs (see additionally [20]). In more detail, they investigated the fire spread starting at a HFV spreading to adjoining vehicles. In scenario 1, a HFV is placed alongside with a gasoline car at a distance of 0.85 m. Ignition point was the HFV’s right rear wheel on the far side to the gasoline car. This is a larger than average parking distance as seen in Figure 2. The TPRD opened at 110 C 30 min after ignition. The vent had an inner diameter of 4.2 mm. The gasoline car ignited at 57min 26s about 28 min after the TPRD opened. Thus, the results indicated that the HFV materials were responsible for the fire spread, but not the hydrogen release through the TPRD.

In scenario 2 [16], three HFVs were placed closely to simulate a ship carrier scenario. The two HFV have been equipped with 2 hydrogen tanks each, positioned front and rear to the rear axis, while the third HFV only had one tank. The parking distances were 0.1 m alongside and 0.3 m between the front and rear sides of the cars. The TPRD opened at 104 C and the vent had a 4 mm inner diameter. The TPRD was designed to release the hydrogen in a 45 -angle configuration rearwards to the floor. The ignition point was placed at the right rear bumper. The car placed alongside to the ignited car started to burn after 109 min, while the third car positioned front to rear of the ignited HFV ignited after 114 min. First, the rear tank TPRD of the ignited HFV opened at 117 min, Second, the rear tank TPRD of the alongside placed car opened second at 120 min. The front tank TPRD of the ignited car opened after 122 min. Tamura et.al conclude that the direct cause of fire spread is not the hydrogen flames after activation of the TPRD’s, but the HRR from the burning vehicles. *“[…]However, in car carrier ships and other similar situations with closely parked HFCV, the test results point to the possibilities of a fire in an HFCV to activate its TPRD and thereby to generate hydrogen flames which in turn may cause the underfloor TPRD of adjoining HFCV to activate.[…]”* [16, Ch. Conclusion]

Other tests by the author on single hydrogen gas cylinders and on hydrogen gas tanks built in vehicles found TPRD activation times after about 1 min. Other ignition points as e.g. the ashtray in the car or a gasoline pool fire below the trunk room close to the position of the hydrogen storage in the car activated the TPRD after 15 -17 min and about 4 min, respectively. Watanabe et.al. [13] measured peak release heat fluxes of 190 kW/m^2 for hydrogen for vertical downwards TPRD activation tests.

The above findings show the very wide time range for the activation of the TPRD. The influence of the geometry of the car park has not been considered in detail for the hydrogen scenarios, but it is known that the heat radiation back from the walls and the parking distance between the cars is of importance for fire spread scenarios, as e.g. found by Marton et.al. [19]. Therefore, the question may be raised, whether an early release of hydrogen could contribute to a faster heating of the walls and facilitate the fire spread from car to car in a car park. The aim of this paper is to further investigate this based on the case of a semi open carpark building (Figure 1) and the development of appropriate car models. The simulation applied numerical models implemented in the Fire Dynamic Simulator (FDS) and partly using Pyrosim.

The results are intended to improve the general understanding, whether different design rules should be envisaged for such structure or a sufficient safety level can be obtained by ensuring specific parking condition for the hydrogen-fuelled cars.

Figure 3. Example of semi open carpark in Copenhagen Denmark [*foto: Denice Søgård 2018*]

The car park building shown in Figures 3, 4, 5 has dimensions 120m x 17.5m, while each floor has a free height of 2.81m. The building is constructed using concrete columns on each side and has concrete beams in between to support the TT-decks above, which span over the whole width. These therefore create prolonged cavities were the heat and smoke from a car fire may be captured in and is expected to influence the results of an assessment of the spread of car fires.

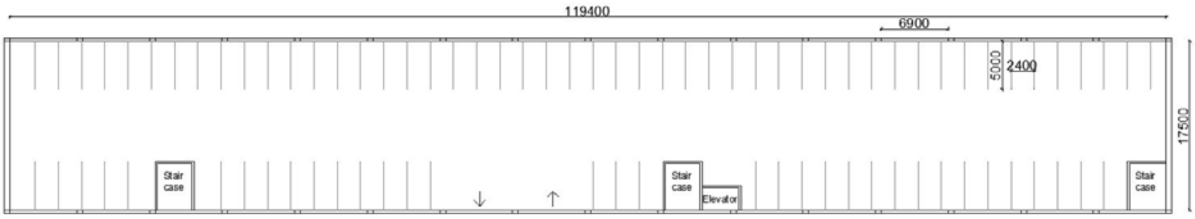

Figure 4 Floor plan of semi open car park with dimensions

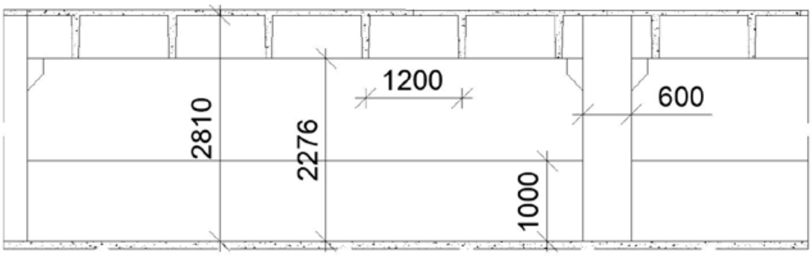

Figure 5 Section of semi open car park with dimensions

3 NUMERICAL MODELS AND RESULTS

The development of modern, sustainable vehicles with a minor carbon footprint is important in our society. In order to achieve the goal, two developments are seen: 1) the substitution of common materials to lightweight materials and 2) the research into new engines driven on new fuels.

In the following, the substitution of materials is detailed as it involves an increasing use of combustible polymers in all types of vehicles. Patil et al [10] investigated the use of polymers in the automobile industries in the period of 1970 to 2006 shown in Figure 4 stating that the average mass of them was 150 kg per car in 2006. This corresponds to about 10 to 15% of a modern cars weight. They recognized the following additional benefits of using plastic compounds in vehicles: minor corrosion giving longer lifetime; design freedom; flexibility in integrating components; safety comfort and economy; and recyclability. Three polymers represent about 65 % by mass of the built in car materials: Polypropylene (32 %), Polyurethane (17 %) and PVC (16%).

3.1 Materials used in the vehicle models

3.1.1 A simple car model

In order to enable the simulation of fire spread effects involving hydrogen driven cars appropriate car models are developed by Søgaard [21], [22]. The first approach is shown in Figure 6. The car is made of blocks with different materials consisting of rubber, PU foam, PVC, PP and PC [22]. The primary materials that contribute to fire are the tires and the interior parts such as plastics and seats.

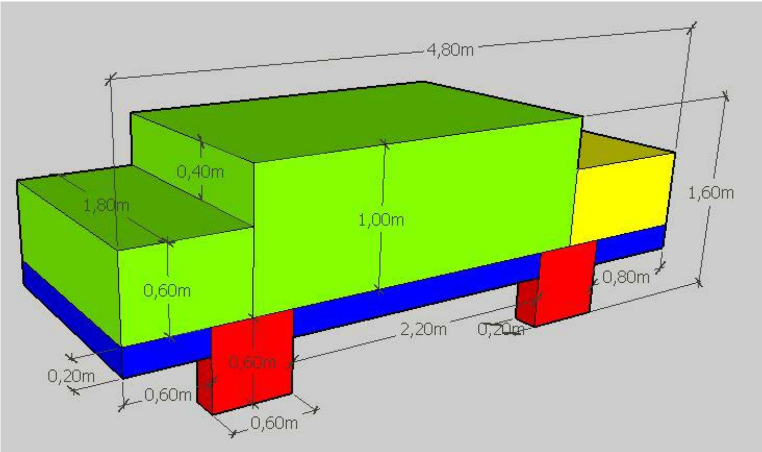

Figure 6 Simple car model used in FDS. *[22]*. 1) Rubber For the tires (Red) *[23]*; 2) Polyurethane foam (PU) For seats in the middle, and back part of the car (Green); 3) Polyvinyl chloride (PVC) For the plastic parts in the middle and back part of the car (Green); 4) Polypropylene (PP) For the engine cover in the front part of the car (Yellow); 5) - Polycarbonate (PC) For the bumpers (Blue)

This car model is inspired by some former work by Noordijk and Lemaire [24]. The materials are modelled based on the parameters listed in Table 1, including the total masses of the chosen materials. These are calculated using the volume (surface area of the parts times an estimated thickness) and the materials density. The heat release rate curve is defined from the peak heat release rate and the total heat release from table 3.2. It is assumed that the peak occurs halfway and that the curve is linear both in the growing and decay phase. On fig. 3.6 the heat release rate curves for the different parts can be seen. The HRR curve for rubber is from section 2.1.3 of a paper from Watanabe et al. [13]. The middle and rear part of the vehicle is build using a PU / PVC composite with a material fraction 50 / 50 %. The ignition temperature is assumed to be the lower of the two pure materials ignition points, while the peak heat release rate and the total released heat is assumed as the average of the respective materials.

Table 1 Simple car model. Material properties

Parameters	Unit	Rubber	PU	PVC	PP	PC	Ref.
k	W/(m K)	0.13	0.03	0.19	0.15	0.19	[25]
C	kJ/ kg K	2.01	1.8	1.0	1.92	1.2	[25]
ρ	Kg/m3	1100	30	1390	900	1200	[25]
Hc	kJ/kg	32600	19800	20000	46000	31000	[26] [27]
T_{ig}	oC	289	205	238	211	450	[28] [29]
HRRPUApeak	kW/m2	538.76	296	183	1170	429	[30] [31]
Q_{total}	MJ/m2	216.18	128	90.8	231.3	120	[30] [31]
l	m	0.02	0.05	0.05	0.05	0.05	
m_{total}	kg	77.44	14.43	668.92	147.53	441.60	

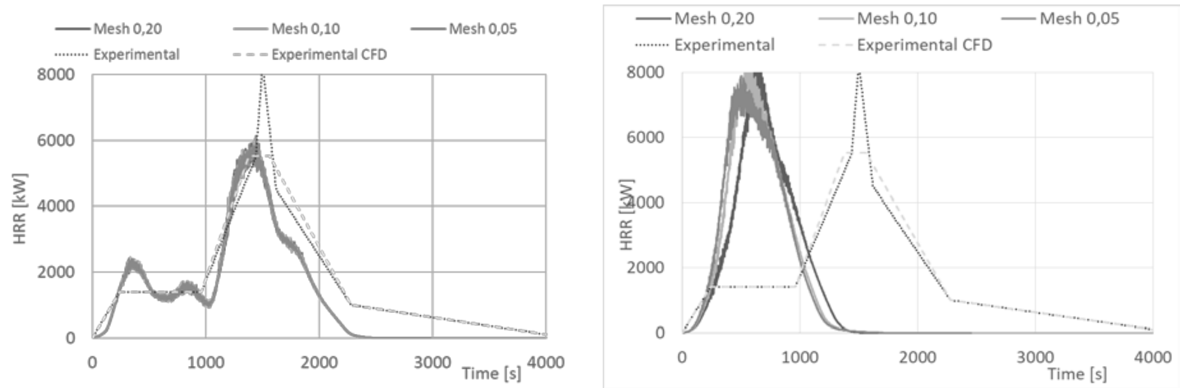

Figure 7. a) The simulation of the HRR for the current car model in relation to the experimental reference heat release curve for car fires [11] using time triggered time ramps for starting the HRR of each car component. b) The simulation of the HRR in relation to the reference heat release curve for car fires [11] using ignition temperatures for the car materials

In Figure 7 a), each material of the vehicle is assigned a time ramp to simulate the overall HRR. This has been calibrated applying the experimental reference curve for car fires [11]. In Figure 7 b), the second car (target) is simulated using an ignition temperature for each of the materials. Here, it is seen that the fire development is much faster and reaches the peak HRR at about 500 s, while the design fire defines 1500 s. On the other hand, the HRR up to about 100 s of the starting fire is still close to the experimental reference curve. Therefore, it is believed that this model still can predict the ignition of the second car, while fire spread to third cars will not be accurate.

3.1.2 An advanced car model

Nielsen and Lauridsen [32] developed a more advanced car model that also enables the modelling of the fire spread inside a car. In this way, the model could be used to predict the temperature at the hydrogen storage vessel and thereby predict the activation time of the TPRD. This model is shown in Figure 9. The inside fire spread is compared to findings in a study by Krüger et al. [33]. In order to simulate the hydrogen driven car and the activation of the TPRD, the HRR histories of the interior have been simplified by a controlled release of two burners at the floor of a car. One burner is simulating the HRR of the cabin seats, while the second simulates the HRR of the car interior. Both burners are based on timer controlled ramps in the FDS model.

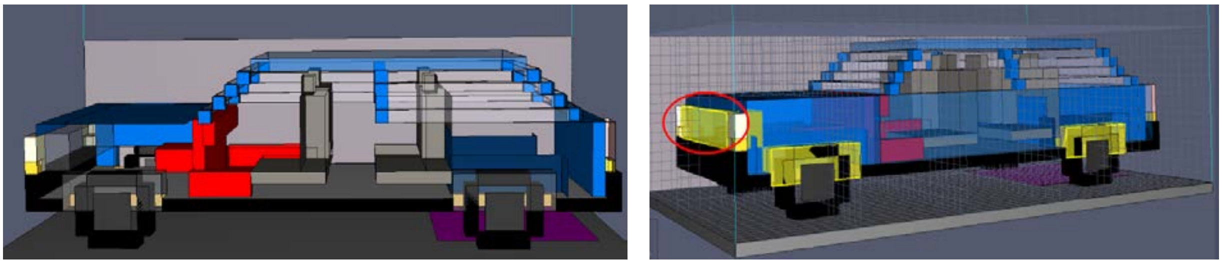

Figure 8 Advanced car model. Red circle opening to allow for sufficient ventilation inside the car

3.2 The hydrogen release model

For the release of hydrogen after activating the TPRD a simple burner is assumed. The momentum jet that will appear at the initial phase of the activation cannot be directly modelled in FDS, but it is assumed that the release is directed vertical downwards and impacting the floor, which turns the release into a kind of a "pool fire".

Table 2 Material properties for the car seats [25], [34, Fig. table A.27]

Material	Density [kg/m3]	Heat capacity [kJ/(kg K)]	Thermal conduction [W/(m K)]
Steel	7850	0.46	45.8
Rubber	650	2.01	0.13
Aluminium	2710	0.91	205
Glass	2500	0.8	0.8
Foam	65	1.0	0.05
Fabric	100	1.0	0.1
Air (Cavity)	100	1.0	0.1
Polypropylene (PP)	910	1.7	0.22

This is assumed to happen after a certain period of time according to some test fires of hydrogen cars .The seats are modelled assuming two polymers, as recently reported by Krüger et al [33] who did experiments combined with car simulations. See Table 2 for the specific data.

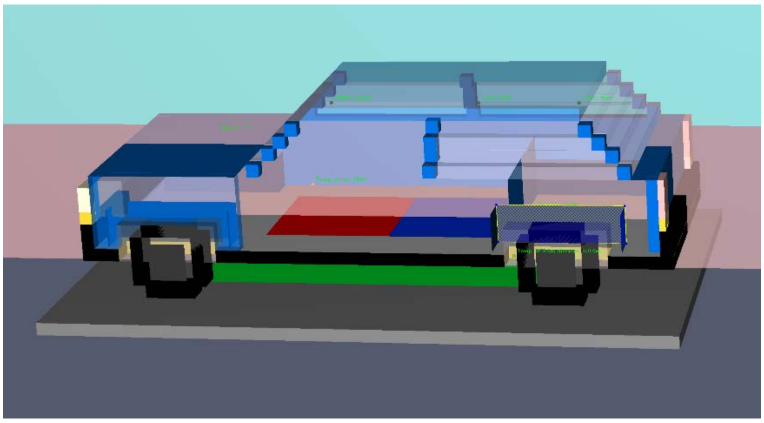

Figure 9 The advanced hydrogen car model based on time ramps in FDS. The red area is a burner mimicking the burning seats, while the blue area is the interior materials (PP) burning in the car. The vent appearing after the activation of the TPRD represents the hydrogen fire after release.

The hydrogen module is tested in a domain of 560 m^3 and the release area has been varied with 1, 4 and 6 m^2 and assuming constant hydrogen release flux of 0.45 kg/s/m^2 as shown in Figure 10. This flux is based on a TPRD vent of 5 mm inner diameter, a little higher than the diameters reported in the Tamura tests [16]. Thus, the release is to be seen as a worst case scenario. Currently, TPRD vent diameters are being reduced to 2-3 mm. Future models will include the effects on the fire spread scenarios due to lower release fluxes. The availability of oxygen is providing well-ventilated conditions as shown in Figure 11. The effective HRR is shown in Figure 12 together with the distribution of the heat Q in the domain. For the sole hydrogen fire, the dominant heat fraction is transported by convection, while radiation and conduction still are of minor importance. For the advanced car described in Figure 9 only preliminary model runs have been done so far and are not reported further in this paper.

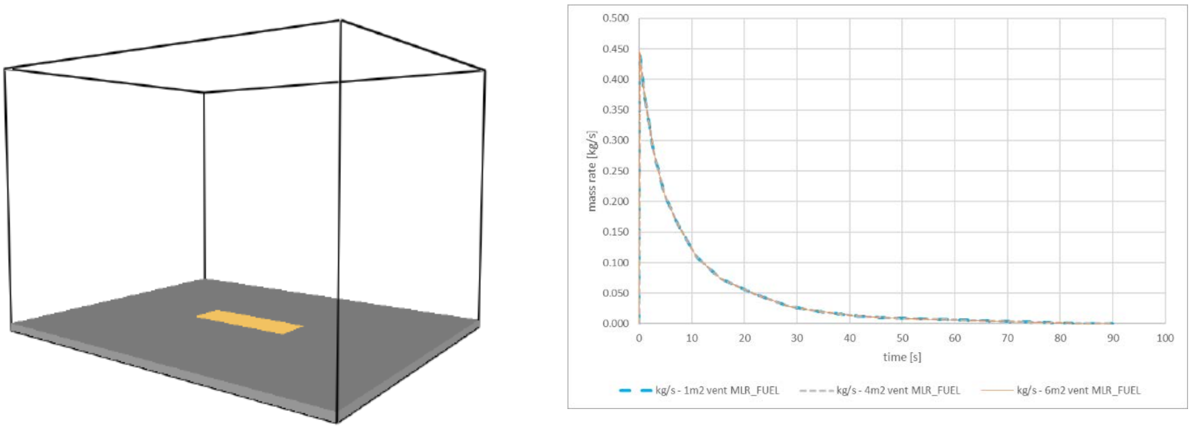

Figure 10 a) hydrogen release sub-module with the yellow burner area. Domain volume is 560 m^3; b) total mass release vs time for 3 hydrogen fluxes at 1, 4 and 6 m^2 vent area.

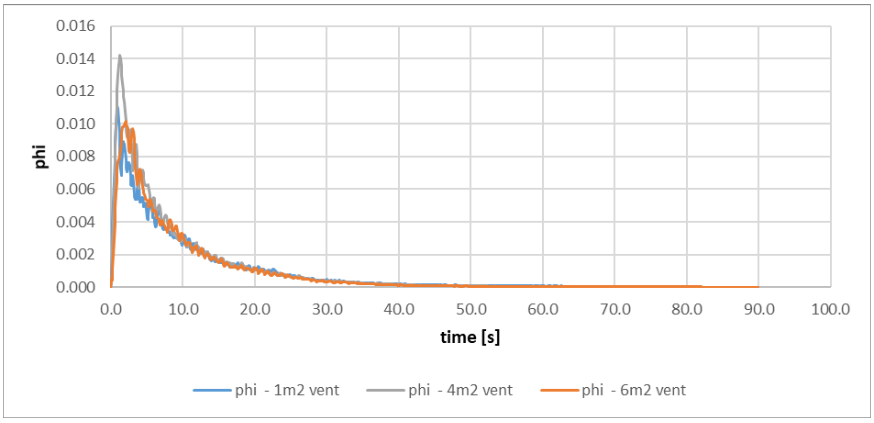

Figure 11 Phi value in the calculation domain indicate well-ventilated conditions (phi <1) for the entire hydrogen combustion process under the release.

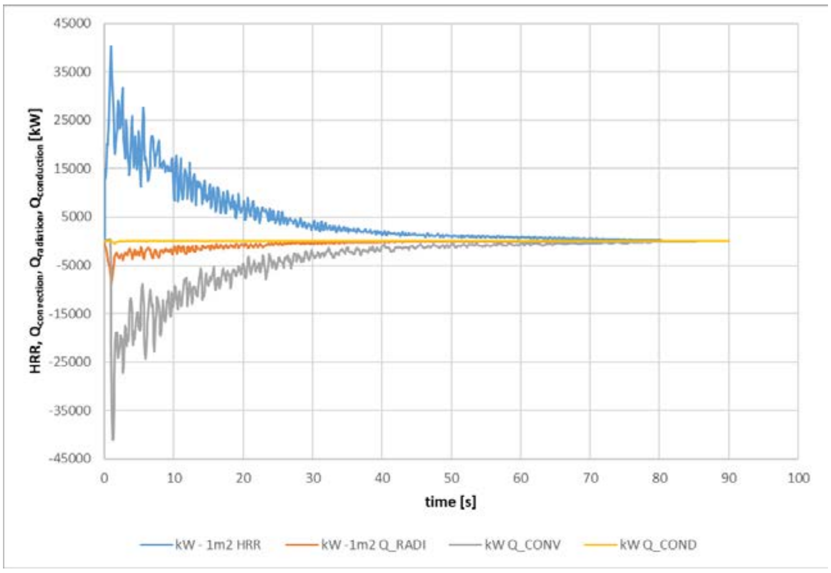

Figure 12 HRR for hydrogen combustion and the resulting transport of heat Q by convection, radiation and conduction for a 1 m^2 vent in the 560 m^3 domain and a hydrogen flux of 0.45 kg/s m^2.

4 DISCUSSION AND CONCLUSION

The simple car model was used to simulate a few scenarios. In Figure 13 one scenario and the structural geometry is seen as well as the fire development at 250 s. The typical HRR is shown in Figure 14 together with the distribution of the heat Q for radiation, convection and conduction. In the fire spread scenario the heat radiation is dominant, while the convective contribution is only half with a minor contribution of the heat conduction to the car materials and the concrete structure of the car park.

The reference scenario consider gasoline fuel cars separated by a parking distance of 60 and 80 cm (see Figure 2). The results shown in Table 3 indicate that the fire propagation to the adjacent gasoline car needs about 7 minutes when the parking distance is 60 cm between the cars. It is increased by a factor 1.1 for a parking distance of 80 cm. This would be about 4 to 5 min quicker than design criteria established by the European commission [19]. The ignition of car 2 is depending on the ignition temperature of the materials, which is crucial and needs to be further elaborated using the advanced model in a future simulation. The ignition of the second car for the ignited hydrogen car is faster and decreased by a factor of 0.6 for both distances.

Table 3 Simulation of fire spread compared to gasoline reference scenario

Scenario and distance]	**Relative time to ignition**
Two gasoline cars separated 60 cm	1.0 (423s)
Two gasoline cars separated 80 cm	1.1
HFV and gasoline car separated 60 cm	0.6
HFV and gasoline car separated 80 cm	0.6

The fire spread for the hydrogen case seems faster than for the gasoline reference case. It is though very depending on the time of the hydrogen release. For this scenario the worst case was investigated to see the effect a hydrogen release could have. In this worst case scenario, the adjoining car is ignited by the heat, created by the hydrogen flame. For the distance of 80 cm the adjoining car is ignited at about the same time interval, which shows that the larger distances to HFV des not seems to affect the fire spread to the same extent as for the reference gasoline case.

As several studies have indicated, the activation time of the TPRD is dependent on the ignition point of the car. This is therefore also of interest for future studies of the fire spread involving HFV.

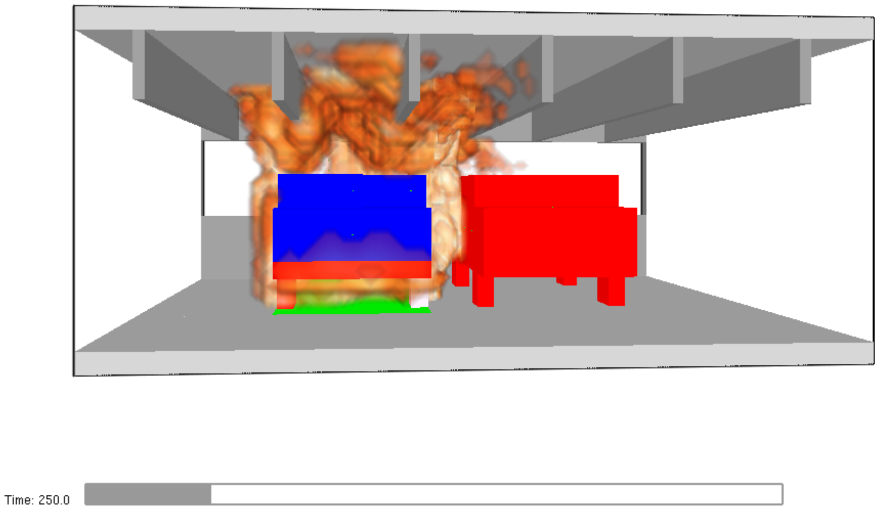

Figure 13 Fire development at 250 s. Ignition of the hydrogen.

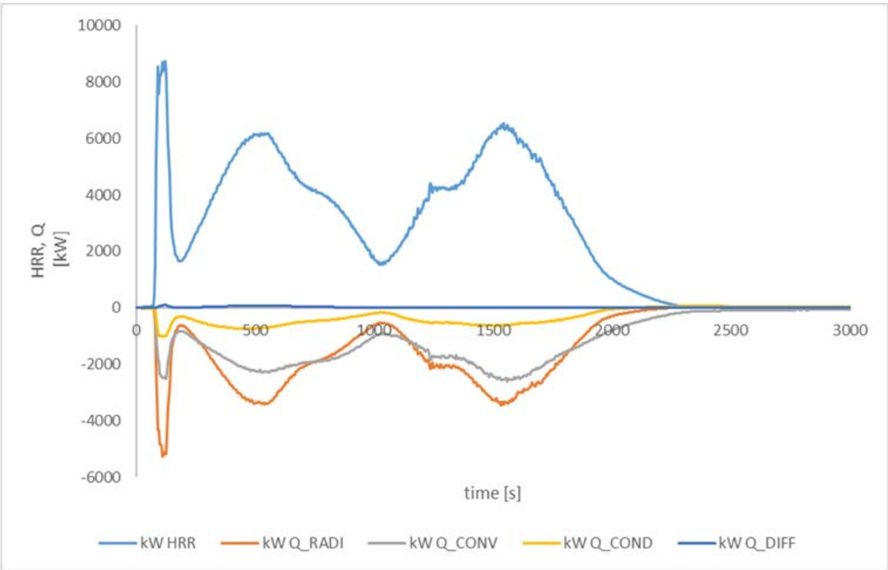

Figure 14 HRR of the two-car scenario inclusive hydrogen release at the early stage of the fire scenario. The heat is balanced by heat radiation and convection, mainly

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