Risk assessment methodology for onboard hydrogen storage

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ABSTRACT

A quantitative risk assessment of onboard hydrogen-powered vehicle storage, exposed to a fire, is performed. The risk is defined twofold as a cost of human life per vehicle fire, and annual fatality rate per vehicle. The increase of fire resistance rating of the storage tank is demonstrated to drastically reduce the risk to acceptable level. Hazard distances are calculated by validated engineering tools for blast wave and fireball, which follow catastrophic tank rupture in a fire, act in all directions and have larger hazard distances compared to jet fire. The fatality cash value, probabilities of vehicle fire and failure of thermally activated pressure relief device are taken from published sources. A vulnerability probit function is employed to calculate probability of emergency operations' failure to control fire and prevent tank rupture. The risk is presented as a function of fire resistance rating of onboard storage.

Keywords: hydrogen safety, quantitative risk assessment, onboard hydrogen storage, blast wave and fireball, fire resistance rating, socio-economics

1.0 INTRODUCTION

1.1 Hydrogen hazards

Due to unique hydrogen properties, its safety characteristics are quite different from those of commonly used fuels such as gasoline and natural gas. The low density of hydrogen (14 times lighter than air) makes it buoyant and inherently safer than other fuels in the open atmosphere and well-ventilated areas. Because of buoyancy hydrogen disperses fast in the open atmosphere to concentrations below the lower flammability limit and only a small fraction of released hydrogen would contribute to combustion if ignited [1]. Lower minimum ignition energy and a wider flammability range (4-75% by volume), however, make hydrogen more susceptible to ignition. Hydrogen is not more dangerous nor safer compared to other fuels [2]. Safety of hydrogen systems and infrastructure fully depends on how professionally it is handled at the design stage and afterwards [3]. The findings of empirical studies of public engagement [4] indicate that, while knowledge of hydrogen is limited, attitudes are agnostic. People are keen to learn more about hydrogen energy technologies, but reluctant to express explicit approval – or outright rejection – until more information is available about the relative costs, benefits and risks compared to existing systems. It was confirmed [4] that to be accepted by public as an emerging technology, the risk associated with hydrogen-powered transport must be less than, or at least equal to that of today's fossil fuel transport. These are reasons the authors engaged in this study.

1.2 Onboard storage of hydrogen

Onboard compressed gaseous hydrogen (CGH2) storage for hydrogen-powered vehicles is designed for typical operating pressures 35 MPa and 70 MPa. Type III (aluminium liner) and IV (polymer liner) composite tanks are accepted for onboard CGH2 storage due to their light weight and exceptional mechanical strength characteristics. Type IV tank is made of a high-density polyethylene liner (to limit permeation to regulated level), which is over-wrapped with a carbon fibre reinforced polymer (epoxy resin) to bear the pressure load of CGH2. Unfortunately, light weight and mechanically strong composite tanks degrade under a thermal load such as fire. The fire resistance rating (FRR), i.e. time from the start of fire to catastrophic rupture of tank (in conditions of thermally activated pressure relief device (TPRD) failure to operate, or its blockage, in an accident), of current thermally unprotected tanks is about 6-12 min [5, 6]. The European Regulations on type-approval of hydrogen vehicles require TPRD to be installed on hydrogen onboard tanks to release its content in a fire event and therefore to prevent catastrophic tank rupture. However, TPRD activation and safe hydrogen blowdown are impossible in some accident scenarios, e.g. in the case of a fire affecting only the localised area of a tank far from TPRD, or when a vehicle design does not exclude a blockage of the TPRD sensing element in jammed parts of the vehicle during a road accident. In these cases, a tank can experience a strong and fast thermal load from a fire and thus progressing degradation of the composite tank wall. Rupture of a tank equipped with TPRD in CNG-vehicles fires has been repeatedly reported, e.g. [7]. This is probably the most important current safety concern for hydrogen-powered vehicles. Explosion-free in a fire composite tank (infinite FRR), which is currently under development at Ulster University, would be a solution to drastically increase safety of hydrogen vehicles and gain public acceptance of the technology.

1.3 Relevant safety studies

The interest of OEM in hydrogen-powered vehicles has stimulated research into safety of onboard hydrogen storage, including studies on fire and explosion hazards and performance of CGH2 tanks in a fire with TPRD being removed [5, 6, 8]. The experimentally observed hazards from a storage tank failure in a fire, i.e. pressure effects of a blast wave and thermal effects of a fireball, were documented [5, 6] and analysed [9, 10]. The same experimental data [5, 6] were recently analysed in a study [11], where the contribution of combustion into the blast wave strength was demonstrated and accounted for the first time, making prediction of hazard distances more accurate. The effect of different thermal protection of a tank on its FRR was studied [12]. The development of the Computational Fluid Dynamics (CFD) model to evaluate the effect of intumescent paint on FRR of Type IV tank in a fire is described [13].

There are studies on quantitative risk assessment (QRA) of hydrogen refuelling stations and storage infrastructure, e.g. [14], and relevant tools, e.g. HyRAM toolkit by Sandia National Laboratories [15]. The HyRAM focus is currently on the thermal effects from jet fires and pressure effects from deflagrations. One may calculate fatal accident rate, average individual risk, and potential loss of life from jet fires and deflagrations only. HyRAM is still under development and there are hazards yet to be included in the consequences analysis part of the toolkit, e.g. hazards from blast wave and fireball in the case of catastrophic tank rupture in a fire. These two hazards are identified as the main hazards in our study. Work [14] suggested a risk-informed approach for the selection of a leak diameter to establish the safety distances in National Fire Protection Association standards NFPA 2 "Hydrogen technologies code" [16] and NFPA 55 "Compressed gas and cryogenic fluid code" [17]. Their study involved the analysis of frequency and risk of leakage for typical hydrogen facilities, and the cumulative frequency of a system leakage. Due to limited hydrogen-specific leakage data, a Bayesian statistics approach was exploited to generate leakage frequencies from other non-hydrogen sources. In 2005 the authors of [18] performed a QRA study for a gaseous hydrogen storage tank with regards to unconfined vapor cloud explosion and fireball. The "functional modelling" approach was introduced in [19] and it was proposed as an efficient method for the high-level risk assessment of hydrogen supply chain. The role of uncertainty in hydrogen emerging technologies was introduced and a step-by-step investigation methodology to quantify the uncertainty was attempted in study [20]. Safety barrier diagrams technique was introduced in [21] as a complimentary tool for both quantitative and qualitative risk assessment of hydrogen technologies and it was followed by the development of the software "SafetyBarrierManager" in the Technical University of Denmark [22].

In [23] a risk assessment framework for onboard hydride-based hydrogen storage systems for light-duty vehicles was proposed and uncertainties involved were discussed. There are other hydrogen related risk assessment related studies including, but not limited to, an overview of risk assessment studies on hydrogen safety [24]; discussion on challenges towards hydrogen technology risk assessment [25, 26]; risk assessment of hydrogen and CNG refuelling stations [27]; quantitative risk assessment of the mobile hydrogen refuelling station [28]; presenting a hydrogen risk assessment methodology [29];, proposing and implementing a risk assessment methodology during the production of hydrogen in an oil refinery [30]; proposing and modelling of a risk matrix framework of cryogenic liquid hydrogen filling systems [31]; 3D risk management on hydrogen installations [32]; a grid-based risk assessment method in hydrogen refuelling stations [33] and performance-based design of refuelling stations [34].

ISO TC197 Hydrogen Technologies has recently introduced a term "hazard distance" as "*a distance from the source of hazard to a determined (by physical or numerical modelling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition ranging from "no harm" to "max harm" to people, equipment or environment"* [35]. Hazard distance is the transparent "consequence only" deterministic distance that will be applied in this study as an alternative to separation or safety distance currently used by industry [35].

The authors of [36], [37] studied the damage probability of storage tanks exposed to a fire and its relationship with FRR. The probit function was employed to estimate the escalation probability (EP), i.e. the likelihood of emergency operations to fail to extinguish the initiating fire (leading to a tank rupture). The probit function gives the "inverse" computation associated with specified cumulative probability. The QRA methodology [36], [37] was used to assess the performance of fireproofing materials to protect a fuel storage tank from a fire. The authors of [36], [37] used the general equation from the probit analysis of [38] which assumes log-normal distribution:

$$Y = a + b \cdot \ln(FRR), \tag{1}$$

where Y represents the probit function, a and b are constants, and FRR is measured in minutes. The probability of emergency actions to fail can be calculated as a function of Y through the cumulative expression for a normal Gaussian probability distribution [38, 39]:

$$EP = \frac{1}{\sigma\sqrt{2\pi}} \cdot \int_{-\infty}^{Y-5} e^{-\frac{u^2}{2}} du. \tag{2}$$

However, there would be complications with integration of Equation (2) and finding of σ - the standard deviation of the emergency response time value to calculate $u = \frac{emergency\ resonse\ time - \mu}{\sigma}$ and the mean value of emergency response time μ. In our study, instead of integration of Equation (2), we use the error function (erf) for its solution following [40]:

$$EP = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{Y-5}{\sqrt{2}}\right)\right]. \tag{3}$$

In study [37] the authors applied regression method to determine coefficients "a" and "b" for the probit function in Equation (1) observing real life data available for the deployment of efficient emergency operations in a refinery. Only 10% of the tank cooling process could have started in less than 5 min, and 90% of cases in less than 20 min. Thus, the failure probability for 5 min response time of fire brigade is 90% and for 20 min it is 10%. Value of probit function Y was estimated from Equation (3) and totalled 6.28 and 3.72 for 5 min and 20 min, respectively. The coefficients "a" and "b " were then calculated using Equation (1) as:

$$b = (6.28 - 3.72)/(\ln(5) - \ln(20)) = -1.85 \text{ and } a = 6.28 - b \cdot \ln(5) = 9.25.$$

Thus, the probit function for a scenario of fire brigade arriving at an accident scene with a hydrogen-powered vehicle fire is defined here similar to [36, 37] as:

$$Y = 9.25 - 1.85 \cdot \ln(FRR). \tag{4}$$

It is worth underlining here that the effect of safety barriers, i.e. thermal protection of onboard storage, on the reduction of the risk associated with a rupture of hydrogen storage tank, was not within the scope of previous studies.

This paper aims to study the impact of an FRR of onboard storage on a level of risk and its acceptance for hydrogen-powered vehicles using QRA and its application to an example of roads in London. The QRA is carried out by employing publicly available data on FRR of onboard hydrogen storage, TPRD failure frequency, London population density and other data to evaluate the socio-economic impact of safety engineering on emerging hydrogen-powered transport.

2.0 THE QRA METHODOLOGY

Flowchart of the QRA methodology is shown in Fig. 1. The QRA output is a value of risk in terms of human fatality per vehicle per year (Fig. 1a), and in terms of cost of human loss per accident (Fig. 1b). The risk in terms of fatality per vehicle per year (Fig. 1a) is assessed using the frequency of accidents per vehicle per year. The consequence analysis aims to identify dominant hazards in an accident fire and their consequences, which are considered here only as fatality per accident. The risk in terms of the cost per accident (Fig. 1b) is assessed using analysis of probability of tank rupture in a fire, and the same consequence analysis, but is extended to account for the cost of life per accident.

The first step in the consequence analysis is the identification of the key hazards relevant to the accident scenario with a high-pressure composite tank in a fire. They are identified, based on other studies at Ulster University, as a fireball and a blast wave following a catastrophic tank rupture in a fire. The detailed comparative analysis of different hazards, including jet fires from TPRD and projectiles emanating from a tank explosion, is out of the scope of this paper. It has been concluded that a key thermal hazard will occur due to a fireball but not a jet fire, and a key pressure hazard is produced due to a blast wave from a tank rupture but not a blast from a deflagration.

The next step is the estimation of hazard distances at which pressure and thermal effects cause fatality, serious injury, slight injury, and where there is no harm from the fireball and blast wave. Here the hazard distances for blast wave and fireball were calculated using the validated engineering tools against experiments theory [11]. Current research at Ulster University has demonstrated that a thermal dose during the comparatively short duration of a fireball lifetime is not harmful unless a human is within the fireball [41, 42]. To make things easier, in our QRA we neglect the non-fatal injury effects and assume that fatality occurs only when a human is resident inside a fireball.

The techniques and tools mentioned above, including [11], are used to calculate the number of individuals who are affected to estimate the number of fatalities per accident as per flowchart in Fig. 1a, and the cost per accident as per flowchart in Fig. 1b. To this end, databases available through [43] and [44] are used to obtain the population density, measured in persons per m^2, within the hazard zone, and to develop the cost metrics, i.e. cost per injury type (in this study for fatality only), respectively.

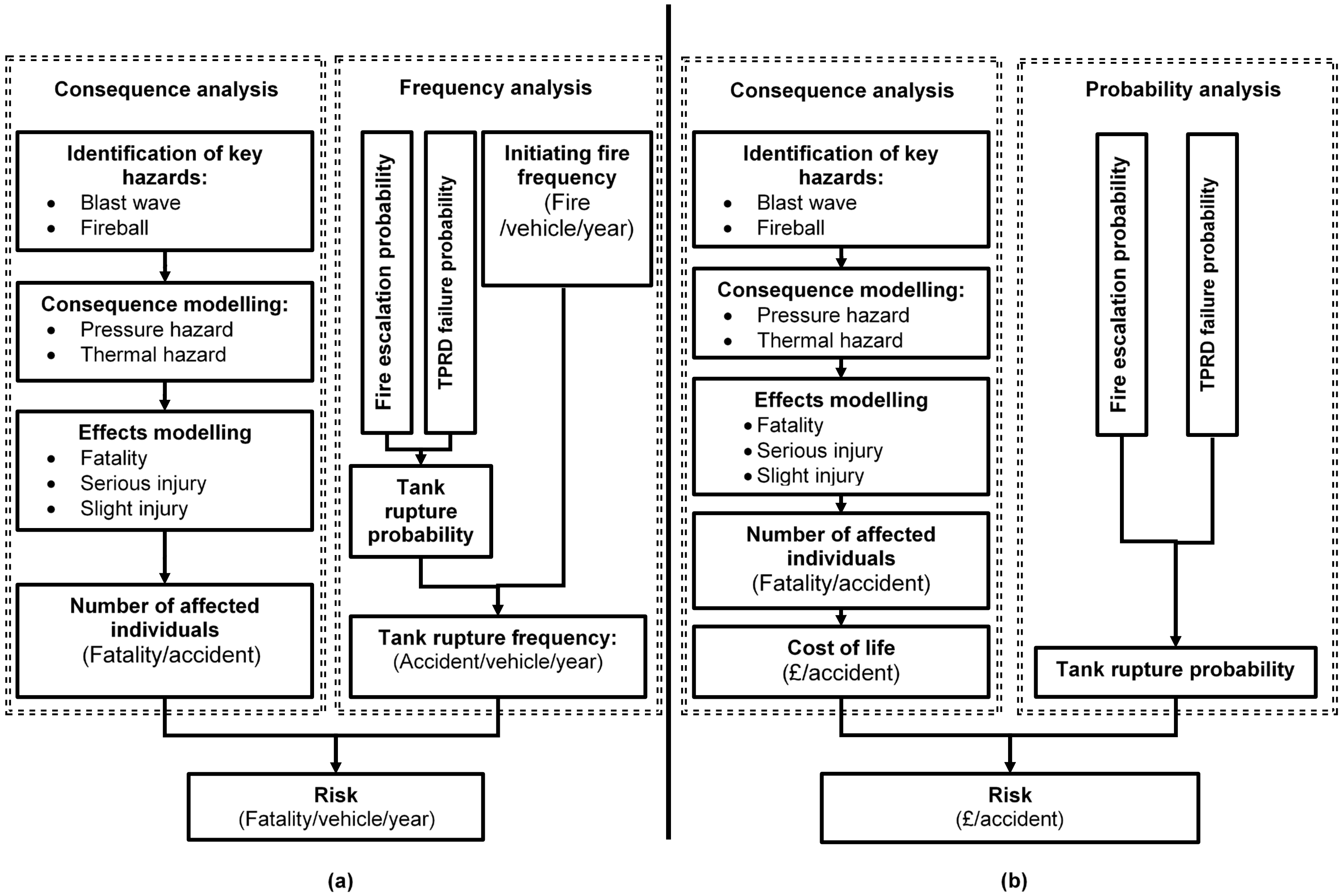

Figure 1. The QRA methodology flowchart: (a) risk in terms of fatality per vehicle per year, (b) risk in terms of cost of human loss per accident with a hydrogen-powered vehicle.

In the case of calculating risk as fatality per vehicle per year (Fig. 1a), the frequency analysis includes estimation of the initiating event (fire) frequency, TPRD failure, and calculation of the escalating probability of emergency operations failing to extinguish fire (EP) leading to a tank rupture in a fire. In this study, the initiating event frequency is calculated as a sum of frequencies for the following generic scenarios: a vehicle fire due to an accident [45, 46], a fire caused by leaking high-pressure fittings, valves or piping connections [47], and a fire while filling hydrogen/tow away [47]. The EP is obtained by exploiting the Equation (3) following [40] and Equation (4) following [36, 37]. The tank rupture frequency is calculated here by multiplying three parameters: initiating event frequency, TPRD failure probability, and EP.

As demonstrated in Fig. 1b, when calculating the risk as a cost per accident, the TPRD failure probability and EP are calculated assuming that the initiating fire has already occurred.

Finally, the risk in terms of fatality rate (fatality/vehicle/year) is calculated as a product of fatality per accident and frequency of an accident (Fig. 1a), and the risk in terms of an accident cost (£/accident) is obtained as a product of cost per accident and the tank rupture probability (Fig. 1b).

3.0 EXAMPLE OF THE QRA APPLICATION

3.1 Onboard storage parameters

The onboard hydrogen storage volume of 62.4 litres, similar to an existing fuel cell car [48, 49] was selected in this QRA. The stored amount of hydrogen weights 2.514 kg at nominal working pressure of 70 MPa.

3.2 Consequence analysis

Figure 2 shows the sequence of events for an accident which starts with the occurrence of at least one of three fire scenarios: the fire due to the car accident, fire due to high pressure (HP) fittings, connections or valves, and the fire while filling hydrogen/tow away.

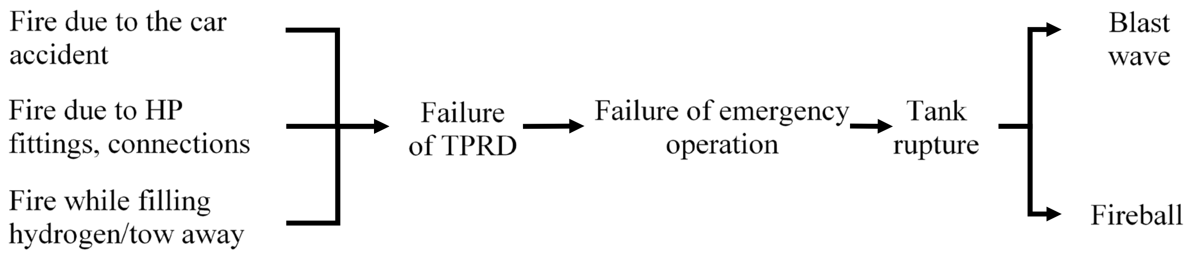

Figure 2. Sequence of events leading to a tank rupture in a fire resulting in blast wave and fireball.

Considering the occurrence of accident in an open environment, it is known that the hydrogen release through initiation by the fire TPRD of a comparatively small diameter, which is the tendency for onboard hydrogen storage to exclude the pressure peaking phenomenon [50, 3], cannot cause serious harm as the flame is of a limited length and the buoyancy reduces hazard distance even further. By this reasoning these higher frequency lower consequences scenarios are eliminated from our analysis. Thus, we focus here on low frequency high consequence events, i.e. the rupture of a tank in a fire with the consequent blast wave and fireball [11]. The rupture of a tank occurs due to exposure of the tank to the initiating fire given that both safety barriers, i.e. TPRD initiation by the fire and the fire extinction by emergency actions, fail.

For a 62.4 litre onboard storage tank at 70 MPa, the hazard distances for fatality, serious and slight injury due to a blast wave can be calculated as 1.68 m, 13.4 m and 76 m, respectively using the "under-vehicle" technique [51]. The areas corresponding to these hazard distances (diameters) are shown in Table 1. The area of lower harm is calculated as the area within hazard distance for this type of harm, minus area for higher harm.

Table 1. Hazard distances for the blast wave and fireball.

Effect	Blast wave hazard distance (m)	Blast wave area (m2)	Fireball hazard distance (m)	Fireball area (m^2)	Area selected for QRA (m^2)
Fatality	1.68	9	35	962	962
Serious Injury*	13.4	555	-	-	N/A
Slight Injury*	76	17,573	-	-	N/A

* - for information only (not included in the present study).

Due to the short duration of fireball, only fatalities resulting from humans being engulfed in a fire are considered in this study (the thermal dose for people outside the fireball is far below serious and slight injury levels for the few seconds duration of the fireball). The fatality hazard distance of a fireball is equal to its maximum radius, which should be calculated. For the considered hydrogen onboard storage, i.e. 62.4 litres tank at 70 MPa pressure [49, 48], two techniques were applied.

The first technique is suggested by the authors and assumes a simplified calculation of a fireball size after a stand-alone tank rupture. The technique is a part of the methodology for the calculation of the blast wave decay after compressed gas vessel rupture [11] and hazard distances attributed to the blast parameters. According to the technique, the fireball size is calculated as a hemisphere occupied by combustion products resulting from complete combustion of released hydrogen in air (non-premixed turbulent combustion at contact surface occurs at stoichiometric concentration of reactants). This approach resulted in a fireball diameter of 13.5 m for the considered tank (62.4 L and 70 MPa) rupture. The estimated fireball size for stand-alone tank is then scaled for onboard tank ("under-vehicle" tank in terminology [11]) based on the experimental data [5, 6]. These tests were performed in the USA by Weyandt et al. in 2005-2006. The experimentally observed fireball size was 7.6 m and 24 m for stand-alone and under-vehicle tanks respectively for storage pressures 35 MPa. The fireball scaling factor is suggested to account for the difference in fireball diameters, (24 m and 7.6 m), and tank volumetric capacities (72.4 and 88 L), as: (24/7.6) · (72.4/88)=2.6. Hence, the scaling of the fireball diameter for stand-alone tank 13.5 m (calculated above) to an onboard application results in the new fireball diameter 13.5 m · 2.6=35 m. The area covered by such a fireball is calculated as $A=\pi r^2=3.14\cdot(35\text{ m}/2)^2=962$ m^2.

The second technique is based on the use of empirical correlation [52] for a wide variety of explosives including hydrogen-air and rocket bipropellants, and is later applied for calculation of hydrogen fireball diameter [9]:

$$D_f = 7.93 \cdot W_f^{1/3}, \tag{5}$$

where D_f (m) is the diameter of the fireball, W_f (kg) is the mass of hydrogen gas (2.514 kg, [48]). Zalosh stated that the fireball diameter calculated by Equation (5) is only 40% of that observed in the test with under-vehicle (onboard) tank rupture [10]. Thus, calculated by the "scaled" Equation (5) fireball diameter (multiplied by 1/0.4= 2.5) our example is:

$$D_f = 2.5 \cdot 7.93 \cdot 2.514^{1/3} = 27\ (m).$$

The diameter calculated by the second technique of 27 m (fireball area 570 m^2) is about 30% less than the diameter of 35 m obtained by the first technique. The conservative value of fireball diameter of 35 m is chosen for the calculation of risk in this study. Table 1 demonstrates that the fatality area of the fireball is larger than the fatality area of the blast wave. It is even larger than the serious injury area for the blast wave. The number of potential fatalities is estimated as:

$$N = N_0 \cdot A_{effect}, \tag{6}$$

where N_0 represents the population density in the location of the accident and A_{effect} is the area within the hazard distance. The location of an accident is assumed to be in London, hence the population density data, provided in [43], is applied to estimate N_0 value. The possible decrease, e.g. due to people leaving the scene, or increase, e.g. due to help and rescue actions attempted by other people, of population density at the accident scene is not considered in further calculations. The mean value and standard deviation for the population distribution data was obtained as follows:

$$N_0 = \frac{1}{n}\sum_{i=1}^{n} x_i, \tag{7}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - N_0)^2}, \tag{8}$$

where σ (person/m^2) is the standard deviation, n (-) is the total number of available population density data for various locations in London, and x_i (person/m^2) is the population density in location "i" in London. Accounting for all 626 locations available from Greater London Authority [43], the average population density N_0 was calculated as 0.008 (person/m^2) and based on [53] it is assumed that 1.5 person are in the vehicle. Thus, the number of fatalities for catastrophic rupture of a tank was calculated as N=9.19 fatality/accident.

Table 2 shows the cost of eliminating the risk from explosion used by UK's Health and Safety Executive (HSE) [44] and adopted in this study. Multiplying the cost of a fatality in Table 2 (£1,336,800 per fatality) by the number of fatalities (9.19 fatalities per accident) the cost of human loss associated with an accident with a hydrogen-powered vehicle with no thermally protected onboard storage is estimated as 12,289,202 £/accident.

Table 2. Cost benefit of eliminating the risk from explosion [44].

Effect	Value (£/person)
Fatality	1,336,800
Serious injury*	207,200
Slight injury*	300

* - for information only (not included in the present study).

3.3 Frequency analysis

3.3.1 Frequency of the initiating fire event

The use of hydrogen as an energy carrier for vehicles is still under development. Thus, the number of hydrogen-powered vehicles in the market is currently very small compared to conventional fuel vehicles. This results in very low frequency of initiating fire events being obtained if relying on the statistical accident data associated with hydrogen-powered vehicles only. In our study it was assumed that the parameters relevant to assessing frequency of initiating fire events associated with hydrogen-powered vehicles are equal to those of conventional fuel cars (Table 3). Frequency of fires due to a vehicle accident was estimated using data [45, 46]. Number of cars (row "1") and number of car accidents (row "2") in the UK were taken from [46] and the frequency of car accidents calculated as $8.57 \cdot 10^{-3}$ accidents/year (value of "2" divided by the value of "1"). The later value was then multiplied by the probability of a car accident leading to fire [45] and the frequency of the initial fire due to a car accident was thus calculated as $3.89 \cdot 10^{-5}$ fire/vehicle/year. The frequencies for the other two initiating fire scenarios were accepted from European FireComp project [47] and are shown in Table 3 too.

Table 3. Statistical data and calculated frequencies of initiating fire events.

No.	Probability or frequency	Value
Fires due to a car accident		
1	Number of cars [46]	$3.11 \cdot 10^{+7}$
2	Number of car accidents [46]	$2.67 \cdot 10^{+5}$
3	Frequency of car accidents (accident/year)	$8.57 \cdot 10^{-3}$
4	Probability of accident leading to fire [45]	$4.54 \cdot 10^{-3}$
5	Frequency of initiating fire (fire/vehicle/year)	$3.89 \cdot 10^{-5}$
Fires due to leaks of high-pressure fittings, valves and piping connections		
6	Frequency of initiating fire, [47] (fire/vehicle/year)	$1.00 \cdot 10^{-3}$
Fires due to hydrogen filling/tow away		
7	Frequency of initiating fire, [47] (fire/vehicle/year)	$1.00 \cdot 10^{-6}$

3.3.2 Failure probability of TPRD

As yet there is no published information and data on the failure rate of TPRD for hydrogen-powered vehicles. The conservative characteristic value for the random mechanical failure probability of pressure relief devices (PRD) was proposed in the publicly available database NPRD [54] as $6.04 \cdot 10^{-3}$. This value was used to calculate TPRD failure probability in FireComp [47] risk assessment study by considering TPRD failure probability due to accident/fire conditions (0 for the engulfed fire and 0.5 for the localised fire). Similarly to FireComp project [47], the failure probability of TPRD is accepted here as $(1-0) \cdot (6.04 \cdot 10^{-3}) + 0 = 6.04 \cdot 10^{-3}$ and $(1-0.5) \cdot (5.03 \cdot 10^{-1}) + 0.5 = 5.03 \cdot 10^{-1}$ for engulfed fire and localised fire, respectively.

3.3.3 Escalation probability (EP)

For the FRR=8 min, which is a bare tank rupture time reported in [12], the use of Equations (3) and (4) [37], allow calculation of the EP value as $6.57 \cdot 10^{-1}$:

$$Y = 9.25 - 1.85 \cdot \ln(8) = 5.4030 \quad \Rightarrow \quad EP = \frac{1}{2}\left[1 + erf\left(\frac{5.4030-5}{\sqrt{2}}\right)\right] = 6.57 \cdot 10^{-1}.$$

3.3.4 Frequency of tank rupture

According to FireComp risk assessment study [47], the three accident scenarios are unlikely to occur simultaneously, and thus are mutually exclusive. Hence, the values for the initiating fire frequency in Eq. [9] are summed. Having the values for the initiating fire frequency (Section 3.3.1, Table 3), the failure probability of TPRD (Section 3.3.2), and EP (Section 3.3.3), the frequency of tank rupture (rupture/vehicle/year) can be calculated as:

$$Tank\ Rupture\ Frequency =$$

$$\left[\sum_{i=1}^{3}(Initiating\ fire\ frequency)_i\right] \cdot TPRD\ Failure\ Probability\ \cdot Escalation\ probability, \quad (9)$$

where the (Initiating fire frequency)$_1$, (Initiating fire frequency)$_2$ and (Initiating fire frequency)$_3$ correspond to initiating fire due to a car accident, HP fittings/connections/valves, and hydrogen filling/tow away (see Table 3).

For the scenario when onboard storage is fully engulfed in a fire, this frequency is equal to:

$Tank\ Rupture\ Frequency = [(3.89 \cdot 10^{-5}) + (1.00 \cdot 10^{-3}) + (1.00 \cdot 10^{-6})] \cdot (6.04 \cdot 10^{-3}) \cdot (6.57 \cdot 10^{-1}) = 4.12 \cdot 10^{-6} (rupture/vehicle/year)$,

and for a localised fire, the catastrophic rupture frequency is:

$Tank\ Rupture\ Frequency = [(3.89 \cdot 10^{-5}) + (1.00 \cdot 10^{-3}) + (1.00 \cdot 10^{-6})] \cdot (5.03 \cdot 10^{-1}) \cdot (6.57 \cdot 10^{-1}) = 3.41 \cdot 10^{-4} (rupture/vehicle/year)$.

Schematic illustration of events leading to the catastrophic tank rupture and corresponding frequencies are shown in Fig. 3 for a fully engulfing fire and in Fig. 4 for a localised fire.

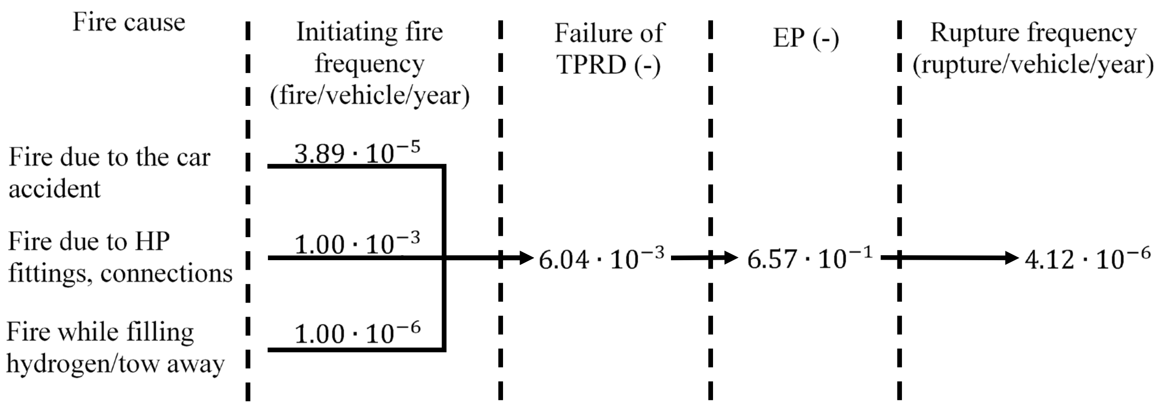

Figure 3. Frequency of a tank rupture in an engulfing fire.

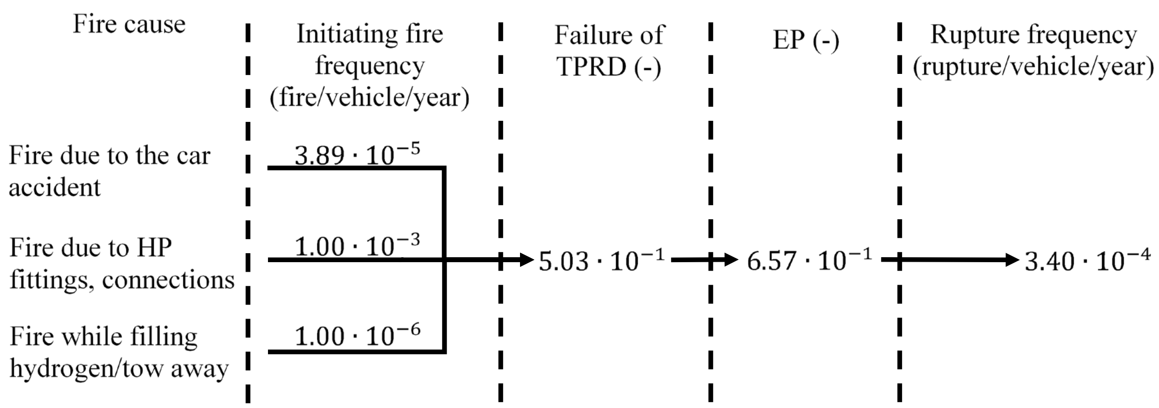

Figure 4. Frequency of a tank rupture in a localised fire.

4.0 RESULTS AND DISCUSSION

4.1 Effects of FRR on the risk value

4.1.1 Risk in terms of fatality rate

The risk of fatality per vehicle per year is calculated as

$$Risk_{fatality} = Rupture\ frequency \cdot N, \tag{10}$$

where $Rupture\ frequency$ (rupture/vehicle/year) is calculated by Equation (9) and the number of fatalities N (fatality/rupture) is calculated by Equation (6). The fatality rate strongly depends on a tank FRR, which may vary over a wide range depending on whether the tank is bare or thermally protected.

In this study, FRR of onboard hydrogen storage tank was adopted from recent fire tests [12] as FRR=8 min for bare tank, and at least 111 minutes for a tank thermally protected by intumescent paint.

Table 4 presents values of risk calculated for bare and thermally protected onboard storage tanks in cases of engulfing and localised fires. In the case of engulfing fire, the fatality rate for the bare tank and thermally protected tank is $3.79 \cdot 10^{-5}$ and $2.34 \cdot 10^{-10}$ (fatality/vehicle/year) respectively. According to [14, 55, 56], the acceptable risk for the third party (public) is $1.00 \cdot 10^{-5}$ (fatality/vehicle/year). Thus, for the selected conditions within made assumptions the risk for the bare tank is about three times more than the acceptable level of risk of 10^{-5}. In the case of a localised fire, the risk for bare tank of $3.14 \cdot 10^{-3}$ (fatality/vehicle/year) is almost two orders of magnitude above the acceptable level of risk.

Table 4. Risk for various FRR of onboard storage tank for engulfing and localised fire.

Fire exposure type	Thermal protection	FRR, min	Risk, fatality/vehicle/year
Engulfing fire	No (bare tank)	8	$3.79 \cdot 10^{-5}$
	Yes	111	$2.34 \cdot 10^{-10}$
Localised fire	No (bare tank)	8*	$3.14 \cdot 10^{-3}$
	Yes	111*	$1.93 \cdot 10^{-8}$

* - assumption.

The QRA results in Table 4 for thermally protected tank demonstrate a drastic increase of hydrogen-powered vehicle safety in terms of the risk. This is due to a longer time available to first responders to extinguish fire in the case of higher FRR. The radical decrease of fatality rate is observed. Thermal protection of onboard storage and increase of FRR to 111 minutes lowers the risk to a negligible value of $2.34 \cdot 10^{-10}$ fatality/vehicle/year for engulfing fire and $1.93 \cdot 10^{-8}$ fatality/vehicle/year for localised fire.

Figures 5 and 6 present the fatality rate as a function of FRR of onboard hydrogen storage tank. For engulfing fire (Fig. 5), the risk for bare tank with FRR=8 min is about three times higher than the acceptable level (top of the blue area). The acceptable level of risk here is $1.00 \cdot 10^{-5}$ following previous studies [14, 55, 56]. The increase of FRR to 16.6 min reduces the risk for the case of engulfing fire to the acceptable level of $1.00 \cdot 10^{-5}$ and further increase of FRR lowers the risk even more, as expected. This underlines the importance of thermal protection of onboard storage.

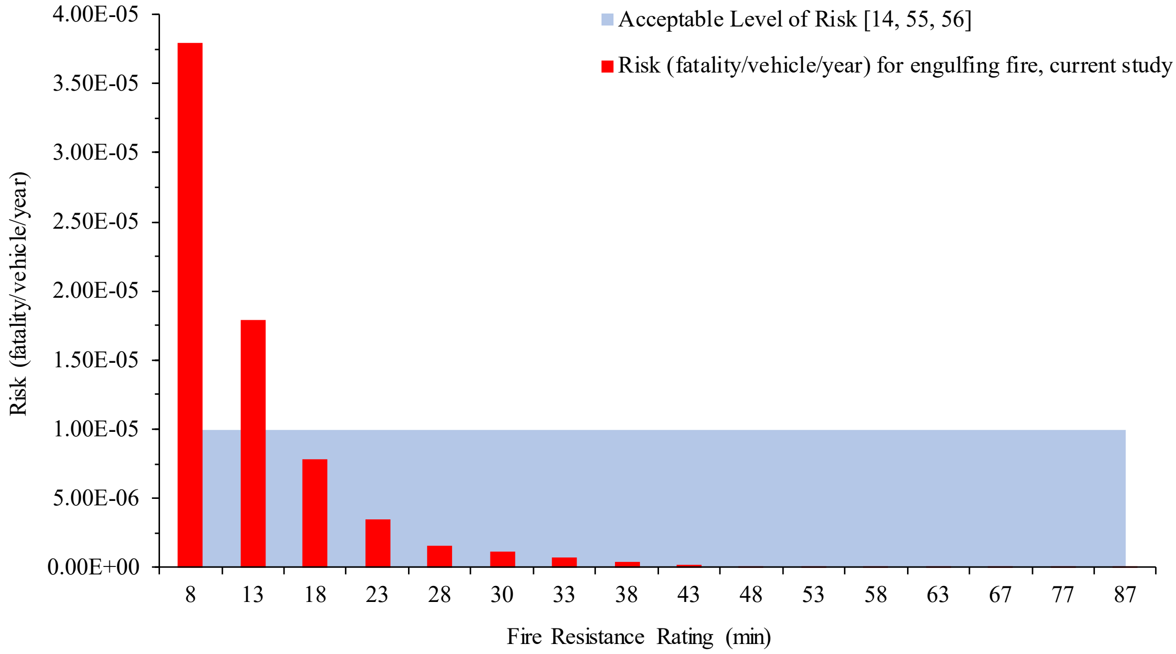

Figure 5. Risk (fatality/vehicle/year) as a function of FRR (min) of onboard storage tank: engulfing fire.

In a localised fire, the TPRD may be not affected by fire at all. This increases the probability of TPRD initiation failure and the risk is considerably higher compared to the case of engulfing fire (see Fig. 6). In the case of localised fire, the fatality rate for a bare tank with FRR=8 min is $3.14 \cdot 10^{-3}$ (fatality/vehicle/year). This is two orders of magnitude higher than that in the case of engulfing fire, i.e. $3.79 \cdot 10^{-5}$ (fatality/vehicle/year). The increase of FRR for a localised fire gradually decreases the fatality rate until the risk reaches the acceptable level only at FRR=47 min. This implies a higher level of thermal protection of onboard storage, which should be applied in practice.

Such FRR of hydrogen storage vessels is greater than that of any known experimentally observed FRR of unprotected vessels (typically 6-12 min). Various engineering solutions can be applied to increase FRR: additional heat detection means for initiation of TPRDs, various thermal protection techniques e.g. explosion-free in a fire safety technology for composite tanks [57], etc.

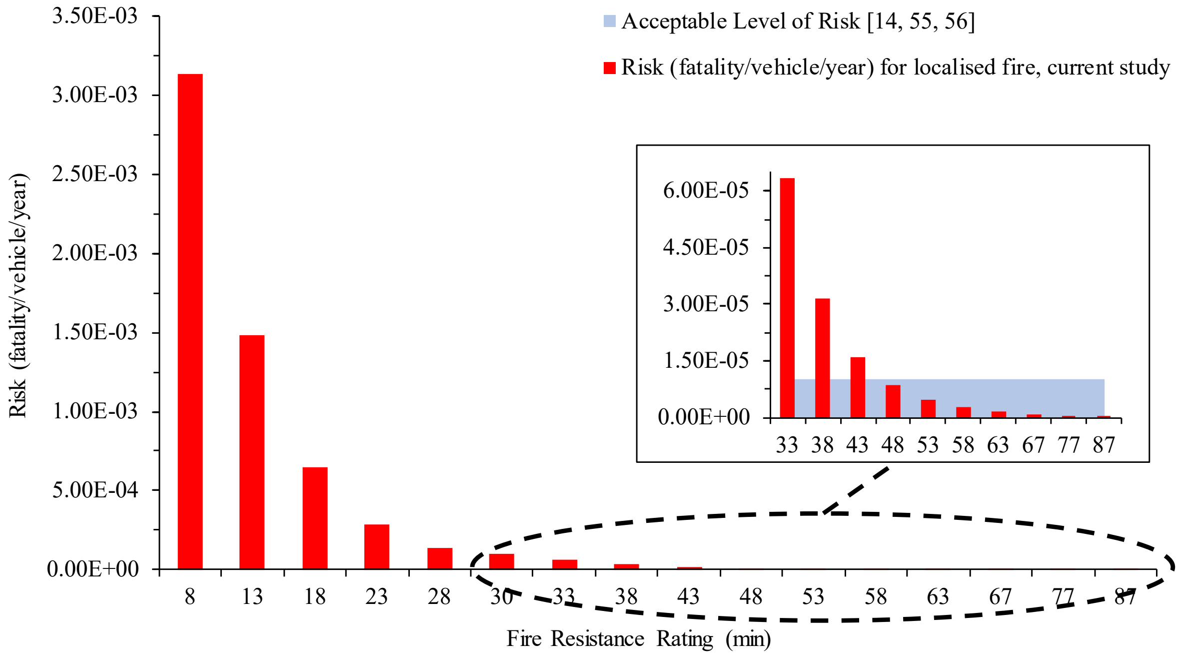

Figure 6. Risk (fatality/vehicle/year) as a function of FRR (min) of onboard storage tank: localised fire.

4.1.2 Effect of hydrogen safety engineering (improved FRR) on accident cost

To evaluate the effect of FRR on the cost of human loss in a hydrogen-powered vehicle accident with a fire, the following procedure was applied. According to the flowchart in Fig. 1b, the cost of fatality per vehicle accident with a fire is calculated as a function of fire EP, given TPRD has failed to operate or was blocked from the fire during the accident, and the cost associated with the number of fatalities is known (HSE value in our study). This means that for a bare tank with FRR=8 min (see Table 4) EP is calculated using Equations (2) and (3) as:

$$Y = 9.25 - 1.85 \cdot \ln(8) = 5.4030 \quad \Longrightarrow \quad EP = \frac{1}{2}\left[1 + erf\left(\frac{5.403-5}{\sqrt{2}}\right)\right] = 6.57 \cdot 10^{-1}.$$

It is important to mention again that for the calculation of the risk in term of cost per accident, the TPRD failure probability and EP are calculated assuming that the initiating fire has already occurred (Fig. 1b). Thus, in this case, the frequency of fire accident is not considered in Eq. (11). The cost associated with fatalities, in our case in an accident with the catastrophic rupture of a storage tank in a fire, is calculated as 12,289,202 £/accident (section 3.2). The probability of TPRD failure in cases of engulfing and localised fires are $6.04 \cdot 10^{-3}$ and $5.03 \cdot 10^{-1}$, respectively. Thus, the risk in terms of cost per accident (£/accident) is calculated as:

$$Cost = Cost\ of\ fatality \cdot TPRD\ failure\ probability \cdot Fire\ escalation\ probability\ (EP), \qquad (11)$$

will give the following values for engulfing and localised fires, respectively:

$Cost\ associated\ with\ tank\ rupture\ during\ engulfing\ fire =$

$$12{,}289{,}202\left(\frac{£}{accident}\right) \cdot (6.04 \cdot 10^{-3}) \cdot (6.57 \cdot 10^{-1}) = 48{,}733\ \left(\frac{£}{accident}\right).$$

$Cost\ associated\ with\ tank\ rupture\ during\ localized\ fire =$

$$12{,}289{,}202\left(\frac{£}{accident}\right) \cdot (5.03 \cdot 10^{-1}) \cdot (6.57 \cdot 10^{-1}) = 4{,}034{,}165\left(\frac{£}{accident}\right).$$

The cost of human loss for various FRR values can be obtained by using the same procedure as for the above case of FRR=8 min. Figures 7 and 8 represent graphically the cost as a function of FRR for engulfing and localised fire, respectively. For the engulfing fire, the cost drastically decreases with the increase of FRR and reaches a negligible value of £100 per accident for FRR=50 min.

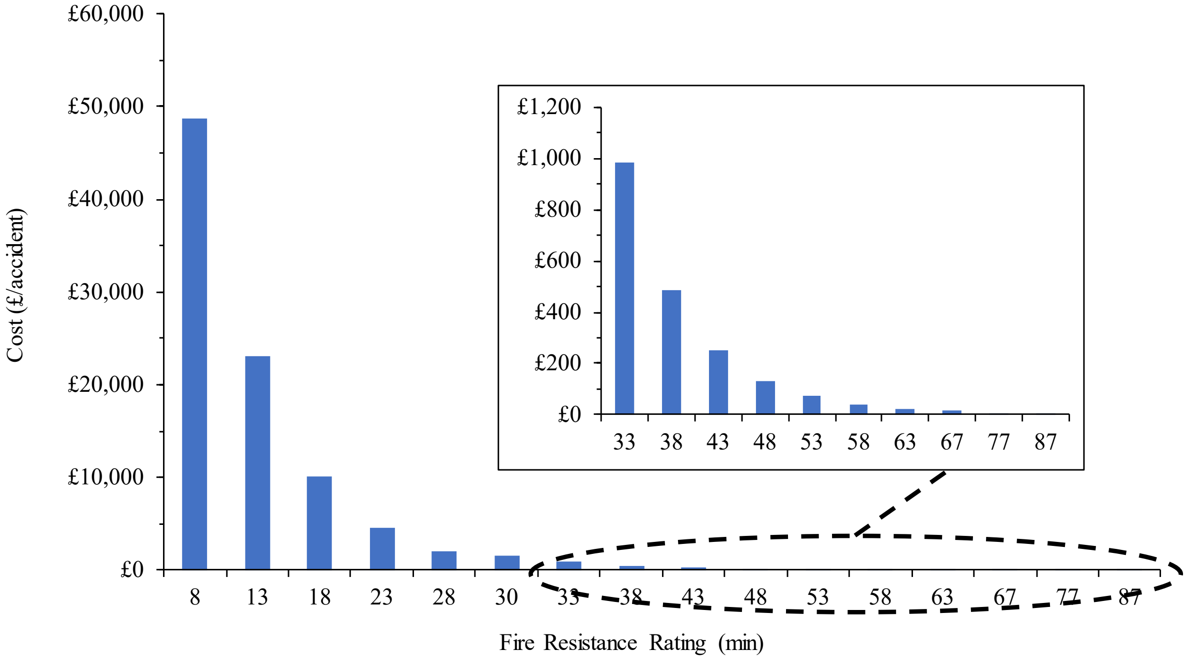

Figure 7. Effect of FRR of onboard storage on the cost of human loss: engulfing fire.

Figure 8 shows that in the case of a localised fire the effect of FRR on the risk is more prominent. The cost descends quickly with the increase of FRR and falls to £12,500 per accident at FRR=47.0 min (at this value of FRR, the risk measured in fatality/vehicle/year reaches the acceptable level of $1.00 \cdot 10^{-5}$). Here it should be mentioned again that the costs for a vehicle damage or damage to natural and the built environment are not included in this QRA exercise.

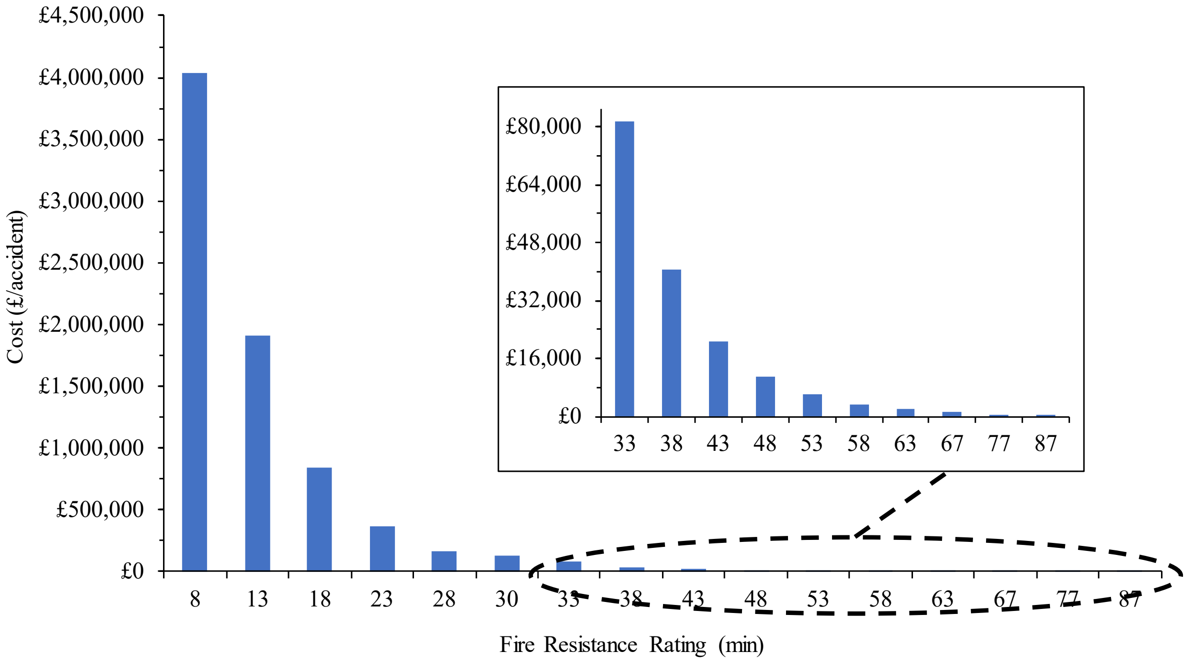

Figure 8. Effect of FRR of onboard storage on the cost of human loss: localised fire.

4.2 Towards uncertainty analysis

The detailed uncertainty analysis is not in the scope of this study and the authors envisage undertaking a separate study and publishing the results. The uncertainty sources comprise the assumptions made in the absence of statistical data for emerging technologies, the limiting number of scenarios in the QRA, and the use of models or correlations for assessment of hazard distances which have own uncertainties. More sources of uncertainties are:

- Assumption that TPRD failure probability is equal to that of PRD,
- Uncertainty of the model for blast wave overpressure as a function of distance,
- Uncertainty of the technique to calculate the upper limit for fireball diameter,
- Uncertainty of the population distribution over various areas,
- Assumption that population density in vicinity of a burning hydrogen-powered vehicle will not decrease or increase and remain steady under normal conditions.

It must also be mentioned that the adopted experimental values of FRR in this study were obtained for a tank of specific design, and is likely to vary for tanks of different size, volume, maximum allowable working pressure (MAWP), etc.

The overall analysis of uncertainties is currently hampered by the lack of data. Only the effect of uncertainty of population density is assessed here. Using the population data available for London from [43] and the assumption that the population data is log-normally distributed [58, 59], and for the natural logarithm of the data set, the mean value of population density logarithm μ=-5.0270 and its standard deviation σ=0.6820 were obtained through Eqs. (7) and (8), respectively. Basically, when a data set is log-normally distributed, its natural logarithm values have the normal distribution with probability density function [40]:

$$P(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{\sigma^2}\right) dx. \tag{12}$$

To integrate Eq. (12), the error function may be used similar to that in Section 1.3:

$$P(x) = \frac{1}{2}\left[1 + \mathrm{erf}(\frac{x-\mu}{\sigma\sqrt{2}})\right]. \tag{13}$$

To demonstrate the effect of uncertainty of population density in terms of fatality per vehicle per year (Fig. 1a) the QRA methodology is applied here for 5% percentile of population density, mean value and 95% percentile of population density. Using Eq. (13) with the above values of μ and σ the 5% percentile for the population density is obtained as 0.00201 person/m^2 and 95% percentile as 0.021 person/m^2 (mean population density value is $N_0 = 0.008$ person/m^2).

Table 5 presents the sensitivity of the risk value to the population density distribution in London. To reach the safe level of the risk for 95% of hydrogen-powered car accidents with fires across London, FRR=47.03 min (associated with mean value of population density) is not sufficient and FRR must be increased to the value of 52.9 min.

Table 5. Uncertainty of the risk (fatality/vehicle/year) as a function of uncertainty of population density distribution for hydrogen-powered vehicle accident with a localised fire.

FRR (min)	**Risk (fatality/vehicle/year)**		
	Risk for 5% lower bound population density	**Risk for mean value of population density 0.008 person/m²**	**Risk for 95% upper bound population density**
8	$7.18 \cdot 10^{-4}$	$3.14 \cdot 10^{-3}$	$6.63 \cdot 10^{-3}$
10	$5.42 \cdot 10^{-4}$	$2.37 \cdot 10^{-3}$	$5.01 \cdot 10^{-3}$
20	$1.07 \cdot 10^{-4}$	$4.69 \cdot 10^{-4}$	$9.91 \cdot 10^{-4}$
30	$2.25 \cdot 10^{-5}$	$9.83 \cdot 10^{-5}$	$2.08 \cdot 10^{-4}$
35.6	$\mathbf{1.00 \cdot 10^{-5}}$	$4.38 \cdot 10^{-5}$	$9.25 \cdot 10^{-5}$
47.0	$2.22 \cdot 10^{-6}$	$\mathbf{1.00 \cdot 10^{-5}}$	$2.05 \cdot 10^{-5}$
52.9	$1.09 \cdot 10^{-6}$	$4.76 \cdot 10^{-6}$	$\mathbf{1.00 \cdot 10^{-5}}$

Figure 9 shows that FRR=35.6 min will be sufficient time to provide acceptable level of risk only for 5% of cases of hydrogen-powered cars accidents with fire across London. To be sure that the acceptable level of risk is reached for 95% of accidents within London, the required FRR should be at least 52.9 min. To better understand the effect of population density uncertainty on the risk value, Fig. 9 demonstrates the risk as a function of FRR and uncertainty of population density distribution for a hydrogen-powered vehicle accident with a localised fire in London.

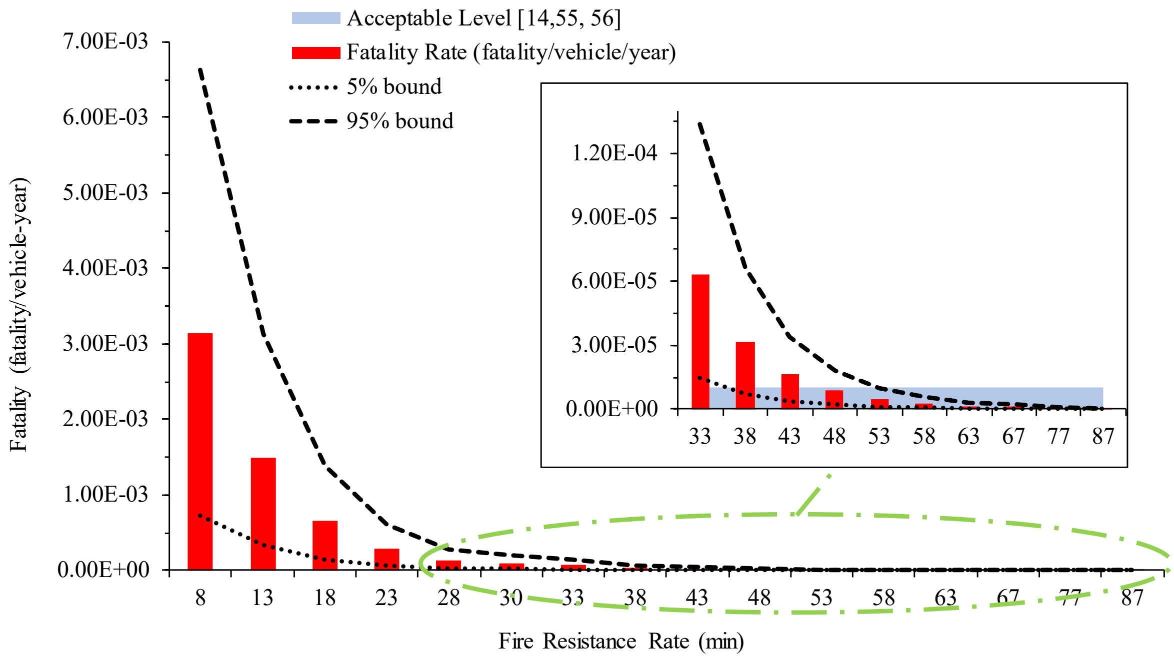

Figure 9. The risk as a function of FRR and uncertainty of population density distribution for a hydrogen-powered vehicle accident with a localised fire.

The carried out QRA shows that typical for today's onboard storage tanks in hydrogen-powered vehicles with FRR=8 min [12] cannot provide acceptable level of risk in densely populated areas like London. To provide the acceptable level of risk $1.0 \cdot 10^{-5}$ (for 95% of accidents in a city with a similar population to London's population density) the onboard hydrogen storage systems should have FRR of at least 52.9 min.

CONCLUSIONS

Hydrogen-powered vehicles have already hit the roads. The stakeholders, including the public, should be informed on the acceptable level of state-of-the-art preventions and mitigations of specific hazards and associated risks. Considering the previously "missed" risks due to insufficient knowledge of hazards of blast wave and fireball during the catastrophic rupture of a tank in a fire, it is to the best of the authors' knowledge, that this is the first publicly available QRA of onboard hydrogen storage of hydrogen-powered vehicles applied to roads in London. This paves the way to inherently safer design of the vehicles. This underlines the significance of the study for the deployment of hydrogen systems and infrastructure in addressing problems of climate change, environmental protection, shortage of fossil fuels and independence of energy supply.

The risk is assessed here by both, fatality per vehicle per year and as cost per accident with a vehicle fire. The originality of this study is based on the merging of contemporary probabilistic and deterministic methods in engineering to achieve synergies through their complementarities. For the first time, the QRA analysis includes the use of innovative validated engineering tools to consider previously "missed" hazards such as a blast wave and fireball following the tank rupture in a fire.

The authors have made all possible efforts to underpin the rigour of this study by using the most recent relevant data from a variety of safety science and engineering sources. The described QRA methodology is applied to a hypothetical accident with a fire on London roads with a hydrogen-powered vehicle having a 62.2 litre hydrogen tank capacity at storage pressure of 70 MPa. The QRA is based on available statistical data on car accidents and vehicle fires in the UK. The cost associated with an accident was determined by using the numbers available from the Health and Safety Executive (UK). TPRD failure frequency is taken as the conservative characteristic values for failure rate of pressure relief devices available from industry and European hydrogen project FireComp.

The study has demonstrated that the assumed thermally unprotected composite onboard storage tank, which FRR is typically 6-12 min, has the risk of human life loss in an accident escalating to a fire and consequently the tank rupture of $3.14 \cdot 10^{-3}$. This is two and half orders of magnitude larger than the acceptable level of risk of $1.00 \cdot 10^{-5}$. The cost associated with loss of life in the accident in this case is 4.03M £/accident.

The study has demonstrated that the increase of FRR of onboard storage can drastically decrease the risk of hydrogen-powered vehicles to the acceptable level or even bring it to negligible level if engineering solutions such as thermal protection means for composite tanks for high-pressure hydrogen storage are applied.

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