SOCIO-ECONOMIC ANALYSIS AND QUANTITATIVE RISK ASSESSMENT METHODOLOGY FOR SAFETY DESIGN OF ONBOARD STORAGE SYSTEMS

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ABSTRACT

Catastrophic rupture of onboard hydrogen storage in a fire is a safety concern. Different passive, e.g. fireproofing materials, the thermally activated pressure relief device (TPRD), and active, e.g. initiation of TPRD by fire sensors, safety systems are being developed to reduce hazards from and associated risks of high-pressure hydrogen storage tank rupture in a fire. The probability of such low-frequency high-consequences event is a function of fire resistance rating (FRR), i.e. the time before tank without TPRD ruptures in a fire, the probability of TPRD failure, etc. This safety issue is “confirmed” by observed recently cases of CNG tanks rupture due to blocked or failed to operate TPRD, etc. The increase of FRR by any means decreases the probability of tank rupture in a fire, particularly because of fire extinction by first responders on arrival at an accident scene.

This study of socio-economic effects of safety applies a quantitative risk assessment (QRA) methodology to an example of hydrogen vehicles with passive tank protection system on roads in London.

The risk is defined here through the cost of human loss per fuel cell hydrogen vehicle (FCHV) fire accident and fatality rate per FCHV per year. The first step in the methodology is the consequence analysis based on validated deterministic engineering tools to estimate the main identified hazards: overpressure in the blast wave at different distances and the thermal hazards from a fireball in the case of catastrophic tank rupture in a fire. The population can be exposed to slight injury, serious injury and fatality after an accident. These effects are determined based on criteria by Health and Safety Executive (UK), and a cost metrics is applied to the number of exposed people in these three harm categories to estimate the cost per an accident. The second step in the methodology is either the frequency or the probability analysis. Probabilities of a vehicle fire and failure of the thermally activated pressure relief device are taken from published sources. A vulnerability probit function is employed to calculate the probability of emergency operations’ failure to prevent tank rupture as a function of a storage tank FRR and time of fire brigade arrival. These later results are integrated to estimate the tank rupture frequency and fatality rate. The risk is presented as a function of fire resistance rating.

The QRA methodology allows to calculate the cost of human loss associated with an FCHV fire accident and demonstrates how the increase of FRR of onboard storage, as a safety engineering measure, would improve socio-economics of FCHV deployment and public acceptance of the technology.

1.0 INTRODUCTION

Due to its physical properties, the safety characteristics of hydrogen gas 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 inherently safer than other fuels in the open atmosphere and well-ventilated areas. Due to buoyancy, hydrogen disperses fast to concentrations below the lower flammability limit, and only a small fraction of released hydrogen would contribute to combustion if ignited. Lower ignition temperature and a wider range of flammability limits (4-75%), however, make hydrogen more vulnerable to ignition. For example, [1] ranked hydrogen between propane and methane for safety.

Several hydrogen related accidents have been reported in the literature, accident reports and databases: Hindenburg disaster at Larkhurst, New Jersey, in 1937 [2], Chellenger explosion at Kennedy space centre, Florida, in 1986 [3], hydrogen vapour cloud explosion at a polyethylene plant in Pasadena, Texas, in 1989 [4], pressurised hydrogen tank rupture at Hanua, Frankfurt, in 1991 [3], and hydrogen explosion at Fukushima nuclear plant in 2011 [5] are some examples.

This study is focused on QRA of hydrogen onboard storage for FCHV and effects of hydrogen safety engineering on socio-economics.

1.1 Onboard storage of hydrogen

Compressed gaseous hydrogen (CGH2) vessels are designed for hydrogen-powered cars at storage pressures typically 35-70 MPa. The fuel cell buses with CHG2 typically operate at pressures 20 MPa. Type IV tanks are typically accepted as onboard CGH2 storage for their exceptional weight and strength characteristics. It is made of a high-density polymer liner over-wrapped with a fibre reinforced composite. The liner layer in composite cylinders prevents hydrogen gas permeation. A composite laminate over-wrapped outside of the liner bears the pressure load. Although composite overwrapped pressure vessels (COPV) have good mechanical performance and light weight, they tend to degrade under thermal load and have a high failure risk under accidental fire exposure. The Regulations, Codes and Standards (RCS) require TPRD to be installed on hydrogen onboard tanks to release the tank's contents in the event of a fire and therefore to prevent its catastrophic rupture. Unfortunately, activation of TPRD and safe hydrogen blowdown are impossible in some scenarios, e.g. in the case of a fire affecting only localised area of a tank far from TPRD, or when a car design allows blockage of the TPRD sensing element with jammed parts of car(s) during a road accident, preventing TPRD initiation. In this case, the tank will experience a thermal load and subsequent onset of degradation of the composite. The rupture of tanks due to TPRD failure in CNG-vehicles has been recently reported by [6].

1.2 Relevant safety studies

There is a global community of researchers closing knowledge gaps and resolving technological bottlenecks in hydrogen safety. It works under auspices of the International Association for Hydrogen Safety. Several published studies are related to hazards of onboard hydrogen storage, including experiments with hydrogen storage vessels tested in a fire and with pressure relief devices removed. Consequently, the tests results were vessels failures, as expected, and the valuable data on created hazards, i.e. blast wave and thermal effects of a fireball, were thoroughly documented [7, 8, 9, 10]. There are other studies on blast wave decay accounting for combustion contribution into the blast strength [11], effects of different thermal protection of a tank on its FRR [12], and development Computational Fluid Dynamics (CFD) models to evaluate the effect of intumescent paint on FRR [13], etc.

There are several relevant QRA studies, e.g. [14], and tools, e.g. HyRAM toolkit recently introduced by Sandia National Laboratories [15]. They are intended mainly for QRA of hydrogen refuelling stations and storage infrastructure. A combination of probabilistic and deterministic methods has been used for assessment of consequence, estimating the number of fatalities using probit functions. Fatal accident rate, average individual risk, and potential loss of life can be calculated via HyRAM. The focus of HyRAM is mainly on the thermal effects from jet fires and pressure effects from a deflagration.

HyRAM, however, is still under development, and there are various hazards yet to be included into 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 were identified as the main hazards in our study. HyRAM currently lacks the accident cost metrics as well. LaChance et al. (2009) suggested a risk-informed approach for the selection of a leak diameter to establish the separation (safety) distances in National Fire Protection Association standards NFPA 2 "Hydrogen technologies code" and NFPA 55 "Compressed gas and cryogenic fluid code". Their study involved the analysis of frequency and risk of leakage for typical hydrogen facilities, and the cumulative frequency of system leakage. Due to limited hydrogen-specific leakage data, a Bayesian statistics approach was exploited to generate leakage frequencies from other non-hydrogen sources. Work [16] 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 [17] and it was propped 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 [18]. Safety barrier diagrams technique was introduced in [19] 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 [20].

ISO TC197 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"*. Hazard distance is the transparent "consequence only" deterministic distance that will be applied in this study as opposed to separation (safety) distance that includes other arguments, which are not clear to the authors.

The effectiveness of safety barriers on the reduction of the risk associated with escalation of a primary fire to fuel storage tanks, but for fuels other than hydrogen, has been investigated in several studies. [21] investigated the damage probability of storage tanks exposed to a fire and its relationship with FRR. They exploited vulnerability probit function to estimate the escalation probability (EP). EP is the likelihood of emergency operations to fail to extinguish the initiating fire (the latter failure leads to the rupture of a tank). Using probit functions, the QRA based methodology was proposed by [21, 22] to assess the performance of fireproofing materials to protect a fuel storage tank from a fire. They used the general equation from the probit analysis of Finney (1971):

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

where Y represents the probit function, a and b are constants; the FRR was 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 [23, 24]:

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

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 μ - the mean value of emergency response time values. In our study, instead of integration of Equation (2) we solve it including the use of error function (erf) presented in the form [25]:

$$EP = 0.5 \cdot \left[1 + \mathrm{erf}(\frac{Y-5}{\sqrt{2}})\right]. \tag{3}$$

Coefficients "a" and "b" for probit function in Equation (1) are further determined by using real life data and regression method. Using regression method and the field data available for the refinery, Landucci et al. (2009) calculated values of "a" and "b" by comparing the FRR value with the observed time for the deployment of effective emergency operations. Thus, only 10% of the tank cooling process could have started in less than 5 min and 90% of cases – in less than 20 min; the failure probability was assumed to be log-normally distributed. Therefore, the failure probability for 5 min response time of firemen is 90% and for 20 min is 10%. Equation (3) was used to estimate the Y and it totalled 6.28 and 3.72 for 5 min and 20 min, respectively. The coefficients "a" and "b " were calculated then using Equation (1) as:

$$b = (6.28 - 3.72)/(\ln(5) - \ln(20)) = -1.85, \qquad a = 6.28 - b \cdot \ln(5) = 9.25\ .$$

Thus, the probit function was defined as [21]:

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

The effect of safety barriers on the reduction of the risk associated with a rupture of hydrogen storage tank, however, is not within the scope of those studies. Here the authors evaluate the effect of *FRR* of onboard storage on socio-economics of FCHV deployment.

This study aims to develop a QRA methodology to evaluate the socio-economic impact of hydrogen safety engineering on deployment of FCHVs, and apply it to an example of roads in London. This is done to assess an acceptance of risk of current hydrogen storage solutions and propose, if needed, requirements for making FCHVs inherently safer with an acceptable level of risk.

2.0 THE QRA METHODOLOGY

Flowchart of the QRA methodology is shown in Fig. 1. The methodology includes assessment of risk in terms of human fatality per vehicle per year (Fig. 1a), and the cost of human loss per accident (Fig. 1b). The risks are assessed using:

1) Consequence analysis, aiming at identifying dominant hazards in an accident fire and their consequences which are fatality per an accident (Fig. 1a) and cost per an accident (Fig. 1b), and

2) Either frequency analysis (Fig. 1a) resulting in frequency of accidents (accidents per vehicle per year), or probability analysis (Fig. 1b) resulting in rupture probability in a fire.

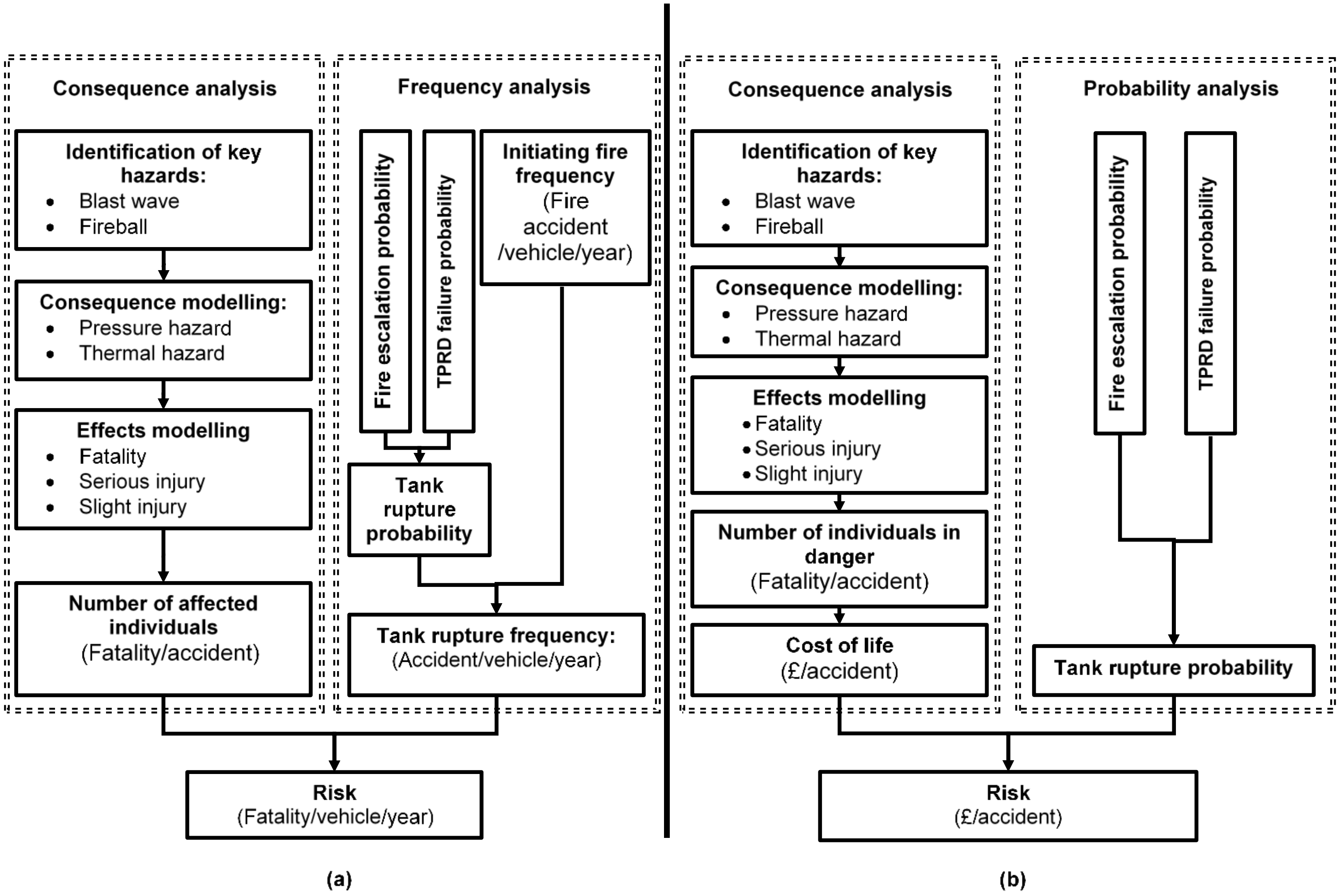

Figure 1. The QRA methodology flowchart: (a) risk in terms of fatality per vehicle per year, (b) risk in terms of cost of human loss per an accident with a FCHV.

The first step in the consequence analysis is the identification of hazards relevant to the accident scenario, considered in this study, i.e. tank rupture followed by a fireball and a blast wave. It was presumed, based on other HySAFER's studies which are out of the scope of this paper, that key thermal hazard is a fireball (but not a jet fire) and key pressure hazard is due to a blast wave from a tank rupture (but not a deflagration pressure). Projectiles are not accounted for in this study.

The next step is to estimate distances at which pressure and thermal effects cause fatality, serious injury and slight injury. Here the hazard distances for blast wave and fireball were calculated using the validated against experiments theory [11] assuming all people within a particular hazard distance (fatality, serious injury and slight injury) are exposed to the respective harm effect. Current research at Ulster demonstrated that a thermal dose during comparatively short duration of a fireball lifetime is not harmful unless a human is within the actual fireball [26, 27]. We can conclude that for tank rupture under the vehicle, the fatality distance from a fireball is larger than the fatality distance from a blast wave. To simplify the use of the QRA methodology and to be on a conservative side, we neglect here by cost of non-fatal injuries and we assume that fatality occurs only when a human is inside a fireball.

The results obtained through the previous steps are used as input to calculate the number of individuals who are affected to estimate the number of fatalities per an accident (Fig. 1a) and cost per an accident (Fig. 1b). To this end, databases available through [28] and [29] are used to obtain the population density (person per m^2) within the hazard distance and to develop the cost metrics (cost per injury type), respectively.

In the case of calculating risk as fatality per vehicle per year, (Fig. 1a), the frequency analysis includes estimation of the initiating event frequency, TPRD failure and to calculate EP, in other words the probability of emergency operations to fail leading to a tank rupture. In this study, the initiating event frequency is calculated as a sum of frequencies for the following generic scenarios: a car fire due to an accident [30, 31], fire caused by leaking high-pressure fittings, valves or piping connections and a fire while filling hydrogen/tow away [32]. The escalation probability is obtained by exploiting the Equations (3) and (4) following [22]. The tank rupture frequency is calculated here by multiplying three parameters: the initiating event frequency, TPRD failure probability and the escalation probability.

As demonstrated in Fig. 1b, when calculating risk as a cost per an accident, the escalation probability and TPRD failure probability are calculated by considering 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 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 APPLICATION OF THE METHODOLOGY

The onboard hydrogen storage volume of 62.4 litre like at existent FCHV [33] was selected to apply the QRA methodology. The stored amount of hydrogen weights 2.514 kg. The service pressure is 70 MPa. Here we are going to study the effect of tank thermal protection on the risk in terms of both, the fatality rate and the cost.

3.1 Consequence Analysis

Figure 2 shows the sequence of events for an accident which starts with 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.

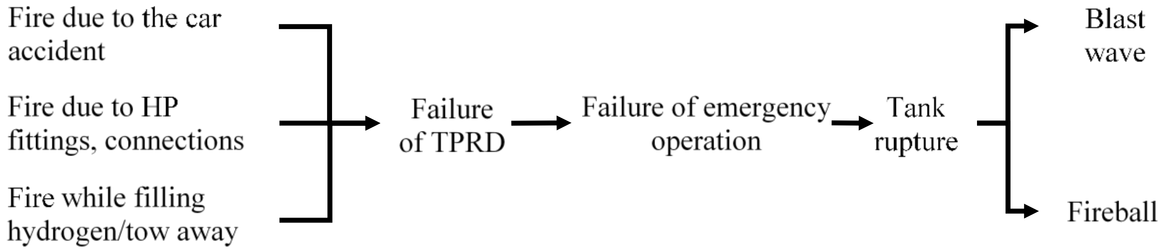

Figure 2. Event sequence for an accident due to various initiating fire leading to a tank rupture

Considering the occurrence of accident in an open environment, it is known that the hydrogen release through initiated by the fire TPRD of comparatively small diameter does not cause any serious harm as the flame is of a limited length and the buoyancy reduces hazard distance even further. By this reasoning this higher frequency lower consequences scenario is eliminated from our analysis. Thus, we focus on low frequency high consequences event, i.e. the rupture of a tank in a fire with the consequent blast wave and fireball. The rupture of the tank occurs due to the exposure of the tank to the initiating fire given that both safety barriers, i.e. TPRD initiation by the fire and 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 [34]. The areas corresponding to these hazard distances are given in Table 1. The area of a lower harm is calculated as the area within hazard distance for this type of harm minus area for higher harm.

Due to the short duration of fireball, only fatalities are considered in this study (thermal doze for people outside the fireball are below serious and slight injury levels). To determine a number of people within the fatality hazard distance, which is equal in our case to the fireball size, the fireball size has to be calculated.

For the considered hydrogen storage application, i.e. 70 MPa, 62.4 litres, [35, 33]) two existing techniques were applied. One assumes stand-alone tank rupture at first place [11]. This results in a fireball diameter of 13.5 m for the tank under consideration. Then, the calculated fireball size for stand-alone tank is scaled for onboard tank (under-vehicle location) following the experimental data by [7, 8]. The tests by Weyandt et al. give fireball size 7.6 m and 24 m for 35 MPa stand-alone and under-vehicle tank respectively. Thus, the scaling factor with taking into account difference in volume of tested tanks (72.4 and 88 L) can be calculated as (24 m/7.6 m) · (72.7 L/88L)=2.6. For use of selected tank onboard this gives fireball diameter of (13.5 m) · (2.6)=35 m. The obtained diameter gives the fireball area $A=\pi r^2$=3.14· (35 m/2)^2=962 m^2.

The second technique is the empirical correlation developed by [36] for a wide variety of explosives including hydrogen-air and rocket bipropellants, and later applied by [9] for calculation of hydrogen fireball diameter:

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

where D_f (m) is the diameter of the fireball, W_f (kg) is the mass of hydrogen gas (2.514 kg [33]). 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 corrected Equation (5) fireball diameter (multiplied by 1/0.4= 2.5) is:

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

This calculated by the second technique diameter 27 m (fireball area 570 m^2) is less than diameter 35 m obtained by the first technique by 30%. For the purpose of this paper the smaller radius was chosen for further calculation of risk in an attempt to see if current FCHV are at the acceptable risk level.

Table 1 clearly 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.

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

Effect	**Distance (m)**	**Blast wave area (m2)**	**Fireball area (m^2)**	**Area selected for QRA (m^2)**
Fatality	1.68	9	570	570
Serious Injury*	13.4	555	-	-
Slight Injury*	76	17,573	-	-

* for information only (not used in the QRA).

The potential number of fatalities are estimated as follows:

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

where N_0 represents the population density in the location of the accident and A_{effect} is the area within hazard distance, which is selected here as a fireball diameter as it is larger than fatality hazard distance from a blast wave. The location of the accident was assumed to be similar to London, hence the population density data, provided by Greater London Authority (2015), is applied to estimate N_0 value. The mean value and standard deviation for the population distribution data was obtained as follows:

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

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

where μ (person/m^2) is the mean value, σ (person/m^2) is the standard deviation, n (-) is the total number of available population density data based on various locations in London, and x_i (person/m^2) is the population density in location "i" in London. According to Greater London Authority (2015), there were 626 various locations with available population density data, hence $n = 626$. Using Equations (7), μ was calculated as 0.008 (person/m^2).

The mean value μ = 0.008 person/m^2 was used then in equation (6) as N_0. Thus, for the assumed conditions the number of fatalities for a catastrophic rupture of a tank was calculated as N=4.56 fatality/accident.

The cost analysis metrics by HSE (2015) is adopted here. Table 2 presents the cash valuations of preventing health and safety effects on people [29]. Multiplying the cost of the fatality in Table 2 by the number of fatalities the cost of human loss associated with one accident with FCHV is estimated as 6,095,808 £/accident.

Table 2. Cost analysis metrics (HSE, 2015)

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

* for information only (not used in the QRA).

3.2 Frequency analysis

3.2.1 Estimating the initiating event frequency

The frequency of the initiating fire due to a car accident was estimated using data in Table 3. Number of cars and number of car accidents in UK were taken from [31] and used to calculate the frequency of car accidents as 8.57E-03 accidents/year. The later value was then multiplied by the probability of a car accident leading to fire [30] and the frequency of the initial fire due to a car accident was thus calculated as $3.89\mathrm{E}-05$ fire/vehicle/year.

Table 3. Statistics used to estimate the frequency of initiating fire

No.		**Value**	**Reference**
1	Number of cars in (2014)	3.11E07	[31]
2	Number of car accidents (2014)	2.67E05	[31]
3	Frequency of car accident (2014) (accident/year)	8.57E-03	No.2÷No.1
4	Probability of accident leading to fire	4.54E-03	[30]
5	Frequency of initiating fire (fire accident/vehicle/year)	3.89E-05	No.3·No.4

The frequencies for the other two initiating fire scenarios, used in the current study, were provided by Air Liquid and used in the FireComp project [32]: 1.00E-03 fire/vehicle/year and 1.00E-06 fire/vehicle/year for leaks through high-pressure fittings, valves or piping connections, and hydrogen filling/tow away respectively.

3.2.2 The failure probability of TPRD

There is no published data for the failure rate of TPRD for hydrogen-powered vehicles. Similarly, to FireComp study [32] the conservative value λ = 1.38E-06 (failure/hour) characteristic for failure rate of PRD is accepted. This value was proposed by public database NPRD [37]. Considering a proof test interval of 1 year, the failure probability of TPRD is then calculated as 6.04E-03 and 5.03E-01 for the engulfment fire condition and localised fire condition, respectively.

3.2.3 Estimating escalation probability (EP)

For the *FRR* value of 8 minutes (bare tank rupture time according to [12]) with the use of equations (3) and (4) [22], the escalation probability value was calculated as 6.57E-01.

$$Y = 9.25 - 1.85 \cdot \ln(8) = 5.4030 \quad \Rightarrow \quad EP = \frac{1}{2} \cdot \left[1 + erf\left(\frac{5.4030-5}{\sqrt{2}}\right)\right] = 6.57E-01$$

3.2.4 Frequency of catastrophic tank rupture

Having the values for the initiating fire frequency (Section 3.2.1, Table 3), failure probability of the TPRD (Section 3.2.2) and the escalation probability (Section 3.2.3), the frequency of catastrophic rupture of tank (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)$_3$ states for the initiating fire due to a car accident, high pressure fittings/connections/valves, and H_2 filling/tow away.

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

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

and for the localised fire, the catastrophic rupture frequency is

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

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

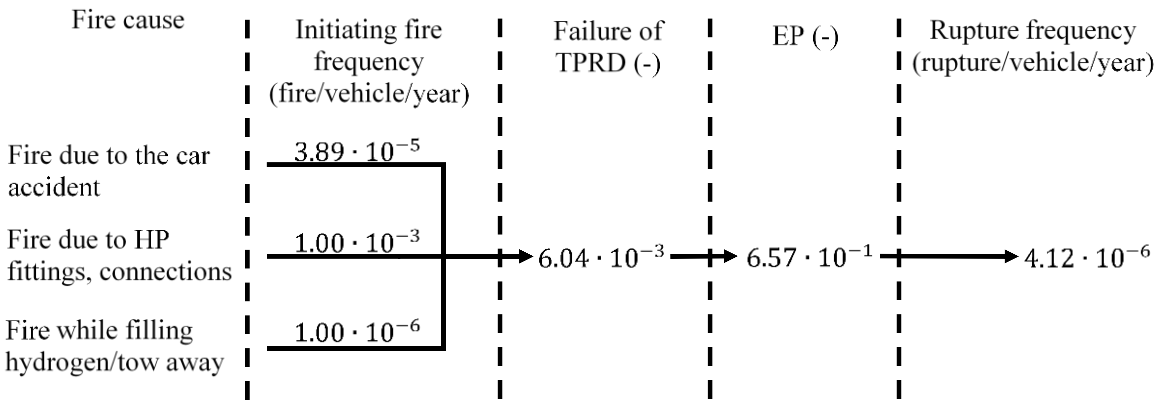

Figure 3. Frequency of a tank catastrophic rupture: engulfment fire

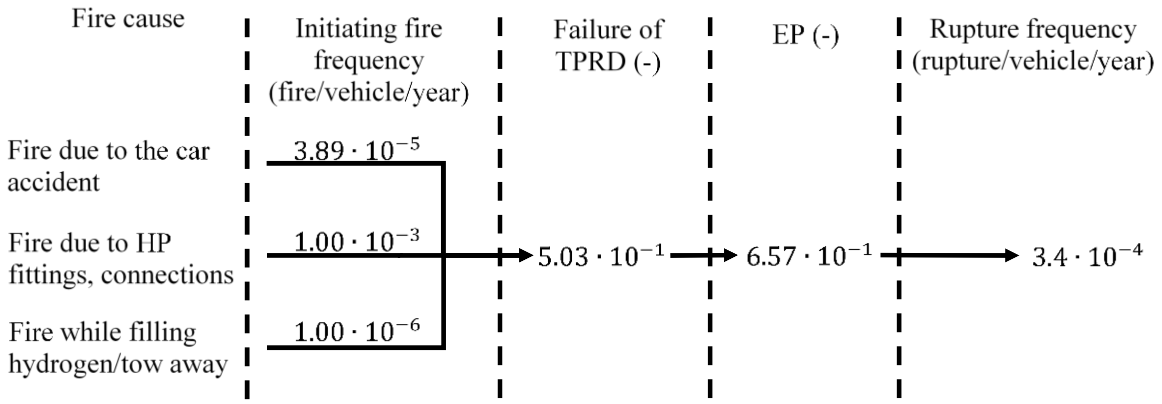

Figure 4. Frequency of a tank catastrophic rupture: localized fire

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 tank *FRR*, which may vary in a wide range depending on whether the tank is thermally protected or not. In this study, *FRR* of onboard hydrogen storage tank was adopted from a recent fire tests [12]: 8 minutes for bare tank, and at least 111 minutes for a tank thermally protected by 20 mm thick intumescent paint.

As follows from Table 4 the fatality rate for the bare tank and intumescent coated tank is 1.88E-05 and 1.16E-10 fatality/vehicle/year respectively. According to [14, 38, 39], the acceptance level of risk for the third party (public) is 1.00E-05 fatality/vehicle/year. Thus, we can conclude that for selected conditions within made assumptions the risk for the bare tank is about twice more than acceptable risk. In the case of a localized fire, the bare tank results in 1.56E-03 fatality/vehicle/year, which is around two orders of magnitude above the acceptable risk (!).

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

Fire exposure type	Thermal Protection	FRR, min	Risk, fatality/vehicle/year
Engulfing fire	No protection (bare tank)	8	1.88E-05
	Thermally protected	111	1.16E-10
Localised fire	No protection (bare tank)	8*	1.56E-03
	Thermally protected	111*	9.60E-09

* assumption.

The QRA results presented in Table 4 for thermally protected tank demonstrate a drastic increase of FCHV safety in terms of risk. This is due to the fact that increased FRR of a tank results in a longer time available to first responders to extinguish fire. The radical decrease of fatality rate is observed. Thermal protection of onboard storage and increase of FRR to 111 min lowers the risk to negligible value 1.16E-10 fatality/vehicle/year for engulfing fire and 9.60E-09 fatality/vehicle/year for localised fire.

Figures 5 and 6 present the fatality rate as a function of FRR. For engulfing fire, the risk for bare tank with 8 min FRR is about twice higher than the acceptable level (top of blue area), but by having a FRR value of about 10 min, the risk value for engulfing fire reaches the acceptable level and further increase of FRR lowers the risk more as expected.

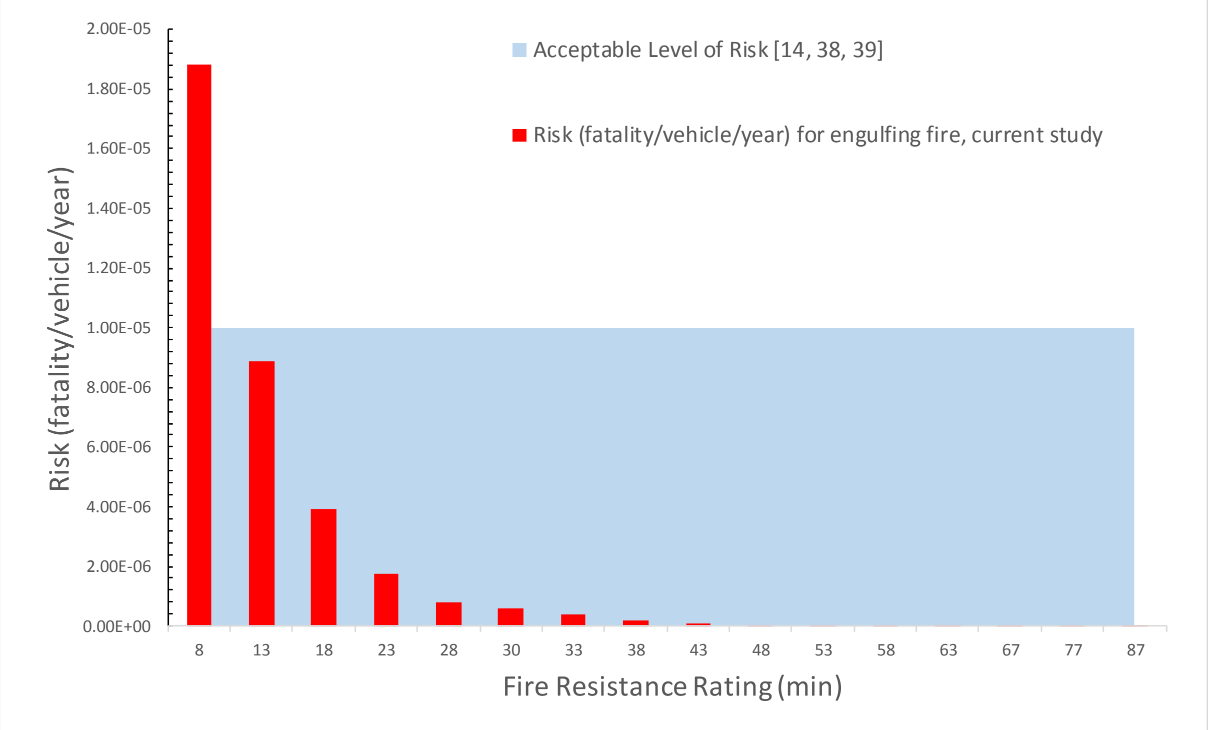

Figure 5. Risk (fatality/vehicle/year) versus fire resistance rating (min): engulfing fire

In a localised fire the TPRD may be not affected by fire at initial test period, which increases the probability of TPRD initiation failure and the risk is considerably higher compared to the case of engulfing fire. For localised fire, the fatality rate is by over two orders of magnitude higher, 1.56E-03 fatality/vehicle/year, than that for a bare tank with the same FRR of 8 min in engulfing fire. The increase of FRR for a localised fire case gradually decreases fatality rate, until it reaches the acceptable level only at FRR =41.3 min.

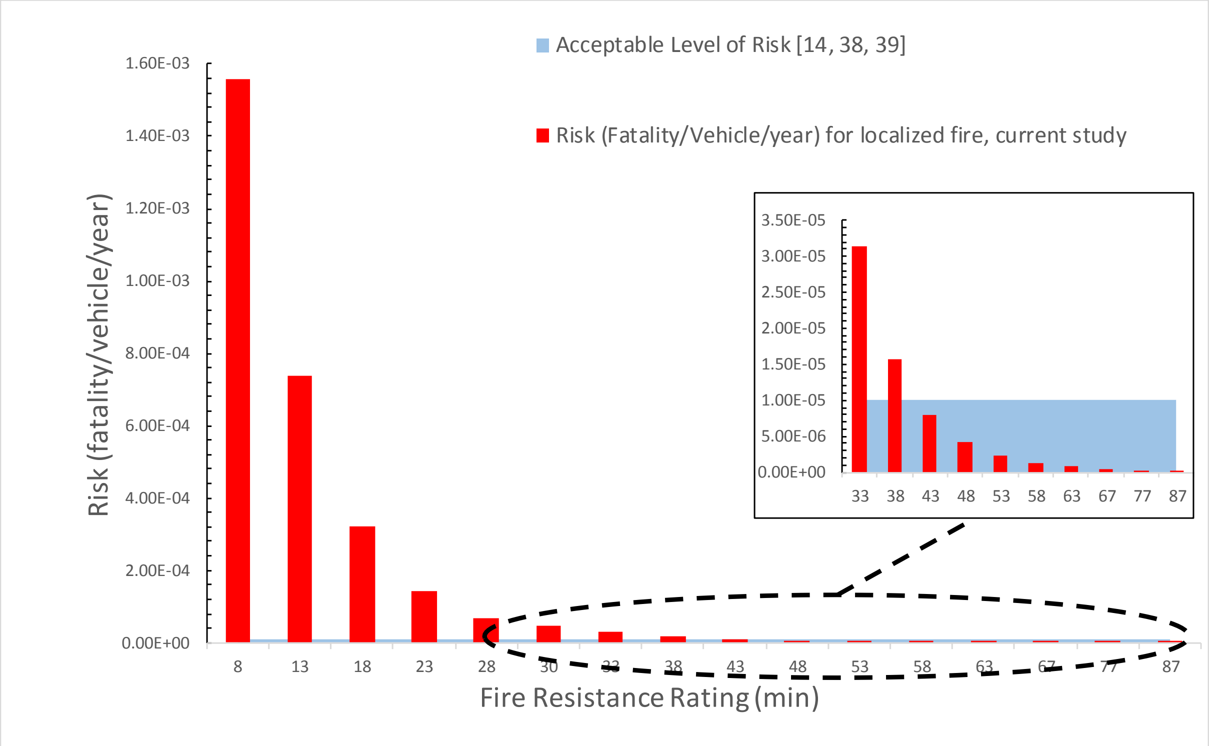

Figure 6. Risk (fatality/vehicle/year) versus fire resistance rating (min): localised fire

4.1.2 Effects of FRR on an accident cost

To evaluate the effect of FRR on the cost of human loss in FCHV accident with a fire, the deterministic approach is chosen. According the flowchart in Fig. 1b, the cost of fatality per car accident with fire is calculated as a function of fire escalation probability, given the failure of TPRD, and the cost associated with the number of fatalities in a case of catastrophic tank rupture. This means that for bare tank with FRR=8 min in cases of both engulfing and localized fire (see Table 4) the escalation probability is calculated using Equations 2 and 3 as:

$$Y = 9.25 - 1.85 \cdot \ln(8) = 5.4030 \quad \Rightarrow \quad EP = \frac{1}{2} \cdot \left[1 + erf\left(\frac{5.403 - 5}{\sqrt{2}}\right)\right] = 6.57\text{E} - 01$$

The cost associated with fatalities in an accident due to catastrophic rupture in a fire is calculated as 6,095,808 £/accident (section 3.1). The probability of TPRD failure in cases of engulfing and localised fires are 6.04E-03 and 5.03E-01, respectively. Thus, the risk in terms of cost per accident (£/accident) is calculated as

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

where cost of fatality (£/rupture) is, the cost associated with the number of fatalities after a rupture. Thus, the cost in both cases of engulfing fire and localized fire is obtained as follows:

$$Cost\ of\ rupture\ during\ engulfing\ fire =$$

$$6{,}095{,}808 \cdot (6.04 \cdot 10^{-3}) \cdot (6.57 \cdot 10^{-1}) = 24{,}024\ \ (£/accident)$$

$$Cost\ of\ rupture\ during\ localized\ fire =$$

$$6{,}095{,}808 \cdot (5.03 \cdot 10^{-1}) \cdot (6.57 \cdot 10^{-1}) = 2{,}000{,}658\ \ (£/accident)$$

the cost of human loss for various FRR values is obtained by using the same procedure as for the case FRR=8 min. Fig. 7 and Fig. 8 represent graphically the Cost (£/accident) versus FRR (min) for engulfing and localised fire, respectively. For engulfing fire, the cost is 24,024 £/accident for bare tank with FRR=8 min. The cost is drastically decreasing with increase of FRR and after FRR=30-40 min reaches negligible values.

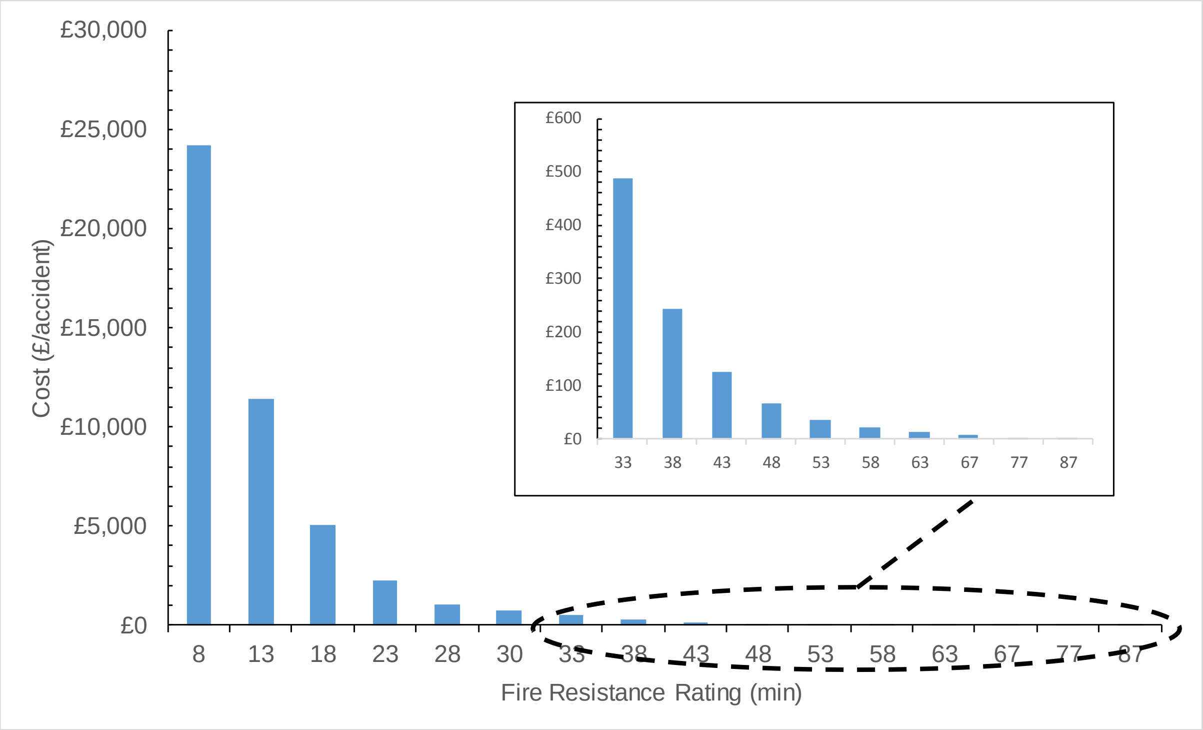

Figure 7. Effect of FRR (min) on the cost of human loss (£/accident): engulfing fire

In the case of localised fire, the effect of FRR on risk is significantly more prominent (Fig. 8). The cost of road accident with a fire for FCHV with a bare tank of FRR=8 min is unacceptably high 2,000,658 £/accident. The cost descends quickly with increase of FRR and falls down to 15,000 £/accident at FRR=41.3 min (at this value of FRR the risk measured in fatality/vehicle/year reaches acceptable level of 1.00E-05). Here it should be mentioned again that the costs for a car damage or damage to natural and the built environment are not included in this QRA exercise.

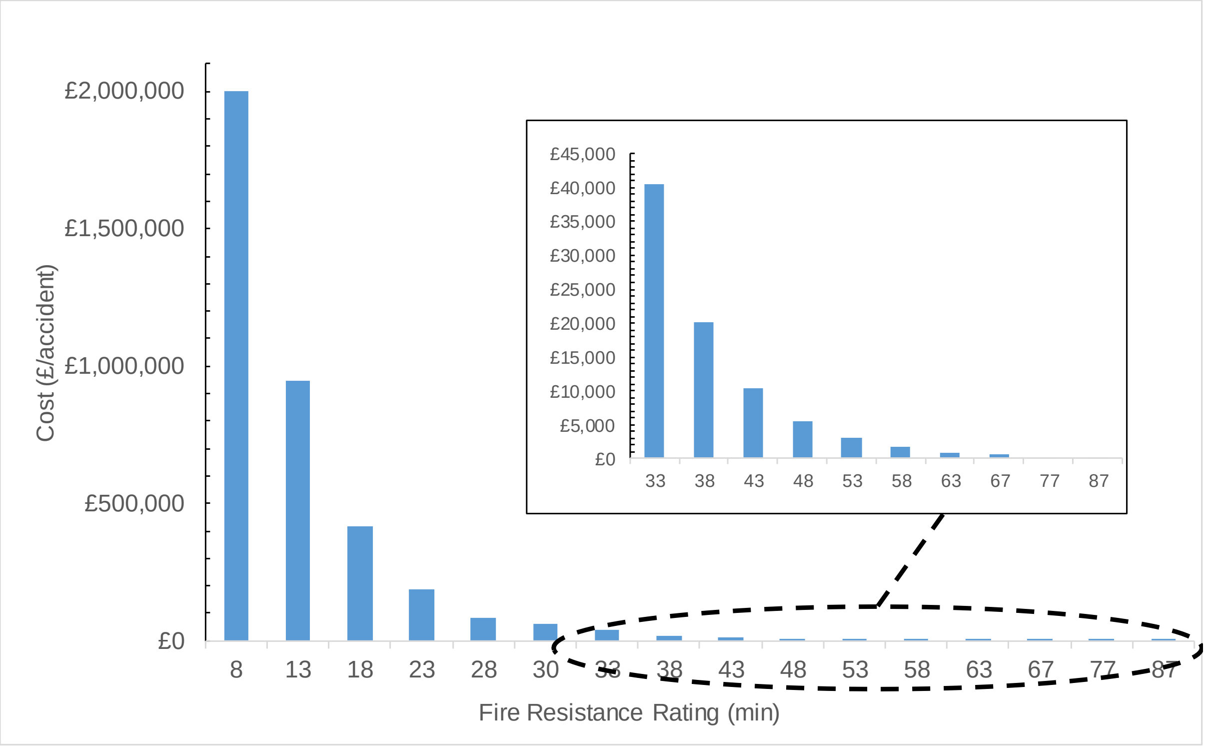

Figure 8. Effect of FRR (min) on the cost of human loss (£/accident): localised fire

4.2 Towards uncertainty analysis

The detailed uncertainty analysis is not in the scope of this study and the authors envisage to undertake a separate study and publish 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, the use of models or correlations for assessment of hazard distances which have own uncertainties, etc. 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 that 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 likely to vary for tanks of different size, volume, maximum allowable working pressure (MAWP), etc.

The carried out QRA shows that typical for today's unprotected onboard storage tanks in hydrogen-powered vehicles with FRR=8 min [12] cannot provide acceptable level of risk in densely populated areas modern cities like London. Carried out QRA demonstrates that to provide the acceptable level of risk $1.0 \cdot 10^{-5}$ the onboard hydrogen storage systems should have FRR at least 41.3 min.

5.0 CONCLUSIONS

A QRA methodology is applied in this study to evaluate the effect of fire resistance rating of onboard hydrogen storage vessels on the risk of human loss in case of road accident with a fire. The hazards under consideration are blast wave and fireball generated in a case of catastrophic onboard high-pressure hydrogen storage tank rupture in a fire. These two produce longer overpressure and thermal effects associated hazard distances compared to other pressure (deflagration) and thermal (jet fire) effects considered in other QRA tools. Statistical data on car accident and fire frequencies available in the literature are used to assign the probability value for individual events in the escalation scenario. The QRA methodology accounts for such fire modes as an engulfing and a localised fire. The vulnerability probit function is introduced to account for the probability of emergency services failure to extinguish a fire. Such a scenario, in conditions of TPRD failure to operate and vent the contents of onboard hydrogen storage, leads to a catastrophic tank rupture. In the absence of statistical data on failure of TPRD for hydrogen onboard storage, the assumption, similar to other studies for hydrogen storage tanks, was applied, stipulating that its frequency is equal to that of an ordinary PRD failure. Finally, the population density data is used to evaluate the social risk in terms of human fatality per vehicle per year. An economic effect of safety measures for onboard storage, i.e. thermal protection of a compressed gas tank to increase its fire resistance rating, is assessed using the cost-benefit analysis conducted by Health and Safety Executive in the UK. It provides cash valuations of preventing health and safety effect on people normalised per vehicle per year.

The example introduced in this study, which is used to demonstrate the QRA methodology performance, considers an accident with FCHV having 62.2 litre hydrogen tank with storage pressure of 70 MPa, occurred in the location with the population density around this scene of accident 0.008 person/m^2, which is representative for roads in London. For a localised fire the fatality rate in the case of bare tank with typical FRR=8 min is 1.56E-03 fatality/vehicle/year, which is higher than generally accepted risk level of 1.00E-05. The increase of FRR to 41.3 min decreases the risk to the acceptable level of 1.00E-05 fatality/vehicle/year. With the further prolongation of a FRR through the safety means, the risk continues to decrease to a negligible value. The cost associated with health and safety effects of the accident on people was calculated: for the tank subject to the localised fire and FRR=8 min the cost is 2,000,658 £/accident; for the longer FRR=41.3 min the cost totals 15,000 £/accident. Similar to the risk behaviour depending on the FRR, the cost tends to reduce to negligible values as the FRR further increases.

The QRA methodology can be applied to optimise safety engineering solutions for FCHV. It is a valuable tool for decision making analysis by considering the costs and fatality rate associated with hydrogen hazards. The methodology aids to design safety measures for prevention and mitigation of socio-economic consequences of accidents with FCHVs.

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