RISK ASSESSMENT ON LIFE SAFETY AND FINANCIAL LOSS FOR ROAD ACCIDENT OF FUEL CELL VEHICLE

Sun, K.[1], Li, Z.Y.[2]
[1] Safety and Risk Management Research Team, Jiaxing University, 314001, P.R. China, sunke326@163.com
[2] Institute for Built Environment and Energy Engineering, Jiaxing University, 314001, P.R. China, z.li@mail.zjxu.edu.cn

ABSTRACT

Vehicular use of hydrogen is the first attempt to apply hydrogen energy in consumers' environment in large scale, though hydrogen has been widely used in industrial field for over one hundred years. The increasing number of hydrogen fuel cell vehicles has raised safety concerns in both public authorities and private bodies such as fire services and insurance companies. This paper analyzes typical accident progressions of hydrogen fuel cell vehicles in a road accident. Major hydrogen consequences including impinging jet fires and catastrophic tank ruptures are evaluated separately in terms of accident duration and hazard distances. Results show that in a 70 MPa fuel cell car accident, the hazards associated with hydrogen releases would normally last for no more than 1.5 minutes due to the empty of the tank. This indicates the first responders would be able to approach the vehicle, conservatively, approximate two minutes after hearing the hissing sound as the hydrogen hazards have been eliminated. For the safety of general public, a perimeter of 100 meters is suggested to be set in the accident scene if no hissing sound is heard. However, the perimeter can be reduced to 10 meters once the hissing sound of hydrogen release is observed. For the first responders, if there's no sigh of hydrogen release, they should stand at least 10 m away from the burning car, otherwise their risk of fatality would be over 50% in case of catastrophic tank rupture. Furthermore, risks of fatalities, injuries, and damages are all quantified in financial terms to assess the impacts of the hypothetical accidents. Results show that costs of fatalities and injuries contribute most to the overall financial loss, indicating the insurance premium of fatalities and injuries should be set higher than that of property loss.

1.0 INTRODUCTION

The dream of a hydrogen economy envisioned by politicians, economists, and environmentalists has been pursued for decades, and one of the most promising fields is the application of hydrogen powered vehicles such as fuel cell vehicles (FCVs). Lux Research Report forecasts that the FCVs market will reach a total of $2 billion by 2030 [1]. FCH-JU predicates that the number of FCVs in Europe is expected to reach 500,000 by 2020 [2]. The increasing number of hydrogen vehicle will inevitably introduce unfamiliar hazards that are different from those of conventional vehicles. Unlike conventional petrol fuel that is stored in normal condition, hydrogen onboard is usually stored in pressurized condition with high pressure up to 70MPa. Such high pressures have the potential to cause tank explosion. Therefore onboard hydrogen systems are commonly equipped with pressure relief devices to prevent tank explosion from happening. Pressure relief devices significantly reduce the risk of tank catastrophic rupture by venting the high pressure hydrogen outside. However the released hydrogen could raise additional safety concerns such as hydrogen jet fires. Compared with conventional hydrocarbon fuels, hydrogen has wider flammability range, larger diffusion constant, higher buoyancy, lower ignition energy and nearly invisible flame in daylight, etc. These unique properties entitle hydrogen vehicle different hazard features and raise safety concerns to all stakeholders including consumers, first responders, government authorities and insurance companies, etc.

Vehicular use of hydrogen is the first attempt to apply hydrogen energy in consumers' environment in large scale, though hydrogen has been widely used in industrial field for over one hundred years. Hydrogen hazards in consumers' environment poses new challenges to all people including drivers, passengers, first responders and other general public in the vicinity of the vehicle accident scene, etc. Actually in an event of hydrogen vehicle fire accident, the severity of the consequence depends on how well people know of the accident and whether they could properly respond to the potential hazards or not. Consumers and first responders not only need to know the basic features and characteristics of hydrogen vehicle accidents, but also need to know how long the hydrogen accident would last and how far the hydrogen hazards could reach, i.e. the hydrogen accident duration and hazard distances. Furthermore, government authorities and insurance companies would like to know more about the details of typical accident progressions and to predict the risks of life safety and property losses. To achieve that, risk based methodology that incorporates both probabilities and consequences will be adopted in this paper to assess the losses of a typical accident. The losses of an accident can be divided into three categories in general: fatalities and injuries of people, damage to equipment and properties, and environment clean-up cost with the damage. These different terms are difficult to combine as they have different measurement. To solve the problem, each type of losses will be quantified in financial terms, which makes it possible to combine and compare them directly. Frequency-Cost Curve, which shows the frequency of a given financial loss or greater, will be analyzed in the paper.

2.0 GENERAL HAZARD ANALYSIS OF HYDROGEN FUEL CELL VEHICLES

There are generally two categories of hazards for hydrogen fuel cell vehicles. One is the hazard associated with the onboard hydrogen storage and piping systems, the other is the hazard related to the onboard battery. An example of the layout of fuel cell vehicles is shown in Fig. 1 which is taken from Honda Clarity [3].

It can be seen that hazards associated with hydrogen systems are mostly in the rear of the vehicle and the electrical hazards are mainly in front of the car. The two types of hazards are not isolated and one type could affect the other. For example, in a car crash accident, the battery in the front could be on fire, and the fire would spread towards the rear of the vehicle to cause hydrogen releases.

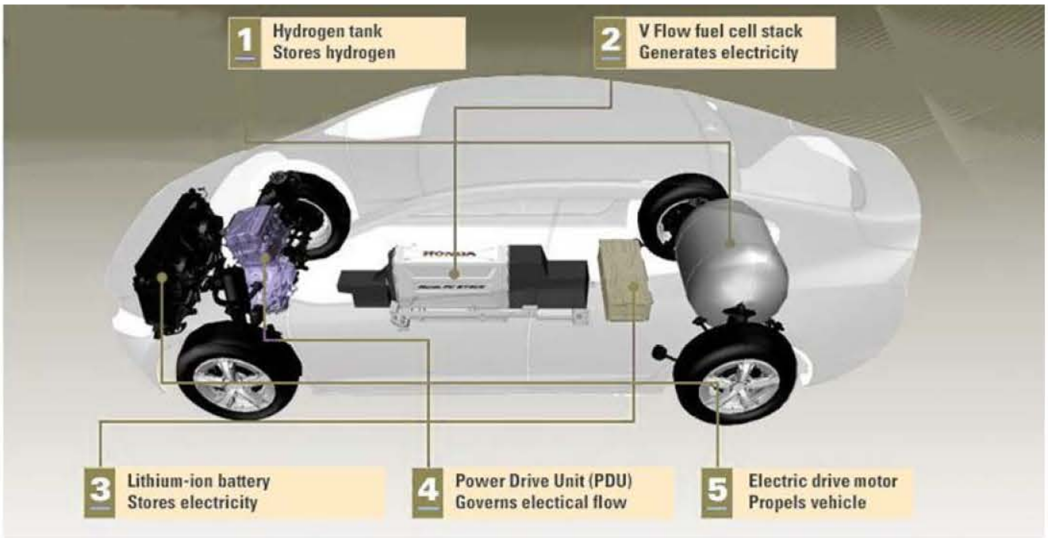

Figure 1. Example of layout of fuel cell vehicles [3].

For the hazards associated with hydrogen systems, the unintended hydrogen release and subsequent potential flammable effects are the major concern. The release of hydrogen can be either a continuous release from the onboard storage tank or instantaneous release such as a catastrophic rupture of the high-pressure tank. The consequence of a continuous release depends on the time of ignition. An immediate ignition of a continuous release of hydrogen will result in a jet fire, while delayed ignition of the flammable hydrogen cloud will lead to a flash fire or an explosion if in confined space. The heat radiation from the jet fire and overpressure from the explosion are harmful to people and property. Without ignition, the released hydrogen will be harmless in an open environment since hydrogen is non-toxic gas. One might argue that an accumulation of hydrogen could result in breathing difficulties or even asphyxiation due to oxygen deficiency, but it is very unlikely to occur in hydrogen car accidents on road because of the limited hydrogen inventory of just a few kilograms.

As for the instantaneous release in case of catastrophic rupture of hydrogen tank, it is a sudden release of the total inventory of the hydrogen storage. The result will be the violent depressurization from the high pressure tank, creating outward blast wave and fragment projectiles. The likelihood of such event is not high because onboard hydrogen tanks are commonly equipped with thermally activated pressure relief devices (TPRDs) which are mandatory or so called “standard” safety devices in high-pressure hydrogen storage systems. If a tank is subjected to heating in case of vehicle fires, normally TPRD will open and release the excess pressure to eliminate the risk of the catastrophic rupture of tank. It is expected that the failure probability of TPRD in a commercialized hydrogen vehicle should be small, but there are still chances of TPRD failure and occurrence of catastrophic explosion of hydrogen tank.

3.0 ASSUMPTIONS OF TYPICAL ACCIDENT SCENE

Typical accidents can be perceived as representative examples of accidents with high credibility of occurrence in real world conditions. For a hydrogen vehicle, traffic accidents on road are common incidents through its lifetime and can be considered as typical to be studied in this paper. The assumptions of hypothetical typical car accident are described below.

3.1 Typical Accident Descriptions

The accident is assumed to be a collision on a city road. As shown in Fig. 2, a fuel cell car is running on the road heading east and accidentally collides on crash barriers due to a sudden tyre burst. The crash may damage the high voltage systems and lead to a fire. The fire would spread toward the rear of the car where the hydrogen tank is located. It is assumed that three people are in the fuel cell car including one driver and two passengers. For the vulnerable targets outside the car, there are three categories as shown in Fig. 2. The first type is the people in the vicinity of the accident including the crowd in the bus stop and shelters, bicycle riders on the bike lane, pedestrians on the sidewalk and the vendor in the kiosk, etc. The second type is the municipal facilities such as the crash barrier, lamppost, roadside plants, bus shelter, fire hydrant, and public bicycle services, etc. The third type is the private properties near the accident including the nearby vehicles, telephone box, kiosk, and the commercial buildings as well.

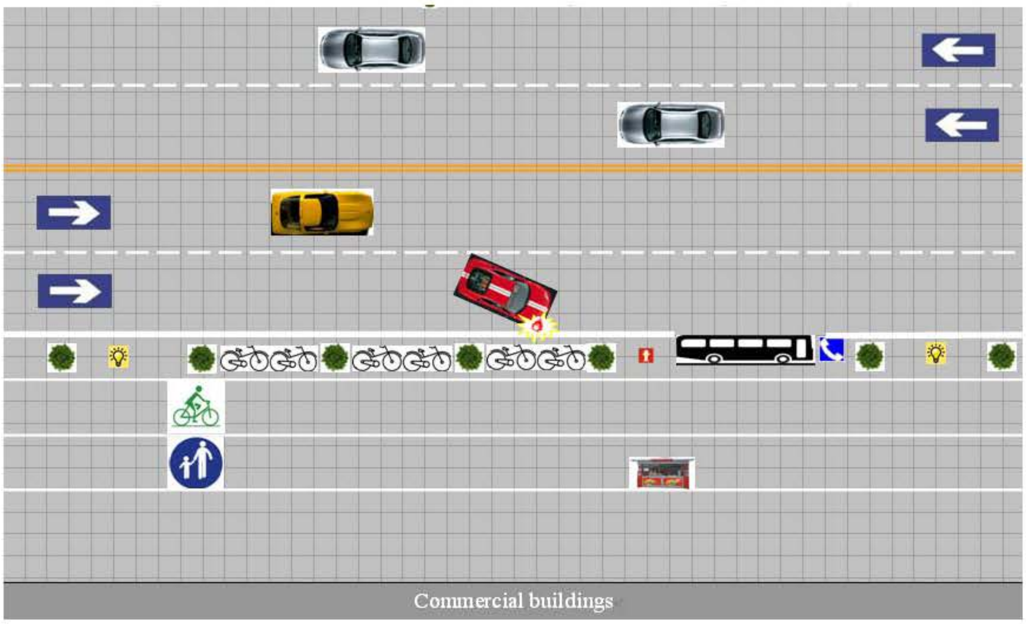

Figure 2. Scenario assumptions of a road traffic accident of a fuel cell vehicle.

The TPRD of the hydrogen tank, which commonly located at the bottom of the car, will be triggered once the temperature is over 110 centigrade. If the vehicle fire is not extinguished shortly, the TPRD of the hydrogen tank will open and release hydrogen rapidly downward with a hissing sound. The hydrogen release will be immediately ignited and produces hydrogen flames spreading outward. A similar scenario of TPRD release can be found in Yohsuke Tamura's experiment [4] which is conducted on a TPRD downward release from a 70MPa hydrogen tank of a car. A snapshot of the experiment is shown in Fig. 3. If the TPRD fails, the pressure in the tank will build up in the fire environment and the result will be a catastrophic rupture of the tank.

Figure 3. A snapshot of 70MPa ignited hydrogen release from a TPRD [4].

3.2 Assumptions of Vehicle Parameters and Ambient Conditions

Gaseous hydrogen onboard is commonly stored in high pressure up to either 35MPa or 70MPa. At present, most hydrogen storage in light-duty vehicles are under 35 MPa, but in the future, it is expected that the pressure would be 70MPa instead of 35MPa to compete with conventional petrol cars in terms of driving range and compartment space. Besides, from the perspective of conservatism, it is better to apply 70 MPa rather than 35 MPa in safety studies. Therefore, it is assumed that the onboard storage pressure is 70 MPa in this paper.

The release inventory of hydrogen is assumed to be 4 kg, corresponding to an approximately 400 kilometres driving range. The volume of the hydrogen tank is 101 L.

The TPRD diameter for 70 MPa onboard storage in Tamura's experiment [4] is 4.2 mm, which is a typical TPRD diameter for current fuel cell vehicles. Some scientists are trying to reduce the TRPD diameter by increasing the thermal resistance of the onboard tank as they believe smaller TPRD will significantly reduce the hazard distance in a hydrogen release event. They expect that in the future the TPRD diameter should be smaller than the current one. However, many engineers in industrial world disagree with the opinion and refuse to adopt smaller TPRD diameter. They hold the idea that the primary purpose of a TPRD is to quickly reduce the overpressure of the tank to prevent tank catastrophic rupture, and obviously smaller diameter goes against that objective. An appropriate TPRD size in the future is still under debate and far from a well-accepted agreement, so current typical TPRD diameter of 4.2 mm will be adopted in our safety analysis in this paper.

The ambient temperature is assumed at 20 centigrade for the road traffic accident. The ambient pressure is assumed to be at 1 atm. A summary of the parameters is listed in table 1.

Table 1. Assumptions of vehicle parameters and ambient conditions.

Hydrogen storage conditions	TPRD diameter(mm)	Ambient temperature	Atmospheric pressure
70 MPa, 101L, 4 kg	4.2 mm	20℃	1 atm

4.0 ACCIDENT PROGRESSIONS AND EVENT PROBABILITIES

For the road traffic accident, typical accident progressions are analyzed in the event tree shown in Fig. 4. For the probability of high voltage system on fire caused by car collision, the early data from Tesla reported that on average 1 in 6333 Tesla Model S cars had car fires [5], indicating a probability of approximate 1.6×10^{-4} (1/6333).

For the probability of a successful fire extinguishment, it is conservatively assumed that 50% of the fires will not be suppressed in time (before TPRD open). It took about 30 minutes from fire started to the triggering of TPRD in Yohsuke Tamura's experiment [4] that conducted on a TPRD release from a 70MPa hydrogen tank of a car. Half an hour is almost two or three times of the average fire service response time of road vehicles, so it is usually long enough for the fire fighters to arrive at the accident scene to take actions, if the emergency call is received with a couple of minutes from the fire started. However, having sufficient time to take actions on the fire does not mean the fire will be extinguished immediately. NFPA (National Fire Protection Association) of United States conducted a number of full-scale burn tests with Lithium-Ion batteries [6] and the results indicate that the first responders should prepare an extended fire suppression time and greater volume of water. Therefore, in our study a conservative probability of 0.5 is assumed to the vehicle fire not being suppressed in time.

For the failure rate of TPRD, a probability of 2.22×10^{-5} is adopted, based on J.Khalil's report on the analysis of hydrogen storage [7]. It is expected that catastrophic rupture of tank will occur in case of TPRD failure.

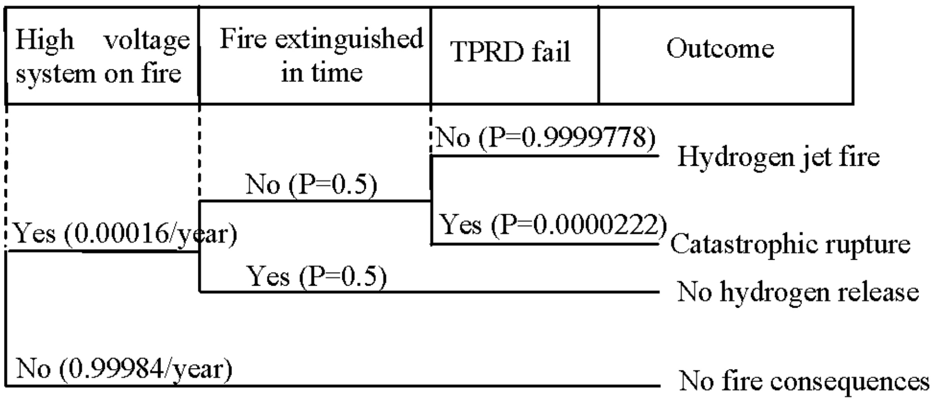

Figure 4. Hypothetical accident progressions and event probabilities for risk analysis in a car collision.

5.0 EVENT DURATIONS AND HAZARD DISTANCES

5.1 Jet Fire Durations

In real world conditions, a hydrogen release from a high pressure tank is not a steady release but a blowdown process with pressure decay in the reservoir until the tank is empty. The blowdown process can be calculated using isentropic flow equations of an Abel–Noble gas described in Schefer's paper [8].

In our case, for the release of 4 kg hydrogen stored at 70 MPa, from the 4.2 mm orifice, the calculated blowdown process is shown in Fig. 5. It can be seen that the total blowdown time is less than 75 seconds. The longest jet fire duration will not exceed the tank blowdown time, so the blowdown time can represent for the jet fire duration. When tank blowdown completes, hydrogen flame hazard will vanish, though the conventional vehicle fire may continue. As the hydrogen flame is almost invisible in daylight, it would be difficult to visually identify when the hydrogen jet fire begins. It would be easier to identify the starting point by listening to the hissing sound of the hydrogen release. Therefore, we may conservatively conclude that the hydrogen jet fire will be self-extinguished within no more than 1.5 minutes after hearing the hissing sound of the hydrogen release.

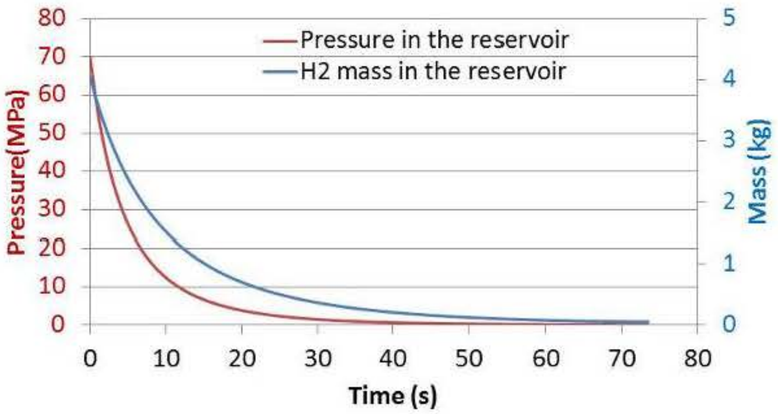

Figure 5. Blowdown of hydrogen releases from 70 MPa hydrogen tanks.

5.2 Hazard Distances

The jet fire under vehicle is not free jet fire but actually jet fire impinging on the ground, so the simple engineering equations for free jet calculation does not apply in hydrogen releases from TPRD under fuel cell vehicles. Onboard TPRDs are commonly installed under a fuel cell vehicle and will release downward in case of TPRD initiation. For such jet impinging release, we apply CFD simulation to calculate the hazard distances. In turbulence modelling, the shear-stress transport (SST) k-ω model is applied as this model is known to allow for a more accurate near wall treatment than k-ω model. The SST k-ω model was developed by Menter [9] to effectively blend the robust and accurate formulation of the k-ω model in the near-wall region with the freestream independence of the k-ε model in the far field. For combustion modelling the eddy-dissipation model is applied. It is a turbulence-chemistry interaction model based on the work of Magnussen and Hjertager [10]. In this model, reaction rates are assumed to be controlled by the turbulence, so expensive Arrhenius chemical kinetic calculations can be avoided. The model is computationally cheap and effective for one or two step heat-release mechanisms. The modelling results are shown in Fig. 6.

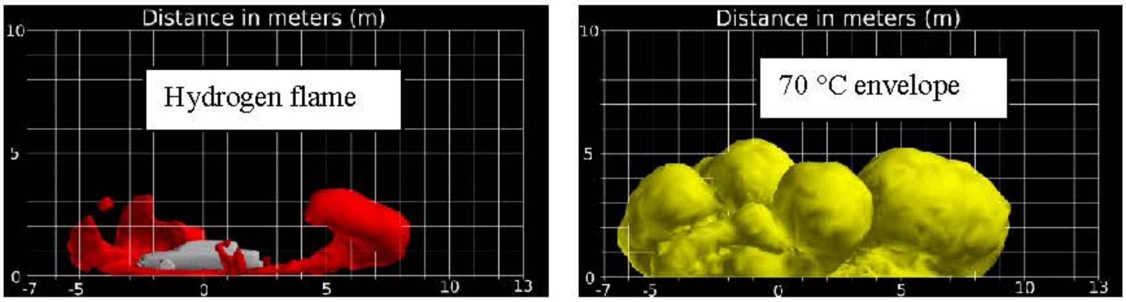

Figure 6. Largest hydrogen flame (left) and 70 °C envelope (right) during TPRD release.

For hydrogen fire hazard, it is assumed that direct contact of hydrogen flame will cause fatalities and a temperature of 70 °C is taken as an acceptance criterion for no harm. Therefore hydrogen flame length can be considered as "fatal distance" or "lethal distance", and distance to 70 °C temperature boundaries can be considered as "no harm distance" or "safe distance".

As shown in Fig. 6, the flame length of hydrogen jet impingement reaches 8 meters and 70 °C envelope reaches about 10 meters, so the lethal distance and no harm distance for the TPRD releases are 8 m and 10 meters, respectively. This indicates that all first responders who deal with the accident must stand at least 8 meters away from the car to avoid possible fatalities. In addition, a perimeter of at least 10 meters should be set around the accident scene to protect the general public.

5.3 Tank Catastrophic Rupture

To determine the hazard distance from tank catastrophic rupture, Kashkarov and Li, et al. developed engineering tools for predicting blast wave overpressure from catastrophic rupture of onboard tank under fuel cell vehicle. The nomogram, as shown in Fig. 7, was built on the basis of experimentally validated model that presented in the international seminar on fire and explosion hazards in 2016 [11].

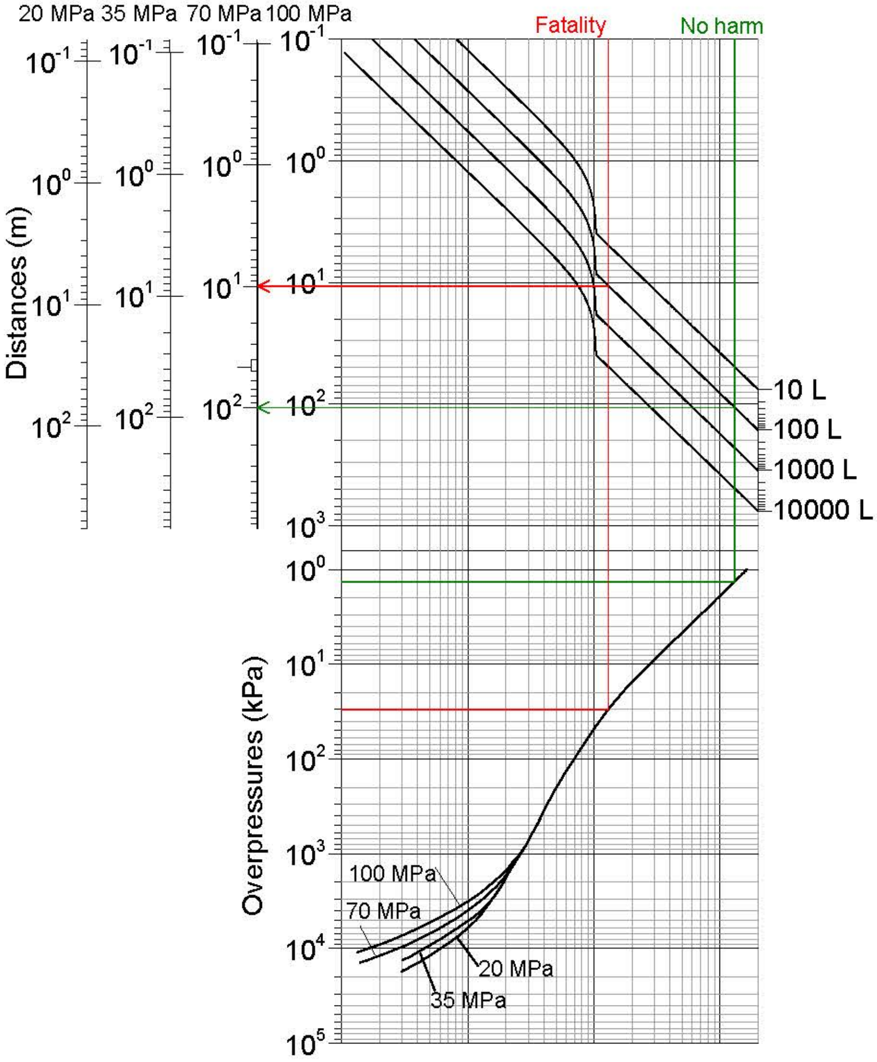

Figure 7. Determination of hazard distances in the overpressure-distance nomogram

The no harm criterion for blast overpressure is selected from Baker et al. [12], who suggest overpressure greater than 1.35 kPa would lead to temporal loss of hearing. The overpressure of 30 kPa is taken as the fatality criterion, which corresponds to 50% probability of fatality from missile wounds [13].

Based on the above harm criteria, the lethal distance and no harm distance from tank catastrophic rupture are 10 m and 100 m, respectively, as shown in Fig. 7. This indicates that fire fighters should not approach the accident vehicle in shorter than 10 m radius; otherwise their risk of fatality will be over 50% in case of tank catastrophic rupture. For the general public, a perimeter of 100 meters should be set as no harm distance or safe distance. Such setback distance of 100 meters is several times longer than the suggested safety distances that exclude the scenario of tank catastrophic rupture in the IGC document [14]. The risk-based safety distance in IGC document is not intended to provide protection against catastrophic events or major releases whose likelihood is lower than the proposed risk acceptance criteria. For the first responders who have to take into account the worst-case scenarios such as tank catastrophic rupture, the perimeters or setback distances should be consequence-based distances rather than the risk-based ones. The Emergency Response Guidebook of the US Department of Transport, also recommends isolating the area from unauthorised personnel in a radius of 100 m.

6.0 FINANCIAL LOSS

This paper concerns the additional risks introduced by hydrogen rather than the overall risk of the road collision accident, as the losses caused by pure physical road collision are no much difference between hydrogen-powered vehicles and conventional vehicles. Therefore, losses immediately caused by physical collision will not be considered in the assessment. Table 2 list the estimated costs assumptions in US dollars.

Table 2. Different types of financial impact and potential cost values.

Category	Losses caused by hydrogen flammable effects		US dollars per item ($)
Impact on people	Cost of fatalities		250000
	Cost of injuries		40000
Impact on properties	Cost of the accident car		63500
		Lamppost	290
		Roadside plants	290
		Bus shelter	1450
		Fire hydrant	80
		Public bicycle	870
	Repairing or replacing cost of private properties	Telephone box	145
		Kiosk	725
		Nearby vehicles	2900
Others	Cost of environment clean-up		700

Based on the costs listed in table 2 and the event tree probabilities analysis in Fig. 4, the risk-cost curve of the car collision accident can be obtained, as shown in Fig. 8. It can be seen that the risk of compensation for fatalities and injuries in the car accident is 8×10^{-5}/year, and compensation costs will be less than 20 million dollars and 2 million dollars for fatalities and injuries, respectively. For repair or replacement loss, the risk of compensation less than 60 thousand dollars is 8×10^{-5}/year, and the risk of compensation less than 7 thousand dollars is 2×10^{-4}/year. The risk of environmental clean up cost is about 2×10^{-4}/ year, while the compensation cost is very small, about 700 dollars. The above data indicate that the insurance premium of fatalities and injuries should be higher than that of property loss, which should be taken into consideration in insurance pricing for fuel cell vehicles.

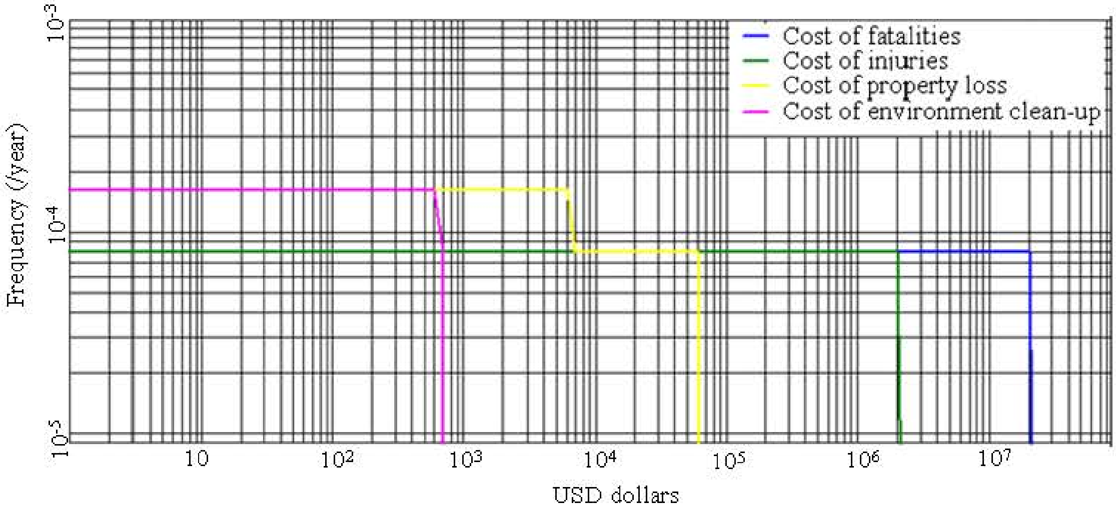

Figure 8. Frequency-Cost curves for the fuel cell car accident

7.0 SUMMARY

This paper performs a case study on a typical road accident of fuel cell vehicle. The accident duration and hazard distances are evaluated and financial losses are assessed. The main results can be summarized as below:

(1) In a 70 MPa fuel cell car accident, the hazards associated with hydrogen releases would normally last for no more than 1.5 minutes due to the empty of the tank. This indicates that the first responders would be able to approach the vehicle, conservatively, approximate two minutes after hearing the hissing sound as the hydrogen hazards have been eliminated.

(2) For the safety of general public, a perimeter of 100 meters is suggested to be set in the accident scene if no hissing sound is heard. However, the perimeter can be reduced to 10 meters once the hissing sound of hydrogen release is observed. For the first responders, if there's no sign of hydrogen release, they should stand at least 10 meters away from the burning car, otherwise their risk of fatality would be over 50% in case of catastrophic tank rupture.

(3) Costs of fatalities and injuries contribute most to the overall financial loss and costs of property loss contribute less. This indicates that the insurance premium of fatalities and injuries should be higher than that of property loss, which should be taken into consideration in insurance pricing for fuel cell vehicles.

REFERENCES

1. Brian, W., The Great Compression: the Future of the Hydrogen Economy, Lux Research Inc., 2013.
2. Fuel Cell and Hydrogen Technologies in Europe-financial and Technology Outlook on the European Sector Ambition 2014-2020. http://www.fch-ju.eu/.
3. Honda FCX Specifications. http://www.hondaclarity.org/.
4. Tamura, Y., Takabayashi, M. and Takeuchi, M., The Spread of Fire from Adjoining Vehicles to A Hydrogen Fuel Cell Vehicle, International Journal of Hydrogen Energy, No.39, 2014, pp. 6169-6175.
5. Elon M., The Mission of Tesla, Tesla, USA, 2013.
6. R. Thomas Lon Jr., Andrew F. Blum, Thomas J. Bress, Benjamin R.T. Cotts, Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results, June 2013 Fire Protection Research Foundation
7. Khalil, J., Mosher, D., Sun, F., Laube, B., Tang X., and Brown, R., Quantifying & Addressing the DOE Material Reactivity Requirements with Analysis & Testing of Hydrogen Storage Materials & Systems, Annual Peer Review, Washington DC, 2010, Project ID ST012.
8. Schefer, R.W., Houf, W.G., Williams, T.C., Bourne, B. and Colton, J., Characterization of High-pressure, Underexpanded Hydrogen-jet Flames. International Journal of Hydrogen Energy, 32, 2007, pp. 2081-2093.
9. Menter, F. R., Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications, AIAA Journal, 8, No. 32, 1994, pp. 1598-1605.
10. Magnussen, B. F. and Hjertager, B. H., On Mathematical Models of Turbulent Combustion with Special Emphasis on Soot Formation and Combustion, 16th Symp. (Int.) on Combustion, Pittsburgh, PA, The Combustion Inst., 1976, pp. 711-729.
11. Kashkarov, S., Li Z.Y., Molkov V., Nomograms for Assessment of Hazard Distances From a Blast Wave After High-Pressure Hydrogen Cylinder Rupture in a Fire, 8th International Seminar on Fire and Explosion Hazards, Hefei, China, 2016.
12. Baker, W. E., Cox, P. A., Westine, P. S., Kulesz, J. J. and Strehlow, R. A., Explosion Hazards and Evaluation. Elsevier Scientific Publishing Company, 1983.
13. Jeffries R.M., Hunt S.J. and Gould L., Derivation of Fatality of Probability Function for Occupant Buildings Subject to Blast Loads, Health & Safety Executive, 1997.
14. IGC Doc 75/07/E/rev, Determination of Safety Distances, European Industrial Gases Association, 2007.
15. Emergency Response Guidebook. A Guidebook for First Responders during the Initial Phase of a Dangerous Goods/Hazardous Materials Transportation Incident, U.S. Department of Transportation, 2012.