Emergency responders' perceptions of Hydrogen Fuel Cell Vehicle: A qualitative study on the U.K. fire and rescue services

Emergency Responders' Perceptions of Hydrogen Fuel Cell Vehicle: A Qualitative Study on the U.K. Fire and Rescue Services

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Abstract

Due to the fast growth of the Hydrogen Fuel Cell Vehicle (HFCV) market, the chances of these vehicles being involved in road crashes is also likely to increase. However, to date, studies into the Emergency Responders' perceptions of the HFCV have been limited. This paper investigates such perceptions of HFCVs through the interviews with firefighters. Through a pilot study results, initial findings suggest that firefighters are the ones who work next to the HFCV in post-crash scenarios, hence, they can provide more insightful information. As a result, 19 themes regarding their perceptions were discovered. The results show that the firefighters have different perceptions of the HFCV regarding the “economic cost”. Further analysis indicates the contradictions in their perceptions, and also shows they had more concerns about rescue-oriented safety rather than the fire-oriented safety. Finally, recommendations to address these concerns are discussed as well as the political implications of the results.

Keywords: Firefighter perceptions, Hydrogen Fuel Cell Vehicle, Safety and Human Factor

1. Introduction

Hydrogen (H_2) has been widely used in the aerospace industry since the 1960s. Thereafter, it has been exploited for use in other transportation sectors. Most of the research relating to perception of hydrogen as a fuel source focuses on how to improve the public acceptance of hydrogen vehicles and in turn, how to accelerate the commercialisation of Hydrogen Fuel Cell Vehicles (HFCVs) across the world [1]–[4]. However, one crucial group from the "public" is missing from the current research interests, and this group is the follow-up First Responders.

Data from the Department for Transport (U.K.) shown, there were 160,378 reported road casualties of all severities in the U.K. in 2018 [5]. Due to the fast growth of the HFCV market, the chance of road causalities that involves the HFCV is also likely to increase in the near future. Moreover, some disasters that have happened in the past (e.g. The Hindenburg Airship) have caused people to be very vigilant about the use of hydrogen and become more aware of the potential for explosion. The high vigilance for such vehicles means that the safety standards for HFCVs have to be higher than those for Internal Combustion Engine (ICE) vehicles. Since HFCVs are not yet well-understood by the public, there is reliance on trust in other external factors to assess and ensure the safety and reliability of the HFCV [6]. That is, when a Road Traffic Collision (RTC) occurs involving an HFCV, the public will rely on emergency personnel to handle the collision and ensure the safety and efficient rescue of the drivers, passengers, and other vulnerable road users. Barilo et al. [7] pointed out that professionally trained emergency responders will be playing an essential role in our future hydrogen-related community and in-so-doing, will effectively promote the commercialisation of the HFCV. The increased safety expectation for the HFCV also means the public will likely expect first responders to act more professionally and develop trust. However, to date, studies into the Emergency Responders' perceptions of the HFCV have been limited. From a human factors point of view, the opinions and feedback of frontline emergency personnel are more worthy of attention as they contain salient information, enabling further improvement of service quality and well-being.

The structure of this paper is as the following: Section 2 reviews literature relevant to this study. The first part reviews the potential hazards and relative counter-measurements associated with the HFCV. The second part reviews policy aspects of the HFCVs, including principal regulations, codes and standards. The third part reviews literature relevant to emergency responders. The aims and objectives of this study are also shown at the end of this section. Section 3 shows the applied method for this study which includes the participant recruitment procedures. The details of the interview design and sampling method are also provided in this section. Section 4 shows the results of this study. The first part of this section presents the sampling characteristics and the codebook of the generated themes. The second part discusses each theme in detail. Recommendations from the study are presented at the end of section 4 and finally section 5 presents the conclusions of this study and includes political implications and study limitations.

2. Literature Review

2.1 Current mainstream hazards and countermeasures

Since the research focus of this article is not a systematic review of existing HFCV hazards, this section only lists the current mainstream concerns and their associated counter measurements.

2.1.1 Hydrogen-related aspect

Hydrogen-related hazards often start with a leakage from the tank. The leakage from onboard tank can potentially create a jet flame of up to 10 to 15 metres [8] and thus cause difficulties for passenger evacuation and First Responder rescue. Also, the worst tank rupture could mean a large explosion that harmful to people within a large area.

However, these issues can be effectively avoided by using suitable storage tanks and technologies. As of 2019, the world's leading HFCV manufacturers are all using Type IV tanks that provide a maximum storage pressure of 700 bar with minimised weight. Compared with the petrol/diesel tank made from plastic, Type IV tanks are

much robust in toughness and impact resistance. Furthermore, the Inland Transport Committee of Economic Commission for Europe (ECE) states that "*the container shall vent through a pressure relief device without bursting*" [9]. This device can detect the fire and automatically release the remaining stored hydrogen into the surrounding before tank rupture occurs, thus preventing the catastrophic tank rupture.

Recent research also states that a Type IV tank's fire resistance rate can be improved from 6-12 min to 2 hr+ by applying an intumescent paint layer [10], [11]. This means that there will be sufficient evacuation time for both onboard passengers and other surrounding road users including time for them to reach a safe distance. Hence, the potential injury and fatality risk are reduced.

2.1.2 Electric-related aspect

Electric-related hazards must also be considered as the HFCVs are fundamentally electric vehicles (EVs). In 2005, a study [12] indicated that electric component failures cause 17% (n=79) of the investigated ICE vehicles fires. A relevant observation here is that an HFCV electrical system could be operating at a much higher voltage (350V +) than an ICE vehicle. The high-voltage system increases the fire safety concerns and increases the risk of fatalities to users and First Responders.

The high-voltage battery pack is a common concern, as Li-ion battery fires or explosions are more frequently exposed to the public nowadays. Such fires or explosions are mainly due to overheating and overload because of the high energy density characteristics, also known as "thermal runaway" [13]. Vehicle manufacturers suggest the users to monitoring the battery pack for any unusual phenomena, including leaks, sparks, and "gurgling" sounds, and report these phenomena to the manufacturers and First Responders in case of an accident.

The high-voltage circuit is another risk that needs to be considered. In general, the voltage below 50V is considered safe when the direct contact time is less than 3 seconds [14]. Regarding HFCVs, the high-voltage connection cables (100 to 300V) exceed such a safety limit [15]. The orange coding for high-voltage cables was one of the safety measures historically advocated by the Society of Automotive Engineers (SAE) but is

now widely accepted by vehicle manufacturers as a means to alert First Responders and other relevant technicians.

It should be noted that electric vehicles and their battery technology are still under development. As yet, there is no specific consensus on the design of electrical-related safety systems. Also, first responders do not have the same level of experience dealing with HFCVs, compared with decades of experiences with ICE vehicles.

2.2 Regulations, Codes and Standards for HFCV

In recent years, local authorities around the world have developed and promulgated comprehensive regulations, codes and standards to deal with the safety issues related to hydrogen vehicles. Due to the complexity of laws and regulations, this section only lists the principal regulations related to hydrogen vehicles. The auxiliary clauses and supplementary regulations included within the principal regulations will not be mentioned because this is out of the scope of research interest.

At present, hydrogen-powered vehicles registered in the U.K. still need to comply with EC regulations, despite the U.K.'s departure from the European Union. The primary regulation is EC No.79/2009 (2009), which introduces the type-approval of hydrogen-powered vehicles. The uniform provisions of the safety requirements of the HFCVs and their components are listed in U.N. Regulation No.134 (2015). This regulation includes the use of non-return valves as a safety measure during the refuelling process, which was also indicated by the SAE standards (SAE J2600 (2012) & J2601 (2014)). Various authorities address this device as it ensures refuelling safety due to the unique high-pressure tank characteristic of HFCVs.

In addition to the safety regulations specific to hydrogen-powered vehicles, the HFCV must also comply with other relevant regulations related to electric and hybrid vehicles promulgated by organisations, such as IEC and ISO. In 2014, the SAE released a Recommend Practice for General Fuel Cell Vehicle Safety (SAE J2578), which focuses on the safety performance of HFCVs concerning the fuel cell system, hydrogen storage and handling, and high-voltage electrical system. Finally, the general vehicle safety requirements are also applied to HFCVs, such as the crashworthiness

requirements, although there are no such specific standards for HFCVs.

2.3 Research relevant to emergency responders

Nowadays, various authorities raised the attention and began to prepare sufficient training/knowledge for emergency responders to support the gradual transition of hydrogen transportation [16]–[19]. The fundamental steps are identifying the fuel type, detecting the leakage position, isolating the power source, and finally putting out the fire. Since then, these fundamental steps remain barely unchanged, but regular reviews are carried out to deal with the newly introduced HFCV models. Besides, the vehicle manufacturers are also required to provide up-to-date Emergency Responders guidelines.

Recently, hydrogen safety engineers have studied the characteristics and behaviours of hydrogen leakage and flame and applied their findings to practical work. Tamura et al. [20] found that the hydrogen cloud concentration around a vehicle can be reduced below the lower flammability limit if a wind flow of at least 10 m/s is applied. They then suggested that emergency responders could apply winds from a blower of at that speed to enhance the operation safety when the leakage position on the HFCV is detected. A similar study [21] also examined the effects of various sizes and shapes of a blower and concluded that a smaller blower with higher wind velocity was the most effective.

Furthermore, Ref [22] reviewed 8 web-based tools and indicated their usefulness to complement traditional resource (e.g. conferences, journals, magazines etc.). However, these web-based tools need to be maintained and kept up-to-date with precisions and timely response to the users' feedback. In 2017, researchers [23] developed an innovative training strategy that combines e-learning and virtual reality pedagogical approach to support emergency responders to understand the emerging HFCVs. This training has been promoted through the efforts of different local authorities. Again, these Emergency Responder-related studies did not focus on their opinions of the HFCVs, and thus, firefighters' perception has never been explored and better understood.

This study aims to explore and understand the Emergency Responders' perceptions of HFCVs through the interviews of a sample of U.K. firefighters. Salient information from the conversations was extracted and analysed to reveal the causes of such perceptions. Also, potential mitigation strategies regarding each causation were discussed. Only by comprehensively understanding these perceptions can researchers, engineers and policymakers work together to ensure that a positive consensus is reached. Eventually, the general public can start to build positive perceptions and trust of the HFCV safety through the leadership of this professional group.

3. Methodology

Since this study investigates the insights of the emergency responders' perceptions, a semi-structured interview approach was used to collect focused and rich descriptive information from the Fire and Rescue Service of people based on their experiences. This approach can balance the focus of specific questions and the flexibility of an open-ended interview, and thus, suitable for the early exploring stage of the research domain.

3.1 Interview design

The interviews are conducted by the same interviewer using the same language for consistency purpose. All questions were carefully designed to prevent participants from giving a preconceived perception of any specific procedures. Also, the words and terms used in the questions were carefully selected to match the participant's understanding and knowledge. Any questions with a strong positive or negative association were deliberately avoided. The survey focused on the following topics:

"*What is your perception of the HFCV?*"

"*What safety concerns or risks that you see when dealing with them?*"

"*What could be your preferred way to mitigate these concerns?*"

Then, follow-up with additional questions according to participants' responses was made to facilitate further discussion.

3.2 Pilot study

Before the formal interview, a pilot study was conducted to determine whether there were any potential biases or inappropriate wording of the questions. The finalised interview was then modified and improved accordingly. The pilot study involved two Ambulance personnel, one Fire and Rescue personnel and one ex traffic Police Officer. The outcomes of this pilot study were as following:

- Due to the unnecessary nature of the ambulance service job, they had no special requirements and perceptions for the future safety of hydrogen vehicles.
- Service location influences their experience and urgency of relevant training. Thus, formal interview participants should be recruited from different areas to obtain a comprehensive view, especially from areas where hydrogen-powered buses were already operational such as London and Aberdeenshire.
- The Police Service primarily ensures public safety by securing the area before the Fire Service arrives or instigating appropriate cordons for the safety zone – something the Fire Service is not empowered to do. Hence, hydrogen-related knowledge is also unnecessary at present.

Therefore, the pilot study indicated that the FRS plays a crucial role in the event of accidents, including (but not limited to) handling of hydrogen-powered vehicles in post-crash settings. They are the one organisation that work next to the hydrogen-powered vehicles in such post-crash scenarios. For this reason, it was decided to focus the formal participant recruitment on the firefighters as it was established that they could provide information-rich cases when talking about perceptions of such vehicles. This recruitment technique is also known as *purposeful sampling*.

3.3 Data collection and analysis

Since the prior knowledge regarding the FRS 's perception of HFCV is limited and fragmented, it was determined that inductive content analysis would be the most appropriate approach to use because codes and themes are generated from the collected data directly. It was intended that clean verbatim transcription would be created for each interview and transcriptions would then be coded at the sentence level systematically

to generate themes. The themes that emerged form the foundation of the analysis and are discussed in the following section.

The sample size was determined using the concept of data saturation. This concept was first introduced in the qualitative research area and it refers to situations when no further data can be found to enable the development of a new additional theme or category. Hence, the number of themes or conceptual category is 'saturated'. For a study using a purposive sample, Guest *et al*. suggested that the initial elements for meta-themes can emerge as early as 6 interviews, and data saturation tends to occur within 12 interviews [24]. The following steps are therefore followed in this study:

Step 1: Six interviews are conducted and coded initially.

Step 2: Further interviews are coded immediately after each interview. When there are 3 continuous interviews with no new themes generated, then that is the point to be considered the data saturation point.

Step 3: Another set of three interviews will be conducted to validate this saturation point.

Step 4: If there are no new themes generated from the validation interviews, then the data saturation point is validated, and further interviews can be stopped. Otherwise, Step 2 and 3 will be repeated.

Finally, the data validity is also achieved by obeying the same transcription and coding rules. The quotes of individual participant's responses are also presented to minimise the occurrence of any further scepticism and to maximise the transparency of the results.

4. Results and Discussions

4.1 Participants' characteristics and generated themes

Figure 1 indicates the accumulated number of generated themes after each interview. The number of generated themes is stabilised at 19 between the 5^{th} and 7^{th} interview. A further set of three interviews (8^{th} to 10^{th}) was conducted to validate these generated themes. As a result, ten interviews were conducted, and this sample size is also in line

with the literature [24].

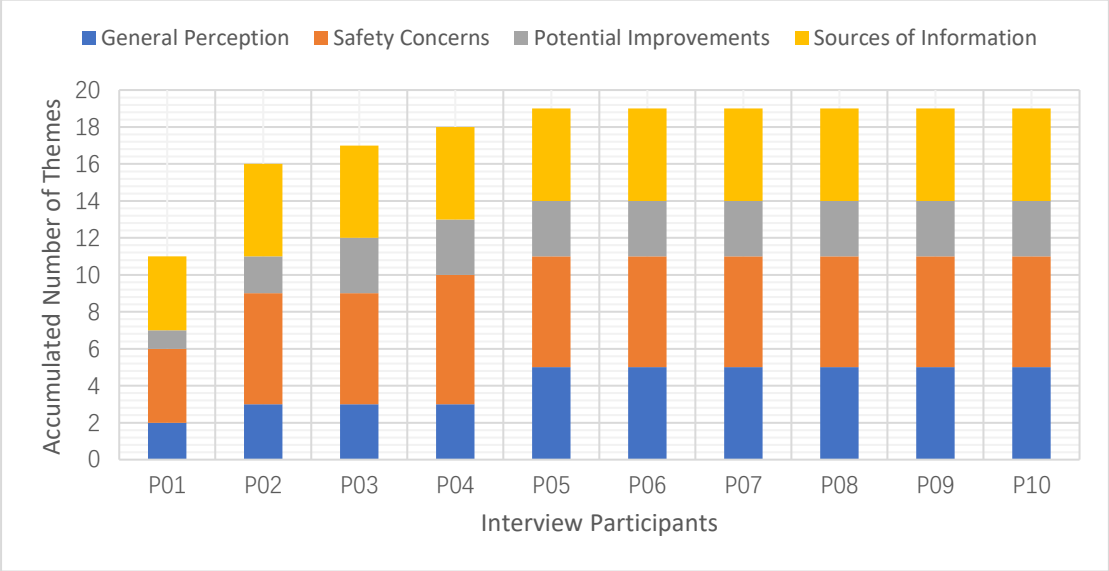

Figure 1: Accumulated number of themes after each interview

The characteristics of these 10 participants are shown in Table 1 below. For data protection purposes, detailed service stations and their actual roles are deliberately not provided. Instead, the traditional rank system is used to reflect their status within the U.K. Fire and Rescue Service. The participant sample has good distribution in terms of rank and service duration. Although these participants come from a limited region of the U.K., they had experienced working in various other regions within their service duration. Some of them are currently even working at a national level in terms of their duties. Hence, the overall sample is sufficient to fulfil the requirement of this study.

Table 1: Characteristics of the participants

	Age	**Service duration**	**Current Rank (1 to 10)**	**Service Region**
P01	50-59	30 years and above	Rank 9	West Yorkshire
P02	40-49	10 - 19 years	Rank 5	Greater London
P03	50-59	30 years and above	Rank 6	West Yorkshire
P04	50-59	20 - 29 years	Rank 4	East Yorkshire
P05	30-39	10 - 19 years	Rank 5	Greater London
P06	50-59	20 - 29 years	Rank 6	East Midland
P07	40-49	20 - 29 years	Rank 9	West Midland
P08	40-49	10 - 19 years	Rank 5	East Midland
P09	30-39	10 - 19 years	Rank 4	West Midland
P10	40-49	20 - 29 years	Rank 6	Scotland

These 19 generated themes are divided into four meta-themes, as mentioned in Figure 1. The first three meta-themes (General Perception, Safety Concerns and Potential Improvement) are associated with each of the questions mentioned in Section 3.1. The last meta-theme is "Sources of Information", which contains every mentioned media from which the participants gain hydrogen knowledge. This meta-theme is very important to facilitate the Discussion section. Table 2 below is the codebook that defines each theme and provides some exemplars.

Table 2: Codebook for each generated theme with sample quotes

Theme	Definition	Exemplar(s)	Occurrence (n=10)
Economic cost	This theme comments on the cost to the business if things went wrong	"It'd be an issue [leak/fire] because of the cost of things to try and replace it [hydrogen storage tanks in facilities]. And obviously, no developer or owner of that business would want to just see all their money literally go into the air. "	10%
Lifecycle concerns	This theme covers consideration of the H2 lifecycle chain, from end to end	"I'm also aware of the efficiency issues around producing pure hydrogen, the efficiency of transportation and storage as well. " "What I need to understand is what happens to them [HFCVs] from the cradle to grave."	20%
Comparison with other AFVs	This theme includes the discussions of the pros and cons of HFCVs compared to AFV but excludes the environmental aspect	"Out of all the alternative fuels available on the market, hydrogen seems to be the one that best suits the way we currently use motor vehicles."	30%
Environmentally Friendly	This theme covers the considerations of the environmental concerns	"Hydrogen is almost that perfectly virtuous green circle."	40%
Contradiction	This theme covers the considerations of the contradiction about the HFCVs	"BMW started this kind of stuff [training] in California with the hydrogen power vehicle. That's how the education we have got and had the contradiction with them [HFCVs], and we knew they [HFCVs] are going to come into the U.K. "	30%
Thermal runaway	This theme includes the discussions of the battery fire, especially Thermal Runaway	"If that lithium-ion battery is abused, overcharged, poorly managed, or subject to mechanical shock, it can enter into thermal runaway and ignite."	30%

Hydrogen flame	This theme refers to participants' concerns with the ignited hydrogen gas and its natural properties	"Probably many firefighters don't know, hydrogen burns differently in a different way, and that's the awareness that we need." "The risk of the release of hydrogen - obviously talking about the flammability range."	60%
Electric concerns	This theme includes the discussions of all other electrical concerns, except the thermal runaway	"For me, that's quite difficult [to] isolating the vehicle. It's always quite stressful for us because we're never completely sure about how to do it" "The cables we are cutting, that's the big one [concern]."	70%
Onboard Hydrogen system	This theme refers to the concerns regarding the vehicle's hydrogen system, includes the storage and pipelines	"My concerns was to go to an incident involving a hydrogen vehicle would obviously be: how well constructed those pressure vessels, how likely are they to rupture because obviously that is going to cause injury to my crew,"	90%
HFCV safety mechanism	This theme covers the discussions of the HFCV safety mechanism that may affect the rescue operation	"A lot of manufacturers got in this 12V plug, so if a car is going in a crash, the 12V plug can isolates the high voltage circuit or the direct current it involves." "I don't think it's been an incident with a hydrogen vehicle, but there has certainly been in situations with petrol fuelled cars where a tank has erupted whilst the firefighters have been right next to it, and it exploded."	70%
Potential scenarios	This theme comments on the concerns of certain scenarios that firefighters may come across	"Properly the worst scenario we could come across - A road traffic collision in a tunnel which leads to a hydrogen leak, which can't disappear into the atmosphere." "However, a [Hydrogen] vehicle could be on its side etc. This is one problem."	70%
R&D involvement	This theme comments on the potential involvement in the R&D of the HFCVs	"And actually, the only way that I'd like to improve that is by going to production centres and speaking with the manufacturers and engineers that deal with the safety systems and what their expectation of fire services are." "It would have been really good if we [firefighters] were involved in the design stage."	60%
HFCV identification	This theme comments on the identification of the HFCV details, which may enable a safer work environment for firefighters	"Maybe something that would quickly identify it [the HFCV]; Maybe it [identifier] is an insert into quick guide, or a label in the right place"	60%

Comprehensive training and education	This theme includes the discussions of all aspects regarding sufficient knowledge and training improvements	"We would need to have some of these vehicles [HFCVs] that we can cut into small pieces." "I think it's knowledge about: how the systems operate and what systems are in place and what we need to do in terms of a protocol to de-energise the system,"	100%
Daily Experiences	This theme refers to the knowledge being gain through daily works and experiences from themselves and their colleagues	"They [firefighters] like cars, so they'll talk about their own cars, other people's cars and the cars that they find out at an RTC." "Every officer that attends an RTC shows in an incident monitoring form gets sent to our operational assurance team"	40%
Dealership and Manufacturers	This theme refers to the knowledge pass to them from the dealership and manufacturers of the vehicle	"I had some preliminary discussions down with the Society of Motor Manufacturers and Traders where they're just talking about their approach to alternative cell vehicles and how they would work."	20%
Non-specialist media	This theme refers to the knowledge being gain from various non-specialist media, such as T.V. programmes	"I remember seen a television program in the U.K, called Tomorrow's World, and it about 20 years ago or more"	40%
Professional organisations	This theme refers to the knowledge being gain from various professional organisations within the Fire and Rescue Service sector	"There is some very basic guidance in our own fire service NOG [National Operational Guidance] about that." "We [UKRO] did a couple of [competition/event] with BMW hydrogen vehicle. And all the things and knowledge are competed, not only knowledge."	60%
Auto shows/Auto conferences	This theme refers to the knowledge being gain from relevant Auto event	"I've had an opportunity to have a look and drive one of the Toyota hydrogen-vehicles at one of the conferences that I attended."	10%

4.2 Fire service perception vs Public perceptions

Five themes were being generated from this study with respect to the FRS's perception of the HFCV on a macroscopic level (i.e., *economic cost*, *lifecycle concerns*, *comparison with other AFV*, *Environmentally friendly* and *Contradictions*). It can be seen that the perception of the Fire and Rescue Service is different from the public perception (mentioned in the literature), although some similarities are shared.

Environmentally friendly is a theme shared and agreed by the FRS and the public.

Both groups of people see the HFCVs as a promising solution to cope with future green transportation due to their zero-emission characteristics. In addition, the participants of this study also considered that the longer mileage capability of the HFCV would fit into the current driving behaviour better than battery electric vehicle. Similar perceptions also appear from the public group when a comparison was made to other AFVs (Alternative Fuel Vehicles).

The *economic cost* is an aspect mentioned by both groups of people, but it was interpreted in a slightly different way. The public tends to consider the cost of purchasing and maintaining such vehicles, whereas the FRS tends to consider the cost to the local business. *Participant **5*** addressed this point using an electric vehicle accident in London as an example:

> *"We [FRS] need to think about business continuity within London. For instance, if an electric vehicle has a car crash or an RTA (Road Traffic Accident) in the middle of London, [then] how long can we keep those roads in the city of London closed to ensure that it doesn't burst into fire and that sort of thing. If that period is too long, then it starts to have an effect on businesses because of the closures of roads."*

Because an HFCV is driven by an electric motor, therefore, the same concern is valid to them. These questions need to be answered in the context of the HFCV.

Moreover, the Fire and Rescue Service has *lifecycle concerns* regarding the HFCV disposal at the end of its product life. This is because lessons learned the hard way from fires in waste sites caused by inappropriate handling of lithium-ion batteries. In 2021, the statistics showed an estimation of 201 lithium battery fires in waste sites a year at a cost of hundreds of millions of pounds worth of damage to the U.K. economy [25]. Such incidents are becoming a growing concern in the FRS. It is not difficult to predict that the inappropriate handling of the used HFCV parts (e.g., Fuel Cell stack or hydrogen tank) may present an even greater risk to firefighters if there isn't enough information or good operating practices guidance. That is why *Participant **7*** said:

> *"what I need to understand is what happens to them [HFCVs] from the cradle*

to the grave when we talk about the chain of the hydrogen [vehicle]."

The *contradiction* is a unique theme that rarely appears in public perception studies. Even within the Fire and Rescue Service, this theme is only mentioned by participants (Participant 2, 3 & 10) who work more on the practical side. They either participate in preparing relevant guidance or were trained to be prepared for future incidents. The following statements are direct quotes from them:

Participant 2: "If I turned up to one of these, I would be quite anxious, to be honest with you. I'd be quite anxious about that battery at the back [next to the tank]."

Participant 3: "BMW started this kind of stuff [training] in California with the hydrogen-power vehicle. That's how the education we have got and had the contradiction with them [HFCVs], and we knew they [HFCVs] are going to come into the U.K."

Participant 10: "Back to what I said earlier, people are totally trained, but everybody is kind of nervous about electric vehicles and hydrogen [vehicles]."

Interestingly, those less engaged in the practical side are also exposed to the same HFCV-related materials (except the on-site training part). However, this group of people has not contributed to the contradiction theme. In the following section, a more in-depth discussion of this phenomenon will be conducted to reveal its causations.

4.3 Firefighters' safety concerns on the HFCV

First of all, six themes were generated from the interviews regarding the safety concerns on the HFCVs. Of these themes, 2 of them were fire-oriented (i.e., thermal runaway and hydrogen flame) and 3 of them were rescue-oriented (i.e., Electric-related concerns, onboard hydrogen system and HFCV safety mechanism), and the last theme (i.e., potential scenarios) considers specific incidents scenarios that they often attend. Nowadays, firefighters tend to deal more with rescue missions than pure fire missions, so it is not a surprise that more rescue-oriented themes are generated than fire-oriented themes. This is also a sign that the FRS has more concerns on the rescue aspect of an HFCV than the fire aspect.

Participant 6: "We probably attend more RTA's in the year than we do fires, because of the fact that there are so many vehicles on our roads. They do have accidents more regularly than houses catch fire."

4.3.1 Fire-oriented concerns

The most prominent fire-oriented concern in the context of the HFCV is the invisible *hydrogen flame*, and it was mentioned by 60% (n=10) of the participants. There is a risk of being inadvertently in contact with the flame when the firefighters cannot see the hydrogen burning.

Participant 2: "the problem for hydrogen is you can't see it."

Participant 4: "most firefighters won't be aware of that [invisible flame], so that's a significant risk that we need to consider."

Besides, the chemical nature of hydrogen means that it burns differently compared to current petrol/diesel fuel or house fires. Considering the HFCVs, the onboard safety mechanisms (e.g., Thermal Pressure Release Device (TPRD)) could even deliberately start a discharge process in a controlled way to prevent catastrophic tank failure. This controlled discharge could be developed into a fire which is beyond the firefighters' existing knowledge.

Participant 1: "when it is burning in a controlled way, people wouldn't understand how to deal with it."

In addition to the hydrogen flame, participants consider the risk of a *thermal runaway* since an HFCV powertrain also consists of a large battery pack. Nowadays, thermal runaways have become a growing issue to the Fire and Rescue Service because of the increased number of electric vehicles on the road.

Participant 2: "Lithium-ion batteries for us (the U.K. Fire & Rescue Service) are a source of growing concern for all kinds of reasons. And sitting next to a hydrogen cylinder like that, I would be quite concerned lithium-ion batteries can enter into thermal runaway."

4.3.2 Rescue-oriented concerns

Regarding an accident involving an HFCV, the most prominent theme concerns the *onboard hydrogen system*. This theme is mentioned by 9 out of 10 participants and is

centered around the containment of hydrogen fuel. The integrity loss of the hydrogen tank could cause a hydrogen leakage which can be the beginning of a hydrogen flame or explosion. Besides, the residual hydrogen within the pipelines could add extra risks to firefighters during rescue missions (e.g., during cutting operation)

> *Participant **3**: "I actually feel things like tank and pipes are pressurised, what's the explosive risk there? If you consider the airbags and the gas cylinders, you are looking at few hundred bars of pressure when it is coming out."*
>
> *Participant **9**: "The risk of the release of hydrogen - obviously talking about the flammability range."*
>
> *Participant **10**: "If it was an RTC, it would be lost to containment [that] obviously would be a concern."*

However, the only participant who did not have such concern was *Participant **1***. He proactively searches for hydrogen vehicle knowledge via various channels. Hence, he has a better understanding and confidence regarding the HFCV technology.

> *"I would guess, and I would hope that my understanding [of HFCV] is a little more advanced than some [firefighters], rather than many [firefighters]."*
>
> *"I am very relaxed about the issues that most people would jump to, which would be a sort of hydrogen explosions."*
>
> *"I am fairly assured by the safety mechanisms for that."*

Moreover, *electrical-related concerns* are mentioned by 70% (n=10) of the participants. The focuses for this theme are "isolation" and "high-voltage circuit", which is no different from concerns about current electric vehicle (e.g., Nissan Leaf/Tesla S). Hence, the Fire & Rescue Service is more familiar in dealing with the electrical aspect of the HFCVs.

> *Participant **6**: "The biggest risk factor to the service is obviously: in relation to electric shock because it's still relatively new technology in relation to the fire service attending incidents with electric vehicles."*
>
> *Participant **8**: "It is a case of as long as these folks [HFCV], are the same as electric cars, that we have to make sure we can isolate the batteries and the*

power from the drivetrain motors so that there no chance it can move."

Finally, the *HFCV safety mechanism* is another frequently appeared theme, which is mentioned by 70% (n=10) of the participants. During the interviews, the participants often recall their experiences about the conventional vehicles to facilitate their concerns about the HFCVs, because most of them do not have actual experiences with the HFCVs yet due to limited number of such vehicles. The key finding is that the safety mechanism must be reassured they could be fully functioning under all circumstances. Plus, it would be even better if such mechanisms are designed with firefighters' personal safety in mind.

Participant 6: "With an RTC, generally, it's their [vehicle's] safety mechanisms within them that cause firefighters harm."

Participant 7: "Our traditional approach is a firefighter leans into the vehicle and maintains neutral alignment. If there is a curtain airbag running across the top of that and goes off, we've lost a firefighter very, very quickly."

4.3.3 Scenarios concerns

In addition to the above themes, the interview analysis also revealed another phenomenon worthy of attention, referred to as scenario *concerns*. This theme is mentioned by 70% (n=10) of the participants. Due to the current scarcity of the HFCVs, none of the participants had experience handling an HFCV accident under real-world situations. Therefore, when talking about the HFCV perception and concerns, they recalled RTC events from their past experiences to facilitate the discussion regarding the HFCVs. From the interviews, it could be seen that none of the concerns mentioned are new to the Fire and Rescue Services as pressurised vessels, electric motors and high-voltage circuits have all existed for decades. In general, firefighters are capable of applying effective control measures when dealing with any of them individually. However, firefighters don't normally come across all of them together in one compact space (i.e. a vehicle).

Moreover, the existing countermeasures shown in the literature are based on the fact that the hydrogen vehicle has all four wheels on the ground and no occupant rescue

is required. However, an actual RTC event could be much more complicated than that. Hence, firefighters' perception and concerns of the HFCVs consistently links with the practical elements.

> *Participant 7: "it [HFCV] is 4 wheels on the ground. You have the side view, top view, very nice and lovely. However, a vehicle could be on its side etc. and this is one problem."*
>
> *Participant 9: "To larger high-speed crashes, obviously, the more speed energy, the greater the damage, the greater the deformity to the vehicle when it comes to rest, and the stranger the position it is going to come to rest in."*

4.4 Demand for supplementary support to firefighters

4.4.1 Comprehensive training and education

The demand for *comprehensive training and education* is mentioned by 100% (n=10) of the participants. All of them would like to be fully prepared by the time HFCV transportation becomes realistic. The information they would like to gain from this training can be divided into two categories. Category One is the fundamental level of knowledge that provides firefighters with a basic understanding of hydrogen flame behaviour, vehicle structure, and safety mechanisms.

> *Participant 4: "I think it's knowledge about how the systems operate, what systems are in place and what we need to do in terms of a protocol to de-energise the system."*
>
> *Participant 5: "Fire engineering department to effectively work out the energy that's created by burning lithium-ion battery and what kind of flow and pressure of water to try and put it in"*

Category Two is more on the practical side related to their familiarity improvement when dealing with the HFCVs.

> *Participant 8: "And that [pressurised parts] needs highlighting, because of we've got the big cutter, spreaders, things like that, and we just take the car with those. The last thing you want to do is to cut through a pressurised vessel or pressurised feed line or a high voltage cable."*

4.4.2 HFCV identification

HFCV identification is a theme mentioned by 60% (n=10) of the participants. Firstly, the firefighters need to quickly identify whether a vehicle is powered by hydrogen or not, which triggers their relevant awareness of potential risks. Nowadays, HFCV manufacturers commonly have a "hydrogen" label at the back of their vehicles in various format, and some of the models also have the label in the door frame. However, no standard addressed the labelling of the HFCV is mentioned in the literature (section 2.3). In addition, the existing labelling method may not be fully functional under specific scenarios, and hence, cause a significant risk to the firefighters.

> *Participant 5: "A big risk for us is because there's no hazard marking for, say, "a van transporting a lot of [HFCVs]", we've got no way of knowing or no one would identify the van as a [HFCV] because it isn't a [HFCV]."*
>
> *Participant 8: "Like in terms of a vehicle fire, any labelling is probably going to have gone."*

In addition to the vehicle identification, firefighters also would like to clearly identify the state of every vehicle component, whether they are deformed under collision or being replaced.

> *Participant 2: "the technical specification might say nickel-cadmium or nickel-metal hydride [battery], but what can happen is the owners or garage mechanics can sometimes change that battery [to other types]."*
>
> *Participant 3: "you scan the Q.R. code, and it tells you everything about the vehicle - where you can cut and what it is involves in like that."*

4.4.3 R&D involvement

R&D involvement is another theme mentioned by 60% (n=10) of the participants. Considering the Fire and Rescue Service as a whole, it needs to have sufficient information to provide the comprehensive training mentioned in section 4.4.1. Currently, the Fire and Rescue Service is playing catch-up with the fast development in the transportation sector, and the FRS is running behind.

> *Participant 10: "It's very difficult. I'm kind of labouring in the dark a little bit*

here, because the information available to us as a frontline emergency worker is very limited."

It would be very beneficial if the FRS can be involved in the design stage and express their expectations of the vehicle. In other words, the FRS and the manufacturers can understand each other's need and design with them in mind so that no one is left behind when hydrogen transportation becomes realistic.

Participant 7: "It would have been really good if we were involved in the design stage. And yes, you can use boron steel, but we have to change our equipment here to be able to cut boron steel."

4.5 Sources of information

Currently, relevant knowledge and skills regarding the HFCV fires or rescues are not a compulsory part of the firefighter's training package, and thus, it depends on the individual's wishes. Figure 2 show the concerned frequency of each mentioned information channel by the participants.

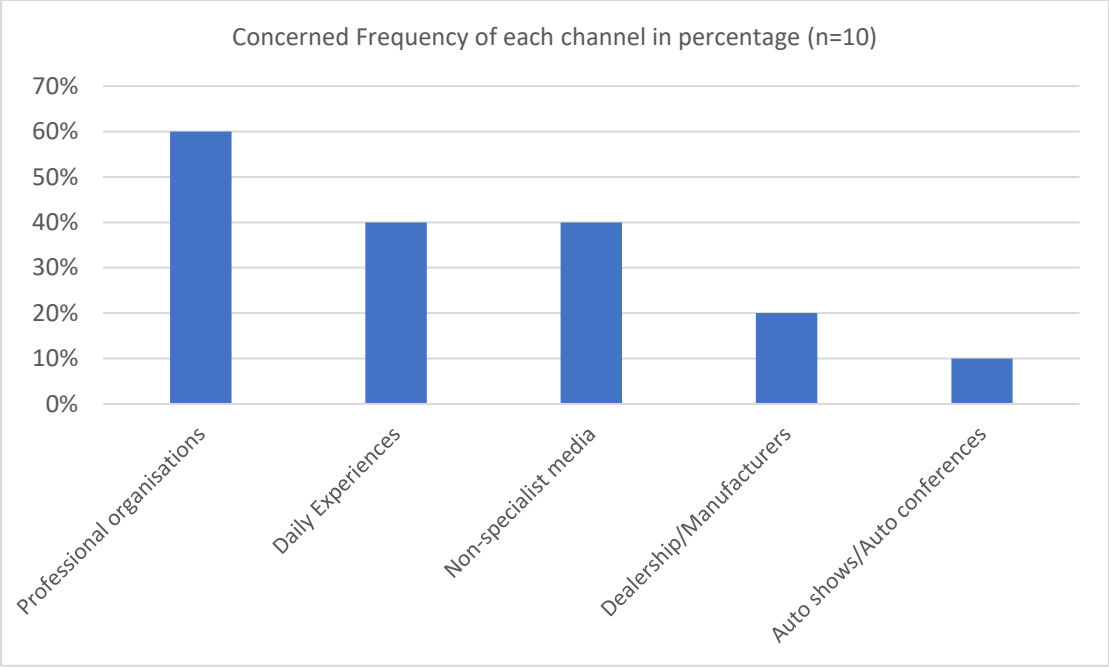

Figure 2: Information channels mentioned by the participants, rated from high to low

It indicates that most of the participants (70%) claim that relevant knowledge comes from professional organisations, such as the UKRO (United Kingdom Rescue

Organisation) and NFCC (National Fire Chiefs Council), although these organisations currently have limited resources. Also, 60% (n=10) of the participants state that HFCV knowledge was gained through their daily work experiences and other non-specialist media (e.g., T.V. programmes). Only a limited number of the participants proactively went to the dealerships (20%) or relevant conferences (10%) to seek the most recent information regarding the HFCVs.

It can also be seen that available HFCV information to the FRS is fragmented. Hence, it would be difficult for individuals to gain a comprehensive understanding of the HFCVs. Their level of knowledge varies depending on the actual information sources, their enthusiasm /attitudes, urgency of needs, and service time. Besides, the most referred channel (Professional Organizations) holds the tiniest information. Participant 1 is the only participant who went to an automotive conference to understand the HFCV better and even had a test drive on an HFCV (i.e., Toyota Mirai). Thus, he is the only participant who has not addressed the "*onboard storage system*" theme and can claim to have more confidence (see section 4.3.2).

4.6 Recommendations for changes

This study has unveiled the difficulties the Fire and Rescue Service is currently facing. If these difficulties remain unsolved, then the implications for hydrogen transportation will be negative, and the trust and usage of the HFCV will likely be low. However, these difficulties can be solved in part or full. Recommendations are discussed at two different levels – individual and organisational level, in the following paragraphs.

Firstly at the individual level, firefighters know which aspect may become potential hazards and affect their safety and know what knowledge is needed to mitigate these issues. However, they do not know where to obtain this necessary knowledge or whether the necessary knowledge exists.

For instance, participant 2 has concerns that the Lithium-ion battery pack may cause a thermal runaway, which may damage the nearby hydrogen tank. However, in reality, some manufacturers already use Ni-Mh battery to mitigate the risk associated with Li-ion battery. Furthermore, firefighters would like to understand the general

hydrogen flame behaviors and their potential consequences in HFCV cases. Again, hydrogen safety engineers had already addressed such concerns and presented them in academic journals [8], [26], [27]. Also, some firefighters consider the risks associated with the pressurised pipelines in an HFCV. Whereas, in reality, the onboard safety mechanism can pull all hydrogen back into the tank. Then, the tank will either be sealed or will discharge the remaining hydrogen in a controlled manner. This information already exists but it is not known by those who need to know it.

Therefore, the problem is that the relevant knowledge has not been made easier for the individual firefighters to access. Hence, the first recommendation is to extract this salient information from various related sectors and integrate them into the existing training package. This action would be the most cost-effective way to provide firefighters with the basic level of awareness and knowledge they need, thus partially mitigating their safety concerns.

In order to fully mitigate safety concerns, firefighters need to have sufficient practices which involve dismantling and cutting multiple HFCVs. This action would not be realistic without tremendous support from the vehicle manufacturers. Hence, effective collaboration work is necessary at the organisational level between the Fire and Rescue Services and the manufacturers. Besides, it would be mutually beneficial for both the FRS and the manufacturers at the organisational level. A group of professionals from the FRS could act in an additional consultation capacity and could be involved in the design of the HFCVs. This action provides the opportunity to fully understand the HFCVs at the component level and ensure the designed safety mechanisms meet their expectations.

On the other hand, the manufacturers can market the fire service involvement as a unique selling proposition (e.g., FRS approved HFCV). Since the FRS already provides fire safety consultation to the building industry, it would also be possible to apply a similar procedure to the emerging HFCVs. Moreover, the FRS's reputation from the past can also enhance public acceptance and trust in such vehicles.

Finally, the collaboration work between the FRS and research institutions also play

a crucial role. Research can reveal the root causes of any safety concern and provide sufficient counter measurements to address them. Researchers can fill the knowledge gaps between the developed hydrogen technologies and the realistic scenarios that the firefighters attended, thus changing the way that firefighters work into a safer one.

5. Conclusions

In this study, ten interviews were conducted, and participants responded from various service locations and ranks within the U.K. Fire and Rescue Service. It has been found that the FRS have a different perception of the HFCV in terms of the economic cost and contradiction when compared to the previous public perception studies. The FRS interprets the economic cost as the potential negative effect on the local business continuity. In contrast, the public tends to consider the purchase and maintenance cost as the economic cost.

This study also revealed the contradiction of the HFCVs. This theme has never appeared in previous studies. The public has the chance of not using the HFCVs if they are not satisfied with them, whereas the firefighters do not have the choice. Further analysis of the interview data leads to emergence of 6 different kinds of safety concerns. Of those, two are fire-oriented, three are rescue-oriented, and one considers the knowledge gap between the laboratory situations and the realistic situations they often attend. The firefighter understands electrical-related safety concerns relatively well together with associated counter-measurements previously mentioned in the literature. However, although counter-measurements for hydrogen-related hazards also exist it has been found that these kinds of knowledge have not been passed to firefighters effectively. The majority of the firefighters still have a significant knowledge gap when considering the hydrogen aspect of the HFCVs. This phenomenon indicates the lack of communication and insufficient information sharing between the FRS and other relevant sectors.

However, there are positive findings. This study shows that existing literature is sufficient enough to address the fundamental knowledge gap in terms of hydrogen fuel

and its flame behaviours, although the relevant literature occurs in fragmented pieces among various sectors. Moreover, professional organisations (e.g., UKRO and NFCC) appeared to be the most prominent channel for the firefighters to gain relevant knowledge, as mentioned by 60% of the participants. This means collaboration works can be carried out at the organisational level by experts from both the industries and the FRS. Then, relevant guidance and documents can be created and eventually passed down to individual firefighters effectively via these professional organisations.

5.1 Political implications

In order to resolve FRS's concerns on the HFCVs, a large amount of public funds and investment from the automotive industry will be required. Suppose the policymakers and the FRS do decide that the purpose of the investment is to resolve the FRS's concern and enhance the public acceptance of the HFCV. In that case, the funds should be targeted to solve the lack of communications and knowledge sharing among the vehicle manufacturers, academia and the FRS, in the early stage of the investment. By doing so, the investment may bring more significant benefits within a relatively short period. In addition, the investment and support from the vehicle manufacturers could appear in the form of unwanted test vehicles and salient information regarding the design and safety mechanisms of their HFCVs. This could be another cost-effective way to solve the problem.

5.2 Limitations of the study

It is worth mentioning that this study was conducted during the 2020-21 SARS-CoV-2 pandemic, and the Fire and Rescue Service were stretched to their limit. Hence, the recruitment process became even more complicated with these hard-to-reach professionals. Although the number of participants satisfies the theoretical requirement [24], the sample could be more representative if participants are from each U.K. county. Furthermore, the participants may have some biases towards hydrogen transportation. For instance, supportive experience bias may exist. This would mean that the participants may hold affirmative views of the HFCVs if they had a positive experience with them and perhaps negative views if they had experienced unpleasant

circumstances. Future studies should look more into their past experiences in order to address this bias. Finally, the firefighter is just a part of the emergency responder's team. Future studies should also include the perception of the HFCV from the ambulance staff and the police team. The joint operation procedure needs to be considered as well.

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