Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces

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Report on existent strategies and tactics for first responders

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Summary

The aim of the present deliverable is to perform a critical analysis of existent strategies and tactics for the intervention in case of incidents with hydrogen driven vehicles. To do so the deliverables from HyResponse project and leaflets by car manufacturers (have been reviewed). The report concludes that the information provided is much too extensive for the education and training of emergency services. Thus, the huge amount of existent strategies and tactics must be downsized to a few pages of background knowledge and one sheet of paper with short and precise Standard Operating Procedures (SOP). To condense the existent information criteria are needed to decide which information to provide and which not. The present report defines as main criteria the usefulness of information under the perspective of emergency services. Information is useful in this sense if it is relevant, reliable and available for the emergency personnel at the scene.

All existent strategies and tactics recommend special measures to be taken if hydrogen is involved. Thus, the information "Hydrogen-incident!" is the most relevant information as it induces special procedures. The existent strategies and tactics do not show how to get this information for sure. The best solution might be to provide this information via the Vehicle Information Number (VIN) which gives access to all relevant information about the vehicle. Therefore, and as a first important result of WP 5, the VIN should be sent to the emergency services automatically.

Some of the existent strategies and tactics require a lot of knowledge on hydrogen-specific (HY-)issues, complex decision-making processes or even situational information which will not be available in a reliable manner at the scene. Much more useful are plain and precise SOPs which match each and any HY-situation. One potential SOP could be to vent the range of operation before any other action is taken.

SOPs are based on scientific knowledge and they include strategical and tactical issues made before(!) an incident occurs. The present report lists the information needed for this basic work as well as questions which should be clarified by the scientific community, e.g. whether provision of ventilation may reduce the risk of an explosion in case of hydrogen leak in a confined area but never increases that risk.

Keywords

Hydrogen safety, first response, standard operation procedures, ventilation, tactics, strategies, HyResponse, Vehicle Identification Number VIN

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Nomenclature and abbreviation

CNG	Compressed Natural Gas
HPV	Hydrogen Powered Vehicle
HY	Hydrogen
HY-SOP	Standard Operating Procedure for HY-incidents
LEL	Lower Explosive Limit
LPG	Liquefied Petroleum Gas
SOG	Standard Operating Guidelines
SOP	Standard Operating Procedure
TPRD	Thermally activated Pressure Relief Device
VIN	Vehicle Identification Number

Definitions

Emergency Services: Organizations which ensure public security and safety by addressing emergency situations, in the HY-context mainly fire services.

First Response: First actions taken at an incident scene; in the HY-context mainly by police, ambulance services or fire services. First response by laymen is not discussed in the present report.

Incident is something that occurs casually in connection with something else.

Risk is the combination of the probability of an event and its consequence.

Standard Operating Procedures: step-by-step instruction to help perform complex operations.

List of tables

1. Introduction and scope

In the course of the project, harmonised recommendations on response to hydrogen accidents (Delivery D5.4) are to be submitted. They should be formulated as standard operation procedures (SOP) (cf. Stowell) or Standard Operational Guidelines (SOG) (cf. Angle et al.).

SOPs include fundamental strategical decisions; e.g. what risks emergency personnel may be exposed to. Such decisions differ within in the huge community of emergency services. Therefore, it should not be expected that certain SOPs will be used by all emergency services. SOPs include tactical decisions which depend on many factors that differ within the emergency services; e.g. legal framework, basic education, equipment. Therefore, the proposed SOPs are expected to be adopted by all relevant emergency services. SOPs are created for the purpose to reduce the burden of decision-making at the scene. Therefore, the number of SOPs should be kept at a minimum. Ideally there is one single SOP for the first measure that matches each and any possible HY-scenario. This is feasible indeed. Most fire services do have one single SOP for each and any case of a fire in a building (cf. Brauner et al.)

SOPs do not cover or even describe all actions to be taken. They give a step-by-step-instruction whereby the steps themselves are not explained within the SOP because they are well known for the emergency personnel. What really matters is the temporal sequence of the measures. SOPs or SOGs must be written in a simple and achievable way and practiced. (cf. Angle).

2. Procedure

The results of the project HyResponse (especially HyResponse D 6.3), as well as individual recommendations (cf. e.g. AGBF) and leaflets of industrial companies (cf. e.g. Tucson) and security organisations (cf. e.g. Wurster), were examined. It stands out that the content statements are largely identical. However, there are significant differences in the usefulness of the available literature for first responders, at least seen from a practical perspective.

The huge amount of information collected is much too extensive for the education of emergency services. Thus, all this information must be downsized to information that is needed to create SOPs and/or adopt them to an individual emergency service's need.

This requires criteria for the decision which information is need and which is merely nice to have. In order to be able to objectively assess the usefulness of individual publications as well as individual content statements, appropriate evaluation criteria were developed. Secondly, requirements for information for first responders were derived from these. Thirdly, the necessary information has been defined, and it has been examined which of this information is already available. Finally, it is listed which information or which open questions (if possible, in the course of the project) are still to be elaborated or clarified.

3. Evaluation criteria for the usefulness of the information

The first deployment in incidents with hydrogen-powered vehicles will be made mainly by rescue and fire services. Technical interventions on the vehicles and, if necessary, firefighting is carried out almost exclusively by the fire services. Therefore, these are to be seen as the primary target audience within the large group of first responders. In many nations, the rescue service is provided by the fire services; but here, too, measures on the vehicles are mainly seen as the operation of the fire service.

Initial deployments by the fire services are regularly under very high time pressure. Many tactical decisions have to be made within a few minutes, often even within seconds.

Decisions are made by combining different information, such as information about the incident and operational options, but also information about legal requirements, service regulations and much more. The more information is taken into account, the more well-founded a decision can be made, but the longer the decision-making process will take. In order to be able to make a quick decision, the amount of information to be processed must be reduced as much as possible. (cf., e.g., Jungermann).

However, if only the amount of information were to be reduced, there would be a risk that essential information would not be taken into account in the decision-making process. This results in the task of limiting the amount of information to be processed to the information relevant in the respective situation.

The quantitative reduction of information also reduces its redundancy. In order to be useful, the information must be not only relevant but also reliable.

Thirdly and finally, the information must be available at the time of making the decision.

Conclusion: In order to be useful during the deployment, the information (for the decisions to be made) must, therefore, be relevant, reliable and available.

4. Requirements for useful information

Subsequent requirements for relevance, reliability and availability of information are discussed.

4.1 Relevance of information

For incident commanders, only the information they need to make decisions is relevant. Which information is relevant in this sense depends solely on which decision is currently pending.

A simple example: Smoke billows from a residential building. The fire service arrives. The incident commander must decide: To first rescue victims or to first fight the fire? Because he does not (yet) have enough resources at the scene to do both at the same time.

In this decision-making moment, only a single piece of information is relevant, namely whether there are still people inside of the building. If the answer is clearly yes, he will command the rescue of people first, because every second actually counts here. If the answer is no, he will command to fight the fire. If he does not receive reliable information, he will decide situationally under probability assumptions and thus under high uncertainty. For example, people are significantly more likely to be in a residential building at night than during the day.

In order to identify which information specific to hydrogen incidents is relevant, it is first necessary to define an idea of the typical order of actions to be taken and decisions to be made in a hydrogen intervention process. This will be one of the tasks of the International Fire Academy in the further course of this project.

Many of the available information in the literature is not relevant for the first deployment, but for general operation preparation. This is because they can help to make cardinal decisions and derive the definition of general tasks for hydrogen incidents.

Conclusion: Information is relevant if it makes a difference for the decisions that have to be made next.

4.2 Reliability of information

In emergencies, all persons directly involved are more or less under stress, which can severely weaken mental and psychological performance. Statements of people (witnesses) under stress are therefore only partially reliable.

On the other hand, there is a high degree of reliability in scientifically proven findings, which can be used practically by fire services. Thus, the information that hydrogen flames are barely visible in daylight, but can be reliably detected by thermal imaging cameras, is a relevant and reliable information (in the case of a fire existing and for the task to fight this fire).

High reliability also has one-to-one information, for example, the indication of a very loud whistling noise from the people at the incident site. This is reliable information that a pressure vessel has leaked.

Conclusion: Most reliable is information from observations that can be made by the incident commander itself.

4.3 Availability of information

A lot of information could be useful for tactical decisions, but it is not, or at least not for sure available at the site under operational conditions. For example, first responders are provided with nomograms (that could be used to estimate danger range depending on the tank volume). In order to be able to use them, however, the incident commander then needs information about the actual tank content. However, this information will not be reliably obtainable on a regular basis.

Recommendations for action depending on the timing of the incident are also of little use, such as proceeding in a certain way when a vehicle fire broke out two minutes ago. Hardly anyone would have looked at the clock during the outbreak of the fire and taken the time.

In terms of availability, a distinction must be made between the initial deployment phase and later phases of an operation. In the initial deployment phase, only little relevant and reliable information will be available. The further the deployment develops, the more information can be obtained and, if necessary, experts can be consulted. This should not be further investigated here, because the necessary procedures are generally established and also cover hydrogen incidents, for example in the form of the technical accident information system TUIS of the German and Austrian chemical industry (VCI).

Conclusion: If it is defined which information is relevant and can be reliable it is to make sure that this information will be available for the incident commander.

5. Required information during the course of the deployment

Furthermore, the terms *conventional vehicle* and *conventional vehicle fire* are used for fires of vehicles with internal combustion engines and petroleum-based fuels. Hydrogen-powered vehicles are simplistically called *hydrogen vehicle* respectively *hydrogen vehicle fires*

The general task of the fire services is to ward off dangers. This always requires the following information:

- What is the danger?
- Who or what is in danger?
- How can the danger be reduced?

5.1 Information on existent danger

In the case of conventional vehicle fires, answering these questions is easy because the fire services have a great deal of experience in dealing with such incidents. What answers can be given and the general procedures are not further discussed here.

To investigate which hydrogen-specific information may be relevant, reliable and available for first responders, it is sufficient to consider the differences between conventional vehicle fires and hydrogen vehicle fires.

The main difference here is a significantly higher risk of explosion in incidents involving hydrogen vehicles compared to incidents with conventional vehicles, depending on the specific situation.

All the literature that has been reviewed, and in particular all the documents produced in the HyResponse project, describe great differences between conventional vehicle fires and hydrogen vehicle fires. In summary, hydrogen incidents must be at least partially approached differently from other incidents. And this starts already from the alarm. For example, it is recommended to approach with the wind during hydrogen incidents and not to cross a possible hydrogen gas cloud (cf. HyResponse D 2.3).

In order to make use - howsoever - of these recommendations, the emergency personnel need to know that this is a hydrogen incident.

Conclusion: The highest relevance has the information that it is a hydrogen incident.

5.2 Information on the risk of explosion

The specific properties of hydrogen necessarily give rise to the second question, namely whether there is a risk of an explosion or a container burst and which areas are endangered. Here we have to differentiate between these parameters.

Table 1: Parameters of risk of explosion

Parameter	Category of parameters	Subcategory of parameters
Types of incidents	Hydrogen vehicle fire	
	Hydrogen release without fire	
	External fire threatening a hydrogen vehicle	
Size of the vehicles	Passenger cars	
	Trucks, buses	
	hydrogen transporters	
Traffic areas	Outdoors	
	Small garages and workshops,	
	Parking facilities (cars only),	
	Road tunnels	single-tube,
		multi-tube,
		with longitudinal ventilation,
		with transversal ventilation,
		without mechanical ventilation
	Railway tunnels	single-tube,
		multi-tube,
		with mechanical ventilation
		without mechanical ventilation

Inquired here is the information as to whether the respective incident and the respective vehicle size in the respective traffic area can basically be an explosion hazard.

If this is the case, the information would be relevant for decision-making, since each procedure would be different.

Conclusion: Incident commanders need to know where there is a danger of explosion and where this cannot be the case.

5.3 Information on options of measures to ward off dangers

Basic options are evacuating, extinguishing or controlled burndown, venting and rescue and measurements as a supporting procedure. (There are many more actions to be taken e.g. water supply. As these are not hydrogen-specific standard procedures they are not being discussed in this report.)

5.3.1 Evacuation issues

As long as an explosion hazard cannot be ruled out or at least is classified as very unlikely, the next measure in the operational process will be to evacuate the danger zone.

In this case, general information about the required safety distance is required, ideally in the form of simple guidance rules which should refer to the categories given in Table 1.

In the case of an incident at a hydrogen-handling facility (production plant, warehouse, filling station and so on) the information needed might be given by operators and/or documents available. Basic information for such cases is given e.g. by the results from the HyResponse Project.

Availability of needed information will be quite different with hydrogen vehicle incidents. It will often be difficult to gain this information without sending emergency personnel into a potential danger zone.

To reduce the risk of emergency personal the following questions should be clarified:

- Is it correct that there is no risk of explosion if blowing-off gas is burning? If this is correct, then it may be correct not to extinguish such fires, but to allow controlled burning, in which the surrounding is constantly cooled, in order to avoid a fire spread. Up to know a clear-cut answer was not found in the literature although controlled burndown is recommended (cf. e.g. Tucson);
- How long will it take at maximum to burn all possibly existent fuel? The given value should be stepped according to vehicle sizes given in Table 1.

Conclusion: It should be clarified how big the risks of an explosion are during a controlled burndown.

5.3.2 Venting issues

The evacuation is one way of reducing the risk to persons (and, possibly, animals) from a potential explosion. The second option is to reduce the risk of explosion by venting.

Useful here would be information as to which ventilation measures can eliminate the risk of an (possible) explosion. Again, simple orientation rules would be helpful. If necessary, it has to be differentiated between fans powered by an electric drive, hydraulic drive with water or driven by internal combustion.

If it were identified that ventilation measures are suitable to quickly, with a high probability and also safely eliminate the risk of explosion, the operating procedures would have to be reconsidered in principle. It might be a good thing to start ventilation at least at the same time as evacuation, or even to ventilate instead of evacuating.

Conclusion: Ventilation should be considered as first action to be taken at the scene.

5.3.3 Rescue and measurement issues

The Emergency Guide for First Responders states: "Nevertheless, the rescue of human lives overrides all other considerations." This formulation does not conform to the usual principles of fire services in its absoluteness. It is true – and probably actually meant – that the rescue of human life as the highest value is a priority objective of all operational measures. However, this does not mean that all other considerations can be ignored. In particular, the risks to the emergency personnel must be reduced to the unavoidable level, even in the case of rescue operations. It is ethically indefensible to risk the life of one person in order to save the life of another person.

It is, therefore, necessary to examine (for all the incident situations given in Table 1) how the risks of the emergency personnel can be effectively limited. The findings to be gained here must then be taken into account in all decisions of the incident command.

Also to be discussed is the question of whether and how emergency personnel are used for taking measurements with mobile devices. Although such measurements are recommended as a standard procedure, it is not specified how to perform them in accordance with personal safety.

Measurements by the fire service with mobile measuring devices are a standard procedure that is not specific to hydrogen. Until now, the rule is that the fire service withdraws when it reaches defined limits (e.g. 25% LEL for hydrogen). This is at odds with the view that rescues should be carried out even in an explosive atmosphere.

This conflict must be discussed and resolved within the fire services.

As part of the project, it is necessary to clarify which measures are to be carried out depending on the results of the measurement or which are triggered by other indicators. This will determine the tactical significance of the measurement methods. This, in turn, results in possible standard rules of engagement and thus the required information.

Conclusion: Strategies and tactics must reduce emergency personnel's risks as well as to increase the chances of rescue.

5.3.4 Extinguishing tactics issue

In the literature and in the discussions among the project partners, there are conflicting opinions on extinguishing tactics. It is unclear on which side of the vehicle an attack is best. One recommendation is to attack from the side, but this can prove to be practically difficult, for example in road tunnels. The International Fire Academy will, therefore, prepare a special questionnaire on this topic and contribute it for discussion with the project partners.

6. Required information

The information required for the initial deployment always includes anticipated strategic and tactical decisions. For example, in the case of gas fires the decision will not be to extinguish the flame, but either to interrupt the gas supply or to let the gas burn off in a controlled manner.

If it has been decided that this should be done, the emergency personnel need, for example, the following information specific to a hydrogen fire:

- How can a hydrogen fire be clearly identified?
- Can the gas supply be interrupted (by oneself)?
- Can the fire be burned off in a controlled manner?
- If so:
    - How?
    - What is the necessary safety distance between the emergency personnel and the fire?

In order to answer these questions <u>in principle,</u> a great deal of information is required, some of which is available as a result of, for example, HyResponse project. During a deployment, however, these questions must be answered unequivocally. Then it gets possible to formulate a standard operating procedure. For example, in this way:

- Hydrogen flames can be detected with thermal imaging cameras.

- In vehicles, the gas supply cannot be turned off.
- Therefore, the gas has to be burned off in a controlled manner.
- Let it burn. Protect surrounding.
- Safety distance to the burning vehicle should be a least: x meters.

In addition to these, much more information is required, but it is not specific to hydrogen incidents, such as how to cool the surroundings of the fire. This information can be assumed to be given.

The difficult task, then, is to condense all the scientific information available today, and if necessary to be supplemented, into simple standard rules of engagement.

However, this reduction in complexity is not only a simplification of complex scientific and technical issues. It also includes decisions of very difficult ethical questions, such as for example, the risks that the emergency services may be exposed to. The information required for the deployment includes, for example, information about when to choose the tactical option of not attacking or giving up.

In order to define the information required in this sense, therefore, the standard procedures of engagement must first be further developed. As previously described, the question must be clarified of whether and, if so, how the risks at the scene could be effectively reduced by early overpressure ventilation measures.

This will be an essential task in the further course of the project.

The current state of knowledge shows the following situational and general information needs:

– type of drive,
– safety distances depending on defined scenarios,
– indicators for specific incidents,
– adequate ventilation measures,
– extinguishing tactics and technology,
– measuring techniques.

6.1 Type of propulsion

The most important information of all is that there is a hydrogen incident. Since incidents with liquefied petroleum gas or natural gas are at least partially similar, information is needed as to whether a gas-powered vehicle is involved. This information is obviously relevant. Without information about the drive type, an incident specifically correct action of the first responders will not be ensured; however, this applies not only to hydrogen-powered vehicles but also to all types of drive, for example, to pure electric vehicles, in view of the battery problem.

The CTIF Commission for Extrication & New Technology[1] accomplished very important work that is beneficial to all relief workers worldwide. Here the ‘UN Decade of Action for Road Safety’ is at the centre, with as the most important goal: shortening the intervention time,

[1] CTIF is the ‘International Association of Fire and Rescue Services’ and has as its main goal supporting and stimulating the cooperation between the fire departments and other emergency services from all over the world. CTIF ensures scientific research, the publication of articles and reports, the organization of different commissions and working groups and the cooperation with other bodies than the rescue services that are also working in the field of prevention and security.

because of which the survival chances of the victims increase, as well as striving for optimal security for both the victims and the relief workers at the place of the incident.

ISO 17840 Road vehicles - Information for emergency responders

The CTIF ISO 17840 project consist of standardising the information that is made available by the industry & car manufacturers for the first and second responders. The CTIF Commission for Extrication & New Technology worked on determining one structure in the *Rescue Sheets* and in the *Emergency Response Guides* that are drawn up by the manufacturers for new models. The rescue information is directly linked to recognizable pictograms.

Of course, in a tunnel this crucial information regarding the type of propulsion is not safely available with the current state of the art, because logos and labels on the vehicles could be unrecognizable due to crash effects or fire. Therefor one way of implementing the standard and optimize the availability of rescue information is the use of data transmission technology (e.g. E-call). Based on the Vehicle Information Number (VIN), a data set about the vehicle's properties can be sent out to a receiver as early as possible, providing the first responders with crucial information.

These technological tools are already being used in Formula 1 by FIA: 'accidents data recorders' & 'telemetry'. This standardized responder device will help us to make critical and lifesaving decisions even when there is no network (3G/4G/…) available.

It is a further developed and improved version of the E-call system that works as an important information source and backbone. The information can be sent out directly to the fire engine & crew, their dispatching or even collected by the tunnel infrastructure itself and forwarded in case of emergency. In these cases, we would talk about 'Vehicle-to-Vehicle' or 'Vehicle-to-Infrastructure' communication lines. All information in case of emergencies could be available by 'scanning' the VIN of all vehicles at the moment they enter an underground infrastructure.

6.2 Safety distances

Safety distances should be differentiated according to the parameters given in Table 1. Useful for emergency services would be phase-related safety distances, for example, what distance should be maintained during reconnaissance, what distance during extinguishing of a vehicle, etc.

6.3 Indicators

Here "indicators" mean unmistakable evidence of damaged vehicle condition or accident state. It is necessary to investigate whether there are other such indicators in addition to the vehicle information linked to the VIN and the specific blow-off noise and how these can be used by emergency services.

6.4 Adequate ventilation measures

There is little basic information on ventilation measures. At the first HyTunnel-CS project progress meeting (Karlsruhe, Germany, 10-12 September 2019), it became clear in the discussion that ventilation measures should not use suction, but can use pressure. The International Fire Academy will contribute a concrete list of questions to the project on this issue.

6.5 Extinguishing tactics and technology

The International Fire Academy will contribute a concrete questionnaire to the project on this issue (see above) and will first create an overview of possible vehicle positions in relation to the surrounding (e.g. tunnels).

6.6 Measuring needs

Measured values are only useful if they are valid and reliable and if one knows what they mean. Against this background it is not helpful just to recommend to measure. It needs a discussion what measured values are really relevant, reliable and available, and respectively can be taken by first responders.

7. Presentation of recommendations

In the case of a general distribution of hydrogen vehicles, all fire services must be trained for the initial deployment in hydrogen incidents (or incidents involving vehicles with an alternative type of drive). This will mean that this issue will have to be the subject of regular training and will no longer be able to be the subject of optional further training.

As a rule, training on alternative drives (including HY, LPG, CNG and others) will be available to crews for a few hours at most, and for officers one to two days at most; it tends to be significantly less for both.

Against this background, the documents provided, for example, from the HyResponse project are far too extensive; the content must be significantly condensed (taking into account the necessary additions outlined above).

To this end, it should be helpful to limit oneself to hydrogen-specific content. Recommendations such as looking for a hydrant are superfluous.

The description of standard procedures should also be largely renounced, because these differ considerably, at least in the wording from one to the other fire service system. The term reconnaissance is understood and taught in detail in very different ways.

Ideally, the recommendations for first responders as a result of the project are formulated in such a way that they can be incorporated by all fire service systems into their respective operational procedures.

Conclusion: Available knowledge on HY-intervention must be reduced to HY-SOPs which include strategic decisions and tactical options.

8. Knowledge gaps

Summarizing the main knowledge gaps for developing HY-SOPs have been identified:

8.1 Hazard identification

How to make sure that emergency services get the information that hydrogen is involved before turn-out from their stations. Proposals are given in chapter **Error! Reference source not found.**.

8.2 Controlled burndown

Is there still a danger of explosion when released hydrogen in vehicle is burning? If not, fire fighters could judge their safety distance on their own. That would simplify SOPs enormously because then controlled burndown might be an effective measure at low risk.

8.3 Usefulness of venting

How effective a (possible) danger of explosion can be reduced by venting?

If danger of explosion can be reduced by venting, venting might be the first thing to do at the scene. At the Karlsruhe meeting it has already been clarified, that such venting should be blowing only and never be sucking.

It should be further clarified under which circumstances venting could increase danger of an explosion. (Venting the fire and heating it up thereby is a problem fire services can control). If properly done venting never can deteriorate the situation but can always improve it, venting possibly is the first action to be taken at the scene.

9. Conclusions

Existent strategies and tactics are too extensive for the education of emergency services. The given knowledge must be condensed. It has to be reduced to SOPs for HY-incidents. The existent recommendations are a perfect basis for that work and will be used for it. Some additional questions must be clarified.

Annex 1. Internal seminar on knowledge and technology exchange

The aim of the internal seminar was to exchange available knowledge on hydrogen safety and first responders' intervention strategies and tactics. The seminar was held on the 10th September 2019 at Leonardo Hotel in Karlsruhe. The following notes report the discussion on first responders' main concerns and questions in dealing with accidents involving hydrogen powered vehicles in tunnels and other confined spaces. These were presented by IFA representative, C. Brauner. The GA, tEC and SAB members were invited to the seminar to actively respond to the fire services questions about hydrogen hazards and associated risks, and contribute to the seminar outcomes. The seminar was attended by 25 participants.

The seminar was chaired by C. Brauner and it was moderated by V. Molkov and T. Jordan. The seminar was opened and introduced by V. Molkov.

9.1.1 Existing strategies, tactics and procedures

The seminar started from a review of the Hy-Response project findings, the firefighter's strategies and operating modes, i.e. the different tactics that firefighters apply when intervening into an accident scenario. The aim of the review is to identify the limits and gaps of existing procedures, so that new ones, more efficient, can be developed. Identified critical issues are:

- Limited time available to first responders for decision making;
- Every scenario in reality is different from any other.

The hazards associated to a general scenario of a dwelling fire is analysed. Firefighters have protections against heat and other hazard sources. It is highlighted that one of the main issues for firefighters is the risk of explosion, as they do not have procedures or protections to react against a blast. The general scenario of a dwelling fire is compared to scenarios involving hydrogen and the main questions rising from the internal seminar are associated to the risk of explosion. A discussion is opened, and the following points are highlighted:

- There are certain protective strategies against explosions effects, e.g. for projectiles: lying on the ground, using protection shields, not staying in direction of more likely rupture and fragments production from tanks;
- It is suggested to integrate all procedures already available in HyResponse;
- It is highlighted the difference between the open-air and enclosed scenarios, e.g. heat in open atmosphere gives limited problems whereas it is a major issue in tunnels or other enclosed spaces;
- The definition of hydrogen explosion itself is still a debated issue in the scientific community;
- It is questioned if it is possible to extinguish hydrogen flame from a TPRD. Experimental studies were conducted in Japan and USN on jet fire extinguishment during blowdown for certain TPRD designs with varying diameter. It is important to investigate further these TPRD designs and possible blow off of the flame.

9.1.2 Definition and discussion of scenarios

During presentation by C. Brauner, different firefighters' questions are posed to the hydrogen safety experts. However, the knowledge exchange is bi-directional, and it includes questions as well by the seminar participants to first responders regarding their intervention procedures. The main questions (Q) are listed below, along with relevant remarks from the discussion.

Q: How to recognise a hydrogen powered vehicle (HPV) when intervening into an accident scenario?

- Some vehicles have only a small sign that is not really easy to spot. In many situations, e.g. vehicles involved in a fire, the signs could be burnt away or covered, so HPV could not be recognisable anyway.
- In Norway license plates have different initial letters according to the vehicle typology: HY for HPV or E for electric vehicles.
- There is a project on the identification of HPV where standardisation bodies are involved as well. It is based on the assignment of a Vehicle Identification Number (VIN). HPV provided with GPS could give information on the location, etc. It would be really important to have information on the number of vehicles for the different typologies entering car parks, e. g. 43 conventional vehicles, 3 HPV, etc.

Q: Which are the general tactics for CNG vehicles up to this moment? Can they be applied somehow to HPV?

There is a general procedure to address alternative vehicles. Afterwards, the fire "is read", as the flame itself can give information on the gas that is burning, and the procedure is adapted if it is a conventional vehicle.

Q: How to understand if we are dealing or not with hydrogen?

The indicators for reconnaissance of hydrogen involvement in a fire are described, as the hissing noise associated to the TPRD opening. For firefighters is important to have values on the distance they shall maintain and the distances for the public to evacuate the area.

There is no acceptable risk probability for firefighters.

Firefighters will act based on different factors rather than a calculated value of risk probability. Anyway, it is important to create situations where the risk is reduced as much as possible, so risk analysis cannot be ruled out. There are though defined rules. E.g. when explosimeters are available, firefighters will not enter a building if they measure a value ¼ of LEL. A strong ethical question rises in case people are trapped inside the building and need to be rescued.

Q: Is it possible to have flash back of the flame to the intern of the tank during an ignited release from the TPRD?

This shall not be possible given the absence of oxygen in the tank. However, even if that may happen not significant consequences may be expected: the storage tank should sustain the high pressure produced by the combustion of hydrogen inside the tank. So, the "flashback" hazard can be ruled out.

Q: Are there other signs that can make us rule out explosion possibility?

Generally, TPRD are pointed downwards. If there is a jet fire from the TPRD, the high temperature flame may leave signs on the surface where it impinges, such as melted materials or other traces. This scenario will be analysed in HSE experiments on erosion of road elements. It is important to record experiments by video camera and find the indicators that can be used by first responders to state that the TPRD has opened and has released the pressurised hydrogen. This indicator would not be of use if the vehicle is turned over, e.g. following a crash. If there is no clear of sign of release of gas, the intervening strategy should be to act as there was no release to be conservative. There are as well ideas of remote activation of TPRD in HPV.

Explosion in risk assessments.

- Even if probability of an explosion is low, it is still >0. Therefore, it needs to be considered as a possible scenario. Furthermore, when doing risk assessments, general public and firefighters should be considered differently, as they are characterised by different circumstances and probabilities.
- Firefighters need to be prepared for any possible accident even if characterised by a very low probability. This is the same as preparing for catastrophes or disasters, etc. They are as well events characterised by really low probability, but yet firefighters need to be prepared to answer it. Both SPFI and IFA partners highlight their concerns on the explosion risk, as first responders do not have any way to react to it and protect themselves. The project outputs should be used to give recommendations to OEMs to produce their designs accordingly to integrate safety optimization. It is not possible to change current infrastructure (tunnel dimension, ventilations, etc.) but the project can give indications to how car safety features should be designed to prevent such situations.

Q: What is the difference in hydrogen and CNG vehicles regarding the hazards in enclosed space and the tactics used by firefighters to respond accidents?

The main difference is given by PPP in garages: hydrogen may lead to a significant overpressure, whereas natural gas can produce a much lower overpressure in the enclosure. Both gases may lead to explosion.

Q: Can the ventilation air flow lead to electrostatic ignition of a hydrogen-air mixture?

The following example is presented: in case of a gasoline leak that can create a flammable atmosphere in a tunnel, the ventilation may be turned off because fans are not ex-protected. What should be done in case of hydrogen? This depends on how the ventilation system works: it is positive if the ventilation fans push the flammable mixture out of the tunnel; if they suck the air, a flammable mixture may be formed within the ventilation ducts leading to possible deflagration and conditions for flame acceleration.

Q: Can hydrogen accumulate in the top structures of tunnel?

Yes, it can accumulate but concentration cannot be higher than the concentration of the jet when it reaches the ceiling. However, in a tunnel there could be still possibility of recirculation, i.e. the hydrogen cloud can descend along the walls and re-entrain into the hydrogen jet. In this case hydrogen concentration may increase at the ceiling. Studies conducted on hydrogen concentration on the top of an enclosure for releases directed downwards, horizontally or vertically. Jets directed downwards and horizontally resulted in similar concentrations. Releases directed upwards resulted in larger concentration. Results may be presented at following project meeting.

It is discussed to use hazard distances as deterministic distance from a harm and use the term evacuation perimeter for people. Some further remarks were made:

- It is important to have simple guidance to set hazard distances and justified evacuation perimeters.
- Need to define a shock prone area, i.e. the area where we can have blast wave effects.

- A blast wave within a tunnel, either created by the rupture of a tank in a fire or a deflagration or detonation, will have a very little decay in a tunnel. So, it will not be possible to define different hazard zones within the tunnel itself.
- Scenarios with HPV could be different as it is not possible to avoid the back-layering of hydrogen releases even if ventilation is activated.
- General experience by firefighters is that ventilation systems do not work appropriately as they should be designed for in accident condition.
- Ventilation direction must not be changed during rescue operations, as this could create dangerous situations for people escaping the fire.
- Railway tunnels are smaller and are not provided with ventilation. Majority of old tunnels may not be provided with emergency exits at all, complicating the rescue operations.
- To the partners' knowledge, there are not references with harm criteria for blast overpressure for protected people.

Q: Would the type of door make a difference if a blast happens in a tunnel?

Tunnels are usually provided with sliding doors due to possible different pressure on the two sides that could create opening problems in case a swing door is used. Sliding doors could be deformed by a blast wave if the produced overpressure is high enough, and the doors may not slide properly and open. The use of swinging doors can have a twofold effect: i) they could work as a pressure wave dumper when they open and release the pressure load created inside the tunnel tube by providing an additional volume where to expand; ii) this could be a problem if on the other side there are people that should be kept safe!
The use of sliding doors changes the considerations done by researchers on the techniques to attenuate the shock wave inside tunnel by swing doors periodically distributed along it.

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