



## Fire-fighting of alternative fuel vehicles in ro-ro spaces

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# Abstract

A literature study has been carried out that compiles the body of research regarding hazards related to fire in alternative fuel vehicles (AFV) in ro-ro spaces. Alternative fuels include liquefied gas (e.g. LNG), compressed gas (e.g. CNG) and batteries. Hazards related to a conventional vehicle on fire are heat, smoke and toxic gases. Another hazard is projectiles related to small explosions of e.g. tyres or airbags. AFVs also include hazards of large explosion, jet flames, more apparent re-ignition, etc.

The study also includes land based fire fighting tactics related to AFV fires. If the fuel storage on an AFV is affected, land-based firefighters often use a defensive tactic, which means securing the area around the vehicle and preventing fire propagation from a distance. This tactic has been evaluated in the context of a ro-ro space and the results are compiled in a test report (Vylund et al 2019). The project has resulted in guidelines on how to handle AFV fires in ro-ro spaces (see appendix 1).

**Key words:** Ro-ro spaces; Fire fighting; Extinguish system; Alternative fuel vehicles; Modern vehicles; Gas cylinder; Lithium-ion; Cargo spaces; Vessel; Ship; Ferries;

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# Preface

BREND is an acronym for the research project *Fire in Alternative Fuel Vehicles in ro-ro spaces* which was funded by the Swedish Transport Administration (Trafikverket) and The Swedish Mercantile Marine Foundation (Stiftelsen Sveriges Sjömanshus). RISE Research institute of Sweden has carried out the project together with in-kind support from Stena, Destination Gotland, Transportstyrelsen, Färjerederiet (Trafikverket), Wallenius Marine, Safety Group, Södra Älvsborg Fire and Rescue Service and Oskarshamn Fire and Rescue Service. The authors would like to extend their thanks to all the above organizations for their contributing knowledge and support.

The authors also thank the suppliers of the manual extinguishing systems that supported the tests conducted in the project. The results of the tests were reported in a separate report [Vylund et al 2019].

# Summary

The project BRENDA aims at increasing and transferring competence on how fire in alternative fuel vehicles (AFV) should be handled in ro-ro spaces, including evaluation of new fire fighting methods. AFV represent other hazards than vehicles with traditional fuel (e.g. gasoline, diesel). Gas tanks can for example produce a jet flame or they may explode. Lithium-ion batteries can produce large quantities of combustible and toxic gases and can be difficult to extinguish if thermal runaway occurs. The new type of dangers introduced by AFV require new routines, tactics, equipment and training to ensure the safety of crew and passengers on ro-ro vessels.

An extensive literature research has been compiled regarding risk and hazard with fires in AFV. These risks were discussed during a workshop together with personnel from different vessels companies, authorities and fire and rescue services with the aim of evaluate possible solutions to deal with AFV fires. Also, relevant guidance for land-based fire fighting tactics have been studied and evaluated with ship owners/crew, both in field tests and in laboratory fire tests.

A pressurized CNG gas tank explosion in ro-ro space has been simulated in a programme called Autodyne. The simulations show that the greatest consequences in ro-ro spaces are obtained if a gas tank explodes near a corner or near a wall. If the explosion occurs near an opening, e.g. in the stern the risks are reduced considerably. A vehicle can act as protection against the pressure wave from an explosion, but at the same time the pressure wave from the explosion can cause the nearest vehicles to be overturned or moved. Furthermore, there may be damage to the interior which may lead to the risk of people being hit by falling parts. The material in gas tanks exposed to fire regains much of its strength when it has cooled. Also, the pressure in the tank decreases with decreasing temperature. This means that tanks that have not exploded during the fire have a safety margin against exploding when they have cooled down. At the same time, there are reports that composite tanks after a fire can leak gas through the tank material.

The critical hazards from lithium ion batteries are judged to primarily be that they are difficult to extinguish and if damaged can start a fire several hours/days after the damaging event. The toxic gases that can be produced from a battery even though the vehicle is not on fire is also identified as a critical hazard while the toxicity of the combustion products from a vehicle on fire are not judged to be significantly more severe if there is a battery involved than when it is not. This is particularly problematic in poorly ventilated spaces such as in closed ro-ro spaces where the gases can accumulate.

A battery fire in an electric vehicle is difficult to extinguish. The battery is often difficult to access, and it can be complicated to cool the battery with water. Normally there are no risks of electric shock when extinguishing water is applied, but the fire may continue for an extended period. There is also a risk that a battery fire will re-ignite after extinguishing. For ro-ro spaces, this means that monitoring the battery is necessary until the vehicle can be unloaded and placed where there is no risk of fire propagation.

Fire development in vehicles varies greatly depending on where the fire started, on materials and on vehicle fuel storage. However, a "normal" passenger car fire can generally be considered to have a burning time of just over half an hour with a maximum fire effect (around 4-5 MW) after about 10-15 minutes. The literature research shows that time for fire spread to the nearest vehicle in a parking garage with conventional vehicles differs quite considerably, 5 to 40 minutes, while fire spread to the next closest and third closest vehicles goes faster. If the vehicles instead include

gas tanks another study shows a high risk of a domino effect where jet flames trigger additional jet flames from adjacent vehicles.

If the fire is small and does not affect the fuel storage, regardless of the fuel the vehicle has, a quick response with e.g. handheld fire extinguisher or fire hose is recommended. However, if a quick first response fails, there is a risk of rapid fire development and the fixed fire-extinguishing system should be activated soon. When a manual fire fighting operation is required, the risk of explosion, jet flame, toxic gases is overveiling. Difficulties in extinguishing the vehicle must be considered when selecting tactics for such fires.

If a fuel storage in an AFV is affected, a defensive tactic is usually selected on land. Defensive tactic can be obtained by securing the area around the vehicle and prevent fire propagation from a distance. This tactic has been evaluated in a ro-ro context and the results are compiled in a test report (Vylund et al 2019). The project has also resulted in guidelines how to handle AFV fires in ro-ro spaces (see appendix 1).

# 1 Introduction

Ro-ro vessels are the most common ships that enter Swedish ports. Fire in ro-ro spaces is common and Swedish seamen are therefore in need of gaining knowledge about how to handle fire in alternative fuel vehicles, and also about how to handle modern vehicle fires in general.

DNV-GL identified 35 ro-ro space fires on SOLAS compliant ro-ro ships between 2005 and 2016 (DNV-GL 2016). They concluded that the most common causes were electrical failures and power connection failure between reefer unit and the vessel. Three fires in open ro-ro spaces resulted in a total loss of the vessel (fixed fire-extinguishing system did not operate). Two major fires occurred in closed ro-ro spaces and on weather deck respectively. Furthermore, DNV-GL concluded that fires in open ro-ro space tend to become more severe, probably due to a combination of hot smoke that gathers below the ceiling and a supply of oxygen through openings that can sustain and spread the fire. Fires on weather deck can be very large but do not affect the structures as much as enclosed fires. Fires in a closed ro-ro space are generally limited by lack of oxygen. However, late activation or failure of the fixed fire-extinguishing system leads to major fires. Successful cases were due to rapid response, either by activating the fixed fire-extinguishing system quickly (0-10 min) or due to a fast response by the fire-fighting team. Many of those fires were furthermore detected quickly by the fire patrol or fire detection system and confirmed with CCTV or fire patrol (DNV-GL 2016).

In another study of ro-ro space fires, 38 incidents were reported to the UK maritime accident investigation branch (North 2017). The fire causes were similar as those that DNV-GL identified, with 5 additional vehicle engine fires. It is noticed that vehicle fires in ro-ro spaces can escalate quickly and develop to a point where they are difficult to control. There is no legal minimum distance required between parked vehicles which may be as little as 0.15 m. This makes it almost impossible to manually fight the fire, due to accessibility problems. The close stowage of cargo coupled with the large open area also means that fires can spread quickly and become very large if they do not become ventilation controlled. This also reduces the effectiveness of the fixed fire-extinguishing systems. To limit fire loss, North (2017) gives recommendations about general housekeeping, familiarity with fire fighting equipment, training and planned maintenance programs.

Alternative fuel vehicles (AFV) include battery, hybrid, fuel cell and gas-powered vehicles. In the event of a fire, gas tanks can give rise to a strong jet flame or explode if they do not work properly or if they are handled incorrectly (for example, if the thermal fuse is cooled). Lithium-ion batteries can produce explosive and toxic gases during thermal runaway and new metals in chassis such as magnesium can cause fires that are explosive and difficult to extinguish.

## 1.1 Objective

The project BREND aimed to raise and transfer the competence of how fire in AFVs should be handled in ro-ro spaces, including evaluation of new methods and equipment. Knowledge in how fire in vehicles with AFV should be handled is generally low and this study will therefore serve as a knowledge base to utilize the knowledge already available on land, in particular with regard to fire fighting tactics, equipment and training. This report includes a literature review of general fire hazards of AFVs, with the aim to provide background for evaluation of new fire fighting methods and equipment. The results of the evaluation can be found in the test report "Methods

and equipment for fire fighting with alternative fuel vehicles in ro-ro spaces” (Vylund et al 2019), while concluding guidelines on how to handle AFV are found in Appendix 1.

## 1.2 Method

The project aims to develop or identify practical and efficient methods and tactics to limit the consequences of AFV fires in ro-ro spaces. This aim is achieved by:

- Background knowledge and literature review of risks with AFVs and land-based procedure when conducting fire fighting operation.
- A workshop with personnel from shipping companies, authorities and fire and rescue services aimed at identifying particular issues with AFV fires in ro-ro spaces and possible solutions to deal with them and methods for evaluation.
- Evaluation of different fire fighting methods and equipment, through fire tests and field tests.

The literature review was initiated at the start of the project to raise the knowledge level about risk connected to fire in AFVs and methods of fire fighting operations on land. This worked as the basis to understand possible solutions for how to handle AFV fires in ro-ro spaces.

Thereafter, the workshop raised many questions, both regarding fire fighting risk assessment and possible solutions to handle AFV fires in ro-ro spaces. After the workshop, the questions regarding risk assessment were handled by complementing literature research and by conducting simulations for the consequences of explosion. The method and results of the computer simulations are presented in Appendix 2. The results from the workshop were presented to extinguishing system suppliers and different systems were selected with regard to the outcomes from the workshop. Methods and results for the evaluation tests are presented in Vylund et al (2019).

## 1.3 Delimitation

This report focuses on passenger vehicles in ro-ro spaces, although the presence of other vehicles, such as heavy goods vehicles, was also considered. The results are valid in ro-ro spaces, but can to some extent be useful in other contexts.

## 2 Fire development

Vehicle fires in ro-ro spaces can cause large problems and the risks have changed over the years. Modern vehicles are very different from older vehicles, especially those manufactured before the early 1990's. While trying to reduce the weight and costs of the vehicles, new materials have been introduced and a lot of steel has been replaced by lighter metals, alloys, carbon fibre and plastic. This increases the fire load and may speed up the fire development and increase the production of toxic gases from a modern vehicle fire.

In addition to the new materials, the search for new fuels has resulted in alternative fuel vehicles with other properties than those of gasoline and diesel. Vehicles using other energy carriers than gasoline or diesel are in this report referred to as AFV, i.e. vehicles that include other liquid fuels (e.g. ethanol or methanol), liquified gas (e.g. LNG, LBG or LPG), compressed gas (e.g. CNG, CBG or GH<sub>2</sub>), batteries (Lithium-ion at present), hydrogen fuel cell vehicles (HFCV) carrying both compressed hydrogen (GH<sub>2</sub>), fuel cells and batteries, hybrid vehicles carrying both a liquid fuel like gasoline and a traction battery (Lithium-Ion, NiMH, or other techniques).

The different AFVs were divided into four categories, based on their type of energy carrier. The division was made mostly because the safety solutions to protect the fuel or energy storage from fire are similar within the different groups and because their failure modes are similar. The division was thus made with regard to how to extinguish fires in the vehicles in each group the consequence severity of a fire involving the fuels. The four categories are:

- Liquid fuel vehicles (including diesel, gasoline, ethanol etc.)
- Liquefied fuel vehicles (including LPG, LNG etc.)
- Compressed gas vehicles (including CNG, GH<sub>2</sub>)
- Battery electric vehicles (including Lithium-Ion, NiMH etc.)

Vehicles carry a lot of energy, both the fuel stored chemically in the energy carrier, but they can also carry solid fuels like plastics and seats, electrically in batteries and as heat stored e.g. in the exhaust system from previous combustion or friction at the brakes. As long as the fuels are separated from heat sources, the electrical system does not malfunction and there is no isolation fault that causes heat production, a fire will not start from a vehicle, unless there are external sources, e.g. arson. Vehicle fires typically last for less than one hour (Ingason et al 2015). A modern vehicle contains up to 9 GJ of energy that can be released within this time frame. The peak heat release rate is around 5 MW after 10 to 30 min. A bus contains around 40 GJ and a bus fire generally peaks at around 30 MW in 7-14 min. The main fire load of heavy goods vehicles (HGV) is the cargo, which can be as high as 240 GJ and have a peak heat release rate of 200 MW (Ingason et al 2015).

### 2.1 Fire sources

The majority of vehicle fires on land today, at least in Sweden, are actually caused by arson (Björnstig et al. 2017), but the case on board a ship will be quite different, and arson seems much less likely. Vehicle fires on board a ro-ro ship can in most cases be considered as parking fires, but since the vehicles are driven on board there are possibilities of other types of fire, resulting from e.g. hot brakes, leakage of fuel onto hot surfaces and even post-collision fires. Since the vehicles are not driven very fast on-board, major damage from an onboard collision was excluded. Such an event could cause a fire, but it will most likely not cause damage the vehicle's fuel tank,

traction battery or any other large energy storage on the vehicle. Therefore, vehicle fires were treated as fires in parked vehicles in this study. Parked vehicles generally do not have any hot surfaces that will ignite fuel leaks, since they have generally cooled down after being parked. Since they are not moving and have no mechanical components moving, those possible sources of fire can be more or less disregarded. Nevertheless, a fire could have started before the vehicle was parked and the fire could have been kept alive and grown very slowly for some time and therefore not detected until the vehicle has been parked for a while.

Ignition sources for parking fires are most likely caused by electrical malfunction. Apart from the pure electrical sources such as battery cables, other automatic and heat generating devices could cause troubles; e.g. parking heaters, block heaters, and cab heaters are possible ignition sources. They should not be in use on board but are yet commonly used. Furthermore, compressors for the air condition system and fans may generate enough heat and, if faulty, could start fires.

Another possible fire source is associated with charging of batteries on-board, regardless of whether the batteries being charged are primary lead-acid batteries or secondary (traction) Lithium-ion batteries, charging them adds to the likelihood of starting a fire. This can be seen as something in-between fires caused by the vehicle or external fires and was therefore considered as a separate fire source.

## 2.2 Fire growth

After ignition the fire will grow, and how rapidly the fire grows will depend heavily on how and where it starts and what fuels it can reach in its early stages. It will also be very dependent on ventilation conditions. For a lot of cases a fire in the cabin of a vehicle may self-extinguish due to oxygen depletion if windows and doors are shut. Experiments show that if the fire does not break a window early enough it will self-extinguish (BRE 2010).

For parking fires, the fire growth will initially be slow in case of an electrical fire cause. If the fire started from an overheated cable, leading to cable insulation catching fire, it will spread slowly along the cable. The cable insulation does not provide much heat energy and the fire will not start to grow before it spreads to adjacent objects, e.g. an oil filter, a fuel line or a hydraulic hose. A fire in its early phase can be very difficult to detect and will unlikely be detected. By then the fire has most likely transformed into a more rapid fire growth.

Arson initiated fires will likely grow rapidly as they will likely become quite large initially and continue to grow as long as windows are open or smashed to provide ventilation. Fires from external sources will likely grow quite fast directly after they spread to a vehicle.

Fires initiated due to charging of a battery will most likely start in the charging system or in the transformer in the vehicle, and not in the battery itself. Similar as for parked vehicle fires, they will likely start rather slow, but if undetected in their incipient phase, they will continue to grow and reach to a stage of fast growing fire.

It is unlikely to detect a fire in its incipient phase since the smoke production is minor. To observe smoke from a cable which is heating up due to an isolation fault, a person or detector needs to be quite close to the vehicle. Heat release from the fire is marginal but a thermal camera could detect hot spots from malfunctioning electric systems, even before the fire breaks out. Most fixed fire detection systems will likely notice the fire at a later stage after or just before the fire enters its growth phase.

## 2.3 Fire stages and timelines

A study ( Development of design rules for steel structures subjected to natural fires in closed car parks ) funded by the European Commission (1999) described diesel/gasoline vehicle fires (not arson) from data derived from fire tests with a reference heat release rate curve. This reference curve was divided into four different stages:

- **Initial growth stage** – When the fire starts growing and produce heat. A fire remains small and difficult to detect until it spreads to a location holding a certain amount of combustibles. It may also be kept small if it is confined in a volume with a small amount of oxygen. When the fire reaches a point where it has sufficient supply of both oxygen and fuel it will start producing more heat and grow.
- **Stationary stage** – When the fire is consuming combustibles in the engine compartment, tires and other exteriors, but before the failure of the fuel storage or the spread to the passenger compartment, i.e. before a sudden increase of available fuel.
- **Secondary growth stage** – When a large amount of fuel becomes available to the fire or when air is made available to a ventilation-controlled fire the fire enters a new growth stage. This often happens when a fire spreads to the passenger compartment through e.g. a broken window, when the window breaks to allow air into a fire in the passenger compartment, or when the fuel storage fails and there is a large pool fire or gas leak.
- **Decay stage** – When most of the combustibles have been consumed, a pool fire has stopped, and the fire slowly decays and self-extinguishes.

The report from the European Commission sets the duration for the different stages to 4 minutes for the initial growth stage, 12 minutes for the stationary stage, 12-15 minutes for the secondary growth stage and roughly 40 minutes for the decay stage. It should also be taken into consideration that the vehicles used in the fire tests to create the above timeline were not modern vehicles. For modern vehicles, the development can be expected to be more rapid (Björnstig et al. 2017), based on the choice of materials in modern vehicles. Therefore, it can be assumed that the time frames for modern vehicles would be more in the line of:

- Initial growth stage: 2.5 minutes
- Stationary stage: 1-5 minutes
- Secondary growth stage: 10-15 minutes
- Decay stage: 40 minutes

These numbers vary and depends on where and how in the vehicle the fire starts. Another important aspect is that the reference curve and its timeline is valid for vehicles using diesel or gasoline as compulsory fuel. AFVs introduce new fire hazards as the consequences are different compared to diesel and gasoline driven vehicles.

## 2.4 Conditions on board

Ro-ro spaces are ship spaces in which vehicles can be loaded and unloaded normally in horizontal direction [SOLAS II-2/3.41]. The vehicles will be stowed quite tightly and the access to the vehicle on fire could be restricted. The heights within ro-ro spaces vary depending on if the space is designed for personal cars or trucks and buses, etc. In ro-ro spaces, vehicle fires will likely develop similar to parking fires, as described in section 2.1 *Fire sources*.

A ro-ro space is normally extending to the entire length of the ship. There are three different types of ro-ro spaces: closed ro-ro spaces, open ro-ro spaces and weather decks. SOLAS defines these spaces as:

*SOLAS II-2/3.35: "Open ro-ro spaces are those ro-ro spaces which are either open at both ends or have an opening at one end, and are provided with adequate natural ventilation effective over their entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides."*

*SOLAS II-2/3.50: "Weather deck is a deck which is completely exposed to the weather from above and from at least two sides."*

*SOLAS II-2/3.12: "Closed ro-ro spaces are ro-ro spaces which are neither open ro-ro spaces nor weather decks."*

Worst case scenario regarding fire development, fire spread, extinguishing accessibility and also visibility are spaces with low ceiling heights. The height in low ro-ro spaces is usually 2.3 m. Ventilation possibilities within ro-ro spaces are limited and can generally not be used to force the air flow in a certain direction (except in specific locations between the inlet and the outlet). Here, the volume air flow can be regulated to achieve ventilation of both smoke and toxic gases to a certain degree, but it cannot be used to create a clear route for a fire fighting team.

The detection possibilities vary between ships and also between different spaces on the same ship. The height will influence the time to detection. Weather decks, open spaces and closed spaces have different requirements. Closed and open ro-ro spaces generally have smoke detectors or sometimes heat detectors, or combined smoke/heat detectors. No fixed detectors are required for weather decks and therefore they seldom exist. In case of detection, personnel are sent to confirm the fire and upon confirmation a fire team is given the order to prepare for fire extinguishing operation and the fixed fire extinguish system is started. From the time of detection until start of the extinguishing operation by the fire team several minutes will likely pass, approximately about 15 minutes. Limited efforts can be made by the personnel sent to confirm the fire before the fire teams arrive.

According to IMO rules<sup>1</sup>, the carriage of AFVs can be permitted on regular vehicle decks provided that:

- The vehicle fuel system is checked for leak-tightness and is in proper condition for carriage.
- Suitable fire protection system is provided in the vehicle space.
- Ignition sources are separated from vehicles.
- Adequate ventilation (6 or 10 air changes per hour).
- Vehicles and engines fueled by flammable gas have their shut off valves closed.
- Lithium batteries meet UN38.3 testing criteria.

By utilizing new or improved detection systems or work routines there can be a chance of detecting a fire earlier. The possibility of detection varies depending on the design, the types of vehicles being transported and the way the vehicles are located. Various detection opportunities

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<sup>1</sup> IMO MSC.1/Circ.1471, SOLAS Ch. II-2 Reg.20-1, SP 961 and SP 962 of the IMDG code.

were discussed during a workshop with personnel from shipping companies, authorities and fire and rescue services. Following detection opportunities was discussed:

- Reading with IR technology,
- Gas sniffers,
- Drone with IR technology and gas detector,
- Flame detectors,
- Fiber Optic Heat Detector,
- Smoke detectors,
- Video surveillance - for fire location and confirmation,
- Sound detectors that can identify outgoing gas.

Different detection systems were also evaluated in part 4 of FIRESAFE 2 (Mindykowski et al 2018).

## 2.4.1 Fire spread on board

Fire spread between vehicles is of great importance when considering fire-fighting operations in ro-ro spaces. It affects how severe a fire can become, how quickly it has to be extinguished to prevent fire spread and can make the fire-fighting operation more difficult and hazardous.

In closed or open ro-ro spaces, a hot smoke layer will be created that enables heat transfer by radiation towards the vehicles. The fire spread between the vehicles can spread very fast from the origin and to neighbouring cars (BRE 2010, Joyeux, 2002, EC, 1999). Fire spread from the origin fire source to an adjacent vehicle (second) will take more time than to the third and fourth etc. Fire spread may even occur simultaneously to vehicle number 3 and 4 in a row of vehicles, positioned door to door. When the fire has become large, the fire-fighting team needs to be careful not to lose sight of a safe withdraw out of the ro-ro space.

Summarising fire tests involving two or more vehicles where one vehicle served as the source vehicle (origin) and where time to fire spread was measured, it can be shown that the time varied greatly (BRE 2010, Joyeux 2002, EC, 1999). The tests were performed in open car parks with ceilings or in closed car parks with or without ventilation. The distances between cars varied but was representative to cars parked in adjacent parking slots. The times to fire spread are summarised in Table 1. In ro-ro spaces, the vehicles are often parked close together and therefore faster fire spread can be expected. Fire spread on weather deck is however expected to be slower due to the lack of radiation from hot smoke at the ceiling.

Table 1. Summary of times to fire spread in car park fire tests (BRE 2010), (Joyeux 2002), (EC, 1999)

	Positioned door-door	Positioned bumper-nose
Time to fire spread to most near vehicle	5 – 41 min	30 and 56 min
Time to fire spread to second nearest vehicle (after the most near ignited)	1 – 2 min	-
Time to fire spread to third nearest vehicle	26 s	-

Tamura et al. (2014) conducted an experiment to investigate the possible spread of fire between hydrogen fuelled vehicles on vehicle carrier ships. Hydrogen tanks of 36-40 l and 700 bars with a temperature-controlled pressure relief valve (tPRD) directed 45° downward towards the back were used in the study. They found that when the vehicles were parked tightly together, there was

an apparent risk of tPRD activations leading to continuous tPRD activation of the adjoining vehicle and thus a potentially very fast fire propagation in case there are many gas vehicles nearby. Upon tPRD activation, a jet fire is formed along the floor below adjacent vehicles. This fire in turn activates tPRDs nearby which means that a domino effect is started if many gas vehicles with thermally activated PRDs are parked next to each other. They therefore concluded that the fire must be detected early and extinguished before the first tPRD activates (Tamura 2014).

For heavy goods vehicles or cargo units, the mechanism for fire spread will work a bit different than for parked vehicles. It can be argued that fire development will be more similar to a warehouse fires than to parking fires. Ingason and Lönnemark (2005) studied the fire spread in warehouse fires in a model scale 1:5. The results show that the distance between the top of the goods and the ceiling is crucial for determining the rate of fire spread between the cargo units. When the flames reach the ceiling, they are deflected to the side and increase radiation to the top of adjacent cargo. As a result, the adjacent cargo catch fire at the top, with the fire spreading downwards from this point. It took approximately the same time for the fire to spread when the heights above the goods were 1 m or 6 m (large scale equivalent); the longest time occurred when there was effectively no ceiling above the cargo, equivalent to a fire on weather deck. The fire spread with a clear height equivalent of 1 m above the cargo was reduced since the combustion was less complete. When the impinged flames reached the layer of hot fire gases formed below the ceiling, they started to be affected by the lower oxygen levels which effectively reduced the flame spread, which most likely resemble the situation in most open and closed ro-ro spaces with HGVs. For this reason, the fire may actually spread faster for cars than for HGVs. Beams along the ceiling will further reduce the fire spread rate. Ingason and Lönnemark (2005) argued that, based on the tests they performed, the only way to protect the goods against this type of exponential fire spread is the use of fixed fire-extinguishing systems. This will be particularly true for an open ro-ro space where oxygen is more readily available. For a closed ro-ro space, low oxygen levels will slow down the fire spread rate.

## 2.4.2 Fixed fire-extinguishing systems

According to SOLAS II-2/20.6.1.1, one of the following fixed fire-extinguishing system is required for closed and open ro-ro spaces:

- *A fixed gas fire-extinguishing system;*
- *A fixed high-expansion foam fire-extinguishing system; or*
- *A fixed pressure water spraying system.*

The first two options are only valid for closed ro-ro spaces which are capable of being sealed and which are not accessible for passengers. The extinguishing system shall be designed according to the FSS Code [ref].

Automatic sprinkler systems or manually activated deluge pressure water spraying systems are designed in accordance with the requirements MSC.1/Circ.1430, which require water discharge densities according to Table 2.

Table 2. Minimum required water discharge density according to Table 4-2 of MSC.1/Circ.1430

Type of system	Minimum water discharge density (mm/min)	
	2.5 m maximum free height	2.5 to 6.5 free height
Wet pipe system	6.5	15

Type of system	Minimum water discharge density (mm/min)	
	2.5 m maximum free height	2.5 to 6.5 free height
Dry pipe or pre-action system	6.5	15
Deluge system	5	10

Automatic water mist and deluge water mist systems can also be approved in accordance with MSC.1/Circ.1430 which allows for performance tests to determine the discharge density. The tests have allowed systems with much lower discharge density than the prescriptive options. This has been criticized with the argument that the test fire scenarios do not reflect the severity of real case vehicle fires (Arvidson 2015). Arvidson (2018) furthermore tested three alternative fire-extinguishing systems with the overall conclusion that a deluge pressure water spraying system designed in accordance with MSC.1/Circ.1430, discharging 10 mm/min of plain water, had a superior performance. In relation to what has been reported, it can be concluded that a fixed deluge pressure water spraying system will likely suppress a ro-ro space fire although it may not always be enough to extinguish the fire, especially not inside a vehicle.

### 3 Risk assessment

All vehicles, more or less, have the same type of material and fire behaviour inside the cabin. Fire growth will be limited by lack of oxygen unless fresh air, e.g. through a broken window, is supplied to the fire which can result in a very fast fire development. Air-bags may have their pyrotechnics affected and cause minor explosions which could cause severe injury, e.g. from throwing small and sharp projectiles with great force.

Vehicles with a combustion engine also share a lot of risks in connection to the engine compartment. They will have fuel hoses or pipes which if they lose their integrity may cause rapid fire growth and they will all have lubricants, e.g. oil that if a tube, filter or tray loses its integrity will cause a rapid fire growth and possible pool fires.

The tyres of most vehicles also share the same hazards. They may burn hot and they may explode. The consequence of a tyre explosion will vary depending on the size and the pressure inside the tyres, but they may all cause severe injuries to persons standing near the tyres.

Gas springs, shock absorbers etc. are present in all vehicles and they could also explode when exposed to heat. Consequently, they may cause harm persons near them and in some cases parts or components have been thrown up to 50 m from the vehicle on fire (Björnstig et al. 2017).

Metallic alloys with properties of good strength while being of low weight are always sought for in the vehicle industry. Magnesium and aluminium alloys can have these properties and they are present in modern vehicles. Aluminium will often not be an issue in a fire, but magnesium alloys on fire burn very hot and may even break water atoms to produce hydrogen. Water can also send the hot magnesium parts flying away without cooling them very much and this could cause damage where they land. A lot of rims in the vehicles today are made from magnesium alloys.

Another collection of materials that has become more used in vehicles are composite materials, much due to the same reasons why metallic alloys other than steel are used. Carbon fibres materials add to the fire load of a vehicle, but the issue of most concern is the risk possibility that harmful nano-particles are produced when it is burning and the effect those may have when inhaled. There is however little conclusive research available on this particular subject (Björnstig et al. 2017). It should be noted that harmful particles of various sizes are available in the everyday air we breathe and are emitted from fires.

Most combustible materials in the vehicle will produce smoke of some toxicity in a fire and HCN can be produced from composites, foams and such, while HF can be produced when some plastics burn, or when the air conditioning liquid is burning. HCl will also be produced in the fire and more toxic substances will be present in the smoke.

These are all hazards which are present in more or less all vehicles, regardless of fuel type or energy carrier. The best approach is to stay out of the smoke and if possible, attack the fire with the wind or ventilation in the back.

The general hazards regarding fires in vehicles are:

- Heat
- Smoke and toxic fire gases
- Pool fires
- Smaller explosions which could throw projectiles with harmful force, e.g.

- gas springs
- airbags
- tires
- New materials / unconventional materials e.g.:
  - Carbon fiber, graphene and similar – increases fire load, produce harmful particles during combustion.
  - Magnesium and aluminum alloys – may catch fire, can cause issues when exposed to water

To this list the hazard of fire spread to other vehicles can be added although it contains the same hazards it will mean that the quantity is higher and that the possibilities of controlling the fire development decreases. Multiple fire locations will be more difficult to control than one.

Making a risk assessment before approaching a vehicle is essential and estimating the fire size as well as the starting point or at least present location is necessary to know what hazardous events that are likely to occur and what risks that are relevant to evaluate. This is valid regardless of the fuel type.

### 3.1 Liquid fuels

Normal liquid fuel driven vehicles contain a tank with diesel, gasoline or ethanol. Fires that affects the fuel storage can lead to a rapid increase in fire growth when the storage loses its integrity. In rare cases fuel tanks may even explode, but the main risk comes from when the fuel tank is exposed to the fire, leading to a more rapid fire development if ruptured and maybe spread of fire through a pool fire. Plastic fuel tanks are designed to withstand fire tests of 2 minute flame exposure (UNECE 2014a) and in a real fire scenario a tank likely would keep its integrity for at least 2 minutes after a fire has started engulfing it.

Regardless of how the integrity loss occurs, the contribution of the fuel in the tank increases the fire size and the likelihood of rapid fire spread. Ethanol is quite similar to the conventional energy carriers of diesel or gasoline, however a pool fire could be more difficult to extinguish. Extinguishing agents have to contain alcohol resistant foam concentrates in order to function properly.

The fuel tank will likely lose its integrity at a later stage than when the general hazardous events described in the previous section occur. It, however, may still occur at or around the time of likely detection or at least when the first responders arrive to the fire. Just as for the general hazards it is important to focus on the fire size and its location in order to assess if and when integrity loss is likely to occur.

The direct consequences of a liquid fuel tank rupture are minor, but the risk of a fire spreading to adjacent vehicles increases due to the leakage of fuel.

### 3.2 Liquefied fuels

LPG, LNG, liquefied DME are all used in vehicles today. LPG is the most common liquefied fuel in vehicles. Liquefied fuels storages are characterized of keeping the fuel liquefied by thermally insulating the storage and keeping the fuel under low pressure. They will also have a pressure relief valve (PRV) which shall activate to release excess pressure and then close again. They can also have pressure relief devices (PRD) temperature-controlled pressure relief devices (tPRD)

which when exposed to a pressure or temperature ( $>110^{\circ}\text{C}$ ) above a certain threshold will activate and release all the fuel (UNECE 2014b).

When a PRV activates due to the presence of a fire the gas flowing out from a ventilation outlet and if ignited there can be a jet-flame that could be several meters long for a couple of seconds. This will occur until the pressure inside the storage tank has been lowered. If a PRD or tPRD activates or if the pressure inside the tank does not drop fast enough to let the PRV close, the jet-flame can last much longer. In a car the released gas will normally be directed downwards and backwards at an angle from an outlet positioned between the rear tyres.

If these pressure relief devices either do not activate or the flow through them is inadequate, the fire may later cause the tank to burst and a gas explosion might follow. Boiling Liquid Expanding Vapor Explosion (BLEVE) can also occur for liquefied fuels (it is possible for liquid fuels as well but not as likely).

If engulfed in flames the activation of a PRV, PRD or tPRD is likely to occur before a conventional fuel tank loses its integrity. However, the liquefied fuel storage tank's position can be better protected from the fire and therefore the time from fire start to PRV, PRD or tPRD activation may be longer.

In a pre-fire scenario where the system leaks the gas may spread and ignite from a spark and cause a gas explosion. This is however not very likely in large spaces, even less so in large ventilated spaces. Accordingly, there have never been a gas cloud explosion or fire onboard a SOLAS ro-ro ship, at least not in the period 1990-2016 (DNV-GL).

LPG tanks are designed to comply with fire tests according to UN ECE Reg. No. 67 – Annex 2 where it will be exposed to a bon fire and shall not burst during that test, the test is however designed so that a large uniform fire source (1.65 m long and at least as wide as the fuel storage tank diameter) affects a large part of the tank. Compared to a small hot flame only affecting a small area of a tank, the large fire increases the pressure inside a tank relatively more than it damages the tank construction. An intense fire affecting smaller area of the tank surface would be a more severe test for these fuel storage tanks. There are no specific time requirements regarding integrity of the fuel storage system except that composite tanks are not allowed to leak gas through their surfaces during the first two minutes of the test. Liquefied DME is similar to LPG, both are naturally liquefied at around  $15^{\circ}\text{C}$  and 7 bars pressure. LNG however is a cooled liquefied (cryogenic) gas.

LNG is stored in a thermos tank to minimize heating of the LNG which causes the pressure to rise which is vented to avoid tank rupture. LNG is stored at  $-162^{\circ}\text{C}$  and at around 5-20 bars pressure. Once parked the liquid starts to heat up and, unless the engine is started, venting of the pressure build up will eventually occur (boil-off). As an example, venting of a 400 l LNG tank from 15.9 bar result in that 3.5 kg of methane gas is vented before the valve closes again at 14.8 bar. When this happens depends on the hold time of the tank, e.g. 7 days, when it was refueled and how full the tank is. A lesser amount of fuel is heated faster which can decrease the hold time of a full tank considerably, e.g. down to 2.5 days when 10 % LNG remains. The holding time can be calculated from the level indicator and either the tank pressure or temperature. It is thus possible to ensure venting does not occur during a specified amount of time. Water should never be applied onto spilled LNG, since LNG then evaporates faster. A suitable extinguishing agent (e.g. dry chemical) shall be applied.

To summarize above; vehicles using liquefied fuels carry different risks compared to liquid fuels. These differences are basically as follows:

- Jet flames from a PRV activation
- Gas tank integrity loss
  - severe increase in fire size
  - BLEVE
  - tank explosion
  - gas explosion
- Gas leak
  - gas explosion (if gas can be accumulated for a while before being ignited)

As with all hazardous events it will be impossible to set time limits for when these events can occur. A risk assessment has to be made by the first responders at the scene of fire. There is, however, a risk that all these events can occur at the time when a first responder approaches the fire. A PRV activation is considered to be an acceptable risk, but care must be taken not to come in contact with a jet-flame. The worst scenario is when the pressure is not released rapidly enough and the tank rupture or a BLEVE occur.

Tank rupture, explosion and BLEVE are all hazards with severe direct consequences at a given distance from the vehicle and could possibly even damage the ship if they occur in an enclosed space.

### 3.3 Compressed gas

Compressed gas vehicles are today using CNG/CBG in an internal combustion engine, where they are often used in combination with a liquid fuel so the vehicle runs either on compressed gas or liquid fuel, or GH<sub>2</sub> (hydrogen) in a fuel cell. Tanks could be positioned in different places in the vehicles. In cars the tanks are often positioned low, above the bottom plate of the car from the mid-section and to the rear. They can also be positioned in the trunk. They are hidden and will be very difficult to reach during a fire (Gehandler et al. 2017).

CNG/CBG are often stored in a gas tank of 200 bar pressure. Hydrogen is stored at higher pressures, 350 bar or 700 bar. Hydrogen is odourless and burns with a very hot flame (about 2000°C) (Gehandler et al. 2017). The gas is colorless and consists of two hydrogen atoms, making it the lightest and least complexed element. As a result, the gas accumulates in garages or under roofs, for example. Hydrogen can diffuse into material and make it brittle, which is another consequence of its small molecular size. Other risks associated with hydrogen are its high-pressure during storage and the low temperature at the outflow. It requires little energy to ignite and the gas burns with an almost invisible flame. The energy it takes to ignite hydrogen is ten times lower than the energy it takes to ignite petrol (Björnstig et al. 2017). One-kilogram hydrogen contains three times more energy as one-kilogram petrol. However, a hydrogen tank is typically only at around 5-8 kg, much less than ordinary petrol or diesel tanks.

The gas storage systems are equipped with thermally activated PRDs (tPRDs) which are to activate at 110°C and could be equipped with PRDs activating at certain pressure thresholds, e.g. at 1.7 times the working pressure of the tank (UNECE 2014c, UNECE 2014d). If engulfed in flames the activation of a PRD or tPRD is likely to occur after a conventional liquid fuel tank loses its integrity (2 min vs 5-10 min for gas tanks), see Table 3. For composite tanks a marginal increase in internal pressure, below 15 % before tank rupture or leak, occur during a fire (Ruban et al. 2012). Since steel conduct heat well, the pressure increase will quickly start to rise if fire-

exposed. The higher the initial pressure, the faster the time to tank rupture for all types of gas tanks. Fire tests and real experience show that gas tanks often are exposed to local fires, then the tPRD may not be heated in time (Ou et al. 2015).

Table 3. Time to critical events for pressurised vehicle gas tanks<sup>2</sup> (INERIS, 2000), (Nina K. Reitan 2015), (Perrette and Wiedemann 2007), (Tamura 2014), (Weyandt 2005), (Zheng 2010), (Ruban et al. 2012).

Time to tPRD activation (tank tests)	Time to tPRD activation (vehicle fire tests)	Time to tank rupture (tank tests, no tPRD installed)	Time from fire detection to tank rupture (real fire events)
1-15 min	15-120 min	3-20 min	10-20 min

When a PRD activates during fire an intense jet flame will be created. The jet-flames from a car should normally be directed downwards and backwards at an angle, but there are no requirements specifying the directions. Jet-flames from other vehicles, like buses and trucks could be directed differently, tanks placed high (e.g. on bus roof) will likely have jet-flames directed sideways or even downwards, tanks placed low (in e.g. trucks) will likely have the jet-flames directed upwards or downwards at a given angle.

The jet-flames from a PRD activation of compressed gas storage are severe and personnel must be kept away from the flame. The flames will most likely extend towards the floor/backwards from a car. They may spread the fire and will damage equipment which comes in their way. Depending on how the vehicle is located in relation to other gas vehicles more tPRDs could activate leading to a plausible domino effect. The design of the tPRD will affect the length and velocity of the jet flame (Reitan et al. 2016). A flame length up to 8.3 m is possible for a 700 bar hydrogen tank with a tPRD diameter of 4 mm. This would result in a radiation level of 5 kW/m<sup>2</sup> 17 m from the vehicle. Without protective gear injuries could occur within 29 m from the vehicle (Bøe and Reitan 2018).

The activation of tPRDs can be reached quicker than a pressure sensitive PRD activates due to increased pressure in the gas tank, but if the fire is localized at the tank's far end away from the tPRD it may never have the chance to reach 110°C before the tank is damaged enough to rupture. During fire fighting there is a risk that the tPRD is cooled by the extinguishing media so that it does not activate, even though the tank is still affected by the fire and the pressure inside increases. The consequence may be that the tank ruptures. Regardless if a tank is equipped with a tPRD or both a pressure activated and a tPRD there is a risk that a tank explodes before the pressure is ventilated and a jet-flame can occur. If PRDs do not activate the tank may rupture and cause an explosion with severe direct consequences at some distance from the vehicle and could possibly even damage the ship if they occur in an enclosed space.

Zaloch (2007) measured blast waves and the following fireball of a hydrogen (350 bar) tank pressure vessel explosion outside. Peak pressures that were measured varied from 3 bar at a distance of 1.9 m to a low at 0.4 bar at 6.5 m from the tank. The hydrogen fire ball measured 8-24 m. Based on several tests and incidents, Zaloch (2008) finds that projectiles resulting from pressure vessel explosions can fly up to 100 m from the vehicle.

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<sup>2</sup> The table shows a large variation in the time values. The tests which these values were extracted from were performed using different setups, tanks and fires. The real events referred to may have had tanks already weakened from wear and tear before being exposed to fire.

The ventilation possibilities affect the outcome. Good ventilation prevents explosive atmosphere, reduces the volume of explosive atmosphere and reduces the duration of explosive atmosphere (Reitan et al. 2016). Ventilation in open ro-ro spaces and weather decks is natural but closed ro-ro spaces requires mechanical ventilation. In a study of a leaking fuel line in a tunnel at low ventilation rates (0.65 m/s and lower), Zaloch et al. (1994) found that leaking petrol cause larger flammable air-petrol clouds than leaking CNG. The CNG leakage requires ventilation below 0.13 m/s to form a larger cloud. Petrol form large cloud along the floor level at 0.65 m/s and a large cloud that extends to the whole cross-section at 0.3 m/s. Vehicles stored in ro-ro spaces are turned off. Then the electro-magnetic valve on the gas tank is closed. Thus, the system can only leak a negligible amount of gas, as long as the tank does not rupture. This means that gas explosion is very unlikely. However, fire ball or jet flame as a result from fire is much more likely in case of a fire. Furthermore, considering the large spaces on ro-ro ships and the small content of stored fuel in each tank makes a gas-cloud explosion unlikely, even if the system was activated and leaked. Hydrogen can transfer to a detonation in enclosed spaces, but a hydrogen detonation is even more unlikely considering the large space and the small amount of gas in each tank.

For compressed gas vehicles the hazards are similar to the liquefied fuels, except for BLEVE which cannot occur from compressed gas. However, with the higher pressure it becomes possibly to obtain more severe consequences. Also, the PRDs required are thermally activated and they will remain open after activation thereby ventilating the complete contents of the gas tank. This will cause a larger and also longer lasting jet-flame than for liquefied fuels.

### 3.3.1 Deterministic limit values from explosions

Bøe and Reitan (2018) summarize resulting pressure consequences for materials and humans. Table 4 summarizes critical events for this study.

Table 4. damages from explosion overpressure.

Event	Overpressure [kPa]
Lower limit for cracked mucous membrane.	14
hazardous window splitter, 50 % mortality	28-35
Steel frames may start to collapse	20 - 30
50 % limit for cracked mucous membrane	35 - 48
Vehicles may turn over	55 - 83
Lower limit for damaged lungs	83 - 103
50 % mortality caused by damaged lungs	138 - 172

As an example this means that the limit of 14 kPa is reached at a distance of 12 m from a 80 l tank and 16 m from a 150 l and 770 bars hydrogen tank if a pressure vessel explosion would occur (Bøe and Reitan 2018). However, inside enclosures, such as ro-ro spaces, corresponding pressures will become higher, as was seen in the previous section.

Note that structures are not only affected by the overpressure, but also the duration of the impulse. For the same overpressure, longer impulses are more severe. A pressure vessel explosion

(physical) with subsequent fire ball (chemical reaction) when the gas mixes with air and burn of, leads to a prolonged impulse (Gehandler et al. 2016).

### 3.3.2 Investigation of the effect from the ship enclosure

A pressurized CNG gas tank explosion in a ro-ro space has been studied in a numerical simulation software called Autodyne. According to Perrette and Wiedemann (2007), the mechanical energy from a physical burst of a 130 l pressurized gas tank of 200 bar being 8.7 MJ. Such energy is equivalent to 1.85 kg TNT. The numerical model assumes that a tank rupture is equivalent to the explosion of TNT. The numerical model is compared with an empirical method, which shows that the numerical model yields conservative but reasonable results. The Autodyn model is useful for studying different explosion scenarios qualitatively. A more detailed account of the simulations can be found in Appendix 1.

A pressure vessel explosion onboard a ship firstly depends on the tank volume and pressure. Larger tanks and higher pressures yield higher explosion pressures and resulting consequences. In this case a 130 l tank at 200 bar pressure has been studied which represent a large tank in relation to personal vehicles, but small for coaches. A tank pressure of 200 bar represents a full CNG tank, but only a half-full hydrogen tank. In the open such an explosion result in injury (48 kPa) within 5-8 m and a safe distance (no harm, 14 kPa) above 10-20 m.

If the tank explosion instead is placed in a ro-ro space, the explosion pressure can be increased due to reflections with the surrounding structure. The worst case is a fully closed space with the explosion close to the side wall. Such a case would increase the injury threshold cited above within 18 m and a safe distance up to 56 m. In other words, the explosion overpressure in a closed ro-ro space is much higher as compared to an open ro-ro space, in particular the difference is significant for minor injuries. The reason is due to the reflections of pressure wave from the front and side walls and ceiling that amplifies the pressure wave inside the ro-ro space.

Due to the effect of reflection, firefighters should not stand next to walls facing the AFV on fire. The amplitude of the incoming pressure wave will roughly double next to the wall.

If the ro-ro space is only partially closed, i.e. the front and stern open, the resulting pressure wave is reduced in the front (10-25 m) and the stern (5 m) in the ro-ro space. The reason is that the pressure wave is amplified due to the reflections from the front and stern in the case of a closed ro-ro space.

It was also studied if a 2 m high vehicle 10 m from the explosion could work as a safe barrier behind which firemen could find rescue in a closed ro-ro space. It was found that the barrier has substantial effect in reducing the explosion overpressure up to around 15 m behind the barrier. At 12.5 m from the explosion, the pressure is reduced from 50 to 35 kPa. The barrier has little effect in reducing overpressure after around 15 m from the barrier. The barrier has a limited effect in reducing overpressure at higher heights than the barrier. The protecting effect is greatly reduced up to a height of 2 m and fully lost at the height of 3 m. However, vehicles also represent a risk in case they are turned over by the pressure wave. This could happen between 55 and 80 kPa.

The calculations also imply that structural damages from this type of explosion in a closed or partially closed ro-ro space will be minor along the whole ship length, and severe locally (10-20 m).

### 3.3.3 Strength of gas tanks after fire

Tamura et al. (2018) exposed carbon fibre reinforced plastic (CFRP) tanks to a fire. Just prior to the expected rupture time (8-15 min depending on the tank type, strength and filling ratio) the fire was shut down and the tanks were cooled naturally (convection) or with water spray from a hose. The pressure continued to increase 5-15 min during cooling with water spray and 5-30 min during natural cooling. The study shows that a margin of safety against pressure vessel explosion for fire exposed CFRP tanks was regained after cooling due to two factors:

- Reduction of the pressure load from the contained gas.
- Restoration of CFRP strength when melted plastic hardens.

Tamura et al. (2018) concluded that there was little fear of tank rupture for the cooled CFRP tanks after fire exposure. Fire extinguishment and cooling with water spray is recommended.

Bo et al. (2017) exposed austenitic stainless steel to a LPG fire at 650 °C and tested the residual strength. The longer the fire duration (20, 40 and 60 min was tested) the more strength degradation occurred. Maximum loss in the measured strength parameter was the yield strength that was reduced to 84 % of the original yield strength after a fire duration of an hour. After 20 min fire exposure the yield strength was reduced to 90% (Bo et al. 2017). Most likely steel gas tanks would vent or fail (due to internal gas pressure increase) within 20 min fire exposure. This means that neither are steel gas tanks likely to fail after they have cooled down, nor that the pressure load from the contained gas is decreased. Since steel conducts heat well, the reduction in pressure load is significantly higher than for composite tanks exposed to the same fire.

Thus, one can conclude that there is little fear of tank rupture for gas tanks exposed to fire, once they are cooled to normal temperature. Note however that composite tanks may leak after fire (Ruban et al. 2012). If so, the tank can be left under surveillance at a well-ventilated place until it is emptied.

## 3.4 Batteries

At present Lithium-ion batteries are the most commonly used in Battery Electric Vehicles (BEV). Because of the limited use of other technologies and the fact that the widely used NiMH-batteries (used to be common in Hybrid electric vehicles) does not burn, this study will focus on the Lithium-ion technologies when it comes to BEV. Also, there are several different technologies used within the Lithium-ion family and that has meant that this report will be general and highlight the hazards rather than pointing out what technologies sometimes might be less hazardous than others.

Lithium-ion batteries exposed to fires may be thermally provoked into a thermal runaway. Battery may also start a thermal runaway due to an internal short circuit either from production fault or if they have received severe mechanical damage from the outside<sup>3</sup>. Regardless of how the fire started, a thermal runaway will mean that the electrolyte within the battery is decomposing in an exothermic reaction. Heat and gases are produced and if oxygen is present a fire will occur. Inside the battery the oxygen content is very limited, but the pressure increases from the gas produced

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<sup>3</sup> Such damage could be seen on the exterior which would have to be deformed to achieve a damage to that extent. Bear in mind that this study focuses on fires on ro-ro decks where collisions of that sort are unlikely.

in the decomposition of the electrolyte will have to be ventilated. When it is ventilated the combustible gases will burn outside the battery if ignited. If the combustible gases are not ignited directly there is a risk of a gas explosion. If the gases are not vented from the battery there is a risk for explosion or that the battery become a projectile (Bisschop et al, 2019). Being protected from external damage also makes the batteries hard to reach and difficult to cool down. Basically, thermal runaways are considered close to impossible to stop if there is no access to the inside of the batteries and since the thermal runaway can go on for several hours, and could even start more than 24 hours after the initial damage took place, the Lithium-ion batteries are tricky in terms of fire-fighting and judging when an extinguished fire will not re-ignite or when a damaged vehicle may catch fire. (Long et al. 2013)

The electrolytes may start boiling at around 90°C (MSB 2016b), which could be used as a limit for what the battery cells cannot be exposed to, but the point-of-no-return or thermal runaways could be at 150°C or likely higher. This is when the cathode materials start to decompose in an exothermic reaction and where the temperature can increase rapidly and without control (Lars Hoffmann 2013, Andersson et al. 2017)

If engulfed in flames a battery may be provoked into a thermal runaway after a time likely to exceed that needed for a conventional fuel tank to lose its integrity. A battery is also better encased and protected than a fuel tank is to start with and it could therefore take more time before the fire reaches the battery. In fire tests the results have varied, but when large fires are acting directly on the battery it has lasted 2-11 minutes before contributing to the fire, see Table 5. When full vehicle tests have been performed, the first contribution came 25-40 minutes into the fire test. In a fire test performed in 2017 a EV-fire was initiated with the aim to start a battery fire, however, although the fire was fully developed into a flash-over fire, it was realized after extinguishment that the battery had not been involved or contributed to the fire (Bøe 2017). This shows that batteries can be well-protected from vehicle fires that does not start in the battery.

The amount of toxic and flammable gas, the heat release rate and the vulnerable to self-heating reaction is not only depending on type of battery but also the capacity and state of charge (SOC) of the battery (Bisschop 2019).

Table 5. Time from fire exposure to thermal runaway or electrolyte involvement in the fire (Blikeng and Agerup 2013), (Egelhaaf et al. 2014), (Lecocq 2012), (Long et al. 2013), (Watanabe 2012), (Bøe 2017), (Bobert 2013).

	Time to thermal runaway or electrolyte involvement in fire
Fire tests using flames directly on battery	2-11 minutes
Vehicle fire tests	25-40+ minutes

Reviewing fire tests involving Lithium-ion batteries leaves the conclusion that for the capacities used today they will likely contribute less to the fire load than a conventional liquid fuel storage and while they will burn extremely hot in specific locations for limited amounts of time they will likely have a lower heat release rate than the other energy carriers used today. They will however very likely burn for a longer period of time although the intensity of the fire will drop and the fire tests show that after 40 minutes the intensity will be low, although possibly high enough to re-ignite a fire to a flaming stage if any combustibles are still present (Blikeng and Agerup 2013, Bobert 2013, Long et al. 2013)

### 3.4.1 Gases formed by battery vehicle fires

In case of fire in an electric vehicle, the battery can emit toxic gases. A burning Lithium-ion battery can generate a lot of gas and smoke. The burning battery can emit gases like hydrogen fluoride (HF), phosphoryl fluoride (POF<sub>3</sub>), phosphor pent fluoride (PF<sub>5</sub>), which are highly poisonous gases, and carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and hydrogen gas (H<sub>2</sub>) which are highly flammable gases (Larsson et al. 2018).

When a Lithium-ion battery is burning there is also a risk for electrolyte leakage (Larsson et al. 2014). Electrolyte solution is irritating to the eyes and skin. Electrolyte vapors (upon inhalation) may cause respiratory irritation as well as acute poisoning.

The ventilated gas composition from the battery contains toxic gases, e.g. HF (hydrogen fluoride) which is both highly toxic and corrosive. It is also a quite light and volatile gas and can pass through some protective gear (chemical suit might be needed for protection when exposed) (MSB 2016b, MSB 2019). In contact with skin, the gas causes severe burns and form skin ulcers. When inhaled, the gas destroys the tissue in the respiratory tract, causing swelling and fluid filling in the respiratory tract. Frequently effects of exposure are not shown directly, but symptoms may occur several hours after exposure. Visible damage can be shown 12-24 hours after exposure (CDC 2013). An important aspect to consider regarding this is that, during a vehicle fire, the amount of toxic gas that is produced is high to begin with and that e.g. HF is produced when the most commonly used air condition liquid is combusted. During fire tests, (Lecocq 2012), (Petit Boulanger et al. 2015), the amount of HF produced from a BEV was higher than for the conventional vehicle, but the amount produced from the conventional vehicle was also high. At the same time as the amount HF measured in the smoke was above tolerated thresholds the measurements made on the fire fighter closest to the fire was below the same threshold. Concentration of smoke depends on the scenario and in confined spaces the concentration can be much higher. Also, fire tests have shown an increase of the production of HF during application of water mist, but the total amount of HF during the test did not change (Egelhaaf 2014).

When HF is dissolved in water, it may be called hydrofluoric acid. Test conducted by Egelhaaf (2013) showed that fire water run-off can have a high concentration of fluoride and chloride and should not be released directly into the environment.

When an internal failure causes a thermal runaway, toxic gases can be produced before there is a fire and a thermal runaway may not even always cause a fire. If the thermal runaway does not cause a fire it can still produce a lot of toxic and combustible gases. Without detection there is a risk that the levels of toxic gases become significant and that people may come in contact with the gas without any prior warning. Also, there is a risk of explosion due combustible gas being accumulated. Not all batteries chemistries will produce a significant amount of combustible gases, but this study will consider the possibility that the batteries in general do (Bisschop 2019).

The fire development and states of thermal runaway in batteries are complex and vary with battery chemistry, state-of-charge, failure mode, etc. and while small scale tests show that there is a large amount of HF being produced (Larsson et al. 2018), tests in larger scale have not shown that the small scale tests are scalable upwards (Lecocq 2012, Petit Boulanger et al. 2015)<sup>4</sup>. Also, the explosive force of one cell will likely not be linearly scalable upwards.

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<sup>4</sup> Note that the full-scale tests do not reveal the battery chemistry that was used in the tests.

## 3.5 Summary of hazards in ro-ro spaces

Below is a list of the general events and hazards connected to vehicle fires followed by a list of more energy carrier specific events and hazards:

- General events and hazards:
  - Heat
  - Smoke and toxic fire gases
  - Smaller explosions which could throw projectiles with harmful force, e.g.
    - gas springs
    - airbags
    - tires
  - New materials / unconventional materials e.g.:
    - Carbon fibre, graphene and similar – increases fire load, produce harmful particles during combustion.
    - Magnesium and aluminium alloys – may catch fire, can cause issues when exposed to water
- Energy carrier specific events and hazards
  - Liquid fuels:
    - Fuel tank integrity loss increase in fire size. Pool fires (consider alcohol and other than gasoline/diesel)
  - Liquefied fuels:
    - Venting of LNG boil-off.
    - Jet flames from PRV activations
    - Gas tank integrity loss
      - Increase in fire size
      - BLEVE
      - Pressure vessel explosion
      - Fire ball
    - Gas leak
      - gas explosion (if gas can be accumulated for a while before being ignited)
  - Compressed gas:
    - Jet flames from PRD activations
    - Gas tank integrity loss
      - severe increase in fire size
      - pressure vessel explosion
      - fire ball
    - Gas leak
      - gas explosion (if gas can be accumulated for a while before being ignited)
  - Batteries (Lithium-Ion) (thermal runaway):
    - increase in fire size
    - small jet flames
    - toxic gases
    - gas explosion (if the released gas can be accumulated for a while before being ignited)
    - long lasting combustion (can ignite or re-ignite more than 24 hours after the provoking incident)
    - difficult to stop/extinguish (increased likelihood of re-ignition)

The probability for the hazards from the general list above to occur is probably lowered for AFV:s since more layers of control systems are designed to avoid failure and resulting leakage, e.g.

electro-magnetic valves that close on parked vehicles and active battery control systems. An exception is LNG boil-off. Neither should the probability for starting a fire be increased for alternative fuel vehicle vehicles. For parked vehicles electric failure is a common fire cause on all type of modern vehicles. What differs is the possible consequences once a fire includes liquified or compressed gases. This is less critical for LNG since it is insulated against heat exposure. A jet flame (larger for compressed gases) is expected in incidents with liquified and compressed gases. If the pressure does not drop fast enough or the PRV is malfunctioning, LPG or DME can result in a BLEVE (explosion) and a fire ball. If the PRD does not release fast enough, compressed gas tanks will result in a pressure vessel explosion. After a fire, gas tanks that have been exposed to fire should be cooled before anyone is allowed near the object. On the other hand, lithium-ion batteries that has been involved in a fire should be cooled or supervised continuously.

## 4 Fire fighting

This chapter summarizes current fire fighting tactics on land regarding extinguish AFV and possibilities and challenges for manual fire fighting onboard.

### 4.1 Risk assessment

The most important task is that a risk assessment of the situation for a ro-ro space is made. For example, what are the consequences a fire can cause? The focus should be to identify what fuel is used, where is the vehicle located, what does the environment look like, what are the possibilities for a fire spread, what will be the consequences if a certain extinguishing agent is selected and how to handle contaminated extinguishing water? Are there any immediate danger for passengers that has to be saved and which calls upon a rapid action? Is there anyone in the area around the vehicle that has to be evacuated to a safe place? Is it possible for anyone to enter the area around the burning vehicle? How can the fire be reached and is there a safe escape route? What is the wind direction? Are there any special areas with greater hazards than others? From where can the fire be approached safely? All these questions should be answered before choosing the strategy and the equipment with which to approach the fire.

Björnstig (2017) lists the following factors that shall be considered in order to identify fire fighting methods and tactics needed at the fire scene:

- Initially there is a need to rapidly judge whether any lives are in danger and thereby the need for immediate actions.
- Ensure the safety of the fire and rescue personnel. Rope off the risk area.
- What type of AFV, i.e. what fuel is present in the vehicle and where?
- The extent of the fire. Only fire gases and smoke or fully developed vehicle fire?
- The location and intensity of the fire can constitute important decision support in cases when the fire does not completely engulf the vehicle. Interpretation can be made from affected structures and broken windows which can indicate a certain fire development. Pool fire below the vehicle can indicate leakage and threats to the fuel storage. If the cabin is on fire there can be a rapid fire growth and seatbelt straighteners, pyrotechnical gas generators, gas springs and shock absorbers can discharge.
- The engine compartment of a modern vehicle is often equipped with plastic casings above and below the engine, which could make extinguishment and application of extinguishant more difficult. Oils and liquids in the engine compartment supply the fire with fuel and leaking liquids can cause pool fires, enabling a more complex and rapid fire development.
- The luggage compartment, the tank, or any other energy storage, such as gas tanks/tubes, traction batteries need to be handled in a specific way.
- Fragments from exploding shock absorbers, gas spring dampers can cause injuries.
- Offensive or defensive strategy?

Further considerations are the effect on the environment. Extinguishing water and foam can contaminate the environment and can have long and short-term effects on animals (including humans) and plants. Therefore, the water as far as possible should be collected and destructed. If that is not possible the possibility to use as small amount of extinguishant as possible is recommended. One option is to use water mist systems (Björnstig et al. 2017).

## 4.2 Vehicle identification

When the emergency service is on their way to the accident scene, they prepare themselves by identifying what kind of vehicles that have been involved in the accident, to get an overview of vehicle type and type of fuel (liquid, gas, electricity). This can be done by searching for the license number on Swedish Transport Agency's web page, or get information from the vehicle register through the alarm center based on the Vehicle Identification Number (VIN) from the e-call alarm (Björnstig et al. 2017). If the emergency service has not managed to obtain information about the fuel before arriving at the scene they can ask the driver. It is also possible to look under the fuel cap to identify type of fuel. To get an even better overview of the construction of the vehicle, crash recovery system can be used.

### 4.2.1 Crash recovery system

When the emergency service arrives to an accident scene, it is often time consuming and difficult to identify the inside construction of the damaged vehicle, i.e. where the battery is placed and other items that could be damaged and cause harm. Crash Recovery System (CRS) is a system that has been developed in cooperation by the Dutch fire service and Moditech Rescue Solutions B.V. Crash Recovery System (2018) is a mobile database that gives information how the emergency service can extricate occupants quickly and safely from crashed vehicles. By registering the license plate the emergency service can easily access all relevant information, such as safety information, and prepare themselves before arriving at the accident scene. The mobile database makes it possible to get vehicle information based on brand, model and production year in 18 different languages.

### 4.2.2 Gas tanks

The gas tank in a gas-powered vehicle can be placed inside the vehicle in two different ways (Lindkvist 2016). Firstly, the gas tank is placed where the conventional petrol or diesel tank is located, i.e. underneath the vehicle, see Figure 1. Here, the tank is subjected to a rough environment and mechanical impact, which in the long term can lead to corrosion.

Secondly, the tanks can be placed in the luggage compartment (Figure 2). Disadvantages of having the tank in the luggage compartment are the risk of leakage in the cabin or the luggage space can potentially damage valves and pipes (Lindkvist 2016). Gas tanks on trucks are normally located where the diesel tank usually is, but can also be placed under the cargo or behind the cabin (Gehandler et al. 2017). On busses the gas tank is normally placed on the roof.

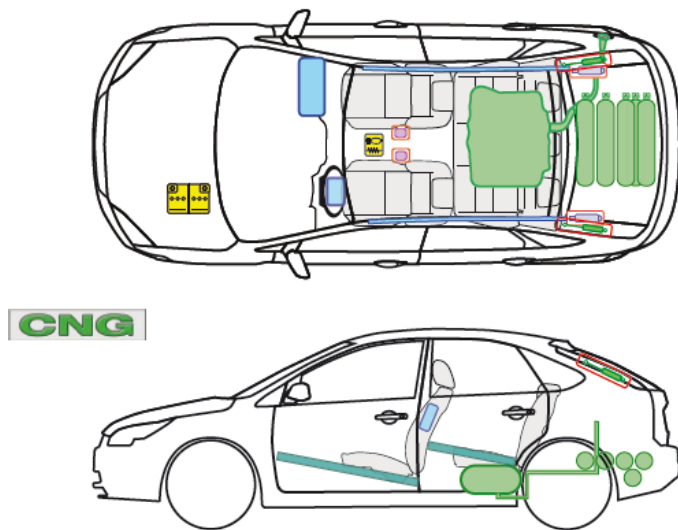


Figure 1: Placement under the floor. Photo: Rescuesheet.info<sup>5</sup>.



Figure 2: Placement in the luggage compartment. Photo (Lindkvist 2016).

### 4.2.3 Battery pack

Hybrid electric vehicles have an internal combustion engine and a battery powered electric engine. Battery electric (all-electric) vehicles are only powered by a battery. The placement and size of batteries differ widely. Usually in a hybrid the battery is smaller and placed in or below the luggage space, see Figure 3. In an all-electric vehicle, the battery is larger and placed below the vehicle, see Figure 4<sup>6</sup>. Even though electric vehicles have huge battery packs, they also have an ordinary 12-volt car battery underneath the hood, partly to drive the car's infotainment system, comfort features and as a safety arrangement (Blomhäll 2016).

<sup>5</sup> [http://rescuesheet.info/files/Ford\\_RettungsdatenblaetterFord\\_25\\_02\\_2010\\_49500.pdf](http://rescuesheet.info/files/Ford_RettungsdatenblaetterFord_25_02_2010_49500.pdf)

<sup>6</sup> Alternative Fuels Data Center, <https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work>

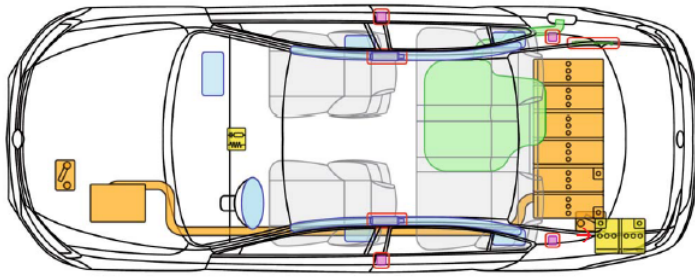


Figure 3: Hybrids placement of the battery. Photo: (Volkswagen 2017).

#### All-Electric Vehicle

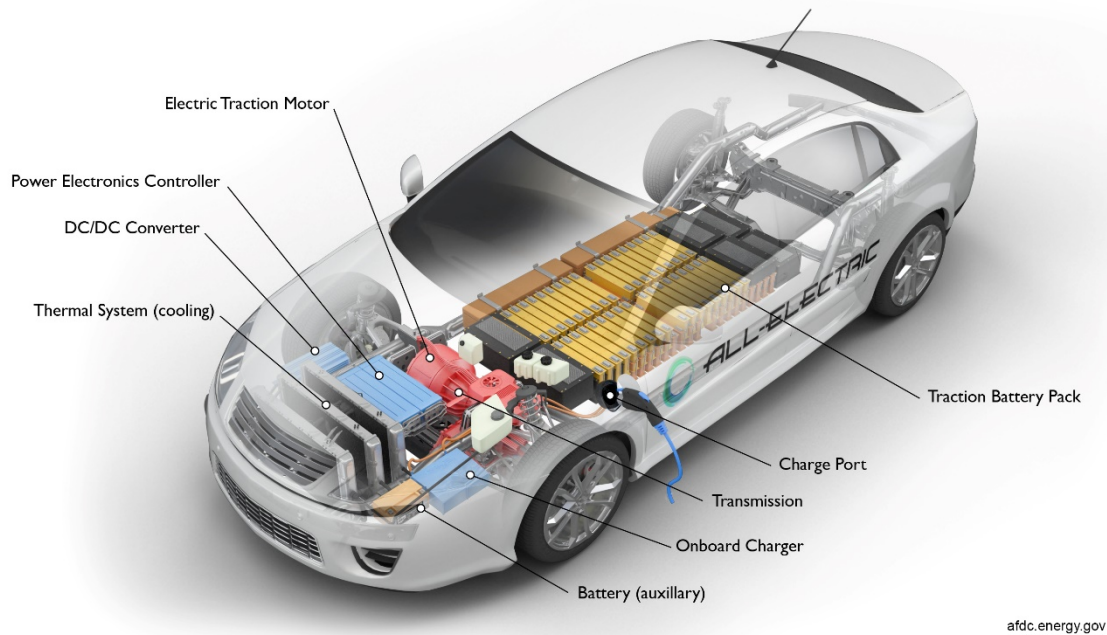


Figure 4: Battery electric vehicle with large traction battery pack placed underneath the vehicle. Photo: AFDC.

## 4.3 Fire fighting tactics

CTIF is a global organisation with the mission to share knowledge, best practice and fire fighting issue worldwide. They published an operational handbook for fire services in 2015 with recommendations on how to handle fires in alternative fuel vehicles (LPG, CNG, GH2, BEV, HEV) and to some extent modern vehicle materials. Based on the initial risk assessment different approaches to the fire may be used. If the vehicle does not threaten any lives and there is no risk of fire spread to buildings or the environment, then a defensive attack is preferable in order to avoid exposure to the hazards of a vehicle fire. If there, on the other hand, is need for rescue or to protect the surroundings fire extinguishing through an offensive attack is preferable.

A defensive attack means to evacuate the risk area and if possible let the vehicle burn if no risk for fire propagation to nearby object. It can also call for suppressing/cooling/extinguishing the fire from a safe distance (outside what is called the hot zone >50 m from the vehicle) to protect the environment and nearby objects.

For fire extinguishing using an offensive approach the CTIF advocates a procedure summarised by the bullet points below.<sup>7</sup>

- Offensive strategy with two teams of firefighters.
  - Team 1: Cool the energy storage.
  - Team 2: Extinguish the vehicle fire.
- Approach vehicle from the front at an angle of at least 45° (3/4 frontal approach). An approach from the rear from 45° angle can be used if a frontal approach is not possible.
- Use breathing apparatus.
- Apply 50 m risk area.

CTIF recommend and base their offensive approach on the use of at least four (five including a team leader) firefighters divided into two teams using one hose in each team with a water supply of at least 250 l/min. The first phase of the fire fighting both teams are to progress simultaneously on the same side of the vehicle and from 40 m distance using a straight jet while approaching. From 10 meters a wide water spray is to be used. As soon as the action is efficient the flow can be reduced. For the second phase, i.e. when near the vehicle, the two teams take on different assignments and here CTIF also differentiates depending on the energy carrier, see chapter 4.3.1 to 4.3.4.

The approach only considers fully equipped firefighters performing a fire and rescue operation with good access to the burning vehicle and personnel of at least five persons.

Björnstig et al (2017) recommend the fire should be approached in the wind direction and a mobile fan can be used to force the airflow and push gases and smoke away from the firefighters. The authors also recommend:

- Water mist can advantageously be used to scrub the air from toxic substances and particles.
- Pool fires below a vehicle can preferably be extinguished with dry chemicals.
- Flaming fires in the engine compartment are most easily extinguished with a CO<sub>2</sub> - extinguisher.
- Do not extinguish fires in magnesium- or aluminum alloys with a powerful water beam. There can be an explosive reaction.
- If possible, stay 1-2 meters away from the vehicle.
- Do not lean into the vehicle unless necessary.

These tactics can be applied to all vehicle fires and below a summary of different fire fighting tactics depending on the fuel type will be found.

### 4.3.1 General tactics gas vehicles

Firstly, the firefighter needs to identify where gas tanks are located and avoid being in the risk area if a jet flame from a pressure relief would occur. Thereafter eliminate risk of fire spread and protect the surroundings from a jet flame, especially ensure other pressurised tanks are protected (safety distance of at least 50 m). An explosimeter can be used for decision support before, during and after extinguishing operation (Björnstig et al 2017).

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<sup>7</sup> Note that a vehicle fire likely has grown to include the larger part of a vehicle when the fire service arrives at the scene.

When the energy carrier in the vehicle is compressed gas or liquified fuel CTIF second phase (i.e. when near the vehicle) of a fire fighting operation will be:

- Team 1:
  - Cool the tank.
    - Low parts are difficult to reach.
    - Do not extinguish the jet-flame if pressure relief valve/device activates.
  - Shield the radiation from the passenger compartment fire.
  - The mission is over when the cooling is complete (judgement based on evaporation of applied water or thermal camera imaging).
- Team 2:
  - Passenger compartment extinguishment.
  - Progress back to front.
  - Pay attention to Team 1.

An 45° angle approached will only consider the danger of being hit by a jet flame or smaller explosion from example gas springs but not consider the explosion hazards connected to fires in liquefied fuel vehicles and compressed gas vehicles. Björnstig et al (2017) recommend that if an offensive operation is needed the firefighter should operate from a protected space, shielded by a vehicle or a building. If not possible to extinguish the fire the firefighter should try to suppress the fire and protect adjacent vehicle, building etc. from a protected space. Wait until the vehicle has burned out, until the tanks explode or the relief valves has open (NFPA, 2018).

For the compressed gases a statistical survey has shown that thermal pressure reliefs did not activate as the safety design intended in 35% of reported fire incidents (Lowell 2013). The CTIF approach never mentions the possibility that a fire fighting operation can cool the tPRD to prevent it from activating. If the pressure in the gas tank keeps increasing tank rupture could occur.

### 4.3.2 Specific tactics liquified fuels

Most common liquified fuels are LPG that are naturally liquified at around 15°C and 7 bars pressure and LNG that is stored at -162°C and at around 5-20 bars pressure.

NFPA (2018) recommend following action related to LPG and LNG:

- LPG vehicles
  - You can extinguish fires involving LPG vehicles using standard techniques.
  - In the event of fire impingement on the tanks, be sure to apply copious amounts of water to keep them cool and prevent a BLEVE. This may occur if the PRD is unable to maintain a safe pressure.
  - If a sufficient water supply is not available, evacuate to a safe distance and allow the fire to burn.
- LNG vehicles
  - LNG vehicle fires can be extinguished using standard tactics unless fire is being fueled by an active leak. In that case protect surrounding objects and allow it to burn.
  - Typically, the tanks are so well insulated that even if the vehicle becomes fully involved, there will be very little pressure increase inside the tank.
  - If there is an increase, the pressure relief valve will activate and bleed off the excess pressure, resetting itself when complete. Application of water to the tanks will not prevent it from working properly.

If there is a leakage without a fire LPG and LNG will act differently. LPG will release gas that are heavier than air and therefore ignitable gas/air-mixture in low spots are possible. Dispersion of the gas cloud can be done using water mist. If there is a release of gas from LNG frost will appear on the tank and it's possible to hear the gas release. It vaporizes quickly and is lighter than air. The vapor cloud will condense moisture from the air and the cloud will probably be ignitable (NFPA 2018). The cloud will be visible at first but after warmed up LNG is colorless and odorless. A thermal camera can be used to detect vapor cloud. As LNG is stored at very low temperature it is important to protect from first degree burns and frostbite when handle leakage, normal protection clothing is not enough protection<sup>8</sup>.

### 4.3.3 Specific tactics compressed gases

Compressed gases mainly involve CNG and hydrogen. NFPA recommend following action related to CNG and hydrogen:

- CNG vehicles
  - Special care must be taken with fires involving CNG vehicles. If the fire is small and remote enough from the tank location that there is no potential for flame or heat impingement, then extinguish it normally. Be aware, however, that fire exposure may not always be apparent.
  - In the case of more significant fire or if the tanks are already involved, do not approach the vehicle. Establish a safe perimeter of at least 24 to 30 meters and allow it to burn while protecting any surrounding objects.
  - Any attempts to extinguish the fire, especially if water is applied to the tanks, may prevent the temperature activated relief device from working properly and could result in catastrophic tank failure.
- Hydrogen vehicles
  - Emergency responders should use a thermal camera when dealing with any hydrogen emergency in order to determine the presence of fire. Hydrogen fires produce almost no radiant heat and no smoke, making it almost impossible to sense the presence of a fire until you are very near or even in the flame. However, at night the flame is visible to the naked eye. Hydrogen burning with other carbon-based flames will likely give color to the hydrogen flame.
  - Composite hydrogen tanks utilize temperature pressure relief devices (tPRDs). In the event there is flame or heat impingement on a composite tank DO NOT attempt to cool the tank. This may cool the tPRD and prevent it from functioning which can result in a catastrophic tank failure.
  - Hydrogen fires should not be extinguished unless the flow of gas can be stopped.

### 4.3.4 Batteries

When a lithium-ion battery cell bursts or opens toxic smoke can be emitted. These heavy, greyish gases formed from the traction battery can be easily ignited. The traction battery can burn intensely for about an hour (Björnstig et al 2017). The possibility of extinguishing a battery is depended of many factors like; size of the battery, size of the fire, where the battery is placed and possibility to reach the battery with extinguish agent. NFPA (2018) recommend using an

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<sup>8</sup> Incident management guidelines for LNG retrieved from: <https://www.ifv.nl/kennisplein/transportveiligheid-weg/publicaties/incidentmanagement-lng> and <http://www.safelng.nl/lng-curriculum-training-field-exposure-fire-brigades/>

offensive attack only if the battery is not involved in the fire or if there is a need to protect buildings or people.

For vehicles with batteries as energy carrier CTIF second phase (i.e. when near the vehicle) of a fire fighting operation consist of:

- Team 1:
  - If there is a fireman access: set a straight water jet in it (Petit Boulanger, et al., 2015)<sup>9</sup>.
  - If there is no fireman access: cool the battery.
  - If the vehicle is plugged in and charging, isolate it from the charging station.
  - The mission is over when the cooling is complete (judgement based on evaporation of applied water or thermal camera imaging).
- Team 2:
  - Passenger compartment extinguishment.
  - Add water boosts if there is a fuel leak.
  - Progress back to front.
  - Pay attention to Team 1.

The approach does not seem to consider that the fireman access to a Lithium-ion battery in e.g. the Renault ZOE will not be available before the rear passenger seat has been consumed in the fire. This means that this can mostly be used as an effort to stop a thermal runaway after the fire has consumed most of the vehicle already. In a situation where the vehicle has vehicles parked nearby, the fire will likely have spread to an adjacent vehicle before the fireman access can be reached.

NFPA (2018) recommend using standard vehicle fire fighting equipment and tactics for an electrical vehicle, but also prepare that a large sustained volume of water can be required. It is not possible to stop a thermal runaway in a single battery cell, but with a large amount of water it is possible to stop the propagation to adjacent cells. There is no electrical hazard to firefighters using water on electrical vehicle fire, but it is not recommended to blindly pierce through the hood with for example fognails or cold-cutting extinguisher (see explanation of different extinguish equipment in 4.4) due to risk of penetrating the battery. NFPA also states “*Continuous application of water on a localized area of the battery for a prolonged period of time before moving to another section of the battery provides for quicker extinguishment. Continue to apply water even after visible flame is no longer present to properly cool battery pack and prevent/reduce the risk of re-ignition.*”

It might be possible to monitoring thermal activity with a heat camera. High temperatures around the cells can be maintained for several hours/days after a thermal runaway and damaged cells not yet having gone through a thermal runaway may enter one long after the fire has been extinguished and the risk of re-ignition is high (Björnstig et al, 2017).

If the high-voltage traction battery is damage but not on fire it is important to monitor the battery and observe for noise, sparks, increase of heat or release of smoke. If any of this is observed water needs to be available to cool the battery (VDA, 2017).

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<sup>9</sup> Some vehicles with Li-ion batteries have a fireman access to the battery which one can aim the water into. On the Renault ZOE this access to the battery vents is below the rear passenger seat cushioning and access is available as soon as the seat has and also a thermal fuse have melted from the heat of a fire.

The amount of smoke after a battery has been extinguished can be larger than for a conventional vehicle therefore it is recommended that the firefighters should block a larger than normal area around the vehicle (Egelhaaf, 2014).

## 4.4 Equipment

A useful, decision support and fire fighting equipment, in comparison to common fire fighter equipment, is listed in the CTIF handbook and complemented in a handbook from the Swedish Rescue Services in Oskarshamn (Arvidsson and Strömberg 2018). Example of decision support:

- Emergency Response Guides – manuals that are normally distributed by the vehicle manufacturer
- Rescue sheets – brief critical information sheets for emergency actions. Often graphical sketches of the vehicles showing the most important information needed for rescue action, e.g. placements of fuel storage, pressure relief locations and directions etc.
- Binoculars – needed for identification of the vehicle from a safe distance
- Gas detector/instrument to detect leaks
- Thermal camera – e.g. to control if leaking hydrogen gas is burning, to control if and temperatures are low enough for the extinguishment mission to be over

Below are some examples of equipment that can be used during fire fighting operations. With a high level of knowledge about various suppression systems' advantages and limitations, the prerequisites for a better and more efficient fire fighting operations will increase. Therefore, fire tests have been conducted and are reported in Vylund et al (2019).

**Mobile fans** – are used to blow smoke and fire gases away from a burning vehicle to improve sense of orientation and enable access to the vehicle. They can also be efficient for avoiding contamination of firefighters and their gear.

**Water mist (300-350 bar, water flow rate 60 l/min)** – Water mist extinguishing systems can be used to scrub smoke and fire gases and reduce the amount of toxic substance in the air. It can also lower the temperature. This improves accessibility to the fire.

**Dry chemical extinguishers (handheld extinguishers 6-12 kg)** – Efficient method of extinguishing fires related to gasoline leakage (pool fires). Also, effective flame knockdown for fires in engine compartments, cabins and luggage compartment. The fire fighter must stand close to the fire.

**CO<sub>2</sub>-extinguisher (handheld extinguisher)** – Advantageously used for extinguishing engine compartment fires. Clean agent where no extra pollution from the extinguishant is left after the fire. Efficient in a smaller volume. The fire fighter must stand close to the fire.

**Low pressure systems – water (10 -12 bar, 75-475 l/min)** – Make use of a mist nosepiece. Effective fire gas and surface cooling.

**Increased pressure systems – water (40-60 bar, 75-150 l/min)** – Requires more training, but more efficient use of droplet sizes than low pressure systems.

**High pressure systems – water (100-350 bar, 20-60 l/min)** – Very effective fire gas cooling. Lower flow requires longer time of application.

**Foam systems** – Optimized for breaking surface tension of the water droplets and thereby creating an increased cooling.

**CAFS (Compressed Air Foam Systems)** – Effective surface cooling. Can be applied from a distance of about 10 meters from the vehicle. Used primarily when need of surface cooling exists or to fill a cabin with foam. Could possibly be applied on adjacent vehicles to protect them from heat.

**Fognails (in Sweden known as dimspik)– water (70-85 l/min, low pressure or increased pressure)** - By putting a fognail through e.g. the cabin roof or the engine hood one can apply water into the space without the need to open the enclosure or stay near the fire. Do NOT put the fognail into a battery, it can cause a short circuit and start a thermal runaway.

**Aerosol (PGA) grenades (500–1000 g)** – High efficiency in enclosed spaces. Can be thrown into the fire area. Activation time 10-15 s, discharge time of about 20 s.

**Vehicle fire blankets** - Fire blankets in large sizes, designed to be placed above vehicles in order to limit the oxygen supply to a fire. Its area of use is considered small, it can delay fire development, but one cannot count on an on-going fire in a lithium-ion battery being extinguished.

**Water tender (tanker) or fire post** – large quantities of water may be needed for extinguishing a battery fire.

**Water cannon** – enabling fire fighting from safe distances.

**Portable sprinkler nozzles** – Can be placed under or inside a vehicle in order to apply water without the need for personnel to stay close to the fire.

#### 4.4.1 Gas detectors

In case of fire in a gas vehicle, flammable gas like methane (methane CH<sub>4</sub>), LPG, DME and hydrogen (H<sub>2</sub>) can be emitted.

In the case of vehicle fires, toxic gas may be emitted from e.g. a burning battery. Today's markets include portable and stationary detectors, gauges and analysis instrument to help detect nitrous gases, flammable gases, toxic gases and substances, and explosives. The devices differ in relation to what kinds of gases they detect and how many gases they are able to detect at the same time. An ordinary one-gas gauge can measure one of the gases: carbon monoxide, hydrogen sulphide, oxygen, carbon dioxide, chlorine gas, hydrogen cyanide, ammonia, nitrogen dioxide, methane, phosphine or sulfur dioxide. Multi-gas detectors that can detect more than one gas at the same time also exists. Some devices are also able to detect lower explosion limit.

#### 4.4.2 Personal Protective Equipment (PPE)

Research about long-term risk of being exposed to smoke from different fires has gained interest in relation to protect firefighters from exposure. In Sweden the standard operation procedure is to avoid standing in the smoke without properly PPE and breathing apparatus. Even with properly PPE it is recommended to avoid smoke and if possible conduct a fire fighting operation upwind or from outside of the building. The risk of being exposed to HF has been discussed and some fire and rescue services has a routine to use chemical suits when there is a risk of being exposed to HF. A recent study (MSB 2019) evaluated the ability of preventing exposure to toxic gases with different combination of protecting clothing. The result showed that a certain combination of clothing would better protect against hydrogen fluoride, carbonyl fluoride and combustion particles than expected. For cyclohexane and hydrogen cyanide the tests showed that the capacity

of protection was still low. During the tests the materials in the clothing were exposed to a high concentration of toxic gases that are only likely close to the fire. The tests are only valid for the material itself and not for the complete system, e.g. test does not show gas leakage through openings, zippers etc. during movement. It was also concluded that contaminated clothing should be removed directly after smoke exposure due to toxic substances are accumulated in the clothes. Although the test result indicates better protection against toxic substances than expected it is still important to reduce the time duration in smoke-filled environment.

## 4.5 Post-extinguishment

The MSB report (Björnstig et al. 2017) gives a detailed guideline on what to do when there are no more flames and the vehicle parts are sufficiently cool to not re-ignite a fire. The post-extinguishment actions are summarized in Table 6.

Table 6. Post extinguishment actions depending on fuel type (Björnstig et al. 2017).

Fuel type	Action or statement
Liquid fuels	<ul style="list-style-type: none"> <li>• Disconnect 12 V-battery.</li> <li>• Empty fuel tanks.</li> <li>• Relocate to where there is no risk of fire spread.</li> <li>• End operation by scanning the temperatures with a heat camera.</li> </ul>
Compressed gases and liquefied fuels	<ul style="list-style-type: none"> <li>• Disconnect 12 V-battery.</li> <li>• Use an explosimeter to determine if the gas system is leaking.</li> <li>• Relocate to where there is no risk of fire spread.</li> <li>• End operation by scanning the temperatures with a heat camera.</li> </ul>
Battery electric vehicles	<ul style="list-style-type: none"> <li>• Disconnect 12 V-battery.*</li> <li>• Monitor temperature development in traction battery with a heat camera.** Thermal runaway can start / restart several hours or even days after the initial event.</li> <li>• Even if visible external flames are extinguished in a battery fire, the cells can still re-ignite the fire if a thermal runaway starts. It is important to cool the battery with water to delay the thermal runaway propagation through the battery*** and to stop the battery from re-igniting the remaining material in the vehicle.</li> <li>• If there is an opening in the battery, providing access to the battery cells water can be sprayed into the battery and fight the temperature development inside.</li> <li>• In cases where the battery has separated from the vehicle, the battery can be lowered into a container with water and 1.5-3% salt.****</li> <li>• Empty the traction battery on electrical energy if possible.</li> <li>• Choose a transportation path to avoid allowing fire gases spreading into a populated area.*****</li> <li>• Choose a safe relocation spot outside preventing fire spread if there is re-ignition.</li> <li>• End operation by scanning the temperatures with a heat camera.</li> </ul>

Fuel type	Action or statement
	* - BMS can be dependent on the 12 V system and disconnecting the 12V may therefore harm the traction battery
	** - difficult to monitor temperature development from outside a battery pack, especially when the pack is still in place inside a vehicle.
	*** - requires large quantities of water and might not be effective enough for cooling the interiors of the battery pack.
	****- can short circuit the cells and could cause intense reactions and gas production.
	*****- dilution of gases likely makes this action excessive.

As mentioned above in the CTIF guideline, it is important to keep low temperature on the battery for some time to avoid re-ignition. A battery pack in a vehicle is well protected and therefore a thermal runaway is difficult to extinguish and re-ignition is likely (Gehandler et al. 2017). Firefighters must pay attention to odours and ventilate as quickly as possible. In such cases a breathing apparatus may be required. Typically, re-ignition is accompanied by a “whooshing” or “popping” sound with white smoke following and/or sparks that re-ignite the smoke to visible flames (NFPA, 2018).

If no smoke remained and the temperature has reduced, the vehicle can be evacuated from the location. The vehicle should be positioned so that a possible re-ignition does not pose danger to the surrounding. It is important to check the temperature continuously with a heat or infrared camera to be able to identify risk of a thermal runaway and re-ignition. If the battery cell temperature exceeds 190 degrees and continues to increase, there is a risk of a thermal runaway. This in turn will increase the risk of a battery fire. Information about these possible consequences must be reported to other rescue teams such as police and wreckers. In the cases where the battery is separated from the vehicle, it can be lowered in a container consisting of a saline solution 1,5 – 3 % (Björnstig et al. 2017). The solution works as cooling but also through its conductive ability to discharge the battery pack faster. The extinguishing water should be disposed so no surrounding nature is damaged.

When an electric vehicle is on fire, hazardous gases such as hydrogen fluoride, which is both highly toxic and corrosive, can be produced. The gas is also quite light and volatile and can pass through some protective gear (MSB 2016b). It is recommended that directly after a fire fighting operation remove protective clothing and the responders should take a shower. Breathing apparatuses should be removed as a final action. Clothing should be taken care of as recommended in “Skellefteå Model” (MSB, 2015).

Decontamination can be relevant for firefighters exposed to smoke. Utkiken (2018) has presented a decontamination and antidote routine after skin exposure of hydrogen fluoride. Before decontamination, three things should be considered to estimate how much impact hydrogen fluoride has had and requirement of decontamination: the size of the battery, the volume of the smoke spread and exposure time. Decontamination is required if the skin is burning or problems arise with respiratory and eyes. As a first action, the exposed responder has to take off contaminated clothes and flush the body with large amounts of water. Calcium gluconate gel or a water solution with 20 sparkling tablets Calcium Sandoz á 1 gram 2 liters of water can be taken until medical care says that it is no longer necessary.

If severe symptoms of smoke inhalation are shown, 100 percent oxygen needs to be inhaled (Björnstig et al. 2017). At exposure of hydrogen cyanide (HCN), Cyanokit 5 gram in 200 ml NaCl as infusion for 15-30 minutes needs to be given right away.

In case of a gas vehicle fire, a sparkling noise indicates a gas leak. A leak in enclosed spaces can accumulate combustible fire gases which may lead to an explosion if the gas-air concentration is within the explosion limits. Outdoor accumulation of gas is not plausible. Based on section 3.3.2, it is clear that the risk of a pressure vessel explosion after a fire exposed gas tanks have been cooled is very low. This means that the vehicle can be taken to a designated place to empty the gas tanks. Another approach is to shoot a hole in the tank at the fire scene, if possible, although this naturally introduces other risks see MSB (2016a). NFPA (2018) recommend that after a cylinder or tanks have been involved in a fire it must be inspected, emptied and removed by trained personnel.

## 4.6 Underground parking garages

The incident command should always perform a risk assessment prior to authorizing the use of strategic methods during a rescue operation. According to the Swedish Work Environment Authority (AFS 2007:7) an indoor fire fighting operation is to be performed only in order to save lives and external fire suppression should be considered as a preferable alternative.

The challenge of fire fighting in underground parking garages can in some ways be the same as in ro-ro spaces. A Swedish undergraduate analysed the working conditions of firefighters by studying seven fire fighting operations in parking garages (Nordström 2015). The selection of the operations investigated was not based on fires involving alternative fuels or fires in modern vehicles, but conclusion made from general literature study.

It is difficult to locate where the fire is and what is burning if the responders are located outside the building. Therefore, an indoor fire fighting operation can be necessary to reach and extinguish a fire. The size of some garages requires many firefighters, as the first pair may run out of air before they have even arrived with water hoses at the fire site. In several of the studied cases, intense heat, made it difficult to use the thermal camera for orientation because there were no differences in the temperatures. The intensive heat also gave rise to a risk of spalling and a collapse of beams and other ceiling installations such as fans. The presence of shafts, which were difficult to identify, created a risk of falling. It was also difficult to vent the fire gases in order to decrease the temperature and improve visibility.

Nordström (2015) concludes that the most serious near-accidents for firefighters were experienced in fire fighting operation in parking garages. This high level of risk is the result of the design of parking garages (large, open spaces that are difficult to ventilate and orientate oneself in) together with large quantities of dense fire gases and high temperature during a vehicle fire. The situation was made even worse by the fact that AFV brings new risks, where the risk of explosion was critical.

Most countries, municipalities, and county councils pose restrictions relating to the presence of gas-powered vehicles in underground structures. These ranges from a total ban, to their being permitted only on the floor immediately below ground level. Measures are also in place that increase safety in garages or with regard to vehicles (Lönnermark 2014).

### 4.6.1 Liquefied fuels and compressed gas vehicles

For vehicle fires in indoor environments (e.g. garages), MSB (2016a) recommends that fire fighting operations should be performed primarily from outside of the building, unless an indoor operation is required in order to save lives. If an indoor operation is needed, all doors and ventilation openings should be open to be able to relieve the pressure wave. The use of extra protective equipment in the form of an armoured fire engine that is resistant to heat, shock waves, and falling beams is recommended in indoor environments. It is important to measure concentration of gas at high points, on the rear-underside of a vehicle, in the interior, and in the engine compartment. Hissing sounds may also indicate a leakage (MSB 2016a).

### 4.6.2 Batteries

The fire and rescue service in Gothenburg recommend that if lithium-ion batteries are involved in a fire in an indoor environment, all personnel who are in connection with the object (also outside the building, for example) are provided with breathing apparatuses. They also recommend high level of ventilation and shorter duration of fire fighting operation inside the building. If possible, extinguish from the outside of the building or from a greater distance.

## 4.7 Possibilities and challenges for manual fire fighting on-board

A workshop with personnel from shipping companies, authorities and fire and rescue services was held on 22<sup>nd</sup> May 2018. During the workshop, different possibilities and challenges with ro-ro space fires were discussed and are summarized below:

In ro-ro spaces detection is likely to be faster than on land which means that a quick first response to control the fire can be carried out. At the same time the vehicles are parked closed to each other, which can both speed up fire spread and make it difficult to reach the fire. It can also be difficult to identify what kind of vehicle is on fire and what hazards could be relevant. The height within a ro-ro space can be quite low which will affect fire development, fire spread, accessibility and also visibility. Questions raised during the workshop concerned what impact an explosion could have on the ship's structure? Can a jet flame affect the fire separation between different ro-ro spaces? How fast can a fire spread with a jet flame? The workshop also concluded that there is a need for simple rules-of-thumb for how to conduct a proper risk assessment related to AFV firefighting onboard.

The possibility of manual fire fighting was discussed during the workshop. Fire fighting methods for a first quick response do not differ between traditional fuel vehicles compared with AFV as the aim is to extinguish a small fire that are not affecting the fuel storage. The aim could also be to delay a fire propagation until a fire fighting team can be ready or the fixed extinguishing system. In this case the most important is that the fire fighting tool is easy to handle and ease the possibility for the crew to reach the burning vehicle. Lightweight handheld extinguishing tools such as powder fire extinguishers, fire extinguishers, aerosol grenades, etc. could be used.

When the fire has grown to a size when the fuel storage is affected fire fighting tactics will differ between different vehicles. Since it may be impossible or inappropriate to extinguish an AFV fire (such as thermal runaway in a battery or jet flame from a gas tank), the participants discussed if the aim should rather be to prevent the fire from spreading. For example, nearby vehicles could

be cooled with some kind of insulating extinguishing agent or locally placed sprinkler. There may also be a possibility to create a portable water wall between the fire and adjacent vehicles. It was also discussed to use high pressure systems to efficiently cool off fire gases at a distance or to use water monitors, which is primarily relevant for weather decks.

Four different fire fighting tactics were discussed:

- Extinguishment near the burning vehicle:
  - Perform a quick first fire fighting operation before the fire has affected the fuel storage, with the aim to suppress/extinguish close to the fire.
- Extinguishment further away from the burning vehicle:
  - If the risk assessment does not allow the firefighters to come close, but the vehicle fire can still be extinguished from a distance or behind a protection.
- Focus only on preventing the spread of fire and protecting adjacent vehicles and ship equipment and structures:
  - Hose system with water curtain or handheld fire fighting equipment able to prevent fire propagation from a distance
- Extinguishment without entering the room where it is burning:
  - Activate the fixed extinguishing system
  - Attack the fire from outside, e.g. with cutting extinguisher, fog nail, etc.

Olofsson and Ranudd (2019) analysed 14 accident reports from ro-ro space fires with focus on evaluating the mechanical ventilation, fire extinguishing system, manual intervention and fire detection system. One conclusion from the report was that fire fighting onboard is problematic due to the densely stowed vehicles and thick smoke that makes it difficult to reach the fire. It is important with rapid detection, a ventilation strategy and a ro-ro loading procedure that allows free spaces between vehicles. Another report (Bram et al 2019) highlights the importance of functioning communication to be able to share information between crewmembers and officers on different locations of the ship. Technical malfunction such as poor audio quality or insufficient coverage together with a loudly environment and language barriers will reduce the possibility of secured communication.

## 5 Discussion and recommendations

A body of research activities have been compiled in previous chapters about risk and hazards of AFV (Alternative Fuel Vehicle) fires, including land-based fire fighting tactics and the prerequisites for firefighting operations in ro-ro spaces. This chapter discusses and recommends what conditions need to be considered to best handle AFVs fires in a ro-ro space.

### 5.1 Risk associated with fires in AFV

In case of a fire in a vehicle, there are several hazards that should be considered for the rescue management, independent of the type of fuel. Generally, this includes the risk of; heat, smoke and toxic gases and smaller explosions which could throw projectiles with harmful force, (e.g. gas springs, airbags, tires). Furthermore, modern vehicle materials such as carbon fibre, graphene and similar will increase the fire load and produce more harmful particles during combustion. Magnesium and aluminium alloys may catch fire and can cause issues when exposed to water spray.

For parked vehicles electrical failures are a common fire cause on all types of modern vehicles, and the probability of starting a fire is not expected to increase for AFVs. The total risk may even be lower for AFVs, since more layers of control systems are designed to avoid failures and resulting leakage, e.g. electro-magnetic valves that close when the main power is off, battery management systems, etc.

The main difference between vehicles with conventional and alternative fuel is the possible consequences once a fire reaches the fuel storage. The hazards with the highest risk (either probable and/or severe consequences) related to AFVs are:

- Liquefied gas:
  - Venting of boil-off LNG (probable but not critical)
  - Jet flames from PRV activations (probable during fire but moderate consequences)
  - BLEVE and fireball (small probability and even lower probability for insulated fuels, i.e. LNG, severe consequences near and around the vehicle)
- Compressed gas:
  - Jet flames from PRD activations (probable during fire and can quickly spread the fire)
  - Pressure vessel explosion + fire ball (less probable, but severe consequences)
- Batteries (Lithium-ion):
  - Fires in batteries are difficult or impossible to extinguish and may continue for a long time and are likely to re-ignite, even a long time after extinguishment (beware in post-fire management).
  - Toxic and flammable gases without fire (risk of intoxication and explosion)

For liquefied cryogenic fuels such as LNG, the tanks will have a significant thermal protection which will limit the risk of tank rupture. For liquefied fuels such as LPG or DME, the main risk relates to PRD activation when the increased pressure is released. In case of significant thermal exposure a BLEVE may occur. For compressed gas vehicles the main risk relates to a jet flame in case the thermal PRD (tPRD) is activated. A jet flame can increase the spread of fire and if the jet flame exposes another adjacent gas-vehicle it is possible to activate the tPRD on that gas tank. In case of local fire exposure, a pressure vessel explosion can occur.

In case there is a risk of pressure vessel explosion in gas-powered vehicles in a ro-ro space, the safety distance depends on the size and pressure of the gas tank. As a rule of thumb, the size of the tank is smaller for personal vehicles and larger for coaches and HGVs. The pressure may be higher for hydrogen vehicles than for CNG vehicles. The enclosure will alleviate the pressure wave and the worst case is if an explosion occurs in a corner, followed by an explosion close to a wall. Similarly, the worst position of firefighters is just in front of corners or walls facing the AFV on fire. Whether the aft and stern are open or closed have an impact close to the opening. In other words, the pressure in case of an explosion is reduced nearby openings. A vehicle will act as a barrier against pressure waves with a reduction in pressure behind them. However, vehicles also represent a risk in case they are turned over by the pressure wave. Other risks from explosions are structural damages that locally could be severe.

After a fire, gas tanks that have been exposed to fire should be cooled before anyone is allowed near them.

For battery vehicles the main risks relate to venting of toxic gases from the battery, the difficulty to extinguishing a battery fire and the risk of re-ignition.

## 5.2 Risk assessment

Before and during a fire fighting operation a risk assessment must be performed and following conditions need to be considered:

1. The location of the vehicle and the surrounding environment; what type of AFV is on fire and what kind of AFVs are nearby.
2. The extent and intensity of the fire upon arrival.
  - a. How do the fire gases look like?
  - b. Where did the fire start and what is the most likely development of the fire?
  - c. Is the fuel storage exposed and what type of risk does it bring?
3. Is there a risk of accumulating combustible gases and thus a risk of explosion?
4. What are the ventilation conditions and the possible fire developments?
  - a. Weather deck: well ventilated, reduced radiation from hot smoke and reduced risk of fire spread
  - b. Open ro-ro space: well ventilated, increased radiation from hot smoke below the deckhead, increased risk of fire spread.
  - c. Closed ro-ro space: limited oxygen supply? Can the fire self-extinguish? Avoid re-ignition of uncombusted gases.
5. Is there an opportunity to attack and reverse from the vehicle without being exposed to toxic fire gases?

The risk assessment must also consider the type of personal protective equipment (PPE) available and how well the equipment can protect against heat and toxic fire gases. Tests have been conducted on the risks of exposure to different toxic substances. The risk is lowered when using a certain combination of clothing as PPE, but more tests are needed to validate the test results.

The communication between firefighters and other relevant crew is important to be able to conduct an appropriate risk assessment and quickly order necessary actions. To be able to have functioning communication, technical functionality, audio quality and communication coverage over the whole vessel should be tested regularly. Furthermore, training in radio communication for the crew is important. Other equipment that may be helpful during a risk assessment is thermal cameras, surveillance cameras and gas detectors analyzing not only flammable gases but also toxic gases.

## 5.3 Fire fighting tactics

During an AFV fire on land, the fire and rescue service as a result of the risk assessment might not be required to adopt an aggressive strategy, i.e. approaching the fire and begin to extinguish it. Generally, they follow a defensive strategy, securing the area and allowing the fire to burn out by itself. This is problematic in ro-ro spaces, where there is an increased risk of fire spread to other vehicles and damage to the ship structures.

Before the fire fighting team is ready it is likely that the fire has grown to a size which is no longer controllable by manual fire fighting. The potential hazards, when the fire has reached this stage, can cause severe injuries to personnel, especially if they are unprotected during the fire fighting operations. In other cases, detection might be fast, or the fire development is slow, then fire fighting could be easily done with e.g. a handheld ABC-powder extinguisher.

The location and the size of the fire needs to form the basis of the decision-making in relation to what fire fighting strategies are appropriate. A person without protective gear shall not approach a fire in a vehicle when it has reached a certain hazardous size. Then, the fire would likely be too large and it would not be possible to extinguish the fire with, for example, a handheld ABC-powder extinguishers. A fire-fighter using proper personal protective equipment including a helmet, protective gear, breathing apparatus, etc. could also be injured from the general hazards of a fire, but it could be approached more safely and with acceptable risk.

If the fuel storage is not affected the tactics can be the same for all kind of vehicles. Preferably, a fire should be suppressed before the fuel storage is damaged and before fire propagation to adjacent vehicles. Early detection is therefore important and ro-ro spaces should be equipped with detection system that can detect and confirm a fire quickly and reliably. The fixed fire-extinguishing system should activated quickly upon confirmation. Because of the risk associated with these types of fire, manual fire fighting tactics and methods for how to suppress the fire from a distance should be developed.

As mentioned in chapter 1.1 a vehicle fire can develop very fast and before the fire-fighting team is ready, gas tanks may be affected and in such case extinguishing near the vehicle should not be performed. If it is an electric vehicle and the battery is affected, it will be difficult to extinguish the fire inside the battery and a large amount extinguishing water may be required to cool the battery. When the battery is suppressed, it could still continue to release a lot of toxic and flammable gases. Even if the fire doesn't affect the fuel storage, firefighters should not be close to a burning vehicle due to the risk of explosion, from example air bags. In many ro-ro spaces it is also difficult to reach to the burning vehicle due to the narrow distances between vehicles. Therefore, it was a priority to investigate the effectiveness of different extinguishing methods combined with defensive tactic. The aim is then to control the fire from a distance and to avoid fire propagation to adjacent vehicles. For compressed gas vehicles, such as CNG or hydrogen, a comparatively long distance may be required as a countermeasure against the risk of a pressure vessel explosion. Larger tanks on HGVs or buses will result in larger explosions. Gas tank explosions nearby walls will result in an amplification of the pressure wave. Vehicles nearby may be turned over, at the same time as vehicles act as a barrier lowering the pressure behind them. At least two vehicles, preferably three, in between the burning gas vehicle and firefighters might be a good rule of thumb, although this needs to be verified in experiments.

Fire in one vehicle can last for more than one hour, which requires endurance for both personnel and equipment. Due to toxic fire gases firefighters should try to attack the burning vehicle with limited exposure to toxic fire gases.

## 5.4 Post- extinguishment

Routines applicable after an AFV fire on land are to isolate the vehicle and to place it at a safe distance from other constructions. This is not possible onboard. A risk assessment must be carried out regarding the kind of safety precaution which are needed.

A fire affected gas tank is harmless if all the gas has leaked out, but if one tank is empty, there are often more tanks on the vehicle that may have been affected by the fire. Therefore, it is important to let the gas tanks cool down before the vehicle is approached. Then the pressure is lowered, and the material strength is regained which gives a safety margin against a pressure vessel explosion. It is also important to secure that there is no leakage from the gas tanks, and therefore personnel should have a gas detector when they approach the vehicle.

For electric vehicles, the risk of re-ignition remains for a long time after the vehicle has been exposed to a fire. Surveillance is required until it is possible to unload the vehicle. Questions raised during this project; Is it possible to put sensors on the battery that warns externally for rising temperatures? Is it possible to secure the area around the vehicle? Is it possible to create an inert environment around the vehicle and how much does this help? Different ways to ensure the safety in such a scenario were evaluated in Vylund et al (2019).

A lot of toxic gases are produced during a fire in a ro-ro space, independently of the type of fuel. During clean-up, protective clothing and respiratory mask or filter should be used.

Personal protective equipment should be removed directly after a fire fighting operation and be isolated from clean equipment. Breathing apparatuses should be removed last.

There should be a decontamination plan so that first aid can be conducted on firefighters if necessary.

## 6 Conclusion

The aim of this report was to summarize knowledge about risks with fires in alternative fuel vehicles (AFV), especially if the fire occurs in a ro-ro space. An objective was also to describe methods for fire-fighting operations on land, with the aim to transfer relevant knowledge on how an AFV fire in a ro-ro space should be handled.

Fire developments of vehicles will in general be similar regardless of fuel type but they depend on when the fuel storage becomes involved. The different stages of the fire may be reached at different times and the critical events connected to different fuels and fuel storages are dependent on the fuel type. More rapidly and intense fires can be expected in modern vehicles compared to older vehicles due to the increased use of plastics and other energy high materials. A larger amount of toxic gases is also to be expected. A very critical potential event during fire relates to the risk of pressure vessel explosion for CNG or hydrogen vehicles. Post-fire actions are primarily related to electric vehicles, as there is a risk of re-ignition for a long time. Gas vehicles that are not leaking gas can be dealt with in the same way as ordinary burnt vehicles once they have cooled down. Electrical vehicles must be monitored until it is possible to unload the vehicles.

Fires in densely packed vehicles can spread quickly regardless of fuel type. Early detection and a fast and efficient response are critical to limit the damages to one vehicle. Vehicle fires are hazardous and the fixed fire-extinguishing system should be activated quickly upon confirmation. If a manual fire fighting operation is required, tactics and methods for how to suppress the fire from a distance need to be considered due to the risk of explosion and toxic gases.

The knowledge compiled in this report has stimulated system suppliers to develop appropriate and useful solutions for how AFV fires should be handled in ro-ro spaces. Different suppression systems have been evaluated and the results can be found in Vylund et al (2019). Guideline based on the results of the project can be found in Appendix 1.

## 7 Future research

The conclusions in the report is based on a limited amount of fire tests and incidents with AFV, therefore there is a need of future research and testing but also experience from real fire fighting so that more accurate guidance can be issued. Future research is required to be able to raise the knowledge about risks and their mitigation. For example, more knowledge how a pressure vessel explosion affects the ship construction is required.

All vehicle fires produce toxic gases, but the knowledge of how the toxic gases affect firefighters are still limit. Also, more research about possible risk mitigation measures is required.

Proactive measures could be gained through research and development into how vehicles can communicate with the cargo handling system onboard and how this can be used in the risk assessment. Batteries (i.e. the BMS) warning for temperature rise and gas tanks that warn if pressure rises for example. Even simple audible warnings could be useful.

To be able to improve decision support research are needed how technical system can assist.

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# Appendix 1 – Guideline: AFV Fire fighting tactics and equipment for ro-ro spaces

MSC.1/Circ.1615 provides interim guidelines for minimizing the incidence and consequences of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships. The guidelines are divided in the following five sections;

1. Prevention/ignition
2. Detection and decision
3. Extinguishment
4. Containment
5. Integrity of life saving appliances and evacuation

BREND mainly focused on section 3 (Extinguishment) but has also highlighted the important of prevention/ignition, early detection and quick decisions. This guidelines in this appendix describe in further detail suitable fire fighting tactics and methods for fires in alternative fuel vehicles (AFV) in ro-ro spaces. The guidelines are based on the results from the research project BREND and from previous research and experience.

## Planning and preparation

For an efficient fire fighting operation, a simple and well-trained concept is important. Since the firefighting teams on-board have a limited time to practice it is important with a simple concept that does not demand a lot of training to grasp.

The recommendations for the planning and preparation are:

- A simple and well-trained concept is essential for an effective fire-fighting operation, especially a fast start-up is important. Questions that should be considered are:
  - How can we in a fast and efficient way reach the seat of the fire?
  - How can the hoses be folded or fitted in hose reel/cabinets to make it as easy as possible to reach the fire? For example, both the rolling out and connecting hoses/nozzles as well as the pressurization of the hose system should be simplified as much as possible.
  - Is it possible to use a lighter hose that are easier to handle?
- It is important to plan and prepare for:
  - Rapid detection,
  - A ventilation strategy,
  - A loading procedure that allows for free space between vehicles to be able to conduct a manual fire fighting operation.
- Crew members should be trained in fire development and risk linked with AFV fires; chapters 2 and 3 of this report can be used as a knowledge base in training.
- Use technical equipment as decision support, for example video surveillance or heat camera (fixed or portable). It can furthermore be very difficult for firefighters to orient themselves in a smoke-filled environment without a thermal camera, but the use of technical equipment must be trained.

- An explosimeter measuring combustible gases and warning if the firefighters are standing in an explosive atmosphere should be used for decision support before, during and after an extinguishing operation.
- Communication between firefighters and other relevant crew is important to be able to conduct an appropriate risk assessment and quickly order necessary actions.
  - Technical functionality, audio quality and sufficient coverage for the communication system should be tested regularly.
  - Crew members should regularly practice radio communication.

## Risk assessment

Firefighters must be aware of possible scenarios of fire development and the type of risks that can be expected when a vehicle is on fire, both conventional vehicles and AFV. The main difference between the two is the possible consequences once a fire reaches the fuel storage. The hazards with the highest risk (either probable and/or severe consequences) related to AFVs are:

- Liquefied gas:
  - Venting of boil-off LNG (probable but not critical)
  - Jet flames from safety valves activations (probable during fire but moderate consequences)
  - BLEVE and fireball (small probability and even lower probability for insulated fuels, i.e. LNG, severe consequences near and around the vehicle)
- Compressed gas:
  - Jet flames from safety valves activations (probable during fire and can quickly spread the fire)
  - Pressure vessel explosion (+ fireball) (less probable, but severe consequences)
    - Worst consequence is if the explosion occurs in a corner, followed by an explosion close to a wall, or if firefighters are placed in corners or next to walls facing the explosion.
    - A vehicle will act as a barrier against pressure waves. However, vehicles also represent a risk in case they are turned over by the pressure wave. At least two, preferably three, vehicles in between the burning vehicle and the firefighters could be a good rule of thumb, although this needs to be verified in experiments.
    - Structural damages could be severe locally.
- Batteries (Lithium-ion):
  - Fires in batteries are difficult or impossible to extinguish and may continue for a long time and are likely to re-ignite, even a long time after extinguishment (requires observation after the fire)
  - Toxic and flammable gases without fire (risk of intoxication and explosion)

Before and during a fire fighting operation a risk assessment must be performed and the following conditions needs to be considered:

- The location of the vehicle and the surrounding environment; what type of AFV is on fire and what kind of AFVs are nearby.
- The extent and intensity of the fire upon arrival.
- Where did the fire start and what is the most likely development of the fire?
- Is the fuel storage exposed and what type of risk does it bring?
- Is there a risk of accumulating combustible gases and thus a risk of vapor cloud explosion?
- What are the ventilation conditions and the possible fire developments?
  - Weather deck: well ventilated, reduced radiation from hot smoke and reduced risk of fire spread

- Open ro-ro space: well ventilated, increased radiation from hot smoke below the deckhead, increased risk of fire spread
- Closed ro-ro space: limited oxygen supply? Can the fire self-extinguish? Avoid re-ignition of uncombusted gases.
- Is there an opportunity to attack and retire from the vehicle without being exposed to toxic fire gases?
- What type of personal protective equipment (PPE) is available and how can this PPE reduce the risk?

## Manual fire fighting tactic

Early detection and a fast first response are critical to limit the damages in case of a vehicle fire. Fire fighting methods for a first quick response do not differ between conventional fuel vehicles and AFV as the aim is to extinguish the fire while it is small and not affecting the fuel storage. The aim could also be to delay fire propagation until a fire fighting team can be ready or until the fixed fire-extinguishing system can be activated. In this case, the most important factors are that the fire-fighting system is easy to handle and to the ease for the crew to reach the burning vehicle. Lightweight handheld extinguishing tools such as powder fire extinguishers, fire extinguishers, aerosol grenades, etc. could be used. Vehicles may be parked close to each other and it can be difficult to reach the fire therefore a delay in the response is therefore a risk. When the fire-fighting team is ready, the fire has likely also grown to a size where the fuel storage is affected unless the the fixed fire-extinguishing system has been started directly. It is important that the fixed fire-extinguishing system is activated immediately upon fire confirmation. Because of the risks associated with this type of fires, manual fire fighting should only be performed if the fire is small, suppressed or if there is a failure in the fixed fire-extinguishing system.

It can be difficult to identify the kind of vehicle that is on fire and the hazards that could be relevant. Therefore, the firefighters must expect that risks associated with AFV can occur. Figure A 1 illustrates the fire development of a modern vehicle mapped against critical events for AFV fires. The most critical events during a fire relate to compressed or liquified gas vehicles. Even if the fire does not affect the fuel storage, it is recommended not to be too close to a burning vehicle due to the risk of smaller explosions from, for example, air bags.

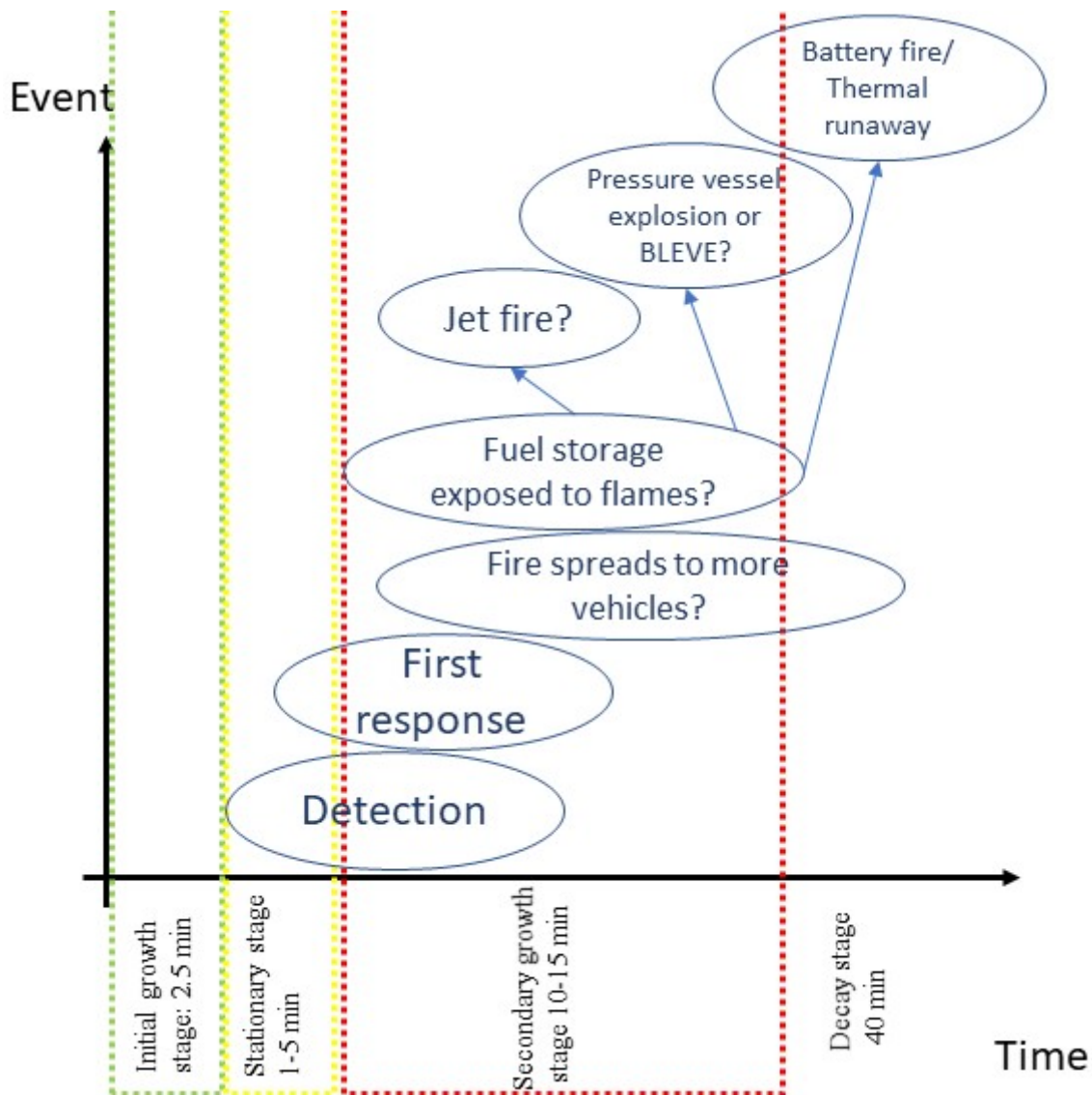


Figure A 1: Time-event diagram of plausible critical events during an AFV fire.

Because of the associated risks once the fuel storage is exposed to flames, firefighters must also be able to conduct the fire fighting operation from a safe distance. Therefore, the research in BREND has focus on fire fighting tactics when the fuel storage is affected by the fire and recommendations for fire fighting tactics in this situation are:

- When gas tanks are affected by the fire, cooling and extinguishing attempts should not be performed near the fire due to risk of gas tank rupture. Use defensive tactic and try to suppress the fire from a distance with the goal to avoid spread of fire to adjacent vehicle.
- If possible, use two or more vehicles as protective shield for firefighters.
- Do not extinguish the jet-flame from a released pressure relief valve/device.
- If the burning vehicle is an electrical vehicle and the battery is affected it is almost impossible to extinguish the fire in the battery and a massive amount extinguishing water may be required for cooling. Even, be aware that even if a battery fire is suppressed it can continue to release a lot of toxic and flammable gases.
- Fire in one vehicle can last for one hour, which requires endurance both for personnel and equipment.

- Due to toxic fire gases, firefighters should try to attack the burning vehicle with limited exposure to toxic fire gases (wind/ventilation in their backs).
- Be aware of fire spread to the ro-ro spaces above or below the burning vehicle and provide boundary cooling to prevent fire spread.
- Special considerations for compressed gases (e.g. CNG, CBG etc.): Any attempts to extinguish the fire, especially if water is applied to the tanks, may prevent the temperature activated relief device from working properly and could result in a catastrophic tank failure and explosion, if the tank is exposed to the fire.
- Special considerations for LPG: In case of fire engulfing the tanks, be sure to apply copious amounts of water to keep the tanks cool and prevent a BLEVE. This may occur if the PRD is unable to maintain a safe pressure.
- Special considerations for LNG: LNG is stored at a low temperature and it is important to protect from first degree burns and frostbite when handling a leakage; normal protection clothing is not enough. The LNG cloud will be visible at first but after being warmed up, LNG is colorless and odorless. A thermal camera can be used to detect a vapor cloud.
- Special considerations for hydrogen: Use a thermal camera when dealing with any hydrogen emergency in order to determine the presence of fire. Hydrogen fires produce almost no visible flame and no smoke, making it almost impossible to sense the presence of a fire until you are very near or even in the flame. However, at night/in darkness the flame is visible to the naked eye. Hydrogen burning with other carbon-based flames will likely give color to the hydrogen flame.

## Post extinguishment

- After a fire, gas tanks that have been exposed to fire should be allowed to cool before anyone is allowed near.
- The above statement applies also to battery vehicles, for which the risk relates to re-ignition. Surveillance is required until it is possible to unload the vehicles. Typically, re-ignition is accompanied by a “whooshing” or “popping” sound with following white smoke and/or sparks that re-ignite the smoke to visible flames and increase of heat. If any such signs are observed, water needs to be available to cool the battery immediately. A water curtain system can be positioned around the vehicle and if signs of re-ignition occur the firefighter can directly start the curtain system and suppress the fire.
- The personnel should have a gas detector when approaching the vehicles (both gas and battery vehicles) to ensure that there is no leakages of explosive or toxic gases.
- During clean-up, protective clothing and a respiratory mask or filter should be used.
- Personal Protective Equipment (PPE) should be removed directly after a fire fighting operation and be isolated from clean equipment. Breathing apparatuses should be removed last.
- Decontamination is required if the skin is burning or if problems arise with respiratory systems or eyes. A decontamination plan is therefore required.

## Fire fighting equipment

The firefighting teams on-board have limited time to practice and therefore it is important that the fire-fighting system does not require a lot of training. The equipment should be logic to use to allow quick and efficient use directly. It is also important that the equipment can be used in many

situations since it is not possible for the firefighting team to carry a lot of different equipment with them. The equipment must be efficient even from a distance, since it is associated with significant risks to be near a burning AFV. A quick response is important which requires that the equipment is easy to operate. Onboard it is also important to consider the total water consumption. The focus must in conclusion be to find fire-fighting techniques that are easy to handle, require limited personnel and education but that are also efficient and avoid risks for crew and persons onboard.

The report “Methods and equipment for fire fighting with alternative fuel vehicles in ro-ro spaces (Vylund et. al 2019) can be used as a guidance of what to be considered when evaluating what types of systems to use.

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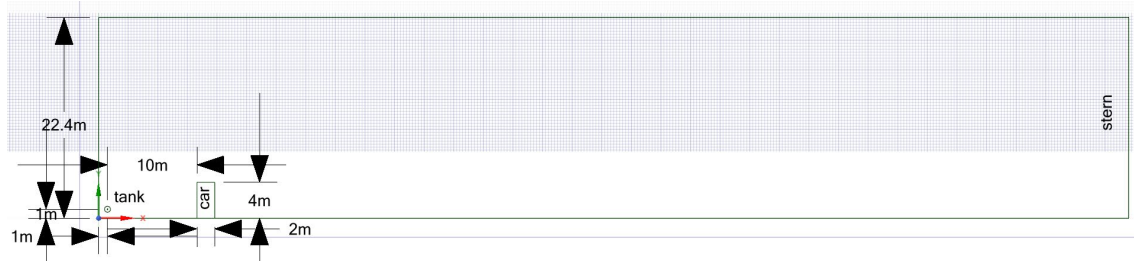
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# Appendix 2 – Simulation of gas tank rupture

## 1. Scenario

Pressurized gas tank explosion in a ro-ro space is studied. The ro-ro space has a dimension of 115.2 m long, 22.4 m wide and 4.8 m high. According to Perrette and Wiedemann [1], the mechanical energy from a physical burst of a 130 l pressurized gas tank of 200 bar being 8.7 MJ. Such energy is equivalent to 1.85 kg TNT using 4690 kJ/kg as heat of detonation of TNT [1]. The gas tank is located at a height of 0.28 m above the ground which mimic the condition when tank is mounted on a vehicle, and it is 1 m from the side walls of the space; see Figure A 2 for layout of tank rupture scenario.

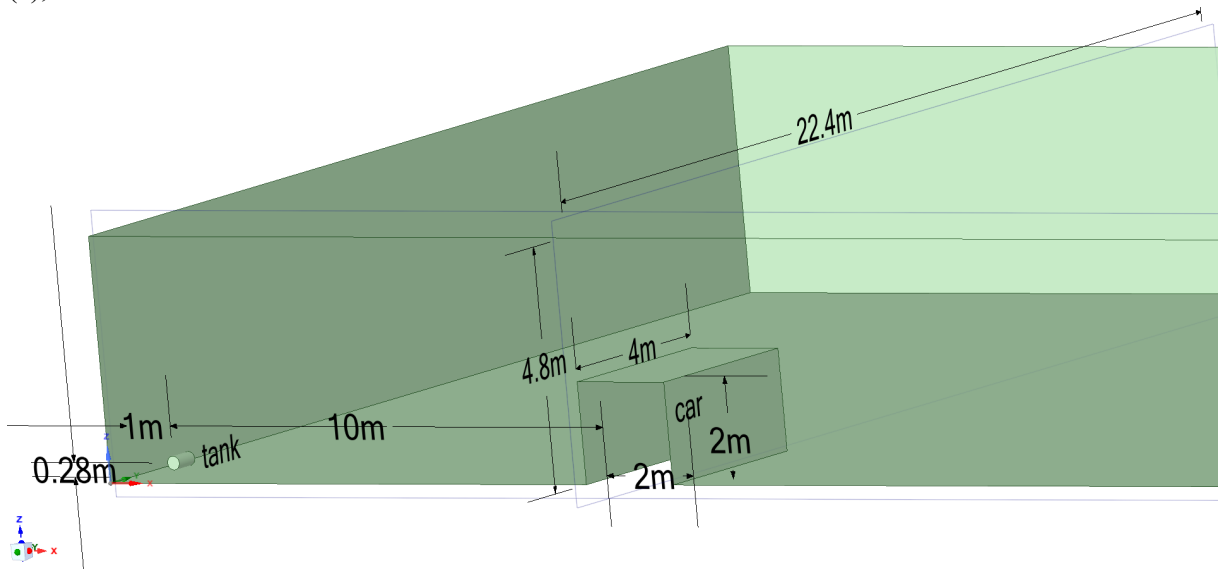
In this work, a blast wave propagation model built in an explicit dynamic code together with empirical method from Baker et al. [2] are adopted to estimate the deterministic separation distance.



(a),

2D

sketch



(b), 3D view

Figure A 2: Layout of tank rupture scenario. The gas tank is located at the circle in the lower left corner of ro-ro space at a height of 28 cm above the ground.

## 2. Model setup in Autodyn

The numerical method for solving transient non-linear dynamics problems such as blast wave propagation and its impact is based on solving the governing partial differential equations for the conservation of mass, momentum and energy using finite difference, finite volume and finite element methods of explicit scheme [3]. In this work an explicit dynamic code Autodyn version 19.2 by Ansys is used. It is worth noting that Autodyn treats the air as an inviscid fluid in which turbulence is ignored. Accordingly, the computational time is substantially shorter as compared to a Computational Fluid Dynamic (CFD) code in which turbulence is modelled. Whilst the advantage of using more advanced numerical methods than empirical method is that the effects of enclosure can be considered.

A three-stage mapping procedure is adopted to maintain a good balance between accuracy in solution and the cpu time. First, an axisymmetric 1D model with very fine grid resolution is used to resolve the initial spherical blast wave propagation. Second, the result of 1D model is mapped to an axisymmetric 2D model with relatively large grid size before the blast wave reaches the side walls. Third, the 2D result is mapped to a 3D model for the full-scale ro-ro space and to perform blast wave propagation simulation.

### 2.1 Setup of 1D model

A 1D model is used to resolve the initial spherical blast propagation, i.e. before the blast wave reaches the floor. The 1.85 kg TNT has a radius of 64.7 mm using a TNT density of  $1.63 \text{ g/cm}^3$ . A wedge shape of mesh is created in Autodyn with a minimum radius of 0.1 mm, a maximum radius of 280 mm and the cell number of 1120; see Figure A 3. Accordingly, a relatively small average cell size of 0.125 mm is yielded which ensures a good resolution of the initial spherical blast prediction. The 1D model simulates explosion from 0 - 0.01 ms, and the simulation took around 16 s CPU time on a laptop with Intel Core i7-7820HQ CPU @ 2.9 GHz processor and 32 GB RAM. If no further information is stated regarding computational hardware, the abovementioned hardware is used.

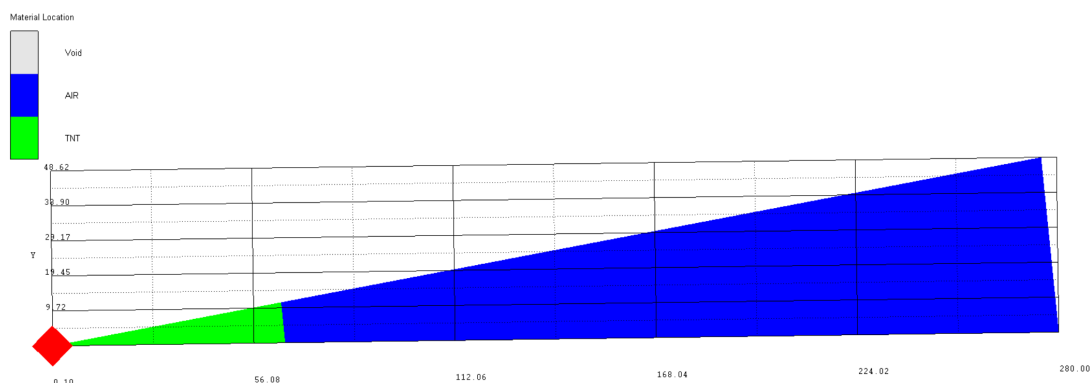


Figure A 3: 1D axisymmetric model in Autodyn. The red diamond is the detonation point; the green colour is the equivalent explosive TNT and the blue colour is the air. The distance unit is in mm.

### 2.2. setup of 2D model

The solution of a spherical blast is mapped to an axisymmetric 2D model. The 2D model is then used to continue the simulation before the blast wave reaches the side walls, i.e. from 0.01 - 0.2 ms. The 2D model covers a domain of  $1 \times 1 \text{ m}$  with a total grid size of 10 000; see Figure A 4. A grading method is adopted for creating the grid to obtain a fine resolution close to the detonation centre and coarse resolution in the far field which is less sensitive to the solution. The average

size of the grid is 0.01 m with a minimum grid size of 0.005 m in the detonation centre. The 2D model took around 15 s.

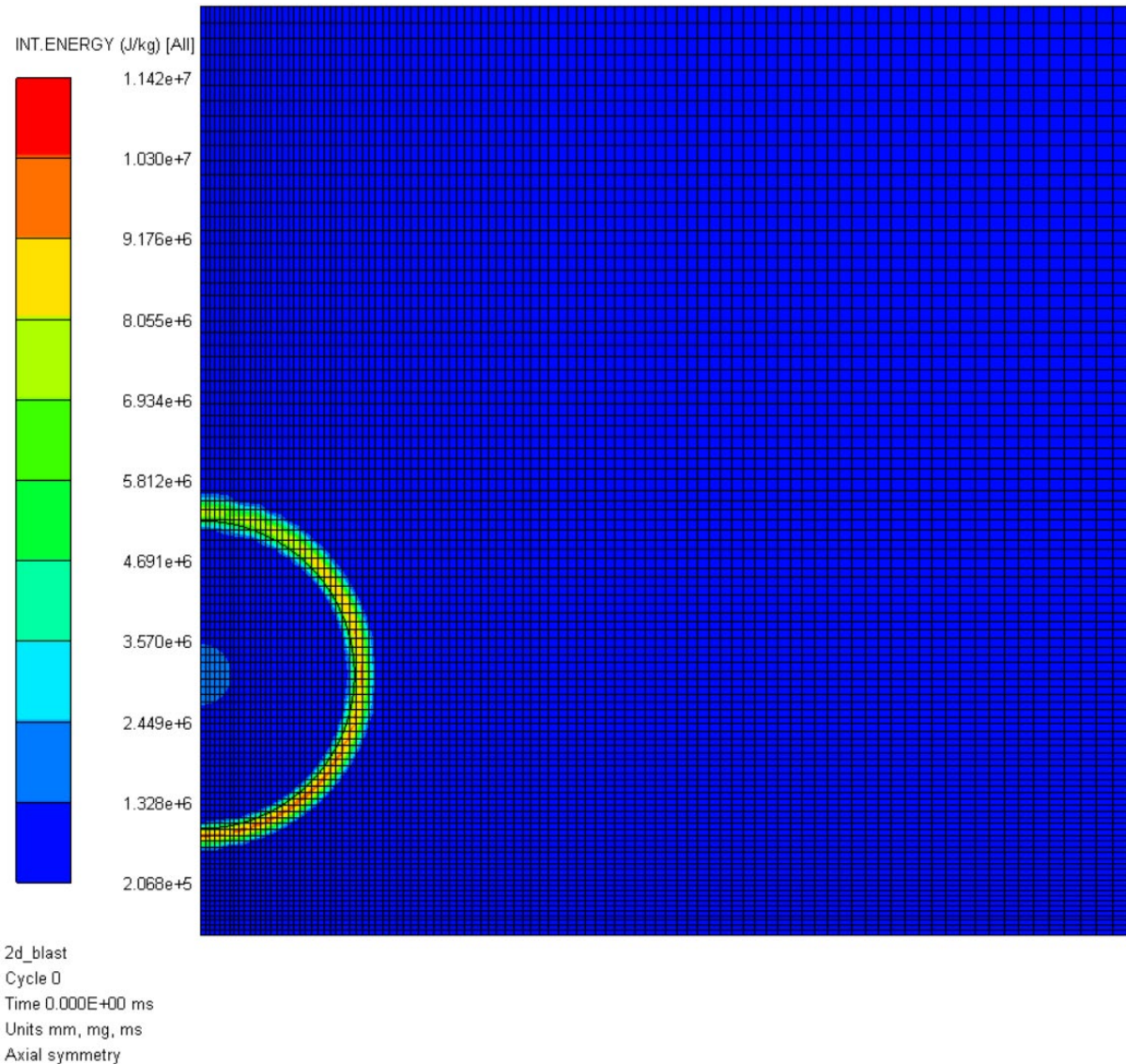


Figure A 4: 2D axisymmetric computational model for an area of 1.0×1.0 m. The colour contour shows the mapped internal energy from 1D axis-symmetric model to the 2D model.

### 2.3. setup of 3D model

A fluid domain of 115.2 m long, 22.4 m wide and 4.8 m high was considered in the 3D model. In order to maintain a good balance between computational time and accuracy and easy mesh generation for the car, a combination of fixed and a grading grid size, i.e. the grid size increases along the distance, is adopted in mesh generation. A domain of 12 m in length, 12 m in width and 2 m in height is meshed with a fixed cell size of 0.2 m, which covers the tank and car region; see layout in Figure A 2. The rest of the domain is meshed using a grading method with an average grid size of 0.4 m, since the solution is less sensitive to the grid size in the far-field. A total grid size of 437 568 cells is created; see Figure A 5. The walls and car are considered as rigid bodies, which means no deformation is modelled. Totally 140 gauges are setup in the model to monitor the propagation of blast wave. 114 gauges are placed 28 cm above the floor along the length side of ro-ro space; 22 gauges are placed 28 cm above the floor along the width side of ro-ro space; 4

gauges are evenly placed vertically above the tank, i.e. 1 m from deck front and deck rear, with a distance of 1 m between the neighbouring gauges. 3D simulation covers the explosion from 0.2 - 300 ms, and one simulation took around 2 h.

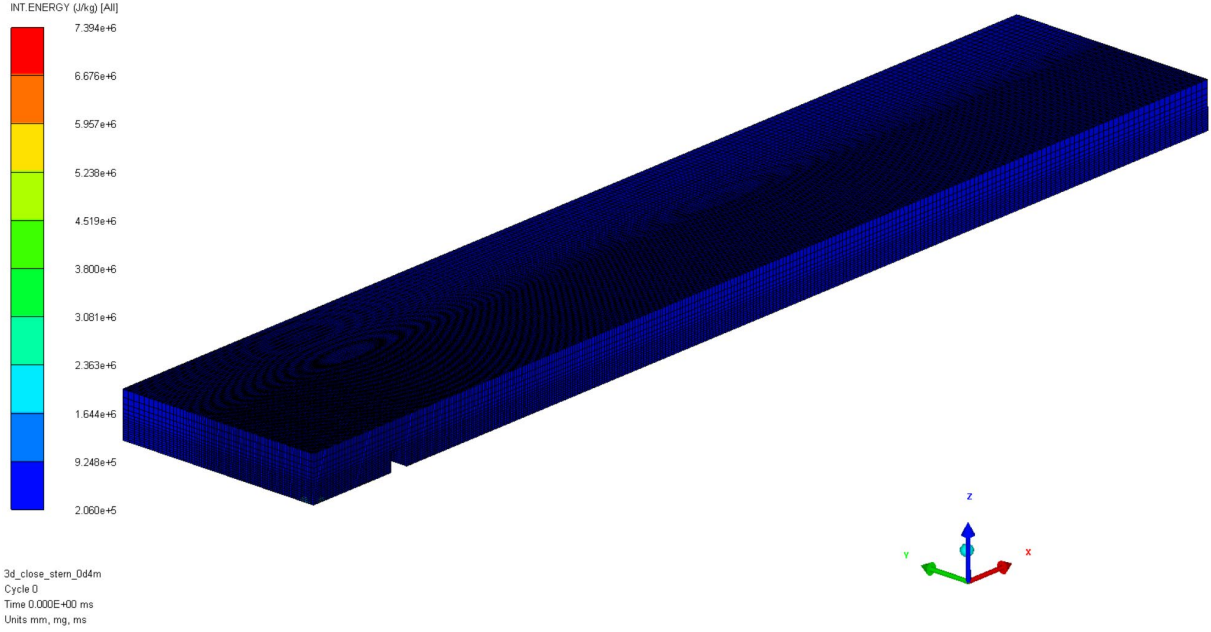


Figure A 5: 3D Computational model for tank rupture with a barrier (2×4×2 m) for an area of 115.2×22.4×4.8 m. The colour contour shows the mapped internal energy from 2D axi-symmetric model to the 3D model.

### 3. Empirical method

Baker et al. [2] has developed a methodology for evaluating physical bursting of a sphere using data fitting from numerical calculation, comparing with measurement and solving one-dimensional shock wave equation together with blast scaling law.

#### 3.1 Definitions of parameters

The blast scaling law is also called Sachs law and the main idea is that the dimensionless overpressure and impulse, which are relative to atmospheric condition, depend on dimensionless scaled distance [4]. Note that the atmospheric condition means the atmospheric pressure  $P_0 = 1.01325e5$  Pa and atmospheric temperature  $T_0 = 293$  K. For example, Sachs' scaled pressure  $\bar{P}$  is defined as the ratio of explosion pressure  $P$  to ambient atmospheric pressure as follows

$$\bar{P} = \frac{P}{P_0} \quad (1)$$

The Sachs' scaled distance is defined as

$$\bar{r} = \frac{r}{(E/P_0)^{1/3}} \quad (2)$$

where,  $r$  is the distance from the explosion center to the location of interest;  $E$  is the energy contained in the explosive, and the quantity of  $(E/P_0)^{1/3}$  is called characteristic length for an explosive source.

The mechanical energy contained in compressed gas of pressure  $P_g$ , compared to the atmospheric pressure  $P_0$  in a volume  $V$  can be evaluated by following the work of Brode [5]

$$E = \frac{(P_g - P_0)V}{\gamma - 1} \quad (3)$$

where  $\gamma$  is the specific heat capacity ratio which taken as 1.4 in this work. Note the gas is assumed to follow the ideal gas law since the maximum pressure in this work is relatively low, i.e. 200 bar.

### 3.2 Starting shock overpressure from tank rupture

When the vessel wall for holding the pressurized gas suddenly disappears, a rarefaction wave is produced and propagates inwards through the compressed air in the tank to balance the large difference of density at the boundary of gas tank and atmospheric air. This means the starting shock overpressure is always much less than the actual pressure in the tank. A non-dimensional starting shock overpressure  $\overline{P}_{so}$  is introduced as follows

$$\overline{P}_{so} = \frac{P_{so}}{P_0} - 1 \quad (4)$$

where  $P_{so}$  is the explosion pressure.

The non-dimensional starting shock overpressure  $\overline{P}_{so}$  is determined using the following method. First, evaluate the non-dimensional parameters, such as square of sound velocity ratio between the gas tank and surrounding air  $(a_g/a_0)^2$  and pressure ratio of tank and atmosphere  $P_1/P_0$ . Then, by interpolating between the lines in Figure A 6 by Baker et al. [2] using the aforementioned parameters, one can obtain the value of  $\overline{P}_{so}$ .

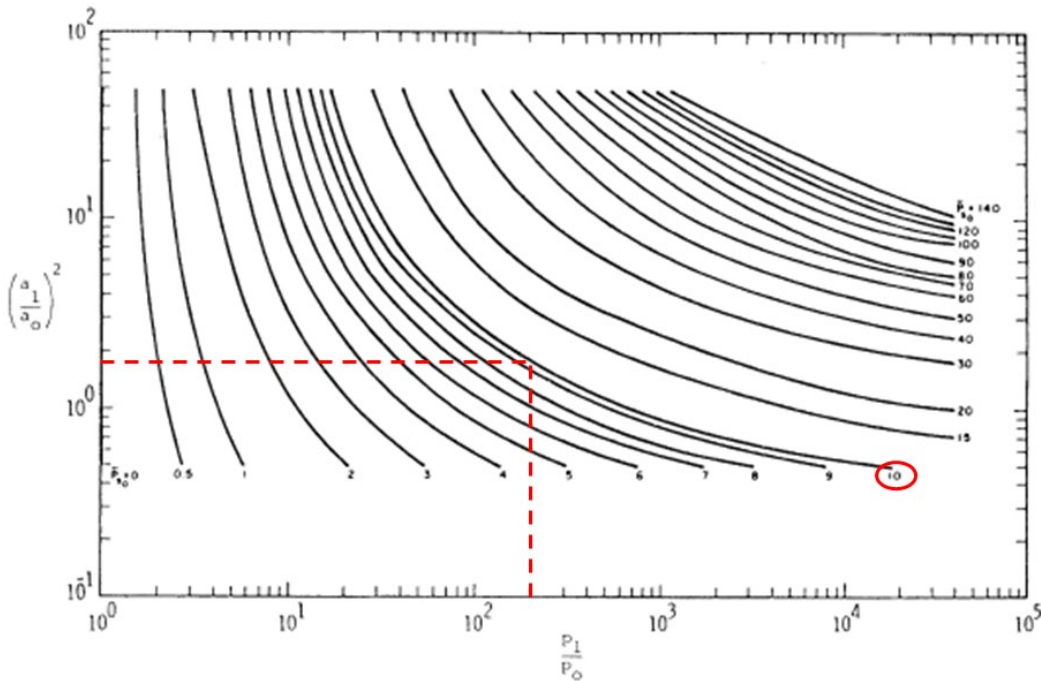


Figure A 6: Starting non-dimensional shock overpressure  $\overline{P}_{so}$  for different square of sound velocity ratio  $(a_1/a_0)^2$  and pressure ratio  $P_1/P_0$ ,  $\gamma = 1.4$ . [2].

Here, the speed of sound in the pressurized gas  $a_g$  is evaluated as follows

$$a_g = \sqrt{\gamma \frac{P_g}{\rho_g}} \quad (5)$$

where  $\rho_g$  is the density of 200 bar methane gas, which is  $\rho_g=128.30 \text{ kg/m}^3$ . The speed of sound in 200 bar gas is  $a_g=467 \text{ m/s}$  using Equation (5). The speed of sound at atmospheric condition is  $a_0=343 \text{ m/s}$ . Therefore, the square of sound velocity ratio between the gas tank and surrounding air  $(a_g/a_0)^2=1.86$ . By looking up into Figure A 6 using  $P_1/P_0=197.38$  and  $(a_1/a_0)^2=1.86$ , we can obtain that  $\overline{P}_{so}$  is around 10. This means that the starting shock overpressure is 10 bar at the instance when tank wall disappears for a gas tank pressure of 200 bar.

### 3.2.3 Tank rupture explosion characteristics

Tank rupture explosion characteristics can be obtained by looking up into Figure A 7 which is produced by Baker et al. [2] using a finite differential numerical code and experimental data. Before looking up into Figure A 7, two parameters, i.e. starting shock overpressure  $\overline{P}_{so}$  and non-dimensional vessel radius  $\overline{r}_v$  are needed. The  $\overline{P}_{so}$  is 10 according to the previous section. Now we should focus on getting  $\overline{r}_v$ .

The radius of the vessel is calculated using  $r_v = (3V/4\pi)^{1/3}=0.31 \text{ m}$ , where  $V=0.13 \text{ m}^3$ . The mechanical energy contained in the 200 bar vessel is 8.7 MJ according to Perrette and Wiedemann [1]. The non-dimensional vessel radius  $\overline{r}_v$  is 0.071 according to Equation (2).

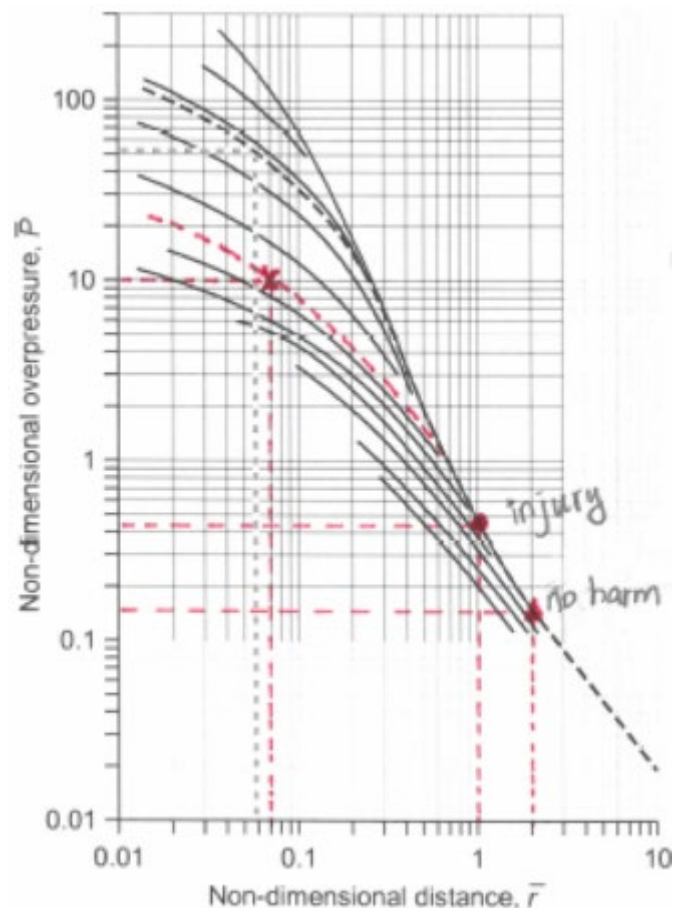


Figure A 7: Sphere burst explosion overpressure versus dimensionless distance. The current explosion curve is shown in red dashed line. Red circle represents injury threshold and red triangle represents no harm threshold. Figure is taken from Molkov and Kashkarov [6], but originally come from Baker et al. [2].

## 4. Results

Totally 4 cases are run in order to study the effects of enclosure, front and stern being opened, and a barrier like a car. The detailed parameters are listed in Table 7.

Table A 1. Descriptions of cases studied.

Cases	descriptions
Case 1	Explosion in an open ro-ro space
Case 2	Explosion in a partially closed ro-ro space (front and stern being open)
Case 3	Explosion in a totally closed ro-ro space with a barrier (a car) located 10 m from the tank.
Case 4	Explosion in a totally closed ro-ro space

### 4.1 Effect of enclosure

The effect of enclosure is studied by comparing case 1 and case 2. The case of explosion in an open ro-ro space is simplified by setting up a 2D axis-symmetric model to reduce the computational time. A computational domain of 200×200 m is considered. The mesh size is 0.2 m in an area of 12×12 m where the tank is located, and a grading mesh with an average size of 0.4 m is used in the rest of the domain yielding a total computational cell size of 280 900. One simulation covers a time period of 0 – 330 ms and one case takes around 14 min. Totally 115 pressure gauges are introduced along the ground at a height of 28 cm above the ground in order to record the arriving of blast wave.

The calculated maximum explosion overpressure for explosion in an open ro-ro space, i.e. case 1, as compared to that in a closed ro-ro space, i.e. case 2, is shown in Figure A 8. The explosion overpressure in a closed ro-ro space is much higher as compared to an open deck. The reason is due to the reflections of pressure wave from the front and side walls and ceiling of the deck that amplifies the pressure wave inside the deck.

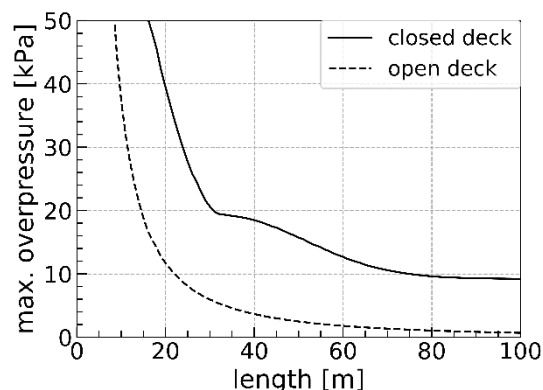


Figure A 8: Calculated maximum explosion overpressure at a height of 28 cm from the floor versus length of ro-ro deck for case 1 (open deck) and case 2 (totally closed deck).

### 4.2 Effect of barrier

Two cases were compared, i.e. case 2 (explosion without barrier) and case 3 (explosion with a barrier, e.g. a car of size of  $2 \times 2 \times 4$  m located 10 m from the tank); see layout in Figure A 2. Note the car is considered as a rigid body, which means deformation of the car is ignored.

The calculated maximum explosion overpressure at a height of 28 cm from the floor versus length of the ro-ro deck for two cases are compared; see Figure A 9. The barrier has substantial effect in reducing the explosion overpressure up to around 15 m behind the barrier. However, the barrier has little effect in reducing overpressure after around 15 m from the barrier.

The barrier has a limited effect in reducing overpressure in height due to the limited height of barrier. For a barrier with a height of 2 m, the protecting effect is greatly reduced above a height of 2 m and fully lost at the height 3 m; see Figure A 10. Such limitation is of great importance to bear in mind in the perspective of a rescue team.

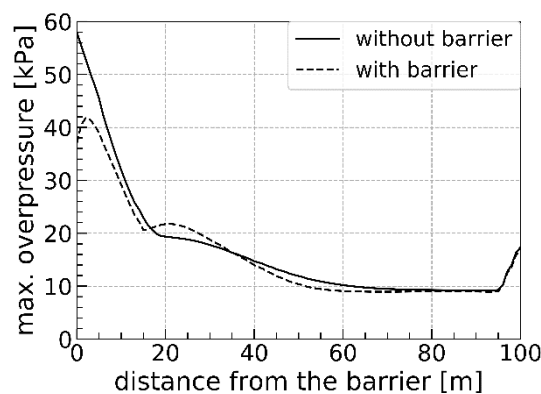


Figure A 9: Calculated maximum explosion overpressure at a height of 28 cm from the floor versus length of ro-ro deck for case 2 without barrier and case 4 with barrier.

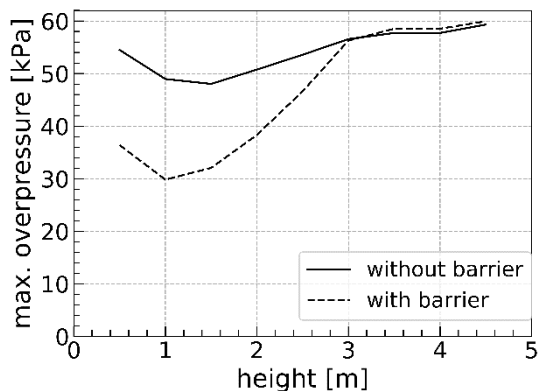


Figure A 10: Calculated maximum explosion overpressure behind the barrier, i.e. 12.5 m from the tank (0.5 m behind the barrier), versus height of ro-ro deck for case 2 without barrier and case 4 with barrier for a computational domain of  $115.2 \times 22.4 \times 4.8$  m.

#### 4.3 Effect of front and stern of ro-ro deck being open and closed

Two cases, i.e. case 2 and 4 in Table A 1, are compared to study the effect of front and stern of deck being open and closed. The simulation result shows that for the scenario of 200 bar 130 l tank rupture in the corner of the ro-ro deck, the front and stern being open has substantial effect in the front (10-25 m along the length of the deck) and 5 m from the stern parts of the deck; see Figure A 11. The reason is that the pressure wave is amplified due to the reflections from the front and stern of the deck for the case of closed deck.

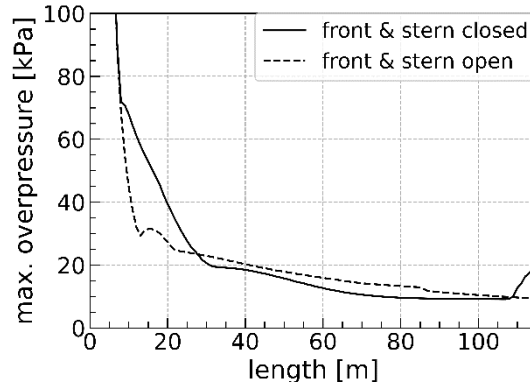


Figure A 11: Calculated maximum explosion overpressure versus length of ro-ro deck for two cases, i.e. side wall being open and closed with a computational domain of  $115.2 \times 22.4 \times 4.8$  m.

#### 4.4 Deterministic separation distances for human and buildings

The so-called deterministic separation distances for human and buildings are determined by comparing the calculated or estimated explosion overpressure and/or impulse against thresholds found in the literature [2, 6-8]. These damage criteria are based on high explosives and they are adopted for gas tank rupture since there is lack of data in this area [2].

It is worth stating that the obtained deterministic separation distances can only be used as a reference value for the emergency service. The emergency service should perform the rescue work based on their experience and the actual situation.

A comparison between the deterministic separation distances for human and buildings based on calculations and empirical method are shown in Table A 2. In this work, for the human, no harm means threshold for temporary loss of hearing [9, 10]; injury means threshold for internal injury [10]; fatality is related to lung damage [10]. For the buildings subjected to a blast wave, the thresholds of the previous work of Jarrett [8] and Baker et al. [2] are adopted. These thresholds were obtained by analysing data points on brick houses subjected to various size of bombs and standoff distances during the second world war [2]. Minor damage means “breakage of glass, wrenching of joints occur and the removing of partitions out of fittings”; major damage means “partial or total damage of the roof, partial damage of an external wall and destruction of the load bearing“, and almost total destruction means “destruction or remaining unsafe of 50-75% of external brick walls” [2].

The deterministic separation distance for “no harm” for case 2, i.e. a partially closed deck, is slightly longer than the case 4, i.e. closed deck. Such result is in line with the result in Figure A 11. The reason is due to the fact that the explosion overpressure at a certain point has possibility of being higher for a vented case as compared to an unvented case due to the pressure wave reflections inside the enclosure. However, if an averaged value of explosion overpressure is evaluated for two cases, the vented case may yield lower explosion overpressure inside the enclosure.

The calculated maximum tank rupture explosion overpressure versus distance in length on the ro-ro deck is shown in Figure A 12. The horizontal lines correspond to different safety thresholds for both human and steel frame.

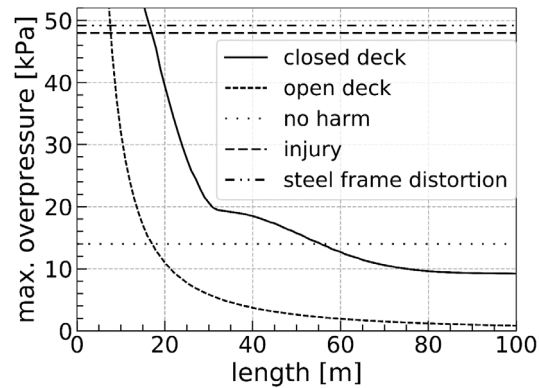


Figure A 12: Calculated maximum explosion overpressure versus distance in length on the ro-ro deck for case 1 (open deck) and case 2 (closed deck).

A comparison of deterministic separation distances for human, building and steel frame for the scenario of a 200 bar 130 l gas tank rupture is summarized in Table A 2. The deterministic separation distances recommended using numerical simulation for case 1 on an open deck is the closest to the empirical method among the four cases with a substantial safety margin. This shows that the numerical model yields reasonable results. The substantial conservative deterministic separation distances recommended by the numerical model as compared to the empirical model is due to the fact that the empirical method is based on a free propagating of pressure wave whereas the numerical model considers the effect of reflection of pressure wave from the deck floor. Moreover, the numerical model assumes that a tank rupture is equivalent to the explosion of TNT using TNT equivalent method. However, a TNT detonation produces much quicker blast wave and much higher overpressure as compared to a gas tank rupture. This contributes to a more conservative result produced by the numerical model. Moreover, the building collapse and projectile fragments produced by explosion is a dominating cause of injury [9] in an explosion and is not considered in this study.

For case 4 of explosion in a closed ro-ro space, the Autodyn simulation yields a quite long deterministic distance since the closed walls amplify the pressure wave and the scenario of tank explosion in the corner of the ro-ro space is the worst-case scenario that the amplification effect is the largest.

Table A 2: Deterministic separation distances for human, buildings and steel frame for a 200 bar 130 l gas tank rupture. [9, 10]

Object	damage level	Criteria		Empirical method, most close to case 1 [2]	Autodyn simulation for case 1 (open ro-ro space)	Autodyn simulation for case 2 (partially closed ro-ro space)	Autodyn simulation for case 4 (closed ro-ro space)
		Overpressure [kPa]	Impulse [Pa s]	Deterministic distance [m]	Deterministic distance [m]	Deterministic distance [m]	Deterministic distance [m]
human	No harm	14 [9, 10]	1	9	18	73	56
	Injury	48 [10]	-	5	8	10	18

Object	damage level	Criteria		Empirical method, most close to case 1 [2]	Autodyn simulation for case 1 (open ro-ro space)	Autodyn simulation for case 2 (partially closed ro-ro space)	Autodyn simulation for case 4 (closed ro-ro space)
	Fatality	103 [10]	1 000	4	5	7	7
buildings	Minor damage	4.8 [2]	130	16	35	>115	>115
	Almost total destruction	34.5 [6]		4	11	12	21
Steel frame	Distortion of frame (minor to major)	49.2 [9]		21	8	10	16

## 5. Conclusions

Four scenarios of a 200 bar 130 l gas tank rupture in a ro-ro space are studied using a numerical model by an explicit dynamic code Autodyn as well as an empirical method. The numerical model yields more conservative results in terms of deterministic separation distance for human, building and steel structure, as compared to the empirical model. The reasons are two-folds. First, the empirical method is based on the physical burst of a freely propagating spherical blast, whereas the Autodyn model is more like a hemispherical blast where reflection from the deck floor is considered. Second, the Autodyn model invokes the TNT equivalent method, which means we assume the blast wave propagation of a physical burst is equivalent to that of a TNT detonation. Despite of the difference in the so-called deterministic separation distances, the Autodyn model is useful in studying different explosion scenarios qualitatively.

The effects of enclosure, vent strategy and barrier are studied. The numerical simulation shows that an open ro-ro space has biggest effect in reducing explosion overpressure, followed by letting front and stern being open. The barrier has significant effect in reducing explosion overpressure at a certain distance behind the barrier, and up to a certain height.

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