Risks associated with alternative fuels in road tunnels and underground garages

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Abstract

Due to environmental considerations, much current transportation policy development is aimed at increasing usage of renewable energy sources. These include gaseous fuels such as LPG, methane, and hydrogen, along with electricity. This research project focused on a literature review that was intended to research the risks involved in using alternative fuels in road tunnels and underground garages. Gaseous fuels and electric vehicles pose new risks that we, due to our greater familiarity with liquid fuels, are unused to. The greatest of these relate to gaseous fuels and pressure-vessel explosions, and the release of toxic gases such as hydrogen fluoride from Li-ion batteries undergoing thermal runaway. Two workshops were organised to obtain feedback from stakeholders and initiate discussion regarding the issue. Future research, risk-reducing measures, rescue service guidance, and changes to regulations and guidelines are discussed and proposed in this report.

Key words: Alternative fuels, vehicles, gas, electrical, risk, road tunnel, underground garage

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Preface

The Nordic Road Association (NVF) funded this literature review and final report through the 'New energy carriers in road tunnels and underground facilities' project. The project ran during 2016 and involved two workshops – one focusing on garages and one on road tunnels – to which interested parties were invited. The project also involved a collaboration with a similar Norwegian project, 'Brannsikkerhet og alternative energibærere: El- og gasskjøretøy i innelukkede rom' ('Fire safety and alternative fuels: Electric and gas-powered vehicles in enclosed areas '). This report was reviewed internally by Professor Anders Lönnermark.

Summary

In the future, a large number of road vehicles will not be powered by fossil fuels, and in order to prevent incidents in connection with such a change in the transportation sector, regulations and practices should stay one step ahead. This project was funded by the Nordic Road Association (NVF), and was intended to review and update current knowledge regarding alternative fuels, provide guidelines for the operations of rescue services, and offer recommendations for the creation of regulations. Road tunnels and underground garages constitute particularly high-risk environments with regard to fires and explosions. This project has focused on commercial gaseous fuels (liquefied petroleum gas; LPG, DME, methane, and hydrogen gas) and electric vehicles.

Sweden has the greatest depth of experience with vehicles powered by methane gas, i.e. CNG. The number of electric vehicles has increased enormously in recent years, particularly in Norway and, to a lesser extent, Sweden. Although the use of alternative fuels often entails risks, these should not be exaggerated, as all vehicle fuels have the potential to cause fire or an explosion. As compared to liquid fuels, however, these new fuels inarguably introduce new forms of risk, such as pressure vessel explosions, boiling liquid expanding vapour explosions (BLEVE), and toxic substances such as hydrogen fluoride, which are released by Li-ion batteries undergoing thermal runaway.

Although that periodic inspection of vehicle gas containers and systems are required in European regulation, this is currently not done in Sweden. Two pressure vessel explosions have recently occurred during refuelling at 230 bars for Swedish CNG vehicles which is about half of the design pressure for the gas container. There could be many more Swedish vehicle gas containers that currently operate with narrow safety margins. Although standardised testing should ensure that pressure relief devices activate in case of fire, there are many cases when they are unable to prevent a pressure vessel explosion due to the increased pressure inside the container and the weakened material following the fire. One reason is that the fire can be either more powerful or local compared to the fire in the standard. Another is poor maintenance and inspection of gas containers and systems. Taken altogether a pressure vessel explosion followed by a BLEVE (for LPG, LNG, DME) or fire ball (for CNG, hydrogen) as a result of a vehicle fire must be accounted for. Future research is required to clarify how large damages that would result on different types of buildings with underground garages. A road tunnel will be robust against this type of explosions with no or minor damages on the tunnel structure. One would further expect that the fire have resulted in evacuation well before any tank ruptures.

At least part of the energy that powers electric vehicles is stored in a battery. Li-ion-based technologies are the most common on the market at present, and will likely continue to be for the foreseeable future. The energy that is released during the combustion of a battery is moderate in relation to that of the rest of a vehicle, and contributes less to the fire load as compared to traditional petrol. In order to prevent battery failure as a result of both external impact and internal error, batteries are equipped with technical safety systems. If the damage sustained nevertheless causes high temperatures or internal short circuits, the battery may suffer failure and undergo thermal runaway.

The fire load of an electric vehicle is thus no greater than that of one with a more conventional fuel, but does involve different risks. The electric system of a traction battery must be taken into account during a rescue operation, particularly when a car is charging; provided the correct information is available to rescue services, however, traction batteries do not increase risk. During a thermal runaway, however, the production of highly flammable and toxic gases may become considerable. When thermal runaway takes place in connection with a fire, the gases produced do not exacerbate the situation

as the fire gases from the fire are themselves toxic; if no fire occurs, however, the production of large amounts of toxic gas, such as hydrogen fluoride (HF), may occur and go unnoticed.

Fires in batteries are very difficult to extinguish due to the extensive insulation of batteries, and a great deal of cooling is required to stop a thermal runaway. Thus, a fire suppression operation involving an electric vehicle should focus on extinguishing the fire around the battery, and preventing fire propagation from it. Damage Li-ion batteries can start or re-start a The thermal runaway process of damaged Li-ion batteries may re-start and/or continue for more than 24 hours after the damage occurred, which can lead to re-ignition or a new fire starting.

One of the greatest dangers posed by electric vehicles at present is arguably not the technologies that constitute them and the possible adverse consequences of their use, but uncertainty regarding how to handle them. The technology is relatively new, and differs significantly from conventional fuels. This may lead to uncertainty during a rescue operation, and thus a greater degree of risk.

1 Introduction

In the future, a large number of road vehicles will not be powered by fossil fuels, and in order to prevent incidents in connection with such a change in the transportation sector, regulations and practices should stay one step ahead. Road tunnels and underground garages constitute particularly high-risk environments with regard to fires and explosions.

The transportation sector is currently undergoing major changes, driven in large part by the gradual transition towards a fossil fuel-independent society. The Swedish government has put forward the vision of a Sweden with no net emissions of greenhouse gases to the atmosphere in 2050, with an important step on this road being priority being given to a fossil fuel-independent vehicle fleet by 2030 (Govt. Bill 2008/09:162). Several types of alternative fuels for vehicles have been introduced, and yet more are in development. These often involve new types of risk, which society must be able to mitigate. It is important that evolving systems be constantly evaluated so that rules, regulations, and practice can be updated and large incidents prevented.

In general, it can be said that vehicle fuels involve some form of risk of fire or explosion. Liquid fuels, such as petrol, and combustible gases may be ignited and begin to burn during a leak; moreover, when they are combined with air, explosive mixtures may be formed. The risks that arise with vehicle fuels should not be exaggerated, however. Considering the extent to which vehicles are used on a daily basis in society, it can be said that relatively few incidents occur in which the type of fuel has influenced the course of events or outcome. This is likely due to the fact that Sweden has a very long tradition of vehicle development, and an extensive set of rules and regulations that govern both the production and use of vehicles.

What is important when a new vehicle fuel is to be introduced is understanding how it behaves in various situations, and producing vehicles, building filling stations, and planning safe handling procedures based on that knowledge. Legal requirements and standards need to be drawn up at an early stage so as to both guide and support this development work. This is particularly true for road tunnels and underground garages that, due to their enclosed nature, constitute particularly high-risk environments during fires, explosions, and gas emissions. The current regulations pertaining to tunnels and garages do not consider the fuels of vehicles (although local regulations may). Restrictions that are currently in place in other countries differ from one another, and may thus be challenged, and risks need to be understood and evaluated in order for efficient regulations to be introduced at an early stage.

Another important aspect is the operations performed by rescue services, and the new dangers that vehicles with alternative fuels pose to them. For example, gas tanks can explode or create a gas flame when the pressure-relief valve is released due to increased pressure during a fire.

1.1 Goal and purpose

The purpose at the outset of the creation of this report was to review and update current knowledge about alternative fuels for vehicles in relation to their use in tunnels and garages. A secondary purpose was to present scholarship, knowledge, and statistics regarding incidents involving vehicles that use alternative fuels.

Important fire- and explosion-related issues that relate to alternative fuels have been surveyed. Areas in which further investigation or the development of new tools for the prevention and handling of fire scenarios are required are described. The overall goal has been to present information that can guide government authorities and the transportation sector in dealing with these risks in future garages and tunnel systems.

Current regulations and practice for the construction of tunnels and garages have also been investigated. Rescue service guidelines for extinguishing fires in vehicles that are powered by alternative fuels have been examined in detail.

The study was limited to those alternative fuels that are used commercially in Sweden, i.e. for which there is at least one filling station open to the public. In addition, at least one of two conditions had to be met; the fuel should behave differently from conventional ones, or there should exist uncertainties regarding the risk of fire or explosion posed by it.

1.2   Report overview

Chapter 2 provides an overview of how rescue operations are performed during underground fires. Chapter 3 presents an extensive discussion of the risks involved in using alternative fuels, focusing on theory regarding gases and explosions, and of electrical batteries and electric vehicles in underground garages and road tunnels. Chapters 4 and 5 can be read wholly separately, and provide a summary of the largest risks posed by alternative fuels in road tunnels and underground garages, and discuss possible measures for risk-reduction. Chapter 6 presents recommendations for regulations and possible avenues for future research.

2   Underground rescue operations

Rescue operations in underground structures often require unconventional strategies and methods. The 'Tactics and Methodology for fires in Underground constructions' (TMU) project has developed recommendations for operations in different kinds of underground structure; these are, primarily, road tunnels, rail tunnels, mines, and underground garages. These recommendations are based on experiments performed in a tunnel, previous research projects, and accounts of real incidents. This chapter presents an overview of the recommendations given in the 'Recommendations for firefighting in underground facilities' report (Lönnermark et al., 2015).

An underground structure presents a different risk scenario than that posed by an above-ground building. The distances to be travelled on foot by rescue personnel are often longer and the environment unfamiliar, meaning that people may need assistance in order to safely evacuate. Moreover, operations involving underground structures are often spread over a larger geographical area; for example, the distance between two tunnel portals may be several kilometres. It is often impossible to predict the course of events in these environments, presenting difficulties in terms of obtaining an overview of the course of an incident. In addition, rescue services are generally not as familiar with the layout of structures as compared to during apartment-building fires, for example.

The development of a fire in an underground structure differs greatly from that in a building above ground. It often involves an extensive and rapid spreading of smoke, and the size and heat flux of the fire can also impact the ability of rescue services to extinguish the fire. The need for additional resources, such as breathable air, extra hoses, and mobile fans, often arises, and special factors must be considered. These include:

- Access to emergency ingress and evacuation routes.
- The materials that surrounding surfaces are made out of, and how this may affect the operation..
- Specific risks in the form of high voltages, shafts, etc.
- Extinguishing systems.
- The number of people, and where they are.
- Technical installations and their control and monitoring.
- The possibility of collapse or spalling of the parts of the tunnel that have been exposed to heat.
- High voltages or highly flammable liquids or gases.
- Traffic in the rail or road area.

The general strategy and method that is recommended is to be well prepared. As the familiarity of such environments to firefighters is limited, a simple and well-rehearsed approach is imperative to an effective operation. Operations in underground structures are resource-intensive; thus, it is recommended that an officer be appointed whose responsibility is to ensure that the necessary resources are available. In this case, resources include both personnel and materials such as breathable air and other supplies. Upon arrival at the incident site, the primary strategy involves facilitating self-evacuation by creating a smoke-free environment with good visibility. Life-saving efforts take priority over extinguishing the fire, unless the fire prevents the undertaking of such efforts.

The selection of the emergency ingress route is of particular importance in underground structures, which are often large and complex. Rescue service personnel should, insofar as possible, avoid travelling through smoke-filled environments. The difficulty, however,

lies in knowing where the fire is without going down into the structure. When there is no risk of flashover or being surprised by a fire, a small team can enter first in order to reconnoitre. The goal of this team is to obtain an overview of the incident and assist in evacuation. They are not to extinguish any fires and so are able to move more rapidly than smoke divers, who need to build a hose system with safe access to water. The reconnaissance team can be equipped with a fluorescent guide line, in order to facilitate both rapidly finding their way back out and assisting in evacuation.

When rescue services decide how to strategically utilise ventilation, consideration should be given as to whether the environment is a tunnel or an underground garage. Fires in tunnels are not fuel-controlled, and thus ventilating them poses no risk. A tail-wind for firefighters also decreases the risk of the need for an emergency ingress into a smoke-filled environment. The problem, however, is that the fans of rescue services are often too small for larger structures. Additionally, the noise that they produce may hamper communication, and thus the operation, and so their placement must be carefully considered. In a tunnel, it is also important to exercise caution with ventilation with regard to ensuring that there are no people in the direction of the air flow. In garages, the fire may be ventilation-controlled, meaning that the development of the fire is strongly affected by ventilation and access to oxygen. It is also critical that an outlet for exhaust air is determined beforehand, so that smoke is not pushed into spaces such as stairwells.

Another recommendation presented by the project was to simplify procedures as much as possible by preparing and coupling hoses prior to operations. For long emergency access routes, travelling light is important; this can be done by, for example, ensuring that the hose system is empty and transporting equipment using a shoulder harness or trolley. The latter was intended to ensure that no energy is spent carrying extra air and hoses, as this is instead transported using a trolley with wheels. It was found, however, that a substantial amount of practice on the part of rescue services was required for it to be effective. Thermal imaging cameras are important assistive devices, but require practice to be used in an efficient manner, such that the small differences in temperature that may occur in a tunnel or a parking garage can be discerned. Due to its requiring the use of a hand, carrying a thermal imaging camera is not optimal, and the possibility of mounting one on a helmet should be investigated. The use of oxygen instead of compressed air in cylinders was another suggestion for increasing operation effectiveness by allowing smoke divers to remain in smoke-filled environments for longer, but requires further investigation before it can be implemented.

Figure 1 : Large-scale trialling of a rescue operation during the TMU project. Photograph: Per Rohlén.

Figure 1 is a photograph of one of the large-scale tests that was performed as part of the TMU project, the recommendations of which are available in full (Lönnermark et al., 2015). The report also includes references to the other reports produced as a result of the project.

3   Fuels and their risks

This chapter introduces various alternative fuels and the risks that their use entails from a fire and explosion perspective. Road tunnels and underground garages are buildings, and the Planning and Building Act (2010:900) asserts that a building must have the technical properties that are essential to ensure, among other things, safety in use (SFS, 2010:900). In the Planning and Building Ordinance (2011:338) it is stated that a building must have a load-bearing capacity such that during fires the structure can be expected to stay erect for a certain amount of time; additionally, it must have been planned and constructed so that the people who are in the building can leave it or be rescued, the safety of rescue service personnel during a fire operation has been considered, and the damage caused by an explosion is limited insofar as is possible (SFS, 2011:338). The chapter concludes with an assessment of the risks involved in using alternative fuels in underground garages and road tunnels, respectively.

According to the Swedish government report 'Fossil-free transport and travel' (SOU 2013:84), both Sweden and the rest of the world have the potential to become fossil fuel-free. It is, however, difficult to predict which fuels will be used for transportation, and which in other areas. Ultimately, the willingness of consumers to pay, along with markets more generally, governs this, influenced by politics. The report gives an idea of what road traffic may look like through comparison to statistics from 2010 (Table 1), and clearly suggests that a significant increase in the use of alternative fuels can be expected. It is, however, difficult to say which will be most widely adopted. A likely future scenario involves a combination of several different fuels, as opposed to only one or a few (Lönnermark, 2014). E85 was the biofuel that had the greatest impact after its launch in 2005, but the amount of ethanol sold annually has gradually decreased since 2012. A clear trend in recent years has seen petrol decrease in popularity, while usage of diesel has increased[1], suggesting the future widespread adoption of DME or ED95, rather than E85 and methanol, if the trend towards diesel engines continues. It is, however, more difficult for diesel engines to meet ever-increasing emissions standards. In recent years, sales of electric vehicles have increased enormously in Sweden[2] and Norway (Reitan et al., 2016), and electricity may become the predominant fuel of the future if this trend continues.

Table 1 : Prognosis for the market share of renewable fuels in 2030 and 2050, as compared to 2010 (SOU 2013:84).

Fuel	Prognosis, 2030	Prognosis, 2050
Electricity	3-14%	19-45%
Biofuels	32-65%	55-?%
Fossil fuels	65-21%	26-0%

Until now, the most common fuels have been liquids, with petrol and diesel the most popular by far. As petrol is highly flammable and volatile, alternative liquid fuels such as ethanol, methanol, and biodiesel entail no increase in risk, and in fact constitute a reduced risk scenario (Machiele, 1990). These will thus not be studied in detail. A vehicle powered by a fuel cell converts hydrogen gas or methanol, for example, into electrical energy through a chemical process. It is thus not a combustion engine, although the fuels used are often possible to use in combustion engines. This study focuses on commercial fuels and their storage, regardless of how the energy is sourced.

Gaseous fuels are handled under pressure, and thus entail a different risk scenario to that of liquid fuels. The gaseous fuels that have been identified as being commercial in

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[1] The Swedish Petroleum and Biofuel Institute: www.spbi.se;
[2] Statistics Sweden: http://www.scb.se/en_

Sweden are dimethyl ether (DME); liquid petroleum gas (LPG); methane in the forms of compressed gas (CNG) and cryogenic gas (LNG) – although the 'N' stands for 'Natural', it is here used to denote methane gas, regardless of its origin (natural gas/biogas); and hydrogen gas.

Another group is electric and hybrid-electric vehicles, which are entirely or partially powered by electrical energy stored in batteries. Electric vehicles behave differently during fires, and can emit gases during thermal runaway. They were of interest to the study, not least as they are often charged in underground garages – a process that entails risk of electrical failure and fire.

3.1 Flammability

The physical parameters that are normally used for estimating the probability of a fire occurring include flashpoint, flammability limits, and autoignition temperature. In addition, the density of the fuel vapours/gases in relation to air is of interest, as this influence how vapours/gases spread during an emission. The flashpoint of a liquid is of crucial importance when assessing its flammability. It should be noted that it is a general assumption that evaporation and vapour pressure increase with a lower flashpoint temperature, and that the two are thus dependent, further highlighting the importance of the flashpoint.

Flashpoint: This is the lowest temperature at which a liquid forms a combustible fuel concentration mixture when mixed with the air in the vicinity of the surface of the liquid.

Flammability/explosive limits: When a combustible gas is mixed with air a mixture is formed, and the quantity of combustible gas is normally expressed as a percentage by volume in relation to the amount of air. A too-low fuel concentration (too-lean mixture) means that the amount of fuel is too small, and the gas is thus not combustible. The point at which the concentration reaches a combustible/explosive concentration is termed the 'Lower Explosive Limit' (LEL). If the concentration of combustible gas increases further, a point will eventually be reached at which the amount of fuel becomes too great (too-rich mixture) and the gas mixture becomes non-combustible; this is the 'Upper Explosive Limit' (UEL). The values between the LEL and UEL of a gas thus comprise its flammability limits.
The flammability limits of liquids can be expressed as a temperature range, i.e. the temperature at which, in ambient conditions in an enclosed vessel, a fuel concentration corresponds to the LEL or UEL. These are then termed 'Lower Explosive Point' (LEP) and 'Upper Explosive Point' (UEP), and are expressed in degrees Celsius. In practice, the LEP of a liquid generally corresponds to its flashpoint.

Autoignition temperature: The temperature required to ignite a gas mixture without an ignition source such as a spark or an open flame.

Relative density: The density of fuel vapours relative to that of air. If fuel vapours are significantly denser than air there is a high risk of combustible accumulations at topographical depressions; reversely, fuel vapours that have a density that is significantly lower than that of air will rise and mix more rapidly with the air, such that the concentration decreases to below the flammability limits. The risk inherent in using less dense gases, on the other hand, is that they can accumulate in hollow spaces just under a ceiling.

Below, the risk parameters for the various fuels are presented in brief, followed by a general description of the various fuels' fire characteristics.

Table 2: Characteristics that influence the probability of ignition.

Substance	Relative density (air=1)	Flashpoint (°C)	Flammability limits (vol%)	Autoignition temperature (°C)
DME	1.6	Gas	3.4-27	350
LPG (PROPANE)	1.56	Gas	1.7-10.9	450
METHANE	0.6	Gas	5-15	540
HYDROGEN	0.1	Gas	4-77	560
PETROL	3.5	<-20	1-8	400
DIESEL	7	60	1-7	220

A liquid with a flashpoint that is less than its working temperature cannot be expected to produce combustible gas mixtures unless the temperature is increased to above the flashpoint. Diesel stands out as having a high flashpoint. For a combustible mixture to ignite, an ignition source, such as a hot surface of an engine or an electrical spark, is required. Several alternative fuels have a broad range of values between their LEL and UEL, increasing the probability of a combustible mixture being produced. Their autoignition temperatures are, however, relatively similar to that of petrol, the notable exceptions being those of diesel and DME, which are relatively low.

3.2 Explosion

The National Fire Protection Association (NFPA) defines an explosion as a rapid release of gas under pressure (Cruice, 1991). The keyword here is 'rapid', as this quick release results in a blast wave. Pertinent examples of such an explosion include the rupturing of a pressurised tank, i.e. a pressure vessel explosion, and a chemical reaction (combustion, for example) that results in a rapid increase in pressure (Bjerketvedt et al., 1997) such as occurs when a combustible gas-air mixture is ignited. An explosion can thus be physical – a gas tank that ruptures due to excessive pressure – or chemical (exothermic reaction) – as a result of ignition, for example (Cruice, 1991). Pressure equalisation takes place at the speed of sound. The initial amplitude of a blast wave created by a pressure vessel explosion is dependent on the pressure of the gas at the moment of release. The energy of the blast wave depends on the volume, pressure, and temperature of the gas in the vessel, and can be estimated by multiplying the pressure with the volume.

The portion of the gas that is in liquid form during a pressure vessel explosion may lead to a BLEVE when the liquefied gas rapidly evaporates in the warmer environment outside of the tank. For a BLEVE to occur, the liquid must be heated to above its 'superheat limit'. Table 3 shows that a BLEVE is only likely to occur in a situation in which a tank is exposed to fire (Cruice, 1991). A BLEVE can inflict fatal damage in not only the immediate vicinity of the vehicle but further away, as parts of the tank can be propelled a great distance. When the gas is ignited a high heat flux occurs, which may expose those at even a relatively great distance to a large amount of heat and ignite adjacent objects. It is impossible to provide a specific safe distance for such a scenario, as this is dependent on the size of the tank as well as other conditions such as its placement, how it is attached to the vehicle, etc.

Table 3: Temperature required for a BLEVE to occur.

Liquid gas	Superheat limit (°C)	Storage temperature (°C)
LNG	-93	-162
DME	Roughly 127	15
LPG	53	15

If a cloud of vapour that is still being emitted from a source is ignited, the energy and duration of the blast is increased, although the wave's amplitude is unaffected. The reaction begins at the ignition source and moves through the combustible mixture in the form of a flame front. The high temperature of the gases that are produced leads to their expansion, which increases the magnitude of the blast wave. A sufficiently high increase in temperature, and combustible mixture of gas in the vicinity in order for ignition to occur, is required for the reaction to continue. The higher the temperature and closer the mixture is to being stoichiometric, the more rapid the ignition and movement (reaction) through the gas is. Adjacent air and combustion products expand as a result of the increase in temperature caused by the combustion reaction. If the material that the gas container is made of is not strong enough it will yield, resulting in an explosion. Few structures are strong enough to withstand the combustion process of a vapour cloud, although such a cloud occupies a relatively small portion of the volume. The way in which gas accumulates in buildings is influenced primarily by the release rate of the gas, and the ventilation of the building. Less dense gases, such as methane and hydrogen, may accumulate under the ceiling of a room or a garage. Denser ones, such as petrol and DME vapours, accumulate at topographical depressions. The ignition of a hydrocarbon-air mixture in open space creates a negligible change in pressure, and in order for higher pressures to occur, obstacles that create turbulent flows, which speed up the reaction, are required. This means that explosions in buildings and pipes, for example, reach higher pressures than ones that occur in open space. In an enclosed environment, even a relatively slow reaction will result in an increase in pressure due to the fact that the gas has no space to expand into. The build-up of pressure during a deflagration is moderate, and a hydrocarbon-air mixture at normal pressure and temperature in an enclosed container can reach a pressure of close to 8-10 bar at ignition (Bjerketvedt et al., 1997).

If the combustion velocity of a vapour cloud mixture exceeds the speed of sound, a deflagration to detonation transition can occur, during which a marked local increase in pressure of close to 50 bar occurs. The detonation then continues at a pressure of 15-20 bar. The probability of a detonation occurring depends on the fuel. According to (Bjerketvedt et al., 1997), it is possible for hydrogen gas to detonate, and much less likely for methane. Spatial constraints, in the form of enclosed containers, rooms, or tunnels, for example, can increase the risk of rapid flame propagation (deflagration to detonation), as they impede the expansion of gases and thus lead to increased pressure. Once the transition to detonation has taken place, no obstacles or enclosures are required for the reaction to continue at its high propagation rate. A detonation is more likely to occur in a pipe than in a container. More obstacles result in the flow more rapidly becoming turbulent, and so increase the likelihood of a detonation. Such a scenario is not, however, likely for a road tunnel with a diameter of at least 6 m, as a very long – roughly 500 m – cloud of combustible gas mixture would be required (Bjerketvedt et al., 1997). Obstacles in the ceiling may accelerate the process, and are sometimes even a prerequisite for a detonation to occur.

According to (Bjerketvedt et al., 1997), deaths as a direct result of an increase in pressure due to an explosion are uncommon, whereas deaths as an indirect result, as caused by fires or collapsing buildings, are more common. Buildings generally fail due to very small increases in pressure, the consequences of which are summarised in Table 4 (Cruice, 1991; Bjerketvedt et al., 1997; Perrette and Wiedemann, 2007; Ingason et al., 2012):

Table 4: The consequences of increases in pressure.

Pressure (kPa) (1 bar=100 kPa)	Physical effects
5-7	People are thrown to the ground, regular windows break, regular

	buildings are damaged
34	Lower limit for eardrum rupture, dangerous glass splinters from regular windows can occur
100	Lower limit for lung injury
240	Lower limit for fatality
345	50% fatality rate
450	99% fatality rate

In a number of explosions involving CNG/LPG-powered vehicles, the damage done to vehicles and adjacent houses has been extensive. In the worst of these, gas has leaked into underground garages or down into basements. A number of explosions have also taken place during refueling or due to exposure to fire. The cases involving fuelling can often be ascribed to defective fuel tanks or faulty mounting. Berg (2014) asserts that the fire testing of fuel tanks currently varies greatly in quality and thoroughness, and often includes a number of unspecified parameters that can influence the test results. A real fire can result in entirely different types of fire exposure than what the tank has been tested for. When the tank is heated, the material is weakened and the pressure of the gas increases due to the increase in temperature. At its maximum pressure limit, a container will rupture at its weakest point, and the blast wave will travel outwards from the rupture.

3.2.1   Explosions in enclosed spaces

Higher pressures can be expected of explosions in buildings than those in open spaces, particularly if no pressure release can take place through windows or lightweight panels that rapidly open or are dislodged. Important factors include whether the integrity of the building is maintained, and whether dangerous fragments are blown away, the latter of which is affected by the materials that the walls are made of. Prefabricated walls and ceilings generally collapse, and bricks and windows can be blown away, while steel frames and reinforced concrete are able to withstand high pressures. A building that is to withstand external explosions should be constructed using steel or reinforced concrete, and have small, hardened windows with heavy frames. For a building to withstand internal explosions, it must have a strong internal structure that supports the floors and ceiling, and its walls should either be open, made of windows or consist of lightweight panels. In a so-called 'smart building', the building components are allowed to fail in a plastic (rather than elastic) manner, without quick breaks (flexible units), absorbing much of the energy of an explosion. Another important factor that influences the response of a building to a blast wave is its natural frequency of vibration, w, in relation to the length of the pressure impulse, t_d (Magnusson, 2007):

- For low w and t_d values, deformation is dependent on resistance and mass, as well as the total blast load of the pressure impulse.
- For large w and t_d values, deformation is dependent only on resistance and maximum pressure.
- w and t_d values that lie between these two extremes fall within the dynamic region, and for these the entire load history needs to considered, i.e. both pressure and impulse, as well as the system's mass and resistance.

Vapour cloud and pressure vessel explosions differ from those of conventional explosives. The latter result in a near-immediate increase in pressure that subsequently decreases in a rapid, exponential fashion. Vapour cloud explosions, however, result in a slower increase in pressure, and an even slower subsequent reversion to normal pressure. This more drawn-out development means that a building withstand twice as much pressure for large w t_d values and half as much (due to resonance) in the dynamic region, compared with conventional explosives. Pressure vessel explosions involve a rapid increase in pressure, similar to that of conventional explosives, but differ in that they emit

a high and long negative pressure impulse, followed by a second impulse of significant size. This leads to a broad dynamic region, and so buildings are more vulnerable to pressure vessel explosions (Baker et al., 1982). In general, secondary explosions, caused by the ignition of gas, for example, lead to longer pressure impulses, in turn leading to increased strain on garages, tunnels, etc.

A stoichiometric fuel-air mixture in an enclosed space will reach an excess pressure of approximately 8 bar. Generally, the less space that is occupied by the fuel-air mixture, the more pressure decreases; a space is that is only 30-50% full can, however, yield a similar increase in pressure, as the fuel-air mixture is displaced and so does not contribute to the explosion that occurs in the enclosed space. If 15% of an enclosed space is filled with a stoichiometric fuel-air mixture, the excess pressure is roughly 2 bar. A space that is as little as 1-2% full can constitute a problem for many structures that are only intended to withstand normal pressures, unless the excess pressure can be equalised using pressure control systems or weak wall panels (Bjerketvedt et al., 1997). A 50 l tank of methane gas at 200 bar contains roughly 100 m^3 of gas diluted to 10%, which means that an underground garage with a ceiling height of two metres and an area of under 5000 m^2 would likely sustain damage.

In an enclosed space, the chamber pressure following a pressure vessel explosion is greatly influenced by the volume of the room (FortH2, 1991). A greater volume means a lower chamber pressure for the same load. The chamber pressure yielded by an explosion in a large garage is likely very small, although the local pressure is generally higher.

The pressure inside a tunnel is initially affected by waves being deflected by the walls, but spreads primarily along the tunnel with a chamber pressure similar to that which is stated above (FortH2, 1991). For a road tunnel of 100 m and a cross-sectional area of 50 m^2 and an explosion corresponding to 2 kg of TNT, the chamber pressure would be roughly 0.1 bar, which would not significantly affect the tunnel, vehicles, or people.

When a blast wave directly impacts a building, the pressure in the direction of the wall is both static and dynamic, as the blast wave is stopped and deflected. This means that the pressure against the wall is roughly doubled for lower pressures, and up to 20 times higher for higher pressures. The point at which a building begins to vibrate depends on the maximum pressure, the rate at which the pressure increases, and the building's mass and natural frequency of vibration.

In 1993, a car bomb of at least 450 kg exploded in a garage below the World Trade Center (WTC) in New York. Six people lost their lives in the explosion, and close to one thousand were injured. Smoke spread rapidly to several buildings in the WTC complex, and roughly 150,000 people were evacuated from the various buildings. Floor B-2, two floors below ground level and the one on which the car was parked, was completely destroyed. Walls and vehicles were blown away like child's toys; reinforced concrete floors were blown to pieces. Steel pillars were damaged, but remained intact. The extensive damage was distributed across seven floors, six of which were below-ground. WTC was a well-constructed complex, and this contributed to its withstanding the powerful explosion relatively well (USFA, 1993).

In 2011, a cloud of vapourised LPG exploded in an underground building made of reinforced concrete in Turkey (Turgut et al., 2013). The LPG leaked into the building from a damaged pipe. The basement level of the building was used as a textile factory, but was similar to an underground garage in terms of layout, with the explosion occurring in a relatively small space of roughly 10 x 30 m. The basement level did not have mechanical ventilation. The outer walls were surrounded by earth, and there was a fuelling station above ground for LPG-powered vehicles. An interior wall separated the

space in which the explosion occurred from the rest of the basement level, which was 40 x 30 m in size. This wall was not sufficiently light to provide ventilation or pressure release during the explosion; instead, it increased the pressure in the space in which the explosion occurred, and its constituent material then became dangerous projectiles when it was destroyed. When the wall failed, the high pressure became directed into the adjacent space. The damage to the structure of the building was severe in the space in which the explosion occurred, and less so on the far side of the building. Contrary to what might be expected in the aftermath of such a powerful explosion, the building did not collapse, but several pillars were compressed; as the pressure lifted the roof, the pillars were pulled apart, and the roof then came back down, landing on the pillars. Parts of the roof hung like a hammock within the building, and large parts of the concrete floor above-ground were broken. The maximum excess pressure was estimated as being 0.6 bar. One person died in the basement level, and 21 were seriously injured (Turgut et al., 2013).

Wijesundara and Clubley (2016) state that the effects of upwards-directed forces on ceilings have not been previously studied, and that they cause a great deal of damage, particularly if the pressure release is limited, as often occurs in basements and underground garages. In enclosed spaces, secondary shock waves that have been deflected by walls are just as strong as the primary shock wave of the explosion, and can cause a great deal of damage as they can occur at the same time as upwards-directed forces remove the load from support pillars, for example. As a rule, reinforced concrete is more resistant to pressure when supporting a higher load, and is thus sensitive to secondary shock waves in combination with upwards-directed forces that remove or re-distribute load. Pillars must be firmly anchored to the floor and walls if they are to withstand such forces optimally.

3.2.2   The behaviour of gases in enclosed spaces

In an enclosed space, less dense gases, such as hydrogen or methane (see Table 2), rise and accumulate below ceilings. The density of a gas-air mixture is dependent on the relationship between the destabilising effect of its momentum as it rises as a result of it being a less dense gas (also known as 'buoyancy momentum') and the stabilising thermal force (also known as 'buoyancy') resulting from the increasing concentration of gas in the gas-air mixture that is caused by height gain. At the point at which a critical density has been reached, a well-mixed layer of a consistent density is formed. Below this critical density, a stratified gas layer is formed below the ceiling, and becomes increasingly dense with distance from the source for the duration of the emission. When the emission ceases, the stratified layer dissolves due to molecular diffusion. After a greater period of time than that of the emission, a homogeneous gas-air mixture forms in the enclosed space. If the emission velocity is high enough to overcome the thermal force, mixing with air will occur due to the air being sucked into the emission plume, which can rapidly create a homogeneous gas-air mixture (HySafe, 2009).

for longitudinal ventilation, the same behaviour as has been observed in smoke plumes in tunnels can be assumed (Ingason et al., 2015). Little or no ventilation results in the gas plume extending to the ceiling and spreading radially along it. Relatively low ventilation – in the order of 1-2 m/s – results in the gas plume rising towards the ceiling and spreading both upstream and downstream along it. Upstream, the amount of gas is limited by the fact that the ventilation eventually overcomes the momentum of the gas, pushing the gas back towards the source. More pronounced ventilation – above roughly 3 m/s – means that the momentum of the air is greater than that of the gas, and so the former carries the latter in the direction of the ventilation (Ingason et al., 2015). The most common gases that are emitted by Li-ion batteries are carbon dioxide, carbon monoxide, hydrogen, and hydrocarbons (Colella et al., 2016).

Gases that are denser than air (DME and LPG, for example; see Table 2) accumulate at floor-level or in topographical depressions such as floor drains. A similar but opposite behaviour as that described above for gases that are less dense than air can be predicted.

3.3 Conventional fuels (petrol and diesel)

During a liquid fire, the vapours that the fuel emits, together with air, constitute the burning material. During an open fuel spillage, the temperature of the liquid must be above its flashpoint in order for ignition to occur. At temperatures above the liquid's flashpoint, there will always be an area of the spill in which the fuel vapours are within their flammability limits; this can be ignited if an ignition source is present.

When a liquefied fuel is stored in an enclosed vessel, an equilibrium is reached that creates a temperature-dependent fuel-air mixture. If the temperature of the liquid lies between its LEP (flashpoint) and UEP, the fuel mixture inside the vessel is combustible, and ignition may involve a small explosion. This means that even a fire outside the fuel tank can cause ignition, either through a flame igniting the fuel vapours in a ventilation opening or another leaking point, or another part of the tank reaching the autoignition temperature of the fuel.

3.3.1 Petrol

Petrol is a highly volatile and flammable fuel that under normal conditions has a flashpoint of between -40 and -30°C. Its properties are governed by the fuel specifications that are standardised to ensure that it functions properly as motor fuel. This means that during the winter months, petrol is available in a 'winter blend' with a higher vapour pressure (measured at 20°C) in order to ensure that engines start at low temperatures. The electrical conductivity of petrol is low, meaning there is a risk of static electricity being generated during handling, for example as a result of free-fall or transportation through long pipes.

Due to the high vapour pressure, the fuel concentration inside a petrol tank lies far outside the flammability limits (roughly 1-8 vol%). Expressed as a temperature range, this means that the LEP is lower than -40 to -30°C, while the UEP is roughly -20°C (summer blend). In practice, if the temperature of the fuel is higher than -20°C, the fuel mixture inside the tank is too rich, and thus not combustible. At present, petrol contains approximately 5-7% ethanol; as vapour pressures are governed by standards, however, this barely affects the ignition properties of the mixture.

The heat release rate of a petrol fire per square metre is very high, and emits a high heat flux towards its surroundings. For fires of a few hundred square metre or more, relative heat flux decreases due to inefficient combustion and increased production of soot inside the flame, which also deflects some parts of the heat.

3.3.1.1 Scenarios involving vehicles

Petrol is a highly flammable substance, although it has been established that, with regard to normal handling, current rules and regulations ensure a very high degree of safety and the occurrence of relatively few incidents. Petrol pumps are equipped with a vapour recovery system that efficiently removes the petrol vapours from the filling pipe, decreasing the risk of ignition. Vehicles are also constructed so as to minimise the possibility of generating static electricity during filling. In the event of ignition, the fuel concentration inside the tank is so high that the fire cannot propagate inside so as to cause an explosion.

During spillage or outflow, however, combustible vapours are rapidly formed, making the fuel highly flammable. The energy required to ignite these vapours is relatively small, and

the risk of ignition relatively high. If the petrol is ignited, it will likely begin to burn at its maximum heat release rate within a few seconds. During collisions that result in petrol leakage, the risk of fire is thus very high, as there are many possible ignition sources; spark formation due to friction or short circuits, hot surfaces, etc.

A spillage fire can also lead to the fuel tank becoming exposed to flames. The petrol tanks of the vehicles of today are often made of plastic, and thus can melt due to heat. According to the current UNECE R.034 regulations (UNECE, 2014b), a fuel tank should be able to withstand a standardised fire exposure for at least two minutes without leakage; it is expected that after this, however, the plastic will melt and the fuel will flow out, rapidly involving the entire vehicle in the fire. There is, however, no great risk of tank explosion, due to the high fuel concentration inside the tank and the weakening of plastic objects such as the fuel tank and hoses and pipes due to the heat, preventing high pressures from building up within the tank.

3.3.2 Diesel

Diesel is a less volatile fuel that ordinarily has a flashpoint of 60°C. This means that, at normal temperatures, an open fuel spillage cannot be ignited by a small ignition source. Due to its high flashpoint, the propagation of a fire over a diesel pool surface is considerably slower than for petrol, although at the point at which a fire has fully developed, diesel burns in a similar manner to petrol. Diesel does, however, result in more pronounced and dense soot formation, and thus a somewhat lower heat flux.

3.3.2.1 Scenarios involving vehicles

Due to the relatively high flashpoint of diesel, fuelling and normal handling entail a much lower fire risk than with petrol – as does, ordinarily, a spillage. However, a leak within the engine compartment resulting from a lack of maintenance or a collision, for example, can present a great risk of fire, as there are many hot surfaces that can heat the diesel and, due to its relatively low autoignition temperature, ignite it.

A fire in an engine compartment can naturally spread and, under certain circumstances, eventually result in the fuel tank coming into contact with or being exposed to fire. Plastic tanks are common in diesel cars, as well as to a lesser extent in larger vehicles such as buses, and these must also fulfil the requirements of the UNECE R.034 regulation, i.e. be able to withstand exposure to fire for two minutes. Just as for petrol, a leak can be expected to occur after this point and, as the fire is already in progress, the outflowing diesel will immediately be involved. As the tanks of buses and trucks are much larger than those of cars, a fuel spill becomes much larger much more quickly, creating a fire that is, more intense, sizable, and longer-lasting. The fuel tanks of trucks are generally made of aluminium or steel sheets, decreasing the likelihood of a rapid outflow during exposure to fire.

3.4 Gaseous fuels

A gas is here defined as a substance that, at room temperature, does not have a defined form or volume. Gaseous fuels can be compressed, liquefied-compressed (which is to say liquefied and compressed, expressed in this way so as to avoid confusion) or take the form of a cryogenically frozen gas, wherein it has been so heavily cooled that the gas condenses into a liquid. The storage and handling of methane takes place in the form of both compressed gas (CNG) and cryogenic gas (LNG). Hydrogen gas is primarily handled in compressed form, whereas LPG and DME are normally handled in liquefied-compressed form (see the summary in Table 5 below). The gas container of a car is normally on its underside or in the lower part of the boot. Those of trucks are often placed in the same location as diesel tanks are currently placed, although they can also be found below the load or behind the cab. On buses, gas containers are often placed on the roof.

Table 5: Type and form of various gaseous fuels.

Fuel	Compressed gas	Liquefied-compressed	Cooled liquid (cryogenic) gas
LPG		X	
DME		X	
CNG	X		
LNG			X
Hydrogen	X		

Compressed gases (e.g. CNG and hydrogen gas) are often handled under high pressure; the maximum pressure used in pressure vessels varies between 200 and 700 bar, depending on the size of the vessel. It should be noted here that pressure vessel explosions can occur during fuelling, due to the fact that it is during this process that containers are exposed to maximum pressure. After extended periods of use, exhaustion phenomena can occur, which can in turn lead to tank rupture. There are four different types of CNG and hydrogen gas container:

1. Metal containers.
2. Metal cylinders that are, aside from the bottom and neck, wrapped in sheets of composite materials.
3. Metal cylinders that are entirely wrapped in sheets of composite materials.
4. Plastic cylinders that are entirely wrapped in sheets of composite materials.

For liquefied-compressed gases (e.g. LPG and DME), the gas condenses when compressed, and so they are found in both liquid and gaseous phases in pressure vessels containing them. The pressure in the vessel varies with the ambient temperature, but is often approximately 5 bar at 20°C, increasing rapidly with increased temperature.

A liquid (cryogenic) gas has been cooled to below its boiling point, and is stored in condensed form in a pressure vessel. An example is LNG, which has a boiling point of -162°C. Cryogenic pressure vessels are very well insulated (in a similar manner to a thermos flask) so as to minimise heat transfer into the vessel. The small amount of heat that is transferred into the vessel in spite of the insulation causes a very small portion of the gas to vapourise, increasing the pressure inside the vessel, and if this is not removed in the course of normal use, some of the gas must be vented through a pressure-relief valve to avoid the pressure becoming too high. The release pressure for the pressure-relief valve is adapted to the design of the pressure vessel, and is often in the range of 5-15 bar.

In 2016, several explosions involving gas-powered vehicles occurred in a matter of months in Sweden. One involved a bus that was ignited, and subsequently exploded while the rescue operation was still ongoing. Two firefighters suffered light injuries; had the bus exploded a few minutes earlier, their injuries would likely have been severe. Another incident was a refuse collection truck that exploded while driving, fortunately causing no injuries. The most recent was a car that was ignited and then exploded; firefighters were not in the vicinity of the car, but part of its roof, launched by the explosion, landed only a few metres away from one[3]. It is important to remember that, even though incidents occur, many of those relating to gas-powered vehicles are no more remarkable than those involving conventional ones (Lönnermark, 2014). Below, the basic properties of the gases used are described, and fire scenarios involving vehicles are presented with reference to the type of storage (compressed, liquefied-compressed, and cooled).

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[3] http://www.ctif.org/sites/default/files/news/files/extra_news_december.pdf

3.4.1   Methane

Methane (CH_4) is an odourless and colourless gas that is highly flammable and explosive, and reacts violently when it comes into contact with strong oxidants. It is less dense than air, and can thus accumulate under the ceiling of a room or garage. Methane is stored either in compressed form (CNG) or as a cooled gas in a cryogenic container (LNG) (Coen, 2010).

The use of methane/natural gas is governed by the UNECE R.110 (UNECE, 2014d) regulation, which also includes a fire test. In Sweden, the fuel systems of CNG-powered vehicles are governed by a Swedish Road Administration regulation (VVFS 2003:22, Chap. 6, § 37-64), along with amendments made by the Swedish Transport Agency (TSFS 2009:16, § 38, 39, and 43). The safety systems of CNG and LNG containers are constructed so as to prevent a pressure in excess of safe limits from building up in the container by venting gas. Compressed gas in a fuel container has a pressure of roughly 200-250 bar, which is necessary for the container to hold enough fuel to provide a vehicle with sufficient range for everyday usage (Coen, 2010). These containers generally consist of a metal cylinder that is coated in a carbon fibre or glass fibre weave. CNG systems have a low-pressure end that is located behind the pressure regulator, reducing the pressure to 10 bar. LNG containers often have an operating pressure of less than 20 bar, although the UNECE R.110 regulation allows pressures of up to 260 bar (see Table 6).

Table 6: Methane-powered vehicle fuel containers

	CNG	LNG
Operating pressure	200 bar	5-20 bar
Temperature	-	-162°C
Volume	Normally 25-250 l for cars and small vehicles. 50-400 l for heavy vehicles (multiple containers can be used).	Normally 100 l for cars and small vehicles. 700-900 l for heavy vehicles (normally divided between two containers).
Design pressure	2 × operating pressure	2 × operating pressure
Pressure-relief valve	1.5 × operating pressure and 110 ± 10°C	1.5 × operating pressure

3.4.1.1   Scenarios involving vehicles powered by compressed methane (CNG)

A number of different fire scenarios may occur involving CNG vehicles. In one a vehicle is on fire, with the fire spreading so as to affect the containers. Another is a collision, in which the other vehicle leaks fuel that is ignited and flows under the fuel container of the CNG vehicle. A third involves a leak occurring in a pipe that is adjacent to the fuel container of the CNG vehicle which, when ignited, causes a jet fire directed towards some part of the container. In all of these scenarios, the fuel container and its contents are heated rapidly, causing an increase in pressure in the container. The pressure-relief valve of the container releases in response to high temperature and/or excess pressure, but this results in a sudden and extremely rapid outpouring of gas that, due to the surrounding fire, is ignited and causes a severe jet fire. According to the UNECE R.110 regulation, the pressure-relief valve of a fuel container should be oriented so as to prevent further exposure of the container to fire; in many cases, however, either directly or indirectly, other parts of the vehicle or adjacent vehicles are exposed. As the quantity of gas is

relatively small when it is stored in compressed form, the container empties relatively quickly, leading to a rapid decrease in pressure. If the effect of the fire on the container is severe, the structure of the container will be heated and thus lose much of its rigidity; moreover, if the pressure-relief valve is unable to vent a sufficient quantity of gas relative to the increasing pressure in the container, the container will explode. This can inflict fatal damage in not only the immediate vicinity of the vehicle but further away, as parts of the container can be propelled a great distance. An explosion can occur during a fully developed fire, generally within 10-25 minutes of the fire beginning (MSB, 2016b). Theoretically, the energy released by a 130 l CNG container at a pressure of 200 bar exploding (8.7 MJ) is equivalent to 1.85 kg of TNT detonating. Such an explosion would break windows in a 30 m radius (the area in which the pressure would exceed 50 mbar) and be lethal within a 12 m radius (where the pressure exceeds 140 mbar) (Perrette and Wiedemann, 2007). In the aftermath of an incident in Indianapolis, USA on January 27, 2015, in which a CNG fuel container exploded, material from the vehicle was found 1.2 km away[4].

An American study (Lowell, 2013) presents international statistics for CNG incidents, the majority of which occurred in the USA (see Table 7). 50 tank ruptures occurred, which can be interpreted as constituting 50 pressure vessel explosions, between 1976 and 2010. This is the most commonly reported incident type, which may be due to the fact that many others, being less dramatic or severe in nature, are not reported. The majority of the pressure vessel explosions reported occurred during fuelling or as a result of exposure to fire. In 18 cases, the tank ruptures were caused by damaged cylinders, which could have been prevented through periodic inspection. In 14 cases, the pressure-relief valve did not release during exposure to fire. In more than half of the cases in which the pressure-relief valve did not release, the gas was ignited, and this was generally due to poor mounting, with pipes going through the engine compartment, for example.

Table 7: Global incidents involving CNG vehicles between 1976 and 2010 (Lowell, 2013).

Incident	Number
Tank rupture	50
Pressure-relief valve did not release	14
Vehicle fire without tank rupture	12
Leaking container	14

Additionally, pressure vessel explosions have recently occurred during the fuelling of gas-powered vehicles in Sweden[5]. According to information provided by the Swedish Civil Contingencies Agency (MSB), all of the containers exploded at a pressure of 230 bar. CNG fuel containers should withstand a pressure of 400 bar, and pressure-relief valves are designed with this in mind. Containers with lower strength are more likely to explode before the pressure-relief valve is able to reduce the pressure during a fire.

3.4.1.2 Scenarios involving vehicles powered by liquefied methane (LNG)

Liquefied methane and natural gas (LNG) containers have a significantly larger capacity due to the fact that the gas is condensed, greatly increasing the range of LNG vehicles. The structure of an LNG container is similar to that of a large thermos flask, and some use perlite insulation to minimise thermal leakage into the container. This means that the structure of LNG containers also reduces the heating of gas during exposure to fire, and provides additional protection against mechanical damage to the container. Cryogenic

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[4] http://www.ctif.org/sites/default/files/news/files/extra_news_december.pdf
[5] http://www.expressen.se/dinapengar/volkswagen-aterkallar-gasbil-efter-explosion/;
http://teknikensvarld.se/gasbil-exploderade-vid-tankning-av-biogas-i-linkoping-182638/

containers intended for use in vehicles should fulfil the requirements of the UNECE 110 regulation, which includes a fire test.

If a container is damaged such that leakage occurs without fire, two possible situations can unfold: If the container is fractured above the liquid surface of the condensed gas, the leaking gas vapours will form a vapour cloud. This leak will, however decrease in intensity as the pressure in the container falls, as vapourisation requires heat transfer into the container. If the container is damaged in such a way that the fracture occurs below the surface of the liquid, cold liquid will flow out under pressure and, initially, instantly vapourise when it comes into contact with the ground or other surfaces (which are, relatively speaking, much hotter, due to the gas being stored at -162°C), but will subsequently, particularly with larger quantities of gas, cool the ground quite quickly, resulting in a liquid pool that then vapourises more slowly to form a vapour cloud that lingers for longer. A cryogenic gas leak can, due to its very low temperature, cause frost injuries and damage to people and objects.

During exposure to fire, the cooled gas inside the container is heated, increasing the vapourisation rate and thus the pressure inside the container; this, in turn, leads to the pressure-relief valve releasing. If the container's insulation is designed to function solely as a 'thermos flask' and is damaged, its insulating effect is drastically reduced, although the structure shields the liquid somewhat from flames. If the insulation is comprised of a 'thermos flask' in combination with other insulating materials, the container's insulation is more effective and the heat transfer into the container is significantly reduced, increasing the likelihood that the pressure-relief valve will be able to maintain the pressure at a safe level until the fire is extinguished or the gas burned up. Under particularly unfortunate circumstances in which insulation is damaged, thermal exposure can be sufficiently severe that the pressure-relief valve has no time to respond to the increase in pressure, leading to a further increase. As the strength of the container simultaneously decreases, a container explosion that results in a BLEVE, in which the now-heated, condensed gas is vapourised instantaneously when the container ruptures and the pressure is equalised, may occur. This results in a large, burning aerosol/vapour cloud that rises and exposes the surrounding area to a very high heat flux for a period of several seconds.

While liquid fuel spills, which produce a vapour cloud, are often 'washed away' using a water spray, the same approach cannot be used for emissions of condensed gas, as the heat of the water increases its vapourisation rate. In such a scenario the water must be prevented from coming into contact with the liquefied gas pool and, if at all possible, some form of tarpaulin or sheet should be used to cover the spillage, or a 'very dry' Compressed Air Foam (CAF) should be applied so as to decrease the vapourisation rate.

Condensed methane gas emissions spread along the ground, rapidly filling topographical depressions, and, after a short time, begin to mix with the air and further disperse. Such a vapour cloud is clearly visible, as the cold gas causes moisture in the air to condense and form a mist. Regardless of whether the gas emitted is condensed or compressed, a combustible mixture of gas and air is rapidly formed. The vapour cloud can be ignited and burn up as the flame front spreads through it and, if it is in an enclosed space when it is ignited, a vapour cloud explosion may occur. Gas containers that are directly exposed to heat and lack a functional pressure-relief valve can produce a BLEVE or pressure vessel explosion. Outflowing methane gas is, due to its low boiling point, cold, and may cause frost injuries (Coen, 2010).

3.4.2   Dimethyl ether and LPG

Dimethyl ether (C_2H_6O; DME), is the least complex ether and, according to current legislation, not considered to be hazardous to either health or the environment. The gas is

sold under the name 'Dimethyl ether' in Sweden, but is also known as 'Methyl ether'. DME is liquefied-compressed in the same way as LPG (Coen, 2010) and has a pressure of approximately 5 bar at 20°C. It does not react when it comes into contact with air, and does not auto-oxidise into potentially explosive peroxides, unlike other alkyl ethers (Naito et al., 2005).

The risks associated with DME are similar to those of LPG, and its use is regulated by the UNECE R.067 (UNECE, 2014c) regulation (see Table 8). DME is a highly flammable gas with a higher density than air. Its lower and upper flammability limits are 3.4 and 27 vol%, respectively (Fujimoto, 2007), which are broader than those of LPG (roughly 2 and 10 vol%), for example, meaning that a larger area containing a combustible mixture is created as compared to LPG. In the same way as for LPG, DME can suffocate, and flows along the ground and accumulates in topographical depressions.

Table 8: LPG-powered vehicle fuel containers.

	LPG (propane/butane)
Normal operating pressure and temperature	7 bar, 15°C
Volume	Roughly similar to those of conventional vehicle fuel containers
Design pressure	30 bar
Pressure-relief valve	32 ± 1 bar (possibly also a melt fuse 120 ± 10°C)

3.4.2.1   Scenarios involving vehicles powered by DME and LPG

During a leak or fire scenario, DME behaves similarly to LPG and (to some extent) LNG. If a container is damaged such that leakage occurs without fire, two possible situations can unfold: If the container is fractured above the liquid surface of the condensed gas, the leaking gas vapours will form a vapour cloud. This leak will, however decrease in intensity as the pressure in the container falls, as vapourisation requires heat transfer into the container. If the container is damaged in such a way that the fracture occurs below the surface of the liquid, cold liquid will flow out under pressure and, initially, instantly vapourise when it comes into contact with the ground or other hot surfaces but will then gradually cool the ground towards the boiling point of the gas (-25°C). A large leakage can produce a liquid pool that vapourises more slowly, forming a vapour cloud that lingers for a longer time.

The result of a simulation of a small (0.21 kg/s) emission of LPG was a negligible vapour cloud with a stoichiometric LPG-air mixture; a 70 l LPG container can, however, produce a vapour cloud of 100 m^3 in a garage if the emission is directed towards the ceiling and has a rate of 0.55 kg/s, and the consequences of igniting such a vapour cloud would likely be severe. A larger (200 m^3) vapour cloud would require a higher emission rate, which can occur if the LPG is emitted in liquid form. In a garage of $30 \times 30 \times 2.4$ m^3, ignition would, in a worst-case scenario, lead to an excess pressure of 30 kPa throughout the garage. A vapour cloud of 50 m^3 would result in a small increase in pressure (5 kPa). A high ventilation rate (0.060 m^3/s, with roughly 100 air changes per hour, or an average air flow of 0.8 m/s in a garage) is required to dilute a stoichiometric LPG vapour cloud of 200 m^3 to below its LEL within 60 seconds (Van den Schoor et al., 2013).

During exposure to fire, the condensed gas inside a fuel container is heated, increasing the vapourisation rate and thus the pressure inside the container; this, in turn, leads to the pressure-relief valve opening. According to the 'bonfire test' that is part of the UNECE R.067 regulation, during which a fuel container is exposed to a fire source, the pressure-relief valve must function so as to ensure that pressure release occurs at such a rate that an

explosion is avoided. The testing method is, however, quite vaguely described in the regulation, and so the exposure to fire can vary considerably depending on how testing is performed.

If a fuel container experiences a higher thermal exposure than that used during its testing (performed in order for it to be approved according to the regulation), there is no guarantee that the pressure-relief valve will be able to handle the increase in pressure, leading to a further increase. Van den Schoor (2013) estimates the probability of any given pressure-relief valve not releasing in such a scenario as 6.2×10^{-8}. As the strength of the container simultaneously decreases, a container explosion that results in a BLEVE, in which the now-heated, condensed gas is vapourised instantaneously when the tank ruptures and the pressure is equalised, may occur. This results in a large, burning aerosol/vapour cloud that rises and exposes the surrounding area to a very high heat flux for a period of several seconds. These events can occur relatively rapidly, and in some instances a BLEVE has occurred after less than 5 minutes of fire exposure. In 2014, an LPG-powered vehicle in Germany that was experiencing flashover exploded and injured 10 firefighters, 5 seriously, who were attempting to extinguish the vehicle. The firefighters suffered, among other injuries, severe burns (MSB, 2016b).

Although fuel containers are equipped with pressure-relief valves that are designed to withstand exposure to fire, problems can arise if the vehicle is overturned and the gas, in liquid form, flows out of the valve. This may result in a very violent jet fire, and a simultaneous and large reduction in the rate of pressure release. This can result in a rapid increase in pressure, increasing the likelihood of a BLEVE occurring.

Several incidents have involved LPG-powered vehicles in garages. In 1999, a vehicle fuel container containing LPG that lacked a pressure-relief valve exploded as a result of arson near Lyon, France, severely injuring six firefighters. In 2002, a building collapsed when an LPG-powered vehicle leaked gas into a basement level, which then exploded. The explosion affected 39 buildings in a radius of 200 m, and the roof of the LPG-powered vehicle was found 150 m from the incident site (Lönnermark, 2014).

3.4.3 Hydrogen gas

Hydrogen gas is odourless, colourless, and non-toxic. Various odorous substances are often added to it to make it possible to detect, although gas that is to be used in fuel cells is not treated in this way due to the high level of purity required in this application. Hydrogen gas consists of two hydrogen atoms, and the element is the least dense known; this is why it can accumulate under the ceiling of a room or a garage, for example. The energy density of hydrogen is high per unit mass, but low per unit volume, making the gas difficult to store and transport. Hydrogen gas can be used as a fuel in a normal vehicle combustion engine, or in a vehicle's fuel cell to produce electricity. Europe-wide regulations have been established for the type approval of vehicles with regard to the use of hydrogen as a fuel, and of hydrogen gas components and systems, as well as for the installation of these components and systems. These regulations were published in Directive 2007/46/EC (Coen, 2010). By 2014, several filling stations that supplied hydrogen gas at a pressure of 700 bar had appeared in Sweden and Norway[6]. Documented experiences of hydrogen gas are still very limited, and relatively few vehicles that use it as a fuel are currently in operation.

When used as a vehicle fuel, hydrogen gas is compressed and stored at a pressure of 350 or 700 bar. Its molecules are small and its diffusion coefficient high, allowing the gas to penetrate porous materials. Thus, carbon steel, which is often used in gas cylinders, is unsuitable for cylinders that are to hold hydrogen gas due to its porosity, as the gas

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[6] Scandinavianhydrogen.org

diffuses into the material, causing it to become brittle ('hydrogen embrittlement'). As a result, stainless steel is generally used (Coen, 2010). The placement of hydrogen containers in vehicles is generally similar to that of CNG containers. The UNECE R.134 (UNECE, 2014e) and GTR13ECE (UNECE, 2014a) regulations contain the requirements on hydrogen gas vehicles and their components (Table 9). The pressure regulators of hydrogen gas vehicles are placed closer to the container than those of CNG vehicles, and the pressure in the system past this is around 1 bar.

Table 9: The fuel containers of hydrogen gas vehicles.

	Hydrogen gas
Operating pressure	350 or 700 bar
Volume	5.6 kg/cylinder Heavy vehicles: 8 cylinders
Pressure-relief valve	Must be installed, but detailed regulations for how this is to be undertaken have not been published, and manufacturers are able to do as they see fit in this matter.

3.4.3.1   Scenarios involving vehicles

Hydrogen gas burns with a very hot (roughly 2,000°C), near-invisible flame that does not produce any soot. Other risks relating to the use of hydrogen gas involve the high pressure at which it is stored, its ability to embrittle various materials, its low temperature during outflow, and the relatively high possibility of it leaking from couplings due to the small size of its molecules. In addition, a very low amount of energy is required for ignition; a combustible mixture with air is achieved at between 4 and 75 vol%. (Coen, 2010). For unknown reasons, autoignition often occurs during the emission of hydrogen gas (Berg, 2014, Groethe et al., 2007). According to FM Global, hydrogen gas should not be stored indoors; indoor emissions almost always result in ignition, and in three out of four cases this results in an explosion – in the fourth, a fire (FM Global, 2012).

The fuel containers that are used to store hydrogen gas are of the same type as those used for CNG. Although Zalosh (2008) asserts that no incidents involving hydrogen gas containers have occurred, they are subject to the same possible failure mechanisms as CNG containers. In order to determine what may happen if a pressure-relief valve does not release, tests were conducted in the USA using a propane burner placed under two hydrogen gas containers of approximately 80 l at a pressure of roughly 350 bar that were not fitted with pressure-relief valves. The containers exploded after 6 and 12 minutes, with the difference being accounted for by variation in internal construction. Parts of the containers were found 82 m from the site. In both tests, a burning hydrogen cloud with diameters of 7 and 24 m developed as soon as the containers ruptured. The energy of the explosions was estimated by Zalosh as being roughly 13 and 15 MJ, although Perrette and Wiedemann (2007) estimate 6.3 MJ, corresponding to 1.35 kg of TNT. It should be noted that TNT equivalents for pressure vessel or vapour cloud explosions are not particularly accurate in terms of comparison, as these explosions vary a great deal from one another. While the energy content of an explosion is easy to measure, this value is relatively uninformative in terms of other parameters of the explosions, as the maximum pressure attained is likely the result of a sudden reduction in pressure when the container ruptures and the gas rapidly expands. The subsequent ignition can result in a powerful explosion in enclosed spaces, with a pressure of up to 8 bar. The test results show that a 100 m-radius around a hydrogen-powered vehicle can be dangerous, considering the risk of pressure vessel explosion. Some manufacturers have begun to insulate the gas containers of vehicles to improve their resistance to fire (Coen, 2010).

On March 3, 1983, a 600 m³-vapour cloud consisting of 4.5 kg of hydrogen gas exploded in central Stockholm. 16 people were injured, 10 vehicles and the façade of the building that was closest to the explosion were severely damaged, and windows were broken in a radius of 90 m. Gas flowed out from two leaks when a T-coupling on a pipe to which eighteen 50 l-containers were connected failed (Venetsanos et al., 2003). An emission of hydrogen gas in an open space from a pressure-relief valve generally results in a jet flame, which is a relatively benign outcome as compared to an explosion. In order for a detonation to occur, a rapid emission is required; 40 kg of hydrogen gas at 350 bar with ignition after 30 seconds in an enclosed environment such as a tunnel, for example (Venetsanos et al., 2008). Note that ignition must take place after a relatively long time (in the order of 30 seconds) for a large explosion to occur; the more likely scenario, however, is that the hydrogen gas ignites at an earlier stage, as it is extremely flammable. In spite of this, hydrogen gas dilutes rapidly in air, particularly when natural or mechanical ventilation is present, meaning that the window for combustible mixtures originating from smaller sources, such as vehicle fuel containers, to occur is relatively small (Berg, 2014; Groethe et al., 2007).

According to Groethe et al. (2007), a hydrogen gas explosion in a tunnel would lead to a much higher pressure than an explosion in an open space; this would, moreover, be constant throughout the entire length of the tunnel. In a model tunnel that was down-scaled 5 times, an explosion involving 30% hydrogen gas (1 kg) in a 37 m³ plastic container resulted in a pressure impulse of 150 kPa, as compared to one of 10 kPa in an open space. In the experiments that were performed using hydrogen gas emissions in ventilated conditions, no ignition occurred, likely due to the rapid dilution of the hydrogen gas in the air. Groethe et al. came to the conclusion that a tunnel is a more dangerous environment for a hydrogen gas explosion to occur in than an open space, but that ventilation in tunnels drastically reduces the likelihood of ignition occurring in the first place. An emission from a pressure-relief valve results in a too-lean mixture, but a larger emission in a ventilated tunnel can create homogeneous mixtures that are near-stoichiometric (Groethe et al., 2007).

3.5 Electric and hybrid-electric vehicles[7]

At present, several battery technology types are available for use in electric and hybrid-electric vehicles. By far the most common form of battery in battery-driven electric vehicles is Li-ion, but within this product group there is variation in terms of the technologies, materials, and types of electrolyte used. NiMH batteries possess a significant share of the hybrid-electric vehicle market, but ZEBRA (liquid metal) and lead-acid batteries are also used. Li-ion technology is, however, increasingly common, and is well on its way to becoming predominant.

The two most common forms of traction batteries are Li-ion and NiMH; because the latter do not burn, this section will focus on the types of battery that are classified as Li-ion.

3.5.1 The construction of the Li-ion battery cells

Li-ion batteries that are used as traction batteries consist of several cells. The current that flows when a battery is connected to an electric circuit consists of positively charged lithium ions; these move between the anode and cathode, through the electrolyte (with or without a separator). Batteries can be constructed in different ways, and there are various techniques for separating the anode from the cathode and a variety of materials and types

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[7] Unless otherwise stated, the information in this section has been adapted from 'Fundamental analysis for risk assessment of e-vehicles involved in traffic accidents' (Hoffmann, 2013).

of electrolyte. Li-ion battery cells can be divided into three main categories: prismatic, cylindrical, and pouch.

Battery cells often have built-in safeguards that activate in response to a situation, such as a fire or explosion that may damage the battery or cause critical failure. The three primary types of battery cell vary somewhat in terms of their suitability for dealing with these situations. In order to avoid explosions and damage to surrounding structures, all three types of cell are able to vent gas in response to an increase in pressure. In addition, the separator, which is often made of plastic, melts when exposed to high temperatures, preventing lithium ions from moving from the anode to the cathode and thus breaking the flow of the current.

3.5.2 The safety functions of battery systems

An traction battery is a floating voltage system. This means that neither of its terminals are connected to the chassis of the vehicle, ensuring that an enclosed circuit is not formed if one (rather than both) of the terminals comes into contact with the chassis of the vehicle as a result of insulation failure. There is, however, always a capacitive connection of between 50 and 200 nF between any terminal and the chassis. This means that anyone coming into contact with any of the terminals and the chassis at the same time can receive an electric shock, although this will not have any significant consequences. Additionally, wear to cables that are connected to traction batteries rarely causes a fire, and nor does insulation failure to the chassis of the vehicle. In addition, traction batteries are equipped with Battery Management Systems (BMS) that turn off the battery at its main contacts so as not to damage the battery and to prevent it from experiencing a failure. In the event of a severe external impact, however, such as may occur during a fire or as a result of considerable mechanical damage, a BMS is not able to prevent battery failure.

A BMS automatically disconnects the battery system in response to the following situations:
- Too-high temperature
- Under-voltage
- Over-voltage
- Over-current
- Failure of the battery's cooling system
- Damaged and/or falsely triggered crash sensor
- The vehicle has begun to overturn (as detected by the sensor)
- Insulation failure
- Current fault, such as arcing

When the battery system disconnects in one of the scenarios listed above, the commutation capacitance of the electronics should be discharged within five minutes if this is done passively, or two seconds if actively. Whether this takes place actively or passively is decided by the manufacturer. Prior to the capacitance being discharged, the cables of the traction system are under a voltage of at least 60V. They are always coloured orange so as to signify that they have a hazardous voltage and that cutting them should be avoided.

3.5.3 Li-ion battery chemistry

Li-ion batteries consist of a cathode, electrolyte, an anode, and other structural or separating components and materials.

There are three main categories of cathode material: lithium transition metal oxide, lithium manganese spinel oxide, and lithium-phosphate compounds. To moderate and increase the thermal stability of a Li-ion cell, its cathode is often treated with transition

metals such as Ni, Al, and Mn. Research into and usage of such materials has increased the temperature at which thermal runaway begins to occur, such that the foremost materials are able to withstand temperatures of near to 200-250°C (Hoffmann, 2013).

The electrolyte of Li-ion batteries consists, in essence, of an organic liquid/solvent and a salt that allows charge to flow using the ions inside the battery. The most commonly used salt in commercial Li-ion batteries is $LiPF_6$, as it is considered the best combination currently possible of properties such as stability, conductivity, and lifespan; however, the augmenting of the salt with fire-resistant additives can further improve its properties, and prevent the occurrence of chemical reactions that can reduce the lifespan of the battery.

As well as improving the operational properties of Li-ion batteries, research and development of new materials aims to prevent battery failure, as a Li-ion battery being pushed to its breaking-point – be that mechanically, thermally, or due to an internal short circuit – may result in a thermal runaway.

3.5.4 Thermal runaway

The first Li-ion batteries were manufactured in the 1990s; their anodes were made of graphite, and their cathodes of lithium-cobalt-dioxide ($LiCoO_2$). The cathodes were, however, less stable than expected, meaning that it was possible for thermal runaways to occur under relatively benign conditions. Critical failure in those Li-ion batteries occurred when the cathode reached between 150 and 170°C and begins to break down in an exothermic reaction, in which it, along with the organic component of the electrolyte, is combusted. This leads to an increase in heat output, and the acceleration of the break-down of the cathode and electrolyte. The temperature of the cell then increases drastically, with ignition and/or explosion occurring if the gases that are created in the reaction are not vented. The organic solvents in the electrolyte in the cell also break down in an exothermic reaction which, with a normal mixture of salts and flame retardants, begins when the temperature is between 140 and 190°C (Hoffmann, 2013). If the cathode material is not broken down, the fire has no access to oxygen, and so combustion with an accelerating heat release rate does not occur. The great amounts of thermal energy released inside an affected battery cell also heat and thus damage adjacent cells, such that the thermal runaway continually propagates.

A thermal runaway is followed by, or comprises part of, the development of a fire, and the fire triangle of a Li-ion battery is described for two scenarios in Table 10.

Table 10: The fire triangle for Li-ion batteries.

	Structurally intact battery cell	Ruptured battery cell
Oxygen	Oxygen is released by an overheated cathode	Oxygen is available from the surrounding air
Heat	The organic electrolyte	Vapours from the organic electrolyte and other combustible gases
Fuel (energy)	Generated inside the battery or supplied from an external source	Generated inside the battery or supplied from an external source

When a thermal runaway occurs an excess of gases is created, and these contribute to an increase in pressure in the affected battery cell, which must vent the gases in the manner described in Section 3.5.2. The time that elapses before the gas is ignited depends on the gas mixture's contents, the temperature, and the conditions in the surrounding area. During thermal runaway, however, there is a great deal of energy in the vicinity, especially in the battery cell itself, and the probability of more than one or two cells being able to vent gases before they are ignited is very low. When some of the cells of a battery

are in thermal runaway, combustion generally takes place according to both fire triangles presented in Table 10. Thus, the fire quickly spreads to both the vehicle and the battery, if both were not involved from the beginning.

Some batteries may, however, due to the chemicals used to make them, produce gases that are non-combustible, in which case it is possible for thermal runaway to occur without an external fire. In such cases, the toxicity of these gases has a strong impact on how a situation evolves.

3.5.4.1 Preventing and suppressing thermal runaway

Dealing with thermal runaway can be performed in two ways: either by ensuring that it does not occur in the first place, or limiting its consequences. A great number of safety functions that accomplish the former have been already been listed. To that list may be added physical barriers that protect the battery from mechanical damage, and which shield it from incoming heat.

In order to suppress an ongoing thermal runaway process, the fire triangle needs to be broken: Either access to oxygen should be limited, or the thermal energy removed. During a thermal runaway, oxygen is released by the cathode; this means that combustion continues, but has a limited effect as compared to a situation wherein the electrolyte is in contact with air and the oxygen supply is plentiful. This does, however, depend on the material used in the construction of the cathode, and some cathodes do not release oxygen. By cooling battery cells, a thermal runaway process can be interrupted, as the propagation between cells is prevented. Furthermore, the severity of a thermal runaway is connected to state of charge (SOC), with a lower SOC resulting in a less violent thermal runaway. This means that a thermal runaway can be more easily suppressed if the battery is discharged. A battery in a car is, however, well-protected and difficult to access, making the suppression of a thermal runaway very difficult.

3.5.4.2 Ventilated gases

During a thermal runaway, a large quantity of toxic and potentially hazardous gases are released as a result of the breakdown of the electrolyte, salt, cathode, and anode. During a fire, the contents of the gases emitted by a Li-ion battery that has suffered a failure are altered in terms of their chemical composition, such that they consist mostly of combustion products.

The numerous studies that have been performed to ascertain which gases are produced during a battery failure have, due to a lack of information, produced an incomplete picture as regards their amounts and composition. The gases formed also vary with the materials that the Li-ion battery is made of.

The gases and vapours that are emitted by a cell that has suffered a failure can be highly flammable, toxic, and pose a danger of suffocation, and include hydrogen gas, carbon monoxide, methane, carbon dioxide, hydrogen fluoride (HF), phosphorus pentafluoride, alkyd carbonates (electrolyte vapours), and a number of other organic compounds (Hoffmann, 2013).

A study of Li-ion batteries in a nitrogen atmosphere found that a number of toxic substances that are irritating to the skin and respiratory organs were emitted. The study did not, however, present any conclusions regarding whether the gases would have reached hazardous levels during a real incident (Sturk et al., 2015).

Another study focused on the gases that were emitted by a battery in relation to the influence of SOC. The study focused on pouch cells (7.7 Wh, 2.1 Ah, 3.7 V) in an argon-

rich atmosphere, and particularly investigated highly flammable gases. At a SOC of 50%, 0.1 l of gas per Wh was produced; at 100%, this figure was 0.33 l/Wh; at 150% SOC, 0.78 l/Wh. The distribution of the gases in terms of vol% is presented in Table 11. With the exception of carbon dioxide, all of the gases are highly flammable, and carbon monoxide, along with several of the hydrocarbons, are dangerous to health. The LEL (lower explosion limit) of the ventilated gases were determined to be 6 vol% at 100% SOC and 150% SOC while the UEL (upper explosion limit) was 38% for 100 % SOC and 40 % for 150% SOC. (Colella et al., 2016).

Table 11: The composition of the gases emitted by a 7.7 Wh pouch cell at various SOC (Colella et al., 2016).

Gas		50% SOC (vol%)	100% SOC (vol%0)	150% SOC (vol%)
Carbon dioxide		32.3	30.0	20.9
Carbon monoxide		3.61	22.9	24.5
Hydrogen		31.0	27.7	29.7
Hydrocarbons	Methane	5.78	6.39	8.21
	Ethylene	5.57	2.19	10.8
	Ethane	2.75	1.16	1.32
	Propylene	8.16	4.52	0.013
	Propane	0.68	0.26	2.54
	Isobutane	0.41	0.20	0.13
	n-butane	0.67	0.56	0.39
	Butene	2.55	1.58	0.60
	Isopentane	0.45	0.07	0.036
	n-pentane	1.94	0.73	0.30
	Hexanes	4.94	2.32	8.21
	Benzene	0.14	0.11	0.33
	Toluene	0.061	0.018	0.052
	Ethylbenzene	0.009	0.002	0.003

During a study performed in 2006 (Yang et al., 2006), battery cells with a 'typical' electrolyte mixture[8] were exposed to a gradually increasing temperature that eventually ignited the emitted vapours and gases. The gases that were released were the same as those listed in Table 11, with each gas being measured in similar quantities. At a temperature of roughly 107°C, $LiPF_6$ begins to break down, and HF is formed inside an enclosed cell. In an open container the process begins at 87°C but, at such low temperatures, is relatively slow; among the gases emitted, CO_2, H_2, CO, ethylene, and other hydrocarbon compounds are the most common. HF and other less common gases occur in low concentrations but are considerably more toxic than the other ones discussed above, and so the tolerances set in regulations are strict. With a higher electrolyte temperature, more gases that are dangerous to health are emitted; HF, for example, has an optimal generation temperature range of 170-250°C.

Just as in the relatively recent study that used a nitrogen gas atmosphere, no conclusions were drawn as regards gas production, its negative effects on health, and the fire hazards presented by a real scenario with a whole battery in a vehicle. Several studies comparing the effects of conventional fuel and batteries on a fire in a car have been performed, and in 2016, the French research institute INERIS published the results of fire tests that measured the emissions of gases from fires in cars with conventional fuel and Li-ion batteries (Truchot et al., 2016). Two of the cars (Cars 2 and 3) that used conventional

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[8] EC:EMC/1.2M $LiPF_6$: Organic solvents, in the form of ethyl carbonate (EC) and ethyl-methyl carbonate (EMC), together with salt in the form of $LiPF_6$ in a concentration of 1.2 mol/dm³ electrolyte, are generated in equal parts.

fuels were of the same class of vehicle as the tested electric car, and lost roughly the same amount of mass as a result of the fire tests (275 kg and 262 kg, as compared to 278.5 kg for the electric car). The fire in the electric car produced roughly 738 kg of gas; this figure was not given for the two other cars. In Table 12, the compositions of the emissions are presented. As the production of HF reached a maximum level of between 350 and 450 ppm in the early stages of the development of the fire, it was considered to be the result of the combustion of liquid within the air-conditioning system. No significant difference in the measured amount of HF was observed until 30 minutes had elapsed. This was the point at which the battery had become involved in the fire, and for 20-25 minutes after this, 50 ppm of HF was measured in the smoke, as compared to 25 ppm for a car with conventional fuel. In 'Fundamental analysis for risk assessment of e-vehicles involved in traffic accidents' (Hoffmann, 2013), the upper limit given for HF is 2 ppm on average for a 15-minute exposure. A lethal concentration for a 5-minute exposure is in the range of 50 to 250 ppm.

Table 12: Emissions of a number of different gases during the fire testing of cars (Truchot et al., 2016).

	Electric car	Car 2	Car 3
Corrosive gases			
HCl	0.30%	0.29%	0.33%
HF	0.23%	0.11%	0.07%
HCN	0.02%	0.02%	0.05%
Carbon and nitric oxides			
CO_2	96.98%	96.95%	97.33%
CO	1.83%	2.11%	1.94%
NO	0.12%	0.1%	0.15%
NO_2	0.05%	0.06%	0.13%
SO_2	-	-	-
Uncombusted			
Total hydrocarbons	0.45%	0.37%	?

At SP, studies have focused on the production of HF during thermal runaway (Larsson et al., 2016). Individual cells were exposed to fire, and the quantity of HF produced was measured. The maximum amounts yielded in the four tests were 5 (50% SOC), 9, 16, and 100 ppm (100% SOC). Total emissions from the individual tests varied between 12 and 81 mg HF/Wh. By extrapolating the results of tests with individual cells and assuming that all cells in a vehicle will undergo thermal runaway and produce an equal amount of HF, 1200-8000 g of HF for a 100 kWh battery was arrived at. The Immediately Dangerous to Life or Health (IDLH) limit for mass per unit volume is 0.025 g/m³. The amount of HF produced by a battery could, when distributed homogenously, reach dangerous or lethal levels in a space with a volume of between 50,000 and 300,000 m³, assuming that the effect of ventilation is negligible.

3.5.5   Scenarios involving vehicles

Of the 40 vehicle fires per year in multistorey car parks or larger garages (based on the MSB's statistics), several were caused by electrical failure, but only one per year on average were caused by battery charging. In 2013, an electric car with a nickel-cadmium battery that was made in 1996 caught fire in a parking garage in Helsingborg, Sweden. Three cars were destroyed entirely, and 75 were damaged by smoke and soot. The car was not being charged when it caught fire, and so the cause may have been arson[9].

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[9] http://sverigesradio.se/sida/artikel.aspx?programid=83&artikel=5673419;
http://www.laddaelbilen.se/2013/10/13/elbil-brann-i-helsingborg-imorse-*update!*-18729893
[accessed 2016-04-28]

There are a number of fire scenarios that are specific to electric vehicles. A fire in a battery can be caused by either an internal failure or external influence, which can take the form of severe mechanical damage or exposure to strong heat originating from a fire elsewhere in the vicinity. Severe mechanical damage may arise due to, for example, a collision. Internal failure should be prevented or limited by the BMS of the vehicle, but cannot be eliminated entirely. During charging, there is an increased likelihood of fire as a result of the stress that the battery cells are exposed to, particularly when substandard or faulty charging equipment is used; using that which is recommended minimises the risk during charging.[10]

The scenarios that can arise during a battery fire differ depending on the cause of the battery failure. This largely relates to whether the gas emitted by the battery cells is ignited immediately after emission or if this is delayed; in a few fire tests, however, an external input of thermal energy has affected the intensity of a battery fire and thus the total amount of energy emitted. The energy output of a battery appears to be greater if it is heated by a fire, and decreases rapidly as soon as this is removed (Bobert 2013), (Long et al., 2013). An ongoing fire constitutes an ignition source for the gas that is emitted by the battery cells that have suffered a failure, but this may be absent if the failure takes place due to mechanical damage, an internal failure, and/or failure caused by charging. If the gas is eventually ignited an explosion can occur, and, in general, a longer delay between failure and ignition leads to a larger explosion. In most cases, ignition takes place prior to the emission of gas from three or more cells, but scenarios in which more cells become involved prior to the ignition of the emitted gas cannot be eliminated. The effects of the gases vented by an electric vehicle exploding would likely be relatively small – sufficient as to not damage a structure – but projectiles may be harmful, and the blast wave can knock people over in such a way as to cause injury.[11]

A Li-ion battery that is involved in a fire contributes thermal energy through the combustion of its electrolyte. In 'Fundamental analysis for risk assessment of e-vehicles involved in traffic accidents' (Hoffmann, 2013), the possible combustion energy of various electrolyte mixtures in relation to a battery's electrical energy-storage capacity is given as 16-18 MJ/kWh. At present, Li-ion batteries in vehicles rarely have a capacity exceeding 90 kWh, and those of hybrid-electric vehicles are generally below 20 kWh. In the future, however, batteries of 100 kWh, corresponding to 1.8 GJ of available thermal energy through combustion of the electrolyte[12], are likely. This is comparable in terms of combustion energy to a 50 l diesel or petrol tank, which contains 2 GJ of energy.

A fire in an electric vehicle increases in intensity when the energy-dense battery becomes involved in the fire, particularly when a cell undergoes thermal runaway and emits

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[10] A 2014 report by the National Electrical Safety Board recommends that Mode 1 charging with a standard plug in a standard outlet be avoided for both one- and three-phase networks, and that HÖJEVIK, P. 2014. INFORMATIONSBEHOV RÖRANDE ELSÄKERHET KRING LADDINFRASTRUKTUREN FÖR ELBILAR. Elsäkerhetsverket. Units that monitor charging and communicate with the car and its battery are used. Regular inspections of the electrical system to which the charger is connected are also considered to be important in order to avoid overload and damage to that system ('Laddat för kunskap. Laddstationer - Den kompletta guiden.' 2014, Emobility.se; 'Charged with knowledge. Charging stations - the complete guide.')

[11] The effects of an explosion of emitted gases from a Li-ion battery undergoing thermal runaway should be investigated, and the number of cells that can be vented prior to ignition occurring should be investigated through studies and testing.

[12] Information taken from the 'Buyers Guide for Electric and Plug-in Hybrid Cars'. Available: http://media.greenhighway.nu/2012/05/Buyers-guide-for-electric-and-plug-in-hybrid-cars-2013_English.pdf [accessed 2009]. Complemented with information from the websites of car manufacturers and BU-1003: Electric Vehicle (EV) - Battery University, 2016.

combustible gas. In this situation, it is unlikely for multiple cells to suffer failure and emit gas simultaneously, although the likelihood of this occurring increases when the battery is surrounded by fire such that all of the cells are heated as compared to when only one cell is experiencing a thermal runaway, which affects only adjacent cells. The maximum contribution of a battery fire to the total heat release rate of a fire has, during multiple fire tests using Li-ion batteries of between 8 and 16 kWh, been measured to lie in the range of 250-600 kW (Bobert, 2013; Long et al., 2013; Egelhaaf et al., 2014).

In conclusion, a fire in an electric vehicle is, in general, no worse than a fire in a vehicle that uses conventional fuel, but there are several aspects that can complicate an extinguishing operation:

- A thermal runaway is very difficult to suppress, and makes the extinguishing and prevention of re-ignition of the fire more difficult.
- The gases that are emitted during thermal runaway are both toxic and highly flammable, leading to a risk of explosion and the need for higher requirements on protective equipment.
- A damaged battery can undergo thermal runaway many hours after an incident, and in this way start or reignite a fire.
- An operation to rescue the occupants of an electric car that has been involved in an incident must bear in mind the cables that carry dangerous voltage.

3.6   Underground garages

Several government authorities can be considered to be responsible for safety in garages. The most obvious of these is 'Boverket ('the Swedish National Board of Housing, Building and Planning'), which is responsible for regulations regarding the construction of buildings. The regulations of Boverket do not, however, take into consideration the fuels of the vehicles that may be parked in a garage within a building, although explosion loads can be factored into an analytical design process or the applying eurocodes in relation to the load-bearing capacity of a building (see below). Boverket is of the opinion that the Swedish civil contingencies agency (MSB), which are responsible for issuing regulations according to the 'Lagen om brandfarliga och explosiva varor' (2010:1011; 'Law on flammable and explosive products'), is also responsible for gas vehicles in garages. According to the MSB, these regulations do not apply to fuel containers that are mounted in vehicles, provided no interference with the containers occurs. According to the MSB, these fuel containers are regulated by the Swedish Transport Agency (STA), which issues provisions regarding permissions for road vehicles and where vehicles can be used, such as weight limits on bridges. The STA, however, does not consider itself to have the authority to issue regulations regarding safety in garages or place restrictions on, for example, gas-powered vehicles in tunnels or garages. The STA is, however, involved in an ongoing effort to ensure that the fuel containers of gas-powered vehicles are periodically checked which will indirectly affect safety in garages. The STA refers the question of safety in garages with regard to parked vehicles back to Boverket. The Swedish Work Environment Authority is responsible for requirements on toxic gas and exhaust fume levels, including those emitted by petrol and diesel vehicles. As a result, adapted comfort ventilation is a requirement in underground garages. Municipal rescue services are responsible for supervision according to the 'Lagen om skydd mot olyckor' (2003:778; 'Law on the prevention of accidents'), and the municipality's local housing committee handles building issues according to 'Plan- och bygglag' (2010:900; 'the Planning and Building Act'). The municipality also manages permits according to 'Lag om brandfarliga och explosiva varor' (2010:1011; 'Law on flammable and explosive products'). These regulations do not factor in alternative fuels. In conclusion, Boverket has, and takes, the greatest responsibility for safety in garages, but vehicles that use alternative fuels fall between the cracks, with Boverket, the MSB, and the STA all pointing to one another.

Most buildings that are classified as underground parking garages have between 3 and 16 floors and an occupancy class that corresponds to housing, stores, and offices, meaning that they fall into the Br1 building class according to Boverket's Building Regulations (BBR; 2011). Thus, there are no requirements on the application of performance requirements and analytical design of garages (for Br0 buildings). Section 5.44 of the BBR states that the risk of fires or explosions in garages due to combustible or explosive gases is to be limited and, in addition to general recommendations regarding heating systems, provides information regarding how this is to be done. This should not be accomplished through analytical design, as fulfilling the prescriptive requirements that are posed is sufficient. The fire load of a car varies between 4 and 8 GJ depending on its size and year of construction (Ingason et al., 2015). If each vehicle occupies an area of 20 m^2, this leads to a fire load of between 200 and 400 MJ/m^2. This results in a fire resistance class of EI 60 for fire compartment-separating building parts. The maximum size of a fire compartment is thus 2500 m^2, 5000 m^2 if there is an automatic fire alarm, or unlimited if there is an automatic sprinkler system. Firewalls should as a minimum fulfil the requirements of the REI 90-M fire resistance class. Garages of over 50 m^2 are to have two emergency exit routes that are independent of each other. The contribution of the floor surface of a larger garage to the development of a fire must be negligible. A garage should be a separate fire compartment, and may extend over two floors. Basements in Br1-class buildings are to be equipped with smoke ventilation or an equivalent system (BBR 5:732). It is likely that the Swedish Work Environment Authority's requirements on air quality will become strongly influential in the design of the capacities of ventilation systems in this type of building. No particular requirements on ventilation with regard to preventing a possible explosion were identified, however. The possibility of an explosion occurring is included in Boverket's applying of the European construction standards, EKS (2011), and the appurtenant eurocodes with regard to stability and strength (BBR19, 2011).

According to MSB, roughly 2000 vehicle fires occur in Sweden each year. Based on the number of rescue operations reported to the MSB between 2011 and 2014, roughly 40 fires take place in multistory car parks or larger garages (either above or below ground) annually. The most common causes of reported fires are arson and electrical or technical failure[13], a conclusion that was independently confirmed by a New Zealand study of car fires in parking garages (Collier, 2011). The same study found that such fires are often limited to one vehicle, and that fires spread to other vehicles in only 3% of cases. The likelihood of a fire propagating to other cars is increased in enclosed underground garages with limited ventilation (Collier, 2011).

A European research project that compiled data relating to car fires in underground garages found that 85% of all car fires involved a single vehicle, and 98% of fires did not spread to four or more cars (Joyeux et al., 2002). A statistical analysis performed in Great Britain (BRE, 2010) showed that more than half of all fires in parking garages did not start in a car, and that it was uncommon for fires that did not start in a car to spread to one. According to the analysis, it was also uncommon for a car fire to spread to further cars. The same study also involved performing various fire tests, which established that a fire in an enclosed garage can easily become ventilation-controlled in the event of a high heat release rate, which can lead to spalling. Despite the fact that the tests showed that cars can withstand high amounts of radiation before they begin to burn, fire propagation between cars is likely if the car fire is not extinguished, but instead allowed to reach its maximum heat release rate. The tests showed that, if a fire in a car is extensive, it can spread to the next car, even if there is a space between them equal to that of an empty parking space (BRE, 2010). The number of fires per year and vehicle in a parking garage

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[13] Statistics from ida.msb.se [accessed 2016-10-15].

was estimated as being 0.9×10^{-5} and 2×10^{-5} for New Zealand and Great Britain, respectively (Van den Schoor et al., 2013). Seven Swiss firefighters were killed when a parking garage collapsed in the aftermath of a vehicle fire in 2004[14]. Additionally, a playground with trees and benches that was above the garage collapsed into it.

A Swedish undergraduate degree project analysed the working conditions of firefighters by studying seven smoke diving operations in parking garages (Nordström, 2015). The selection of the operations investigated in the study was not made based on fires involving alternative fuels, but on investigating the more general conditions and difficulties involved in performing smoke-diving operations in parking garages, which are often vast, meaning that it is frequently difficult to identify where the fire is and what is burning from the outside. Thus, smoke diving can be necessary to reach and extinguish a fire. The vastness of garages requires many smoke divers, as the first pair may run out of air before they have even arrived with water at the fire site. In several of the studied cases, intense heat, which meant that differences in temperature were not visible on the screens of thermal imaging cameras, and difficulty in orientation were issues. The heat also gave rise to a risk of spalling and the 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 so as to decrease the temperature and improve visibility.

3.7 Road tunnels

As stated in an EU Directive (EC, 2004), there exist regulations (SFS, 2006:421, 418) regarding safety in road tunnels of 500 m or more on the European road network. The STA has been authorised to issue regulations regarding safety in road tunnels on the government authority level, and issues mandatory provisions and general recommendations regarding safety in road tunnels (TSFS, 2015:27). These regulations do not factor in alternative fuels in vehicles, and the responsibility for managing these risks is placed on tunnel managers. There is, however, a general recommendation that is relevant to the risk of explosion, which relates to longitudinal ventilation in tunnels of longer than 1000 m: The average air speed of the cross-section of a tunnel should be at least 3 m/s during heat release rates of up to 100 MW. This reduces the risk of larger vapour clouds being formed. Additionally, the STA, which often functions as the 'tunnel manager' in Sweden, has its own technical requirements and recommendations for road tunnels. In general, it can be said that tunnels are very able to resist fire, and in most cases also explosions, as they are placed underground and/or through rock, and have thus been designed to be strongly resistant to fire (Gehandler, 2015; Kim et al., 2007; Ingason et al., 2012). Most of the situations that can be considered to present significant difficulties occur during evacuation in smoke, and most often in two-way tunnels (Ingason et al., 2015; Beard and Carvel, 2012). A number of studies have investigated the risk of vapour cloud explosions in tunnels due to the emission of gas from a vehicle.

Zalosh (1994) finds in a study of the dispersion of CNG fuel release that leaking CNG is rapidly diluted to levels that are well below flammability limits, although a small explosion (roughly 2.2 kPa) of brief duration can occur close to the leak source. This is also the conclusion for tunnels. Modern tunnel environments, fanned by high-powered ventilation systems, would quickly remove and disperse gaseous fuels in the event of an accident. The size of the flammable region from an incident involving a CNG fueled van is significantly smaller than the flammable region from a comparable incident involving a gasoline-fueled van as long as the effective ventilation velocity is in the order of 0.10 m/s or higher (Zalosh et al. 1994).

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[14] http://www.firehouse.com/news/10514192/seven-swiss-firefighters-die-in-collapsed-parking-garage [accessed 2016-04-28].

The study discussed above focused on an incident in which the fuel pipe of a 200 bar container holding 24 kg of CNG broke, resulting in a 0.35 kg/s emission (on average) for 68 seconds. Although trucks generally have somewhat larger pipes, the difference is not sufficient as to affect the risk of explosion. An emission from a pressure-relief valve can be safely assumed to yield a similar result, i.e. the gas is diluted rapidly to below flammability limits.

Weerheijm and Berg investigated the likelihood of an LPG tanker truck exploding in a tunnel. As above, in such a scenario a large emission is required to achieve a large vapour cloud due to the effects of the ventilation. Weerheijm and Berg studied an emission of LPG in a two-way tunnel with 1 m/s ventilation (Weerheijm and Berg, 2014). The worst-case scenario would be an emission of between 5 and 8 kg/s, which would yield an explosive mixture in almost the entire vapour cloud. 60 kg of gas emitted at 6 kg/s would create a vapour cloud with an explosive pressure of 1 bar in a 10 m section of tunnel, giving a low risk of death caused by the explosion. 600 kg of gas can produce a vapour cloud that can fill a 100 m section of tunnel and which, if ignited, could result in a detonation (15-20 bar) that, in a worst-case scenario, would kill anyone in the tunnel (Weerheijm and Berg, 2014).

Higher ventilation rates mean that a much higher gas emission rate – at 5 m/s, at least 21 kg/s – is required for larger flammable mixtures to occur. This reduces the likelihood of any given gas emission mixing sufficiently with air that a combustible mixture is achieved in any given tunnel. At the same time, for ignition to occur, it must do so at the exact moment when the entire cloud is within the gas's flammability limits. Methane and hydrogen have higher flammability limits than propane, meaning that a larger amount of those gases is required for an explosion to occur. During an incident in a tunnel, ignition is more likely to take place immediately than later and further down in the tunnel, where other vehicles are exiting. Early ignition leads to a smaller explosion, followed by a jet fire at the source of the emission. Due to the brief duration (c. 30 seconds per container) of such a jet flame and generally overly sufficient fire resistance of the tunnel (Kim et al., 2007), no severe damage is likely to occur. Another important factor is the cross-sectional area of the tunnel; for those with three or more lanes, even higher emission rates are required for a combustible mixture to be achieved along the tunnel.

The 'HyTunnel' project (Kumar et al., 2009) investigated the risks associated with hydrogen gas, and compared them to those of petrol and CNG. The presence of obstacles in tunnel ceilings, such as lighting and ventilation equipment, was identified as an important factor, as these can increase the risk of a detonation occurring. This is supported by the fact that the primary mechanism behind increases in flame velocity is turbulence. In order to generate sufficient amounts of turbulence for this to happen, the flame front must travel a great distance in relation to the diameter of the tunnel; roughly 50-100 times the diameter for propane and ethylene in pipes (Bjerketvedt et al., 1997). Hydrogen gas yielded an explosion that was four times that of a CNG explosion under the same conditions. Through experiments, the 'HyTunnel' project found that the requirements for a detonation to occur were obstacles in the ceiling and a hydrogen gas concentration of over 25%. It is unlikely that CNG detonations can occur at all (Bjerketvedt et al., 1997). Theoretically, an excess pressure of 12 bar can be achieved if all of the hydrogen gas in the fuel container of a hydrogen gas-powered passenger bus is mixed stoichiometrically with air and ignited. Models of various emission scenarios involving leakage of CNG- or hydrogen gas-powered passenger buses, however, show that the explosion pressure is reduced significantly, to between 0.1 and 0.3 bar (Middha and Hansen, 2009). Minimal tunnel ventilation limits the size of clouds of combustible hydrogen gas-air mixtures from smaller sources, such as pressure-relief valves. The shape of a tunnel also affects the risks associated with the use of hydrogen gas. Tunnels with

high ceilings or a horse-shoe shape offer a lower risk than low and angular tunnels (Kumar et al., 2009, Berg, 2014).

The primary fire load in a road tunnel consists of the vehicles within it. A car can be expected to cause a fire of 4 to 8 MW, which is not normally a great problem in terms of the safety of people and property. Trucks constitute the largest fire load, and may cause much larger fires; 10 MW, plus the energy content of the load. Fires of near to 200 MW have been achieved in tunnel experiments that simulated fully loaded trucks (Ingason et al., 2015). The effect of the fuel contained in vehicles is small from a fire-safety perspective. An explosion involving a gas container that occurs relatively early in the incident timeline can lead to rapid fire development, making evacuation difficult, but is much less likely to occur than an explosion caused by an already existing fire. Gas containers for use in vehicles are constructed to withstand a great deal of collision damage, and disconnect in the event of pipes beginning to leak (Berg, 2014). Pressure vessel explosions have been known to occur during fuelling, when the pressure experienced by containers is at its highest. It should not be possible for containers to explode spontaneously as a result of decreasing pressure during use.

The Swedish 'METRO' project (Ingason et al., 2012) studied explosions in train carriages inside tunnels. In the aftermath of terrorist attacks in Moscow, Madrid, and London, it was noted that damage to trains was often extensive, whereas that done to tunnels was generally limited to lighting and communication equipment. This was in spite of the fact that the pressure from explosions was to a great extent independent of whether they took place within or outside the carriage. Tunnel structures are generally very able to withstand pressure, as they are often surrounded by large quantities of water, earth, or rock. In open spaces, pressure decreases with the cube of distance; in a tunnel, however, pressure decreases linearly with the cross-sectional area, meaning that doubling the cross-sectional area halves the pressure. A full-scale test in which a pressure of 5.5 bars was measured (Figure 2) resulted in only minor damage to the tunnel structure, such as the peeling off of the outermost layers of the concrete, with no damage to the rock behind being found. Projectiles from windows or other objects that may shatter pose a great danger to people. Tempered glass, such as that used in trains and cars (safety glass), is able to withstand higher pressures and pose less of a danger than untreated glass (Ingason et al., 2012). It is covered by a plastic film that holds the sheet together and, when broken, it crumbles into small, granular chunks.

Figure 2 : A photograph of an explosion in a train carriage, taken during the 'METRO' project (FOI).

In conclusion, the likelihood of a large vapour cloud explosion is very small or non-existent in such a scenario, as its occurrence requires the tunnel's cross-sectional area and the ventilation rate, quantity of gas, and emission rate of the gas in the tunnel to all be within specific ranges at the same time. The possibility of a pressure vessel explosion as a result of fire cannot be eliminated. The current system of periodic inspections of gas containers is clearly insufficient, as is the fire testing method used for fuel containers. Just as in an open space, a pressure vessel explosion in a tunnel presents risks in the form of radiation, projectiles, and splinters, but greater damage to the tunnel, vehicles, or people in other parts of the tunnel are unlikely. It is likely in such a scenario that road users have time to evacuate prior to the exposure to fire that causes the pressure vessel explosion, as well as that the tunnel structure, as a result of the large quantity of water, earth, or rock that it is surrounded by, is able to withstand the pressure of the explosion. Thus, tunnels do not involve a greater degree of risk than open spaces with regard to explosions.

4   Safety measures

In this chapter, the risks relating to underground garages, road tunnels, vehicles, and rescue services that are described above are summarised, and the various safety measures that could be undertaken to minimise them are presented.

4.1   Underground garages

New fuels for vehicles introduce new risks in underground garages; charging stations for electric vehicles, for example, present dangers relating to electrical failure. At the same time, electrical equipment in an electric vehicle is exposed to less harsh conditions than those experienced by the components of a vehicle with a combustion engine. Gas container failure can occur as a result of various different factors. The pressure-relief valve of a gas container should release in response to an increase in pressure, and if this occurs due to a fire, it is likely that the outflowing gas will be ignited, creating a jet flame. According to the UNECE R.110 regulation, the pressure-relief valve of a fuel container should be oriented so as to prevent further exposure of the container to fire; in many cases, however, either directly or indirectly, other parts of the vehicle or adjacent vehicles are exposed.

During a leakage scenario in which a jet flame does not occur, a combustible gas-air mixture can form. Ventilation in garages (although its efficacy is lower than in road tunnels) and the generally lower probability of large leaks mean that the likelihood of a vapour cloud explosion occurring is low. If the container is weakened by a fire, for example, a pressure vessel explosion can occur. An explosion of a pressure vessel containing hydrogen gas or CNG yields the most severe consequences due to the very high pressure that these gases are stored under, producing a cloud of burning gas of several hundred cubic metres. The exposure of LPG and DME containers to fire, on the other hand, can cause a BLEVE, which also results in a large cloud of burning gas. An explosion in a vehicle's gas container in an underground garage can cause devastating damage and injury to people, rescue services, and property. Due to the low probability of fire propagation to vehicles (Collier, 2011), the likelihood of an explosion occurring in a non-gas vehicle during a fire is low, but can probably be further reduced. A fire in a gas-powered vehicle, however, is a very dangerous scenario. Likely causes of such a fire include arson and electrical failure, both of which are preventable. Vehicle fuel containers age, and can be weakened relatively rapidly by Swedish road conditions. The testing standard for gas container pressure-relief valves is quite vaguely worded, introducing further uncertainty as regards the exposure of a container to various kinds of real fire. Taken together, these factors increase the probability of a pressure vessel explosion as a result of fire.

Nordström (2015) concludes that the most serious near-accidents experienced by firefighters in connection with smoke diving have occurred 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) and the fact that, during a fire in a car, large quantities of dense fire gases can form and the temperature can be high. The situation is made even worse by the fact that alternative fuels bring new risks, not the least of which is explosion. The risks that rescue services face are discussed in more detail below.

Most countries, municipalities, and county councils pose restrictions relating to the presence of gas-powered vehicles in underground structures. These range from a total ban, to their being allowed 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). Ensuring that these restrictions are adhered to, however, is frequently difficult, as is the more general task of introducing alternative fuels in order to decrease our dependency on fossil fuels.

Leaving aside their plausibility and cost-effectiveness, possible safety measures that may decrease the risk of vapour cloud explosions in underground garages include:

- Ensuring that garages have a large volume so as to reduce the pressure-related consequences of explosions (note that this contradicts the fire-safety recommendation of limiting the size of fire compartments).
- Pressure-relieving windows/lightweight panels (of less than 10 kg/m^2; Turgut et al., 2013) consisting of fire compartment-separating walls. Outwards-facing windows or openings are not possible underground.
- Optimising the structure of the building from an explosion perspective: steel frames and plastic-reinforced concrete are best, while load-carrying masonry/prefab structures are worst. Load-carrying walls and pillars must be well anchored to the ceiling so as to ensure that they are not lifted by a blast, which would cause them to fall again and likely fail
- Private garages, which decrease the risk of arson.
- Greater distances between cars to decrease the risk of fire propagation.
- Marked spaces for charging electric cars, located at safe distances from other spaces and with extinguishing systems.
- Fixed firefighting systems, such as sprinklers, and access to portable firefighting systems, for example hand-held fire extinguishers or fire blankets adapted for vehicles.
- Fire-detection systems.
- Security camera systems to decrease the risk of arson and possibly detect a fire.
- Reserving and marking certain spaces for use by gas cars to reduce risks and facilitate rescue service operations (Reitan et al., 2016).
- Adaptation of alarm-controlled ventilation, which is currently only suited to petrol and diesel products, to the gases that are used by gas vehicles and formed in and emitted by batteries in electric vehicles. The ability to break off the primary current supplied to the premises, including to the ventilation system, in the event of a short-circuited battery, which causes gases to not be vented.

As vehicles are generally replaced more frequently than buildings, it is preferable that efforts to increase safety be directed towards rescue services and vehicles rather than implementing safety measures in buildings, as these are more difficult to implement for existing buildings. Technical measures should primarily focus on garages that are open to the public since arson is more likely to occur in these than in private garages. One measure that may be cost effective (as noted by Collier, 2011) are fixed firefighting systems, such as a sprinkler systems, that could also facilitate rescue operations. Adapting alarm-controlled ventilation systems to the exhaust fumes of alternative fuels makes sense. The risk of building collapse as a result of a pressure vessel explosion should be further investigated for different types of building.

4.2   Road tunnels

From a fire-safety perspective, small car fires are rarely a problem, while trucks with loads constitute the largest fire risk. The risk of fire represented by alternative fuels in vehicles is small; as regards electric cars in tunnels, a fire is a more likely scenario than thermal runaway without fire, due to the fact that thermal runaway rarely occurs when a car is in use. A fire in an electric vehicle can be more difficult to extinguish than a fire in a normal vehicle, but is not necessarily worse with regard to evacuation. Most longer tunnels in Sweden have a longitudinal ventilation velocity of at least 3 m/s, and some have velocities of as high as 8 m/s. As ventilation causes fire gases to be diluted, car fires rarely become problematic in these tunnels.

Gas vehicles involve three types of explosion risk. A large gas-air explosion is the result of an interplay between the emission, the cross-sectional area of the tunnel, the ignition source, timing, and ventilation velocity, such that ignition takes place when a large portion of the vapour cloud is near to stoichiometric conditions. An emission from a pressure-relief valve or fuel pipe is too small to cause a dangerous explosion. The worst-case scenario is a near-instantaneous emission of all of the gas from a gas container (at a rate of 10-40 kg/s). Such an emission would only last for a few seconds as the gas container would be rapidly depleted. The probability of the emission, cross-sectional area of the tunnel, ignition source, ventilation velocity, and timing of all of these interacting in such a way as to create a large explosion is very small, as is confirmed by existing statistics (in that no vapour cloud explosions have occurred in road tunnels) and experiments (Weerheijm and Berg, 2014; Berg, 2014; Groethe et al., 2007; Zalosh et al., 1994).

A spontaneous pressure vessel explosion is unlikely to occur due to the fact that the pressure in containers decreases during travel due to fuel consumption. In addition, containers are able to resist collision damage, although post-incident reports suggest that this is not always, or entirely, the case. The possibility of a pressure vessel explosion or BLEVE as a result of a fire cannot, however, be eliminated. Regardless, it can be assumed that evacuation of the immediate incident area will have taken place during the fire, and prior to the container exploding or jet flame occurring. Thus, road users are unlikely to be injured by an explosion or a jet flame. More broadly, the explosion pressure is unlikely to endanger those in the tunnel. A pressure vessel explosion caused by a vehicle gas container constitutes a relatively small strain on the structure of a tunnel.

In conclusion, the risks (in terms of both probability of occurrence and consequences) associated with use of alternative fuels in road tunnels are relatively low, and there is no need for special regulations or measures to be established. Rescue operations, however, are much more at risk in both underground garages and tunnels; this is discussed in more detail in a dedicated chapter.

4.3　Vehicles

In general, preventive measures are more effective than harm-reducing ones. Two obvious preventive measures are to reduce the number of fire-related electrical failures in vehicles and to reduce arson fires; others involve reducing the probability of a container that is exposed to fire exploding through periodic inspections, slower (and thus safer) venting, and improved fire resistance and testing standards for gas containers. All of these measures could increase the likelihood for the pressure-relief valve not having to release or, in the event of this being necessary, provide sufficient time for it to do so. The safety measures suggested below are intended primarily for use with gas-powered vehicles, as these present the greatest risks:

- Improved fire resistance of gas containers for a time period roughly equivalent to that plausibly required for a rescue operation.
- Improved fire testing that encompasses multiple probable scenarios, including local fire exposure, for gas containers.
- Ensuring that containers are robust throughout their expected life.
- Designing gas containers such that, during exposure to fire, gas emissions are slow, instead of rapid and sudden. It is likely that, under certain circumstances, this already applies to Type 4 containers, as these are made entirely of plastics/composites.
- Pressure-releasing and temperature-regulating pressure-relief valves, as well as an investigation into which is better or whether a combination of the two would

be optimal. An investigation into how new sensors, which are capable of detecting if a material is in the process of weakening, can be developed.
- The requirement on periodic inspections of gas vehicle systems has been proposed by the MSB (2016b), who also assert that the Swedish Association of Vehicle Workshops has called for such a system. Periodic inspections are conducted in the USA and Iran, among other countries in which CNG vehicle usage is common, and appear to have favourable results.
- Marking of vehicles; work is ongoing within the International Organization for Standardization (ISO).
- Decreasing electricity-related vehicle fires, such as those which start in the dashboard, through safer vehicle design (MSB, 2016b).

Performing periodic inspections of vehicle gas containers appears to be very plausible, and such inspections should, according to Jönsson, be based on an external, visual examination intended to detect cracks, corrosion, and damage to the container. Hydrostatic testing is not recommended as a method as it can damage the container and gas system, and is not always suitable for detecting damage (Jönsson, 2003). Further research projects are required in order to improve existing fire testing and evaluate alternative fire protection systems for gas containers. Smart electrotechnical design and containers that are durable throughout their life are quality-control issues that should be dealt with by the automotive industry.

4.4 Rescue operations

An incident involving a vehicle that uses an alternative fuel should, in essence, be handled in a similar manner to any other, but several aspects should be considered by the rescue services. In order to ascertain whether the vehicle is powered by an alternative fuel, the smartphone apps 'Fordonskoll' ('Swedish licence plates') and 'CRS' (Crash Recovery System; also include non-Swedish registration plate numbers) can be used. Their use, however, requires that the registration plate is visible and indeed identifiable, which is not always the case. At present, however, many rescue services are unable to access these services. In the future, a standard for marking cars according to the fuels that they use will be introduced as part of the 'ISO 17840 Road vehicles – information for first and second responders' standard. This will be implemented in four parts; the first two relate to designing a rescue sheet containing information to assist rescue services in rapidly and safely conducting operations, both for cars (Part 1) and heavy vehicles (Part 2). Part 3 will take the form of an extended emergency response guide that will function as an extension of the rescue sheet, while Part 4 specifies the symbols that will be used to assist rescue services in quickly identifying the type of fuel that a vehicle uses.

Larger road tunnels are often monitored by traffic management personnel, who perform camera surveillance. This can provide rescue services with detailed information about the incident and the fuels involved before they arrive on-site. Some garages also have camera systems, which can facilitate the work of rescue services. The leader of a rescue operation on-site should always perform a risk assessment prior to authorising the use of strategic methods during a rescue operation. According to the Swedish Work Environment Authority (AFS 2007:7), an internal extinguishing operation utilising smoke divers is to be performed only in order to save lives, and external fire suppression should be considered as a preferable alternative. Due to the size of some buildings, however, it may not be possible to accomplish fire suppression from outside the building, and so internal fire suppression is often a necessity.

In tunnels, the STA works with a series of contradictory goals: Tunnels are equipped with hand-held fire extinguishers that allow road users to attempt to extinguish a fire, but their existence is in opposition to the strategy of anyone inside the tunnel evacuating as quickly

as possible in the event of an incident so as to ensure that road users do not expose themselves to unacceptably large risks[15]. At the same time, however, it is during the early stages of a fire that its development can be influenced most, and much time can be saved by the efforts of a road user with a hand-held fire extinguisher. Fire blankets for vehicles have been introduced to the market, and these allow road users to slow the development of the fire before leaving, making the work of the rescue services easier when they arrive. Vehicle fire blankets are made using strong materials that can withstand splinters, and can be placed in cars, parking garages, and tunnels. Personnel who are not professionally trained in emergency situations, such as security officers, can be trained in the handling of these, but clear instructions should also be available so that the public is also able to use them[16].

4.4.1 Rescue operations involving an electric vehicle

In Section 3.5, the risks that are particular to electric and hybrid-electric vehicles are described, based on the work of Hoffmann (2013). The report was written as part of a 'triple helix' project (a collaboration between industry, academia, and government authorities) named 'Räddningskedjan' ('the rescue chain')[17]. The project resulted in a literature review that summarises the recommendations and presents a 'what to consider' list for traffic incidents involving e-vehicles. An educational video is available on the 'Räddning e-fordon'[18] ('Rescues involving e-vehicles') blog that shows the safety measures that should be taken or avoided during an incident. In brief, the recommendations are as follows:

- During an incident, the safety system of the car should disconnect the battery from the electric propulsion system and, as an extra safety measure, the ignition should be turned off and the 12-volt battery disconnected. This is done in order to ensure that the car does not 'drive itself' away, as it is often difficult to hear whether the system is running as compared to the sound of a combustion engine.
- If the car is charging, the cable should be unplugged from the post/wall.
- Mass-produced electric vehicles built since 1997 always have orange cables placed in the chassis, meaning that it is safe to cut the pillars. Hydraulic rescue spreaders that are propped against the rear of the back seat should, however, be avoided as batteries are sometimes placed within the rear of the back seat.
- It is safe to wade or dive down to a submerged electric vehicle in order to save passengers. Live battery parts should, however, not be opened or touched when under water.
- Electric vehicles built since 2012 are equipped solely with Li-ion batteries, the battery fluid of which is not corrosive but is combustible.
- During fires, fire gases should be ventilated to decrease the concentration of flammable and/or harmful gases. Flames should then be suppressed and the car cooled (which may require large amounts of cooling agents). If the battery is not visibly smoking and the temperature in the battery decreases, as determined by a thermal imaging camera, the vehicle can be moved from the incident site.
- If the temperature in the battery cells exceeds 190°C and continues to rise, thermal runaway can occur (see Chapter 3.5.4).
- Fognails and cold cutting extinguishers should not be used in scenarios involving battery packs.

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[15] Ulf Lundström of the STA, at a workshop on tunnels held on November 8, 2016.

[16] Krister Palmkvist, an experienced leader of rescue operations, at a workshop on tunnels held on November 8, 2016.

[17] https://www.msb.se/sv/Insats--beredskap/Brand--raddning/Trafikolycka/Raddning-e-fordon/

[18] http://e-fordon.blogspot.se/

- Those responsible for the car after the rescue operation has been concluded should be aware that there is a risk of re-ignition in the battery, which should be placed so that, in the event of a second fire, it can cause no harm or damage.

This project was unable to confirm whether electric vehicles constitute a greater danger than conventional vehicles during underground fires. One problem is that an electric vehicle fire requires a greater amount of extinguishing agent to extinguish, and contaminated extinguishing agents must be properly disposed of so as to not cause damage to the environment. Another unexplored area is the toxicity of fire gases. During both workshops, the issue of whether the current protective clothing of firefighters is designed to protect against toxic smoke arose. At present, no evidence shows that fire smoke from an electric vehicle is more toxic than that from a conventional vehicle; on the other hand, there is nothing to suggest that the current protective clothing is sufficient to protect firefighters from toxic smoke gases created by conventional vehicles. Hydrogen fluoride is a toxic substance that was discussed during one of the workshops. It is formed during vehicle fires but also during thermal runaway in batteries, and can then be difficult to detect.

4.4.2   Rescue operations involving a gas-powered vehicle

During vehicle fires, rescue services often do not dare to adopt an aggressive strategy, i.e. approaching the fire and beginning to extinguish it, as a result of the dangers of gas containers, and instead generally follow a defensive strategy of roping off the area and leaving the fire to burn out by itself. This is problematic in tunnels and underground garages, where there is a risk of the fire spreading to other vehicles or parts of the structure[19]. In order to minimise the risk of explosion, gas-powered cars are equipped with melt fuses that release at 110°C. These are placed close to the cylinder valves, and provide relatively reliable protection against pressure vessel explosion during heating. When a melt fuse releases, however, a jet flame can occur, which can then ignite adjacent objects. If this jet flame hits the gas container of another gas vehicle, a pressure vessel explosion could occur due to the fire affecting the gas container centrally, rather than at either end, where the melt fuses are placed (MSB, 2016b). This is, however, an unlikely scenario at present due to the relatively few gas vehicles currently on the road, and so the likelihood of two being parked next to each other is low. Furthermore, the pressure-relief valve of a fuel container should be oriented so as to prevent further side-on exposure of the container to fire Such a scenario can occur with larger vehicles, such as buses and trucks.

In March 2016, the MSB published a handbook for rescue services detailing procedures for dealing with gas-powered cars at indoor and outdoor incident sites (MSB, 2016a). In brief, the MSB suggests a 'hot' zone[20] of 10 m around the car(s) during a traffic incident, extending to 50 m for a fire in the interior of a vehicle in which there is no jet flame. The protective equipment that is to be worn in 'hot' zones consists of protective clothing, compressed air breathing apparatus, and an explosimeter. Ex-marked communication and lighting equipment is also a necessity. During an incident involving a fire in the interior of a vehicle, active hearing and eye protection are to be worn.

For vehicle fires in indoor environments (e.g. garages), the MSB recommends that operations be performed primarily from outside of the building, unless it has been established that an internal operation is required in order to save lives. If an internal operation is to be performed, it is important that all possible apertures are opened so as to

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[19] Peder Lindström and Krister Palmkvist, experienced leaders of rescue operations, at a workshop on rescue operations in parking garages on September 20, 2016.
[20] During rescue operations, the incident area is normally divided into 'cold', 'warm', and 'hot' zones, in which different safety measures are to be observed.

relieve the pressure to the greatest possible extent. 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. The drainage system of a multi-storey car park in which an incident is occurring should, if possible, be turned off. Extinguishing should be performed by cooling with water. Dry powder extinguishers and compressed air foam systems (CAFS) can be used to extinguish fires inside the interior of a car, but not for cooling. Jet flames should never be extinguished, but allowed to burn out by themselves, and it is important that the concentration of gas at high points on the rear-underside, in the interior, and in the engine compartment of the car be measured, and that hissing sounds that may indicate a leakage be listened for. More detailed information can be found in the handbook produced by the MSB.

In 2015, 5 containers in a refuse collection truck in Indianapolis, USA exploded as a result of being exposed to fire. The containers were equipped with melt fuses and fulfilled American standards. One of the factors that may have contributed to the explosion was the water used by the rescue services, which likely cooled the melt fuses (MSB, 2016b). It is as-yet unclear whether, when a vehicle fire results in gas containers being exposed to fire, rescue services should attempt to extinguish the fire. This uncertainty is due primarily to the fact that the melt fuses of the container may be cooled, increasing the likelihood of a container explosion occurring (MSB, 2016b).

After an operation has been concluded, there may be gas containers in the vicinity that have been exposed to fire but the pressure-release valves of which have not been released, and these must be disposed of in a safe way. Depending on the material in the container and the way in which it has been exposed to fire, dealing with the cylinder and burning the gas may involve a number of risks. The most common procedure is to create a hole in the container using a rifle, but this involves risks relating to the emission of uncombusted gas. An investigation should be performed in order to ascertain whether the safety guidelines that advise against handling Type 1 gas containers that have been exposed to fire can be changed. As these containers are made of steel, the bottle is hardened at a temperature of 900°C during manufacture, whereas during a fire in which a container does not explode, the temperature likely reaches a maximum of 500°C. When the gas container cools, it is at least as likely as any other vehicle gas container to not explode, as the pressure in the bottle is lower and the steel stronger than during the fire.

5   Discussion

The increased risk of explosion in a scenario involving gaseous fuels should be compensated for by safety systems that reduce the risk of emissions and pressure vessel explosions. It is uncertain, however, whether this is a universal truth, particularly as regards parking garages – the site of several incidents in which safety systems have not functioned as expected. Furthermore, there exist ambiguities regarding how, in practice, inspection and maintenance are to be performed in terms of both procedure and regularity, as well as how well fire testing standards correspond with real fires. Based on some of the events that have been described in this report and the MSB's latest report on the risks associated with gas vehicles, it is clear that there exists uncertainty within rescue services with regard to the risk of an explosion during fires in gas vehicles, and how to handle these kinds of fire. Did containers that exploded do so due to a melt fuse being cooled as a result of the extinguishing operation, or would they have exploded anyway? Is there a need for another type of gas system, and how should this be designed in order to ensure a relatively high level of safety for extinguishing operations?

Another great uncertainty in the literature review relates to the states in which different types of vehicle gas container can be expected to be found in as a result of real-world usage. When they undergo fire testing, containers are new and generally able to easily withstand their design pressure, and so pressure-relief valves are designed based on this. Fuel containers are subsequently exposed to a corrosive environment, and sometimes even bumps and collisions. Their life is, in practice, highly uncertain. In Sweden, at least two containers have exploded at a pressure of 230 bar. It may be that many containers do not meet their design pressure in the real world. An analysis of random samples would provide a better overview of the situation, as well as a better picture of the different types of container.

A discrepancy exists between the ways in which risks are handled, as approaches often depend on the presence of gases in general or gases contained within vehicles that are parked in indoor environments. According to FM Global, hydrogen gas should not be stored indoors, and the practice of differentiating between LPG cylinders that are loose or mounted in a car is questionable in light of the fact that the presence of the latter in garages that are situated directly below apartments is considered to be acceptable, while the presence of the former is not. Unlike LPG cylinders, gas containers are required to have a pressure-relief valve. On the other hand, vehicle fuel containers are exposed to a harsher environment. Gas cylinders are relatively well documented in the literature, and a greater number of specifically created regulations exist regarding their handling than for vehicle gas containers.

The data relating to substances and fire and explosion properties is relatively complete in terms of our understanding of the phenomena involved. The explosion pressure in a garage environment can be roughly calculated, but this does not factor in the placement of the containers and deflections from walls, the ceiling, and the floor, and the consequent localised differences in pressure. The consequences of an explosion in different types of underground garage vary; some may be entirely demolished and even affect surrounding buildings, while others experience more localised damage. There are large uncertainties and knowledge gaps regarding the effects of pressure vessel explosions on the structures of underground garages of varying sizes. In a tunnel, road users generally have time to evacuate before a fire causes a pressure vessel explosion or the formation of a jet flame; the risks in such a scenario are generally more related to the rescue personnel and the performing of the extinguishing operation.

Electric and gas-powered vehicles do not pose any significant risks in tunnels as compared to conventional vehicles with regard to effects on the tunnel structure On the

other hand, evacuation can become more difficult in the event of a leak or fire due to a collision, resulting in an increased risk of exposure to an explosion or jet flame.

Based on the discussions that took place during both workshops, quality-control issues with gas containers appear to be part of a larger problem within the automotive industry. The quality, safety, and longevity of a car should be ensured through type approval. There appear, however, to be flaws in this system, which is founded largely on self-inspection, based on the problems that exist for some of the car models on the market. At present, type approval does not guarantee the high quality and safety of a vehicle. Another uncertainty that was discussed at the workshops relates to the fact that there is no clear safety framework to which current and future vehicles can be expected to adhere. Thus, it is difficult to know which risks should be borne in mind during the design of road infrastructure. A third issue that was raised is that road users should be knowledgeable regarding, and be able to extinguish, fires that may occur in the vehicles that they drive. This is particularly important with regard to those for whom driving is a profession, such as truck drivers, who should know how to extinguish a fire, evacuate a road tunnel, and, in so doing, assist other motorists. This issue greatly affects the operations of rescue services, as there is a much greater chance of extinguishing a vehicle fire during its early stages than later, at the point at which rescue services generally arrive. At present, rescue services are very uncertain regarding their working environment and the risks involved in the alternative fuels that are increasingly being used in vehicles, especially in enclosed spaces such as tunnels or underground garages. This uncertainty relates to risk of explosion, being hit by a jet flame, and exposure to toxic fire gases. It is thus important that these risks are investigated, and that methods are developed for extinguishing fires that avoid exposure to toxic fire smoke.

6   Recommendations and future research

Current approaches to handling petrol and diesel are well-tested and relatively safe. However, leaking petrol (in the aftermath of vehicle incidents) causes many vehicle fires (Machiele, 1990). Alternative fuels, in the form of either gas or electricity, will likely lead to fewer leaks that are ignited, and thus fewer vehicle fires in general (Coen, 2010; Berg, 2014).

However, gas vehicles introduce new dimensions with regard to incident outcomes in terms of damage and harm caused, i.e. explosions,in terms of either pressure vessel explosion, BLEVE or ignition of gas-air mixtures. In addition, there is the risk of people being hit by a jet flame, and this is higher in tunnels, as the incident outcome in terms of damage and harm caused is most often the result of a collision. In garages, people generally have sufficient time to evacuate prior to a fire causing a jet flame or explosion. A jet flame can, however, increase the risk of fire propagation to adjacent vehicles in garages, where cars are often parked close to one another.

Explosions generally do not have any serious effect on the structure of a tunnel, as the amount of gas is too small in relation to its size and load-bearing capacity. In underground garages, however, the risks posed by gas vehicles are more critical. The likelihood of a container rupture as a result of a fire cannot be ignored, the possibility of production errors and flaws missed by inspections cannot be eliminated, and even a container that fulfils all of the requirements placed on it and passes all of the relevant tests can explode during a real fire. The incident outcome of such a scenario relates to damage to property, firefighters, and individuals that are in, and possibly above, the garage. This issue falls between the cracks in the approaches of government authorities: Boverket refers to the MSB, which refers to the STA, which in turn refers back to Boverket.

The consequences of an electric vehicle fire are comparable to those of a conventional vehicle fire. However, charging introduces an additional fire source [21]. A thermal runaway, even if it does not cause, or is not caused by, a fire, produces toxic gases, including hydrogen fluoride, in potentially lethal amounts.

In conclusion, a future in which most cars are charged and most gas vehicles are parked in underground garages may lead to a dangerous situation, with an increased likelihood of fires caused by the former and increased incident outcomes in terms of damage and harm caused by the latter. The likelihood of fire propagation between either an electric vehicle and a gas vehicle or two gas vehicles, however, is relatively low (below 15%), and can be further reduced by smart design and the considered placement of charging stations. As the risk of fire propagation between vehicles is relatively low, it is recommended that efforts be made to increase the fire safety of gas vehicles with regard to electrical failure and arson, as well as ensuring that gas containers are able to resist fire and are equipped with robust pressure-relief valves that function correctly and punctually during the various fire scenarios that may occur. Fire propagation can be limited by using sprinkler systems, which also increase the safety of rescue operations.

Regulations need to be adapted with the alternative fuels of the future in mind. This particularly involves the Swedish Work Environment Authority and regulations for ventilation, which should be triggered by the gases, such as methane, hydrogen gas, and hydrogen fluoride, which are emitted by gas and electric vehicles. In addition, the STA's

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[21] Pure electric vehicles, on the other hand, do not use liquid or gaseous fuels, and have no hot surfaces that can ignite flammable leaks; thus, they present fewer fire sources than vehicles with combustion engines.

responsibility to periodically review the state of vehicle gas containers so as to decrease the risk of pressure vessel explosions should be noted.

6.1 Safe gas containers in vehicles

A holistic approach to gas container systems including both the container and safety systems, allows them to be optimised from a safety perspective. Systems should be designed to be better able to resist a pressure vessel explosion as the result of a fire than they are at present in the following ways:

- The standard for the fire testing of gas containers should be improved.
- Periodic inspections of vehicle gas containers in Sweden should be performed.

Investigations should be conducted regarding:

- Whether and how pressure-relief valves or other sensors, along with melt fuses, can be used to prevent container ruptures during exposure to fire.
- Whether it is plausible to require that vehicle gas containers are protected from fire.
- The risk of fire propagation between vehicles as a result of jet flames.
- Whether containers can be constructed so as to ensure that emissions as a result of fire are relatively slow, instead of rapid and sudden.

6.2 Safe underground garages

The uncertainties in our understanding of vehicle fuel container pressure vessel explosions in different kinds of garage are considered to be substantial. Critical building types, i.e. those in which there is a strong risk of collapse, can likely be identified.

- The cost and possible value of requiring sprinklers in underground garages that are open to the public (likely positive according to Collier [2011]) should be assessed.
- Alarm-controlled ventilation in garages must be adapted to detect gases emitted by electric and gas-powered vehicles.
- Further studies should investigate the consequences of a vehicle gas container pressure vessel explosion in underground garages in typical buildings.

6.3 Guidelines and future research for the benefit of rescue services

There are also significant uncertainties in this area, not least regarding guidelines for fires in gas vehicles: For example; should containers be cooled? There is also a great deal of uncertainty as regards the toxicity of fire gases, and how these affect firefighters.

- As fires in underground structures can be difficult to extinguish from the outside, and may consume a great deal of an operation's duration, how oxygen can be used to allow smoke divers to remain in smoke-filled environments for longer.
- Thermal imaging cameras facilitate orientation inside an underground structure, but their status as hand-held units is limiting for firefighters. Thus, investigating how thermal imaging cameras might be placed on helmets would be a fruitful avenue of inquiry.
- Similarly, the toxicity of fire gases in both regular and electric vehicles, as well as the extent to which firefighters' protective clothings protect them from these gases, should be investigated.
- Guidelines should be developed for risk assessment and methodology during operations to extinguish gas vehicle fires.

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